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Natural and social scarcity in water Footprint: A multiregional input–output analysis for Italy

Gino Sturla [*], Lorenzo Ciulla, Benedetto Rocchi

Department of Economics and Management, University of Florence (IT), Italy

A R T I C L E I N F O

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A B S T R A C T

This study estimates the pressure exerted by Italian consumption on domestic and foreign water resources, adopting the Multiregional Input Output (MRIO) approach and using the information of the most recent (year 2014) World Input-Output Database (WIOD). Disaggregated results are obtained at country/industry level, identifying geographical and sectoral hotspots. The standard volumetric measure of the water footprint (WF) is compared with two impact-weighted measures. Scarce Water Footprint (SWF) corrects the volumetric measure accounting physical scarcity as expressed by a Water Scarcity Index (WSI), based on the ratio between withdrawals and supply of water at the national level. To account also for social factors affecting the availability of water, we propose a further measure of footprint, the Social-Scarce Water Footprint (SoSWF). We find that SWF represents 33.9% of volumetric WF, but the geographical breakdown reveals a relevant asymmetry between domestic and external water exploitation: while only 11.2% of WF generated impacts on domestic scarce water resources, SWF for imports amounted to 54.9% of the total water resources used to produce imported goods. About 45% of the Italian external SWF is generated in China and India by manufacturing, agriculture and electricity, gas and water supply. When also social scarcity is considered we find that the 43% of WF generated impacts on scarce water resources, and an even more evident asymmetry between domestic and external footprints (12.8% vs 71.1% of WF).

1. Introduction

The concept of *Water Footprint* (WF) was introduced by Hoekstra and Hung (2002) based on the concept of virtual water proposed by Allan (1993). The water footprint of a nation is defined as the total volume of fresh water used to produce goods and services consumed by the population of a country. The virtual water trade corresponds to the water contained in the products exchanged among countries. The total WF of a country includes two components: the part of the footprint that falls inside the country (domestic WF) and the part that presses on water resources in other countries (external WF) (van Oel et al., 2009). Three sources of water are usually considered in estimating the WF: *blue* water, corresponding to ground and surface water withdrawn for human uses; *green* water which refers to precipitation stored as soil moisture and used by rainfed agriculture; and *grey* water, the amount of fresh water not available to withdrawals for economic purposes and needed to dilute contaminants to restore a minimum standard of quality in water bodies after discharges (Hoekstra et al., 2011).

To calculate the WF can be used both bottom-up and top-down approaches. The former is based on process analysis, providing detailed descriptions of water requirements of individual production processes, without considering both inter-sectoral and inter-regional linkages in production activities (Feng et al., 2011). The top-down approach uses information from input-output tables to trace the whole regional, national or global supply chains. This is done in two different ways: while the Water Embodied in Bilateral Trade (WEBT) method traces water use only within domestic supply chains (accounting for inter-industry linkages), the methods based on Multiregional Input-Output Analysis (MRIO) trace the whole global supply chain to account also for inter-regional exchanges of water through trade (Peters, 2008; Feng et al., 2011). In this paper we adopt the MRIO approach because it allows to know precisely in which country water is extracted to supply Italian consumption, tracing the inter-sectoral and inter-regional linkages of the whole global value chain. In essence the MRIO approach allows the researcher to re-classify through a linear transformation the global amount of water extracted by production activities from countries actually *withdrawing* the resource from the hydrological system to countries actually *using* such water (directly or indirectly through trade)

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* Corresponding autor at: Department of Economics and Management (DISEI), Via delle Pandette, 9 – 50127 Firenze (IT), Italy.
E-mail address: ginostefano.sturlazerene@unifi.it (G. Sturla).

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to support the final consumption of goods and services.

Recent studies have been conducted calculating the water footprint at the national level using the MRIO approach. Duarte et al. (2016) quantify the water footprint and virtual water transfers for the year 2009 within the European Union, using the World Input-Output Database (WIOD). Arto et al. (2016) perform the calculation for all the countries included in the WIOD database, estimating for the case of Italy a water footprint of 149,800 Mm^3 of which 87,000 Mm^3 corresponding to imported goods and services. Steen-Olsen (2012) carry out an assessment of global WF using a global MRIO model based on the Global Trade Analysis Project (GTAP) database for the year 2004. These studies do not provide estimates of water imported (exported pressures of Italian consumption) disaggregated by country and economic sectors of origin.

Italy ranks fifth among virtual water importing countries, being the second largest per capita water importer with a value of 1,680 m^3 per capita (Hoekstra and Mekonnen, 2012), only behind the Netherlands. Thus, an Italian consumer generates significant pressure on water resources in other countries of the world, both the countries from which Italy imports directly, as well as those that supply goods and services to these countries.

Ali et al. (2018) focuses on Italy's WF at the national level using input–output tables.[1] The analysis is carried out for the period 1995–2009 using the WIOD.[2] The study calculates the balance between exports and imports of virtual water associated with the WIOD countries with direct trade relations with Italy, finding that only for three countries (United Kingdom, Germany and Japan) the balance is positive, that is, Italy is a net exporter of virtual water; for the rest of the countries the balance is negative.

An important issue relates to the fact that WF analysis should account not only for the *volume* of water used but also address the environmental impacts generated by the exploitation of water resources. A strong criticism of the volumetric concept of WF is made by Wichelns (2017). Volumetric measures of WF are only able to give an assessment of water consumption per unit of output. However, it is not the same producing in or importing virtual water from regions facing water scarcity problems than regions with water abundance, as discussed in several studies (Pfister and Hellweg, 2009; Ridoutt and Hung, 2012; Ridoutt and Pfister, 2010; Wichelns, 2017; Yang et al., 2013). For this reason, the WF analysis has been extended to move from water use to *scarce* water use. The concept proposed in the literature is the *Scarce Water Footprint* (SWF) (White et al, 2011), weighting the volume of water by an impact indicator, as for example the Water Stress Index (WSI) (Pfister et al., 2009; White et al., 2015).

The concept of SWF (or scarcity-weighted WF) has been developed in the field of Life Cycle Assessment (LCA) studies (Ridoutt and Pfister, 2010, 2013; Pfister, 2011) and is recommended as a guideline in the ISO 14,046 water footprint document (ISO, 2014; Vanham et al., 2018). The approach emerged as a result of the criticism of the volumetric WF (Mekonnen and Vanham, 2021). A first problem is that volumetric WF is tailored to support the study of water scarcity at the global level, while water scarcity and quality mostly are regional and local issues. Another aspect that the volumetric footprint does not take into account is the fact that water withdrawals varies according to seasons and geographical locations (Ridoutt and Pfister, 2010).

A large number of reports in the literature use the SWF concept to calculate water consumption (Feng et al., 2014). A group of papers use the approach to analyze the loss of freshwater catch resulting from excessive water consumption (Hanafiah et al., 2011) and to examine the global footprint of food products (Ridoutt and Pfister, 2010, 2013). Pfister et al. (2011) calculate the specific water consumption and land use for the production of 160 crops and crop groups, covering most harvested mass on global cropland and quantifying indicators for land and water scarcity with a high geospatial resolution. Pfister and Bayer (2014) use a monthly index of stress on water resources to calculate a scarcity weighted water consumption of global crop production with reference to 11.000 watersheds. The study by White et al. (2015) calculates both WF and SWF considering blue water withdrawals in the Haihe River Basin in China, using the MRIO method to account for external footprint. Wang et al. (2015) make a comparison between WF and SWF for the grain products in China. Ridoutt et al. (2018) use spatially explicit water-scarcity factors within spatially disaggregated Australian water-use accounts to develop a water-scarcity extension of a MRIO model. Zhang et al. (2018) investigate water use in agricultural production in the environmentally sensitive Lake Dianchi Basin in China, considering both WF and SWF. At the international scale, the study of Lenzen et al. (2013) use the Water Stress Index (WSI), a measure of water stress at the country level, to calculate WF and SWF for 187 countries, considering blue and green water and adopting the MRIO approach.

In this study we use a stress indicator combining blue and grey water (Water Requirement Index: WRI). This is consistent with considering both water withdrawals and grey water requirements as drivers of impacts on freshwater ecosystems (Ridoutt and Pfister, 2010; Chapagain et al., 2006; Chapagain and Orr, 2009). Two countries with the same WSI for blue water, when considering also grey water could be found in a quite different condition.

From an even broader point of view, water scarcity is not only a natural problem, but is also related to the scarcity of social resources available to overcome the natural resources constraints. (Ohlsson, 2000; Agapitos, 2010). According to Ohlsson (2000) the transformation of natural issues into social issues occurs at various levels. A first level concerns absolute scarcity due to the increase in demand, requiring engineering efforts to increase supply, which may generate regional and local conflicts. A second level when it is impossible to further increase the water supply, to cope with the scarcity of water resources requires increasing the overall end-use water efficiency, which implies both adopting new technologies and modifying the institutional framework; at this level Ohlsson (2020) identifies a "second order" scarcity problem due to conflicts between winner and losers in the technological and normative change. A further level of water scarcity may require a quantum leap in water efficiency through maximizing the revenue from every drop of water mobilized in society; at this last level, the social challenge generated by the water scarcity problem is the integration of an increasing portion of the population into the modern sector and the migration from rural to urban economy (Ohlsson, 2000).

As Ohlsson (2000) points out, weighting the volumetric measure of WF with "scarcity-based" indexes, such as the WRI adopted in this study, accounts for the ability of society to answer to the "first order" scarcity problems only, that is to satisfy an increasing social demand with a limited natural availability of water. Conversely, a *social* weighting of WF should considers also "second order" scarcity issues, the social trade-offs generated by the adaptation to the natural scarcity of water.

The introduction of social aspects in the analysis shifts water scarcity from an absolute (though scarcity weighted) to a relative concept, in the sense that water management is subject to trade-offs among different social uses. The proposed Social-Scarce Water Footprint (SoSWF) concept considers these social trade-offs in the use of water, weighting the WF based on some indicator of achievement of social goals. This is the case of the Social Water Stress Index (SWSI) proposed by Ohlsson (2000), that adjusts an indicator of per-capita water availability to take into account the different ability of countries to adapt to social trade-offs generated by water scarcity.

In this paper we develop a case study with reference to Italy, with a special focus on the external component of WF. For the first time, the pressure exerted by consumption in Italy on the water resources of other regions (43 countries and the rest of the world) is estimated adopting the

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[1] Bonamente et al. (2017) calculate the water footprint of Italy but without using input–output analysis.

[2] Despite the claim to use the WEBT methodology the results seem to yield from a complete MRIO analysis.

MRIO approach, and considering blue, green and grey water. A disaggregation of the analysis at the industry/country level is also carried out. We compare the volumetric measure of footprint with two impact-weighted measures: the Scarce Water Footprint (SWF) and the Social Scarce Water Footprint (SoSWF).

The second section presents the data used and the MRIO approach to calculate the volumetric measure of WF, as well as the methodology used to calculate the SWF and SoSWF. The third section presents the estimates of volumetric Italian WF in the countries where water is actually used to support final consumptions in Italy. Results are disaggregated by country of origin and by sector producing the imported goods. Measures of SWF and SoSWF are compared to the volumetric one. The fourth section presents a summary and discussion of the main results and provides perspectives for future research.

2. Data and methods

2.1. Data

Multiregional input–output databases provide a comprehensive representation of national and international trade (Cazcarro and Arto, 2019). There are several public databases, such as WIOD (Dietzenbacher et al. 2013), EXIOBASE (Tukker et al. 2009, 2013; Wood et al. 2015), EORA (Lenzen et al., 2013a,b; Aldaya et al. 2010), OECD (OECD 2016), GTAP (Narayanan et al. 2012, 2015). These sources of data also contain satellite accounts that allow for environmental economic analysis. For a comparison of these databases, we recommend the reviews by Giljum et al. (2019) and Mangir and Şahin (2022).

