Sustainability assessment of water resources through the ‘Water, Energy and Food Nexus’

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Abstract
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 Water, Energy and Food 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 has been applied worldwide. Two river basins, the Ganges-Brahmaputra-Meghna (GBM) River Basin in Asia and the Po River Basin in Europe are extracted from global maps to demonstrate the results into spatial details. The comparative analysis allows the identification of which dimensions (indicators) require special attention by local and global policy makers.

Keywords: Water, Energy and Food Nexus; Sustainable Development Goals; indicators; security index; assessment.

Introduction

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, Daily, and Ehrlich 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 wellbeing.
Beside climatic change, current population growth, economic development and the related land use changes have direct impacts on increasing demand for freshwater

resources. A common feature of this globalization of water problems is the legacy of poor governance (Vörösmarty et al. 2013), which adds on the long lasting problems of over-withdrawal of surface water and groundwater, inadequate engineering practices, pollution, and biotic stressors (UN-WWAP 2012). The combination of such problems have led to depletion of water resources and environmental damage in some regions and mounted pressures on water systems across the planet, representing a major challenge for achieving sustainability of twenty-first century.

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 paper is to present an approach for quantitative assessment of water, energy and food security at the global scale in a holistic manner, recently published by the authors (Giupponi and Gain 2016)[1]. We selected spatial indicators with specific reference to the Sustainable Development Goals (SDGs), recently approved by the United Nations General Assembly (25 September 2015)[2] and we propose a method to aggregate three goals into a single index, by means of a multi-criteria approach, which allows to take into account different decisional attitudes of policy makers.

The main ambition of the proposed approach is to provide a transparent and reproducible GIS-based approach to assess the state of spatial indicators related to Water, Energy and Food (WEF) Nexus, with a first attempt to go beyond country level aggregation.

The proposed approach represents an operational proposal that 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 WEF Nexus is a relatively new paradigm for natural resources management, with a specific focus on security issues related to three interconnected dimensions that are highly important for society and economy (Olsson 2013). The innovations of the WEF Nexus approach compared to the previously existing approaches lie in: (i) its ability to go beyond the water-centred management approach; (ii) its focus on security concerns (Bakker 2012) for three interrelated resources that are highly important for society and economy; (iii) the opportunity to create sustainable business solutions though public-private partnership (Bizikova et al. 2013, Benson, Gain, and Rouillard 2015).

Even if water can still be considered as *primus inter pares* (first among equals) in the WEF Nexus approach (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

[1] This paper is a synthesis of the cited work by Giupponi and Gain, 2016.

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

that is urgently needed in order to move in the direction of real integrated sustainability assessment, as proposed by Agenda 2030.
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.

Indicator-based sustainability assessment

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. A set of aggregated indicators may produce a more concise and representative index, presenting the available evidence in a much more concise, targeted and effective fashion than would individual indicators (International Council for Science 2002) and thus facilitating communication with policy/decision makers and non-experts.
Regarding the SDGs, it is ideally possible to develop a single aggregated sustainable development index, synthesising 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.
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 SDG goals in the future, we identified the set of indicators to be adopted following the developments of the Sustainable Development Solutions Network (SDSN).
Three of the SDGs 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 different sectoral global sources: energy (WEC 2013); food (GFSI 2014); water governance (Kaufmann, Kraay, and Mastruzzi 2010); water quality (Srebotnjak et al. 2012); groundwater depletion (Wada et al. 2012) and drought index (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 (IIASA/FAO 2012).

