



# Spatial Assessment of Water Use Efficiency (SDG Indicator 6.4.1) for Regional Policy Support

Carlo Giupponi<sup>1\*</sup>, Animesh K. Gain<sup>2</sup> and Fabio Farinosi<sup>3</sup>

<sup>1</sup> Department of Economics, Ca' Foscari University of Venice, Venice, Italy, <sup>2</sup> Institute of Geography, Christian Albrechts University Kiel, Kiel, Germany, <sup>3</sup> Joint Research Centre, European Commission, Ispra, Italy

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### \*Correspondence:

Carlo Giupponi  
cgiupponi@unive.it

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Countries are facing the challenge of identifying the most effective implementation strategies and measures for achieving Sustainable Development Goals (SDG) and their specific targets. The standard procedure proposed by international organizations consists of a set of indicators (one or more per target) assessed at country level. However, such country scale assessments have only limited potential for regional or national policymaking, because of aggregation and averaging effects, which limit the identification of phenomena, their causal relationships, and their spatial-temporal dynamics. The need thus emerges for defining assessment procedures that go beyond national level aggregation and zoom into local phenomena, while maintaining a link with the approach adopted at the global level for monitoring and reporting the progress toward the meeting of the SDGs. SDG 6 focuses on water resources and aims at achieving safe water and sanitation for all, which are essential to human health, environmental sustainability, and economic prosperity. SDG 6 is evidently interconnected with several other SDGs, and in particular with those focused on food production (SDG2) and other socio-economic activities using water as a production factor. This paper proposes an approach to assess SDG 6, based upon freely available global data sets. The methodology is suitable for both reporting at international level in accordance with approved guidelines proposed by custodian agencies and –more importantly–analyzing the spatial features of the phenomena related to the SDGs and their targets, producing information useful to support effective sustainability oriented policies. The proposed approach is demonstrated for the assessment of the indicator 6.4.1 (Change in water use efficiency) in South and South-East Asia, with the ambition to provide operational solutions timely applicable at the global level by exploiting the ever-increasing availability of spatial information deriving from ongoing exercises in the field of global change. This will allow identifying current and emerging water management issues, such as the areas where strategies are required to increase the availability of water resources, or those necessitating transboundary strategies. Scenario analysis driven by the IPCC Shared Socioeconomic Pathways is developed to explore policy and technological solutions across the nexus between water management and agriculture.

**Keywords:** sustainable development goals, water use efficiency, spatial assessment, ISODATA, policy support

## INTRODUCTION

The United Nations (UN) adopted an ambitious global sustainability agenda for the period up to 2030 (UN, 2015). In September 2015, heads of state and government from 193 member states of UN agreed to adopt the 2030 Agenda for Sustainable Development consisting of 17 goals and 169 targets (UN, 2017; UN-Water, 2018). Achieving the Sustainable Development Goals (SDGs) will require major efforts on how the monitoring of the progresses toward the goals can be tracked (UN, 2017; UN-Water, 2017b), and how consequent implementation actions can be identified and targeted to different situations (Gain et al., 2016). The multiplicity of essentially non-comparable measures of sustainable development necessitates the generation of “relevant” SDG indicators so that “clear, unambiguous messages be conveyed to users” (Hák et al., 2016). In this respect, there were attempts by their drafters, the UN Inter-Agency and Expert Group on SDG Indicators (IAEG-SDG), to ensure relevance. Although there are criticisms that many suggested indicators lack comprehensive, cross-country data and some even lack agreed statistical definitions (Schmidt-Traub et al., 2017), the United Nations Statistical Commission (UNSC) adopted a set of 230 indicators proposed by the IAEG-SDG on March 2016 as a practical starting point to monitor progress on the 17 goals and 169 targets of the SDGs (Allen et al., 2017).

Developing countries are usually those with the higher needs, bigger gaps between current capabilities and the targets and the more limited resources for accurate monitoring, due to limitations in the availability of information and in the statistical institutions to manage them (UN-Water, 2017a).

In order to move from agreeing on the goals to implementing and ultimately achieving them, Yonehara et al. (2017) suggested to divide the SDGs’ 15-years time frame into three 5-years phases: a planning phase driven by proactive evaluation and evaluability assessment, an improvement phase characterized by formative evaluation and monitoring, and a completion phase involving outcome and impact evaluations (see **Table 1**). Reyers et al. (2017) and UN-Water (2016) stated that there must be greater attention on interlinkages across sectors (e.g., finance, agriculture, energy, and transport), across societal actors (local authorities, government agencies, private sector, and civil society), and across scales (Liu et al., 2017, 2018). In order to improve these interlinkages, Reyers et al. (2017) also provided seven recommendations pertaining to the following areas: finance, technology, capacity building, trade, policy coherence, partnerships, and, finally, data, monitoring and accountability. Among these seven recommendations, data collection, monitoring and accountability at different levels are highly important for the implementation of SDGs. Vanham et al. (2018) and FAO (2017), for example, suggested that SDGs implementation should be monitored at least three levels: national (e.g., country level), sub-national (e.g., basin level), and local level (see **Table 2**).

The main challenge for monitoring the implementation of the SDGs at national, sub-national and local levels remains in the availability of comparable global raw data collected with

**TABLE 1** | Three 5-years phases for SDG implementation and evaluation, according to Yonehara et al. (2017).

Phases	Activities	Evaluation concern
Phase 1 (2016–2020)	Planning and initiation of major programs	Proactive evaluation Evaluability assessment
Phase 2 (2021–2025)	Project continuation, modification, improvement, addition	Monitoring Formative evaluation
Phase 3 (2026–2030)	Project completion	Follow-up Outcome evaluation Impact evaluation

**TABLE 2** | Monitoring of SDG implementations at different levels, according to FAO (2017).

National level	Sub-national level	Local level
The indicators can be populated with estimations based on national data aggregated to the country level.	The indicator can be populated with nationally produced data, which increasingly can be disaggregated to the sub-national basin unit level.	For more advanced levels, the nationally produced data have high spatial and temporal resolution (e.g., geo-referenced and based on metered volumes) and can be fully disaggregated by source (surface water/groundwater) and use (economic activity).

adequate spatial detail and quality at regular time intervals (Giupponi and Gain, 2017; Farinosi et al., 2018; UN-Water, 2018). Usually, country-level data are available globally from international organizations, such as the global water information system, AQUASTAT of the Food and Agriculture Organization (FAO). However, country-level averaging and aggregation hide the variability of physical and socio-economic phenomena (Gain et al., 2016). Therefore, the spatial detail is crucial to identify hot spot areas of greatest interest for planning the interventions toward the achievement of the SDGs (Giupponi and Gain, 2017; Farinosi et al., 2018). In addition, there is an urgent need for the research community to develop scientifically robust tools to help operationalize the SDGs at the global, regional, national and sub-national levels, with an aim to support the tracking of cross scale, local and aggregate, regional and global trends (Reyers et al., 2017). Specifically, quantitative assessments based on robust models and scenarios are required to foresight sustainable futures to back cast potential development pathways (Reyers et al., 2017).

In order to support implementation of SDGs, several recent studies (Gain et al., 2016; Obersteiner et al., 2016; Allen et al., 2017; Giupponi and Gain, 2017; Schmidt-Traub et al., 2017; Unver et al., 2017; Vanham et al., 2018) proposed approaches for quantitative assessments. Most of these studies have been conducted at national or transboundary river basin scale. Schmidt-Traub et al. (2017) and Gain et al. (2016), for example, developed an SDG index based on selected indicators at global level, while Allen et al. (2017) focused on Arab regions. However, most of those studies focus on a single SDG or sector and they do not consider interactions across sectors and hence the possible

synergies and trade-offs among SDGs are neglected (Liu et al., 2018), while they are extremely important for policy support toward successful implementation of SDGs. Using network analysis approach, Le Blanc (2015) showed that some goals (SDG 12 and SDG 10) are strongly connected to many other goals through multiple targets, while other goals are weakly connected to the rest of the system. Obersteiner et al. (2016) found that coherent cross-sectoral policy combinations can manage trade-offs among environmental conservation initiatives and food prices. Recently, Neely et al. (2017) documented several cases (e.g., Bangladesh, the Gambia, Nepal, Guatemala, India) on cross sectoral coordination for food and agriculture and its benefit to national policies of these countries. A recent study by Giupponi and Gain (2017) provided an integrated assessment of SDG 2 (food), 6 (water), and 7 (energy), highlighting synergies and conflicts amongst and within the three sectors (water, energy, and food), in the Ganges–Brahmaputra–Meghna (GBM) River Basin in Asia and in the Po River Basin in Europe. However, they did not analyze current situations in view of possible future scenarios, which is essential for moving from monitoring of SDGs to the implementation of targeted policies. Recently, Vanham et al. (2018) assessed the indicator SDG 6.4.2 “Level of water stress” for monitoring progress toward SDG, considering future scenarios across different spatial scales (e.g., national, basin, and catchment scales), but they did not consider interactions with other targets and goals.

