Journal of Environmental Management 343 (2023) 118163

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

Methodology for a preliminary assessment of water use sustainability in industries at sub-basin level

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ARTICLE INFO

Keywords:
Environmental assessment methods
Water sustainability
Water management
Indicator system sub-basin scale
Time-frame data

ABSTRACT

The sustainability of industrial production, especially for highly water-demanding processes, is strictly related to water resource availability and to the dynamic interactions between natural and anthropogenic requirements over the spatial and temporal scales. The increase in industrial water demand raises the need to assess the related environmental sustainability, facing the occurrence of global and local water stress issues. The identification of reliable methodologies, based on simple indices and able to consider the impact on local water basins, may play a basilar role in water sustainability diagnosis and decision-making processes for water management and land use planning. The present work focalized on the definition of a methodology based on the calculation of indicators and indices in the view of providing a synthetic, simple, and site-specific assessment tool for industrial water cycle sustainability. The methodology was built starting from geo-referenced data on water availability and sectorial uses derived for Italian sub-basins. According to the data monthly time scale, the proposed indices allowed for an industrial water-related impacts assessment, able to take into account the seasonal variability of local resources. Three industrial factories, located in northern (SB1, SB2) and central (SB3) Italian sub-basins, were selected as case studies (CS1, CS2, CS3) to validate the methodology. The companies were directly involved and asked to provide some input data. The methodology is based on the calculation of three synthetic indexes: the Withdrawal and Consumption water Stress Index (WCSI) allowed for deriving a synthetic water stress level assessment at the sub-basin scale, also considering the spatial and temporal variations; the industrial water use sustainability assessment was achieved by calculating the Overall Factory-to-Basin Impact (OFBI) and the Internal Water Reuse (IWR) indices, which allowed a preliminary evaluation of the factories' impacts on the sub-basin water status, considering the related water uses and the overall pressures on the reference territorial context. The WCSI values highlighted significant differences between the northern sub-basins, characterised by limited water stress ($WCSI_{SB1} = 0.221$; $WCSI_{SB2} = 0.047$), and the central ones, more subjected to high stress ($WCSI_{SB3} = 0.413$). The case studies CS1 and CS3 showed to exert a more significant impact on the local water resource ($OFBI_{CS1} = 0.18\%$; $OFBI_{CS2} = 0.192\%$) with respect to CS2 ($OFBI = 0.002\%$), whereas the IWR index revealed the different company's attitude in implementing water reuse practices ($IWR_{CS1} = 40\%$; $IWR_{CS1} = 27\%$; $IWR_{CS1} = 99\%$). The proposed methodology and the indices may also contribute to assessing the effectiveness of river basin management actions to pursue sustainable development goals.

1. Introduction

Water resources sustain natural ecosystems, human life, and productive activities. The rising water demand due to population growth, economic development, more water-intensive energy production and changing consumption patterns (Mueller et al., 2015) leads to an increase in the competition for water among industrial, agricultural and residential sectors impairing hydrological cycles. Imbalances in the water cycle can deplete surface and groundwater reservoirs, causing ecosystem water shortages and excessive pollution. Climate change is likely to accelerate the pressures on water resources, increasing the frequency, intensity and duration of issues such as drought and water scarcity events.

The overall water demand is expected to rise globally to 5500–6000 billion m^3 per year by 2050, compared to the present value of about 4600 billion m^3 per year (Boretti and Rosa, 2019). During 2018, water

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https://doi.org/10.1016/j.jenvman.2023.118163
Received 23 January 2023; Received in revised form 30 April 2023; Accepted 11 May 2023

use in Europe amounted to 214 billion m^3, of which 60% was ascribable to agricultural activities, 18% to cooling, 11% to industrial sector activities, 10% to civil uses and 1% to services (Ambrosetti, 2021). In Italy, in line with the European Union statistics, the most water-intense sector is agriculture, which uses more than 50% of the resource, accounting for 14.5 billion m^3 per year. In comparison, the industrial sector is responsible for 21% of total water use, amounting to 5.5 billion m^3, and the civil sector accounts for about 20% (ISTAT, 2019) (Braca et al., 2021). Water resources and demands are unevenly distributed over time and space, especially in southern and southwestern Europe. In these regions, during the summer season, the water demand due to agriculture, public water supply and tourism reaches a yearly peak, leading thus to reductions in river flow by up to 40%, with significant resource and ecosystem imbalances (ISTAT, 2019) (Braca et al., 2021) (Ambrosetti, 2022) (Berman et al., 2012).

Water scarcity is generally defined as the lack of water supply, typically calculated as the ratio of human water consumption to available water supply. Water stress occurs when water availability can not meet the demands of the environment, society and economy in terms of quantity or quality. Meeting ecosystem and anthropogenic functions is the main reason for managing water as a natural resource (Mueller et al., 2015) (Giacomoni et al., 2013) (Cantero-Tubilla et al., 2018) (Vanham et al., 2018). The timeframe and the territorial scale are relevant factors to be included in the evaluation of water availability and River Basin Management Plans. The industrial sector can significantly contribute to pursuing sustainability in water use. An effective management approach accounts for the local context of water use and acknowledges the importance of stewarding water as a shared resource. Any organization can reduce its water withdrawal, consumption, discharge and the associated impacts through the implementation of efficiency measures, such as water recycling and reuse and process redesign, as well as through collective actions that extend beyond its operations within the catchment. Water quality level can be improved through different measures, including efficient wastewater treatment processes and the exploitation of lower-quality resources, well-fitted for the related use and thus preserving high-quality aquifers.

