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AWARE historic and 2024 characterization factors for Spain

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Abstract

Purpose Water scarcity is a growing concern, especially in regions with Mediterranean, arid, and semi-arid climates. Conventional indicators often use historical data, limiting accuracy under current hydrological changes. This study aims to develop an improved methodology for water scarcity assessment in Spain, enhancing the AWARE approach by integrating current reservoirs data and refined demand estimates to increase spatial and temporal precision.

Methods he AWARE-based methodology was adapted for Spain by incorporating up-to-date reservoir storage data and demand values sourced from official hydrological plans. The assessment operates at the granularity of Demand Units, the most resolved administrative partition in Spanish basin management, thereby permitting high-resolution spatial disaggregation. Characterization factors reflecting water scarcity were evaluated for each Demand Unit in annual time steps, superseding the static application of historical averages. This methodological refinement facilitates differentiated calculation of local water demand and supply, allowing a temporally dynamic and spatially resolved portrayal of water stress across the national territory.

Results and discussion Application of this advanced methodology to 2024 data reveals an average increase of 8.3% in water scarcity characterization factors relative to historical baselines. However, this national mean conceals significant regional contrasts: certain regions experienced improved availability, while others exhibited intensified drought conditions, highlighting entrenched polarization in Spain's hydrological landscape. The dynamic integration of supply and demand enhances the accuracy and adaptability of scarcity metrics compared to static approaches, facilitating improved identification of at-risk areas and underpinning environmental impact assessments with locally relevant evidence.

Conclusions The developed methodology offers temporally responsive and spatially resolved water scarcity characterization factors tailored for the Spanish context, providing a robust tool for informed environmental assessments and sustainable regional water management. Given its modular and data-driven structure, this framework demonstrates strong potential for replication and adaptation in other regions facing similar hydrological challenges, contributing to the advancement of globally applicable water scarcity assessment practices.

Keywords Water scarcity · LCA · Characterization factors · AWARE methodology · Hydrological planning · Spain

1 Introduction

The SDG6 'Clean Water and Sanitation' emphasizes the challenge of adequate water resources management as a fundamental challenge at a global level, being key in many parts of the world to really have a decent life. There are several indicators that are monitored to quantify the achievement of this target. Water scarcity (WS) refers to an imbalance between the demand for freshwater and its physical availability. In this study, water availability is understood as the volume of renewable freshwater resources that can be effectively mobilized for human and ecosystem uses,

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after considering natural inflows, the regulating capacity of reservoirs, storage dynamics, and the demands established by Spanish hydrological planning.

WS is emerging as one of the most critical challenges that countries and regions, particularly those with Mediterranean climates, as well as arid and semi-arid zones such as the southwestern United States and parts of Australia, will face in the coming decades. This issue is exacerbated by global warming and population increase, as well as the evolving consumption patterns of various economic sectors (IPCC 2023). These changes alter both the availability of freshwater and regional water demands, highlighting the need for a flexible methodology to assess current basin conditions and project future water availability based on climate data and sectoral demand variations.

Water scarcity indicators (WSI), often referred to as water stress indices, typically measure the proportion of freshwater withdrawals relative to available resources (Liu et al. 2017). Various organizations have developed methodologies for calculating WS, including Aqueduct (Kuzma et al. 2023), the WWF Water Risk Filter (WWF, 2021), and AWARE (Boulay et al. 2017). These indicators are valuable tools for assessing basin conditions worldwide and comparing specific scenarios with global average water availability. However, they are often grounded in historical data, rendering them static and potentially unrepresentative of a basin's current status. This underscores the need for enhanced input data, transitioning from broad estimates to information provided by basin management organizations and up-to-date climatic data.

To perform a water footprint assessment for projects, businesses, or regions in line with ISO standard 14,046 (2014), it is necessary to multiply the volume of water used in a given region by the corresponding local water scarcity indicator (Boulay and Lenoir 2020). Accurate assessments require the use of WSIs tailored to the specific climatic conditions of the month or year during which water-related activities occur. This enables a more precise evaluation of the impacts and benefits of human activities on water resources. Given the seasonal variability of water value and the year-to-year fluctuations in availability, it is essential to apply factors that reflect the prevailing conditions. This approach ensures the accurate quantification of impacts and supports the development of water offsetting projects tailored to specific temporal and geographic contexts (Act4Water, 2024).

Several methods have been developed to assess water scarcity within the LCA framework. Pfister et al. (2009) proposed the Water Stress Index (WSI), based on the ratio between water withdrawals and availability, introducing a normalization at the country level. Berger et al. (2018) later developed the WAVE+ method, which accounts for both water availability and deprivation potential, emphasizing regional differentiation. At the national scale, Núñez et al. (2015) adapted a similar approach for principal Spanish basins, combining hydrological and socioeconomic data to estimate regional scarcity factors. These methods differ conceptually from AWARE but share the same objective: providing spatially explicit indicators to support decision-making and hotspot identification in water-related LCA studies.

The AWARE methodology serves as the foundation for the calculation tool and the Spanish water scarcity indicators developed in this paper, as it was selected as the most appropriate approach, as will be further explained in the following section. It quantifies the relative available water remaining per area after meeting the demands of humans and aquatic ecosystems, addressing the question: "What is the potential to deprive another user (human or ecosystem) when consuming water in this area?" The resulting characterization factor (CF) ranges from 0.1 to 100 and can be used to calculate water scarcity footprints, as outlined in the ISO standard (Boulay et al. 2017). Other studies have been conducted in various regions worldwide, including Peru (Sanchez-Matos et al. 2024), Australia (Bontinck et al. 2021), and Thailand (Kaewmai et al. 2021). Spain, in particular, should have a strong interest in refining water scarcity factors, as it exhibits significant disparities in water availability and faces high demand, especially from key sectors such as tourism and agriculture.

This article introduces a series of adjustments to the AWARE methodology to enhance the granularity and accuracy of water scarcity indicators for Spain's river basins. Notably, the adjustments incorporate hydrological plans (Ministerio para la Transición Ecológica y el Reto Demográfico, 2021) to refine demand estimates and redistribute water availabilities based on the demand units (DUs), the smallest territorial unit reported in the hydrological plans. These modifications provide a higher level of detail, resulting in an indicator that reflects more accurately the current conditions of Spanish basins.

2 Method development

2.1 Water scarcity assessment methodologies

Several approaches have been developed to quantify water scarcity (WS) worldwide. Aqueduct (Kuzma et al. 2023), created by the World Resources Institute, provides a broad mapping of water risks through multiple indicators but focuses mainly on qualitative assessments and aggregated indices. The WWF Water Risk Filter (WWF, 2021) is another widely used tool, particularly in the corporate and financial sectors, emphasizing risk management rather than the generation of standardized scarcity metrics.

In contrast, AWARE was specifically developed within the UNEP-SETAC Life Cycle Initiative as a globally consistent midpoint indicator for water use in life cycle assessment (Boulay et al. 2017). Its main strength lies in the provision of numerical characterization factors that measure the potential to deprive other users (human or ecosystem) of water, ensuring direct compatibility with ISO 14,046 and facilitating integration into LCA studies. This methodological alignment and the open availability of its global database have made AWARE the reference framework for water scarcity assessment in LCA.