In summary, an analysis of the most recent literature shows the following gaps: (i) consideration of synergies and trade-offs, or cross-sectoral interactions while assessing SDGs; (ii) assessment procedures that go beyond national level aggregation and zoom into local phenomena, and (iii) analysis of links between past trends and current situations and possible future developments to support the identification of effective and robust policy options.

In order to help fill the above mentioned gaps, this study presents an approach for the spatial assessment of Water Use Efficiency (WUE; SDG indicator 6.4.1), to explore how the economic value generated by water varies within countries. Maps of WUE (US\$ per cubic meter of water) are first produced at country level and then at the level of small administrative units. The most recent spatial estimations of related variables for current times and for the time at the end of the Agenda 2030 planning period are used to characterize future scenarios and guide the identification of water management policies with consideration of expected developments of the economy as a whole and of the agricultural sector in particular, in order to explore the nexus, in terms of potential trade-offs and synergies between water use for food production and other uses of water.

The main aim of the proposed approach is to show how it is possible to provide policy support for the achievement of SDGs (in this case water use efficiency, i.e., indicator 6.4.1 for Target 6.4), by making use of freely available global information with the highest possible spatial detail. It is expected that the possibility would be of particular interest for those countries that may face challenges in the acquisition of data needed for the assessment. The countries of South and South-East Asia are facing many data acquisition challenges. In addition, these countries face similar

challenges, such as overexploitation of freshwater for irrigation, poor governance, and social conflicts for water allocation. In these areas, specifically in South Asia, the authors have significant first-hand experiences, e.g., Giupponi et al. (2013), Gain et al. (2015), Giupponi and Gain (2017), Roy et al. (2017), Gain et al. (2017a), and Gain et al. (2017b). Therefore, South and South-East Asia has been selected as the demonstration area for the proposed approach.

## METHODS

### Assessment of Water Use Efficiency

Target 6.4 of SDGs aims to “by 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity, and substantially reduce the number of people suffering from water scarcity” (UN, 2015). To monitor progress toward this target, two indicators are used: Indicator 6.4.1 measuring water use efficiency (WUE) to address the economic component and 6.4.2 measuring the level of water stress to address the physical component. Recently, Vanham et al. (2018) provided a detailed assessment of the indicator 6.4.2 (i.e., Level of water stress). In this study, we assess the indicator 6.4.1 (change in WUE over time) taking into account interactions across sectors and scales.

As suggested by FAO (2017), the WUE is defined as the value added per unit of water withdrawn over time (showing the trend in water use efficiency over time) and is calculated in US\$ per cubic meter of abstracted water as the sum of the three main sectors (agriculture, industry and services), weighted according to the proportion of water withdrawn by each sector over the total withdrawals (see Equation 1).

$$WUE = A_{we} \times P_A + I_{we} \times P_I + S_{we} \times P_S \quad (1)$$

where:

$WUE$  = Water use efficiency [US\$/m<sup>3</sup>]

$A_{we}$  = Irrigated agriculture water use efficiency [US\$/m<sup>3</sup>]; see below

$P_A$  = Proportion of water withdrawn by the agricultural sector over the total withdrawals

$I_{we}$  = Industrial water use efficiency [US\$/m<sup>3</sup>]

$P_I$  = Proportion of water withdrawn by the industry sector over the total withdrawals

$S_{we}$  = Services water use efficiency [US\$/m<sup>3</sup>]

$P_S$  = Proportion of water withdrawn by the service sector over the total withdrawals

To calculate water use efficiency for irrigated agriculture, the Equation (2) is used:

$$A_{we} = \frac{GVA_a \times (1 - C_r)}{V_a} \quad (2)$$

where:

$A_{we}$  = Irrigated agriculture water use efficiency [US\$/m<sup>3</sup>]

$GVA_a$  = Gross value added by agriculture (excluding river and marine fisheries and forestry) [US\$]

$C_r$  = Proportion of agricultural GVA produced by rainfed agriculture [-]; see below

$V_a$  = Volume of water withdrawn by the agricultural sector (including irrigation, livestock and aquaculture) [m<sup>3</sup>]

$C_r$  can be calculated from the proportion of irrigated land on the total arable land, as shown in Equation (3):

$$C_r = \frac{1}{1 + \frac{A_i}{(1-A_i)^{0.375}}} \quad (3)$$

where:

$A_i$  = proportion of irrigated land on the total arable land

0.375 = Generic Default Ratio Between Rainfed and Irrigated Yields

To calculate water use efficiency for industry, the following Equation (4) is used.

$$I_{we} = \frac{GVA_i}{V_i} \quad (4)$$

where:

$I_{we}$  = Industrial water use efficiency [US\$/m<sup>3</sup>]

$GVA_i$  = Gross value added by industry [US\$]

$V_i$  = Volume of water withdrawn by the industry [m<sup>3</sup>]

For calculating WUE for service sector, the Equation (5) will be used.

$$S_{we} = \frac{GVA_s}{V_s} \quad (5)$$

where:

$S_{we}$  = Service sector water use efficiency [US\$/m<sup>3</sup>]

$GVA_s$  = Gross value added by service sector [US\$]

$V_s$  = Volume of water withdrawn by the industry [m<sup>3</sup>]

Using above equations (Equations 1–5) and collecting the most recent data from variety of selected sources (see **Table 3**),

we have calculated WUE at country level. The data sources for the input variable is summarized in **Table 3**. All the map layers were referenced on the same coordinate system and eventually converted in raster layers to allow for spatial analysis at the highest possible resolution (see **Table 4**). The gaps in input data were filled by alternative sources providing values comparable with those recommended by the custodian agencies. For example, gaps in  $A_i$  values per country in the AQUASTAT databases were filled by data derived from AQUASTAT publications and country reports, while gaps in the socio-economic variables of the World Bank data bases were filled with the corresponding values of the International Monetary Fund.

Initially, we have calculated country-level WUE for the year 2016, as required by FAO, for comparative purposes. Even if almost all data layers were downloaded at global level, as stated above, we have focused our assessment on South and South-East Asia, by framing maps according to a window with North-East corner longitude 73° latitude 34°N and South-West corner longitude 110° latitude 5°N.

