Towards a more comprehensive representation of hydrosystems in water footprint assessments

This is a collective work conducted within the PC4 of the programme OneWater.

Introduction

The concept of planetary boundaries provides a critical framework for understanding the limits within which humanity can safely operate on Earth (Rockström et al., 2009). Defining these boundary concepts at local, regional and global scales presents considerable challenges. The notions of planetary boundaries, water resources, and chemical entities are evaluated through a complex interplay of impacts and pressures, and thresholds are defined within a holistic framework that recognizes the interconnectedness of Earth's systems. These boundaries have been established in relation to their impacts (or footprints), highlighting their role in safeguarding the functional integrity and resilience of the Earth system. However, this framework maintains a predominantly anthropocentric perspective that would benefit from incorporating One Health approaches. Overall, they represent less of an “ideal” pre-Anthropocene reference state, which might be impossible to determine, and more a desirable safe operating space, respecting the Earth capacities.

Given this interconnected framework, water systems are particularly affected by multiple planetary boundaries. Indeed, several boundaries directly influence water footprint such as freshwater quantity, biogeochemical flows and novel entities. Beyond these direct influences, there are other planetary boundaries directly linked to water: the modification of N and P cycles generates water quality degradation phenomena through eutrophication; land use changes modify the global water cycle by altering runoff, infiltration and evapotranspiration phenomena through vegetation, and can favor the lixiviation of nutrients; atmospheric water stock is impacted by the land use and climate change, modifying evapotranspiration processes and the presence of aerosols, which are implied in cloud formation; climate change reduces the stock of frozen water, thus inducing a rise in sea level; the modification of the biogeochemical cycles of nutrients and the introduction of novel entities in the environment can degrade the surface and ground water quality. These boundaries have been exceeded significantly, compelling us to deepen our understanding, establish a comprehensive assessment, and develop improved approaches to water resource management (Gleeson et al., 2020).

Recognizing these complex interactions between planetary boundaries and water systems has led researchers to develop assessment tools that can capture these relationships. Water footprint assessments have been trying to relate to planetary boundaries in various degrees. Blue and green waters are integrated in planetary boundaries, and allow to consider the impact of a consumption use on the Earth capacity. However, traditional life cycle assessments do not assess the contribution of the calculated impacts in relation to Earth’s carrying or assimilation capacity. To address this limitation, recent works are developing the concept of

Absolute Environmental Sustainability assessment, in order to propose indicators related to planetary boundaries in LCA (Bjørn et al., 2015; Ryberg et al., 2018).

This scientific development has occurred alongside growing practical interest in water footprint applications. In 2014, an international standard (ISO 14046:2014) was developed based on the life cycle assessment approach. This standard requires the inclusion of both water quality and quantity indicators, while considering local geographical contexts and seasonal variations. Additionally, several water footprint calculators have emerged to evaluate individual water footprints based on a volumetric approach (Mon Empreinte Eau | Le calculateur d'empreinte eau individual; Empreinte eau : comprendre, évaluer, économiser l'eau). Industrial stakeholders have also developed their own methodologies aligned with the life cycle assessment approach and in compliance with ISO standards, such as Veolia's Water Impact Index, which calculates water footprints for industries and water and sanitation services (Wiix - Water Impact IndeX).

Despite these advances in both scientific understanding and practical applications, significant gaps remain in how water footprints account for the complex interactions within hydrosystems - defined here as encompassing surface and subsurface flows, biogeochemical interfaces, ecological functions, and human use and governance systems. The objective of this work is to identify and discuss the gaps towards a better representation of hydrosystems in water footprints, including all water dimensions, and with the aim of a better understanding of the functioning and evolution of hydrosystems. Developing such an integrated hydrosystem approach is particularly timely given current challenges including climate change impacts on water resources, the ambitious goals of the EU Water Framework Directive for achieving good ecological status, and the need to meet SDG 6 targets for sustainable water management. This is done by 1) reviewing the existing water footprints and their gaps in hydrosystems representation; 2) identifying the gaps in hydrosystems representation and how they affect a comprehensive water footprint assessment; 3) proposing a few parameters necessary to develop a comprehensive framework.

Existing water footprints and hydrosystems' representation

Emerging hydrosystem consideration in existing water footprints

Two primary approaches supported by distinct research communities have been mobilized to develop frameworks, tools, and indicators for investigating, understanding, and predicting human impacts on hydrosystems, with the aim to inform stakeholder decisions.

The first approach, referred to as the water fingerprint method, aims to assess the actual impacts of upstream human activities on hydrosystems. This approach targets a range of hydro-biogeochemical properties to identify and quantify anthropogenic influences and to differentiate among sources such as agriculture, industry, or urban areas, as well as associated reactive transport processes. Within the widely-used Driver-Pressure-State-Impact-Response (DPSIR) framework, this methodology can aid in characterizing impact pathways that connect Pressures, State of the hydrosystem, and resulting Impacts. Over the past decade, significant advances have been achieved through the use of elemental and compound-specific isotopic tracers, or the development of non-targeted chemical analyses, environmental omics, and environmental DNA (eDNA) (Martyniuk and Simmons, 2016; Gouveia et al., 2019; Shi et al., 2024). The principal strength of fingerprint approaches lies in their hydrosystem-specific applicability, enabling the detection of ongoing pressures from human activities on particular systems. Conversely, their main limitation is the inability to evaluate the impacts of production externalization at regional or global scales.

These limitations can be answered by the second approach, known as the water footprint method. This systemic perspective helps to avoid impact shifting, where environmental burdens are displaced to other hydrosystems through resource use, or to other impact categories such as eutrophication or acidification. Thus water footprint assessment has emerged as a critical tool for understanding and managing the complex relationship between human activities and water resources. Two distinct approaches have gained prominence in this field: the volumetric approach, which focuses on water resource sustainability from a management perspective, and the impact-oriented approach, which emphasizes product sustainability through life cycle assessment. While each approach offers valuable insights, both reveal an evolving recognition of the need to incorporate more sophisticated hydrosystem considerations to capture the complexity of water-related impacts.

The volumetric approach, comprehensively defined in the Water Footprint Assessment manual (Aldaya et al., 2011), quantifies the volume of water directly or indirectly utilized across process steps, products, or consumers. This approach introduces the concept of "virtual water" (Allan, 2005), the water embedded in products throughout their production chain, providing a more complete accounting of water dependencies than approaches focused solely on direct water use. By making these hidden water flows visible, the volumetric approach supports more informed water allocation decisions and identifies opportunities to increase water productivity across diverse sectors. A distinctive feature of this methodology is its differentiation between green, blue, and grey water footprints, each representing a different dimension of water appropriation. The green water footprint quantifies rainwater consumption by the functional unit under study, representing water withdrawn from the hydrological cycle without returning to the same watershed. The blue water footprint measures freshwater consumed from surface and groundwater sources, while the grey water footprint represents the theoretical volume of water required to dilute pollutants to acceptable concentration levels in the receiving water body. The grey water footprint calculation component requires establishing reference states or quality standards, either environmental or health-based, against which dilution requirements can be calculated. It follows a pollutant-specific approach, with each contaminant evaluated independently. The highest value obtained across all pollutants determines the overall grey water footprint for the product or process being assessed. This maximum-based approach ensures that the most limiting pollutant drives the overall assessment, reflecting the ecological reality that ecosystems are often constrained by their most stressed components, although it makes the grey water footprint results very sensitive to the quality standard chosen (Liu et al., 2017). To evaluate the sustainability of water demand, the volumetric approach compares blue and green volumes against corresponding water availability, with explicit consideration of environmental flow requirements necessary for ecosystem functioning. Similarly, the grey water footprint is assessed against the assimilation capacity of the receiving environment, providing a measure of whether pollutant loads exceed the ecosystem's ability to process and neutralize them without degradation.