More recently, AWARE 2.0 has been released, introducing updated datasets and methodological refinements (Seitfudem et al. 2025). However, the version currently endorsed by UNEP for life cycle assessment remains AWARE (v1.0). For this reason, and to maintain consistency with international recommendations, our study applies AWARE as the baseline method.

2.2 Assessing impacts of water consumption based on available water remaining (AWARE)

WULCA was established in August 2007 under the auspices of the UNEP/SETAC Life Cycle Initiative. Its primary objective was to harmonize the methodological framework for water use impact assessment in life cycle assessment (LCA), ensuring fair representation of various water use types while accounting for regional scarcity impacts. Researchers and stakeholders within the WULCA working group played a pivotal role in developing the AWARE model. Officially launched in 2015, AWARE provides a consistent and scientifically robust approach, enabling a wide range of stakeholders—including governments, businesses, and NGOs—to comprehensively evaluate water scarcity impacts.

During the development of AWARE, the 48-member LCA expert panel identified the demand-to-availability (DTA) ratio as the most effective solution for assessing pressure within basins. Three approaches were proposed during workshops (Boulay et al. 2015): DTAA, DTAx, and 1/AMD.

- DTAA incorporates the DTA ratio while applying a filter to account for arid regions.
- DTAx combines two parameters: relative availability (DTA) and absolute availability per unit of surface area.
- 1/AMD (Surface Time Equivalent or STe, as described in Eq. 2), represents the inverse of Availability Minus Demand (AMD) and was ultimately selected as the recommended method for determining water scarcity indicators (WSI).

This selection underscores the rigorous analysis and consensus-building efforts that defined the development of the AWARE methodology.

$$\begin{aligned} & AMD_i = \begin{pmatrix} Availability\ - \\ HWC\ -\ EWR \end{pmatrix} /\ area \\ & Availability = \\ & Water\ availability\ in\ the\ region\ (m^3/m^2\ month) \\ & HWC\ = \\ & Human\ water\ consumption\ (m^3/m^2\ month) \\ & EWR\ = \\ & Environmental\ water\ requirements\ (m^3/m^2\ month) \\ & Area\ =\ Region\ surface\ (m^2) \end{aligned} \tag{1}$$

$$\begin{aligned} & STe\ =\ 1/\ AMD_i \\ & STe_i = \\ & Surface\ time\ equivalent \\ & (m^2\ month/m^3) \end{aligned} \tag{2}$$

STe is based on the remaining available water on the territory after the human and environmental water consumptions. STe can be used to compare relatively different areas and produce a $\mathrm{CF}_{\mathrm{AWARE}}$ (Eq. 3) that reflects the water availability in a region with respect to the average availability in the world.

$$\begin{aligned} & CF_{AWARE} =\ STe_i/STe_{world\ average} \\ & =\ AMD_{world\ average}/\ AMD_i \\ & CF_{AWARE} =\ {m^3}_{world\ eq}/{m^3}_i \\ & AMD_{world\,average} \\ & = 0.0136\, m^3/m^2 \cdot\ month \end{aligned} \tag{3}$$

On the original modelling (Boulay et al. 2017) water availability was obtained from the WaterGAP2.2 (Müller Schmied et al. 2014) where more than 11,000 basins in the world are modeled using precipitations and evapotranspiration over the period 1960–2010 to model each runoff.

Human Water Consumption (HWC) is based on statistical data of freshwater withdrawals, including domestic, industrial, agricultural, livestock and energy production sectors modeled for the year 2010 (Flörke et al. 2013).

Environmental water requirements (EWR) represent the share of natural flow that must remain in the river to sustain ecological functions and ecosystem services. It was originally elaborated by the model from Pastor et al. (2014) validated with Variable Monthly Flow method (VMF) and Tessmann. Methods easement implemented in global hydrological models. Both methods use a simple algorithm and also take into account intra-annual variability and estimate a % of the water requirements needed by ecosystems in base of the natural availability.

2.3 Method adjustment for spanish case study

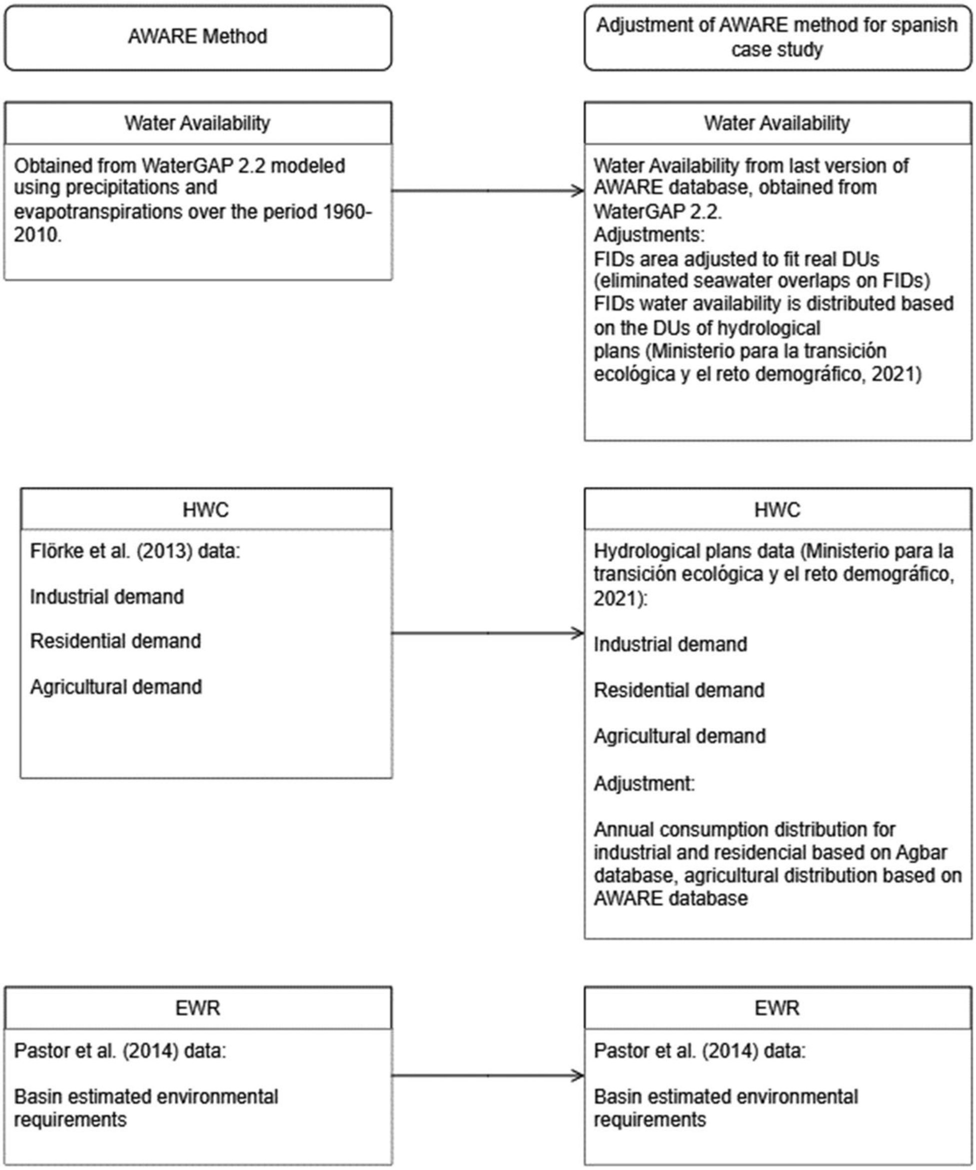
To more accurately reflect the diverse realities of Spain's basins, the adjustments consider the country's wide range of climates. These include oceanic climates in the northern and northwestern regions, continental Mediterranean climates in the center of the peninsula, semi-arid conditions in the southeast, and subtropical climates in the Canary Islands.