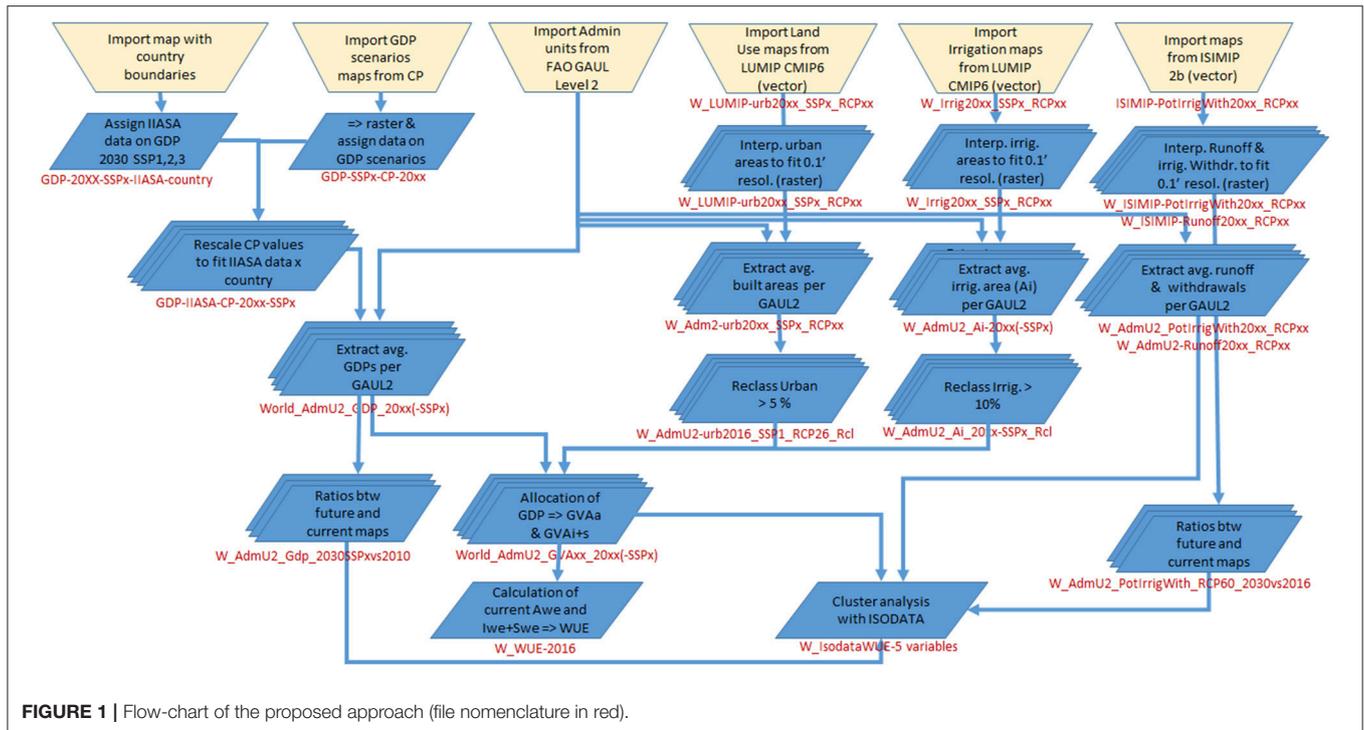
The entire data processing has been conducted in the TerrSet GIS environment, by Clark University (version 18.31) and coded in a single macro file, to allow for easy revisions and updates. **Figure 1** presents a flow-chart of the procedure.

**TABLE 4** | Metadata information of developed GIS layers.

Variables	Metadata
Reference System	EPSG:4326–WGS84–Geographic Coordinate System
Bounding Box	–180, –90, 180, 90
Rows	2,160
Column	4,320
Resolution	0.083333333
Units of Measure	Decimal degree
Approximate area of one cell	ca. 80 sq. km, depending on the latitude

**TABLE 3** | Data sources for country level calculation of WUE.

Variables	Indicators	Temporal resolution	Data sources
$V_a$	Volume of agricultural water withdrawal	Yearly	FAO AQUASTAT <a href="http://www.fao.org/nr/water/aquastat/data/query/index.html">http://www.fao.org/nr/water/aquastat/data/query/index.html</a> <a href="http://www.fao.org/nr/water/aquastat/data/popups/itemDefn.html?id=4250">http://www.fao.org/nr/water/aquastat/data/popups/itemDefn.html?id=4250</a>
$GVA_a$	Agriculture, value added	Yearly	World Bank <a href="https://data.worldbank.org/indicator/NV.AGR.TOTL.CD">https://data.worldbank.org/indicator/NV.AGR.TOTL.CD</a>
$A_i$	proportion of irrigated land on the total arable land	Yearly	World Bank <a href="https://data.worldbank.org/indicator/AG.LND.IRIG.AG.ZS">https://data.worldbank.org/indicator/AG.LND.IRIG.AG.ZS</a>
$V_i$	Volume of industrial water withdrawal	Yearly	FAO AQUASTAT <a href="http://www.fao.org/nr/water/aquastat/data/popups/itemDefn.html?id=4252">http://www.fao.org/nr/water/aquastat/data/popups/itemDefn.html?id=4252</a> <a href="http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en">http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en</a>
$GVA_i$	Industry, value added	Yearly	<a href="https://data.worldbank.org/indicator/NV.IND.TOTL.CD">https://data.worldbank.org/indicator/NV.IND.TOTL.CD</a>
$V_s$	Volume of services water withdrawal	Yearly	FAO AQUASTAT <a href="http://www.fao.org/nr/water/aquastat/data/popups/itemDefn.html?id=4251">http://www.fao.org/nr/water/aquastat/data/popups/itemDefn.html?id=4251</a> <a href="http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en">http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en</a>
$GVA_s$	Services, value added	Yearly	<a href="https://data.worldbank.org/indicator/NV.SRV.TETC.CD">https://data.worldbank.org/indicator/NV.SRV.TETC.CD</a>



## Spatial Analysis of WUE

The gridded estimations of GDP carried out by Murakami and Yamagata (2016) in the Carbon Project<sup>1</sup> were used for building spatially explicit maps of the values of economic activities, going well-beyond country level. Murakami and Yamagata (2016) assessed global population and GDP scenarios in  $0.5 \times 0.5$  degree grids between 1980 and 2100 with an interval of 10 years. For the historical period (1980–2010), the data is estimated by downscaling actual populations and GDPs by country, while for the future (2020–2100) values are estimated by downscaling projected populations and GDPs under three Shared Socioeconomic Pathways (SSP): SSP1; SSP2; and SSP3, by country (source: IIASA SSP database version 1)<sup>2</sup>.

Using the above method, gridded GDP value in 2010 is considered as the most recent available map, while the GDP projection for 2030 (end of Agenda 2030 period) is mapped for three SSPs (SSP1 refers to “Sustainability-Taking the Green Road”, SSP2 indicates “Middle of the Road,” while, SSP3 refers “Regional Rivalry–A Rocky Road”). A series of tests were conducted to verify the coherence between different sources of GDP information (WB, IMF, and IPCC-SSP) and sector GVA’s. Eventually, the spatially explicit maps of GDP sum up at the total GVA country values, provided by WB, thus allowing for obtaining comparable results between the country level exercise and the spatial analysis. While future projections fit the values of IIASA.

In order to increase the visibility of the maps we aggregated the cell values (ca. 80 km<sup>2</sup>) at the level of FAO Global Administrative Unit Layers (GAUL) 2, reported in **Figure 2** (source: FAO Geonetwork)<sup>3</sup>.

In order to allocate total GDPs per GAUL2 into agriculture as well as industry and service sectors, we have incorporated the land cover map for current and future periods (i.e., 2030) of 3 SSPs in the GIS layer. The land cover maps were collected from the Land Use Model Intercomparison Project (LUMIP) (Lawrence et al., 2016), data set prepared for the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Eyring et al., 2016). In addition to a land cover map, irrigation maps for current and future periods (considering the 3 SSPs) were also imported from LUMIP. The imported land cover and irrigated agriculture maps were used to guide the allocation of GDP, to irrigated areas as the sources of agricultural value added of water withdrawn and built up areas for the allocation of industrial and services value added. By comparing GDP maps with land use and irrigation maps, we distributed total GDP estimations by the Carbon Project into 3 land typologies: (i) GDP of industrial or service origin in those areas with higher GDP and high percentages of built up areas; (ii) GDP of agricultural origin in areas with significant percentage of irrigated agriculture and intermediate GDP values; and (iii) the remaining areas where low GDP values in areas with no significant presence of irrigated agriculture.

