

Integrated spatial assessment of the water, energy and food dimensions of the Sustainable Development Goals

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Abstract Water is considered the bloodstream of the biosphere, but its management is one of the most important challenges for human development. In view of the sustainable water management, several approaches have been proposed: Integrated Water Resources Management, Adaptive Management and, more recently, Water–Energy–Food (WEF) Nexus. Considering these approaches, over the last few decades, extensive efforts have been made to develop assessment methods and tools framed within the paradigm of sustainable development. As part of a holistic assessment of water resources, the recent approach based upon the WEF Nexus narrows down the consideration of intersectoral linkages to three dimensions that are of prominent interest, in particular in developing countries. This study presents a comprehensive indicator-based approach for the assessment of water, energy and food securities, with reference to the Sustainable Development Goals of the United Nations. The main ambition of the proposed approach is to provide a tool to monitor progresses, compare different geographical areas, highlight synergies and conflicts amongst and within the three dimensions of the WEF Nexus, and provide support for improved—more effective—management strategies to meet the goals. The proposed approach is demonstrated in the Ganges–Brahmaputra–Meghna (GBM) River Basin in Asia and to the Po River Basin in Europe. The comparative

analysis suggests that WEF security is currently rather low in the GBM basin compared to the other case study and other parts of the world and allows the identification of which dimensions (indicators) require special attention on the part of local and global policy makers.

Keywords Water, Energy and Food Nexus · Sustainable development goals · Indicators · Security index · Assessment

Introduction

The global picture and the regional problems

Given the unique role as the essential resource sustaining life and providing important ecosystem services, water is considered the bloodstream of the biosphere (Pahl-Wostl et al. 2013). Globally, the available renewable freshwater supply exceeds the current human demand (Oki and Kanae 2006), but its high variability and uneven distribution in time and space makes its management one of the most important challenges for human development (Postel et al. 1996). Moreover, climatic change, population growth, economic development and the related land use changes have direct impacts on increasing demand for freshwater resources (Immerzeel and Bierkens 2012). The Intergovernmental Panel on Climate Change (Stocker et al. 2013) suggests there is a high likelihood that observed and projected increases in temperature and change in precipitation patterns will result in an overall decrease in precipitation in the tropics and increase in the mid-latitudes. Moreover, the probability of extreme events is expected to increase, with increased frequency of droughts and floods and important consequences on ecosystems and people's livelihoods and well-being.

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Beside climatic change, current population growth, economic development and the related land use changes have direct impacts on increasing demand for freshwater resources. Providing safe drinking water for the world's growing population is one of the greatest challenges of the century (Oelkers et al. 2011). Human interactions with the hydrological cycle are often characterized by mismanagement and ecosystem impairment. A common feature of this globalization of water problems is the legacy of poor governance (Vörösmarty et al. 2013), which is a major challenge for achieving sustainability of twenty-first century.

Over-withdrawal of surface water and groundwater, inadequate engineering practices, pollution and biotic stressors have led to depletion of water resources and environmental damage in some regions and mounted pressures on water systems across the planet (UN-WWAP 2012).

From the above, the need clearly emerges for adequate approaches to monitor the evolution of natural resources under the pressure of natural and anthropogenic stressors, to synthesize the information acquired and to support assessment of the sustainability for social and ecological systems at various scales, from local to global. Sustainability assessment should first of all identify proper ways to describe the phenomena to be assessed, and significant measurable variables should then be identified, monitored and processed to transform the acquired data into information that can be used for communication with non-experts (Giupponi et al. 2006). In particular, data collected should be integrated and aggregated to provide concise and meaningful messages to decision-makers, stakeholders and the general public. A quantitative index assessing the status of water, energy and food resources and their nexus, i.e. their mutual relationships, could significantly contribute to provide concise information to support policy makers, but it is currently lacking.

The aim of this study was to develop an approach for quantitative assessment of water, energy and food security at the global scale in a holistic manner. Based on the recent acquisitions of the literature about sustainable water management (Sect. 2), we developed upon the concept of Water–Energy–Food (WEF) Security Nexus, to propose a set of indicators for comprehensive assessment of water resources. We selected spatial indicators with specific reference to the sustainable development goals (SDGs), recently approved by the United Nations General Assembly (25 September 2015),¹ and we propose a method to aggregate them in a single WEF security index, by means of a multi-criteria approach, which allows to take into

account different decisional attitudes of policy makers (see Sect. 3). The main ambition is to provide a transparent and reproducible GIS-based approach to assess the state of WEF spatial indicators, which could be adopted in the future to monitor the progresses in meeting the SDGs, allowing to compare different geographical areas and highlighting synergies and conflicts amongst the three dimensions of the WEF Nexus. The proposed approach has been applied at global level and it is demonstrated in Sect. 4, by extracting the results in two river basins: the Ganges–Brahmaputra–Meghna (GBM) River Basin in Asia and the Po River Basin in Europe.

Paradigm shifts in sustainable water resources management

Until recently, the paradigm for water resource management was based on a traditional command and control approach, which assumes the existence of predictable outcomes and reversible trajectories of change within natural systems (Milly et al. 2008). However, a series of failures resulting from the adoption of this traditional approach demonstrate that sectorial, fragmented and top-down methods in water management have to be replaced by more holistic procedures recognizing the complexity of the social and ecological system known as the water resources system (WRS). Mounting evidence of the failure of conventional approaches to achieve equitable and sustainable water management has pushed scholars and policy makers towards the identification of new paradigms and operational approaches (Pahl-Wostl et al. 2011). To date, at least three relevant solutions for sustainable water management have emerged as reference paradigms: Integrated Water Resources Management (IWRM), Adaptive Management (AM) and Water–Energy–Food (WEF) Nexus.

