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Aquatic ecosystem indices, linking ecosystem health to human health risks

Fanny G. De Carvalho¹ · Adeline Loyau¹ · Michelle Kelly-Irving² · Dirk S. Schmeller¹

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Abstract

The good functioning of aquatic ecosystems is essential for providing diverse ecosystem services that benefit humans. The degradation of ecosystem health due to continuous stressors, such as climate change or water pollution, is leading to an increase in human health risks and well-being. Indicators have been developed to determine human health risks from recreational and drinking water. Still, a general application to aquatic ecosystems linking ecosystem health and human health risks has not been done. We here reviewed indicators and indices applied to assess the health of aquatic ecosystems and their links with human health risk and well-being. We evaluated the extent to which indicators can witness a risk to human health and well-being. A total of 245 articles were reviewed, consisting of 185 on the assessment of aquatic ecosystem health and 60 linking ecosystem health and human health or well-being. Out of the 65 indices described, we evaluated the use of several parameters and their relevance to evaluate human health risks, including physico-chemical parameters, bioindicators, contaminants, and pathogens, therefore covering the various sources of ecosystem disturbance. Based on our assessment, we propose a set of indicators that would allow for the inclusion of risks for human health and well-being in the assessment of ecosystem health (e.g. coliforms, algae, pH, nutrients, chemical compounds, and ecosystem services). Measuring these parameters should be incorporated into future studies to allow an understanding of the linkage of ecosystem and human health.

Keywords Aquatic freshwater ecosystems · Health assessment · Health indicators · Human health

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Introduction

Humanity is an integral part of the global life-support system. This system provides many different resources and services, named ecosystem services, without which the existence of any life would be impossible. Ecosystem services represent all outputs or processes provided by an ecosystem that directly or indirectly benefit humans, most prominently clean air and drinking water (Millennium Ecosystem Assessment 2005). They are classified into four categories: provisioning, regulating, supporting, and cultural ecosystem services. These ecosystem services depend on the good functioning of ecosystems, which in turn is the result of the rich interactions between species, as well as between species and their environments. Simply said, ecosystem functioning and the resulting ecosystem services depend primarily on biodiversity (Hooper et al. 2005; Le Provost et al. 2023). The different health concepts EcoHealth, OneHealth, and Planetary Health (Lerner and Berg 2017), all suggest that biodiversity loss will lead to a degradation in ecosystem services which in turn will lead to increased health risks for humans, livestock, and wildlife (Schmeller et al. 2020).

Pressures on ecosystems from stressors such as chemical pollution, habitat destruction, climate change, and introduced harmful species have constantly increased over the past decades. The series of Scientists' Warnings all outline the consequences of those pressures on the global life-support system (Cavicchioli et al. 2019; Ripple et al. 2017; 2021; Schmeller et al. 2022). Some studies reported on the effects of water pollution on human health and well-being. One such study, assessing the health of people living close to a polluted river in Bangladesh, demonstrated that water pollution incurs skin disease, diarrhea, gastric problems, and respiratory illness (Halder and Islam 2015). As the last decades have seen ever-increasing water contamination and pollution, even in remote areas (Machate et al. 2022, 2023), the degradation of water quality and aquatic ecosystems has become a threat to human society. These degradations can have severe impacts on ecosystems, including lower resilience to dealing with pressures and stresses, as well as increased loss of biodiversity. Above a certain threshold, ecosystem functioning and the resulting ecosystem services will lose the capacity to support human society (Reader et al. 2023). The ecosystem then has entered an unhealthy state with numerous direct and indirect impacts on the human nervous, respiratory, digestive, and other systems of the human body, leading to the degradation of human well-being and health (Cairns 1995). These impacts also have the potential to reduce not only the physical but also the mental health of humans (Fig. 1). The manifold health consequences, particularly disruption of social interactions and cohesion, emergence of infectious diseases and disease vectors, as well as intoxication events, have been widely studied to understand the evolution of the quality of life in human societies (e.g. Martinez-Juarez et al. 2015; Summers et al. 2012; Sandifer et al. 2015; Karr 2011).

Despite the rich literature on the consequences of degraded or unhealthy ecosystems for human health, there is no consensus on a final definition of ecosystem health. Definitions of a healthy ecosystem range from a sustainable ecosystem, modified and impacted by human intervention, that uses its vital functions to prosper and is resilient to stress (Costanza and Mageau 1999) to definitions revolving around human health analogies, or ecological integrity (Lackey 2001; Scrimgeour and Wicklum 1996). The notion of ecosystem health is often used as a synonym of ecological integrity, despite their obvious differences (Karr and Chu 1995; Karr et al. 2020). Ecological integrity was described as the ability of an ecosystem to support and maintain diverse, balanced, integrated, and adaptive biological

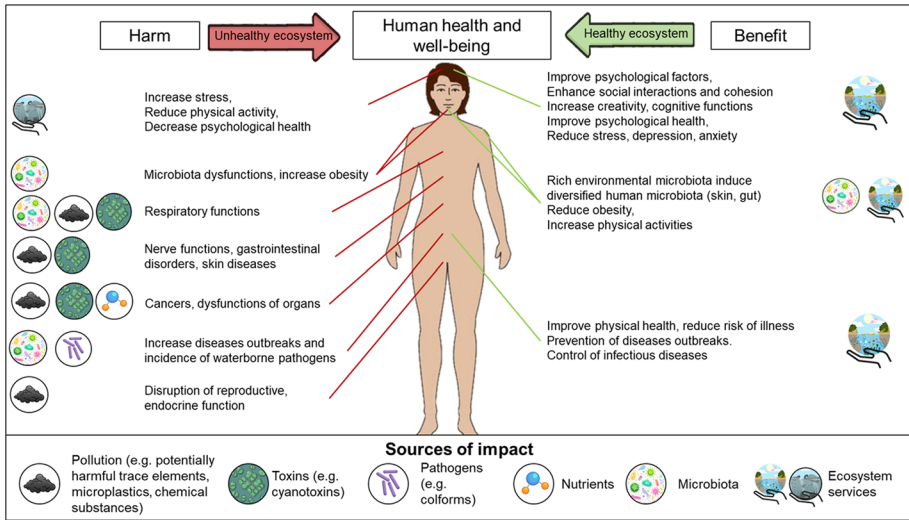


Fig. 1 Impacts of the aquatic ecosystem on human health and well-being. Direct and indirect consequences of the health of aquatic ecosystems found in the included literature were compiled. The indicators that can be used to assess the risk of direct impacts have been listed