For assessing the proportion of agricultural GVA produced by rainfed agriculture ( $C_r$ ) per GAUL2, using Equation (3), the proportion of irrigated land on total arable land is extracted from LUMIP irrigation area map. Current aggregated figures of water

<sup>1</sup><http://www.cger.nies.go.jp/gcp/population-and-gdp.html>

<sup>2</sup><https://secure.iiasa.ac.at/web-apps/ene/SspDb/dsd?Action=htmlpage&page=about>

<sup>3</sup><http://www.fao.org/geonetwork/srv/en/metadata.show?id=12691>

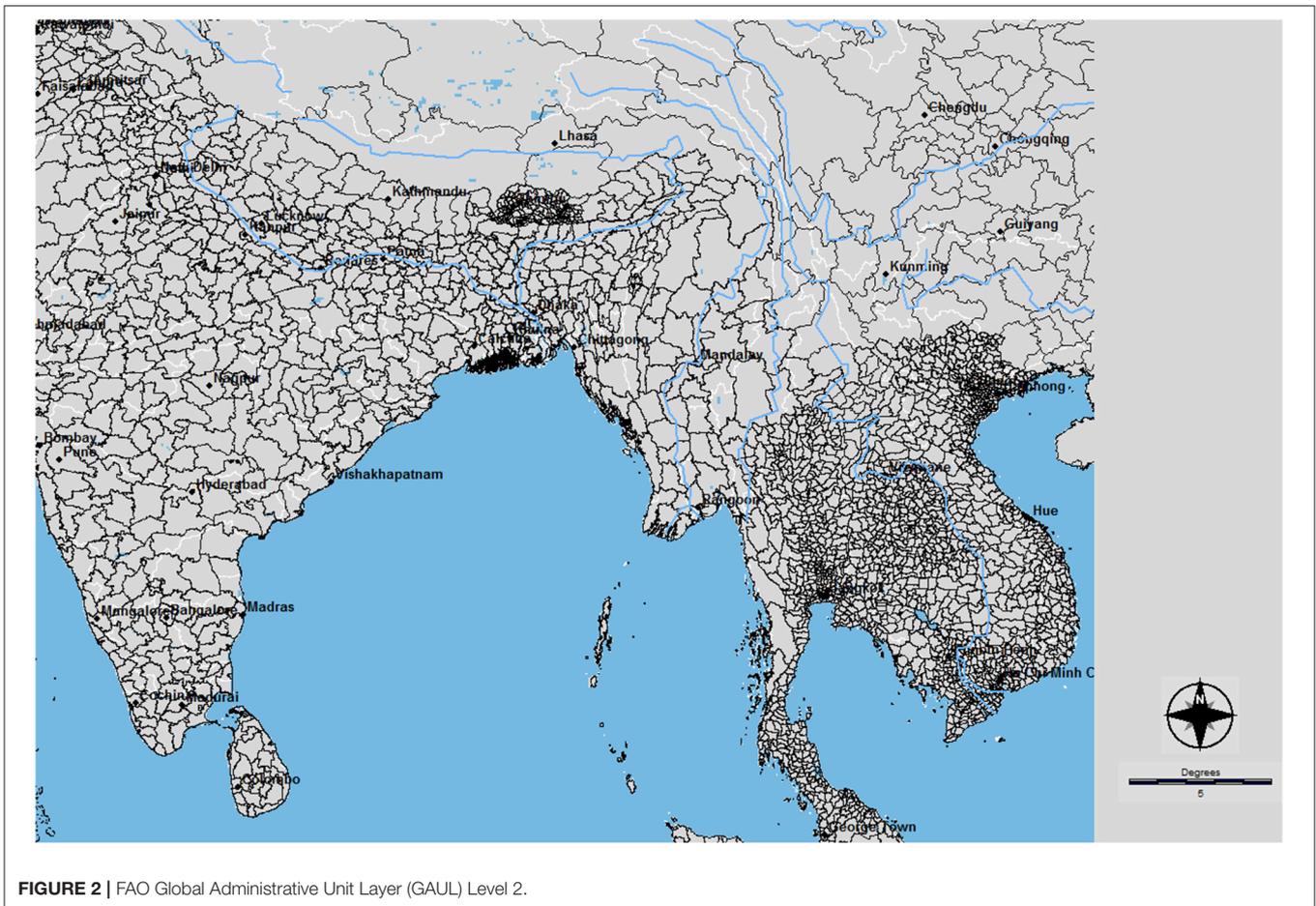


FIGURE 2 | FAO Global Administrative Unit Layer (GAUL) Level 2.

withdrawal for agriculture and other sectors are extracted from recent national statistics shown in **Table 3**.

An important caveat we would like to stress here is that the data used for this analysis, both the SSP and the LUMIP projections, are result of global scale modeling exercises affected by a certain degree of uncertainty. As stressed in the literature presenting the results of those projects (Lawrence et al., 2016; Riahi et al., 2017), the number of models used for the production of these datasets is relatively limited, and the observed data use for their calibration and validation rather scattered over space and time. Moreover, the future outcomes of current climate change adaptation and mitigation policies, or the lack of effective strategies, are likely to change the socio-economic conditions that have been hypothesized for the scenarios here utilized (Prestele et al., 2016). The uncertainty brought to the analysis presented in this paper by the use of these data is rather difficult, if not impossible, to estimate.

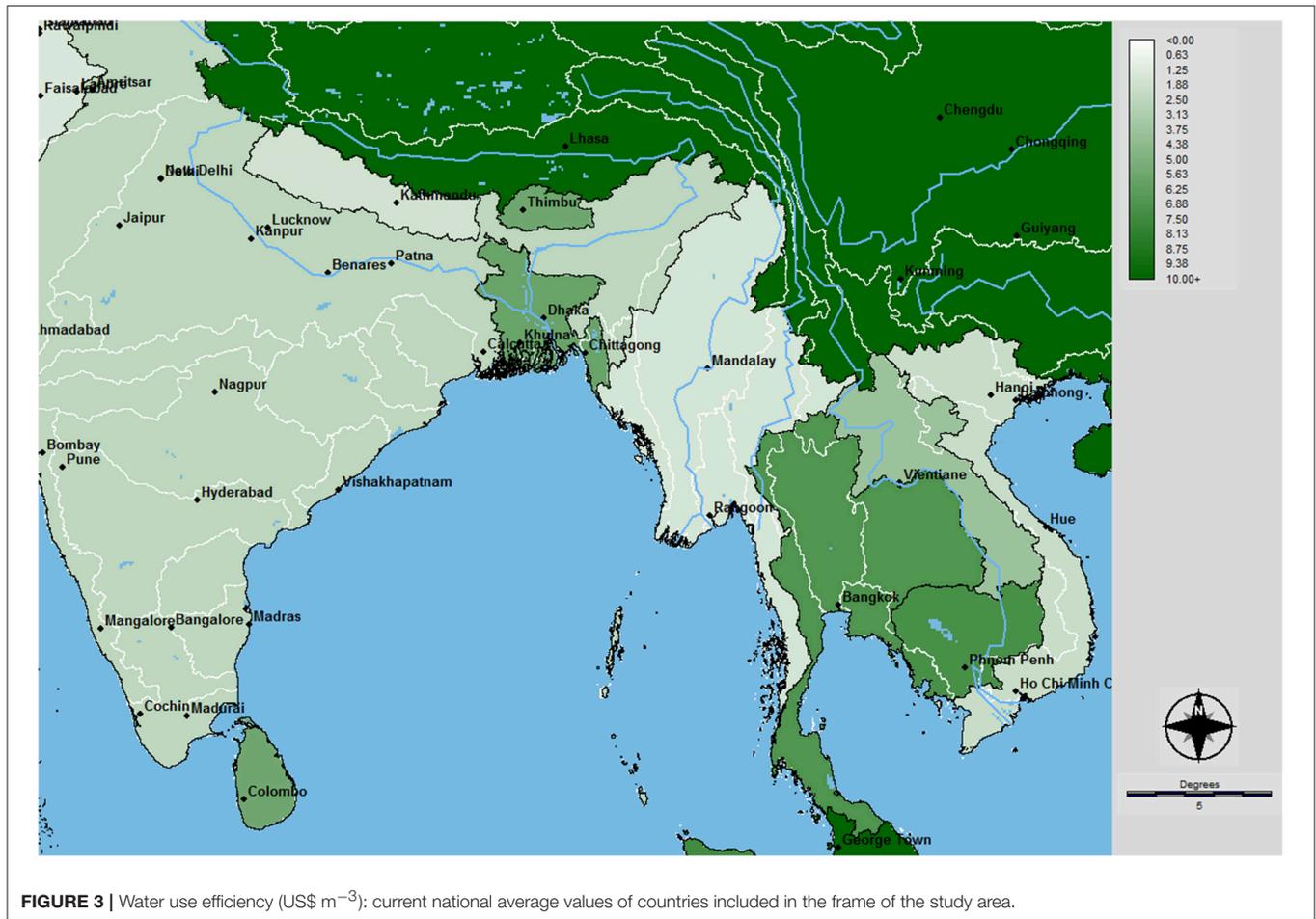
## Assessment of Nexus Between Water and Agriculture

Given that the purpose of the work is to make use of freely available spatial information, in order to explore the nexus between water use for economic purposes in general and food production, we acquired the results of the most recent projections

of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b) (Frieler et al., 2017).