In this study the input–output analysis of water footprints and virtual water flows uses data from the WIOD for 2014 as its main source (WIOD, 2016). WIOD is considered one of the major databases on international production and trade, with satellite accounts related to environmental and socio-economic indicators across a long time series (from 1995 to 2014). The WIOD provides information for 56 sectors in 43 country (30 Europe, 13 Non Europe) and a region called Rest Of The World and also returns information on the categories of final consumption of households, not-for-profit organizations serving households, government, capital investment, and changes in inventories (Timmer et al., 2012, 2015, 2016). Although there are several databases available, WIOD is the most widely used for the study of virtual water trade in the literature for various reasons (Duarte et al.,2016; Alì et al., 2018). First, it provides country-specific information for all EU member states. Second, despite some limitations, the WIOD is the only database providing green, blue, and grey water use for a significant number of industries. Third, the homogeneity of the economic and environmental information provided for more than 15 years allows replicating the analysis for different countries and periods.

Information on direct green, blue, and grey water use in sectors and countries was obtained from the WIOD environmental accounts (Genty, 2012) and is based on the WF studies conducted by Mekonnen and Hoekstra (2011, 2012).

In this paper we use data from the 2009 environmental accounts (satellite accounts), as data on the impact on water resources are still not accounted for following years. This table provides information for 35 industries in 40 countries (27 Europe, 13 Non-Europe). In order to make data consistent with those of 2014 (reference year of the analysis), to the industry in the 2009 table that were disaggregated in 2014 was assigned the same water coefficient. Three countries do not present in the 2009 table are Switzerland, Croatia and Norway; for these states, the water coefficients were equated to those of Austria, Slovenia and Sweden respectively, based on geographical and economic similarity.

Based on the volumes of blue, green and grey water and the outputs by economic sectors of each country, the coefficients of water use per monetary unit of output have been calculated, considering the 2009–2014 change in the value of the US dollar (WIOD currency unit). The assumption corresponds to the non-existence of technological change in the 5 years of differences. A particular case is the Electricity and Water Supply sector, which in the 2014 table is disaggregated into two separate industries. In this case, it would make little to use the same coefficient of the 2009 aggregated sector because the two sub-sectors are very different production activities in the intensity of water use. We adjusted the coefficients to meet the following two conditions: first, the aggregate coefficient of these two industries for 2014, must be equal to the deflated 2009 coefficient; second, the coefficient associated with the water supply industry must be 42 times greater than the coefficient associated with electricity (Kenny et al., 2009; Macknick et al., 2012; Rocchi and Sturla, 2021). The two sectors, however, are presented together in the results.

The WIOD database extended to water resources is essentially an accounting framework. Input-output tables are a disaggregation of the production account included in any standard sequence of national accounts (United Nations et al., 2009). Represented as a double entry table, the accounts record the resources available and their use in production activities, with gross value added resulting as the balancing item of a standard double-keeping accounting system. The disaggregation by commodity/industry allows to record flows of goods and services used as intermediate inputs in production, thus depicting the interdependency among industries and regions in production.

The entries of a multi-regional input–output table extended to water resources record the total flows of commodities within the global economy (expressed in monetary units) and a vector of water uses (in physical terms). The quantification of water intensity coefficients is mostly based on theoretical models of production technologies. Such models are used to adapt a sparse empirical evidence on water requirements to the variety of natural and technological conditions affecting the use of water in different countries. Information on standard errors of these average point estimates are usually not available (Hoekstra et al., 2011; Mekonnen and Hoekstra, 2011; Mekonnen and Hoekstra, 2012). This is not surprising, given the high level of aggregation of the water hydro-economic accounting and the engineering approach to the quantification of water requirements.

2.2. Methods

2.2.1. Volumetric WF

We start from the usual linear, input–output model of the production system (Miller and Blair, 2009):

$$x = (I - A)^{-1} y = Ly \tag{1}$$

where × is the (n × 1) vector total output by industry, y is the (n × 1) vector of final consumption, A is the (n × n) matrix of direct requirements (technical coefficients) and I is a conformable identity matrix. The (n × n) matrix L is the Leontief inverse (Leontief, 1941); a single element l_{ij} of the L matrix represents the total value of output from industry j required to produce a (value) unit of output in industry i.

To study WF, the v (n × 1) vector of natural resource use intensity coefficients is defined in terms of volume of water used by each economic sector to produce 1 dollar of output.

$$v = \hat{x}^{-1} W \tag{2}$$

where W is the (n × 1) vector of total direct requirement of water by industry (direct water uses according to the production-based approach to WF).

Combining equation (1) and (2), the total direct amount of water used in the economic system can be expressed as follows:

$$W = \hat{v} L y \tag{3}$$

where the symbol ˆ indicates the diagonalization of vector v.

Production in a given region requires imports of inputs from several countries, generating a corresponding consumption of water. Moreover, the production process in such countries also requires imports from and generates water consumption in other regions, and so on. The pressures on water resources spreads indefinitely through the global production system. To take into account these indirect requirements of water it is necessary to adopt a Multi-Regional Input–Output approach (Peters, 2008).

We follow the methodology used by Feng et al. (2011), Wood (2017) and Arto (2016), considering *n* regions and *m* sectors, yielding disaggregated results by country and economic sector. This methodology captures both the inter-industry and inter-regional interdependency in water use.

The water footprint for a region *r* is calculated considering the Leontief matrix of the global economic system:

$$L^* = (I - A^*)^{-1} \tag{4}$$

where A^* is the (nm × nm) matrix of direct requirements coefficients for *n* industries in *m* regions.

The A^* and L^* matrices are composed by m^2 sub-matrices of dimension (n × n):

$$A^* = \begin{bmatrix} A^{11} & \cdots & A^{1m} \\ \vdots & \ddots & \vdots \\ A^{m1} & \cdots & A^{mm} \end{bmatrix} \tag{5}$$

$$L^* = \begin{bmatrix} L^{11} & \cdots & L^{1m} \\ \vdots & \ddots & \vdots \\ L^{m1} & \cdots & L^{mm} \end{bmatrix} \tag{6}$$

The A^{rr} elements along the main diagonal of matrix A^* are the matrices of technical coefficients representing inter-industry interdependencies within single regions, while a single element of each sub-matrix A^{rs} is calculated as:

$$a_{ij}^{rs} = \frac{z_{ij}^{rs}}{x_i^s} \tag{7}$$

where the z_{ij}^{rs} is the trade from industry *i* in region *r* to industry *j* in region *s* and x_i^s is the total output of industry *i* in region *s* (interindustry-interregional trade).

The (nm × 1) vector W_E of direct water use associated to production in each one of the *m* regions, disaggregated by industry (in a similar way that equation (3)) is given by:

$$W_E = \widehat{v}^* L^* Y^* i' \tag{8}$$

where Y^* is the (nm × m) matrix of final demand from the *m* regions towards *n* different industries in *m* different regions and *i* is a (1 × m) vector of ones.

Equation (8) allows to calculate the direct use of water for the production of goods and services in the global economy, disaggregated by industry and region. This equation corresponds to the water used within the economic system, that is, it does not include household consumption as part of the domestic water footprint of each country.[3]

The estimates of interest based on the MRIO methodology for this paper correspond to the water used in Italy (domestic economic water footprint[4]) and abroad (external water footprint) to satisfy the Italian final demand. This result is obtained directly with equation (18), considering non-zero only the column associated to the Italian final demand (final domestic goods and final imports) in the matrix Y^*. Appendix A provides a detailed description of these calculations for a global value chain subdivided into 3 regions.

To include corrections to the water coefficients by a single factor for each region, equation (8) can be modified by including a (nm × nm) matrix $\widehat{\Phi}$ with *m* diagonal matrices of *m* equal elements with the correction factors by region:

$$W_{E\_Mod} = \widehat{\Phi} \bullet \widehat{v}^* L^* Y^* i' \tag{9}$$

Appendix A details the way in which the calculation of W_{E_Mod} is performed considering the change in coefficients based on the WSI and SWSI (presented in the following two sections) to calculate the SWF and SoSWF associated with a particular country.

2.3. Water stress Index (WSI)

In this paper we use the concept of the water stress developed by Pfister et al. (2009) and White et al. (2015) to account for water scarcity in the calculation of WF. Water stress is an important information for assessing the impact of freshwater use, since one liter of water consumed in a water scarce region is likely to have a higher impact than in a water rich region (Gheewala et al., 2018, 2017). Pfister et al. (2009) propose the concept to calculate a Water Stress Index (WSI) varying from 0 (no water stress) to 1 (maximum stress). Such an index is used in the Life Cycle Analysis as a characterizing factor for assessing “water deprivation”, to indicate the portion of renewable resources subtract to other uses (White et al., 2015).

To calculate the WSI Pfister et al. (2009) consider the ratio of total annual freshwater withdrawals to hydrological availability (Withdrawal To Availability ratio), which corresponds to the sum of total blue water withdrawals divided by the total long-term water availability (including the ecological flow). Lenzen et al. (2013a,b) use instead a Water Exploitation Index corresponding to the percentage of total *actual* blue renewable freshwater resources withdrawn. In their calculation, withdrawals are net of discharges; similar to Pfister and colleagues they include ecological flow into the total long-term availability.

An interesting indicator of water stress available for several years is the 6.4.2 Sustainable Development Goals indicator, approved by the Inter-agency and Expert Group on SDG Indicators under the United Nations, with the FAO as custodian (FAO, 2022). The indicator is computed as the total freshwater withdrawn divided by the difference between the total renewable freshwater resources and the environmental flow requirements. (FAO, 2022; Dickens et al., 2019).

$$SDG_{Ind} = \frac{TotalFreshwaterWithdrawn}{TotalRenewableFreshwaterResources - EnvironmentalFlow} \tag{10}$$

A value below 25 % conventionally indicates a safe situation in which there are minimal impacts on resources and competition between users; above 25 % the indicator could depict situations potentially problematic, up to the extreme case where the stress level exceeds 100 %, indicating that total water withdrawals are exceeding the amount of “allocable” water available and affecting the ecological flow.

The study by Guan and Hubacek (2008) calculates the *extended* water demand corresponding to the net demand for blue water (withdrawals minus discharges) plus grey water, based on an economic input–output model; however, this study does not calculate any ratio with respect to availability. Rocchi and Sturla (2021) calculate the ratio between the extended demand and a *feasible* supply for the case of Tuscany in Italy. Feasible supply corresponds to the average long-term groundwater recharge and surface runoff net of the ecological flow.

In this paper we consider both blue and grey water to calculate the SWF. Grey water is included to take into account all factors affecting water availability. We consider both the volume of water used *and* the quality of water expressed in terms of volume: grey water becomes an extension of blue water demand. For consistency in scarcity weighting, a Water Requirements Index (WRI) is proposed to be used in the

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[3] This part is aggregated for the case of Italy as in the equation (5).

[4] In this study the expression “domestic economic water footprint” is used to refer to that part of the domestic water footprint generated in the economic system, i.e., the domestic water footprint minus direct household consumption.

calculation of WSI at the national level. The WRI corresponds to the ratio of blue *and* grey water to the *feasible* long-term water availability (average runoff plus average groundwater recharge, minus ecological flow)[5] (equation (11)).

$$WRI = \frac{BlueWater + GreyWater}{FeasibleSupply}*100 \tag{11}$$

In equation (11), the denominator (availability) is defined as in the SDG indicator, that for the average values converges to the feasible supply, while the numerator (requirements) considers both blue water and grey water obtained on the basis of WIOD information. In particular, to quantify the feasible supply (equivalent to water availability) equation (10) is used, considering the blue water withdrawals resulting from the WIOD database (Hoekstra et al., 2011), the value of the SDG indicator (FAO, 2022) and an ecological flow of 20 % (FAO, 2022; Dickens et al., 2009) for each of the countries involved. In this way the "Total Renewable Freshwater Resources" component of equation (10), which for this study is the chosen measure of the feasible supply, is obtained for each of the country considered.