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
Water Security (SDG Goal 6. Ensure availability and sustainable management of water and sanitation for all)			
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: EPI, 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: EPI, 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/yr) 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	Transboudary 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]
Energy Security (SDG Goal 7. Ensure access to affordable, reliable, sustainable, and modern energy for all)			
eavailabi	[51]	Aggregated Energy Availability	Aggregated energy availability calculated through aggregation (equal weighting) of (i) ratio of energy production to consumption; (ii) diversity of electricity generation; (iii) distribution losses as percentage of generation; (iv) five-year compound annual growth rate of the ratio of total primary energy consumption to GDP; (v) days of oil and oil product stocks; (vi) aggregation of net fuel imports as a percentage of GDP. [Source: WEC, 2013]
eaffordab	[51]	Aggregated Energy Affordability	Aggregation (equal weighting) of (i) electricity relative to access; (ii) retail gasoline. [Source: WEC, 2013]
eenvsusqu	62; 78	Environmental Sustainability	Aggregation (equal weighting) of (i) total primary energy intensity; (ii) CO_2 intensity; (iii) Effect of air and water pollution; (iv) CO_2 grams/kWh from electricity generation [Source: WEC 2013]
epolitics	[91]	Political Strength	Aggregation (equal weighting) of (i) political stability; (ii) regulatory quality; (iii) effectiveness of government. [Source: WEC 2013]
esocialst	[94; 31; 37; 17-30]	Social Strength	Aggregation (equal weighting) of (i) control of corruption; (ii) rule of law; (iii) quality of education; (iv) quality of health. [Source: WEC 2013]
Food Security (SDG Goal 2. End hunger, achieve food security and improved nutrition, and promote sustainable agriculture)			
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 (percent) as a share of total household

			expenditure.
fpoverty	1	Poverty	Percentage of population living under $2/day purchasing power parity (PPP).
fagrimpt	17.7	Agricultural Import Tariffs	Percentage of tariffs on agricultural import. The higher tariffs lead to decrease food security. [Source: GFSI, 2014]
fundernour	[8]	Prevalence of undernourishment (% of people)	The higher index value lead to decrease food security. [Source: GFSI, 2014]
fdietdiv	[2.2]	Diet Diversification	Percentage of diversification. The higher index value lead 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 lead to increase food security. [Source: GFSI, 2014]
fpreobes	24	Prevalence of Obesity (% of people)	The higher index value lead to decrease food security. [Source: GFSI, 2014]

The WEF-SI 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. organised 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, McDonnell, and Lloyd 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[3].

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

[3] http://www.clarklabs.org.

Figure 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.).