The rationale behind the approach developed here is that having assessed the current status of economic uses of water, the strategies to be implemented to improve WUE should be tailored to the local situation in terms of: (i) potential for future economic development in general, i.e., GDP changes between future (2030) and current period; (ii) potential for future development of irrigated agriculture, in terms of changes of potential irrigation withdrawal between future (2030) and current period; and (iii) estimated future availability of water resources, using as a proxy the estimated runoff volume. Runoff volume can be considered a good indicator of the surface components of the locally generated blue water resources that, however, is limited in capturing the amount of resources flowing from upstream and fails to account for stocks of groundwater resources.

Depending on current levels of value added generated by water withdrawals and on what emerges from future scenarios (in terms of development, irrigation expansion and water availability), competent administrations can identify promising strategies for the achievement of the SDGs. For example, in areas with relatively low level of current development, but with great future potential, strategies would depend on expected water availability. They could be oriented toward infrastructural



investments, in case of high availability of water resources, or toward investments for improving the efficiency per cubic meter of water, when expected availability of water resources is low.

A very preliminary exercise of zoning in support of policy design was thus carried out by using an ISODATA cluster analysis technique (Iterative Self-Organizing Data Analysis Technique), which is a consolidated k-clustering method used for identifying land classes from stacks of multiple images in remote sensing studies (Johnson and Wichern, 2007; Richards, 2013). The map of ISODATA clusters provides a synthesis of multivariate spatial variability of the most important variables characterizing current and future WUE in the region and can be considered as a preliminary support for the identification of a series of different zones characterized by relative internal homogeneity, thus requiring different approaches in terms of policies and measures for the achievement of Target 6.4.

For assessing GDP changes, we calculated the ratio of GDP values between 2030 and current period. Similarly, the ratio of potential irrigation water withdrawal has been calculated between the values of 2030 and those of 2016. Given that runoff estimations varied a lot across the studied area, but showed only limited spatial changes in the comparison between future projection and current estimates, we preferred to use the map of

future projections in the ISODATA procedure than calculating the ratio with current values.

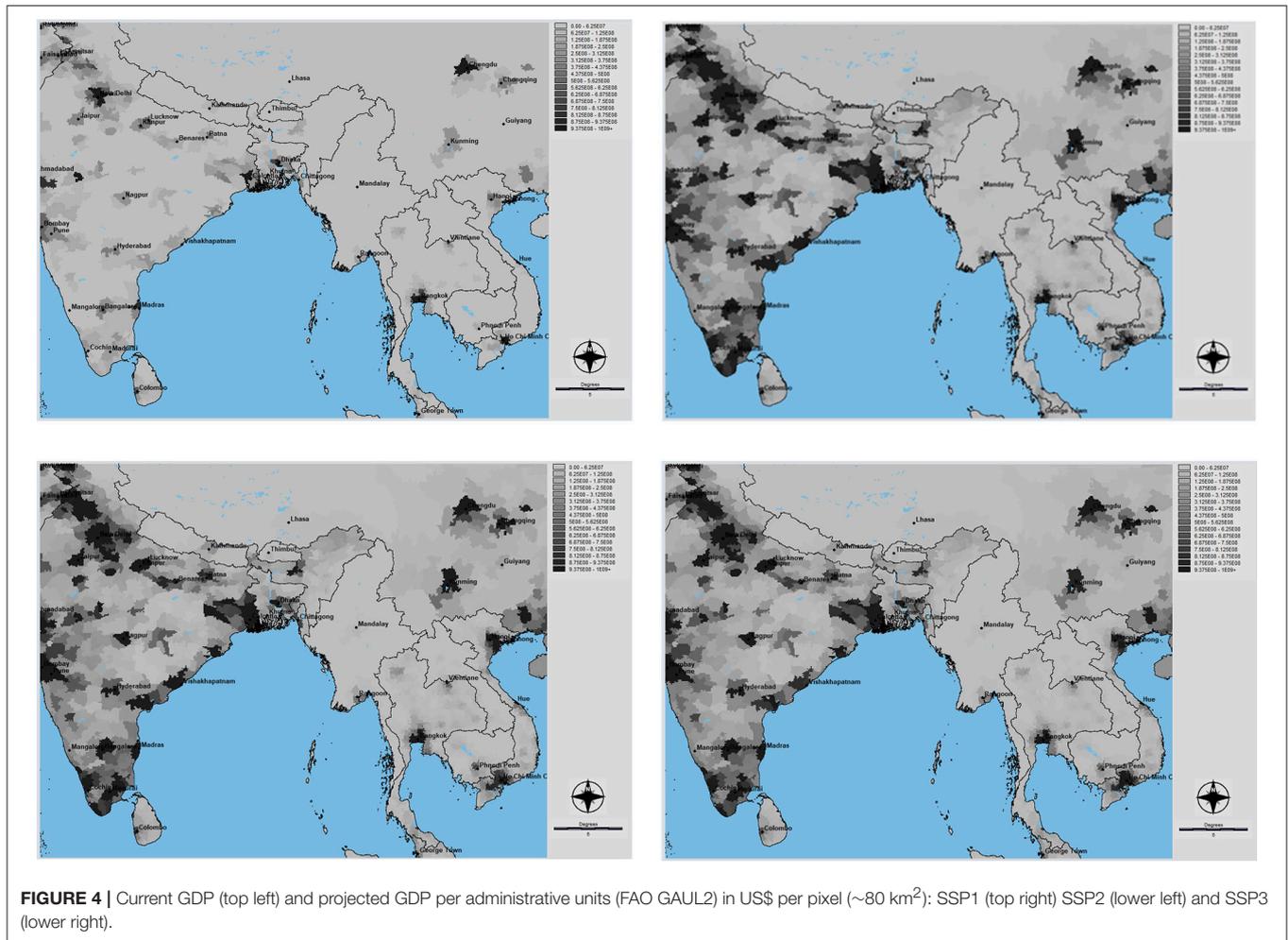
We have considered yearly agricultural water withdrawal data for multi-model-mean of four General Circulation Models (GCMs) [GFDL-ESM2M (Donner et al., 2011), HADGEM2-ES ((Bellouin et al., 2011; Collins et al., 2011)), IPSL-CM5A-LR (Dufresne et al., 2013), MIROC5 (Watanabe et al., 2010)] under two climate scenarios (RCP 2.6 and RCP6.0) from global hydrologic model, H08 (Hanasaki et al., 2018). In order to account for inter-annual variability, water withdrawal data are calculated based on 10 years average: current period 2015 represents average yearly value of 2011–2020 and future (2030) value by averaging yearly value of 2026–2035.

## RESULTS

### Country Level Water Use Efficiency

The current WUE values per country, calculated with the most recent information available in the databases reported in Table 3 is shown in Figure 3.

The country level results of WUE as shown in Figure 3 are in line with those produced by international organizations (UN-Water, 2018). Only very simplistic comparisons can be derived



from the map: e.g., the relatively high value of China, or the relatively lower value of Nepal. Evidently, values averaged at national level are too aggregated and do not present any regional and local variations and hence, there is no information useful for the analysis of the cause-effect links of the phenomena that produced such results, and thus no sound basis for the development of strategies for improving current values to meet Target 6.4, by country or regional governments. Therefore, the assessment of WUE should go beyond country boundaries, with a spatial detail that allows the identification of the combination of environmental and socio-economic drivers, determining the current situations in terms of WUE. Moreover, future projections are needed to compare the current situation with possible future trajectories of those drivers, thus being able to anticipate possible future developments and to design robust policies in view of future scenarios.