The WSI indicator developed by Pfister et al. (2009) serves as a characterisation factor for "water deprivation", using the ratio of withdrawals to water availability (WTA) as an input. By considering the WRI we are reformulating the concept of water deprivation. Specifically, in the case of grey water we are assuming that while there may be water still available in the hydrological system it cannot be withdrawn, as it is required to dilute the discharges of lower quality. In this sense grey water corresponds to an *additional* water demand no longer available for extraction for economic or other purposes.

As regard as the nature of grey water, we assume that is provided by the same water sources from which withdrawals are made. This is consistent with the WIOD, where grey water has been calculated considering dilution requirements, based on the work of Hoekstra et al. (2011). Considering grey water as an additional component of water demand for dilution is usual in literature, especially for comparisons on a national scale, which requires the adoption of homogeneous criteria. More specific approaches, would require information not easily available in most countries (Hoekstra et al., 2011; WIOD, 2016).

The relation between WRI and the WSI is not linear, the latter being adjusted according to a logistic function that returns continuous values between 0 and 1 (Pfister et al., 2009):

$$WSI = \frac{1}{1 + e^{-6,4 \bullet WRI} \bullet \left(\frac{1}{0,01} - 1\right)} \tag{12}$$

WSI has a minimal water stress of 0.01 as any water consumption has at least a marginal local impact (Pfister et al., 2009).[6]

This version of the WSI is more prudent than those that could be defined on the basis of Withdrawal to Availability, Water Exploitation or SDG ratios: our WRI is strictly higher than these indicators and, therefore, a higher impact is associated to water use.

2.3.1. *Social water stress Index (SWSI)*

As Ohlsson (2000) points out, weighting the volumetric measure of WF with "scarcity-based" indexes, such as the WSI, accounts for the ability of society to answer to the "first order" scarcity problems, that is to satisfy an increasing social demand with a limited natural availability of water. Conversely, a *social* weighting of WF should considers also "second order" scarcity issues, the social trade-offs generated by the adaptation to the natural scarcity of water.

The overall ability of a society to respond to complex challenges is assessed by UNDP through the Human Development Index (HDI). The human development index measures the average achievements in a country in three basic dimensions of human development - longevity, knowledge and a decent standard of living. A composite index, the HDI thus contains three variables: life expectancy, educational attainment and real GDP per capita (Ohlsson, 2000); the value is in a range between 0 and 1.

We calculate a Social Water Stress Index (SWSI) by dividing the WSI by the HDI[7]:

$$SWSI = \frac{WSI}{HDI} \tag{13}$$

This equation indicates an exacerbation of water scarcity problems as the human development index decreases. This leads to an increase in the SWSI compared to the WSI, the trade-off of social benefits being expressed as a deterioration in water conditions. The value of the index could in theory vary between 0 and infinitive; values higher than 1 are adjusted to unit. This assumption ensures that SoSWF is never greater than WF (blue and grey), thus not generating "additional" water uses beyond the simple, volumetric measure of footprint. Specifically, if the SWSI is equal to unity, this means that all water contained in the volumetric WF generate both physical and social scarcity.

3. Results

3.1. *Volumetric water footprint*

Table 1 presents the aggregated results by type of water. Italy's water footprint for 2014 amounts to 136,543 Mm^3, the external water footprint corresponds to 81,491 Mm^3 (59.7 % of the total WF) and the domestic water footprint is equal to 55,052 Mm^3 (40.3 % of the total WF). The blue water footprint represents 20 % of the total WF, the green WF 64 % and the grey WF 16 %.

The results for the 56 industries have been aggregated in Table 2 into

Table 1
Water uses in Italy (Millions of cubic meters, Mm^3).

Variable	Blue Water	Green Water	Grey Water	Total
Household Direct Consumption	847	0	4,085	4,932
Domestic Economic Water Footprint	12,742	31,640	5,738	50,120
External Water Footprint (Imports)	13,081	56,157	12,253	81,491
Water Embodied in Exports	3,840	13,890	4,005	21,735
Direct Use of Water (Production-based)	16,581	45,530	9,865	71,976
Water Footprint (Consumption-based)	26,670	87,797	22,076	136,543

Source: own elaboration on WIOD data.

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[5] This indicator does not correspond exactly to the one proposed by Rocchi and Sturla (2021) since it does not consider net demand, but rather abstractions, as the WIOD environmental database does.

[6] The curve is calibrated to result in a WSI of 0.5 for a WTA of 0.4, which is the threshold between moderate and severe water stress (Pfister et al., 2009).

[7] Different from (Ohlsson, 2000) where water scarcity was measured by an index of per-capita availability of water.

Table 2
Italian Domestic and External Water Footprint by industry (Millions of cubic meters, Mm^3).

Economic Sector	Domestic WF				External WF			
	Blue	Green	Grey	Total	Blue	Green	Grey	Total
Agriculture	3,381	31,640	4,020	39,041	6,349	56,157	5,746	68,252
Food Industry	110	0	651	761	60	0	443	504
Electricity, Gas and Water Supply	9,069	0	0	9,069	6,055	0	0	6,055
Manufacture	165	0	970	1,135	610	0	5,996	6,606
Services	17	0	97	114	7	0	68	75

Source: own elaboration on WIOD data.

Table 3
Italian External WF, SWF and SoSWF by country.

Country	WF (Mm^3)	WF_bg (Mm^3)	WSI	SWF (Mm^3)	SWSI	SoSWF (Mm^3)
China	6,973.0	4,002.1	1.000	4,002.1	1.000	4,002.1
Brazil	4,936.0	460.9	0.120	55.1	0.158	72.9
United States of America	3,863.0	1,093.5	0.464	507.9	0.505	552.0
France	3,231.0	864.9	0.127	109.7	0.142	122.8
Spain	3,191.0	938.9	0.196	184.2	0.221	207.4
India	2,820.0	1,186.3	0.996	1,182.0	1.000	1,186.3
Indonesia	2,289.0	231.9	0.695	161.3	1.000	231.9
Germany	1,970.0	615.6	0.089	54.6	0.095	58.3
Hungary	1,937.0	342.6	0.015	5.3	0.018	6.3
Turkey	1,866.0	530.9	0.351	186.6	0.441	234.4
Canada	1,808.0	484.1	0.035	16.7	0.038	18.2
Russian Federation	1,642.0	940.2	0.014	12.8	0.017	15.9
Poland	1,374.0	484.3	0.098	47.2	0.114	55.0
Romania	1,139.0	457.4	0.062	28.1	0.076	34.7
Bulgaria	775.0	243.5	0.907	220.8	1.000	243.5
Australia	771.0	111.3	0.016	1.8	0.018	2.0
Austria	588.0	203.2	0.558	113.3	0.611	124.1
Czechia	573.0	133.9	0.051	6.8	0.057	7.7
Switzerland	429.0	356.5	0.390	139.1	0.414	147.7
Denmark	356.0	64.1	0.053	3.4	0.057	3.6
Ireland	337.0	46.3	0.014	0.7	0.015	0.7
Greece	301.0	87.4	0.040	3.5	0.045	4.0
Mexico	246.0	62.6	0.135	8.4	0.177	11.1
Lithuania	242.0	8.1	0.012	0.1	0.014	0.1
Belgium	238.0	137.3	0.267	36.6	0.290	39.9
Sweden	231.0	110.7	0.698	77.3	0.747	82.7
Croatia	225.0	108.2	0.014	1.5	0.017	1.8
United Kingdom	220.0	54.6	0.022	1.2	0.024	1.3
Netherlands	209.0	58.3	0.031	1.8	0.033	1.9
Slovakia	204.0	48.1	0.012	0.6	0.015	0.7
Portugal	182.0	54.6	0.043	2.3	0.050	2.8
Slovenia	177.0	104.9	0.050	5.3	0.056	5.9
Taiwan	160.0	95.1	0.188	17.9	0.257	24.5
Finland	116.0	26.1	0.180	4.7	0.194	5.1
Latvia	111.0	20.1	0.037	0.7	0.044	0.9
Norway	105.0	27.8	0.168	4.7	0.178	5.0
Estonia	68.0	7.4	0.032	0.2	0.037	0.3
Japan	32.0	25.7	0.125	3.2	0.138	3.6
South Korea	31.0	14.8	0.705	10.4	0.780	11.5
Luxembourg	9.0	2.2	0.013	0.0	0.014	0.0
Cyprus	5.0	1.6	0.066	0.1	0.076	0.1
Malta	3.0	0.7	0.752	0.5	0.861	0.6
Rest of the World	35,507.0	10,485.2	0.637	6,680.8	1.000	10,485.2

Source: own elaboration on WIOD data.

Table 4
Italian WF by industry and region.

Economic Sector	Italy (Mm^3)	42 WIOD Countries (Mm^3)	Rest of The World (Mm^3)	Total WF (Mm^3)	% Total
Agriculture	39,041	38,514	29,738	107,293	78.6 %
Food Industry	761	363	140	1,265	0.9 %
Electricity, Gas and Water Supply	9,069	2,639	3,416	15,123	11.1 %
Manufacture	1,135	4,444	2,162	7,741	5.7 %
Services	114	24	51	189	0.1 %
Households Consumption	4,932	0	0	4,932	3.6 %
Total	55,052	45,984	35,507	136,542	100.0 %

Source: own elaboration on WIOD data.

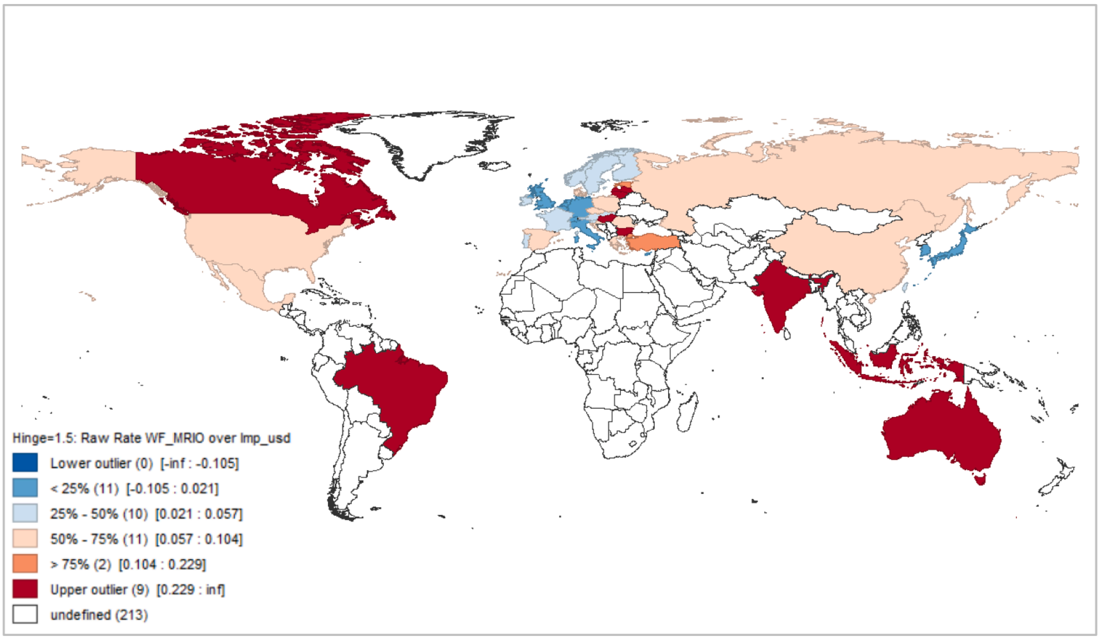

Fig. 1. Italian Water Footprint (WF) intensity (Cubic meters by US dollar of direct and indirect imports). Source: own elaboration on WIOD data. *The category "undefined" refers to countries not considered individually in the WIOD database.*