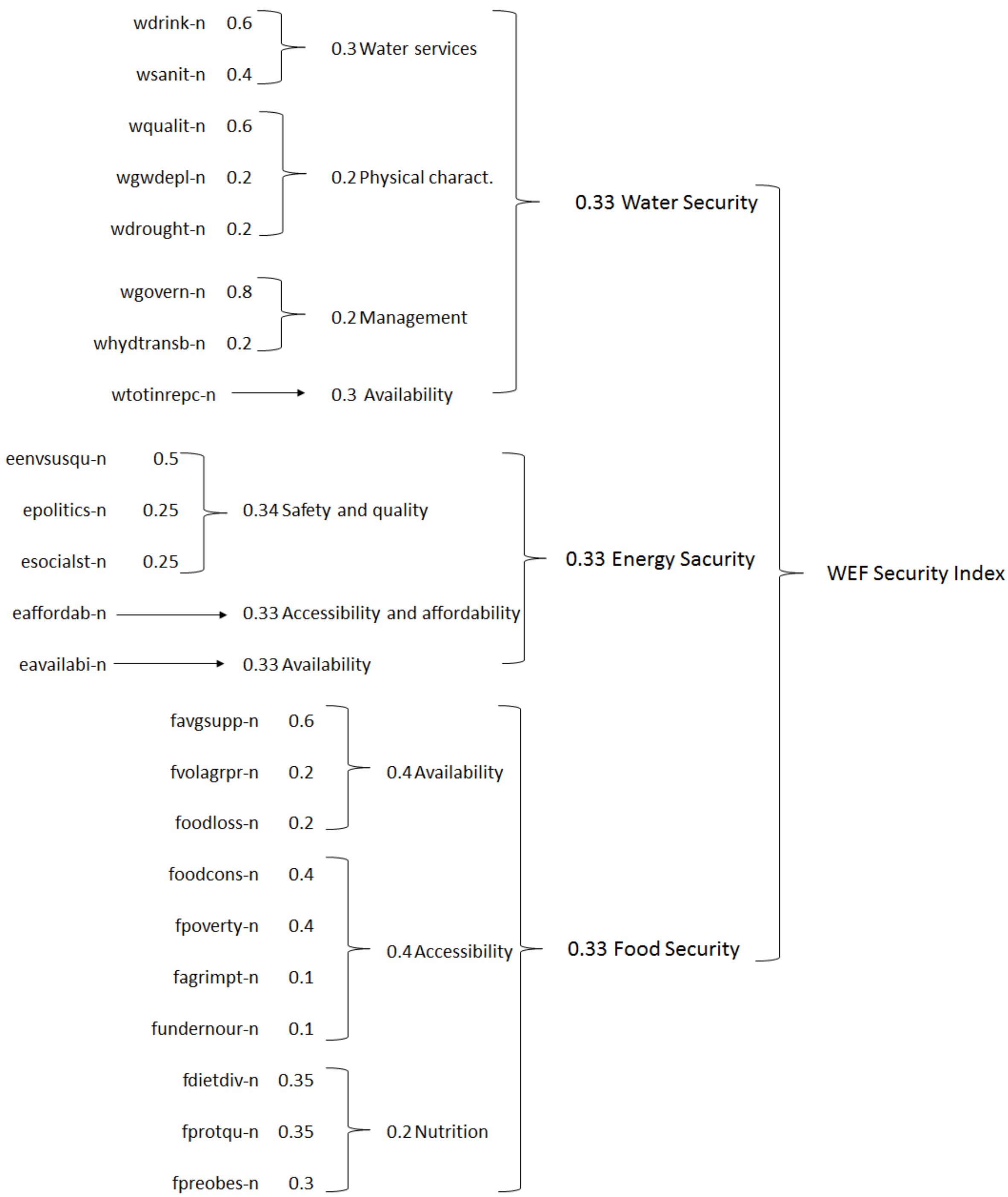

Figure 1. Hierarchical aggregation of indicators for the calculation of the WEF Security Index.

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-Monzonís 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 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 improves the representation of different risk attitude, and thus significantly improves 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.

Results of the application to global maps and the study cases

A peculiar feature of the proposed index is its ability to explore different theoretical attitudes of policy makers, by exploiting the capabilities of fine tuning the aggregation algorithm provided by the OWA multi-criteria method, to explore the sensitivity of the results to varying compensation levels amongst indicator values. Two OWA runs were performed in addition to the SAW: (i) 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; (ii) 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.
Global results are reported in Figure 2, with the comparison of the effects of different attitudes towards aggregation.