This diversity extends beyond climatology to encompass cultural differences. Industrial and commercial activities vary significantly across regions, necessitating finer adjustments to capture the unique characteristics of each basin. Similarly, residential typologies and consumer habits differ notably, particularly between areas with Mediterranean and oceanic climates.

To adapt the AWARE methodology to these varied conditions, adjustments have been made in two key areas: modifications to the input data of the model and changes to the distribution of the catchment areas (Fig. 1).

Water availability for Spanish case study is obtained from the latest available version of AWARE, these data are divided by Feature Identifiers (FID) and provide data of availability in m^3 and surface area (m^2) of the consumption area. These data are used and adapted by making an adjustment for coastal areas where that availability is calculated for areas of 0.5º x 0.5º, and in coastal profile locations, sea area is included. This situation is solved by recalculating the DU areas, and redistributing the availability and ecosystem

Fig. 1 Adjustment of AWARE method in Spanish case study



requirements among the new surface using geographical information systems (GIS). The new availability related to the adjusted FID would be obtained from Eq. 4:

$$\begin{aligned}&Availability_i = \\ &(Availability_j x\ Area_i)\ /\ Area_j \\ &Availability_i = \\ &\ Adjusted\ availability\ (\mathrm{m}^3) \\ &Availability_j \\ &=\ AWARE\ availability\ (\mathrm{m}^3) \\ &Area_i = \\ &\ GIS\ Adjusted\ area\,(m^2) \\ &Area_j = \\ &AWARE\ area\ (m^2)\end{aligned} \tag{4}$$

Once the new availability for the FIDs have been adjusted, having eliminated the seawater surfaces and using GIS, the FIDs availability are translated into the different DU present in the river basin hydrological plans, using Eq. 5. The aim of this distribution is to achieve for the DU an availability data directly comparable with the demand of the different sectors in the region.

$$\begin{aligned}&Availability\ DU = \\ &\sum FID_i Availability\ \times \begin{pmatrix}Area\ FID_i/ \\ Area\ DU\end{pmatrix} \\ &Availability\ DU: \\ &\ Demand\ unit\ availability\ (m^3) \\ &FID_i Availability: \\ &FID\ availability\ overlapping \\ &DU\ area\ (m^3) \\ &Area\ FID_i: \\ &\ FID_i area\ overlapping\ DU\ area\ (\mathrm{m}^2) \\ &Area\ DU: \\ &Area\ DU\ (\mathrm{m}^2)\end{aligned} \tag{5}$$

DU availability thus provides a value that is proportional to the number of FID layers that comprise it and the surface area that each of them occupies in the DU.

In the original modeling approach, HWC was based on the estimations of Flörke et al. (2014). To improve the accuracy of this input data, the human water demand from various sectors is now derived from the basin hydrological plans of the third cycle (Ministerio para la Transición Ecológica y el Reto Demográfico, 2021), as regulated by the Water Framework Directive of the European Union (European Parliament and Council, 2000). For this study, the projected sectoral demands for the year 2027 are utilized. DU are the smallest territorial scale in which demand data is reported and enables reflect the actual types of activities conducted within each region.

EWR maintains the values provided by the Pastor model, available in the AWARE database, are retained (Wulca, 2020). However, the demands are adjusted using GIS to align the demand for exploitation systems with the value of the FID that has the highest representation within the territory.

2.4 Integration of climatic variability into water scarcity characterization

Given the necessity for territories to assess water availability and adjust water scarcity factors in accordance with annual climatic conditions or short-term projections, a tool has been developed to enable the monthly modification of water scarcity results. To partially automate the calculation, the availability parameter has been linked to the state of water reservoirs, specifically the main reservoir within each DU (Supplementary material). Additionally, demand can be adjusted based on climatological data, given its significant influence on key sectors such as agriculture, or in response to variations in population dynamics compared to historical data. For this initial assessment, and considering that demand data is available from hydrological plans until 2027, only the availability component has been adjusted, incorporating the reservoir status in relation to historical averages. The WaterGap2.2 model (Müller Schmied et al. 2014) utilizes climate data from 1960 to 2010 to simulate runoff as a function of precipitation and evapotranspiration. The dataset, available on a monthly time scale, also incorporates infrastructure elements such as dams (Boulay et al. 2017). The climatological adjustment of water availability is grounded in this state of the reservoirs. They reflect the overall availability within exploitation systems, and their capacity allows for estimating resource variations compared to the historical series from the WaterGap2.2 calculation. To achieve this, historical reservoir levels from 1988 to 2010 are modeled and compared to the actual reserves for the year under study (Ministerio para la transición ecológica y el reto demográfico, 2024). In this case, the scope focuses on Spain in the year 2024 (Fig. 5). To adjust availability, the following equation is applied:

$$\begin{aligned}&AvailabilityDU_{year} = AvailabilityDU \\ &\times (Reservoir_{year}/Reservoir_{historical}) \\ &AvailabilityDU_{year} : Demandunitavailability \\ &forstudiedyear(m^3) \\ &AvailabilityDU : Demand\,unit\,availability(m^3) \\ &Reservoir_{year} : \%reservoir\,fillinghistoric \\ &Reservoir_{historical} : \%reservoir\,year\,studied\,filling\end{aligned} \tag{6}$$

2.5 Adapted CFs for spanish DU

Given the significant heterogeneity within Spain and the inherent polarization of the AWARE water scarcity indicator, an analysis of AMD becomes valuable for gaining deeper insights into basin availability. Spain's diverse climate, with very dry regions alongside relatively humid ones, often causes the water scarcity factor to spike to 100 in some months, reflecting AMD values 10 times lower than the global average, or drop to 0.1 with values 100 times higher. In this context, a monthly comparison of AMD provides a meaningful approach to evaluate varying degrees of scarcity that the original indicator fails to capture effectively.