Several assessment methods have been developed to analyse the sustainability of industrial water use (Willet et al., 2019) (Gaidajis and Angelakoglou, 2016) (da Silva et al., 2020) (Angelakoglou and Gaidajis, 2015). Willet and co-authors (Willet et al., 2019), in particular, proposed a review to gain insight into the effectiveness of the assessment methods, developed to evaluate the environmental sustainability of industrial water use. While some papers adopt holistic approaches to define conceptual models for a thorough evaluation of water sustainability in different industrial sectors (da Silva et al., 2020) (Angelakoglou and Gaidajis, 2015), others highlight key water scarcity or availability indicators and related assessment methods (Giacomoni et al., 2013) (Chaves and Alipaz, 2006).

Indeed, developing a pool of indicators suited to address several aspects of productive systems, including water consumption facilities, can support industries to monitor the water-related performances significantly and to define a more sustainability-oriented approach.

Among the existing methodologies applied to assess water usage, water footprint (Jeswani and Azapagic, 2011) and life cycle assessment (LCA) are mainly oriented to evaluate the quantity of water used and the related impacts (Pfister et al., 2009) (Milà I Canals et al., 2009) (Berger and Finkbeiner, 2010). However, difficulties are raised from the lack of reliable data on water usage in life cycle databases; furthermore, there is no agreed life cycle impact assessment procedure for estimating impacts related to freshwater use. Although the volumetric water footprint indicator is helpful from a water-resource management perspective, it does not reflect the potential environmental (and social) impacts related to water use, which are instead relevant from the LCA perspective (Jeswani and Azapagic, 2011). Some boards and institutions proposed standards (GSSB, 2022) (Schulte, 2014) to drive companies to evaluate and report their impacts on the environment. For instance, the GRI Standard 303 - Water and Effluents (GSSB, 2018) was issued to support organizations in analysing the related value-chain and report information about their water-related impacts by accounting for resource withdrawals, consumptions and discharges. The aforementioned methodologies (GSSB, 2022) (Schulte, 2014) (GSSB, 2018) suggest some reference web sources to identify the water risk level on a territorial scale. Nevertheless, the available information is often provided in an aggregated form by indices and indicators generally estimated on an annual basis, thus neglecting the seasonal variability of water availability against the fluctuating water demand of the different products and civil sectors. Moreover, only territorial water stress information is provided, while no methodologies are proposed to evaluate the impacts on local water resources due to the productive activities of specific industrial sites. In such a context, the present study focused on the definition of a methodology based on user-friendly indicators to support the water management sustainability evaluation regarding a specific productive site, addressing both the spatial and temporal dimensions. The implemented methodology was targeted to i) assess the water stress at sub-basin level, taking into account also the seasonality and periods with greater criticalities, and ii) evaluate the local impacts on the water resource related to industrial production.

2. Material methods

A three-step procedure was developed for the impact assessment of productive site (i.e. an industrial factory) on local water availability and to evaluate the related induced water stress. First, companies were directly contacted and asked to provide data about water uses in some selected factories. Further, reference databases were selected to characterize all Italian river sub-basins by surveying and evaluating available data on water resources in the country (section 2.1). Then, water uses in the sub-basin where the selected factory operates (i.e. the reference sub-basin) were characterised by calculating appropriate indicators (section 2.2). The derived indicators were combined and aggregated into three synthetic indexes named withdrawal and consumption water stress index (WCSI), Overall Factory-to-Basin Impact (OFBI) and Internal Water Reuse (IWR). Finally, the factory water-related impacts on the sub-basin were assessed by comparing the index values (section 2.3).

2.1. Data acquisition and preliminary elaborations

A questionnaire on a spreadsheet was elaborated to collect the relevant data from the companies. Data related to industrial water withdrawals, discharges, reuse and production rates were considered of primary relevance. Such information was collected monthly for the most recent year available. At the same time, supplementary elements referred to factory location, exploited water sources, on- or off-site wastewater treatments, and the related final discharge points were acquired. Several companies in the paper, building, and textile sectors were contacted and asked for data on their production sites in Italy. Three factories were thus selected as relevant case studies (CS) to test the proposed methodology.

Meanwhile, several open-source water assessment tools and geo-referenced datasets (Hofste et al. 2019) were consulted. The criteria driving the dataset choice involved the assessment of the conceptual model applied, data reliability, accessibility and shareability, the spatial and temporal resolution as well as the vector data storage format for geographic features. The Aqueduct tool (Hofste et al., 2019) (WRI, 2023), developed by the World Resources Institute (i.e. WRI), was identified and selected as the reference dataset platform, due to the capability to provide all relevant water data at the river sub-basin level (Hofste et al., 2019). The updated 3.0 version introduces a water risk framework and territorial-based water indicators which are calculated according to a gridded hydrological model featuring (1) integrated water supply and demand for industrial, agriculture, livestock, and civil sectors, (2) surface water and groundwater modeling and (3) monthly time series covering the timeline 1960–2014 (Hofste et al., 2019). The applied resolution level (i.e. grid cell size of 5 × 5 arc minutes) is currently the highest among the available open-source water assessment tools (Cantero-Tubilla et al., 2018). Another reason for the choice of Aqueduct 3.0 as a reference dataset was driven by the wide use of the generated outputs in scientific assessments (; Schulte, 2014; GSSB, 2018, 2022; Duan et al., 2020; Katz, 2022; Yano et al., 2018; Schaefer et al., 2019). In addition to the open access web resource, WRI experts kindly shared (on request) monthly raw data on water availability, withdrawals (W), and consumptions (C) by sector for the Italian river sub-basins. The provided dataset was structured reporting for each sub-basin the related extension in squared meters, whereas water availability, withdrawals, and consumptions were expressed in meters (i.e. ratio of the volume of water to the basin surface) per month thus allowing to derive the corresponding volumetric amounts as a product. Raw data were interpolated by linear regression on a 10-year moving window, in analogy to Aqueduct 3.0 data elaboration procedures. The sub-basins effective water availability (WA) was calculated as the difference between the maximum theoretical water availability and the total consumption. The congruity of the sub-basin water balances was verified. Once the database was geared up, sub-basin water balances were evaluated on an annual and monthly basis temporal lifespan. The monthly (m) sub-basin data were then summed by annuity (a). The data referring to July were separately elaborated, being on average the month of greater imbalances between water resource availability and consumption.