communities and ecological processes in a stable state, combining physical, chemical, and biological integrity (Karr and Chu 1995). Ecological integrity is considered to be measurable by comparing composition, structure, and function to natural or historic ranges of variation (Bridgewater et al. 2014). However, in the Anthropocene, it appears to be difficult to define a natural state or a historical reference state of an ecosystem due to the dominance of human activities and the high degree of environmental alteration (Hansen et al. 2021). The concept of ecosystem health does evaluate the condition of ecosystems, using diverse indicators of habitats, species, and resources, as well as indicators of function, allowing to assess if an ecosystem is able to retain natural functions and the capacity to deliver ecosystem services (Burkhard et al. 2008). The ecosystem health concept, in a decisive difference to ecological integrity, integrates environmental conditions with anthropogenic impacts to inform about the sustainable use and management of natural resources. Understanding both concepts, ecological integrity and ecosystem health, ask for a large amount of data on abiotic and biotic variables, which are often only available on local scales, but not at larger scales, an issue also addressed with the concepts of Essential Biodiversity Variables (Haase et al. 2018; Schmeller et al. 2018) or Essential Climate Variables (Thornton et al. 2021). Those data needs are further exacerbated by system variability and system complexity (Schmeller et al. 2018). For a better understanding of the state and trends of ecosystems, independent if we want to look at ecological integrity or ecosystem health, a common measurement approach is urgently needed. As drinking water is a particularly precious natural resource, we here focus on aquatic ecosystems.

Water is a key element and an important resource for all living organisms, as it supplies adequate and rich environments for wildlife (Karr 2011). A plethora of parameters can be analyzed in water that allows the assessment of the status of the aquatic ecosystem by looking at species abundance, chemical composition, and water body condition (Burkhard et al. 2008). As ecosystems are spatially heterogeneous and vary over time, indicators or indices of ecosystem health need to take this variability into account. Modifications of aquatic

ecosystems will create stress and pressure on their biodiversity and ecosystem health, reducing at best the benefits of ecosystem services and at worst render them disservices (Grizzetti et al. 2016; Pongsiri and Roman 2007). These changes may affect economic activities, hydrological structures, and human well-being. As human well-being is composed of four principal elements: physiological and safety needs (which are the primary needs), economic needs including social requirements, environmental needs, and subjective happiness (Summers et al. 2012). The impacts of aquatic ecosystem degradation on humans differ depending on social and economic groups and their dependence on aquatic ecosystems (Horwitz and Finlayson 2011). Therefore, the link between green/blue environments and human well-being is not always obvious and depends on contextual determinants such as socio-economic, demographic, and climatic factors (Martinez-Juarez et al. 2015), a notion that is corroborated by the World Bank, recommending that the assessment of human well-being should consider the quality of life, security, health, freedom, and social connections (Narayan et al. 2000). As there is an interdependence between economics, human health, and ecosystem health (Boischio et al. 2009; Webb et al. 2010; Jax and Heink 2016), linking ecosystem health and human health and well-being is a complex task.

In many parts of the world, human health issues are visible, such as increasing allergies, anxiety, depression, obesity, and immune system disorders, impacting physical and mental health (Sandifer et al. 2015). Cohort studies have outlined a range of socio-economic factors contributing to degrading human health (Stringhini et al. 2017). However, only a few studies also take into consideration ecosystem health and environmental variations, particularly in aquatic ecosystems. Two threats to human health are particularly related to aquatic ecosystems, vector-borne diseases where vectors are closely linked to water bodies, and waterborne pathogens. In 2019, about 1.4 million people died worldwide due to the lack of safe drinking water, sanitation, and waterborne pathogens (Wolf et al. 2023). The number of people falling ill every year due to waterborne pathogens accounts for several million (Wolf et al. 2023). Waterborne pathogens can be present in various types of water due to contaminated fecal matter from the discharge of contaminated wastewater and partly from problems with water treatment (Gibson 2014). In addition, a large diversity of parasites can be found in aquatic ecosystems, even in ecosystems considered healthy (Adlard et al. 2015). These parasites are sensitive to climate change such as changes in temperature, which can influence their life cycle, transmission, geographical distribution, biodiversity, or else their interaction with hosts.

By weakening aquatic ecosystems, humans are creating more suitable environments for new pathogens, particularly for non-specific host pathogens (Boesch and Paul 2001; Newman and Reantaso 2010). These pathogens create a risk for aquatic wildlife and humans (Johnson and Paull 2011), leading to multiple ways of spreading infectious diseases. Climate change and modifications of the ecosystem increase the number of infectious diseases and the spread of aquatic invasive species, modifying parasite load, and the transmission rate and pathways of other aquatic pathogens (Conn 2014). Johnson showed in an experiment that eutrophication of an aquatic environment increases the density of infected snail hosts and stimulates per-snail production of the parasite *Ribeiroia ondatra* (Johnson et al. 2007). The Anopheles fly (*Anopheles gambiae*), the vector responsible for Malaria spread, has seen its niche and number increase due to climate change, deforestation, and modifications of human behavior, leading to a change in its behavior (Grieco et al. 2006). Habitat deterioration alters the communities, decreases predators, and increases invasive species, reducing competition and increasing the competent host population (Sandifer et al. 2015). Aquatic ecosystems provide fundamental ecosystem services, such as purification of water, regulation of eutrophication by recycling nutrients, support of food storage, and

balancing energies. They can further play a role in the prevention of disease outbreaks, control processes, and species, and avoid natural disasters by regulating climatic conditions. The establishment of indices capable of determining the presence of waterborne pathogens, and preventing their emergence is important for preventing health risks for ecosystems, wildlife, and humans (Stewart et al. 2008).