Integrated Water Resources Management (IWRM) is probably the most widely acknowledged in current water policies worldwide (GWP 2012). As a global paradigm of sustainable water management, IWRM was codified in 1992 via international norms such as the Dublin Principles of the International Conference on Water and the Environment, and Agenda 21 of the Rio United Nations Conference on Environment and Development (UNCED). At the World Water Forum in The Hague (in 2000), 113 countries adopted IWRM principles (Savenije and Van der Zaag 2008). Further international endorsement came in same year when the UN adopted IWRM as part of its Millennium Development Goals (De Stefano 2010), and Europe formulated the EU Water Framework Directive (EC/60/2000) for managing water resources at the river basin scale (Benson et al. 2012).

While conceptions of IWRM principles vary between contexts, it is widely recognized that the main aim should

¹ http://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E, last accessed 27 February 2016.

be to ensure more coordinated management between different aspects of water issues such as water quality, land management and habitat protection. Recent studies (Gain et al. 2013b; Rouillard et al. 2014) identified six key dimensions of IWRM: (1) integration between different water-related components—water quality, climate adaptation, agriculture and energy production; (2) hydrologically relevant scales for management; (3) good governance through institutionalization of IWRM across different levels and actors; (4) stakeholder participation—local communities and individuals, businesses, civil societies, policy makers and public organizations; (5) valuation of water resources as economic and social goods; and (6) demand management by increasing efficiency in water use, rather than increasing water supply.

However, despite IWRM being promoted as an attractive approach, the actual implementation of IWRM is lagging behind. Hering and Ingold (2012) argued that one of the main impediments to IWRM implementation is the normative value placed on integration per se. The failure to define and constrain the scope of integration almost inevitably leads to ill-posed and unmanageable problems (Biswas 2008). In addition, although IWRM features the key dimensions of an integrated approach, its capability to readily enhance flexibility and adaptability through consideration of uncertainty as required for water systems affected by global environmental change has been questioned.

Adaptive Management (AM) lies in many different intellectual and practitioner fields, referring in general to a systematic process for the continual improvement of management practices by learning new experiences ('learning by doing' approach) and insights from the outcomes of implemented decisions (Allen et al. 2011; Holling 1978). This approach is primarily concerned with the management of uncertainty through formalized experimentation and process-based learning (Huitema et al. 2009).

The global water resources system is facing multiple challenges due to increasing uncertainties caused by climate and global change, and by fast changing socio-economic boundary conditions (Pahl-Wostl et al. 2011, 2007). Adaptive management has received increasing attention for its ability to manage water resources under complex, changing conditions and in the presence of knowledge gaps (Allan et al. 2013). Adaptive management is expected to increase the capacities of water resources systems by considering several key dimensions: (1) a manageable complex social-ecological system with few foreseeable thresholds and surprises; (2) an effective innovation and capacity-building system based on adaptive cycles; (3) a flexible decision-making system that enables local self-determination; (4) accessible participatory mechanisms

that support fair exchange between social actors (Rouillard et al. 2014).

AM has been widely promoted as a solution to complex natural resource management problems. However, while a few projects have been able to effectively apply adaptive management to complex problems, it remains more an ideal than a reality (Allen and Gunderson 2011). These theoretical management approaches (both IWRM and AM) are difficult to translate into practice and consequently successful examples of implementation are limited. According to Medema et al. (2008), the major obstacles to implementing both IWRM and AM are as follows: little evidence of success; ambiguity of definition; complexity; institutional barriers; risk; and cost.

Water–Energy–Food (WEF) Security Nexus is a relatively new paradigm, with a specific focus on security issues related to three interconnected dimensions that are highly important for society and economy (Olsson 2013). The Bonn 2011 Nexus Conference is internationally recognized as the first relevant event to the launch of the WEF Security Nexus worldwide, with a specific emphasis on the relationships with green economy. Acknowledging the significant contribution of the Bonn Conference, the 2012 Mekong2Rio Conference took a step forward in exploring the Water, Energy and Food Security Nexus in a trans-boundary context.

The innovations of the WEF Nexus approach compared to the previously existing approaches lie in: (1) its ability to go beyond the water-centred management approach; (2) its focus on security concerns (Bakker 2012) for three inter-related resources that are highly important for society and economy; (3) the opportunity to create sustainable business solutions through public–private partnership (Benson et al. 2015; Bizikova et al. 2013).

Even if water can still be considered as *primus inter pares* (first among equals) in the WEF Nexus approach, as noted by Beck and Villarroel Walker (2013), the emphasis given to the two other connected sectors can allow water managers to think 'out of the water box', i.e. beyond the conventional water-sector-centred discourse (UN-WWAP 2009), something that is urgently needed in order to move in the direction of real integration and sustainability of resources management.

From the above, it appears that the three paradigms described above are not to be considered as alternatives, while key dimensions of IWRM (e.g. multi-stakeholder involvement, assessment and management at river basin scale, demand management) and AM (e.g. adaptable and flexible decision-making and consideration of uncertainty) can be aggregated with the WEF Nexus principles with the aim of achieving sustainability. The more focused approach of WEF Nexus for sustainable development can then be implemented by combining basinwide

management, governance, multi-stakeholder resource planning and policy integration, coordination and harmonization, promoting innovation and green economy, influencing policies on trade and investment in uncertain environment and climate (Bizikova et al. 2013).

In the following section, we present the proposed indicator-based methodology to calculate an aggregated WEF Security Index (WEF-SI), the approach adopted for the selection of indicators, and the method developed for aggregating spatial indicator to calculate the index.