2.2. *Calculation of indicators*

In the present study, starting from a specific factory (F) and related sub-basin data, a pool of indicators was proposed and calculated to quantify the impact of factory water use on the local water balance (Table 1). Baseline indicators were calculated as the percent ratio of the factory water withdrawal (W_F) over total (W) and industrial (W_I) sub-basin withdrawal, deriving the indicators factory withdrawal to total basin withdrawal (FTW) and factory withdrawal to industrial sub-basin withdrawal (FIW). Similarly, the indicators factory consumption to total basin consumption (FTC) and factory consumption to industrial sub-basin consumption (FIC) were calculated by relating the factory water consumption (C_F) over the total (C) and industrial (C_I) sub-basin consumption. An indicator describing the quality of water used was then derived, as a weighted average of the annual amounts of water withdrawals by sources (QWS). Specifically, the weights (w) assigned to water sources (S_{WF}) were: 1 for aqueduct; 0.9 for groundwater; 0.8 for surface water; 0.75 for greywater; 0.6 for recovered water (i.e. treated wastewater). Moreover, further indicators were defined to consider the seasonal variability of factory water uses about the seasonal variability of sub-basin water exploitation. In this view, after normalization, the monthly factory consumption and withdrawal time series were compared to the corresponding sub-basin data, allowing the calculation of the related correlation coefficients (SCW, SCC). A specific indicator was built to assess water reuse rates within the factory activities and calculated as the percentage ratio between the reused treated annual water volume and the total water consumption (IWR). Table 1 shows the indicators defined for the impact assessment of the factories' water uses and discharges on the reference sub-basin.

Table 1
Indices assessing the impact of the factory water resource use on the sub-basin.

Factory Indices		Units
Factory withdrawal to Total basin Withdrawal	FTW	%
Factory withdrawal to Industrial sub-basin Withdrawal	FIW	%
Factory consumption to Total basin Consumption	FTC	%
Factory consumption to Industrial sub-basin Consumption	FIC	%
Impact of Quality of Water Sources	QWS	
SEV[a] factory-basin Correlation of Withdrawals	SCW	
SEV[a] factory-basin Correlation of Consumptions	SCC	
Index on Internal Water Reuse	IWR	%

[a] Seasonal Variability.

Furthermore, a different set of indicators was conceived for the river sub-basins, to assess the overall water stress from different significant points of view (Table 2). Baseline indicators were calculated as the ratio of total consumptions and withdrawals to the effective water availability (CWS, WWS). For such indicators, both the annual and monthly indicators were calculated. Furthermore, some indicators were developed to evaluate water resource variability over time. For the annual-based data, the inter-annual variability (IAV$_a$) was calculated as the standard deviation of the 1960–2014 time series values compared to the mean value. Such inter-annual variability was calculated for water availability, total consumptions, and total withdrawals (IAV$_{WAa}$, IAV$_{Ca}$, IAV$_{Wa}$). Indicators of trends in water use (Tr$_a$) were also calculated by deriving the angular coefficient of the regression line of annual data for the 1960–2014 series of water availability (Tr$_{WAa}$), total consumption (Tr$_{Ca}$), and total withdrawal (Tr$_{\mathrm{Wa}}$). The dataset provided by WRI experts additionally covered the variable groundwater table decline (Dec) measured as the average decline of the groundwater table over the reference years 1990–2014, expressed in centimeters per year. Higher values indicate higher levels of unsustainable groundwater withdrawals (Hofste et al., 2019).

In analogy with Aqueduct 3.0 data processing, further indicators were calculated to estimate seasonal variability (SEV), expressed as the average within-year variability of available water supply, including both renewable surface and groundwater supplies. It was calculated using the time series of the monthly means of the period 1960–2014 as the ratio of the standard deviation over the mean (SEV$_{WAm,}$ SEV$_{Cm}$, SEV$_{Wm}$). Finally, the extracted data related to July were processed to calculate the inter-annual variability indicator (IAV) for the time series of water availability (WA), total consumptions, and total withdrawals (IAV$_{\mathrm{WAm}}$, IAV$_{\mathrm{Cm}}$, IAV$_{\mathrm{Wm}}$).

2.3. *Synthetic index calculation methodology*

2.3.1. *Overall factory-to-Basin Impact (OFBI) index*

Indicators for the quantification of the impacts of the factory water use on the local water balance (Table 1) were aggregated and synthesised into one stress index, the Overall Factory-to-Basin Impact (OFBI), according to the following steps (Fig. 1):

Table 2
Sub-basin indicators.