This approach incorporates an implicit representation of the water cycle by distinguishing between green and blue water, establishing a connection between water origin and use within two distinct hydrological compartments. Furthermore, it offers an innovative method for addressing water quality concerns by translating quality issues into quantitative terms, ultimately enabling the use of a single water quantity indicator that nonetheless captures both quantity and quality dimensions. While maintaining a straightforward conceptual framework accessible to diverse stakeholders, this approach highlights the emerging recognition that water footprint assessments must be rooted within an hydrosystem representation to provide meaningful insights.

The impact-oriented approach builds upon life cycle assessment methodology to evaluate and minimize the impacts of water consumption and use on human health, ecosystems, and natural resources. This approach employs multiple water scarcity factors at both midpoint and endpoint levels to assess the consequences of water use, consumption, and broader alterations to the water cycle (Maeseele et al., 2021). Midpoint indicators represent intermediate environmental impacts and include water deprivation for humans and/or ecosystems, water resource depletion, freshwater eutrophication, freshwater acidification, freshwater ecosystem toxicity, and human toxicity. Endpoint indicators attempt to capture final environmental impacts, typically focusing on damage to human health, ecosystems, and natural resources. If LCA was initially developed for product assessment under an ecological engineering perspective, this methodology was then adapted to assess spatially distributed activities, for instance entire urban water systems or territories (Lemos et al., 2013; Loiseau et al., 2013, 2014). By incorporating a diversity of water quality indicators, the impact-oriented approach underscores the multifaceted nature of water-related impacts. It extends consideration beyond water quality alone to encompass broader impacts on hydrosystems, including quantity-related stresses and ecosystem disruptions. Perhaps most significantly, this approach moves toward establishing causal chains between water cycle alterations, including consumption, use, and indirect actions on water flows and quality, and their ultimate effects on human health, ecosystems, and resources.

This causal chain perspective represents an important advancement in hydrosystem consideration, explicitly acknowledging that water impacts propagate through complex pathways rather than manifesting as simple, direct relationships. This recognition aligns with ecological understanding of hydrosystems as complex, interconnected networks where perturbations can create cascading effects across multiple components and scales.

Advancing water footprint assessment: identifying the gaps in hydrosystem representation

Water footprint assessment methodologies have evolved significantly in recent years, yet several critical gaps persist in how hydrosystems are represented within these frameworks.

These limitations hamper the collective ability to fully understand and accurately quantify human impacts on water resources. By examining these shortcomings, a path toward more comprehensive and effective water footprint methodologies can be charted.

The temporal dimension represents one of the most significant gaps in current water footprint approaches. They have a monthly or annually temporal definition and don't take into account extreme events variability. Moreover, neither of the predominant methods adequately incorporates delayed or long-term environmental impacts. For example, it does not adequately consider the case of water withdrawn from fossil or nearly fossil aquifers and subsequently discharged into river systems after use. While this practice provides immediate benefits to ecosystems and human activities in the short term, it simultaneously contributes to the gradual depletion of crucial aquifer resources that may prove essential during critical periods such as extended droughts (Berger and Finkbeiner, 2012; Pradinaud et al. 2019a; Maeseele et al., 2021). This temporal disparity between immediate benefits and long-term consequences creates a significant gap in our understanding of true water sustainability.

Although water inherently encompasses both quantity and quality dimensions, these aspects are rarely considered in tandem within existing frameworks. Environmental flow requirements, encompassing quality, quantity, and timing of water flows necessary to maintain aquatic ecosystem functions, components, processes, and resilience, lack standardized assessment approaches that would help determine the receiving environment's vulnerability. Assessments tend to prioritize water quantity-induced stress over quality-induced stress, and the crucial impact of pollution on water availability remains largely unaddressed (Gerbens-Leenes et al., 2021; Wang et al., 2021; Pierrat et al., 2023). This aspect is however important, because the degradation of the quality of a water resource can lead to the cessation of its use to avoid impacts on health, and to the exploitation of other water resources, causing increased quantitative pressure on the latter (Pradinaud et al., 2019b, 2019c). For example, between 1980 and 2019, 12 500 drillings of drinking water have been closed in France due to problems of water quality, out of the 35 000 currently exploited (Lambert, 2025).

The cumulative effects of multiple pollution sources represent another significant gap in current methodologies. Few studies account for the combined impact of various pollution sources in receiving environments, particularly the interactive effects between point source and diffuse pollution. Current water footprint approaches typically assess systems individually at single discharge points, without considering the influence of other pollution sources within the same river basin. This isolated approach fails to capture how multiple sources may collectively reduce the degradation and dilution capacities of receiving water bodies. Furthermore, while individual substances might remain within defined threshold concentrations, they can pose significant risks when combined with other substances in the environment, a phenomenon known as the cocktail effect. Additionally, both water footprint approaches focus primarily on commonly monitored pollutants rather than the most critical ones, especially when legal thresholds are absent. Many emerging or unknown contaminants escape environmental and health standards altogether, resulting in their omission from surveillance and monitoring frameworks (Gerbens-Leenes et al., 2021; Wang et al., 2021; Ansorge et al., 2022).

Geographic resolution presents yet another methodological challenge. Though global spatial scales can help identify potential hotspots, they inevitably introduce high uncertainty. Water footprint analyses prove more effective at smaller or local scales, as highly concentrated hotspots significantly influence larger-scale footprints without indicating their specific location or remediation strategies. While smaller analytical units provide more detailed information about local unsustainable practices and enable inter-catchment comparisons, the lack of harmonized approaches makes it difficult to compare water footprint assessments across different geographical levels. In both assessment methods, global hydrological models must be used, despite their limitations. These models have common weaknesses such as limited spatial resolution, calibration realized on large basins, strong assumptions in the location of activities, and they are thus unreliable in small river basins (Pellicer-Martínez and Martínez-Paz, 2016; D'Ambrosio et al., 2020; Berger et al., 2021; Ansorge et al., 2022).

Environmental flow requirement methods also remain largely perfectible. They are based on empirical studies and assumptions and the choice of method can thus have a strong influence on final results in terms of water scarcity. Indeed, the calculation needs to integrate both the influence of location and seasonality on water scarcity, and the local water demand assessment requires the use of global hydrological systems in a global perspective (Hoekstra et al., 2012; Richter and al., 2012; Pastor et al., 2014; Liu et al., 2021).

Finally, existing water footprint approaches remain predominantly focused on direct water consumption and use. However, numerous human activities impact water systems without directly extracting or using water, including soil sealing, energy consumption, physical alterations, and disruptions to hydrological connectivity. Indirect water quality changes resulting from water consumption have yet to be adequately modeled in Life Cycle Assessments (Pradinaud et al., 2019a, 2019b).

Addressing these gaps requires a more holistic approach to water footprint assessment, one that integrates temporal dimensions, combines quantity and quality considerations, accounts for cumulative pollution effects, incorporates emerging contaminants, accounts for spatial dynamics with appropriate geographic scales, and recognizes both direct and indirect impacts on water systems.