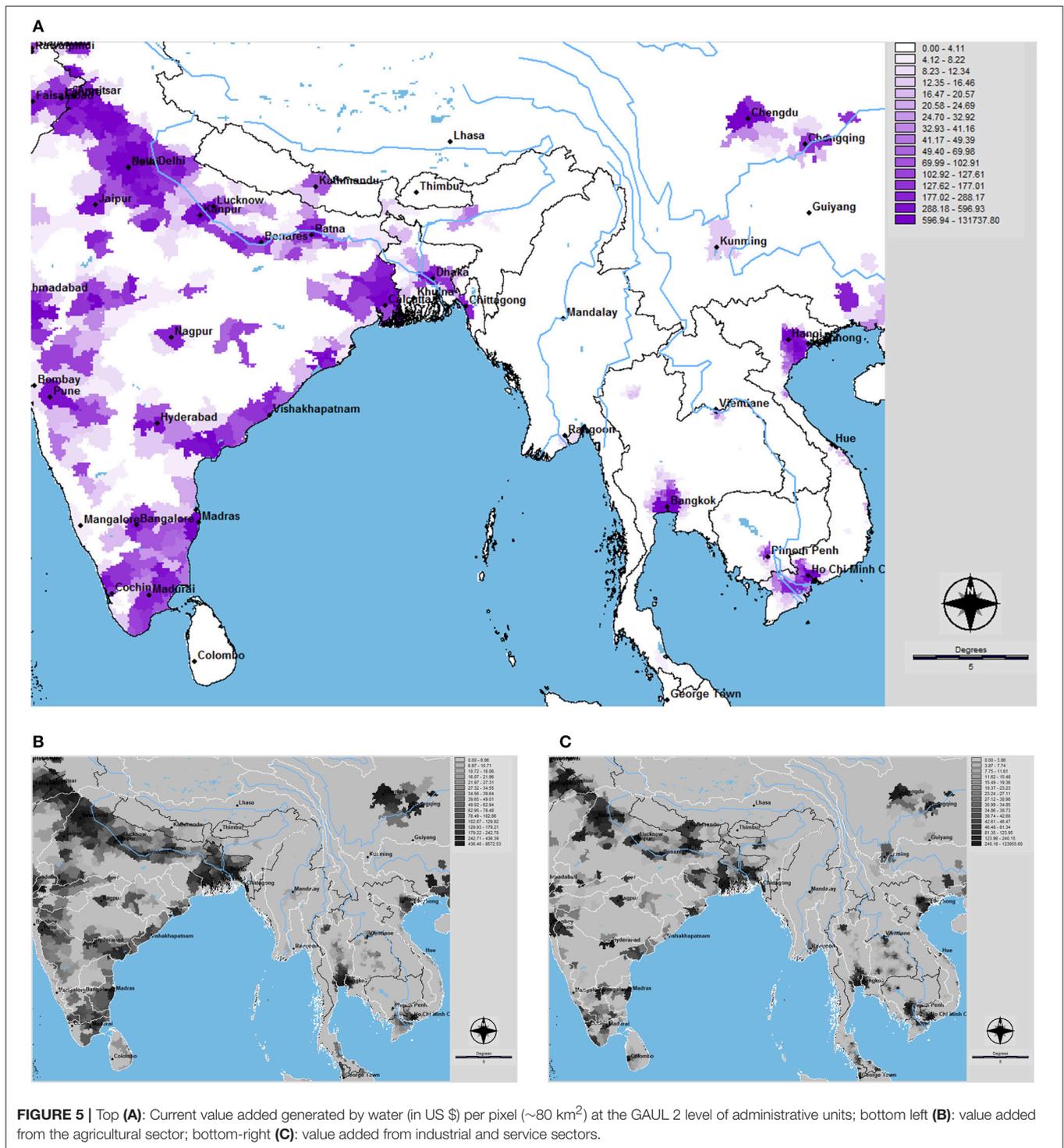
## Spatial Analysis of WUE

Following the procedure concisely described above, we first mapped GDP values at 0.5° resolution from the Carbon Project as at FAO GAUL 2 level for current period and for three scenarios of SSPs of the future period of 2030. The results of aggregating GDP

values at the GAUL 2 level are reported in **Figure 4**, showing, in general, projected increases in GDP for the studied area, independently from the SSP scenario, but with some differences in the allocation of economic activities moving across the SSPs.

Considering the most recent statistics on water withdrawals (agricultural, industrial and domestic) and disaggregated GDP into irrigated agriculture and built-up areas as described above, the current value added of water (in US\$) at the GAUL2 has been assessed. The spatial allocation of WUE for Southeast Asia is shown in **Figure 5**. The high value of WUE (represented through deep magenta color in **Figure 5A**) is shown mainly in built-up areas where industry and urban centers are located, while intermediate levels of water value added are found in irrigated agricultural area (see also **Figure 5B,C** for more details). By comparing **Figure 5** with **Figure 3**, the potential of accurate spatial analyses clearly emerges. **Figure 4** shows all the areas in which current human activities are generating value added from water withdrawals. These are areas where policy interventions to improve WUE required by SDG Target 6.4 should find priority implementation.

Having identified the priority areas, the need emerges to identify which policies to implement, taking into consideration



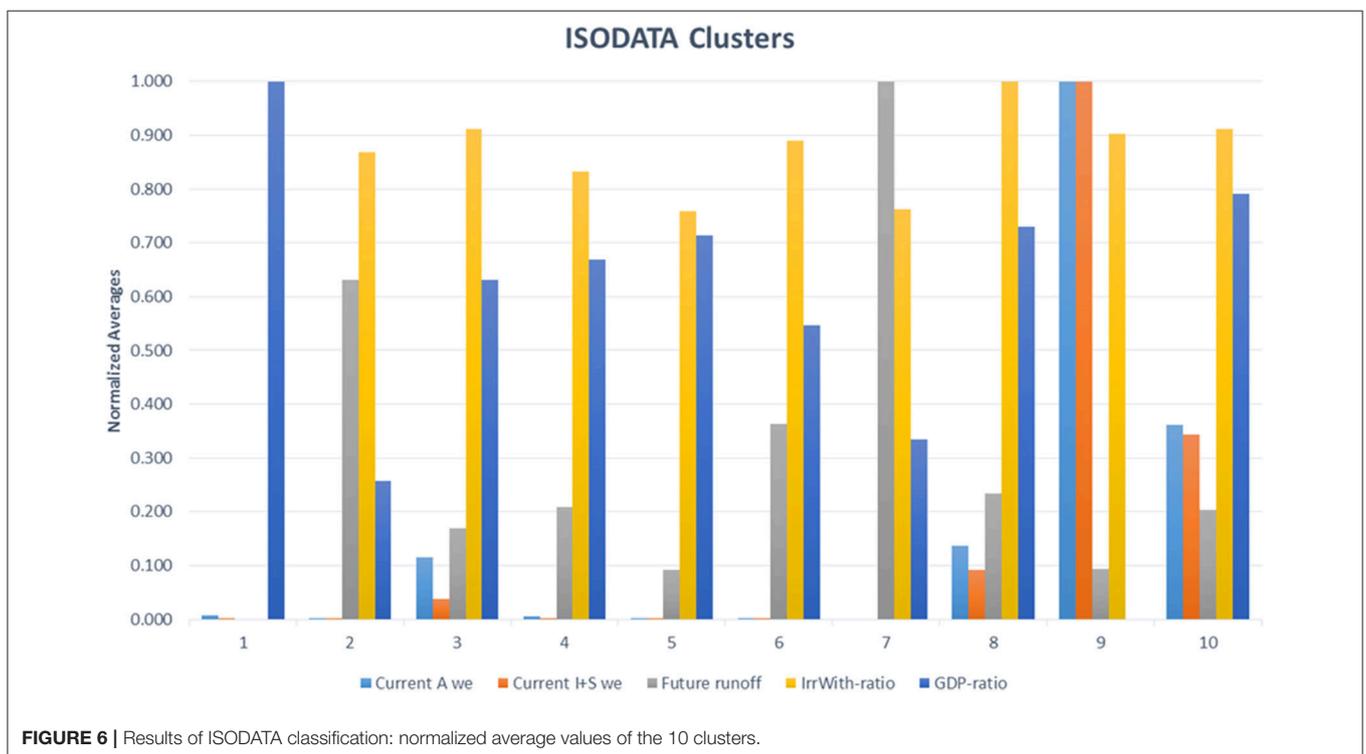
the relationships among water intensive economic activities and other environmental and socio-economic dynamics. Here, the nexus between food production—and more specifically food produced with irrigated agriculture, and other uses of water is of greater relevance. In terms of value added per unitary volume of water, the primary sector cannot compete with the secondary

and tertiary ones, but strategic decisions should be taken at policy level to rule the emerging trade-offs and conflicts and exploit potential synergies, with the aim of maximizing the benefit for society as a whole.