To address this, it is proposed to evaluate an AMD indicator on a monthly basis. This approach assesses water availability in m^3/m^2.month across different DU. The calculation involves analyzing the monthly distribution of AMD (Fig. 6), for which a lineal equation (Eq. 7) is designed to align with the whisker points of the graph. These whiskers represent the lowest and highest values within 1.5 times the interquartile range (IQR) from the first quartile (Q1) and third quartile (Q3), respectively. Under this framework, the highest AMD value is assigned a score of 0.1, while the lowest is assigned a score of 100. Outlier values outside this range are assigned the maximum or minimum scores, depending on whether they fall above or below the whiskers.

$$\begin{aligned}
&CF\ Spain_{DU.month} = mxAMD_{\ DU.month} + b\\
&CFSpain_{DU.month} : CFs\,for\ SpanishDU.month\\
&m = \ (100 - 0.1)\,/\,(LW - UW)\\
&Lower\,whisker\ (LW)\ = Q1 - 1.5 \times IQR\\
&Upper\,whisker\ (UW)\ = Q3 + 1.5 \times IQR\\
&b = \ -m\,x\,UW + \ LW
\end{aligned} \tag{7}$$

3 Results

3.1 Regionalized water scarcity characterization factors (CFs) for Spain

Spain's geographic location results in significant climatic diversity, ranging from oceanic to Mediterranean and arid climates. This diversity leads to a pronounced polarization in the CFs calculated for different Spanish regions. The design of the water scarcity factor, where regions with availability 100 times higher than the global average yield a factor of 0.1, while those with availability 10 times lower result in a factor of 100, exacerbates this polarization. This effect is illustrated in Fig. 2 for the months of January and August where this effect is amplified.

The adapted methodology, as illustrated in Fig. 3, allows for a detailed assessment of monthly variations in water scarcity and territorial trends across Spain's climatic regions, also in Supplementary Material 2 higher-resolution figures are included. In oceanic zones, such as the north and west, water scarcity remains consistently low throughout the year. In contrast, the central peninsula, with its continental climate, experiences scarcity levels nearly double the global average. The Mediterranean regions, particularly the arid and semi-arid areas in the south, such as Murcia and Almería, face extreme scarcity, with CF values reaching the maximum threshold of 100. Seasonal variations further intensify these differences, with summer months showing the most pronounced scarcity, coinciding with peak water demand, particularly in agriculture or tourism.

On an annual basis, the refined default CFs for Spain average 36.85, significantly surpassing the global reference value of 20.96 (Boulay and Lenoir 2020). This highlights the critical water scarcity in Spain, especially in its southern regions. In the north, including Galicia, Asturias, Cantabria, and the Basque Country, CF values remain below 5, reflecting more stable water availability. In central Spain, values range from slightly above the global average to nearly twice as high. Meanwhile, the southern regions endure persistent scarcity year-round, with CF values surpassing 70 in the internal basins of Andalusia and reaching 100 in parts of southern Alicante and Murcia. The islands also face chronic scarcity due to limited surface and groundwater resources, relying almost entirely on desalination, which results in CF values consistently approaching 100.

Figure 4 presents the refined CF factors for the different demand units. 'Non-Agri CFs' refer to factors that exclude agricultural demands, while 'Agri CFs' consider only agricultural demands. 'Default CFs' are the most representative factors for assessing water availability in the DUs, as they account for all types of demand, including agricultural, industrial, and general supply (Boulay et al. 2017). As observed globally, the Agri CFs are significantly higher than the Default or Non-Agri CFs. This is primarily due to agricultural demands typically peaking during drier seasons when water availability is lower, thereby intensifying competition for the resource.

The Tajo basin provides a clear example of the advantages of refining global characterization factors with regionalized data. It is the longest river on the Iberian Peninsula, originating in the Montes Universales in eastern Spain and flowing westwards through central Spain into Portugal, where it discharges into the Atlantic Ocean at Lisbon. Covering more than 80,000 km², the basin is one of the most important in both Spain and Portugal due to its high population density (including Madrid and Toledo), extensive irrigated agriculture, hydropower production, and the presence

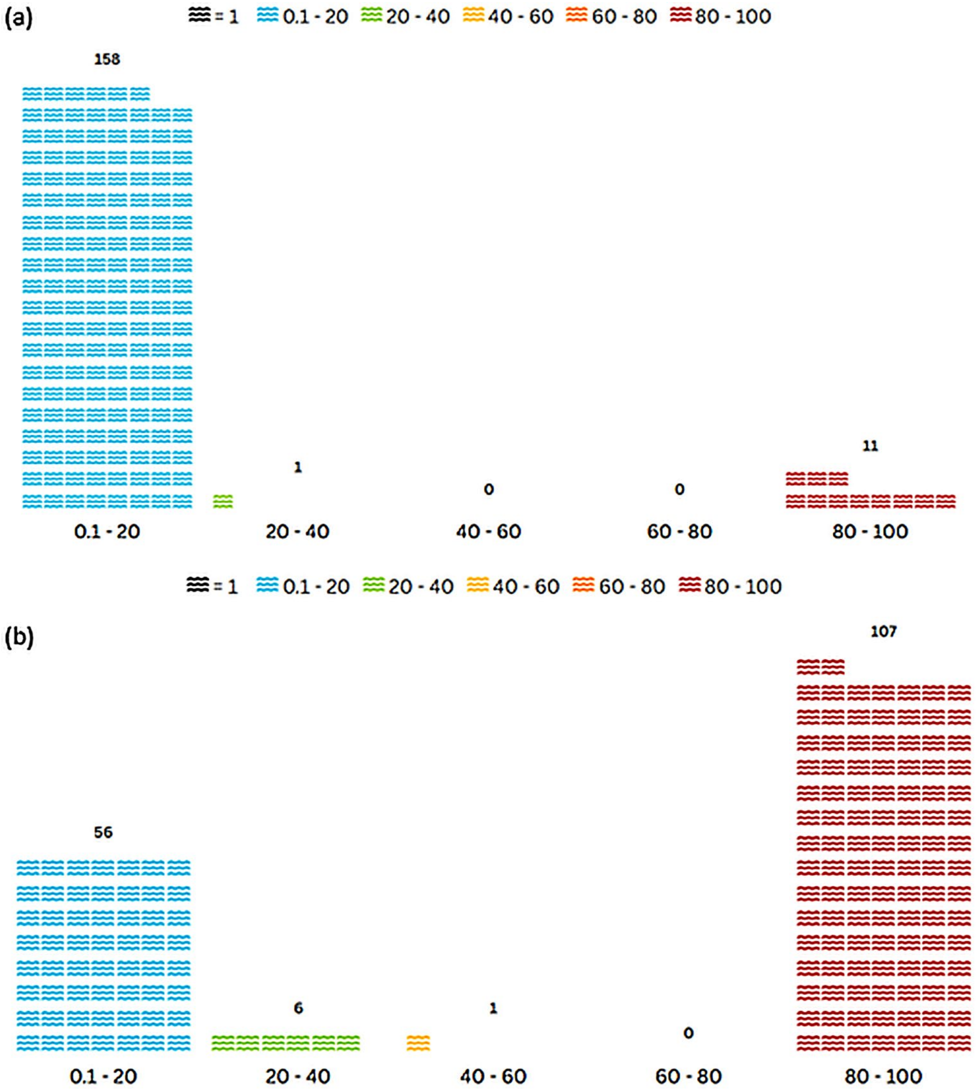


Fig. 2 January (**a**) and August (**b**) DU spanish CF distribution

of large reservoirs that regulate water supply and enable inter-basin transfers. Under the original AWARE methodology, only a single default factor of 10.30 was assigned to the entire basin (WULCA, 2024), which masks the internal heterogeneity of water availability and demand. By applying our refinement, however, we were able to disaggregate results to the DUs level, obtaining a broad range of CF values that better capture the spatial variability within the basin (Table 1). This heterogeneity is illustrated in Fig. 5, where the Tajo basin demonstrates significant differences between DUs, highlighting the added value of regionalized CFs for accurately representing localized water scarcity conditions.