Aquatic ecosystems have also beneficial effects on human well-being, concerning social life, and physical and psychological well-being (Fig. 1). In healthy ecosystems, contact with nature may have positive impacts on physical and psychological health and can contribute to improving physical health, moods, and behavior (Sandifer et al. 2015; Moore et al. 2007). Bergou et al. (2022) showed that contact with canals and rivers is associated with mental well-being. Additional cultural services such as the attractiveness of sceneries, recreational activities, spiritual and moral utilities, and cultural and scientific interests are also beneficial (Limburg 2009). The reduction of recreational activities, social and economic isolation, psychological decline, loss of culture and environmental knowledge, and environmental injustice can therefore impact human mental health if cultural services of aquatic ecosystems are reduced or absent (Sandifer et al. 2015; Moore et al. 2007; Bergou et al. 2022). Aquatic ecosystems are the focus of the European Water Framework Directive (WFD, Directive 2000/60/EC), the main law for water protection in Europe. This directive aims to ensure that there is enough water of sufficiently good quality to support wildlife as well as human needs. The aim is to provide an integrated approach to water management, focusing on the integrity of aquatic ecosystems by regulating pollution and setting regulatory standards in regard to good chemical and ecological status. The different national water agencies are therefore monitoring aquatic environments and producing a large amount of data, allowing to assess ecosystem status. The Water Framework Directive, directed by the European Commission, has helped to advance a common assessment methodology, but, apart from drinking water and recreational water specific indices were not developed to assess the linkage of human health and ecosystem health.

While interest in assessing ecosystem health is growing, more work is needed to discern a robust set of aquatic ecosystem health indicators. Therefore, in our literature review, we provide an overview of currently available and applied biological, chemical, and physical indicators and indices that provide information on aquatic ecosystem health. We specifically aim to provide an overview of which ecosystem health indicators might be closely linked to human health risks and human well-being. To improve knowledge on the links between aquatic ecosystem health and human well-being, we evaluated the applicability across environments, ease of use, and identification of the source of disruption, in currently used aquatic ecosystem indicators and indices. We also provide an overview of available studies linking aquatic ecosystem health to human well-being. Based on our analysis, we recommend a set of aquatic ecosystem health indicators and indices that should be prioritized to improve knowledge on the link between ecosystem and human health. We here address an important gap in the literature by summarizing the relationship between indicators of aquatic ecosystem health and human health risk.

Materials and methods

Firstly, we identified articles dealing with the assessment of aquatic ecosystem health and articles about the link between ecosystem health and human health and well-being. We aimed to gather the main aquatic ecosystem indices used to analyze their link with human

health risks. The articles were searched for in Web of Science, Science Direct, Springer, PubMed, and Google Scholar databases. Articles cited by selected articles were also analyzed and included if they were dealing with aquatic ecosystem health assessment. To find articles about aquatic ecosystem health several keywords and combinations of them were used (Table 1). The aim was to identify broad indices containing indicators usable in the context of a wide variety aquatic environments. The keywords used were then selected to provide access to the main articles dealing with and linking ecosystem health and human health in a wide variety of aquatic ecosystems. Our review did not examine the contents of the grey literature, which may contain important information about the implementation of certain indicators. Examining this literature was not within the scope of our review, which focused on the peer-reviewed scientific literature.

We yielded a total of 245 articles, published between 1963 and 2023, of those 185 articles focused on the assessment of aquatic ecosystem health, and 60 articles made the link between ecosystem health and human health and well-being. We then extracted 65 indices that we categorized into four groups depending on what they evaluate: habitat quality, water quality, biological communities, and/or overall ecosystem health. Indices per definition comprise several indicators, i.e. parameters measured to assess the quality or the health of the ecosystem, such as abiotic factors (e.g. pH, temperature, oxygen concentration) and ecological components (e.g. number of species, relative proportions of taxa). For each index, we listed the indicators that compose them and the ecosystem type to which it has been applied. We also assessed the frequency of use of 50 headline indicators among the 65 indices to identify the most frequently used indicators. We evaluated the applicability of each index, using information about the types of water bodies in which the index can be applied (lake, river, stream), the practical ease for non-experts to measure abiotic factors and to easily identify organisms down to species level without expert training (e.g. fish, plants). For example, some organisms like diatoms, even if they are starting to be increasingly documented and used (Bere et al. 2014), as well as some species of macroinvertebrates, may require experts to be identified. Fish may be easier to identify but are not found in all aquatic ecosystems, and in others such as e.g. mountain lakes where fish are non-native, they have low diversity rates (Allardi 1994; Herman and Nejadhashemi 2015) and rather witness the degradation of an ecosystem (Miró et al. 2019). We also considered if the index can discriminate or not the stressor(s) which can trigger an ecosystem-wide stress response. For that, we identified 10 such stressors to aquatic ecosystems (i.e. degradation of the water quality, variation of the pH, rise of temperature, eutrophication, increase bacterial load, increase solids materials, increase pollution, modification of the habitat, cyanobacterial bloom and anthropogenic activities and stress).

We used the 60 articles dealing with the link between human health and well-being and ecosystem health to evaluate the link between indicators/indices, and human health deterioration, defining a ‘human health deterioration score’. This score varied from 0 to 3. Zero corresponded to no direct impact on human health. A value of 1 was assigned to behavioral or psychological impacts via visual modification of the ecosystem or modification of human activities. The presence of a pathogen or pollutant that could cause slight impacts or lead to temporary illness development was categorized as deterioration score 2. The final category, 3, corresponds to the presence of pathogens or pollutants that may cause a chronic pathology, disruption of body function, or even mortal risk.