Indicators on annual-time based dataset Units			Indicators on monthly-time based dataset Units	
Consumption Water Stress	CWS$_a$		**Consumption Water Stress**	CWS$_m$
Withdrawal Water Stress	WWS$_a$		**Withdrawal Water Stress**	WWS$_m$
Water availability Inter-Annual Variability	IAV$_{WAa}$		**Water availability Inter-Annual Variability**	IAV$_{WAm}$
Consumption Inter-Annual Variability	IAV$_{Ca}$		**Consumption Inter-Annual Variability**	IAV$_{Cm}$
Withdrawal Inter-Annual Variability	IAV$_{Wa}$		**Withdrawal Inter-Annual Variability**	IAV$_{Wm}$
Total consumption growth Trend	Tr$_{Ca}$	m/y	**Water availability Seasonality**	SEV$_{WAm}$
Total withdrawals growth Trend	Tr$_{Wa}$	m/y	**Consumption Seasonality**	SEV$_{Cm}$
Water availability growth Trend	Tr$_{WAa}$	m/y	**Withdrawals Seasonality**	SEV$_{Wm}$
Groundwater level Decline	Dec	cm/y		

a = annual; m = monthly.

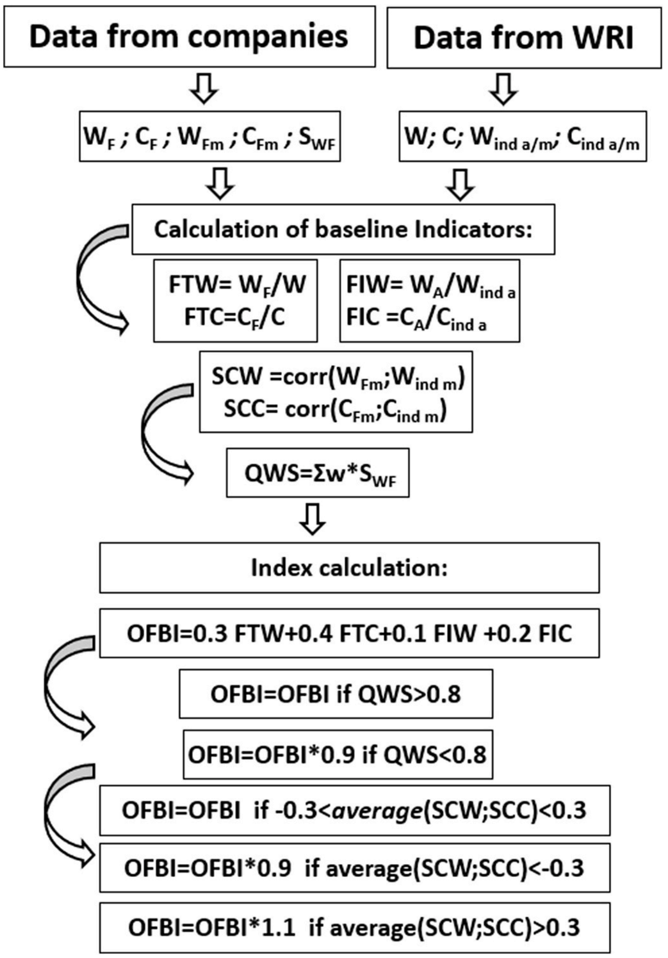

Fig. 1. Flow chart for the calculation of the synthetic index for the estimation of the company's impact on the local water balance.

- The overall factory impact index (OFBI) was calculated as the weighted sum of indicators of factory withdrawal and consumption on the total and industrial sub-basin withdrawal and consumption (FTW, FTC, FIW, and FIC), multiplied by corresponding weight factors of 0.3, 0.4, 0.1 and 0.2, respectively, established giving more relevance to consumptions.
- The OFBI value was further modulated based on the indicator of water sources quality QWS. For QWS values less than 0.8, OFBI value was decreased by 10% and, otherwise, left unchanged.
- Again, the OFBI value was changed based on the average between the seasonal variability correlation indicators (SCW, SCC). In particular, OFBI was decreased by 10% at an average value of SCW and SCC lower than 0.3. For a value of the average of the correlation indicators greater than 0.3, the OFBI index was increased in the calculation procedure by a factor of 10%.

2.3.2. *Withdrawal and consumption water stress index (WCSI)*

A global stress index, named withdrawal and consumption water stress index (WCSI), capable of depicting the status of the water balance for each river sub-basin, including withdrawals and consumptions, was defined.

The methodology involved in the aggregation and synthesis of the indicators is described as follows (Fig. 2):