Building the framework: core principles for hydrosystem representation in water footprints

Temporal dynamics

Temporal dynamics play a crucial role in understanding the relationship between water use and its impacts on both ecosystems and human health. Far from being static, hydrosystems demonstrate complex temporal patterns that necessitate nuanced approaches to assessment and management. This temporal complexity demands sophisticated and adapted frameworks that can integrate multiple time scales into coherent assessment methodologies.

These differences, from daily to seasonal scales, extend beyond direct biological responses to include variations in hydrosystem dynamics themselves. During summer months, reduced flow rates in many river systems concentrate pollutants and limit dilution capacity, potentially amplifying toxicity. Conversely, autumn/winter conditions may induce different challenges, with rapid flow events potentially mobilizing sediment-bound contaminants that remained sequestered during lower flow periods (see connections with section Extreme events). The transfers of pesticides to the aquatic environment are also well-known to be driven by the combination of the temporality of agricultural practices with climatic seasonality (Weisner et al., 2022; Pesce et al., 2023). Intra-annual changes in ecotoxic contaminants concentration have been evidenced at widescale thanks to the Water framework directive monitoring programs, and associated to the natural hydrological and biological seasonal variations. Dilution effects in rivers or river-connected groundwaters, runoff contributions, but also biological process influencing the contaminants speciation, have been diagnosed as drivers for these variations (Baran et al., 2021; Staub et al., 2024). From the perspective of the receptors exposed to stressors, ecological systems are for instance also governed by intrinsic temporal dynamics such as biological cycles, species phenology, and interaction networks within biocenoses, which leads to evolving patterns of vulnerability to disturbances over time (Coulaud et al., 2014). Additionally, seasonal variations in water temperature can significantly alter the impact or even the toxicity of certain compounds (nutrients, pollutants) through changes in their bioavailability and metabolism within organisms. Cyanobacteria species, whose growth with the elevation of temperature is superior to other algae, can form harmful algae bloom, with possible formation of cyanotoxins. This biomass dies in autumn, causing anoxic conditions. Moreover, the impact of anthropogenic activities on hydrosystems also varies significantly between seasons, creating temporal patterns that must be accounted for in comprehensive assessment frameworks. A compelling example of this seasonal variation is observed in salmon populations, where winter and summer cohorts demonstrate markedly different vulnerabilities to identical pollutant concentrations. Winter salmon may exhibit different physiological responses to contaminants compared to their summer counterparts due to differences in metabolic rates, reproductive status, and environmental conditions such as temperature and dissolved oxygen levels. Moreover, the water demand of both ecosystems and human activities is subject to variabilities. The contaminant inputs in hydrosystems, or water abstraction, exhibit strong seasonality, e.g. in agriculture. Vegetation growth, which takes place in spring and summer, requires water at specific times, often during dry periods. Touristic activities also have a seasonality, with possible local large impacts. Effective water footprint methodologies must therefore incorporate these seasonal patterns, rather than relying on annual averages that obscure critical temporal variations. This might involve developing season-specific thresholds (water extraction or consumption, minimum water flow, maximum concentration of nutrients or pollutants, etc.) that reflect the changing vulnerability of ecosystems throughout the annual cycle or adopting monitoring regimes that capture these temporal dynamics rather than relying on isolated sampling events that may miss crucial seasonal patterns. One example could be with the reuse of wastewater that can be used to ensure a minimum water flow to support low-flow augmentation.

Hydrosystems also exhibit long-term temporal dynamics. This is partly induced by interannual climatic variability and by the storage capacity (infiltration, flow, discharge) of the study area, with “memory” or buffering effects often caused by aquifers or by surface reservoirs, etc. Surface waters often follow an annual hydrological cycle, and some groundwater sources do as well. However, often, groundwater is not recharged annually and exhibits a certain degree of inertia, ranging from multi-annual, decadal, centennial, or even millennial timescales. More frequently still, groundwater resources actually consist of a mix of waters that have infiltrated at various times in the past. Ultimately, these different compartments of a hydrosystem (aquifers, sometimes of multi-layered systems, and surface waters) interact with each other (e.g., streamflow feeding or draining aquifers, upward or downward leakage between aquifers, etc.). Moreover, among the forcing climatic variables of hydrosystems, precipitation is marked by the highest interannual variation. This variability in climate forcing induces interannual variability in the hydrological regimes of rivers and aquifers. Thus, a hydrosystem may, on average, not be very sensitive to a level of anthropogenic pressure, such as a rate of water withdrawal or a contaminant input, but may show a high vulnerability in some extreme years. The interannual hydroclimatic variability over several decades can also influence the footprint: a given water abstraction from a river may have a low footprint nine years out of ten, but a high footprint in the tenth year if it happens to be drier. The same applies to regular discharges. Therefore, the determination of the water footprint should not be based on an average interannual functioning of the hydrosystem or on too narrow temporal window. Instead, it must consider the interannual variability of the hydrosystem dynamics and must rely on a probabilistic approach regarding this variability.

Finally, effects can manifest after extended periods of chronic exposure even without apparent accumulation of the contaminant itself, or an acute pollution event. The impact of trace compounds, for instance, is not solely determined by instantaneous concentration at a specific moment but rather by the integrated effect of exposure over time. This multi-temporal, multi-scale integration of effects necessitates approaches that can account for long-term consequences of even low-level exposures. In human health contexts, exposure to water contaminants may not manifest as clinical symptoms for decades, as demonstrated by the long latency periods associated with many environmental carcinogens. Similarly, in ecological systems, transgenerational effects may emerge long after the initial exposure, with genetic and epigenetic changes potentially altering population dynamics across multiple generations. An example is certain threatened amphibians whose exposure to herbicides in their tadpole stage reduces the incidence of their parasitic diseases, but subsequently leads to increased mortality in their adult stage (Rumschlag and Rohr, 2018). Coming back to the example on salmon populations, the phenological effects due to seasonal variations extend across generations, potentially affecting population dynamics far beyond the immediate exposure period. A growing body of evidence from both wildlife aquatic populations and experimental studies shows that environmental stressors can have adverse effects that extend beyond the directly exposed generations. This time lag between exposure and observable biological effects poses a major challenge for ecological risk assessment frameworks, as delayed impacts can significantly affect the long-term viability of populations in their natural environments (Beckerman et al. 2002; O’Connor and Cooke, 2015). Ecotoxicological research has also increasingly demonstrated that these delayed effects contribute to the persistence or worsening of long-term impacts from chronic contaminations. Moreover, long-term chemical exposure can influence how vulnerable populations are to additional environmental stressors, further complicating risk assessments and management strategies. These delayed impacts necessitate assessment frameworks that extend beyond immediate effects to incorporate longer temporal horizons and future generations. This expanded temporal perspective challenges traditional monitoring approaches based on immediate biological responses and requires innovative methodologies that can establish causal relationships across extended time periods. Biomarkers of exposure and effect may offer partial solutions by providing early warning indicators of potential long-term impacts, but significant methodological challenges remain in establishing definitive linkages between current exposures and future outcomes. The Adverse Outcome Pathway (AOP) framework offers a promising approach by establishing links between exposure and ecotoxicology at the organism level, though significant challenges remain in scaling these insights to entire ecosystems with their complex trophic chains. The goal of AOP is also to connect molecular responses (biomarkers) with ecologically relevant harmful effects, which may provide a solution, although still under development. Long-term impact assessment demands non-reductionist definitions that capture cumulative and interactive effects across multiple temporal scales. Rather than focusing exclusively on instantaneous concentrations or acute responses, comprehensive water footprint assessments must consider chronic exposures, delayed effects, and system-level adaptations that unfold over extended time periods. This expanded temporal perspective aligns with ecological resilience concepts that emphasize dynamic system responses rather than static thresholds.