Methods: indicator-based assessment of water resources

Indicator-based assessment methods

The 1992 Earth Summit recognized the important role that indicators can play in helping countries make informed decisions on sustainability. This recognition is articulated in Chapter 40 of Agenda 21, which calls on governmental and non-governmental organizations to identify Indicators of Sustainable Development (ISDs) that can provide a solid basis for decision-making at all levels. More recently, at the United Nations Rio+20 Summit 2012, the member states agreed to create a set of sustainable development goals (SDGs) to guide global development after the phasing out of the Millennium Development Goals (MDGs) in 2015. As in the case of MDGs, SDGs are defined through a series of measurable targets, thus requiring a considerable monitoring effort worldwide.

Ideally, the dynamics of spatial-temporal phenomena would require capabilities for dynamic and integrated assessment modelling of the complex water cycle and its relationships with energy and food production processes at multiple scales, but this is rarely possible. Therefore, indicator-based assessments emerge as a pragmatic operational solution to support the monitoring of phenomena through a series of static pictures of the state of social and environmental system variables at subsequent times (e.g. on an annual basis) and communicate their evolutions in a concise and effective way. In this context, indicators can provide crucial guidance for policy making in a variety of ways. They can in general translate physical and social science knowledge into manageable units of information that can facilitate the decision-makers in their efforts to measuring, monitoring and reporting on progress towards meeting the SDGs, and sustainability in general.

According to the scheme proposed by the Organisation for Economic Co-operation and Development (Organisation for Economic Co-operation and Development 1991, 1994), variables which can be observed and measured can later be transformed into indicators, values

whose significance extends beyond that of the variables themselves, with respect to specific purposes. Moreover, a set of aggregated indicators may produce a more concise and representative value called an index. Combining relevant indicators into a composite index presents the available evidence in a much more concise, targeted and effective fashion than would individual indicators (International Council for Science 2002) and, as stated above, it facilitates the use of such information by policy/decision-makers and non-experts.

Regarding the SDGs, it could be ideally possible to develop a single aggregated sustainable development index, synthesizing the progress towards the whole set of 17 SDGs in a given place and time, but quite likely it would be of limited use for policy makers for excessive simplification and loss of information. Thematic indexes focused on one or a few SDGs could be more meaningful and effective and that could be the case of the index focused on the goals related to WEF Nexus we describe below.

Selection of indicators

Despite the existence of several integrated approaches for water resources management (as described in the previous section), assessment methods for water resources at larger geographical scales usually have a mainly physical and biological dimension, with a limited consideration of the social dimension. By having sustainability assessment as the main objective, we instead considered all three pillars of sustainable development (environment, society and economy) to provide a comprehensive indicator-based approach for the assessment of the WEF Security Nexus. With a specific focus on the notion of security, the most suitable indicators in terms of availability, affordability, accessibility, quality and safety (Bizikova et al. 2013) were selected to analyse and describe the status and security of water, energy and food sectors, and their interconnections.

Given its relevance for the current agenda of policy makers worldwide, and our ambition to propose an assessment method that could contribute to the monitoring of the achievement of the SDGs in the future, we identified the set of indicators to be adopted following the developments of the Sustainable Development Solutions Network (SDSN). SDSN indicators went through a long process of revisions and, even if they do not have any official international recognition or official endorsement so far, nowadays they represent a key reference of the current state of the art of the efforts towards the official adoption of SDG indicators by international agencies and statistical offices.

Initially, SDSN focused not only on the human dimension but also extended to the notion of planetary well-being

or boundaries, as reported in the May 2014 proposal.² Later on (March 2015³), the second dimension disappeared from the front line, and the previous set of ten SDGs, evolved into a wider set of seventeen in total. Three of them correspond broadly to the three dimensions of the WEF Nexus as they aim at ending hunger, achieving food security and improved nutrition and promoting sustainable agriculture (Goal 2), ensuring availability and sustainable management of water and sanitation (Goal 6), and access to affordable, reliable, sustainable and modern energy (Goal 7) for all.

The indicators selected for this work, along with references to the SDSN indicators, definitions and data sources are shown in Table 1.

For each of the selected indicators, data are collected from a diverse range of global sources: energy data are collected from WEC (2013); food data from GFSI (2014); water governance from Kaufmann et al. (2010); water quality from Srebotnjak et al. (2012); groundwater depletion data from Wada et al. (2012) and drought index from Wada et al. (2013). The structure of the geographical information system (GIS), the delineation of river basins and other physical and human features were derived from the IAASA and FAO project of Global Agro-Ecological Zones (IAASA/FAO 2012).

The assessment model

As stated above, the development of a concise index deriving from the aggregation of multiple indicators may contribute significantly to facilitate the transformation of scientific evidences into effective information for policy/decision-making, but several problems emerge in the processing of raw data to obtain meaningful indicators and eventually to aggregate them into a single index. The main issues and the solutions adopted are briefly discussed below.

Firstly, we need procedures coded in a software environment for efficient processing of huge amounts of spatial information. In our work, data about each indicator were stored as raster map layers (i.e. organized as unitary information cells, the picture elements or pixels), with a resolution of approximately 0.083 decimal degrees (around 10–15 km at intermediate latitudes). Each indicator map is represented as a matrix of pixels with 4320 columns and 2160 rows. Many geographical information system (GIS) software tools (Burrough et al. 2015) are available for that purpose, and we opted for a tool providing good capabilities to implement complex data processing algorithms in a transparent and reproducible manner, thanks to the

availability of a macro language. The whole assessment procedure was coded in the TerrSet macro language and executed within that GIS software environment.⁴

Secondly, we have to provide a solution for comparing and aggregating indicators measured with different units. The solution can be found in normalizing all the values of collected indicators, to obtain homogeneous non-dimensional scales between 0 and 1. In doing so, we attach also a valuation scale to the indicator ranges, with lower values expressing a negative situation in term of security and higher ones indicating improved security. The normalization procedure was carried out in the GIS environment through fuzzy membership functions (Schmucker 1983), which were linear (the higher the better of the lower the better) or in some cases trapezoidal (linear normalization with a plateau to express stable valuation to indicator values below or above a given threshold). We envisage the opportunity to consolidate the value functions in the future, when SDG targets will be consolidated, so that the output of the classification could explicitly demonstrate the areas in which the SDG targets are being accomplished, or the distance towards the goals.