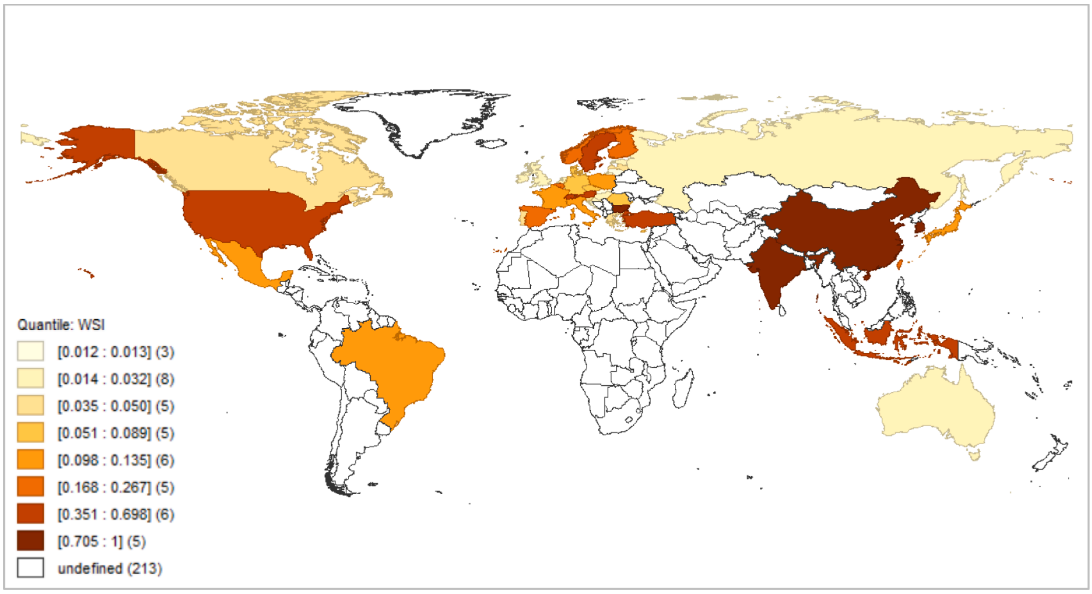

Fig. 2. Water Stress Index (WSI) by country Source: own elaboration on WIOD data. *The category "undefined" refers to countries not considered individually in the WIOD database.*

5 macro-sectors: Agriculture; Food Industry; Electricity, Gas and Water Supply; Manufacture; and Services (see Appendix B). Table 2 presents the domestic (excluding household direct consumption) and external economic WF of Italy, disaggregated by industry and by water type.

When considering the breakdown by country of origin of virtual water (Table 3, second column) China (6,973 Mm^3, 8.6 %) is the single country with the highest share (8.6 %) of external volumetric WF, followed by, Brazil (6.1 %) and United States of America (4.7 %). The Rest of the World represents a 45.6 % of the external water footprint of Italy.

A different ranking of countries emerges when only blue and grey water contributions to footprint (WF_bg) are considered (Table 3, third column). China is still the largest contributor to the Italian WF, with an even larger share (15.8 %), followed by India (4.7 %) and USA (4.3 %).

Table 4 presents the breakdown by industry and region of the Italian WF. The largest sectoral component corresponds to agriculture (78.6 %), mainly due to green water, followed by the Electricity-Gas-Water Supply sector (11.1 %).

The map in Fig. 1 shows the Italy's external water footprint *intensity*, that is the external WF divided by the value of imports (direct and indirect) in the 42 countries with individual values included in the WIOD.[8]

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[8] Appendix C provides the maps for blue, green and grey components of WF.

Table 5
SWF Industry distribution by region.

Economic Sector	Italy (Mm^3)	42 WIOD Countries (Mm^3)	Rest of The World (Mm^3)	Total SWF (Mm^3)	% Total
Agriculture	833	3,412	3,005	7,249	43.8 %
Food Industry	86	100	89	275	1.7 %
Electricity, Gas and Water Supply	1,020	1,084	2,176	4,281	25.9 %
Manufacture	128	2,619	1,378	4,124	24.9 %
Services	13	6	33	52	0.3 %
Households Consumption	555	0	0	555	3.4 %
Total	2,634	7,221	6,681	16,536	100.0 %
% Total	15.9 %	43.7 %	40.4 %	100.0 %	

Source: own elaboration on WIOD data.

Table 6
Italian Scarce Water Footprint (SWF) by región (Millions of cubic meters, Mm^3).

	Italy	42 WIOD Countries	Rest of the World	Total
WF_bg	23,412	14,848	10,485	48,745
SWF	2,634	7,221	6,681	16,536
SWF/WF_bg	11.3 %	48.6 %	63.7 %	33.9 %

Source: own elaboration on WIOD data.

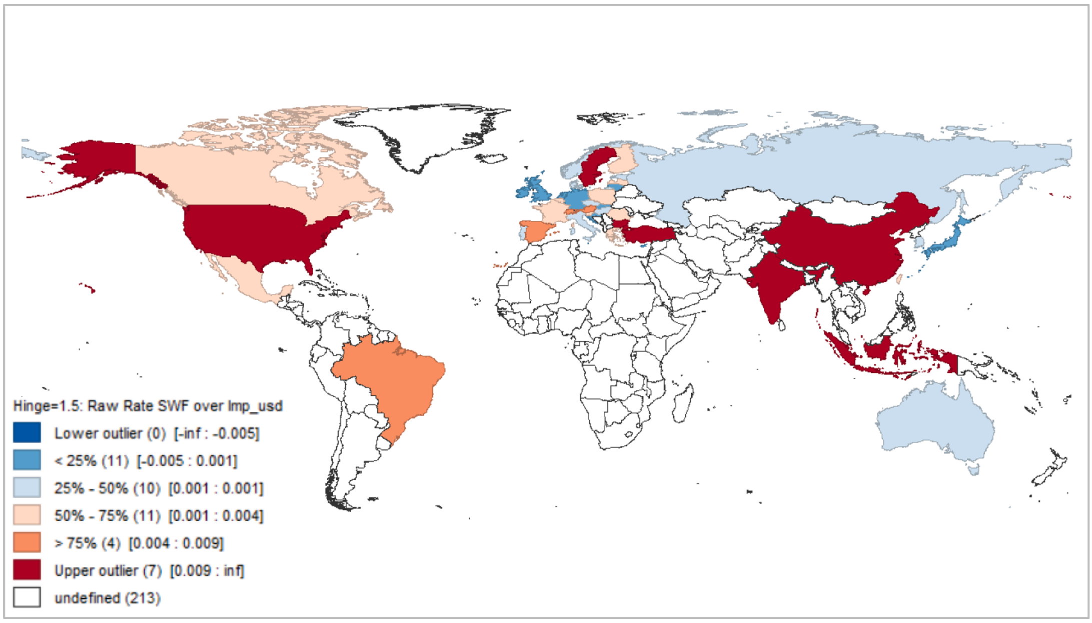

Fig. 3. Italian Scarce Water Footprint (SWF) intensity (Cubic meters by US dollar of direct and indirect imports). Source: own elaboration on WIOD data *The category "undefined" refers to countries not considered individually in the WIOD database.*

The value of intensities is driven by the composition of imports by each country. In the case of the total measure of WF, including also green water, imports of agricultural products are likely to play a major role.

3.2. Scarce water footprint

As explained in section 2, the SWF calculation has been carried out considering only blue and grey water uses (WF_bg), the component of WF generating impacts on environmental flows necessary for the health of the freshwater ecosystems, while green water use is mostly linked to impacts of land use (Ridoutt and Pfister, 2010). Both the external SWF (42 WIOD Countries and the Rest of The World) and the internal SWF of Italy (including direct household consumption) are considered. The map in Fig. 2 shows the geographic pattern of water stress in the world resulting from the WIOD database, considering blue and grey water (WSI based on WRI indicator).[9]

Table 5 shows the distribution of SWF considering both industry and geographic origin of imports. The largest contribution to the SWF is generated by Agriculture in the 42 WIOD Countries (3,412 Mm^3, 46.2 % of agricultural WF_bg). For the Electricity, Gas and Water Supply sector, the largest share is shown by the Rest of the World (2,176 Mm^3) while in the case of Manufacture the contribution of the 42 countries (mostly industrialized) is two times that of the Rest of the World.

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[9] Additional results on the change in the value of WSI when using the WRI instead of the SDG indicator of water stress are available in Appendix D.

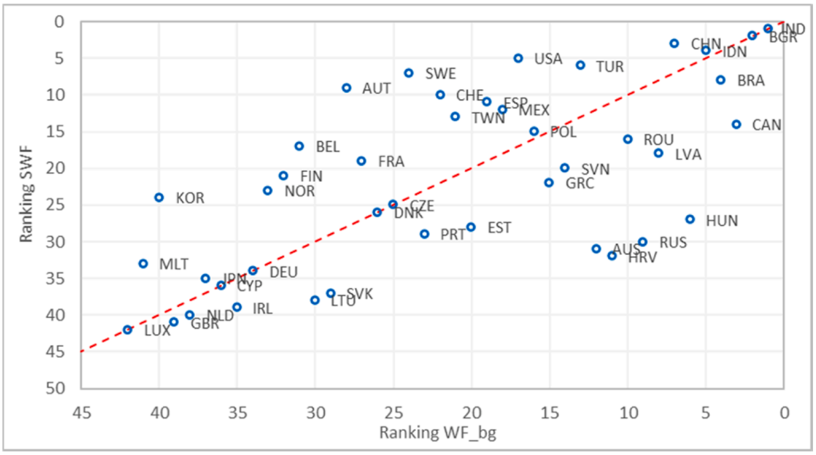

Fig. 4. Ranking of countries for Italian water footprint intensities Water Footprint (WF_bg) vs Scarce Water Footprint (SWF). Source: own elaboration on WIOD data.

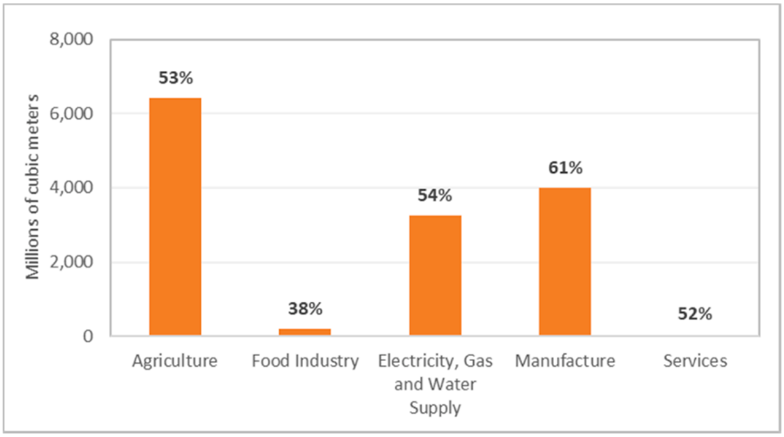

Fig. 5. Industry distribution of Italian External SWF (Absolute value in Mm^3 and Percentage of the WF_bg). Source: own elaboration on WIOD data.