Based on the 12 most used indicators (e.g. diatoms, macroinvertebrates, pH, nutrients, coliforms) we assessed from the literature if and how they vary depending on the 10 stressors previously identified. We considered that there was an impact of the stressor when there was a covariation (an increase, a decrease or change in both parameters) between

Table 1 Selection criteria and keywords for articles on aquatic ecosystem health and links to human well-being

	Aquatic ecosystem health	Human well-being
Keywords	<ul style="list-style-type: none"> - aquatic ecosystem health - aquatic health - aquatic ecosystem OR ecosystem health - water quality 	<ul style="list-style-type: none"> - ecosystem health AND human health OR well-being - aquatic environment AND human health OR well-being - aquatic ecosystem AND human health OR well-being
Exclusion criteria	<p>Articles dealing with green space only. Repetitive articles with the same index or no specific index used, derived indices too similar or too specific for one place. Indices with too little information on its applicability.</p>	<p>Articles focusing only on green space and human health.</p>
Inclusion criteria	<p>Assessment of aquatic ecosystem health, review on aquatic indices, development of new or derived index.</p>	<p>Description of the impacts on human well-being or health linked to ecosystems health and aquatic ecosystems. Link to human health and perturbations of aquatic ecosystems.</p>
Number of articles included	185	60

the stressor and the ecosystem indicator or human health simultaneously over time. These variations made it possible to assess the extent to which these indicators can witness environmental change and be applied in the assessment of ecosystem health. The levels of community sensitivity to disturbances have been described in the literature, and compared between communities with a short or long-life cycle. We considered a community to be of high sensitivity, when the literature suggested a rapid and significant change in community composition. We assume a moderate sensitivity, where the literature suggests less rapid and moderate changes in the community composition. In cases, for which the literature reported slow and small changes, we classified the community sensitivity as low.

Finally, to understand the direct and indirect impacts of aquatic ecosystems on human well-being, we compiled and categorized the potential effects of aquatic ecosystems on human well-being.

Results

We extracted a non-exhaustive but representative list of 65 main indices applied in the assessment of aquatic ecosystem health (Table 2). Among these indices, the majority focused on biological communities ($n=39$), on water quality ($n=22$), and on habitat structure ($n=2$). The direct integration of indicators from at least two categories in one index was rare ($n=2$). Only the Spatial Ecosystem Health Index and the Ecosystem Health index directly use water quality and biological community parameters into the calculation of the index. On average, 8.71 indicators were applied per index ranging from 1 to 39 indicators (Fig. 2). Among biological indices, the Index of Biological Integrity (IBI, Karr 1981), was the most cited and used one ($n=11/65$). Biological indices were mainly represented by diatom communities ($n=15$) and macroinvertebrates ($n=11$). Studies applying a biological index often added physicochemical indicators to estimate the overall ecosystem state. The most frequent physicochemical indicators, among water quality indices, were Dissolved Oxygen (DO) ($n=20$), pH ($n=16$), Biological Oxygen Demand (BOD) ($n=15$), Suspended Solids (SS) ($n=14$), and ammonia ($n=12$) followed by 7 others (Tables 2 and 3). Of the 65 indices, no index scored in all three categories (applicability to multiple environments, ease of application, and discrimination of sources of disruption), 53 were applicable to multiple environments, 37 were easy to use, and 10 indices were described as being able to discriminate between the stress factors for which the index was developed and other ecosystems in the same geographical region. 31 indices scored in two categories, of which 21 were easy to use and applicable to different environments, 2 were applicable to multiple environments and able to discriminate stress sources. Finally, 8 indices were easy to use and discriminated between sources of stress that impact indicator variations (Tables 2 and 3). Most indices are specific to certain aquatic ecosystems due to the difference in the flow regime and species diversity (Table 2). Moreover, the ease of application depends on the cost and the facility of collection, the difficulty of identification of biological organisms, and the complexity of the index calculation.

All indices allow different assessments of aquatic ecosystem health, however, most of them could not evaluate directly the link between ecosystem health and human health or well-being ($n=42$) based on our human health deterioration score (Table 2). Only a few indices could identify a risk of chronic pathology, body function, or mortal risk on health ($n=5$) through the analysis of the presence of pathogens or pollutants known to cause harm to humans. The remaining indices assessed impacts on psychological well-being ($n=3$), or

Table 2 List of indices and their ability to assess aquatic ecosystem health

Categories	Index	Derived from the index	Indicators measured	Environment	Applicability index		Human health deterioration score	References	
					App	Ease DoS			
Habitat quality	River habitat quality index	Habitat quality index (HQI)	Substrate, habitat complexity, velocity-depth, bank stability and conservation, channel alteration, stream conditions, water quality, vegetation cover and diversity, and human activities	River, stream	-	+	-	1	Texas Commission on Environmental Quality (1999), Chen et al. (2019), Chen et al. (2022)
	Qualitative habitat evaluation index (QHEI)	Original	Substrate, embeddedness, velocity-depth regime, canopy cover, channel alteration, bottom, deposition, pool run/bend ratios, (habitat complexity and channel alteration)	River	+	+	-	1	An et al. (2002)
Water quality	Horton index or weighted arithmetic water quality index	Original (1960)	pH, DO, conductivity, alkalinity, chloride, fecal coliforms, sewage treatment and carbon chloroforms extract	River	+	+	/	3	Horton (1965), Gupta et al. (2017)

Table 2 (continued)