Third is the issue of defining whether all the indicators should have the same relevance (i.e. weight) in contributing to the WEF-SI. We opted for applying weights to normalized indicators, providing a vector of weights applied in the aggregation procedure (see Fig. 1). Since weighting is inherently subjective, in the future applications weights should be the result of participatory processes with stakeholders (policy makers, institutions, NGOs, etc.).

Finally, the aggregation algorithm has to be defined. Many examples of aggregated indexes can be found in the literature. For example in the field of water resources, several indexes have been proposed for water scarcity and drought (Pedro-Monzónis et al. 2015), vulnerability (Kumar et al. 2015), quality (Abbasi and Abbasi 2012), etc. The aggregation algorithms are typically additive (weighted or not) and in some cases multiplicative. In this work, we went beyond the usual additive approach, where aggregated indexes are the result of the summation of the normalized and possibly weighted values to be aggregated. Although that method (defined as Simple Additive Weighting; SAW) is simple and easy to understand, it is fully compensatory: the result of aggregating a very good and a very bad value is the same as when two average values are aggregated (this situation is usually defined as ORness). At the other extreme is the case of multiplicative aggregation (ANDness), having an opposite problem: when only one of the indicators has zero value, the whole aggregated index is zero. In order to overcome these limitations, a multi-criteria analysis method (Belton and

² <http://unsdsn.org/wp-content/uploads/2015/02/140522-SDSN-Indicator-Report-MAY-FINAL.pdf> last accessed 4 May 2015.

³ <http://unsdsn.org/wp-content/uploads/2015/03/150320-SDSN-Indicator-Report.pdf> last accessed 4 May 2015.

⁴ <http://www.clarklabs.org>.

Table 1 Definition of water, energy and food security indicators with data sources. SDSN codes refer to the March 2015 release (see footnote 2; codes in square brackets are a proxy, even if not coincident with the SDSN definitions)

Acronyms of indicators	SDSN indicator code	Indicators	Definition, notion and data source
<i>Water security (SDG 6. Ensure availability and sustainable management of water and sanitation for all)</i>			
wtotinrepc	[49]	Total internal renewable water resources per capita	Unit: m ³ per inhabitant per year. A higher value leads to increase water security [source: FAO AQUASTAT]
wsanit	46	Access to sanitation	Percentage of population with access to improved sanitation. The values with higher access lead to increase water security [source: Hsu et al. 2014]
wdrink	45	Access to drinking water	Percentage of population with access to improved drinking water source. The values with higher access lead to increase water security [source: Hsu et al. 2014]
wqualit	[47; 48]	Water quality index	The values with higher index value lead to increase water security. [source: Srebotnjak et al. 2012]
wgwdepl	[49]	Groundwater depletion rate	Groundwater depletion rate (million m ³ /year) is calculated using global hydrological model. The values with higher DI lead to decrease water security. [source: Wada et al. 2012]
wdrought	[85]	Drought index (DI)	DI is calculated using global hydrological model. The values with higher DI lead to decrease water security. [source: Wada et al. 2013]
wgovern	[48; 6.9]	World Governance Index	World Governance Index calculated through the aggregation of six governance dimensions (source: Kaufmann et al. 2010)
whydtransbd	6.8	Transboundary Management Index	A proxy of the challenges deriving from the management of transboundary river basins, calculated by means of GIS context analysis operators. The normalization procedure produced a map with null values attributed to basins entirely included within country boundaries and increasing values up to 1 to those that cross national boundaries and have increasing level of complexity (length of drainage paths) and number of riverine countries [maps from the FAO GAEZ]
<i>Energy security (SDG 7. Ensure access to affordable, reliable, sustainable and modern energy for all)</i>			
eavailabi	[51]	Aggregated energy availability	Aggregated energy availability calculated through aggregation (equal weighting) of (1) ratio of energy production to consumption; (2) diversity of electricity generation; (3) distribution losses as percentage of generation; (4) 5-year compound annual growth rate of the ratio of total primary energy consumption to GDP; (5) days of oil and oil product stocks; (6) aggregation of net fuel imports as a percentage of GDP. [Source: WEC 2013]
eaffordab	[51]	Aggregated energy affordability	Aggregation (equal weighting) of (1) electricity relative to access; (2) retail gasoline. [Source: WEC 2013]
eenvsusqu	62; 78	Environmental sustainability	Aggregation (equal weighting) of (1) total primary energy intensity; (2) CO ₂ intensity; (3) Effect of air and water pollution; (4) CO ₂ grams/kWh from electricity generation [Source: WEC 2013]
epolitics	[91]	Political strength	Aggregation (equal weighting) of (1) political stability; (2) regulatory quality; (3) effectiveness of government. [Source: WEC 2013]
esocialst	[94; 31; 37; 17–30]	Social strength	Aggregation (equal weighting) of (1) control of corruption; (2) rule of law; (3) quality of education; (4) quality of health. [Source: WEC 2013]
<i>Food security (SDG 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture)</i>			
favgsupp	[8]	Average food supply	Unit: kcal/capita/day. The higher food supply value lead to increase food security. [Source: GFSI 2014]
fvolagrpr	[13; 2.14]	Volatility on agricultural production	The higher volatility value represent lower food security
foodloss	73	Food loss	Calculated as total waste/total supply quantity (in tonnes). The higher food loss value lead to decrease food security. [Source: GFSI 2014]
foodcons	[8]	Food consumption	Food consumption (per cent) as a share of total household expenditure
fpoverty	1	Poverty	Percentage of population living under \$2/day purchasing power parity (PPP)
fagrimport	17.7	Agricultural import tariffs	Percentage of tariffs on agricultural import. The higher tariffs lead to decrease food security. [Source: GFSI 2014]