- The indicators of inter-annual variability (IAV_{WAa}, IAV_{Ca}, IAV_{Wa}) were assembled in a single parameter, by summing the IAV indicator value for water availability (IAV_{WAa}) to the average value between IAV total consumption (IAV_{Ca}) and total withdrawal (IAV_{Wa}). The time series were therefore normalized to 1 by min-max scaling (IAV_{COa}) (Han et al., 2012).
- The indicators related to growth trends (Tr_{Ca}, Tr_{Wa}, Tr_{WA}) were aggregated into a net trend index (Tr_{Na}) by performing a weighted sum of the consumptions and withdrawals minus the value of the trend in water availability. The assigned weight is 0.6 for water consumptions and 0.4 for water withdrawals, thus giving greater relevance to the water flows not returned to the environment.
- Water stress indicators (WCS_a, WWS_a) related to the annual time-based series were aggregated into an intermediate index representing Withdrawal and Consumption water Stress Index ($WCSI_a$) through weighted averaging. Again, more emphasis was given to consumptions rather than withdrawals applying multiplicative factors of 0.6 and 0.4, respectively.
- A 10% increase in $WCSI_a$ values was then attributed to river sub-basins with an overall inter-annual variability greater than 1.
- The Withdrawal and Consumption water Stress Index value was then further varied, depending on the sub-basin values of net trend and groundwater level decline. In this case, the criterion used included an incremental factor of 10% for cases where there was an increase in net trend or decline in the water table of at least 0.01 m per year, and 15%, for cases where such an increase in net trend and such a decline in the water table are simultaneously present.
- In analogy with IAV_a, the July inter-annual variability indicators (IAV_{WAm}, IAV_{Cm}, IAV_{Wm}) were combined to obtain an overall IAV index (IAV_{COm}), derived as the sum of the IAV for water availability and the average of the variability of total withdrawals and consumptions.
- Seasonality indicators were aggregated into an overall index (SEV_{COm}) by summing the values of the variability of water availability with the average of seasonal variability of consumptions and withdrawals.
- The monthly water stress indicators were aggregated, by weighted averaging, into an intermediate index representing the Withdrawal and Consumption water Stress Index ($WCSI_m$). The definition of the intermediate index included a weighting factor of consumptions of 0.6 and withdrawals of 0.4.
- A criterion of a 10% increase in the $WCSI_m$ value was then defined for sub-basins with an overall monthly inter-annual variability greater than 1.
- Subsequently, the $WCSI_a$ value was further modulated by considering monthly-derived intermediate indicators. The applied criterion provided an incremental factor of 10% for $WCSI_m$ values greater than 0.8 or for SEV_{COm} values greater than 1.2 and an incremental factor of 15% for $WCSI_m$ values greater than 0.8 together with SEV_{COm} values greater than 1.2. The elaboration was performed to integrate into the final index (WCSI) value the critical issues due to monthly fluctuations in water availability and overall withdrawals and consumptions at the sub-basin level.

The numerical results of WCSI and the most relevant intermediate indicators were mapped by using the open-source Quantum Gis software (QGIS Development Team, 2021). The related dataset distributions were subdivided into 6 categories established by using the Natural Intervals functionality (i.e. Jenks) offered by QGIS. In the map rendering, the categories were assigned a different color intensity, with heavier pitches corresponding to more critical sub-basin situations (Supplementary material).

3. Results and discussion

3.1. *Case studies*

The selected case studies, signed as CS1, CS2, and CS3, were georeferenced on map (Fig. 3) and the corresponding sub-basins (SB1, SB2, SB3) were identified to carry out a document analysis on the state of

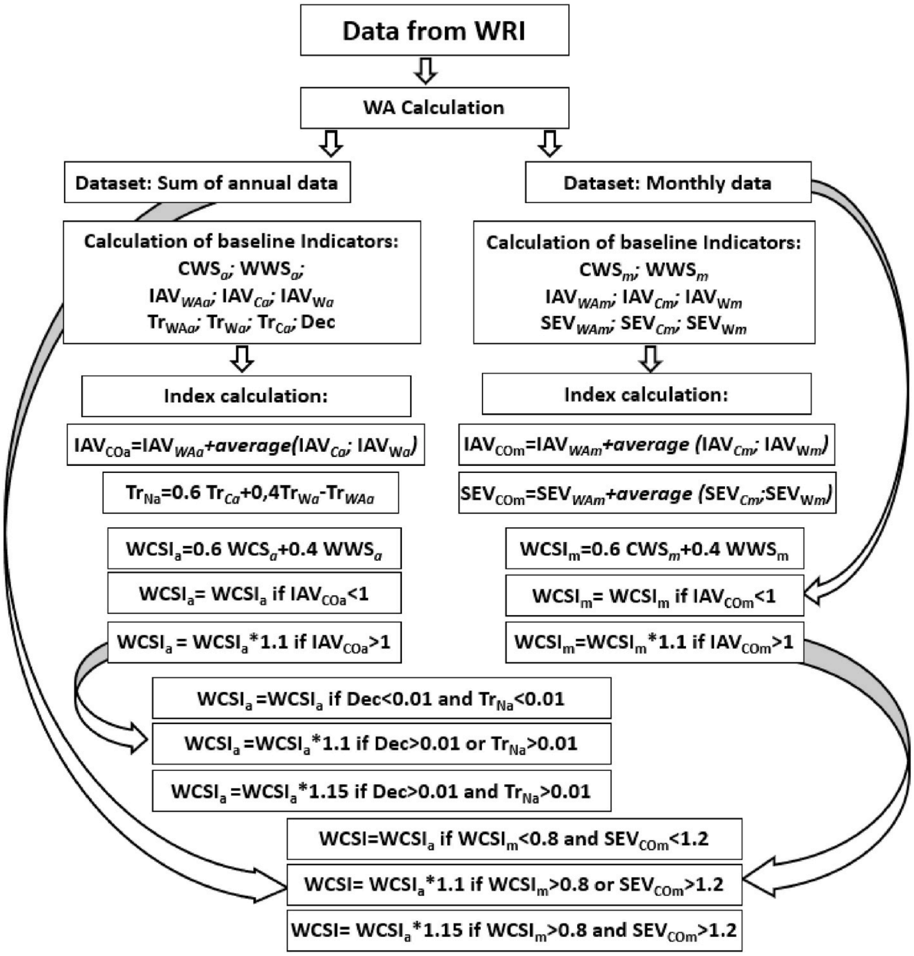

Fig. 2. Flow chart for the calculation of the proposed synthetic index of sub-basin water stress.