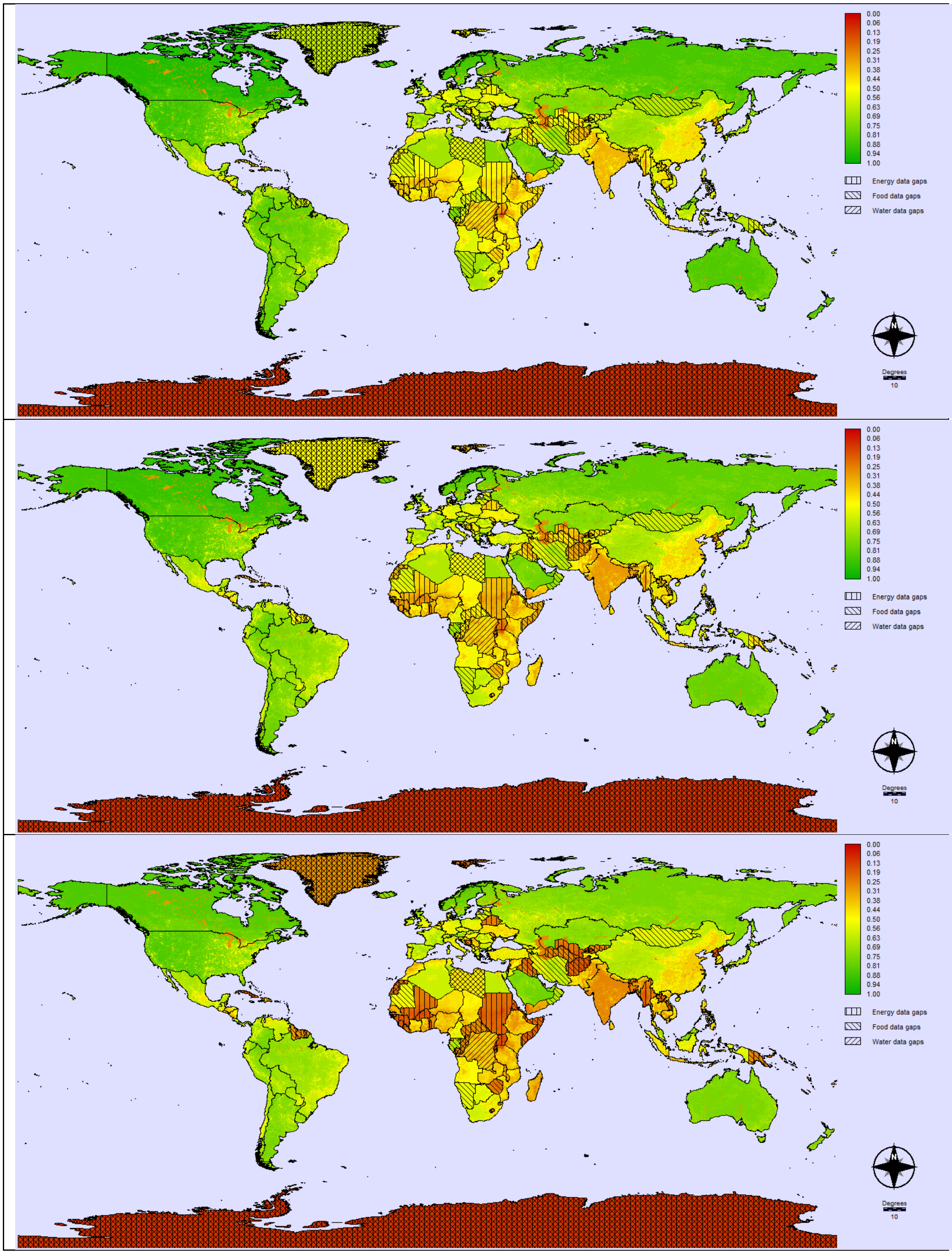

Figure 2. Comparison of global WEF-SI results with different theoretical attitudes of policy makers. From top to bottom: optimistic attitude, with focus on good performance indicators; weighted average, with full compensation of good and bad performances; pessimistic attitude, with higher consideration of those indicators with the worst performances.

The results of the indicator-based approach obtained 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, Bendoricchio, and Artioli 2005).

The comparison of the Po with the GBM Basin show better values in particular for the indicators measuring water quality, sanitation systems, and governance. Details about the results are reported in the full paper (Giupponi and Gain 2016), while here we present an example of possible further analyses that can be conducted with the proposed GIS-based approach.
One example is the calculation of difference maps between different aggregation methods, by means of subtractive map overlay. The difference maps allow us for example to explore the compensations and trade-off effects in the GBM basin, as a consequence of the SAW and OWA aggregations (see Figure 3 top), and to identify the areas with higher differences (brighter white), i.e. those in which trade-offs between good and bad indicator performances were calculated. In this case the area of Bhutan pops up because of lack of data, but trade-offs are evident also in mountain areas and Bangladesh.
Similarly, the difference maps between WEF and the Water, Energy and Food Security indexes can be calculated to explore compensatory effects and trade-offs in the final aggregation of the three SDGs into the final WEF Security Index. The example for comparing WEF with Food Security for the GBM Basin shows brighter areas in which the performance of the Food Security Index is relatively lower than the WEF-SI.

Discussion and conclusions

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 were implemented and their consequences on spatial analysis were 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, instead than on country level aggregations.