Table 1 continued

Acronyms of indicators	SDSN indicator code	Indicators	Definition, notion and data source
fundernour	[8]	Prevalence of undernourishment (% of people)	The higher index value leads to decrease food security. [Source: GFSI 2014]
fdietdiv	[2.2]	Diet diversification	Percentage of diversification. The higher index value leads to increase food security. [Source: GFSI 2014]
fprotqu	2.8	Protein quality	Amount of protein (in gram) in daily-consumed food. The higher protein value leads to increase food security. [Source: GFSI 2014]
fpreobes	24	Prevalence of obesity (% of people)	The higher index value leads to decrease food security. [Source: GFSI 2014]

Stewart 2002) was designed to aggregate indicators first into assessment criteria, then into three security indexes, and eventually further aggregated into the final WEF-SI, adopting the Ordered Weighted Average (OWA) approach (Eastman et al. 1993). OWA applies a second round of weighting in which weights are applied to the ordered sequence of values previously weighted as in SAW. For example, if three indicators have to be aggregated, first, their values are weighted as usual (weighted scores) and then they are ordered (ordered scores) and weighted again with a new vector of weights. This second weighting step makes it possible to overcome the full compensation of SAW and to implement the preferred degree of ANDness, with two extremes: the pessimist case of the limiting factor (i.e. the entire weight is given to the lowest ordered score) and the optimist case in which only the highest score determines the value of the aggregated index. The case in which all the ordered weights are equal reproduces the SAW case. Variations in the level of skew in the ordered weights result in solutions with different levels of risk aversion. Therefore, the balancing between ANDness and ORness, and the values of the weight vectors improve the representation of different risk attitude, and thus significantly improve the chances of reproducing the preferences of the involved decision/policy makers.

The assessment model was applied at global scale on a pixel-by-pixel basis (2,181,285 in total). Therefore, the values stored in the output maps allow to identify the status of the calculated indexes within the variability observed at the global scale, thus allowing also for comparisons between different areas, as for the two study cases described in the next section.

Application to the study cases

The results of the indicator-based approach applied at the global scale have been extracted for two river basins, to examine and discuss the potential of the proposed method.

The two study areas have been selected in the geographical areas of origin of the authors (south Europe and south Asia), thus providing basins with quite distinct characteristics in terms of climate, economic development, size and—in accordance with the aims of this special issue—different policy and governance frameworks: the Ganges–Brahmaputra–Meghna (GBM) and the Po river basins. River basins share similar problems across the globe: overexploitation of freshwater, pollution, effects of climate change, saltwater intrusion, poor governance, social conflicts for water allocation, etc., but each basin shows also combinations of peculiar WEF Nexus issues, requiring ad hoc solutions. In the Brahmaputra River Basin, for example, development of new hydropower projects, upstream water diversions and possible climate changes introduce concerns among riparian countries about future water supply for energy and food production (Yang et al. 2016). Similarly, water pollution and excessive water use for different sectors including energy are harming ecosystems in Europe and elsewhere, affecting the quality of food and water supplies. The Po river basin covering the majority of the Italian northern plain, but shared also with Switzerland, is an emblematic example of highly developed territory and pollution problems (Palmeri et al. 2005).

The GBM system is the third largest river basin in the world after the Amazon and Congo, covering over 1.7 M km². Connecting the Himalayas to the Bay of Bengal, the river basin is shared between India (64 %), China (18 %), Nepal (9 %), Bangladesh (7 %) and Bhutan (3 %). The world's highest population density is supported by GBM water resources, which contribute to the survival of about 630 million people. The region is endowed with considerable natural resources (e.g. huge hydropower potentials, fertile agricultural lands and rich aquatic resources) that could be used to foster sustainable economic development (Rasul 2015). However, the current spatial and temporal variability, and the projected hydrological impacts of climate change are expected to be particularly strong in this region because of glacier melt,