Fig. 3. Sub-basins of the selected case studies.

water resources. Respectively, CS1 falls into the Brenta-Baccaglione sub-basin (SB1), CS2 into the Ticino sub-basin (SB2), and CS3 into the Arno sub-basin (SB3). CS1 and CS3 belong to the paper industrial sector, whereas CS2 to the textile sector. Both textile and paper sectors are known to have water-intense production processes (Karthik and Gopalakrishnan, 2014) (Boguniewicz-Zabłocka and Kłosok-Bazan, 2020).

The three sub-basins present different water status and balances from both a qualitative and quantitative point of view (see Supplementary material). SB1 and SB2 are located in the sub-Alpine region of Northern Italy, while SB3 is in central Italy.

In Table 3, elaborations of the WRI database are reported. SB2 presents the greatest water availability with a mean WA value of 1.25 m, for a total amount of 10.1 10^9 m^3/y, calculated on the base of the related sub-basin extension. SB1 and SB3 have a net total water availability of 0.517 m and 0.264 m, respectively. However, due to the different sub-basins extensions, the total availability in volume is similar being respectively 2.49 10^9 m^3/y and 2.42 10^9 m^3/y. On the other hand, the incidence of total withdrawals and consumptions is particularly high in SB3, accounting for 32% and 10% of net water availability, respectively. These values are significantly lower for the other basins, 0.25 and 0.08% in SB1 to 0.06 and 0.02% in SB2. The industrial sector in turn affects withdrawals and consumptions in the three sub-basins by quite similar

Table 3
Sub-basin mean values for water availability, withdrawals and consumptions.

	Area	WA	W	W_I	C	C_I
	m^2	m	m	m	m	m
Sub-Basin 1	4824	0.517	0.143	0.072	0.047	0.015
Sub-Basin 2	8081	1.25	0.078	0.037	0.03	0.007
Sub-Basin 3	9172	0.264	0.097	0.053	0.032	0.010

WA = Water Availability**; W** = water Withdrawal**; WI** = industrial Withdrawal. **C** = Consumption; $\mathbf{C_I}$ = industrial Consumption.

percentages of around 50% for withdrawals and 30% for consumptions, respectively.

3.2. *River sub-basin indicators*

The elaborated maps allowed to compare the different indicators for the sub-basins in which the case studies production sites fall, with the rest of Italy. Among the investigated sub-basins, SB3 resulted to be the sub-basin experiencing the highest critical issues and a wider temporal variability for water availability, as well as water exploitation (Fig. 4, Supplementary material).

The overall stress index WCSI proposed and calculated in this study concisely summarizes the overall basins stress (Table 4). According to the map shown in Fig. 4, a geographical unevenness of the water resource balance arises. It's also noticeable that none of the considered case studies is placed in the most critical areas of the Italian landscape. Among the considered sub-basins, SB3 presents the most problematic overall picture with a $WCSI_{SB3}$ value of 0.413, whereas SB1 and SB2 show a value of 0.221 and 0.047, respectively. These results may be ascribed more to the relative quantitative abundance of water resources in the considered areas, than to exploitation rates.

3.3. *Industrial indices*

The activities carried out by the selected factories impact the water resource status of the reference sub-basins differently. Industrial water demand is mainly met by groundwater withdrawals, with contributions also from the aqueduct and surface water. CS1 only uses groundwater for a total amount of 1 159 000 m^3/y, while CS3 includes various supply sources with withdrawals, albeit lower, also from aqueduct and river bodies for a total amount of 714 000 m^3/y. For CS2, the total annual withdrawals are much smaller, 3700 m^3/y and the supply source is the public aqueduct. As a consequence, all the indices comparing the company withdrawals and consumptions to the corresponding sub-basin values (FTW, FTC, FIW, and FIC) are very low for CS2 and quite significant for CS1 and CS3, while the water quality impact (QWS) is high for all the companies, due to the high quality of the water sources (Table 5).

In all three assessed factories, water withdrawals in production processes slightly vary over the year. Fig. 5 shows, for the three case studies, such fluctuations after normalization (obtained by dividing the company's monthly withdrawals by the annual withdrawal) in comparison with the monthly fluctuation of the normalized sub-basin withdrawal. The resulting correlation degree for all the cases (SCW) appears low. Similarly, a poor correlation is also evident for consumptions (SCC) (Table 4).

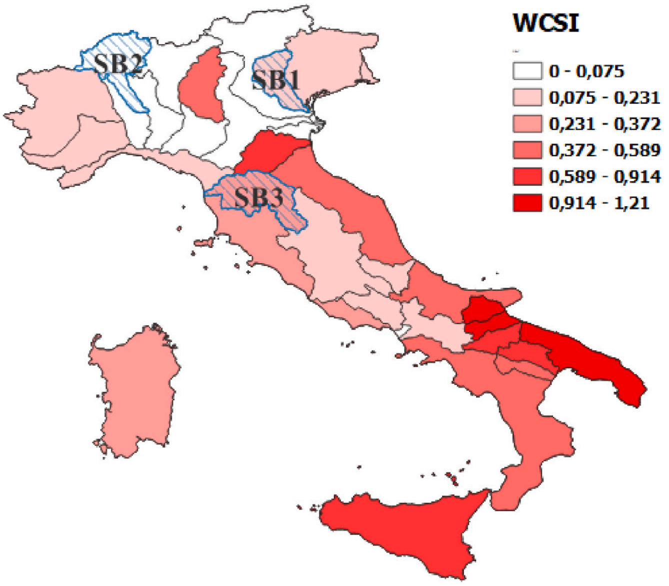

Fig. 4. Map of the total Withdrawal and Consumption water Stress Index (WCSI) displaying the sub-basins of the selected case studies.