3.2 Regionalized water scarcity CFs for demand and climate change scenarios. (2024)

Based on the methodology explained in Sect. 2.4, a detailed analysis has been conducted to evaluate the variability of CFs in relation to climatic conditions in Spain. The results obtained are calculated exclusively for DUs that rely on reservoirs, excluding those dependent on aquifers or, in the case of Spain, islands that do not rely on reservoir systems (Fig. 6).

Based on the results obtained for 2024, it is observed that, in overall terms, CFs in Spain have increased by 8.3% compared to historical values. However, this variation is not uniformly distributed across the country. In the north and west of the Peninsula, where water availability is higher, CFs have decreased by 13%. Similarly, the central region of the peninsula has experienced a general decline, with CF values 19% lower than historical records. In contrast, the south of Spain, particularly the Andalusia region, has seen a slight increase of 1%, while the east and southeast of the peninsula have recorded a 2% reduction. The most drought-affected region in 2024 was Catalonia, in the northeast of the peninsula, where CFs increased by 72%. Notably, in

Fig. 3 Spain CF comparation

critical demand units such as Embassaments Ter-Llobregat, which supplies the Metropolitan Area of Barcelona (AMB), the default CF value reached 100 for all months of the year.

These results not only provide a comprehensive overview of the changes in CFs across Spain but also highlight the growing need for adaptive water management strategies. Beyond facilitating short-term water resource management, this information is particularly valuable for calculating offsetting projects (Act4Water, 2024) and designing infrastructure aimed at enhancing territorial water resilience. By enabling a dynamic understanding of water availability, it provides insights not only into the monthly impacts of such projects but also into the periods when compensation measures are most needed or the risk of water shortages is highest.

3.3 AMD and adapted CFs for Spanish DU

After analyzing the AMD results for the different DUs and applying the methodology outlined in Sect. 2.5, the monthly distribution (Fig. 7) is developed to formulate the adjustment Eq. 7 for CFs within the Spanish scope. The objective of this approach is to design a communicative indicator that helps reflect, in comparative terms, the relative value of water across Spanish river basins.

Once the new CFs have been generated based on the monthly AMDs (Supplementary material), the results provide a non-polarized indicator that facilitates comparisons between different DUs while also enabling the assessment of a basin's status relative to its historical trends (Fig. 8). Similar to the AWARE model at the global scale, these CFs serve as a comparative measure of resource availability, offering a standardized approach to evaluating water scarcity across regions. To calculate these CFs adapted for Spain in a specific year, the regression equation based on historical AMDs, along with the adjusted AMD values for the study year, is applied. This approach ensures comparability across different years and accurately captures variations relative to the historical series.

It is important to note that these adapted CFs for Spain do not serve as substitutes for the original AWARE values at a global scale and are not suitable for conducting environmental analyses within the framework of LCA. However, they function as a valuable indicator for administrations, operators, and water consumers, aiding in the prioritization of investments and the assessment of infrastructure vulnerability and climate-related risks.

4 Discussion

This study develops water scarcity characterization factors that more accurately represent Spain's hydrological reality while enabling the disaggregation of water availability and

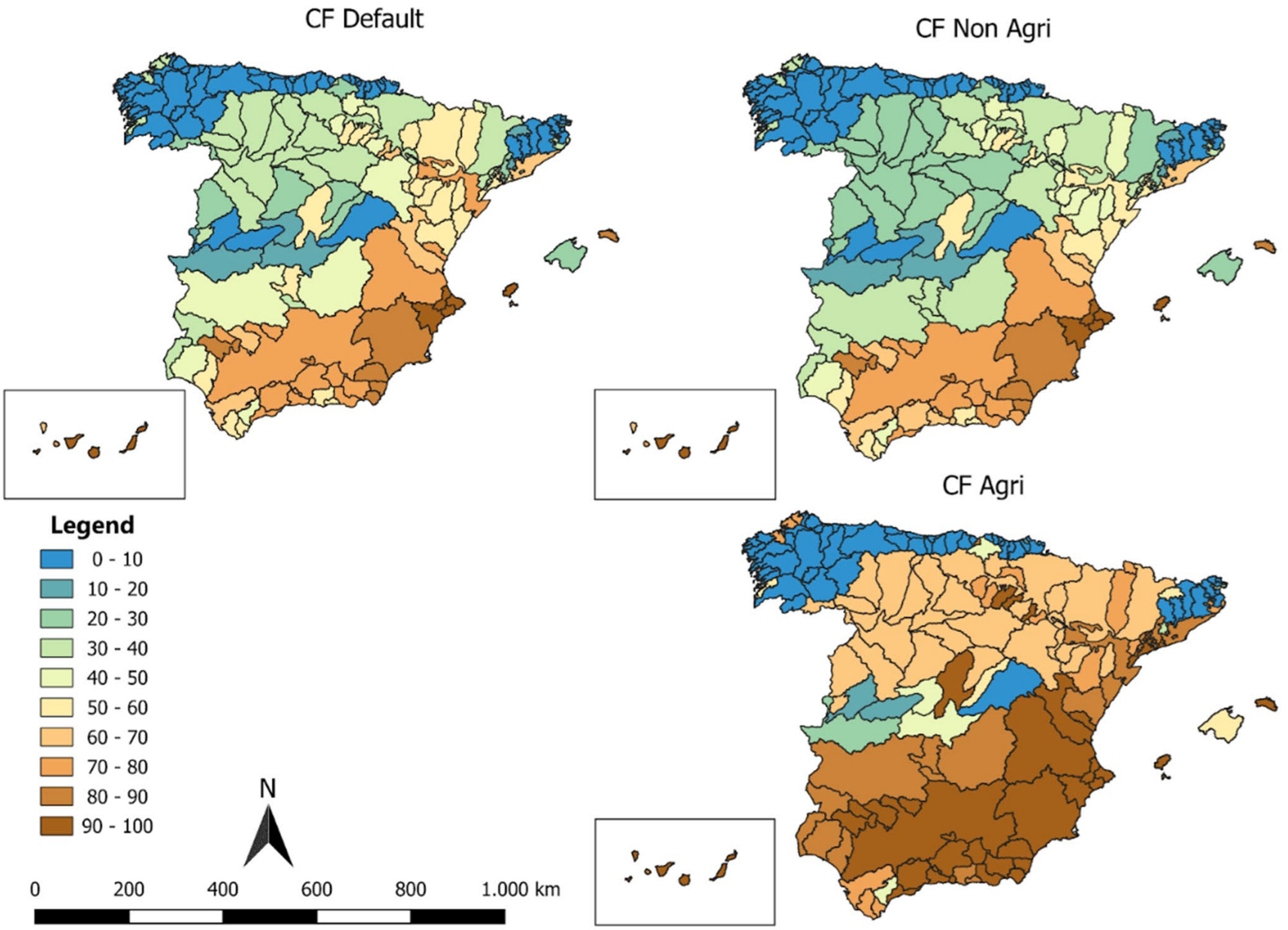


Fig. 4 DU Spanish CFs

Table 1 Aware refined factors for Spain. Tajo River Basin example

Aware methodology		Aware refinement	
Tajo Basin	Default factor	DU	Default factor
Tajo Basin	10.30	Alagón	6.38
		Alberche	19.03
		Árrago	31.12
		Bajo Tajo	13.27
		Cabecera	4.90
		Henares	27.41
		Jarama-Guadarrama	56.80
		Tajo Izquierda	19.36
		Tajuña	28.57
		Tiétar	5.71