Extreme events

Beyond seasonal and interannual variations, extreme events whether climatic in nature or related to pollution also represent an essential component that is still insufficiently integrated into water footprint methodologies. In the context of global change, their frequency and intensity are tending to increase, requiring a revision of traditional assessment frameworks. Extreme hydrological events such as floods or droughts have major consequences for both water flows and contaminant fluxes. From a chemical perspective, extreme events often play a key role in determining annual pollutant loads. Floods, for example, can cause massive remobilization of sediment-bound pollutants, sometimes in a single event accounting for a disproportionate share of annual inputs (Crawford et al., 2022). An example is the Saint Martin d'Aigrefeuille mining site, that suffered an extreme climate event in 1976 which led to the rupture of a dam containing mining residues. This led to the spread of fine particles contaminated with arsenic along the Gardons, up until the Mediterranea Sea. These different types of pollution can also lead to the closure of water drill, leading to a ban of drinking water network, for instance in Ledignan at the beginning of 2025, and to an increase in quantitative pressure on uncontaminated resources. Other terrigenous biological pollutions can impact human activities: mineral waters for Perrier, oyster farming in local lagoons (Thau), or swimming prohibited in beaches. This is also the case for dissolved contaminants, considering the contribution of wet-weather runoff from impervious surfaces, or of the by-passed untreated wastewater overflows. Acute pollution associated with the temporary overload of wastewater treatment plants (e.g., bypasses during heavy rainfall) must also be considered. Conversely, prolonged droughts, which are increasingly frequent in regions such as southeastern France, reduce dilution capacity and increase contaminant concentrations (Lentz et al., 2024).

Beyond physico-chemical impacts, these extreme events influence the ecological dynamics of aquatic ecosystems. Their effects vary depending on their frequency and intensity. Rare but catastrophic episodes can cause the local collapse of biological populations by exceeding ecosystem resilience thresholds and durably altering their structure and functioning. Conversely, more moderate but repeated events may play a dual role: when they remain within the limits of the system's natural variability, they can maintain habitat heterogeneity and enhance resilience (Jones et al., 2013). But beyond a certain threshold of frequency or duration, they may become a chronic pressure, limiting recovery capacity. The intermittence of watercourses, for example, fundamentally alters ecological processes (Datry et al., 2014). Related concepts, such as ecological flow requirements (the minimum daily flow needed to maintain ecological integrity) highlight the vulnerability of ecosystems linked to water scarcity. Landscape connectivity further complicates the assessment of the impacts of extreme events, as it influences the potential for recolonization after localized extinction events. In highly connected systems, organisms can rapidly recolonize affected areas from adjacent refuges, potentially justifying higher acute tolerance thresholds. However, regulatory frameworks such as the Water Framework Directive generally reject approaches that accept mortality events, even when ecological recovery is theoretically possible. This creates a tension between the concepts of ecological resilience and regulatory compliance objectives, which deserves particular attention in the development of water footprints.

From hydrological, chemical, and microbiological perspectives, current regulatory frameworks such as the WFD, which are mainly based on average values or maximum point values, do not enable the detection of the frequency, duration, or magnitude of extreme events, largely due to sampling that is too infrequent over time (monthly monitoring frequency). A more robust and representative water footprint should explicitly integrate these events through indicators sensitive to the frequency, magnitude, and duration of threshold exceedances, as well as critical thresholds contextualized according to the local hydrological regime.

Spatial dynamics

Properly addressing hydrosystem-mediated challenges requires clearly defining the relevant spatial domains of these water systems and identifying key stakeholders. Unlike carbon dioxide emissions that operate globally with long atmospheric residence times, water pollution issues demand scale-appropriate approaches that recognize hydrosystems as critical vectors between human activities and ecological impacts. Hydrosystems operate across multiple spatial scales, from the pore scale (biogeochemical processes), to the stream/wetland and hillslope/watershed scales (hydrological processes), up to the regional or territorial scale (the scale of decision-making) (Abbott et al., 2016). For example, surface water systems might require management at watershed scales, while groundwater systems might need approaches aligned with aquifer boundaries that often cross administrative jurisdictions.

Hydrosystems create teleconnections that link distant regions through hydrological flows, economic relationships, and ecological processes. As mediating systems, they create interdependencies through their transfers across regions and borders. These connections can be physical, as when pollutants travel through interconnected water bodies or are deposited via atmospheric fallout, or socioeconomic, as when water-intensive production and consumption take place in different locations. Addressing these complexities requires governance structures supported by scientific representations that effectively capture how hydrosystems mediate interactions across spatial scales, from local to regional and global dynamics. For example, the initial conceptual model developed for a site (particularly regarding its hydrological functioning, such as whether it is groundwater-dominated) plays a crucial role, and is closely linked to the choice of measurement and modeling methods. Moreover, when pollution enters hydrosystems, its impacts go beyond local boundaries and become globalized through various transport mechanisms. This dual nature of pollution, being both territorially specific and globally influential, necessitates translating planetary boundaries into localized limits that communities can meaningfully engage with. By contextualizing global environmental thresholds within local hydrological realities, we make abstract concepts actionable for regional water management. Thus, water footprint assessments must integrate these multi-scale interactions and teleconnections to provide meaningful assessments that bridge local hydrological realities with global environmental thresholds. This requires developing methodologies that can simultaneously capture site-specific hydrosystem functioning while accounting for broader regional and planetary boundary constraints.

Upstream-downstream dynamics exemplify how hydrosystems mediate territorial challenges. For example, groundwater flows can be "nested" at multiple scales (local, intermediate, and regional) in hierarchical patterns described by Tóth's model. Another example is the intermittency of streams, with the expansion or contraction of the river network from downstream to upstream, illustrating strong surface-groundwater connections. Economic value is frequently captured upstream while negative environmental effects are exported downstream through the connecting medium of water. For instance, the anoxic conditions affecting aquatic ecosystems near Bordeaux demonstrate how upstream agricultural and industrial activities can lead to oxygen depletion downstream, resulting in significant fish mortality. An integrated approach to the land-sea continuum, encompassing river basins, port areas, and lagoons, would be valuable in order to better characterize the fluxes of contaminants and sediments from upstream watersheds to coastal environments, and thus prioritize sources of pressure to guide management actions. For example, the contribution of river basins to port and lagoon areas have rarely been studied. Until now, these zones have mostly been considered as independent entities, primarily in relation to their internal activities (boat maintenance, nautical tourism, marinas), without quantifying the share of inputs from upstream catchments. However, these inputs (particularly suspended matter potentially loaded with contaminants) can significantly contribute to the degradation of water quality in both port environments and coastal lagoons. Quantitative management of water resources shared between different countries requires international cooperation (such as the management of water quality for the Rhine and Danube), but it can also cause geopolitical tensions, as Tigris and Euphrate basins or Brahmaputra River. Hydrosystems thus function as both conveyors of wealth and impacts, and can be themselves affected ecosystems, a triple role that must be taken into account by the water footprint assessments.