Table 4
Sub-basin Indices related to the case studies.

Indices		Units	CS1	CS2	CS3
Total Annual Inter-annual Variability	IAV_a		0.507	0.493	0.671
Total Net growth trend	Tr_{Na}	m/y	0.001	−0.010	0.001
Withdrawal and Consumption annual water Stress Index	$WCSI_a$		0.221	0.047	0.341
Total monthly Inter-annual Variability	IAV_m		0.612	0.633	2.393
Total monthly Seasonality	SEV_m		0.694	0.879	0.972
Withdrawal and Consumption monthly water Stress Index	$WCSI_m$		0.636	0.068	1.100
Global Withdrawal and Consumption water Stress Index	WCSI		0.221	0.047	0.413

Table 5
Indices assessing the impact of water uses on the reference sub-basins.

Indices		CS1	CS2	CS3
Factory withdrawal to Total basin Withdrawal	FTW	0.170%	0.001%	0.080%
Factory consumption to Total basin Consumption	FTC	0.112%	0.002%	0.153%
Factory withdrawal to Industrial sub-basin Withdrawal	FIW	0.334%	0.001%	0.146%
Factory consumption to Industrial sub-basin Consumption	FIC	0.372%	0.006%	0.458%
SEV Correlation factory-basin Withdrawals	SCW	−0.383	−0.433	−0.225
SEV Correlation factory-basin Consumption	SCC	0.099	−0.434	0.088
Water Quality Impact	QWS	0.900	1.000	0.886
Overall Factory-to-Basin impact Index	OFBI	0.180%	0.002%	0.192%
Index on internal Water Reuse	IWR	40.00%	27.00%	98.00%

Only CS2 showed negative values for the correlations of withdrawals and consumptions (i.e. SCW_{CS2}, SCC_{CS2}) in relation to sub-basin water uses. These results suggest that, on average, the effect of factory water use reduces, albeit slightly, seasonal fluctuations in local water stress.

The final overall index (OFBI) then leads to summarizing the informative contributions obtained and expressing such impact in a single value. CS3 and CS1 both, have a significant impact on the respective territories with an OFBI index of 0.192% and 0.180%, while the $OFBI_{CS2}$ is 0.002%, showing a lower territorial impact.

Highlighting the company's propensity to adopt water reuse practices, the IWR index presents significant values in all three companies, with a value of 40%, 27%, and 98% in CS1, CS2, and CS3, respectively. These results indicate that all the factories are already committed to recovering and reusing water resources to varying degrees, also depending on the opportunities present in the various production sectors.

The information provided by companies allowed also to verify that the three case studies employ adequate wastewater treatment cycles to ensure the final quality before discharge into the sub-basin water networks. Therefore, the impacts on the qualitative status of surface water bodies receiving the treated wastewater are to be considered negligible.

3.4. *Methodology limitations and opportunities*

The defined procedure, in line with the objectives of the work, allowed for the assessment of various aspects of the status of the local water resource and the impacts related to industrial production.

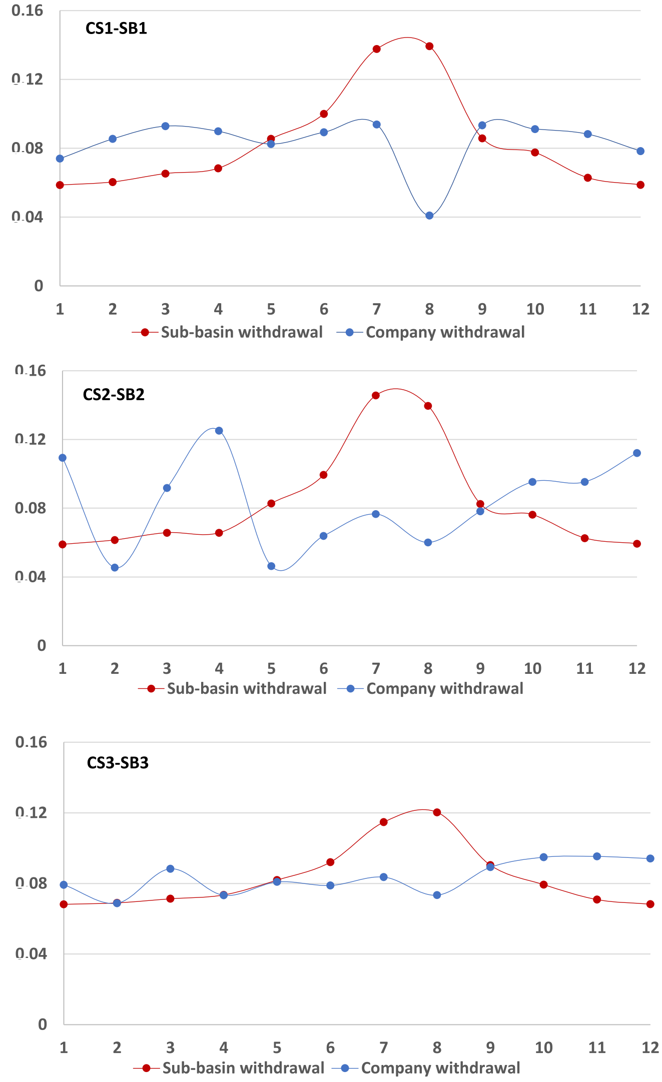

Fig. 5. Monthly water withdrawals over the year for the three case studies and the reference sub-basins.