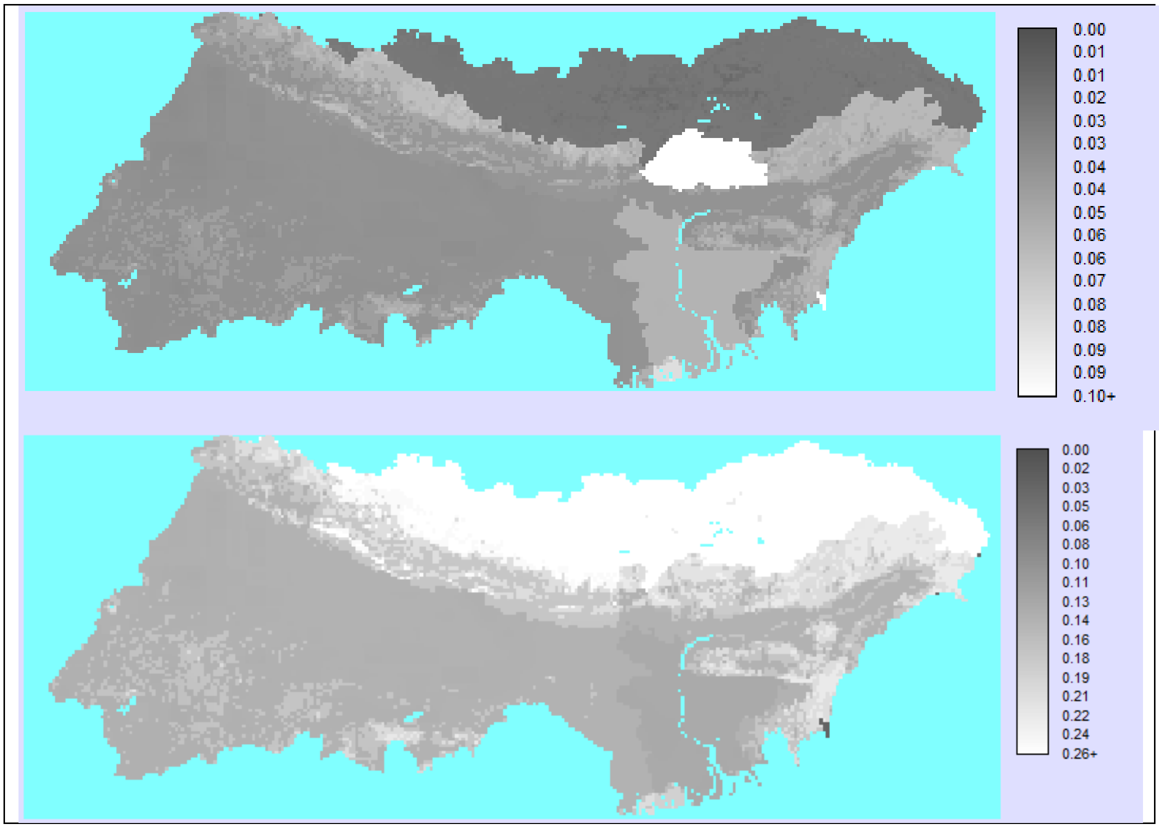

Figure 3. Examples of difference maps for the GBM Basin to analyse trade-offs between different goals and indicators. Top map shows trade-offs of the WEF-SI, by comparing pessimistic and compensatory aggregation. Bottom map shows trade-offs between WEF-SI and the Food Security Index.

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, one of the main challenges 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.
A concise list of conclusive remarks are reported below.

- A comprehensive assessment of water, energy and food indicators requires the consideration of a multitude of indicators
- There is a trade off-between the information contents and the synthesis needs required for communicating with policy makers and the general public.
- Aggregated indices may hide some important features, like local or sectoral

specificities. Here, the application of OWA improves the usual weighted sum approaches, and allows for exploration of the effects of different attitudes of policy makers.

- The availability of global data sets is dramatically increasing, and their levels of spatial detail allows for analyses at regional or even river basin scales, as in this work, allowing for going well beyond the usual adoption of country-level data.
- This study demonstrated how the principles and requirements of Agenda 2030 in terms of sustainable development can be implemented through an indicator-based approach for spatial assessment of WEF Security
- The set of indicators and the aggregated indices are consistent with the UN SDGs.
- The approach is:
  - transparent in that it is coded in a modelling procedure that can be reproduced and which stores all the data, metadata, parameters, coefficients, etc.
  - efficient, in that it allows for easy exploration of the effects of the varying parameters (aggregation method, weighting, etc.) by means of sensitivity analysis.

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Figures

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

Figure 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.

Tables

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).

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