Beyond the spatial dependencies that govern the interrelations between processes and impacts outlined in water footprint frameworks, the significant spatial heterogeneity of socio-environmental conditions across hydrosystems must be considered. Climatic, geological, geographical, and biogeographical contexts strongly influence the magnitude and dynamics of transfers (e.g., topography, groundwater–river exchanges), the exposure to stressors (e.g., ecological refuges, contaminant bioavailability), and the vulnerability of targets (e.g., trophic conditions of organisms, species reservoirs, population status, economic dependence, etc.). It has thus become essential to explicitly account for regional specificities, or implicitly for the spatial heterogeneity, of the factors influencing exposure and impact patterns that underpin the concept of the water footprint of anthropogenic activities on hydrosystems. This territorialization has already been well developed within the framework of Life Cycle Assessment for water scarcity across geographic zones, taking into account variations in the needs of both societies and ecosystems (Boulay et al., 2017). Extending this approach of contextual specification to processes identified as key in the transfer of stressors, exposure, and the vulnerability of targets would offer significant benefits.

Interaction and accumulation of stressors

Interactions between pollutants, commonly referred to as "cocktail effects" have emerged as a significant concern in contemporary water quality management. These interactions extend beyond the simple additive effects of individual pollutants to include synergistic or antagonistic relationships that can fundamentally alter toxicity profiles. The probability of co-location of these substances, influenced by the spatial arrangement and timing of activities within catchments, further complicates assessment efforts. Water footprint assessments don't take into account these cocktail effects and simply adds the individual potential effects of each individual substances. Other risk evaluation approaches, such as the Mixture Allocation Factor, attempt to account for these interactive effects by incorporating weighting factors that adjust regulatory standards in multi-contaminated environments (Drakvik et al., 2020; Treu et al., 2024). These approaches recognize that the ambient mixture of contaminants can significantly modify and often intensify the impacts of individual substance on the organisms, necessitating more stringent standards in highly contaminated contexts. In risk assessment, the cumulative effects of toxic impacts from micropollutant mixtures can also be analyzed at the level of ecological communities, using approaches such as msPAF (multi-substance Potentially Affected Fraction of species) (Posthuma et al., 2019). This allows for a direct link to be made with the endpoints used in LCA (Zijp et al., 2014; Owsianiak et al., 2023). Today, through the combination of these predictive approaches and ecological monitoring data, it is increasingly recognized in the field of environmental surveillance that accounting for cumulative effects using multi-substance indicators provides a more accurate understanding of the actual impacts of chemical toxic pressure on aquatic biological communities (Oginah et al., 2025).

Nevertheless, the assessment of the water footprint related to micropollutant toxicity is based mainly on comparing environmental concentration data to toxicity thresholds for a limited number of substances. This approach can be applied spatially and enables the definition of the chemical footprint associated with various anthropogenic sources within river networks, provided that contaminant transfer pathways are known (Posthuma et al., 2018). However, this "substance-centered" risk assessment only considers a very small fraction of the total toxic compounds present in aquatic environments, given the diversity of released substances and their possible transformation processes, for which toxicity thresholds are often unknown (Brack et al., 2019). This predictive assessment strategy also tends to overlook bioavailability processes and the combined effects of these substances in mixtures. In this context, it has long been proposed to complement chemical monitoring with biological methods that integrate the effects of all present substances (Chapman, 1990). The assessment of ecological status through the study of aquatic community structures - a holistic approach - can be supplemented by examining organism-level (biomarkers, bioassays) or molecular-level (omics) responses to identify the specific effects of chemical contamination and to help determine the sources of degradation responsible for ecological disturbances (Milinkovitch et al., 2019). As a result, increasing interest is now being directed toward effect-based tools (bioanalytical approaches, biomarker-based methods, active biomonitoring), which, alongside predictive approaches, provide in situ evidence of chemical quality degradation and the overall toxic impact on water quality (Wernersson et al., 2015). Thus the water footprint must evolve beyond substance-specific toxicity assessments to incorporate effect-based tools that provide holistic evidence of chemical impacts on ecosystem health. Such integration would better represent the complex reality of multiple contaminant interactions and their cumulative effects on hydrosystem functioning.

Accumulation also represents a fundamental characteristic of water-based pollution, as contaminants progressively build up along flow pathways throughout the water cycle. This spatial accumulation creates gradients of impact that intensify as water moves downstream, making the position within a watershed a critical determinant of exposure. This issue has been known for at least 25 years (Kennet, 1999), and never operationally addressed at a proper dimension. The assessment of water footprints must therefore account for these cumulative effects that can transform seemingly insignificant individual contributions into collectively substantial impacts as they concentrate through hydrological processes.

Emerging stressors

Among the pollutants of concern, we can distinguish two classes: legacy pollutants and emerging contaminants. The term legacy pollutants often refers to persistent, bioaccumulative, and toxic substances (e.g., heavy metals, polycyclic aromatic hydrocarbons, dioxins, etc.). These pollutants are regulated (REACH, Stockholm Convention) and are, for the most part, subject to mandatory monitoring at the European level, notably under the lists of priority substances and priority hazardous substances of the Water Framework Directive (Directive 2013/39/EU) and the Groundwater Directive (Directive 2006/118/EC). The term emerging contaminant refers to synthetic or natural chemical substances (and their environmental transformation products) and microorganisms (e.g., vectors of antibiotic resistance) whose presence in the environment is of concern and which are, to date, not or only minimally regulated and thus not or only rarely monitored (e.g., pharmaceuticals, PFAS, etc.). Although some of them are included in watch lists (for example, at the European level, the Water Framework Directive recently published a new watch list: Commission Implementing Decision (EU) 2025/439), their inclusion in regulations remains limited. Yet these compounds are indeed present in aquatic environments (Rodriguez-Mozaz et al., 2015; Wilkinson et al., 2017; Morin-Crini et al., 2022;) and are of concern due to i) their physico-chemical properties making them persistent and mobile in aquatic systems and often poorly removable by treatment plants and ii) their potential effects on ecosystems and, ultimately, on human health (Lei et al., 2015; Pereira et al., 2015; Hale et al., 2020).

The main challenge in integrating these contaminants into a water footprint lies in the wide diversity of substances in circulation, not to mention environmental transformation products or specific issues such as antibiotic resistance. This complexity makes it difficult to achieve a robust qualitative or quantitative characterization of a water footprint, particularly when the chemical structures of certain substances are unknown. Advanced analytical approaches (e.g., suspect screening and non-target screening using mass spectrometry, Schymanski et al., 2015) allow exploration of the environmental chemical exposome, but their technical complexity, cost, and interpretation challenges currently limit their large-scale application within water footprint methodologies. In parallel, effect-based approaches (Brack et al., 2019) are being developed to assess the status of aquatic environments, but they do not yet allow identification of the substances responsible for the observed alterations or attribution of specific pressures to human activities. However, breakthrough approaches in ecotoxicology, leveraging the latest advances in environmental omics, are now revolutionizing our ability to detect the specific toxic impacts of emerging contaminants. These approaches make it possible to study how environmental species modulate their transcriptomes, proteomes, or metabolomes in response to exposure (Wernersson et al., 2015). As a result, with limited number of simple and operational tools, it remains difficult to translate these emerging contaminations into synthetic indicators that can be directly used to quantify and compare the water footprints of different uses or regions. Nevertheless, the convergence of advanced analytical methods, effect-based approaches, and computational advances presents opportunities to develop water footprint indicators that can capture the full spectrum of stressors while remaining operationally feasible for stakeholders and decision-makers.