demand at the most granular unit defined within hydrological plans (DUs). The results provide a more reliable characterization of territorial water conditions, and by linking water availability with Spain's reservoir network, it becomes possible to estimate an annual factor. This factor not only assesses the actual water scarcity of a given year but also enables the analysis of its evolution and long-term trends over the coming decades in response to climate change and shifts in precipitation patterns. Previous national studies (Núñez et al. 2015) reported that water scarcity in Spain is highly heterogeneous, with Mediterranean and southeastern basins showing considerably higher stress levels than the national average. This aligns with our findings and supports the relevance of developing locally refined CFs. Compared to global models such as AWARE and AWARE 2.0, our results suggest that regionalization introduces greater variability than the methodological updates between model versions. This implies that, while global models provide a consistent framework for international comparison, locally adapted factors remain essential for accurate assessment and policy relevance at basin or country level.

Our findings are consistent with international experiences showing that the regionalization of water scarcity indicators significantly enhances accuracy and decision relevance. In Brazil, the AWARE-BR adaptation demonstrated that replacing global WaterGAP data with national balances from the Brazilian Water Agency aligned CFs more closely with official scarcity indices (Andrade et al. 2020). In Peru, Sánchez-Matos et al. (2024) developed watershed specific

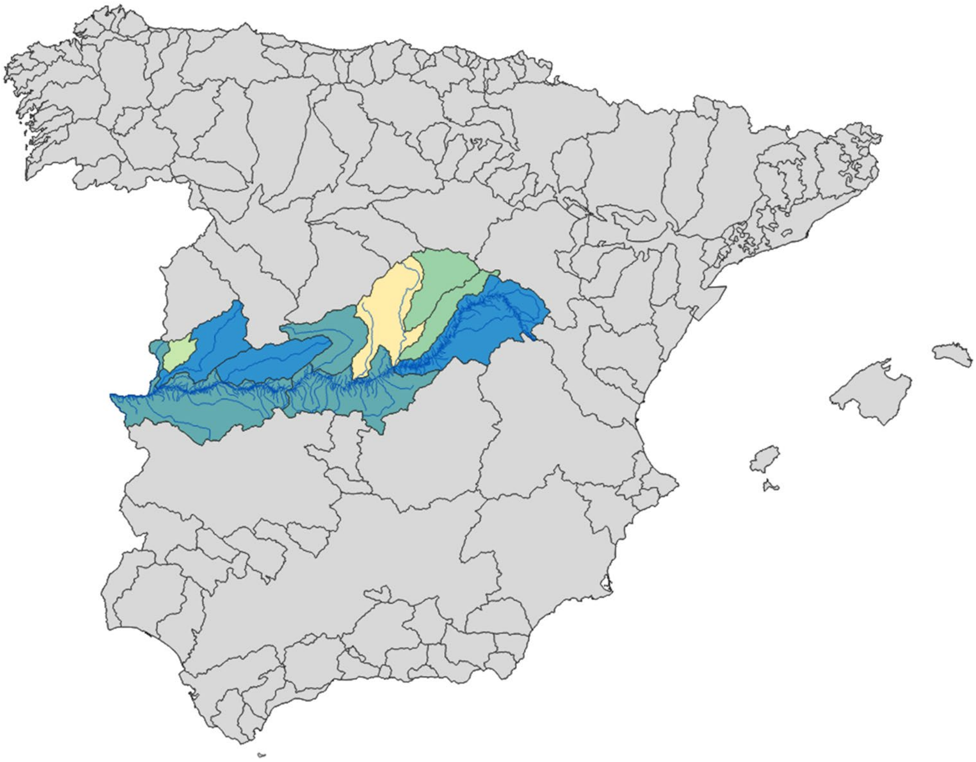


Fig. 5 Tajo Basin DUs

CFs that revealed much higher scarcity levels than global AWARE factors, especially during the dry season, and highlighted that monthly CFs during El Niño events were lower than the updated CFs. In the United States, Lee, U. (2018) developed county-level CFs (AWARE-US) and found that recalculated CFs are lower in most parts of the western and eastern U.S., and higher for most counties in the High Plains and lower Mississippi River aquifer regions. Similarly, in Australia, Bontinck et al. (2021) recalculated AWARE CFs at basin level and showed substantial deviations from global results, suggests that irrigation water requirements are 72% lower than the value currently used in AWARE, and that the characterisation factor for Australia should be up to 35% lower than currently reported. These examples confirm that incorporating sub-national resolution is crucial for improving accuracy and decision relevance, particularly when applying water scarcity metrics within LCA studies.

However, to enhance methodological robustness and reduce uncertainties, it is crucial to address certain methodological gaps. These include obtaining precise EWR values for different basins and exploring alternative hydrological models for estimating water availability, thereby mitigating uncertainties associated with sub-scaling processes.

These regionalized and annual factors are particularly valuable for assessing environmental impacts, especially in the calculation of water footprints using the ISO 14,046 methodology. Moreover, they could play a crucial role in territorial planning and water resource governance, enabling the implementation of localized measures to enhance water availability and adapt infrastructure to future periods of increased scarcity, ensuring sustained access to water for socioeconomic sectors. The CFs factor adapted for Spain can serve as a key indicator for assessing water scarcity at a finer spatial resolution within a national framework. This adaptation facilitates more straightforward comparisons between neighbouring demand units and enables the evaluation of water asset management performance over multiple years. Additionally, it highlights the impact of specific measures aimed at increasing water availability or reducing demand at a localized scale.