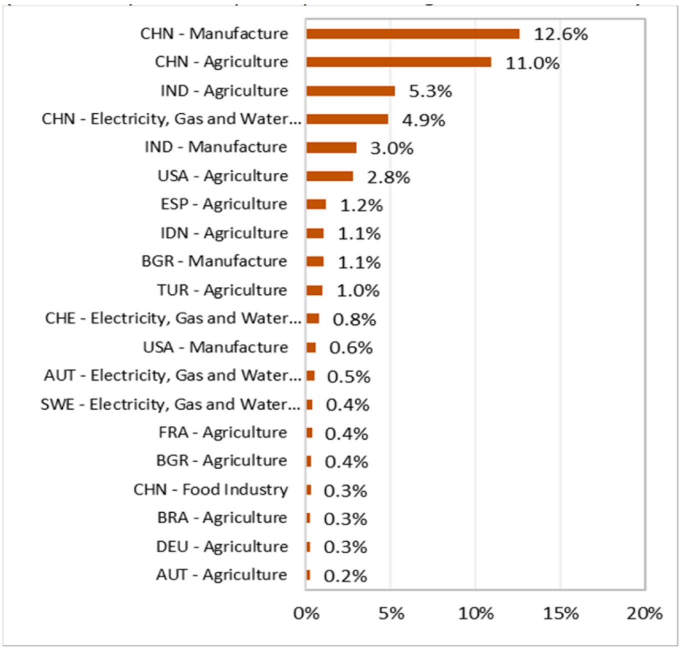

Fig. 6. Percentage of Italian External SWF by country-industry (20 Country-Industry hotspot with higher External SWF). Source: own elaboration on WIOD data.

The pressures exerted by Italian consumptions on global water resources depends on the industry and geographic composition of imports. The total SWF for Italy (Table 6) corresponds to 16,536 Mm^3, a share of 33.9 % of WF_bg. Interestingly, Italian consumptions generate a lower average impact on domestic than external water resources (11.3 % vs and average SWI/WF_bg ratio of 33.9 %). The largest amount of the SWF of Italy (7,221 Mm^3, about 44 % of the total) is concentrated in the 42 WIOD Countries, with a 48.6 % average ratio over the volumetric measure of WF. The Rest of the World shows a 63.7 % average ratio over the volumetric measure of WF, due to the higher average water stress assumed for these countries.

The fourth and fifth columns of Table 3 show the water stress index (WSI) and the resulting external scarce water footprint (SWF) of countries. The map of *intensities* changes when SWF is considered (Fig. 3), showing a prominent role of China, India and USA together with other minor trade partners of Italy. Sweden, showing one of the highest intensities, is the country for which the inclusion of grey water in the calculation of WSI mostly affects the value of SWF.[10]

The effect of moving from a simple volumetric measure of WF to a scarcity-weighted one is represented in Fig. 4. The graph compares the ranking of countries associated with the Italian external water footprint, considering the WF and SWF intensities. The countries above the red dashed line show an increase in the ranking when considering SWF while the countries below the line show a decrease. India is ranked first for both the indicators. Moving from WF to SWF the most notable change in ranking refers to Austria, rising from 28th to 9th place, due to its relatively high WSI (0.558), while Russia, a country with abundance in water resources, falls from 9th to 30th place due to its low WSI value (0.014). China rises from 7th to 3rd due to its WSI equal to one.

Fig. 5 shows the industry distribution of external SWF. The sector where the SWF represents a larger share of external WF_bg is Manufacture (61 %) while the industry with the lower share of scarce water exploitation is Food Industry (38 %).

The graph in Fig. 6 shows the contribution to the Italian external SWF of the first country-industry pairs, accounting for almost the half (48.1 %) of the total external SWF. The participation of Manufacture in China and India, Agriculture in China, India and United States of America, and Electricity, Gas and Water Supply in China stand out, these 6 country-economic sector pairs representing about 40 % of the external Italian SWF.

A further interesting result is the contribution of Italian consumptions to the impact on freshwater ecosystems in other countries, expressed as the percentage change generated on the average country WSI by exports to Italy. The most affected are European countries for which Italy is a relevant partner in international trade.[11]

3.2.1. Social-Scarce water footprint

The SoSWF calculation weights the volumetric footprint (WF_bg) with the Social Water Stress Index (SWSI).

Table 7 provides the breakdown of the SoSWF by industry and origin of imports. The largest contribution is generated by imports from the Rest of the World (4,716 Mm^3), now exceeding for Agriculture the 42 WIOD countries (3,614 Mm^3), due to the lower level of human development of countries included in the region. Also, in the case the Electricity-Gas-Water Supply sector, the largest share comes from the Rest of the World (3,416 Mm^3). In the case of Manufacture, the contribution of the 42 countries for which disaggregated accounts are available (mostly industrialized) is still higher than the Rest of the World (as in the SFW case).

The total SoSWF for Italy is the 43.1 % of the volumetric WF_bg (Table 8), against the 33.9 % share obtained without adjusting for social trade-offs. The share relying on domestic water resources (2,987 over 21,003 Mm^3) increases to 14,2% (compared to 11.3 % in the case of SWF). The largest amount of SoSWF is no longer concentrated in the 42 WIOD Countries (7,531 Mm^3), now showing a higher value in the Rest of The World (10,485 Mm^3), due to the higher average water stress and the lower average value of the human development index in the countries included in this region (including the whole Africa).

The sixth and the seventh columns of Table 3 presents the Social Water Stress Index (SWSI) and the Social-Scarce Water Footprint (SoSWF) for the 43 regions (42 WIOD Countries and the Rest of the World). The consideration of "second order" social scarcity in the assessment of impacts generates little changes in the ranking of countries, mainly due to cases when SWSI reaches the upper limit of one (beside China also India, Indonesia and Bulgaria).[12]

Fig. 7 shows the industry distribution of external SoSWF and its

Table 7
Italian SoSWF industry distribution by region.

Economic Sector	Italy (Mm^3)	42 WIOD Countries (Mm^3)	Rest of The World (Mm^3)	Total SWF (Mm^3)	% Total
Agriculture	944	3,614	4,716	9,274	44.2 %
Food Industry	97	106	140	344	1.6 %
Electricity, Gas and Water Supply	1,157	1,127	3,416	5,699	27.1 %
Manufacture	145	2,677	2,162	4,984	23.7 %
Services	15	7	51	73	0.3 %
Households Consumption	629	0	0	629	3.0 %
Total	2,987	7,531	10,485	21,003	100.0 %
% Total	14.2 %	35.9 %	49.9 %	100.0 %	

Source: own elaboration on WIOD data.

Table 8
Italian Social-Scarce Water Footprint (SoSWF) by región (Millions of cubic meters, Mm^3).

Region	Italy	42 WIOD Countries	Rest of the World	Total
WF_bg	23,412	14,848	10,485	48,745
SoSWF	2,987	7,531	10,485	21,003
SoSWF/WF_bg	12.8 %	50.7 %	100.0 %	43.1 %

Source: own elaboration on WIOD data.

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[10] More detailed results on the modified WSI used in this study are available in Appendix D.

[11] See Appendix E for detailed results.

[12] The maps showing the geographic pattern of SWSI and SoSWF intensity are provided in Appendix C.

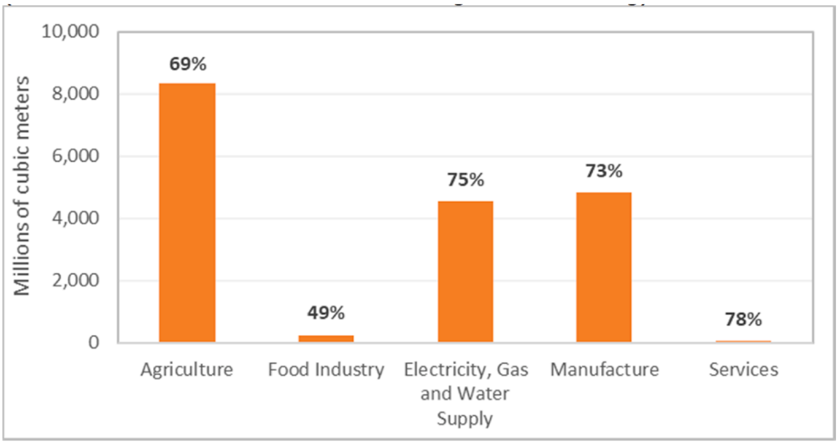

Fig. 7. Industry distribution of Italian external SoSWF (Absolute value of in Mm^3 and Percentage of the WF_bg) Source: own elaboration on WIOD data.

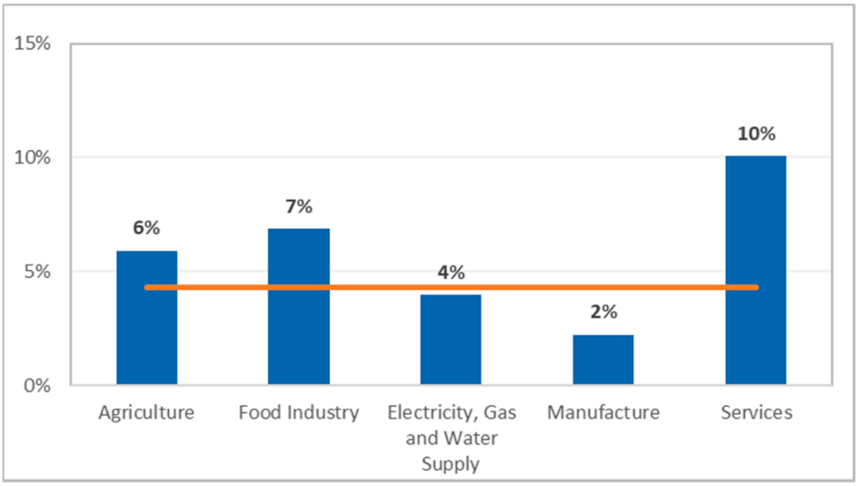

Fig. 8. Percentage difference between industry SoSWF and SWF for the 42 WIOD Countries Source: own elaboration on WIOD data.

relevance within the volumetric WF_bg. The scarce water used to produce good imported by Italy increases when social trade-offs are considered, representing in some industries the major part of the total. The industries where external SoSWF is more relevant are on average those included in the Services sector (78 %), anyway accounting for a small share of the total in absolute terms, while the lowest impact on social scarce water is generated by imports of Food Industry products (49 %).

Fig. 8 shows the percentage difference between external SoSWF and SWF of Italy across the five macro-sectors of the economy. The increase in the scarcity weighted indicator of water footprint due to the consideration of social trade-offs in different industries depends on the geographic composition of imports. It is important to further stress here that, given the use of the MRIO methodology, the contribution of different industries to Italy's external water footprint (scarce and social-scarce) reflect the structure of the whole value chain, not only to those industries/countries from which Italy imports directly, which makes the interpretation less intuitive.

The increase on average is 4.3 %, however, there is a sectoral variability. The percentage difference for Agriculture, Food Industry and Services is above average, i.e., on average the water used to produce these imports comes from countries with a lower HDI compared to imports from Electricity-Gas-Water and Manufacture.

4. Discussion and conclusions

The aim of this paper was to provide an in-depth analysis of water footprint generated by Italian consumptions. The study of the Italian case was an opportunity to review the debate on the WF concept, comparing alternative approaches to its quantification proposed in the last two decades. We developed an improved version of the volumetric and scarcity-weighted WF indicators and proposed a further index to account for social trade-offs generated by the exploitation of water resources.

The analysis was based on the World Input Output Database (WIOD), a multiregional input–output table of the world economy with a satellite account of water resource use. This information allowed to quantify the total WF of Italian consumptions, considering both domestic and foreign demand and taking into account the structure of the global value chain in quantifying (direct and indirect) virtual water flows associated with Italian imports.

The production of goods and services consumed in Italy in 2014 required the use of 136,543 Mm^3 of water. This amount was composed for the largest part (about 64.3 %) of water from precipitation and soil moisture (green water), while renewable groundwater and surface water sources (blue water) provided about the 20 % (26,670 Mm^3) of total requirements. The exploitation of blue water generated an additional requirement of 22,076 Mm^3 (16.2 %) to restore the quality of freshwater renewable sources (grey water).