Link between footprint and fingerprint

Developing efficient and realistic assessment frameworks requires distinguishing between fingerprint indicators for exposure to specific sources or stressors and footprint indicators that capture impacts across multiple scales. The exposure trajectory concept emphasizes keeping characterization as precise as possible while acknowledging the challenges of long-term exposure effects. Drawing parallels from cancer epidemiology, this approach recognizes that impacts may result from the accumulation of effects over time rather than from elevated concentrations at any single moment, a perspective particularly relevant for trace contaminants with subtle but persistent influences on ecosystem health. Moreover, the reversibility of impacts represents a critical consideration, some contaminants may cause permanent organ damage during brief exposure spikes, while others produce more transient effects that recover once concentrations return to baseline levels. The pesticide assessment paradigm explicitly considers this distinction, evaluating both acute and chronic exposure scenarios. Thanks to fingerprinting approaches, which are now feasible by leveraging non-targeted chemical analyses, environmental omics tools, or high-resolution environmental sensors, there is a growing possibility to develop strategies that can define, within a given context (e.g., identified source, specific protection goal or endpoint), specific tracers of the spatial or temporal influence of a pollution source. This can follow two main approaches: a data-driven strategy, moving from broad-spectrum data toward targeted measurements, or a hypothesis-driven strategy, based on prior knowledge from existing databases. This calls for a reflection on the possibility of defining simple, robust proxy measurements that may differ in nature from those directly targeting a specific quality element or evaluated process (e.g., electric conductivity *versus* measurement of micropollutants downstream of a discharge). These proxy measures would provide access to key dimensions of the environmental footprint in a given context and would enable high-resolution spatial and temporal characterization of the dynamics linking sources and impacts at various scales. The ultimate goal is not merely to trace degradation sources for their own sake, but to assess, through different proxy measurements, the footprint of these sources, or of the alteration of processes that affect one or more dimensions of environmental quality. This involves combining indicators of pressure presence with indicators of impact. Provided that large-scale datasets are available, capturing all relevant aspects of the state and dynamics of a hydrosystem, data science approaches could be used in the near future to establish these links. Coupled with modeling approaches for causal pathways, which may extend beyond toxicology alone, this improved understanding of source-impact relationships at multiple scales can be integrated into dynamic modeling frameworks or Bayesian interaction networks. This represents a critical pathway for transforming water footprint methodologies from simple consumption metrics to sophisticated assessment tools that can trace and predict the environmental consequences of water use patterns through comprehensive fingerprinting and impact evaluation across hydrosystem scales.

Indirect impacts

One of the key challenges in current water footprint assessment frameworks is the need to move beyond relatively linear and disconnected adverse effect pathways from stressors to midpoints, which are ill-suited to capturing the complexity of hydrosystem dynamics and the highly interwoven nature of impact pathways leading to selected endpoints. Assessing the water footprint (more precisely, the impacts on ecosystems, human health, or resource availability) must indeed be conducted within a multistress, multiscale, and multi-endpoint (multicriteria) framework. Water should be simultaneously considered as a resource (e.g., drinking water, irrigation, and industry), a vector (e.g., transporting contaminants), a habitat (supporting ecosystem services and biodiversity), and, more broadly, a mirror of systemic health, reflecting cumulative environmental pressures.

Adopting a framework based on a functional representation of the hydrosystem allows for a more integrated understanding of the links between water quantity, water quality, and human/environmental health - aligning with *eco-health* and *One Health* paradigms. Cross-cutting challenges such as cumulative impacts, threshold effects, and system vulnerability require integrated, holistic approaches. Thinking in terms of impact on integrated levels of organization (e.g. ecological communities), which can align with selected endpoints in footprint assessment exercises (Owsianiak et al., 2023), already makes it possible to compare and aggregate impacts from stressors of different nature. Multi-substance impact models at the ecological community level have already demonstrated their ability to integrate, for example, the toxic effects of micropollutants alongside the impacts of degraded physico-chemical conditions, hydrological changes, habitat alterations, and thermal stress (de Zwart et al., 2006; Posthuma et al., 2016; Lemm et al., 2020). Integrating multiple dimensions into a unified environmental assessment framework and adopting multidimensional monitoring approaches should allow to account for non-linear responses, synergies between stressors, and both direct and indirect effects of stressors from various origins.

Various approaches, drawing either from Adverse Outcome Pathway (AOP) frameworks (originally developed in toxicology and chemical risk assessment but adapted here to the ecosystem scale (Mentzel et al., 2023) and/or from pressure-impact modeling frameworks (Villeneuve et al. 2018; Sarkis et al., 2021), are now enabling the conceptualization of key driving processes and interdependencies between stressors of different types and dynamics across multiple scales, within simplified functional schematics of hydrosystems. These effect pathway diagrams are most often built using expert knowledge, but could increasingly be constructed using data-driven approaches in the era of artificial intelligence, for example, through proposed eco-epidemiological frameworks for aquatic systems (Kapo et al., 2014). Such schematics inherently integrate processes and disturbances of varying natures and can serve as a basis for the parameterization of statistical models (e.g., Bayesian networks) that quantify the interrelations and both direct and indirect impacts of stressors, mediated by the processes represented (e.g., climate change and pesticides) (Piffady et al., 2021; Mentzel et al., 2023). These process-based modeling approaches provide tools that can be used in scenario-building exercises, allowing for the calculation of water footprints and the design of management trajectories. These trajectories account for interdependencies and the cascading effects of stressors, aiming toward the conservation or restoration of hydrosystem health.

Water quantity and quality

Effective water management increasingly requires an integrated understanding of the complex interactions between water quantity and quality across various environmental compartments. Current practices, models, and regulatory frameworks often treat these dimensions separately, despite growing evidence that their interdependence is central to addressing emerging challenges in hydrological and ecological sustainability. A major challenge lies in developing quantitative approaches that explicitly link water quantity and quality within hydrosystems, accounting for natural processes, anthropogenic pressures, and evolving climate conditions. This necessitates a paradigm shift toward integrated models that couple hydrological, biogeochemical, and socio-environmental processes. In particular, indicators capable of revealing and quantifying the relationships between water quantity and quality are urgently needed to support decision-making and policy development. Another pressing need is improving the interoperability of water-related data across environmental compartments (such as surface water, groundwater, soils, and the atmosphere) as well as between different types of data (e.g., physical, chemical, biological). This includes advancing the FAIR (Findable, Accessible, Interoperable, Reusable) principles for all water-related datasets to facilitate cross-disciplinary research and collaborative water management strategies.