Categories	Index	Derived from the index	Indicators measured	Environment	Applicability index		Human health deterioration score	References
					App	Ease DoS		
The national sanitation foundation WQI (NSF)	Horton index		Water temperature, total solids, pH, DO, BOD, fecal coliforms, total phosphorus, nitrates, turbidity, pesticides and toxic components	Lake, river, stream, marine water	-	+	/	Brown et al. (1970), Brown et al. (1973), Gupta et al. (2017)
Dinius index	The National Sanitation Foundation (NSF) WQI		Water temperature, color, pH, DO, BOD, conductivity, alkalinity, chloride, fecal coliforms, total coliforms and hardness	River	+	+	-	Dinius (1987)
Oregon index	NSF WQI		Water temperature, suspended solids, pH, DO, BOD, ammonia, fecal coliforms, total phosphorus, nitrates and total nitrogen	River	-	+	-	Dunnette (1979), Clude (2001)

Table 2 (continued)

Categories	Index	Derived from the index	Indicators measured	Environment	Applicability index		Human health deterioration score	References	
					App	Ease DoS			
Scottish research development department (SRDD-WQI)	Original (1970)	River	Water temperature, suspended solids, pH, DO, BOD, conductivity, ammonia, fecal coliforms, total phosphorus and total nitrogen	River	+	+	-	2	Bordalo (2001)
					+	+	/	3	Abrahão et al. (2010)
The bascaron index	SRDD WQI	River, marine water	Water temperature, color, turbidity, pH, DO, BOD, conductivity, chlorite, ammonia, total coliforms, total sulfate, nitrates, total hardness, detergent, permanganate reduction, pesticides, oil and grease, CN ⁻ , Na ⁺ , free CO ₂ , Mg ²⁺ , P, NO ₂ ⁻ , Ca ²⁺ and visual appearance	River, marine water	+	+	/	3	Abrahão et al. (2010)

Table 2 (continued)

Categories	Index	Derived from the index	Indicators measured	Environment	Applicability index		Human health deterioration score	References	
					App	Ease DoS			
House index		SRDD WQI	Water temperature, suspended solids, pH, DO, BOD, chloride, ammonia, total coliforms and nitrates	River	-	+	-	2	House (1989)
Dalmatian index		SRDD WQI	Water temperature, mineralization, corrosion coefficient, DO, BOD, total nitrogen, protein nitrogen, total phosphorus and total coliforms	Marine water	+	+	-	2	Stambuk-Gijjanovic (1999)
Ross index or Fuzzy interface system (FIS)		Original (1977)	Suspended solids, DO, BOD, ammonia	River, lake, marine water	+	+	-	0	Ross (1995)
Environmental quality index (EQI)		Original (1982)	Suspended solids, specific conductance, chloride, fecal coliforms, total phosphorus, chlorophyll a, obvious pollution, toxic inorganic contaminants, toxic organic contaminants	River, lake	+	+	/	3	Steinhart et al. (1982)

Table 2 (continued)

Categories	Index	Derived from the index	Indicators measured	Environment	Applicability index		Human health deterioration score	References
					App	Ease DoS		
Smith index	Original (1990)	Water temperature, temperature difference, pH, turbidity, suspended solids, DO, BOD, ammonia, fecal coliforms	River		+	+	2	Smith (1990)
Dojlido index	Original (1994)	Suspended solids, pH, DO, BOD, Chemical Oxygen Demand (COD), chloride, ammonia, total phosphorus, total sulfate, nitrates, total hardness, total nitrogen, cadmium, manganese, zinc, copper, mercury, lead, nickel, chrome, iron, etc	River		+	+	3	Dojlido et al. (1994)
British Columbia WQI (BCWQI)	Original (1995)	DO, pH, turbidity, total suspended solids, ammonia, copper, lead, zinc, etc	River		+	-	2	Dunn (1995), Zandbergen and Hall (1998)

Table 2 (continued)

Categories	Index	Derived from the index	Indicators measured	Environment	Applicability index		Human health deterioration score	References
					App	Ease DoS		
Canadian council of ministers of the environment (CCME)	BCWQI	Water quality indicators of choice, no recommendations were made	Coastal water, river, lake, marine water	+	+	/	0	Canadian Council of Ministers of the Environment (2001), Gupta et al. (2017)
Liou index	Original (2003)	Water temperature, turbidity, suspended solids, pH, DO, BOD, chloride, ammonia, cadmium, zinc, copper, lead and chrome	River	+	+	/	2	Liou et al. (2004)
Said index	Original (2004)	Turbidity, DO, conductivity, total coliforms and total phosphorus	Marine water	-	+	-	2	Said et al. (2004)
Hanh index	Said index	Orthophosphate, turbidity, suspended solids, DO, BOD, COD, ammonia, and total coliforms	River	+	+	-	2	Hanh et al. (2011)
Malaysian index	Original (2007)	Suspended solids, pH, DO, BOD, COD and ammonia	River	+	+	-	0	Gazzaz et al. (2012)

Table 2 (continued)

Categories	Index	Derived from the index	Indicators measured	Environment	Applicability index		Human health deterioration score	References	
					App	Ease DoS			
	Almeida index or recreational water quality index	Original (2012)	pH, turbidity, detergents, total coliforms, fecal coliforms, <i>E. coli</i> , Enterococci, nitrate, orthophosphate- and COD	River	+	+	-	2	Almeida et al. (2012)
	Aquatic Health Index (AHI)	Aquatic Health Index (AHI)	Salinity, pH, water temperature, transparency, DO, nitrate, phosphate, silicate, oil and grease, lead, zinc, copper, fecal coliforms, BOD	Coastal water, estuaries	-	+	/	2	Barua and Rahman (2020), Saha et al. (2017)
	Coastal Water Quality	Coastal Water Quality	Total suspended solids, oil and grease, COD, total nitrogen, ammonia, total phosphorus, phosphate, chlorophyll a, total coliforms, fecal coliforms, DO and total organic carbon	Coastal water	-	+	-	2	Nguyen and Sevando (2019)