When considering only blue and grey, water about the half of Italy's WF exerted its pressures on resources of other countries, through imports for the largest part from Agriculture (24.8 %) Manufacture (13.5 %) and Electricity, Gas and Water Supply (12.4 %) sectors. The three top countries exporting virtual blue and grey water to Italy were China (15.8 %), India (4.6 %) and USA (4.3 %). However, when looking to the *intensity* of virtual water imports (Mm^3 per import $) the top countries included, together with China and India, also Canada, Brazil and Indonesia.

The volumetric measure of WF depicts the contribution of Italy to the exploitation of global water resources but hardly allows to evaluate the impacts generated on water resources and the environment. A first methodological achievement of the study refers to the use of an improved indicator of water exploitation, the Water Requirement Index (WRI), to support a scarcity-based measure of WF. Different from previous studies we also considered the requirements of grey water. This modification is coherent with the use of the WF as an indicator of *environmental impacts*, introducing an interesting way to take into account the effect of human activities on water *quality*. This led also to relevant changes in the estimated values of SWF by single country.

The effective pressure on water resources has been measured as an impact-weighted water volume, considering an indicator of stress on water resources of a given country. The logic of the *scarce* WF consists of assigning a positive value only to water that is used in a context of adverse environmental impacts. Overall, SWF accounts only for 33.9 % of the volumetric measure of WF but the breakdown by geographic area highlights a relevant asymmetry between domestic and external water exploitation: while only 11.3 % of domestic WF generated adverse impacts, SWF for imports amounted to 54.9 % of water resources used for producing imported goods. A relevant part of impacts generated by Italian consumptions were *exported* to other countries. The SWF was directed to few main countries: about 45 % of these impacts were generated by Manufacture, Agriculture and Electricity, Gas and Water Supply in China and India.

A further qualification of Italian WF was obtained quantifying, for the first time, the Social-Scarce Water Footprint (SoSWF). In broad terms this indicator assigns a different impact to water used in regions with the same level of scarcity/impact on their water resources if they have different degrees of fulfillment of social goals. A country with a higher level of human development has better opportunities to improve the management of its water resources (infrastructures and human capital), reducing the negative social consequences of the adaptation to natural water scarcity. About 43 % of volumetric WF generated impacts on environmentally *and* socially scarce water resources, deepening the asymmetries between domestic and external footprint (12.8 % vs 71.1 % of WF). The highest pressures of Italian imports were directed to water resources in countries belonging to the Rest of the World group of the WIOD database, including several developing countries.

These results suggest interesting policy implications. Italian consumptions generate relevant impacts on water resources mainly in third countries while, at least in aggregate terms, the impacts generated in Italy remains below a critical threshold. Furthermore, the adverse effects of Italy's WF is concentrated in countries with a high level of stress on water resources (mainly China and India) and with a relatively lower achievement of social goals (developing countries). Their competitiveness in international trade seems at least partially based on a non-sustainable use of water resources. This is a typical case of market failure.

While the discussion on what policy measures should be designed to address such a problem is beyond the scope of this study, our results suggest the need for an increase and an improvement of information available for the analysis of this issue at the global level. To design effective policies, more flexible and improved methods for the assessment of water stress should be used, as the average figures at the country level often hide large regional differences. The marginal change in the stress on water resources generated by the increase of production (both to support domestic and foreign demand) heavily depends on the nature and the distribution of water resources within the country, as well as on their matching with the geographic pattern of the productive system. The latter is often driven by social and economic more than ecological factors. The use of the same logistic function to calculate a WSI based on a national average indicator of exploitation on water resources, is likely to yield a significant bias in the estimation of SWF in the case of large economies such as China, USA, or India.

The last remark leads to the first main limitation of the study that is worth to stress here. The choice to use an average index of water exploitation to produce a scarcity (or socially) weighted measure of water stress for all production activities in a given country was driven by data availability. A further limitation refers to the country disaggregation of the analysis. The use of WIOD database left a high number of countries grouped in the Rest of the World region. This mainly affected results for SoSWF, where critical situations would be likely to emerge when more disaggregated data were available. A matching between different global databases to obtain more disaggregated data could support a possible improvement of results of the study.

In this analysis available data are considered only at their average level, without considering the possible sources of uncertainty that could affect the estimates of water intensity coefficients underlying the satellite account of water resource use of the WIOD database. Data availability is widely recognised as a main limitation in global WF studies (Hoekstra et al., 2011: 119). A sensitivity analysis of results, using a Montecarlo approach as for example in the global sensitivity and uncertainty analysis (GSUA) methods (Pianosi et al., 2016) could add relevance to results of WF studies, above all when the hydro-economic accounting framework is used to calibrate a model to simulate scenarios to support water management and water policy design. A possible example could be the economic assessment of new regulations to implement a system of environmental constraints to global trade. The question of uncertainty seems less relevant in this study, whose main focus is a *structural* analysis of Italian WF in terms of industry and country composition. This rather suggest a first, possible direction for further research: the availability of harmonised time series of MRIO tables integrated with satellite accounts of water use (as in the case of WIOD database), allows an analysis of the dynamics of the main drivers affecting the exploitation of water resources, for example using structural decomposition analysis methods (Miller and Blair, 2009).

The uncertainty issue suggests a further development of research. The calculation of scarcity-weighted WF is based on water stress indicators, such as the WRI used in this study, usually estimated as multi-annual averages (Hoekstra et al., 2011) at the national level. As such, they hide different levels of inter and intra-annual variability of water scarcity components (water supply and demand) as well as different degrees of *regional* variability in the water balance. The use of the same pressure-impact relation, as the logistic function used to weight water footprint for physical scarcity, could lead to relevant bias in comparing SWF of countries facing different degrees of natural and regional variability of the hydrological system. This is the reason why in many studies carried out at the regional and local levels, WF calculation is fully combined with hydrological modelling (see for instance: Guiyesse et al., 2013; Zhuo et al., 2014; Seok Lee et al., 2018; Sturla and Rocchi, 2022). What is missing so far are rather studies aiming at assessing how the geographical scale of the analysis affects the effectiveness of WF indicators in detecting environmental impacts due to overexploitation of water resources. Values of WF indicators apparently "sustainable" at the national levels are likely to hide the trespassing of critical thresholds in water resources exploitation at the subnational level. Multi-scale hydroeconomic models could be used to improve the weighting of WF to account for scarcity in international comparisons".

A final remark on future research concerns a possible move towards the economic assessment and evaluation of WF. Both the volumetric and the scarcity/socially adjusted measures are expressed in physical terms. However, all the more when the estimation is developed within an input–output framework (as in this study), the transformation into monetary values is a fairly natural development of the analysis. Environmentally extended input–output models can be easily used to estimate an opportunity cost-based value of water. Furthermore, the accounting framework could be integrated with satellite accounts for ecosystem services produced by water resources, as the System of Environmental-Economic Accounting for Ecosystem Accounting (United Nations et al., 2021) recently released by UN and other international bodies suggests. This could potentially transform scarcity-weighted measures of WF into the first step of a full economic assessment of impacts on water resources for policy analysis at the national and the global level.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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1.5 Appendix A.

To better illustrate the calculation of WF with the MRIO approach, a scheme with $M = 3$ is proposed below, which is easily replicable for *M greater than 3*, as proposed by Arto et al. (2016). Italy (or the interest region/country) it represented by the region 1.

Equation (8) for three regions ($M = 3$) and N sectors can be written as follows:

$$\begin{bmatrix} W_E^1 \\ W_E^2 \\ W_E^3 \end{bmatrix} = \begin{bmatrix} \widehat{v}^1 & 0 & 0 \\ 0 & \widehat{v}^2 & 0 \\ 0 & 0 & \widehat{v}^3 \end{bmatrix} \begin{bmatrix} L^{11} & L^{12} & L^{13} \\ L^{21} & L^{22} & L^{23} \\ L^{31} & L^{32} & L^{33} \end{bmatrix} \begin{bmatrix} y^{11} + y^{12} + y^{13} \\ y^{21} + y^{22} + y^{23} \\ y^{31} + y^{32} + y^{33} \end{bmatrix} \tag{A1}$$

Where the $(nx1)$ vector W_E^1 represents the total direct water used (production-based approach) in the region 1, without considering households direct use, by economic sector.

To obtain the domestic water (nx1) vector (W_{Dom}^1) and the (nx1) vectors of virtual water imports associated to the consumptions in region 1 it is imposed $y^{i2} = y^{i3} = 0$. That is, only the domestic and external water associated to the final consumptions in region 1 is considered.

$$\begin{bmatrix} W_{Dom}^1 \\ W_{Imp}^{12} \\ W_{Imp}^{13} \end{bmatrix} = \begin{bmatrix} \widehat{v}^1 & 0 & 0 \\ 0 & \widehat{v}^2 & 0 \\ 0 & 0 & \widehat{v}^3 \end{bmatrix} \begin{bmatrix} L^{11} & L^{12} & L^{13} \\ L^{21} & L^{22} & L^{23} \\ L^{31} & L^{32} & L^{33} \end{bmatrix} \begin{bmatrix} y^{11} \\ y^{21} \\ y^{31} \end{bmatrix} \tag{A2}$$

Solving equation (A.2) we get:

$$W_{Dom}^1 = \widehat{v}^1 \left(L^{11}y^{11} + L^{12}y^{21} + L^{13}y^{31}\right) \tag{A3}$$

$$W_{Imp}^{12} = \widehat{v}^2 \left(L^{21}y^{11} + L^{22}y^{21} + L^{23}y^{31}\right) \tag{A4}$$

$$W_{Imp}^{13} = \widehat{v}^3 \left(L^{31}y^{11} + L^{32}y^{21} + L^{33}y^{31}\right) \tag{A5}$$

The total virtual water imports for domestic consumptions (external water footprint) can be expressed as the sum of water imports of region 1 from region 2 (W_{Imp}^{12}) and from region 3 (W_{Imp}^{13}):

$$W_{Imp}^1 = W_{Imp}^{12} + W_{Imp}^{13} \tag{A6}$$

The terms $\widehat{v}^1 L^{12} y^{21}$ and $\widehat{v}^1 L^{13} y^{31}$ in equation (A.3) correspond to the feedback effect (Moran et al., 2018), that is, water exports from region 1 that then return to region 1 from regions 2 and 3. In this work this water is associated with domestic production. To avoid double counting these terms are not considered in exports.

The total water footprint (consumption-based) is obtained using equations (A.3) and (A.6):

$$WF_{Cba}^1 = \left(W_{Dom}^1\right)' i + \left(W_{\mathrm{Imp}}^1\right)' i + W_{hh}^1 \tag{A7}$$

To obtain the water exports (nx1) vector (W_{Exp}^1) from region 1 to regions 2 and 3, it is imposed $\widehat{v}^2 = \widehat{v}^3 = 0$ and $y^{11} = y^{21} = y^{31} = 0$. That is, water exports refers to water from region 1 that goes to other countries and does not return to region 1.

$$\begin{bmatrix} W_{Exp}^1 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} \widehat{v}^1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} L^{11} & L^{12} & L^{13} \\ L^{21} & L^{22} & L^{23} \\ L^{31} & L^{32} & L^{33} \end{bmatrix} \begin{bmatrix} y^{12} + y^{13} \\ y^{22} + y^{23} \\ y^{32} + y^{33} \end{bmatrix} \tag{A8}$$

Solving equation (30) we get:

$$W^{1}_{Exp} = \hat{v}^{1}\left[L^{11}\left(y^{12}+y^{13}\right)+L^{12}\left(y^{22}+y^{23}\right)+L^{13}\left(y^{32}+y^{33}\right)\right] \tag{A9}$$

Unlike Arto et al. (2016), terms associated with the feedback effect (see above) are not considered to avoid double counting in the production-based water footprint.