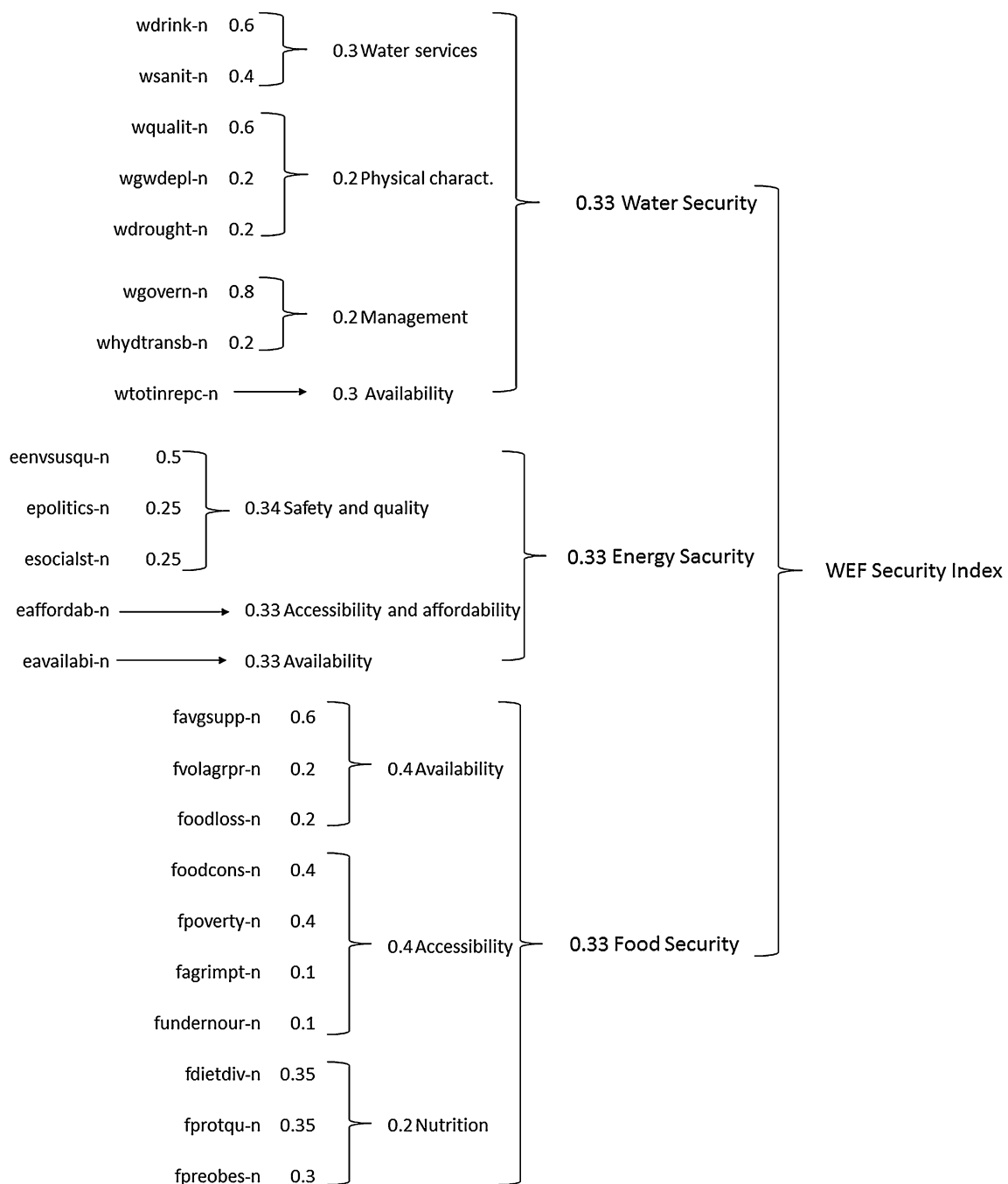


Fig. 1 Hierarchical aggregation of indicators for the calculation of the WEF Security Index

extreme monsoon rainfall and sea level rise (Gain et al. 2013a).

The Po River is the largest and in many respects the most important Italian river, with a basin extending over 71,000 km² and covering 25 % of Italy, but it comprises also minor parts of Swiss and France in the upper Alpine area to the north-west. The Po River collects water discharged from the Alps and the Apennines and ends in the Adriatic Sea, a northern branch of the Mediterranean.

Agriculture covers approximately one-half of the basin, but the basin includes also the economically most important activities in the secondary and tertiary sectors, with 17 million inhabitants and producing 40 % of the Italian GDP (Marchina et al. 2015).

Even though the GBM basin is considered one of the world's water-abundant regions, our analysis illustrates that water security calculated through physical, social and economic dimensions with the SAW aggregation method is

relatively low in this region, with an average value of 0.36, compared to a global average of 0.44. The Water Security Index in the Po Basin is relatively higher, with an average value of 0.48 (see Table 2 for details). During the dry seasons, water scarcity for the GBM Basin is already evident and is expected to become more severe in the coming decades (Gain and Giupponi 2015). Due to the increased demand for competing uses, freshwater is under growing threat (Babel and Wahid 2008). A significant portion of the population in the GBM region lacks access to safe drinking water and sanitation. The deterioration of both surface water and groundwater quality in the countries of the GBM river basin is now a matter of serious concern. Water security is also hindered because the shared countries (China, India, Bangladesh and Nepal) of the basin have been unable to develop an integrated river basin plan. In the case of the Po River, rather good availability of water resources is counterbalanced by very high demands from agriculture and other sectors, which generate conflicts for water allocation (Bozzola and Swanson 2014). Moreover, the area is affected by climate variability and extremes causing frequent floods and seasonal droughts. The comparison with the GBM Basin shows better values in particular for the indicators measuring water quality, sanitation systems and governance.

According to our assessment, energy security shows much greater gaps in the GBM Basin with respect to the global average and the situation in the Po Basin. The average Energy Security Index (SAW method) is 0.21, compared to the global value of 0.35 and the average of the European basin of 0.46. Per capita energy consumption in the GBM region is among the lowest in the world which is a major constraint for industrialization and economic growth (Kumar Singh 2013). Moreover, limited resources, geographical location and economic conditions make the region highly insecure in terms of energy resources. Although there is high potential for hydropower generation in the upstream countries (China and India), it creates a serious threat for the social and ecological system in the downstream countries. The much better situation in terms of energy security found in the Po Basin is the main contribution to significantly different WEF indices in the two areas.

The results for the Food Security Index in the Asian area are above the global average (0.29 and 0.24, respectively). The average food supply (mainly rice) is very high in this region. However, the region also contains the largest number of the world's poor. The income gap between the rich and the poor is very high in this region. The *fpoverty* indicator shows an average value of 0.37 in the GBM Basin, while it is everywhere at the maximum value in the Po Basin (no population living under \$2/day purchasing power parity). Diet diversification and protein quality in

daily-consumed foods is very low (average values for *fdiv* is 0.46, with respect to 0.84 in the European basin, while *fprotqu* averages are 0.35 and 0.85, respectively), which also contributes to the low food security of the region.