As stated before, the policy options to be implemented will depend on how social and ecological systems will evolve

**TABLE 5** | Average values of clusters.

Cluster	Current A w.e. (US\$ per grid cell)	Current I + S w.e. (US\$ per grid cell)	Future estimated runoff (mm yr <sup>-1</sup> )	Ratio of future vs. current potential irrigation withdrawals	Ratio of future vs. current GDP
1	53.1	17.4	96.1	0.472	4.767
2	12.2	8.9	1,739.6	0.983	3.459
3	633.6	3,994.6	535.1	1.010	4.118
4	38.7	15.3	641.9	0.962	4.184
5	23.3	6.5	333.8	0.919	4.263
6	23.2	11.9	1,043.1	0.996	3.969
7	7.9	6.0	2,699.0	0.921	3.596
8	746.9	9,565.4	705.1	1.061	4.292
9	5430.0	103,631.6	338.4	1.003	3.006
10	1969.2	35,625.4	627.1	1.010	4.400

**FIGURE 6** | Results of ISODATA classification: normalized average values of the 10 clusters.

in the future. In this work, we considered future projections of economic growth, the expected development of irrigated agriculture and the changes in water availability as three very important drivers for policy design in water management.

As previously stated, cluster analysis was chosen as a technique to identify areas with similar combination of current and future values of driving variables. By analyzing a stack of 5 images in ISODATA, we produced a map with the identification of typologies of areas that can be used as a preliminary zoning to support the development of water management policies in the region. The five images were current value added for the agricultural sector, the value added of services and industry, future water availability (using estimated runoff volumes as a

proxy), the GDP ratio (between 2030 and current period) and the potential irrigation water withdrawal ratio (between 2030 and current period). The procedure was set to obtain 10 clusters showing interesting distinctive average features (see **Table 5** and **Figure 6** with the histogram of normalized values). The description of each cluster deriving from the different combination of the five independent variables is shown in **Table 6**, while **Figure 7** shows the spatial distribution of the clusters. Indeed, the clusters produced by the ISODATA procedure depend on the specific geographical frame of analysis. With a different frame, but also with different parametrization the results will not be the same. However, the analysis of sensitivity for exploring the effects of variations on ISODATA inputs demonstrated that the main

**TABLE 6** | Identification of clusters.

Cluster	Description
1	Very low levels of value added from both agriculture and other sectors, with very low water availability and—in relative terms—expected future development in the non-agricultural sectors and decreasing irrigated areas (arid areas e.g., in Rajasthan, Tibet and south India, with grasslands and rainfed crops)
2	Very low levels of current value added in both agricultural and non-agricultural sectors, as Cluster 1, but with relatively high water availability and thus expectations for future developments in particular in irrigated agriculture (forest areas scattered across the region under the influence of monsoons)
3	Low levels of value added from both agriculture and other sectors, with relatively low water availability and expectations for rather high future developments in particular in irrigated agriculture (small periurban areas)
4	Very low levels of value added from both agriculture and other sectors, with relatively low water availability and expected future development (in relative terms) in both agricultural and non-agricultural sectors (very large areas with mainly rainfed agriculture and forests)
5	Very low levels of value added from both agriculture and other sectors, with low water availability and expected future development (in relative terms) in both agricultural and non-agricultural sectors (very large agricultural areas with crops and grasslands located between cluster 1 and 4)
6	Very low levels of value added from both agriculture and other sectors, with limited water availability and expected future development (in relative terms) in both agricultural and non-agricultural sectors (large areas with high presence of forests)
7	Very low levels of value added from both agriculture and other sectors, with very high water availability and limited expected future development (mainly forests in areas close to cluster 2)
8	Rather low levels of value added from both agriculture and other sectors, with low water availability and expected high future development in the agricultural sector and not only (areas close to main cities)
9	Very high levels of value added from both agriculture and other sectors, with low water availability and expected future development only in the agricultural sector (small areas close to Delhi and Bangkok)
10	Rather high levels of value added from both agriculture and other sectors and further expectation of future development (areas around main cities)

typologies of zones concisely described in **Table 6** remain rather stable.

The results of cluster analysis briefly described in **Table 6**, point out at least three macro-areas that should be subject to different policies. Cluster 2 and 7, are mainly forested and with limited future needs of investments in water infrastructures given the current status and future prospect of availability of water resources and land uses. Cluster 1, 3, 4, 5, 6, 8 are areas of potential future development, where improvements of WUE are to be considered as a priority to avoid conflicts over water resource allocation among different economic sectors. Cluster 3 and 8 are in a peculiar situation, since they are mainly located close to very important urban areas, as are Cluster 9 and 10, where the demand and the potential value added of water are high and so are potential future conflicts for water resource allocation between agriculture and other sectors.

The uncertainty associated with the various input layers should be carefully considered, taking into account the spread of

the values of the same variables in various locations. For example, scenario maps of potential irrigation withdrawals vary more in areas of active development, such as the Indo-Gangetic plain, while GDP estimation varies a lot with changing scenarios in built up areas. The robustness of proposed policies will depend on their capabilities to maintain their benefits even with varying future contexts.