Table 2 (continued)

Categories	Index	Derived from the index	Indicators measured	Environment	Applicability index		Human health deterioration score	References	
					App	Ease DoS			
Biological communities <i>Fauna</i>	Fuzzy Comprehensive Evaluation Method	Fuzzy Comprehensive Evaluation Method	DO, pH, water temperature, ammonium, water color and taste, and floating object	Aquaculture water, pond	+	+	-	1	You et al. (2021)
	Shannon–Wiener biodiversity index	Shannon–Wiener index	Number of species, and proportion of individuals per species	River	+	+	-	0	Shannon (1963), Zhao et al. (2017), Zhao et al. (2019), Scotti et al. (2022)
	Sladecek index (SLA)	Original (1984)	Species, saprobic valence, weight of species and individual saprobic index	River, lake, stream	+	-	-	0	Sládeček (1986)
<i>Diatoms</i>	Leclercq and Maquet index (ILM)	Saprobic indices	Indicators value and saprobic valence for diatom	River	+	-	+	0	Leclercq and Maquet (1987)
	Diatom index (DI)	Saprobic indices	Diatom species, relative abundance, sensitivity index and indicating value	Marshe, river	+	-	/	0	Naqeeb et al. 2020
	Generic Diatom Index (GDI)	Diatom index (DI)	Number of diatom taxa, taxa abundance, global sensitivity and stenocia degree	Marshe, river	+	-	/	0	Rumeau and Coste (1988), Naqeeb et al. (2020)

Table 2 (continued)

Categories	Index	Derived from the index	Indicators measured	Environment	Applicability index		Human health deterioration score	References
					App	Ease DoS		
	Generic index (GI) / Generic diatom index	Generic Diatom Index (GDI)	Ratio of individual abundance	River	+	-	0	Wu (1999)
	Specific Pollution Sensitivity Index (IPS)	Diatom index (DI)	Diatoms species and sensitivity/tolerance to pollutants	River, lake	+	-	+	CEMAGREF, AERMC (1982), Prygiel and Coste (1993), Descy and Coste (1991), Stenger-Kovács et al. (2013)
	Indice Diatomique Pratique (IDP)	IDG and IPS	Diatom species, sensitivity to pollution and indicator value	River	+	-	/	0 Prygiel et al. (1996)
	Diatom Assemblage Index (DAI ou DAIPo) or Watanabe's index	Diatom Community index (1982)	Diatom taxa, relative abundance of taxa, sensitivity to organic pollution	River, lake	+	-	/	0 Watanabe et al. (1986)
	Commission for Economical Community / European index (CEE ou CEC)	Original (1991)	Relative abundance of taxa, taxa species, tolerance and indicator value	River	+	-	+	0 Descy and Coste (1991)
	Schiefele & Schreiner index (SHE)	Original (1991)	Relative abundance of taxa, diatom species, sensitivity/tolerance to pollutants and indicator value	River, lake	+	-	/	0 Schiefele and Schreiner (1991)

Table 2 (continued)

Categories	Index	Derived from the index	Indicators measured	Environment	Applicability index		Human health deterioration score	References	
					App	Ease			DoS
	Trophic Diatom Index (TDI)	Original (1995)	Relatives proportion of taxa and species, sensitivity of species and indicator value of species	River, stream	+	-	/	0	Kelly and Whitton (1995), Naeqeb et al. (2020), Stenger-Kovács et al. (2013)
	Diatom-based Eutrophication/Pollution Index (EPI-D)	Original (1996)	Species abundance, sensitivity to organic load, mineralization degree and nutrients load	River	+	-	+	0	Dell'Uomo et al. (2004)
	IBD	Biological Diatom Index (IBD)	Diatoms taxa and relative abundance	River, lake, stream	+	-	+	0	Prygiel and Coste (2000), Stenger-Kovács et al. (2013)
	Benthic Diatom Index of Biotic Integrity (BD-IBI)	Index of Biological Integrity (IBI)	Percentage of prostrate individuals, percentage of Amphora individuals, Diatom-based Eutrophication/Pollution Index, and percentage of polysaprobic species	River	+	-	+	0	Tan et al. (2015)

Table 2 (continued)

Categories	Index	Derived from the index	Indicators measured	Environment	Applicability index		Human health deterioration score	References
					App	Ease DoS		
<i>Algae and diatoms</i>	Algae-IBI	Index of Biological Integrity (IBI)	Number of heterotroph diatom, diatom sedimentation tolerant, haplobiontic diatom, etc	Stream	+	- / 0	0	Fetscher et al. (2013)
<i>Macroinvertebrates</i>	Hilsenhoff Biotic Index (HBI)	Original (1977)	Tolerance/sensitivity to pollutants and number of individuals per species	Stream	+	- - 0	0	Hilsenhoff (1982), Bennett et al. (2004)
	Family Biotic index (FBI)	Hilsenhoff Biotic Index (HBI)	Number of individuals within a taxon, tolerance value to organic pollutants and total number of organisms	Streams	+	- / 0	0	Chen et al. (2019), Bennett et al. (2004)
	Biological Monitoring Working Party (BMWP)	Original (1980)	Pollution tolerance value to organic pollution	Stream, river	+	- / 0	0	Chesters (1980)
	Ephemeroptera Plecoptera Trichoptera (EPT)	Original (1988)	Ephemeroptera, Plecoptera and Trichoptera populations richness and percentage abundance	Stream, river	+	- - 0	0	Barbour et al. (1999), Liu et al. (2017)

Table 2 (continued)

Categories	Index	Derived from the index	Indicators measured	Environment	Applicability index		Human health deterioration score	References
					App	Ease DoS		
Benthic-IBI	Index of Biological Integrity (IBI)	Community richness, proportion of species, nutritional structure, tolerance and habitat quality	River, stream	+	-	-	0	Kerans and Karr (1994)
Basin-wide Benthic Integrity (B-IBI)	Index of Biological Integrity (IBI)	Ephemeroptera/Plecoptera/Trichoptera taxonomic richness, Hilsenhoff Family Biotic Index, proportion of clingers, collectors, percent contribution of the dominant taxon, proportion of EPT individuals, total taxonomic richness	Basin	+	-	+	0	Astin (2007)