The direct use of water (production-based approach) is obtained using equations (A.3) and (A.9):

$$DW^{1}_{Pba} = \left(W^{1}_{Dom}\right)' i + \left(W^{1}_{Exp}\right)' i + W^{1}_{hh} \qquad 10)$$

The study by White et al. (2015) calculates the WF and SWF for the Haihe River Basin in China, considering the MRIO approach; this study is taken as a reference. As explained in the introduction, blue water and grey water are used to calculate SWF and SoSWF.

Following the previous methodology and considering equations (A.2-A.6), by incorporating the water stress indicator (WSI) of each country, it is possible to calculate the domestic economic scarce water (nx1) vectors (SW^{12}_{Imp},SW^{13}_{Imp}) and the components of the external scarce water footprint (nx1) vector (SW^{1}_{Imp}).

$$SW^{1}_{Dom} = WSI_{1} \bullet \hat{v}^{1}\left(L^{11}y^{11}+L^{12}y^{21}+L^{13}y^{31}\right) \qquad 11)$$

$$SW^{12}_{Imp} = WSI_{2} \bullet \widehat{v}^{2}\left(L^{21}y^{11}+L^{22}y^{21}+L^{23}y^{31}\right) \qquad 12)$$

$$SW^{13}_{Imp} = WSI_{3} \bullet \hat{v}^{3}\left(L^{31}y^{11}+L^{32}y^{21}+L^{33}y^{31}\right) \qquad 13)$$

It is also calculated the scarce consumption of households in Italy and the external scarce water footprint (nx1) vector (SW^{1}_{Dom}) to obtain the total scarce water footprint (SWF^{1}_{Cba}).

$$SW^{1}_{hh} = WSI_{1} \bullet W^{1}_{hh} \qquad 14)$$

$$SW^{1}_{Imp} = SW^{12}_{Imp} + SW^{13}_{Imp} \qquad 15)$$

$$SWF^{1}_{Cba} = \left(SW^{1}_{Dom}\right)' i + \left(SW^{1}_{\mathrm{Imp}}\right)' i + SW^{1}_{hh} \qquad 16)$$

In the same way, by incorporating the social water stress indicator (SWSI) of each country, it is possible to calculate the domestic economic social-scarce water (nx1) vectors ($SoSW^{12}_{Imp}$,$SoSW^{13}_{Imp}$) and the components of the external scarce water footprint (nx1) vector ($SoSW^{1}_{Imp}$).

Appendix B

Table B.1, Table B.2 and Table B.3 presents the results of the blue, green and grey water footprint by industry, calculated using the MRIO

Table B1
Water Footprint by industry (Blue Water) (Millions of cubic meters).

Industry	Macro Sector	MRIO Blue Water			
		Italy	42 Countries	Rest of the World	Total
Crop and animal production, hunting and related service activities	Agriculture	3,167.0	2,604.4	3,019.4	8,790.7
Forestry and logging	Agriculture	103.0	127.3	193.2	423.5
Fishing and aquaculture	Agriculture	111.4	191.0	213.9	516.2
Manufacture of food products, beverages and tobacco products	Food Industry	110.5	51.4	8.8	170.7
Manufacture of textiles, wearing apparel and leather products	Manufacture	43.9	61.2	39.7	144.7
Manufacture of paper and paper products	Manufacture	23.9	34.5	5.2	63.7
Printing and reproduction of recorded media	Manufacture	16.9	8.2	1.6	26.7
Manufacture of coke and refined petroleum products	Manufacture	0.0	0.0	0.0	0.0
Manufacture of chemicals and chemical products	Manufacture	27.0	188.4	39.0	254.4
Manufacture of basic pharmaceutical products and pharmaceutical preparations	Manufacture	7.7	71.6	2.7	82.0
Manufacture of other non-metallic mineral products	Manufacture	24.5	15.5	3.0	43.0
Manufacture of basic metals	Manufacture	6.6	72.3	26.1	104.9
Manufacture of fabricated metal products, except machinery and equipment	Manufacture	14.2	35.4	5.6	55.3
Electricity, gas, steam and air conditioning supply	Electricity, Gas and Water Supply	1,532.3	1,498.5	1,697.5	4,728.3
Water collection, treatment and supply	Electricity, Gas and Water Supply	7,536.2	1,140.6	1,718.1	10,395.0
Publishing activities	Services	16.5	4.1	3.1	23.7

Source: own elaboration.

Table B2
Water Footprint by industry (Green Water) (Millions of cubic meters).

Industry	Macro Sector	MRIO Green Water			
		Italy	42 Countries	Rest of the World	Total
Crop and animal production, hunting and related service activities	Agriculture	29,634.1	27,984.6	22,049.0	79,667.8
Forestry and logging	Agriculture	963.7	1,671.8	1,410.9	4,046.4
Fishing and aquaculture	Agriculture	1,042.4	1,479.0	1,561.8	4,083.1

Source: own elaboration.

Table B3
Water Footprint by industry (Grey Water) (Millions of cubic meters).

Industry	Macro Sector	MRIO Grey Water			
		Italy	42 Countries	Rest of the World	Total
Crop and animal production, hunting and related service activities	Agriculture	3,765.0	3,909.3	1,136.2	8,810.5
Forestry and logging	Agriculture	122.4	309.1	72.7	504.3
Fishing and aquaculture	Agriculture	132.4	237.8	80.5	450.7
Manufacture of food products, beverages and tobacco products	Food Industry	650.6	311.9	131.5	1,094.0
Manufacture of textiles, wearing apparel and leather products	Manufacture	258.5	581.4	647.6	1,487.5
Manufacture of paper and paper products	Manufacture	140.9	326.1	82.1	549.1
Printing and reproduction of recorded media	Manufacture	99.5	76.8	25.8	202.1
Manufacture of chemicals and chemical products	Manufacture	159.2	1,440.6	627.4	2,227.2
Manufacture of basic pharmaceutical products and pharmaceutical preparations	Manufacture	45.4	283.7	43.5	372.5
Manufacture of other non-metallic mineral products	Manufacture	144.1	134.5	49.3	327.9
Manufacture of basic metals	Manufacture	38.6	796.5	463.5	1,298.6
Manufacture of fabricated metal products, except machinery and equipment	Manufacture	83.9	317.0	100.2	501.0
Publishing activities	Services	97.4	19.5	48.1	165.0

Source: own elaboration.

methodology. The results are disaggregated by region (Italy, 42 Countries and the Rest of the World).

Out of a total of 56 industries, 16 directly withdraw water from surface and groundwater sources (blue water), 3 directly capture water from rainfall and soil moisture (green water) and 13 presents water requirements to dilute the pollutants associated with their direct discharges into surface and groundwater sources (gray water).

Appendix C

Fig. C1.Fig. C2.Fig. C3.Fig. C4.Fig. C5.

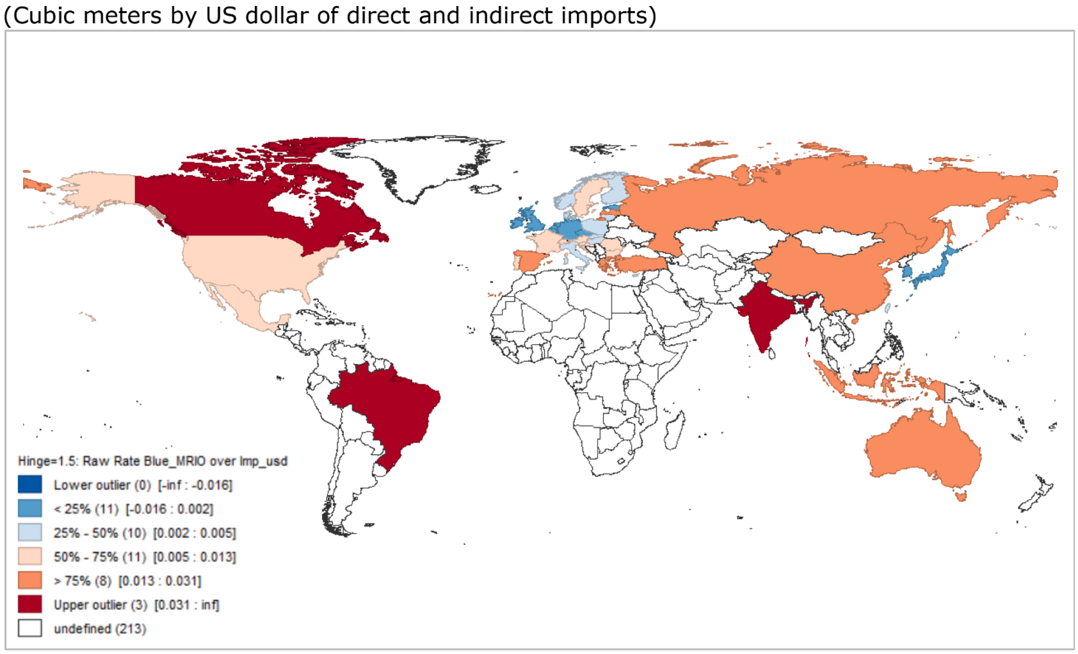
(Cubic meters by US dollar of direct and indirect imports)

Fig. C1. Blue Water Footprint intensity (Cubic meters by US dollar of direct and indirect imports) Source: own elaboration on WIOD data *The category "undefined" refers to countries not considered individually in the WIOD database.*

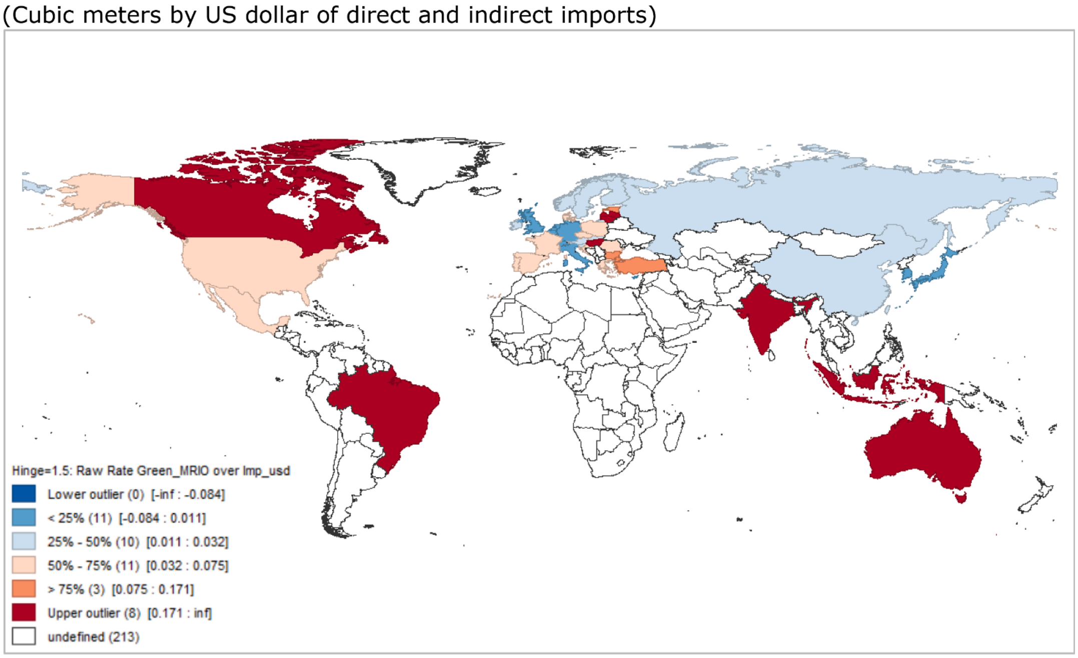
(Cubic meters by US dollar of direct and indirect imports)

Fig. C2. Green Water Footprint intensity (Cubic meters by US dollar of direct and indirect imports) Source: own elaboration on WIOD data *The category "undefined" refers to countries not considered individually in the WIOD database.*