However, for an appropriate interpretation and evaluation of the results, some elements underlying the methodology have to be taken into account. The methodology is affected by the accuracy of the input data as well as by the related temporal and spatial resolution. The available data resources are based, not on direct measurements, but rather on estimations and spatial models. Therefore, the data accuracy is strongly dependent on the estimation procedures and the model's basic assumptions. Furthermore, the spatial resolution, although quite elevated, is not enough for a punctual evaluation of factory impacts on local resources. For such a specific purpose, more appropriate tools and software should be applied.

Anyway, to the best of the authors' knowledge, database reporting data on water availability, withdrawals and consumptions at a very detailed spatial and temporal scale and based on measured data are not yet available.

The highlighted limitations do not invalidate the proposed methodology, which could be applied with more up-to-date and higher precision data derived, for example, from field measurements, as soon as they become widely available. In any case, even with the current dataset, the developed methodology can provide useful information and allow a general characterization of the state of the local water resource and the impacts of production activities. The methodology supports the comparison of different production sites and their impacts on different sub-basins and the monitoring of the indicator trends over time. For instance, it could provide useful information to the company management or to the authorities in land-use planning decisions by identifying the situations with greater criticalities where dedicated analyses have to be carried out to identify the level of intervention priorities.

4. Conclusions

An index-based methodology was developed to provide an overall assessment of industrial water use impacts on local basin water cycles, seeking to evaluate and compare the effective incidence of any industrial production site on territorial water balance as well as on water bodies quality status. The methodology requires the qualitative and quantitative assessment of industrial activities water uses as well as of reference river sub-basin water resource status.

Regarding river sub-basins, a geo-referenced database with a high-resolution level was elaborated according to several open-source water assessment tools and geo-referenced datasets to depict the water resource status in Italy and the related exploitation level. The developed indicators were mainly based on the balance, at the local sub-basin level, between resource availability and its exploitation, integrating at the same time the effects of inter-annual variability, seasonality and peaks during periods of maximum water stress.

The methodology here proposed encompasses the calculation of three synthetic indexes to resume and characterize the impacts of a given industrial settlement on local water stress. The Water Stress Index due to consumption and withdrawal (WCSI) is proposed as a valid and synthetic description of the local water resource status. It depends not only on the average annual balance at the sub-basin level between the available water and the industrial and total human uses. Indeed, it takes into account also the withdrawn and consumed water, the seasonal and inter-annual variability, the balance in the most critical periods of the year, and the historical trends of data. For factory water cycle characterization, an overall factory impact on the basin index, OFBI, was defined to integrate the information on withdrawals, consumptions, seasonality of the water demand, and quality of the exploited resource. Finally, the Internal Water Reuse (IWR) index, which allowed to assess water reuse rates within the factory activities has been defined.

The proposed methodology was tested on three case studies regarding companies employed in the paper and the textile sector in northern and central Italian regions. The analysis of related sub-basins evidenced a significant difference between northern areas, characterised by a contained water stress (i.e. $WCSI_{CS1} = 0.221$, $WCSI_{CS2} = 0.047$) and central ones, subjected to high stress (i.e. $WCSI_{CS3} = 0.413$).

Regarding the considered case studies, the resulting OFBI index varied between a minimum of 0.002% (CS2), which indicates a negligible impact on local basin water balance, and a maximum value of 0.192% (CS3), which instead enlightens a more significant impact at local basin level. The methodology also resulted in comparing the application of water reuse practices within the case studies. The WRI index ranged from a minimum of 27% (CS2) to a maximum of 98% (CS3), indicating variable degrees of commitment to water recovery and reuse depending on the opportunities given by each specific production sector.

Based on the assessed case studies, the proposed methodology appears suitable for evaluating the impacts of a specific productive settlement on the local basin water cycle, thus providing companies, consumers, and decision-makers with useful information for interpreting the environmental impacts associated with the production processes of market goods, as well as to contribute to site-referred evaluations of other complex parameters, as a local-referred water footprint indicator. Finally, the proposed methodology is not particularly burdensome to be applied, both in terms of time and work required for its proper application, with the results provided being relatively simple to interpret.

Contributions

G. Sabia: Conceptualization; Data curation; Formal analysis Investigation; Methodology; Software; Validation; Visualization; Roles/Writing – original draft. **D. Mattioli**: Conceptualization; Data curation; Formal analysis Investigation; Methodology; Software; Validation; Visualization; Roles/Writing – original draft. **M. Langone**: Conceptualization; Supervision; Validation; Visualization; Writing – review & editing. **L. Petta**: Conceptualization; Supervision; Validation; Visualization; Writing – review & editing.

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

The authors do not have permission to share data.

Acknowledgements

This work was realized within the activities carried out within the project RECiProCo - Implementation of tools and initiatives on Circular Economy for the benefit of Consumers, 2020–2022, funded by the Ministry of Development. A Task in the Work Package 2 WP2 - Development of identification methods for products and services with a reduced environmental impact was completely dedicated to the definition of circularity indicators on the water resource. The authors acknowledge experts of WRI for the kind availability of the shared database, showing the raw data on the availability of the water resource by sub-basin and uses by sector.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.118163.

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