Table 2 (continued)

Categories	Index	Derived from the index	Indicators measured	Environment	Applicability index			Human health deterioration score	References
					App	Ease	DoS		
	Invertebrate Community Index (ICI)	IBI and EPT	Total number of taxa, total number of mayfly taxa, total number of caddisfly taxa, total number of dipteran taxa, percent of mayflies, percent of caddisflies	River, stream, coastal water	+	-	/	0	DeShon (1995), Bennett et al. (2004)
	The Global Biological Normalized index (GBNI)	Original (2004)	Sensitivity, class variety, number of indicators faunistic group and taxonomic richness	River	+	-	-	0	Archambault and Dumont (2010)
	Urban Stream Multimetric Index (USMI)	Original (2017)	The number of taxa, Hill diversity, the percentage of Ephemeroptera, Odonata and Trichoptera and the percentage of collector-filterer	Stream	+	-	-	0	Liu et al. (2017)
	Benthic Macroinvertebrate Index (BMI)	Original	Contamination index species, number of species and weight index species	Stream	+	-	-	0	Kang et al. (2022)

Table 2 (continued)

Categories	Index	Derived from the index	Indicators measured	Environment	Applicability index		Human health deterioration score	References
					App	Ease DoS		
	River Invertebrate Prediction and Classification System (RIVPACS)	Original	Altitude at site, distance from source, slope, mean width, mean depth, discharge category of the site, date of sampling, maximum surface velocity, pH, DO, chloride, alkalinity, total nitrogen, mean percentage macrophyte cover	River, streams	+	- / 0	Wright (2000)	
Fish	Fish Community Index	Original	Number of species, species abundance, trophic index	Stream	+	- / 0	Jordan et al. (2010)	
	Fish Assessment Index (FAI)	Original	Native fish species, riffle-benthic species, sensitive species, tolerant species, nutritional structure	River, stream	- + + 0	+	Klemm et al. (1993), Kang et al. (2022)	
	Fish-IBI	Index of Biological Integrity (IBI)	Species composition and abundance, nutritional structure, reproduction, tolerance and distribution	River, stream	- + / 0	+	Karr (1981), Karr et al. (1986), Wu et al. (2020), Zhao et al. (2019)	

Table 2 (continued)

Categories	Index	Derived from the index	Indicators measured	Environment	Applicability index		Human health deterioration score	References	
					App	Ease			DoS
European Fish Index (EFI)	Index of Biological Integrity (IBI)		Trophic structure, benthic species, rheophilic species, tolerant and intolerant species	River	-	+	+	0	Pont et al. (2007)
Aquatic Ecosystem Health Index (AEHI)	Original		Ethoxyresorufin-O-Deethylase, creatinine, alanine aminotransferase, triglyceride, condition factor, liver-somatic index, spleno-somatic index, viseral-somatic index, gonado-somatic index, fecundity, atretic oocyte and size	River	-	-	/	0	Yeom and Adams (2007)

Table 2 (continued)

Categories	Index	Derived from the index	Indicators measured	Environment	Applicability index		Human health deterioration score	References
					App	Ease DoS		
<i>Fauna</i>	Index of Biological Integrity (IBI)	Original (1981)	Fish assemblages: native fish species, benthic species, sensitive species, proportion of tolerant species, nutritional structure, number of individuals, proportion of exotics individuals and proportion of individuals with anomalies	Stream, river	-	+ /	0	Karr (1981), An et al. (2002), Kim et al. (2007), Royle et al. (2014), Hoyle et al. (2018), Xu and Zhang (2020)
	Zooplankton-IBI	Index of Biological Integrity (IBI)	Species density, species richness, species biomass	River	+	- +	0	Yao et al. (2021)
	Freshwater Ecosystem Health Index (FEHI)	Based on Z-IBI	Taxonomic composition, individual abundance, body size, biodiversity of zooplankton	River, lake	+	- /	0	Cai et al. (2020)

Table 2 (continued)

Categories	Index	Derived from the index	Indicators measured	Environment	Applicability index		Human health deterioration score	References
					App	Ease DoS		
<i>Plankton</i>	Plankton-IBI	Index of Biological Integrity (IBI)	Crustacean zooplankton biomass, percentage of the species biomass on the total biomass, biomass of edible algae taxa, zooplankton ratio, <i>L. macrurus</i> density	Lake	+	-	/	Kane et al. (2009)
<i>Aquatic plants</i>	Aquatic Plant-IBI	Index of Biological Integrity (IBI)	Species richness, Shannon index, exotic species, number of individuals per species, dominant species, tolerance to pollutants, percentage of individuals per species	Wetland	+	+	/	Miller et al. (2006)
<i>Algae</i>	TSI	Trophic State Index (TSI)	Chlorophyll a, Secchi disk depth, total phosphorus	Lake	+	+	/	Carlson and Simpson (1996), Carlson (1977), Devic et al. (2014), Roley et al. (2014)
<i>Dragonfly</i>	DBI	Dragonfly Biotic Index (DBI)	Species distribution, threat status, and the tolerance of a specie	All waterbodies	+	-	-	Samways and Simaika (2008), Moor (2017)

Table 2 (continued)