Aggregating water, energy and food securities produces the WEF Security Index. Maps for the two basins obtained with the SAW method are shown in Fig. 2. In both basins, the WEF Security Index is relatively higher in mountain areas, where population is scarce and water resources are abundant. While in the Po area the discontinuity due to national boundaries (i.e. between Italy and Swiss in the Ticino Canton) is not evident, the GBM map shows evident discontinuity between China and the other countries due to the better performance of indicators based upon country polygons in several indicator maps. Moreover, the GBM map shows the effect of data gaps for Bhutan, which makes the WEF Index results not valid for that area. Compared to other regions of the world, the WEF Security index in the GBM river basin is once more lower than the global average (0.40 vs. 0.45), while the WEF Security Index in Po Basin is remarkably higher (0.55).

The application of the OWA aggregation method allows us to explore the sensitivity of the results to varying compensation levels amongst indicator values. Two OWA runs were performed in addition to the SAW: (1) optimistic (more than 50 % of the ordered weight is given to the indicator with the best performance), thus allowing the calculation of high security indexes in all the areas in which at least a very good indicator was present; (2) pessimistic (more than 50 % of the ordered weight is given to the indicator with the worst performance), thus producing low security index values in all the circumstances in which the bad performance of one indicator is considered to limit the overall security. In general, and as expected, the optimistic method produces a distribution of index values in the area compressed towards higher security values, as reported in Table 2: in the GBM area, the WEF Security Index average is above 0.45 for the optimistic weighting, as compared to 0.35 in the pessimistic case and 0.40 for SAW. Po values are 0.58, 0.52 and 0.55, respectively.

Further analysis of the results was conducted by calculating difference maps between SAW and optimistic aggregation as well as SAW and pessimistic aggregation by means of subtractive map overlay (not reported here for brevity). The difference maps allow us to dig into compensations and trade-off, as a consequence of the SAW and OWA aggregations, and to identify the areas with higher differences, i.e. those in which trade-offs between good and bad indicator performances were calculated. Similarly, the difference maps between WEF and the Water, Energy and Food Security indexes were calculated to explore compensatory effects and trade-offs in the final aggregation of

Table 2 Descriptive statistics of security maps for the two case study areas

Map	Minimum	Maximum	Average	Range	SD
<i>Ganges–Brahmaputra–Meghna Basin (Asia)</i>					
Water security SAW	0	0.733	0.362	0.734	0.093
Energy security SAW	0	0.479	0.206	0.479	0.122
Food security SAW	0	0.525	0.274	0.525	0.114
WEF OWA optimistic	0	0.719	0.448	0.719	0.128
WEF OWA pessimistic	0	0.668	0.353	0.668	0.141
WEF SAW	0	0.692	0.395	0.692	0.135
<i>Po Basin (Europe)</i>					
Water security SAW	0	0.728	0.479	0.728	0.105
Energy security SAW	0	0.932	0.460	0.932	0.124
Food security SAW	0	0.594	0.4243	0.592	0.091
WEF OWA optimistic	0	0.904	0.581	0.904	0.129
WEF OWA pessimistic	0	0.822	0.516	0.822	0.116
WEF saw	0	0.868	0.553	0.869	0.123

the three dimensions into the final WEF Security Index (see statistics reported in Table 2).

Discussion and conclusions

Despite significant differences with IWRM, the recent approach of WEF Nexus can be considered as complementing IWRM through a more targeted securitization focus (Benson et al. 2015). Whereas IWRM aims at ‘water-centrism’, the nexus appears more ‘multi-centric’ and more focused on the prioritization of resource security within sustainable development. Importantly, the WEF Nexus approach is acknowledged in three specific SDGs, thus allowing to consistently integrate the nexus approach in the analysis and monitoring of sustainable development.

A comprehensive assessment of water, energy and food indicators requires the aggregation of a multitude of indicators, and thus, the final index(es) may easily hide some important features, like local or sectoral imbalances. Our approach is transparent in that it is coded in a procedure that can be reproduced by anyone⁵ and which stores all the data, parameters, coefficients, etc. adopted for the current version of the assessment method. Moreover, it is efficient, in that it allows for easy exploration of the effects of the varying parameters (aggregation method, weighting, etc.) by means of multiple runs and sensitivity analysis. Therefore, the adoption of OWA multi-criteria aggregation improves the usual approaches by overcoming the compensatory effect of simple additive weighting, and, thanks

to the coding in a GIS spatial modelling procedure, it allows for exploration of different attitudes of researchers and policy makers towards risk.

Policy makers’ attitudes for accepting good performances as resulting by even a limited number of good indicator values, or, vice versa adopting a very conservative approach based upon the concept of limiting factors can be implemented and their consequences on spatial analysis can thus be simulated. This, in our opinion, is a substantial improvement of the current state of the arte in the direction of combining a unified approach applicable to existing spatial databases at global scale, with the capability to adapt the algorithm to take into account different attitudes and preferences of decision-makers. Another evident improvement is the implementation of the algorithm on a pixel-by-pixel basis, rather than on country-level aggregations.

The results extracted for the two river basins demonstrate how the WEF-SI can support comparative analyses in space and in time, whenever indicators’ time series would become available. Our results suggest that WEF security is in general low in the GBM basin compared to other parts of the world. The rather low WEF security values in the GBM basin suggest that the WEF Nexus approach has not yet been recognized among policy makers in the GBM countries while conflicts over these resources are growing. These problems could be solved through the improved management of water, energy and food resources; advances in technology; and a valuation of these resources that reflect their importance to society.