4.1 Limitations

The limitations of the methodology are largely inherited from the early stages of AWARE. One major limitation is the uncertainty surrounding human demand data. While there is a significant methodological improvement through the use of hydrological plan consumption data, these figures are still estimates, and calculation methods can vary across different hydrographic confederations. Additionally, one of the greatest uncertainties lies in estimating water consumption by ecosystems, with potential inaccuracies reaching up to 50% (Boulay et al. 2021). Another aspect to consider is the uncertainty introduced by the downscaling of water availability to the DUs. To minimize this uncertainty,

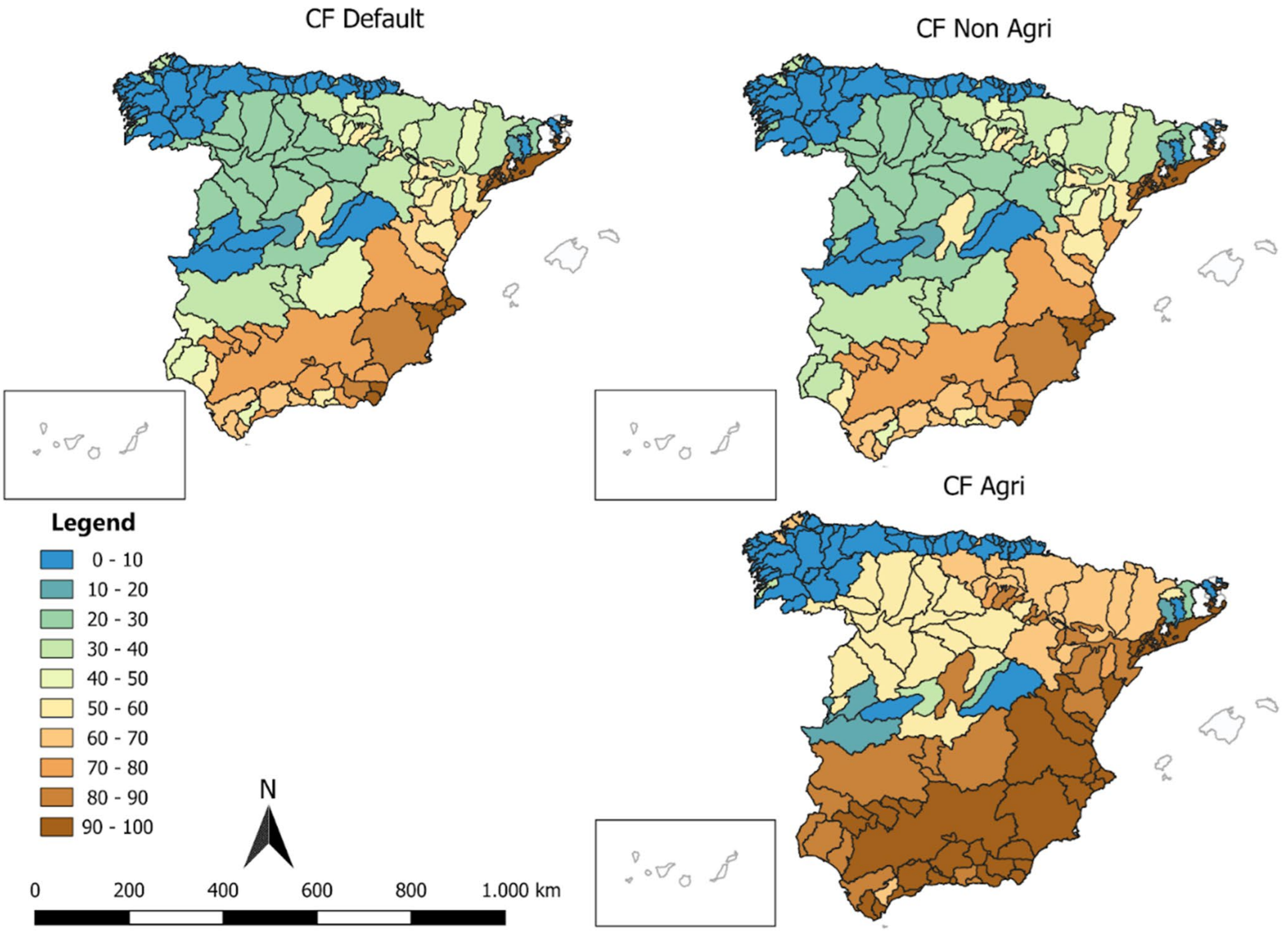


Fig. 6 2024 DU Spanish CFs

a more ad hoc modelling approach tailored specifically to Spanish basins would be optimal.

Additionally, a major limitation lies in the availability of historical data on aquifers, which hinders the replication of availability modelling in the same manner as for DUs dependent on reservoirs. Furthermore, island systems present an additional layer of complexity, as a significant portion of their water supply is not directly influenced by meteorological conditions but rather by the desalination capacity of local infrastructure. Future studies will consider how to proceed in these island and aquifer-dependent systems.

4.2 Sensitivity analysis

To provide additional insights into the effects of the variables considered for the AMD calculation, a sensitivity analysis was conducted. This analysis aimed to assess the impacts of demand and water availability on the AMD indicator.

After a preliminary review of the results obtained from the aforementioned analysis, it was concluded that the most significant factor influencing the AMD was net availability. Several scenarios were stablished by increasing or decreasing the availability values by a fixed number ranging from −30% up until +30%. The primary differences across the various scenarios occur in the months of January and December. This is likely due to the impact prevalent during the winter and spring months compared to summer across the entire country, thereby producing a greater effect on water availability during these periods. It is important to note that for rainfall on Spanish territory, which is more this analysis, the average value of water availability for each exploitation system was used to evaluate this effect. The months exhibiting the highest dispersion rates across all scenarios are April, May, and November, in terms of AMD values related to availability. This phenomenon may arise from the fact that these months, which fall between the driest season (summer) and winter, also exhibit the greatest variability, both within the same basin across different years and among different basins in Spain. As previously discussed, Spain has significant climatic variations across its regions, which may contribute to the observed effects.