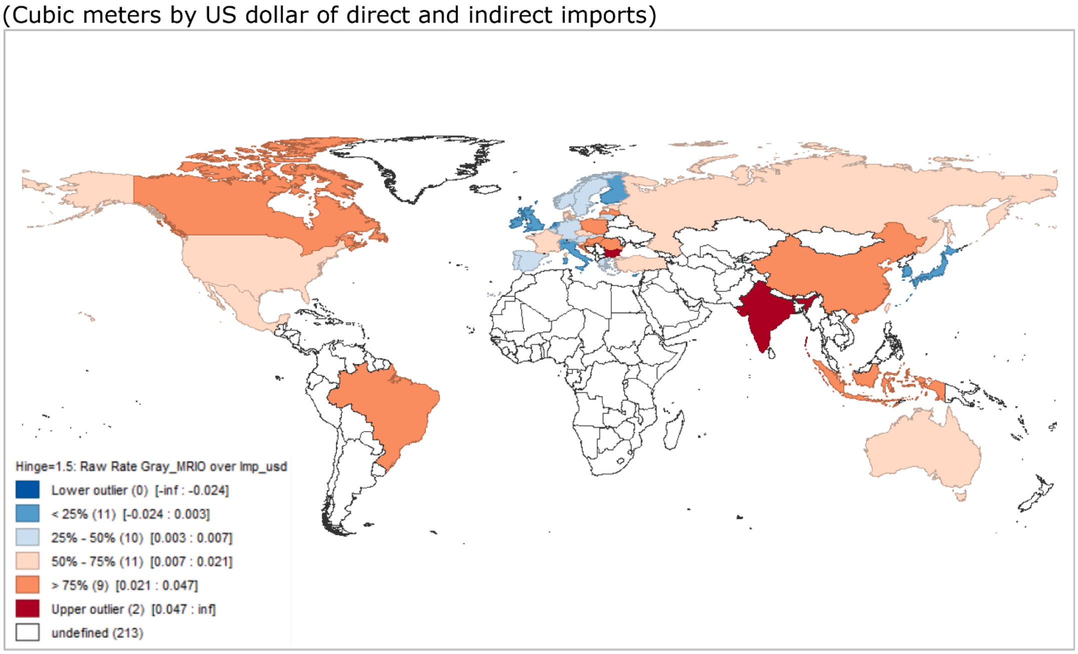
(Cubic meters by US dollar of direct and indirect imports)

Fig. C3. Grey Water Footprint intensity (Cubic meters by US dollar of direct and indirect imports) Source: own elaboration on WIOD data *The category "undefined" refers to countries not considered individually in the WIOD database.*

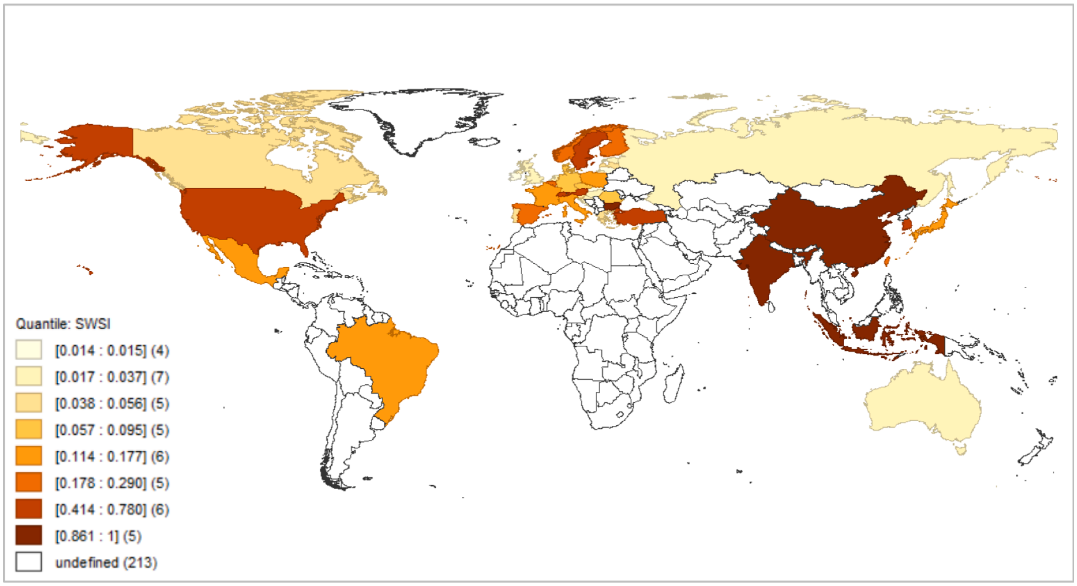

Fig. C4. Social Water Stress Index (SWSI) by country Source: own elaboration on WIOD data and UNDP data. *The category "undefined" refers to countries not considered individually in the WIOD database.*

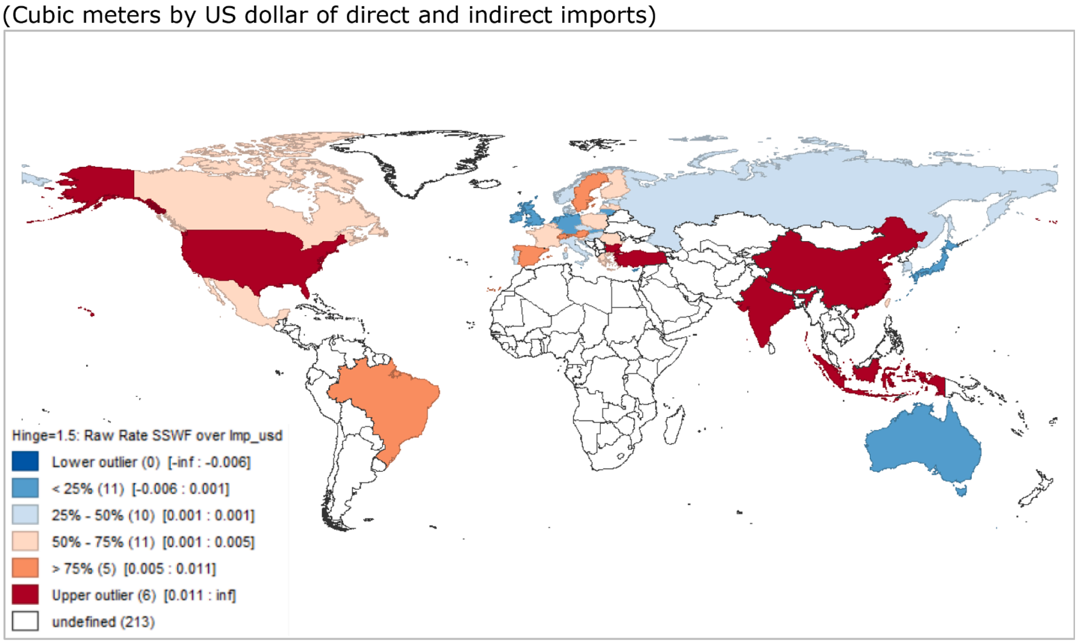
(Cubic meters by US dollar of direct and indirect imports)

Fig. C5. Social-Scarce External Water Footprint (SoSWF) intensity (Cubic meters by US dollar of direct and indirect imports) Source: own elaboration on WIOD data *The category "undefined" refers to countries not considered individually in the WIOD database.*

Appendix D

Fig. D.1 shows the difference between the calculation of WSI using the SDG indicator of pressure on water resources (considering only blue water) and with the WRI indicator (blue and grey water) proposed in this study. The countries in which the difference exceeds 100 % (WRI is at least 2 times greater than SDG) are shown. The effect of considering grey water for the calculation of the WSI is significant, which confirms the need to include it.

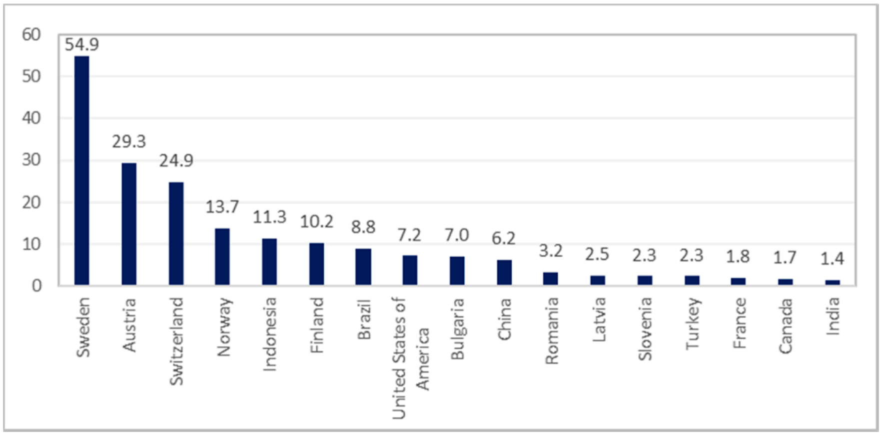

Fig. D1. Ratio between the calculation of WSI with WRI and SDG. Source: own elaboration on WIOD data.

Appendix E

A further result of interest that can be derived is the contribution of Italian consumption to the impact on freshwater ecosystems in other countries. To evaluate this, the WSI of each country (considering blue and grey water external footprint) has been calculated excluding the share of water withdrawals required by Italian imports. The Fig. E.1 shows the percentage change in WSI in countries for which export to Italy mostly affects the pressures on scarce water resources.

Belgium, Poland, Estonia and Hungary correspond to the most affected countries, both considering the percentage change in WSI and the initial value of WSI (without Italian consumption). When the initial value is higher the marginal effects of an increase are most important, due to the fact that WSI is a non-linear measure of impacts increasing more than proportionally beyond a given level of the exp0loitation of water resources. Table E.1 shows the changes in the countries most affected by Italian consumption.

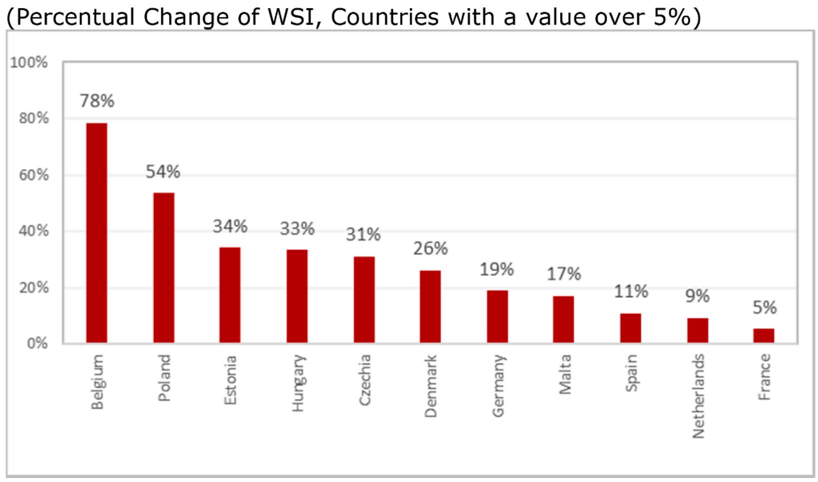

Fig. E1. Change of WSI due to Italy's Consumption Pressure by country (Percentual Change of WSI, Countries with a value over 5%). Source: own elaboration on WIOD data.

Table E1
WSI with and without Italy's Imports (Countries with a value of change over 5%).

Country Name	WSI without Italian Consumption	WSI	Change in WSI
Belgium	0.149	0.267	78.4 %
Poland	0.064	0.098	53.5 %
Estonia	0.024	0.032	34.1 %
Hungary	0.012	0.015	33.3 %
Czechia	0.039	0.051	31.0 %
Denmark	0.042	0.053	26.2 %
Germany	0.075	0.089	18.9 %
Malta	0.642	0.752	17.1 %
Spain	0.177	0.196	10.7 %
Netherlands	0.028	0.031	9.1 %
France	0.120	0.127	5.3 %

Source: own elaboration on WIOD data.

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