Development of new hydropower projects, upstream water diversions and climate changes introduce major concerns among riparian countries about water, energy and food securities. The WEF Nexus thinking facilitates international level of cooperative management actions

⁵ The data and the spatial modelling procedure coded in the macro language of the TerrSet software can be obtained from authors upon request.

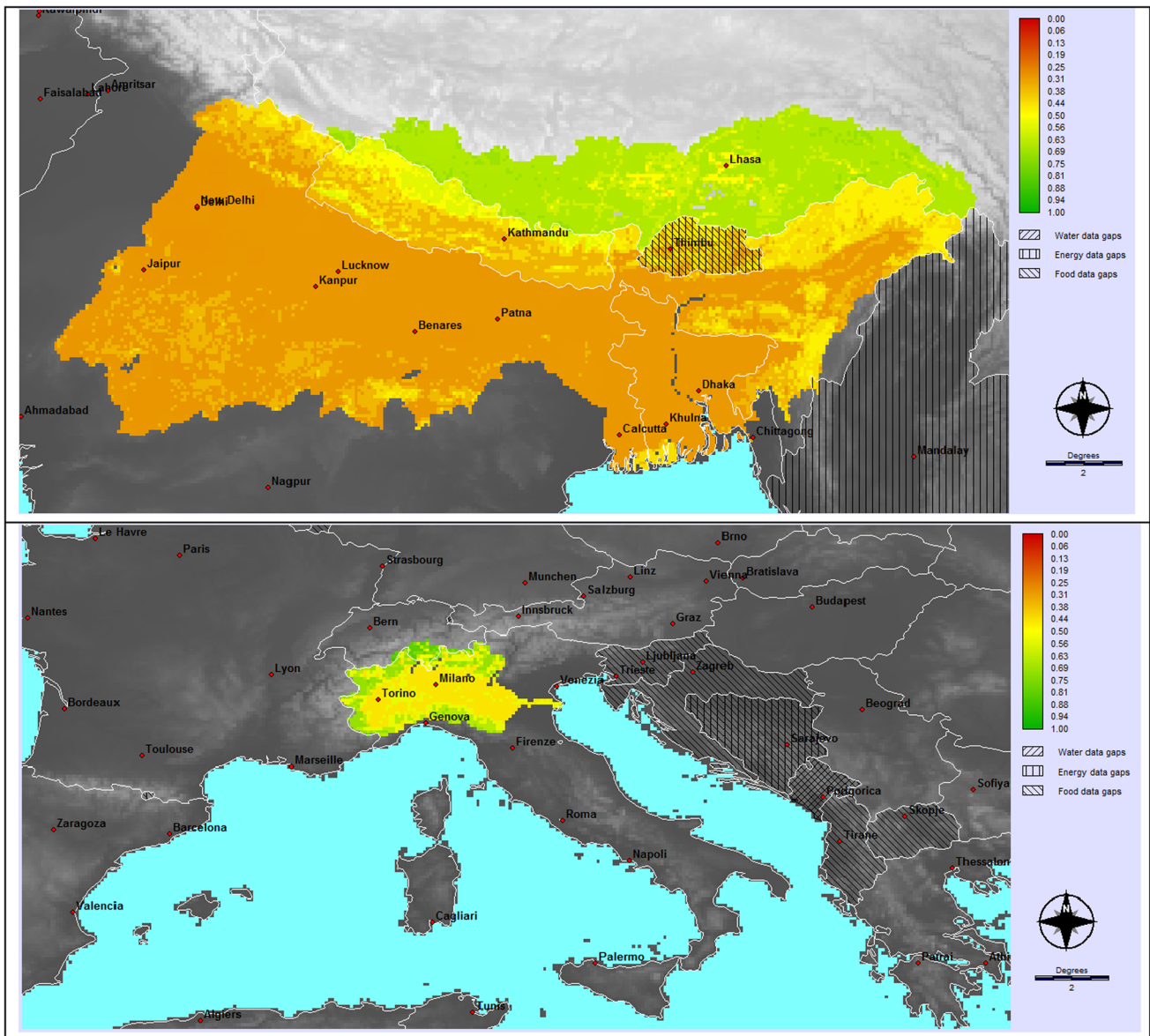


Fig. 2 WEF security maps (SAW method) of the study areas: the GBM Basin above (note: areas with *linear hatches* identify data gaps, which affected the calculation of Energy and Food indexes in Bhutan) and the Po Basin below

through addressing the socioeconomic needs of different riparian countries.

Indeed, resource monitoring, development of novel wastewater treatment technologies, renewable energy supplies, increased use of food diversification and protein qualities and determination of the quantities of water that can be withdrawn without causing adverse effects on the environment will be essential for the efficient management of water, energy and food resources in the future.

The results obtained with the proposed approach in the two river basins and elsewhere can be used to contribute to the initial assessment of the situation at the time of launching the SDGs. Future efforts are needed to

consolidate the selection of raw data to calculate indicator values whenever new information sources will become available. The availability of global spatial data is steadily increasing and the approach proposed can be easily adapted to new spatial data. Probably, the main challenge for monitoring the implementation of the SDGs will lay in the availability of comparable global raw data collected with adequate spatial detail and quality at regular time intervals. The spatial detail is crucial, because country-level averaging and aggregation hide the variability of physical and socio-economic phenomena and thus the hot spot areas of greatest interest for planning the developments towards the SDGs. Remotely sensed data provided by the new

constellations of satellites (e.g. those of the Sentinel Programme of the European Space Agency) will play a greatest role in providing the spatial and temporal information required.

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