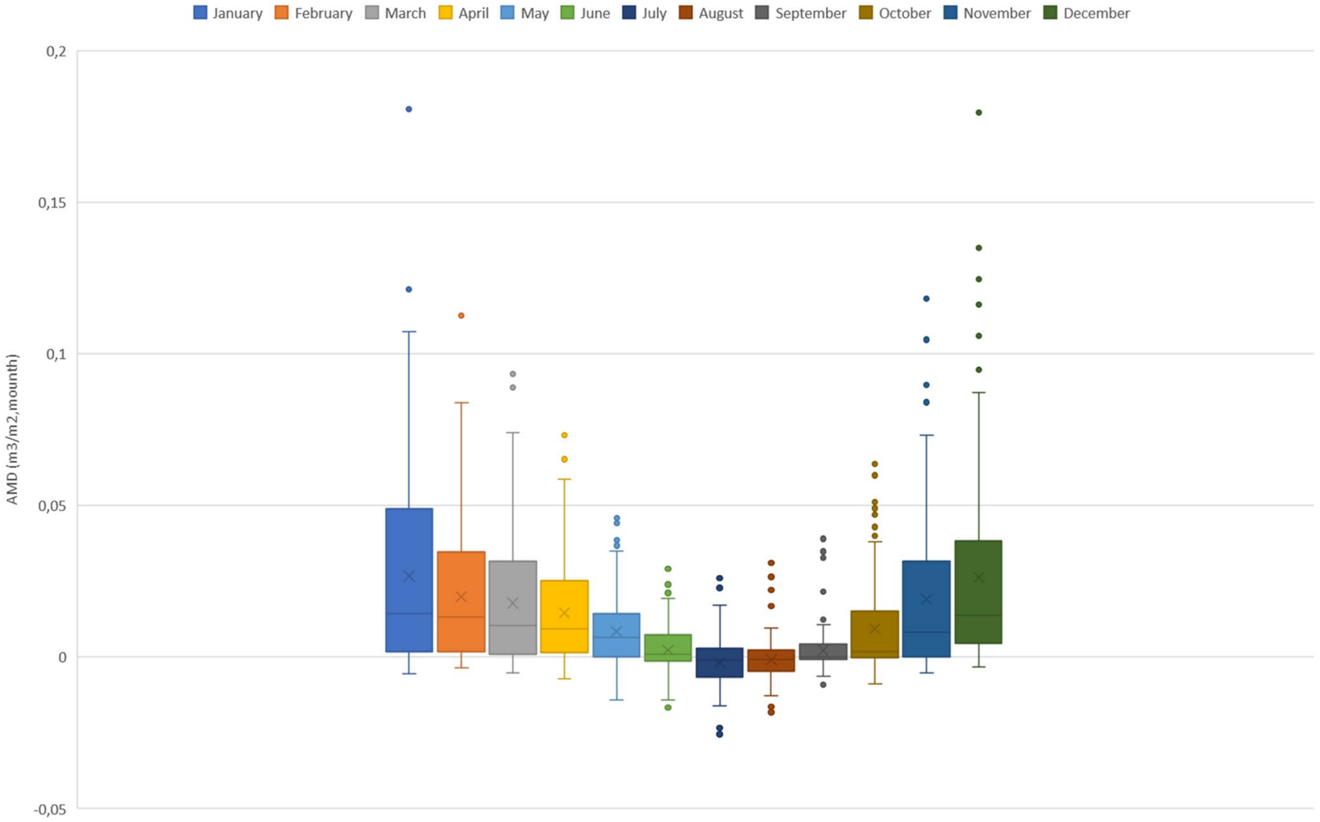


Fig. 7 Spanish historical monthly AMD distribution

It's possible to conclude that the main factor affecting the AMD is the availability obtained throughout the year and that said availability is by the geographical situation of the measure point as well as the monthly distribution of said measurements.

5 Conclusions

The methodology for characterizing AWARE factors in Spain enhances the accuracy of environmental impact assessments and decision-making in water resource management by adjusting the AWARE methodology to each specific demand unit in which management actions and assessments are taking place The adaptation to the demands outlined in hydrological plans allows for a more precise characterization of Default, Agri, and Non-Agri CFs. A notable example of this adjustment is observed in the Default CF for the Metropolitan Area of Barcelona (Embassaments Ter-Llobregat), one of the most water-stressed regions in Spain, where the factor increased from 5.6 to 67.35. This sharp rise reflects the intense competition for water resources in one of Spain's most pressured basins in recent years, with projections reaching a maximum value of 100 by 2024, as detailed in the supplementary material. The overall results indicate that in 2024, the Default CF values in Spain increased by 8.3% compared to historical values. However, this increase was highly uneven across the country. While CF values declined in the northern and central regions of the peninsula, the southern and eastern areas experienced a slight increase. Notably, the northwestern regions of Spain saw the most significant rise, with average CF values increasing by 72%.

In light of these findings, we conclude that regional adaptation of water scarcity characterization factors, through the integration of national reservoir operations, seasonal demand profiles, and official hydrological planning, can have a greater effect on CFs representativity. While methodological upgrades such as AWARE 2.0 improve input accuracy and conceptual implementation, their benefits may remain constrained if not coupled with region-specific data. Thus, the refinement of water scarcity indicators at the national level is a crucial step toward increasing the relevance and reliability of environmental footprinting, especially in water-stressed regions with heterogeneous supply-demand dynamics.

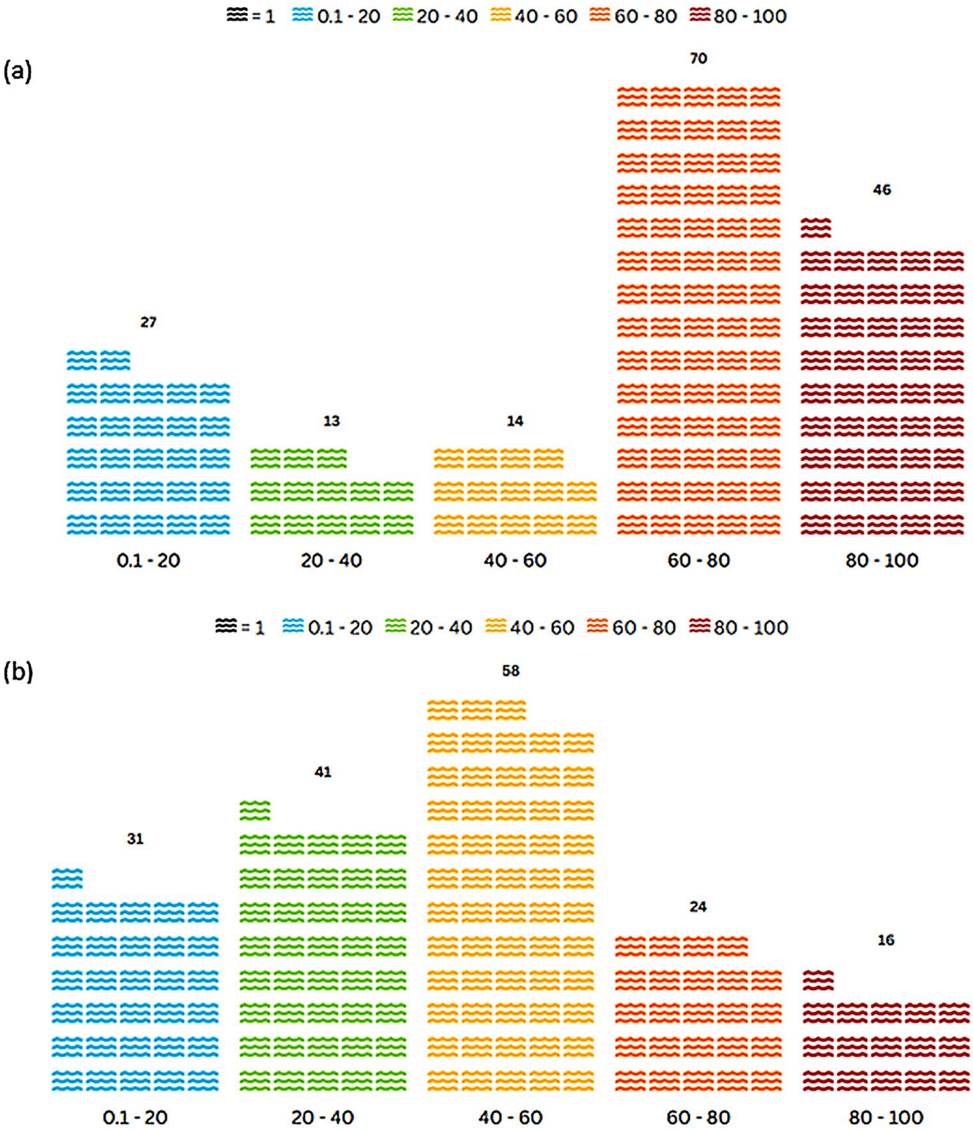


Fig. 8 Spanish adapted DU historical CF distribution. January (**a**) and August (**b**)

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Data availability All data generated in this study are included in the published article and its supplementary information files.

Declarations

Competing interests The authors declare no competing interests.

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