A critical knowledge gap concerns the role of environmental interfaces, such as the hyporheic zone, as dynamic hydro-biogeochemical reactors that regulate both the quantity and quality of water. The impact of these interfacial zones on water quantity-quality relationships remains poorly quantified. Understanding the evolution of such processes and their responses to external forcing (including land use, water abstraction, and pollutant inputs) is essential. Human activities not only influence but are also affected by changes in water quality and quantity. However, the feedback mechanisms between human behavior and hydro-biogeochemical processes remain insufficiently characterized. These interactions are often non-linear, scale-dependent, and spatially heterogeneous. For instance, the effects of anthropogenic forcing may propagate within a specific environmental compartment or extend across different compartments of a watershed, or even between distinct watersheds, depending on connectivity and system sensitivity. For example, when water quality deteriorates, abstraction may be shifted to alternative sources, placing additional pressure on already scarce resources. In the Bordeaux metropolitan area, a groundwater extraction site located near a river experienced several contamination events of urban and industrial origin between 2009 and 2019 (e.g., Cousquer et al., 2019). Some contaminants were introduced directly into the aquifer, while others reached it via surface pathways. The exploited aquifer is hydraulically connected to the adjacent river, with predominant flow from the river toward the aquifer. In response to these pollution events, the water operator implemented protective measures, which resulted in the suspension of over 14 million cubic meters of groundwater extraction over a 10-year period. This lost volume had to be compensated by increased withdrawals from other water sources, in a region already under pressure regarding water availability. In addition, changes in water and soil quality can alter surface runoff patterns and drive land use changes, for example the conversion of forests or meadows with high water quality to conventional agricultural land. Such transitions can degrade water quality further and modify hydrological pathways, including increased surface runoff and pollutant transport.

The impact of water quantity on water quality is mediated through a variety of physical, chemical, and biological processes. For example, floods can mobilize and leach contaminants and pesticides into aquatic systems, while drought conditions often lead to the concentration of chemical elements due to reduced dilution capacity (Kragh et al., 2020; Graham et al., 2024). In lake systems, water volume plays a critical role in regulating both chemical and biological dynamics. Inflows, outflows, and internal storage influence nutrient cycling, while nutrients delivered by rivers can accumulate in sediments and contribute to internal loading, potentially sustaining algal blooms even after external inputs have declined. Water level fluctuations also affect phytoplankton dynamics and the stability of the water column, often creating favorable conditions for the proliferation of cyanobacteria. Climate change and extreme weather events further exacerbate these interactions. At Lake Filsø, for instance, alternating periods of drought and intense rainfall have triggered episodes of oxygen depletion and mass fish mortality, linked to the sudden influx of labile organic carbon and subsequent microbial oxygen consumption (Kann and Walker, 2020; Yin et al., 2024). Similarly, reduced water availability caused by drought or excessive abstraction can impair the biotransformation functions of aquatic vegetation, compromising ecosystem resilience. More broadly, changes in water quantity directly influence the provision of aquatic ecosystem services, including water purification, habitat maintenance, and nutrient regulation (Mitsch et al., 2015). In groundwater systems, overexploitation can lead to a degradation of water quality. Excessive abstraction from aquifers may reduce dilution capacity, reverse hydraulic gradients, and facilitate the intrusion of lower-quality water from surface or overlying sources. A welldocumented example is the salinization of coastal aquifers under high extraction pressures (Werner et al., 2013). In the Gironde region, the Oligocene aquifer is a key resource for drinking water, with 65 million cubic meters extracted in 2021. Although current management practices have stabilized the system, past overuse led to flow reversals and partial dewatering, which may have impacted water quality (Loiseau et al., 2009; Zektser et al., 2005). These changes have been associated with reduced groundwater contributions to surface waters, increased risk of contamination, and disruption of the aquifer's physico-chemical equilibrium, manifesting in processes such as mineral leaching, iron oxidation, microbial activity, and the cessation of natural denitrification.

Addressing these challenges requires an interdisciplinary approach that brings together hydrology, geochemistry, ecology, data science, and social sciences. Only by integrating dynamic processes, human influences, and interoperable data can we develop robust, predictive frameworks for sustainable water resource management in a rapidly changing world. Conventional approaches to water footprint assessments often overlook the complex interactions between water quality and quantity that are critical for sustainable water resource management. To address this gap, an integrated water footprint framework that jointly accounts for water quantity and quality and their dynamic interdependencies across the aquatic environment is necessary. This integrated approach begins with the systematic identification of aquatic compartments, encompassing all regions through which water flows, including surface waters (rivers, lakes), subsurface reservoirs (soil, groundwater), and transitional interfaces (e.g., hyporheic and vadose zones). Within these compartments, particular attention is paid to reactive interfaces, or "environmental reactors," where key hydro-biogeochemical processes occur. These reactors are characterized by the processes they host, which can affect either water quantity (e.g., infiltration, evaporation, abstraction) or quality (e.g., microbial transformation, geochemical reactions, pollutant retention/release). An important aspect of this framework involves the weighting of dominant processes within each reactor. Such weighting enables prioritization based on environmental events or scenarios, for example, in cases where an extreme event (e.g., drought or flood) compromises the function of a given reactor. Furthermore, the framework emphasizes the analysis of interactions between compartments, with a focus on identifying propagation pathways. This includes determining which processes in one compartment influence those in another, either directly or indirectly, and whether such effects remain localized or extend across watershed boundaries. These interactions may lead to cascading impacts that must be accounted for in both footprint and management strategies (e.g. Macias et al., 2025). A critical component of this approach is the identification of tipping points such as glacier retreat, river drying, or the collapse of microbial ecosystem functions, that signal thresholds beyond which the system may undergo irreversible change. Integrating these thresholds into the water footprint/fingerprint concept is essential to ensure that management strategies are not only reactive but also anticipatory (e.g. Büttner et al. 2022). An integrated framework should thus provide a comprehensive, process-based perspective on water resources, supporting the development of diagnostic tools that reflect both the quantity and quality dimensions of water.

Building the framework: balancing complexity and building on existing practices

Ensuring practicability

In developing a water footprint that encompasses hydrosystems as mediators, we face a fundamental challenge of determining the appropriate level of complexity in our models. The principle of "representation as advanced as possible, but no more than necessary" guides our approach to characterize the relationships between human activities, water cycle modifications, and their resulting impacts. This balanced perspective helps us avoid both oversimplification that obscures critical dynamics and unnecessary complexity that hinders practical application.

In developing frameworks that position hydrosystems as mediators, we must strike a balance between scientific rigor and practical utility. Models that are too simplistic may miss critical mediation pathways and lead to misguided decisions, while excessively complex representations may create barriers to implementation through data requirements and computational demands. The appropriate level of complexity depends on the decision context, available data, and the significance of the mediating processes being assessed. The boundaries of our modelling efforts, determining how comprehensively we should describe, characterize, and model hydrological processes to meaningfully connect anthropic activities, including water use, to their multifaceted consequences, should be carefully defined. These consequences manifest across multiple scales, from localized flooding events to far-reaching effects on human health and ecosystem integrity. The optimal level of detail depends on the specific questions being addressed and the decisions our analyses aim to inform.

In the realm of water resource management, there is a growing recognition of the need to shift towards an efficient non-reductionist approach when defining water footprints. This approach avoids oversimplifying the intricate relationships between human activities and ecosystems by acknowledging the complex web of interactions that characterize hydrosystems. A non-reductionist perspective is not merely about using aggregated indicators; rather, it emphasizes the inclusion of diverse indicators that can effectively capture the multiple interactions resulting from both accumulation processes and dynamic interactions within water systems. Moving beyond reductionist approaches to impact definition requires engaging with ecological concepts that capture system-level responses to anthropogenic pressures.