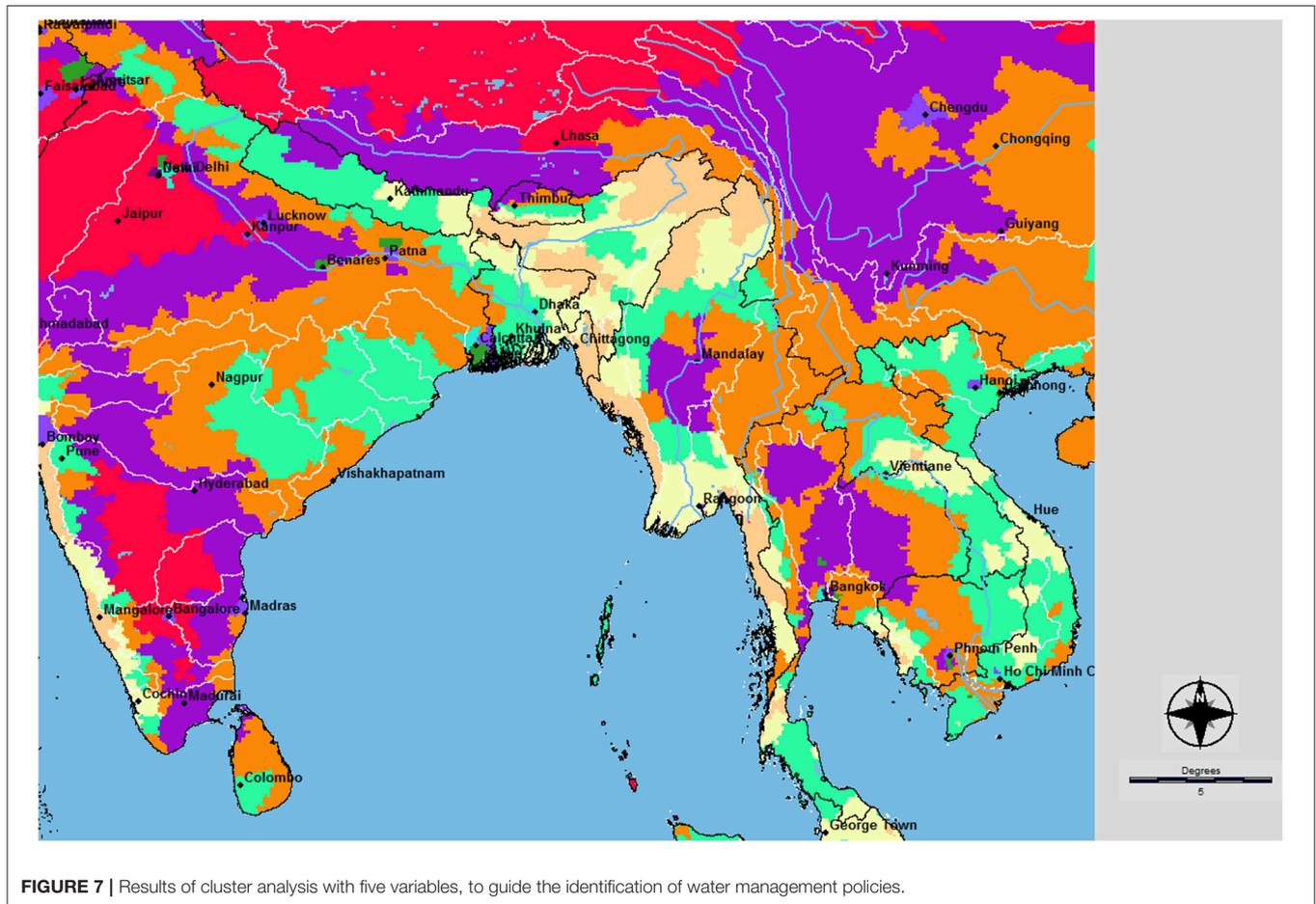
## CONCLUSIONS

Agenda 2030 imposes huge challenges to governments all over the world in their efforts to identify the most effective strategies and implementation measures for achieving the numerous goals and targets. These challenges are particularly strong for those countries with lower resources and more limited data. Considerable efforts have been invested by international institutions and UN agencies for facilitating the identification and access to data sources with global coverage. UN Water launched an Integrated Monitoring Guide for SDG 6 and released a series of step-by-step monitoring guidelines<sup>4</sup>, for monitoring the various indicators, in which data sources at national level are identified. Unfortunately, the quality of available information is often not adequately documented by metadata, thus making an accurate assessment of uncertainty practically impossible as it was in this case. Moreover, the available country statistics presented are referred to different years and time series are very limited, making historical dynamic analyses impossible in vast parts of the world.

In parallel to those efforts focused on national statistics, a wealth of coordinated modeling efforts are in progress to support climate change studies and policy analyses. Here we took advantage of the Land Use Model Intercomparison Project (LUMIP) (Lawrence et al., 2016), set up for the forthcoming Coupled Model Intercomparison Project Phase 6 (CMIP6) (Eyring et al., 2016) and the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b) (Frieler et al., 2017). While it is evident that modeling efforts cannot replace data limitations, it seems also evident that such coordinated efforts developed upon shared scenarios and common assumptions represent a great opportunity in particular for less developed countries. In particular, they make freely available state of the art historical simulations and future projections with global coverage, which allows for global, but also regional synoptic analyses across country boundaries (e.g., transboundary river basins) with unprecedented spatial detail.

In this work we attempted the integration of available statistics with those recently released global datasets, considering that the combination of the two can substantially improve monitoring and analyses based only upon country statistics. Very importantly, the use of spatially disaggregated future projections is a prerequisite for moving from SDG monitoring, to policy support for the achievement of the Goals. The identification of effective policies is impossible without having the capability to make projections into the future, but not necessarily

<sup>4</sup>See <http://www.unwater.org/publications/integrated-monitoring-guide-sdg-6-2/>



**FIGURE 7 |** Results of cluster analysis with five variables, to guide the identification of water management policies.

developing new models, particularly when the ambition is to explore operational solutions to current and emerging water management issues, at regional and sub-national levels, in areas where national statistical systems are less developed, as in most of developing countries.

Official documents and guidelines ask for country scale assessments, but instead the emphasis should be placed on detailed spatial analysis brought to a level of detail which allows for understanding of the mechanisms behind observed situations and thus also for the design of targeted policies to improve the current status. The first step in policy development consists in the acquisition of the information needed to develop a knowledge base, organized through a long series of indicators, but assessment procedures should go beyond national level aggregation and zoom into sub-national phenomena. Spatially explicitly future scenarios are needed to design sustainable development policies, with the required medium to long term perspectives. The proposed approach goes in that direction, while being still consistent with the approach proposed at country level by the custodian agencies, to allow for both monitoring and reporting the progress toward the meeting of the SDGs with international coordination and for supporting the identification of targeted policy measures needed at local level.

The approach is demonstrated in South and South-East Asia, an area of great relevance in addressing open issues related to sustainable development and the assessment of the indicator 6.4.1 (Change in water use efficiency), which better exemplifies the integration of socio-economic and environmental issues. Moreover, cluster analysis applied to both current estimations and future projections allows a comparison of the current state of the WUE indicator (SDG6) with future prospects of agricultural and non-agricultural development (SDG 2; 8 and others), and changes in water availability (SDG 15). For example, it allows for the identification of territorial ambits to guide tailored water management policies, with consideration of their linkages to other policy contexts, and thus also other SDGs.

Indeed, this work is focused on a single indicator, without explicit assessment of its interlinkages with others, but the calculation of Water Use Efficiency is in fact focused on the analysis of the nexus between water resources and different economic sectors, agriculture and food production in particular. Strong interlinkages are evident with several targets. In particular target 2.4 on sustainable agricultural systems, of which we analyzed the use of water for irrigation, 6.5 for the contribution of efficient water management across sectors to Integrate Water Resources Management (IWRM) policies, and 15.1 focused on the status of freshwater ecosystems. Some of the input data used

for the assessment of target 6.4 can be used for the assessment of other indicators, and the flow chart designed for this work can be easily expanded to include the calculation of other indicators.

Although the kind of analysis that we proposed provides concrete support to the policy making, important limitations are still in place and should be clearly discussed. First of all, the use of modeling outputs especially in areas characterized by limited data availability is certainly a huge advantage, but, at the same time, it brings levels of error and uncertainty that are difficult to estimate and are likely to affect the conclusions of the presented and similar analyses. In this work, uncertainty has been dealt with only by means of sensitivity analysis to explore the effects of varying inputs to the final territorial clusters for policy support, obtaining results which showed limited effects on the identification of clusters. Nevertheless, further research efforts are needed to assess the uncertainty levels brought, respectively, by input data and modeling options, in order to provide an accurate estimation of the robustness of the results. Ideally, data uncertainty could be limited by a more detailed monitoring campaign that the custodian agencies should pursue: the first step toward this direction was represented by the identification of a clear set of indicators, but the course taken will surely be costly and hardly free of impediments.

The approach in this paper should be intended to be a procedure for capitalizing on existing information, applicable in different parts of the world, such as South and South-East Asia, selected in this application for the relevance of open issues related to sustainable development, but also for demonstrating the feasibility in regions with strong limitations in data availability. The same procedure (see **Figure 1**) can be easily applied to the rest of the world, even though accuracies will vary depending

on the uncertainties in the input data. Cluster analysis should be carefully reconsidered at global level, for example by revising the number of clusters, in order to obtain meaningful results.

In the near future, this approach will substantially benefit from the continuous flow of new spatial information made available by the intercomparison modeling exercises mentioned above and by improved statistics. Even more, the zoning proposed here could benefit from *ad-hoc* integrated modeling exercises, but that would increase time and financial resources needed by orders of magnitude.

## DATA AVAILABILITY STATEMENT

The datasets utilized as inputs for this study can be found in the repositories and links identified in the article above (see **Table 3**, in particular). Intermediate and final results, including data sets, maps and the macro file will be made available by the authors to any qualified researcher.

## AUTHOR CONTRIBUTIONS

CG designed the methodological framework and conducted GIS analyses. FF and AG contributed to the development of the methodology and collected raw data. The three authors jointly wrote the article.

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**Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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