Derived from ecosystem services, Rapport et al, 1999 and then Costanza et al., 1992 have developed the concept of ecosystem health as a healthy ecosystem who is “active, maintains its organization and autonomy over time, and is resilient to stress”. However, this proposition remains anthropocentric. Karr has thus proposed the concept of river health, centered on ecosystems and their relations with humans, and introduced the term of ecological integrity (structural and functional) as an important dimension of river health. In this framework, the choice of indicators produces a diagnosis, but provide useful information to determine the causes of a health state.

Moreover, the OneHealth and EcoHealth paradigms offer promising frameworks for conceptualizing impacts in more integrated ways, recognizing the interconnectedness of human, animal, and ecosystem health. These approaches challenge traditional siloed perspectives that separate human and environmental impacts, instead emphasizing their fundamental interdependence.

This integrative perspective necessitates reconsideration of typical life cycle assessment (LCA) approaches that often compartmentalize impacts into discrete categories. The question remains whether water footprint methodologies should adopt more complex endpoint modelling that explicitly connects environmental and human health outcomes, or whether simpler approaches might prove more practical for implementation. While theoretical arguments support more comprehensive endpoint integration, practical considerations regarding data requirements and methodological complexity may favor more focused approaches in certain contexts.

Existing knowledge and practices

Practical implementation of water footprint approaches must leverage existing operational measurements rather than creating entirely new monitoring systems. The considerable data already collected under frameworks like the Water Framework Directive or health monitoring systems represents a valuable resource that can be repurposed for footprint assessment with appropriate methodological adaptations. This integration requires rethinking deployment strategies for water footprint monitoring, actively involving field practitioners already engaged in long-term observation and trend surveillance. These practitioners bring valuable contextual knowledge and practical experience that can enhance the relevance and feasibility of monitoring approaches. Their involvement also creates natural pathways for knowledge transfer and capacity building, increasing the likelihood of sustained implementation beyond initial project periods.

The foundation of any robust water footprint assessment lies in comprehensive, well-structured databases that can support various analytical needs. These databases must integrate diverse data types, including chemical parameters, hydrological measurements, biomarkers, biological indicators, and land use and pressure information across multiple spatial and temporal scales. While extensive data collection is technically possible, practical constraints necessitate strategic approaches to data management that balance comprehensiveness with accessibility. The development of interoperable database systems enables efficient data sharing between different stakeholders and applications, reducing redundancy and enhancing analytical capabilities. Modern database technologies offer opportunities for incorporating both structured and unstructured data, including real-time monitoring outputs, remote sensing observations, and citizen science contributions. These diverse data streams, when properly integrated, can provide more comprehensive views of hydrosystem conditions than traditional monitoring approaches alone.

Modelling represents a critical bridge between raw data and actionable insights in water footprint assessment. Effective models must integrate our scientific understanding of hydrosystem processes while remaining tractable for practical application. The USEtox model provides an instructive example, offering separate but interconnected modules for human health and ecosystem impacts that maintain scientific validity while providing operational simplicity. When developing modelling frameworks, particular attention must be paid to parameter selection and weighting. These choices fundamentally shape assessment outcomes and should reflect both scientific understanding and stakeholder priorities. The challenge lies in finding appropriate balance points that capture essential system dynamics without overwhelming users with excessive complexity or data requirements. This might involve hierarchical approaches that allow for simpler assessments in data-limited contexts, while enabling more sophisticated analyses when additional information becomes available. The most successful modelling frameworks are designed with end-users in mind, offering modular structures that allow for customization based on specific application contexts. This optionality ensures that the same fundamental framework can be deployed across diverse contexts, from rapid screening assessments to detailed regulatory analyses, without requiring entirely different methodological approaches for each application.

Theory must be grounded in real-world application to ensure practical relevance. Pilot site demonstrations serve as critical testing grounds for new methodological approaches, allowing for refinement before broader implementation. These sites should represent diverse hydrosystem types, anthropogenic pressure patterns, and management contexts to ensure broad applicability of the resulting frameworks. Selected pilot sites should enable comprehensive testing of methodological approaches. Ideal pilot sites would have rich existing datasets that can be leveraged for initial assessment, clearly defined management challenges that water footprint approaches could address, and engaged stakeholder communities willing to participate in framework development and testing. The pilot site approach facilitates iterative development cycles, where methodological frameworks are progressively refined based on practical implementation experiences. This iterative development process helps identify unforeseen challenges, data gaps, and interpretation difficulties that might not emerge from theoretical development alone. By documenting these implementation experiences, future applications can benefit from accumulated practical wisdom rather than repeating similar challenges. These sites may be designed as living labs, ie "user-centred open innovation ecosystems based on a systematic user co-creation approach, integrating research and innovation processes in real-life communities and settings".

Facing a changing world, with many uncertainties, classical linear predictive approaches are unusable. Other approaches must be developed, in order to codesign, constructure desirable futures. Narrative foresights or storyline approaches offer a promising framework for scenario planning, allowing the exploration of multiple plausible futures rather than relying on single predictions. These narrative-based scenarios can integrate diverse factors including climate change projections, technological developments, policy evolutions, and societal transformations into coherent futures that support robust decision-making. By considering multiple storylines, water footprint assessments can identify management strategies that perform well across a range of possible futures rather than optimizing for a single predicted outcome.

Conclusion

The water footprint is currently used to assess the impact of processes, products, and companies or industries on water resources. Addressing the limitations outlined in this article would not only improve the evaluation of these impacts but also directly support the management of hydrosystem evolution. Long-term and delayed impacts of human activities or extreme events on hydrosystems, various forms of pollution and their "cocktail effects," as well as the interconnections between water quantity and quality, all need to be assessed to determine a hydrosystem's adaptability and long-term sustainability. In turn, the evolution and characterization of a hydrosystem can influence how a water footprint is determined. Indeed, as previously mentioned, there is a direct relationship between the state and sensitivity of a hydrosystem and the magnitude of pressure it can withstand. Therefore, both the characterization and management of hydrosystems are essential for establishing a comprehensive water footprint, and vice versa.

Additionally, the way hydrosystems are represented extends beyond measurable biophysical parameters; it also encompasses how we, as humans, perceive and relate to them. This perception can be limited (for example, judging water quality by its color, which is not always a reliable indicator, or failing to recognize the ecological role of wood in rivers, which is natural but often absent and misunderstood in large rivers). On the contrary, incorporating the knowledge and memories of local inhabitants is also crucial for understanding the functioning and richness of a hydrosystem. These human representations (perception, knowledge) can influence how we assess a hydrosystem's condition, potentially leading to over- or underestimation of the pressures it faces. Co-constructing hydrosystem management and sharing knowledge inclusively could thus contribute to the evolution of the water footprint concept itself.

Throughout all stages of water footprint assessment, a fundamental imperative remains: maintaining and reinforcing the connection between water uses and their corresponding impacts, as is already established in current frameworks. Caution must be exercised not to weaken this essential connection by introducing representations that are currently obscured or incompletely visible. Instead, the goal should be to enhance the connections and exchanges among stakeholders involved in water management and assessment. Furthermore, natural and anthropogenic water cycles should be interconnected, and integrate the cycle of elements including contaminants and all agents that may affect the holistic concept of one-health, into the comprehensive understanding of water systems. The link between social hydrology and the water footprint provides a more comprehensive understanding of water-related issues, taking into account social dynamics of the relationship between water and human societies.

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