Categories	Index	Derived from the index	Indicators measured	Environment	Applicability index		Human health deterioration score	References	
					App	Ease DoS			
Ecosystem health	Spatial ecosystem health index (EHI)	Ecosystem health index	Secchi depth, seagrass loss, total phosphate, concentration in nitrogen-stable isotope, percentage of <i>Lyngbya majuscula</i> presence, and chlorophyll a	River, bay	+	+	/	0	Pantua and Dennison (2005)
	Ecosystem health index (various derived)	Ecosystem health index (EHI)	Water temperature, pH, turbidity, salinity, DO, BOD, ammonia, orthophosphorus, silicate, nitrite, nitrate, total suspended solids, COD, chlorophyll a, diatoms	Lake, coastal water	+	+	/	2	Padua et al. (2023), Simčić and Brancelj (2009), Flint et al. (2017)

App Applicable to multiple environments, Ease Ease of application, DoS Discrimination of the stressors, +: yes, -: no, /: unknown. DO Dissolved Oxygen, BOD Biochemical Oxygen Demand

Human health deterioration score (0 = no direct impact on human health, 1 = behavioral or psychological impacts, 2 = slight impacts or risk of temporary illness development, 3 = risk of development of a chronic pathology, disruption of body function, or mortal risk)

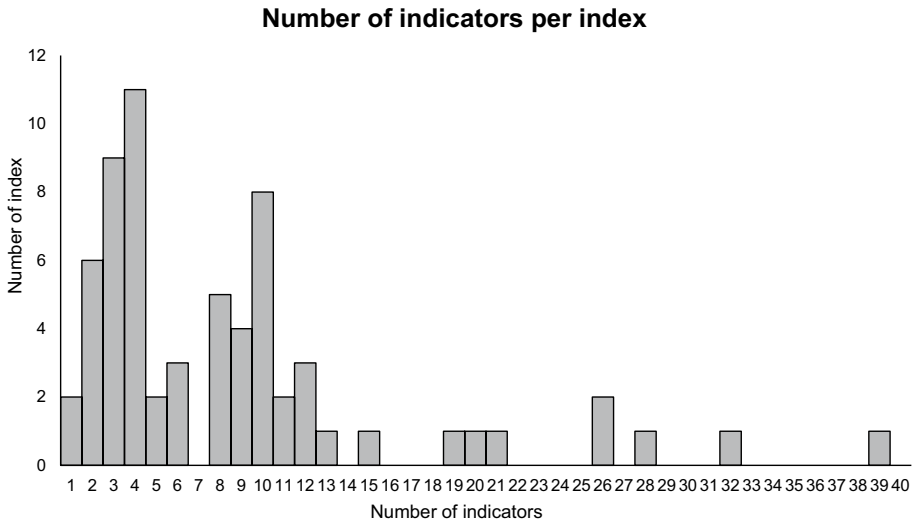


Fig. 2 Distribution of the number of indicators per index

slight impacts on physical health, or development of temporary illness ($n = 14$). These latter indices make it possible to fully or partially assess the impact of the state of the ecosystem on human health and well-being (Table 2).

When investigating indicators, we found that the 12 most used physicochemical and biological indicators were able to evaluate 10 environmental stressors which comprise e.g. bacterial load, eutrophication, and organic pollution (Table 3). The degradation and change in water quality, anthropogenic stress, the rise of temperature, eutrophication, the increase of pollution, and cyanobacteria bloom have strong impacts on seven physicochemical metrics and five bioindicators (phytoplankton, diatoms, macroinvertebrates, zooplankton, fish), and make these parameters good indicators of environmental change. The species richness, the diversity and the composition of these aquatic communities vary according to the presence of stressors and environmental parameters (Dey et al. 2023). For example, the distribution of zooplankton species will be most affected by temperature and electrical conductivity, but also by pollution. Machate (Machate et al. 2022) demonstrated the impact of pollution by showing that certain zooplankton species were absent or had low abundance in the most polluted environments. In addition to zooplankton, macroinvertebrates and fish respond strongly to degraded water quality (Marzin et al. 2012). These changes, such as acidification, oxygen depletion or the presence of pollution, will create selection pressure and lead to a loss of biodiversity and/or a change in the most sensitive communities.

Examining the external stressors for aquatic systems in terms of indicators of aquatic ecosystem health revealed that six of the 10 stressors can be directly linked to human health (Fig. 3). Those include a reduction in general water quality, which can have an impact on the taste of drinking water, the increase of pollution and bacterial load, and cyanobacteria bloom, which can cause fever, skin irritation, and increased cancer risks.

Human health impacts measured by aquatic ecosystem indicators included impacts on mental, neurological, and physical health issues (Table 4).

Aquatic ecosystems can also impact human well-being regarding socio-cultural and psychological effects (Table 4). Within these impacts, we can find the reduction of recreational

Table 3 Indicators linking stressors of ecosystem health to responses to environmental change

Indicators	Potential responses to change	Sources of disruption of ecosystem health	References
Dissolved Oxygen (DO)	<ul style="list-style-type: none"> - Oxygen depletion can increase nitrate and decrease nitrite concentrations - Extremely low and high oxygen concentration impact aquatic organisms - Eutrophication can lead to oxygen depletion, and induce hypoxia or anoxia - High water temperature can decrease pH - Extremely high and low pH values can increase risks of eutrophication, or acidification, and can create a toxic environment for aquatic organisms - High water temperature and low level of dissolved oxygen increase the BOD and COD. - High BOD and COD levels can lead to increased mortality of aquatic life - Pollution increase levels of suspended and dissolved solids, inducing a decrease of phytoplankton biomass, diversity, and can impact the growth of some aquatic organisms - Pollution leads to nutrient enrichment - High concentration can be toxic for the aquatic organisms - It can lead to eutrophication, algae bloom, perturbation of the nitrogen cycle, acidulation water, and reduction of dissolved oxygen 	Bacterial load, extreme water temperature, high chemical and biological treatments, and eutrophication	Rabalais and Nixon (2002), Rose et al. (2019), Karr et al. (2020), Trbojevic et al. (2021), Rose et al. (2023)
pH	<ul style="list-style-type: none"> - Rise of water temperature (higher than 25 °C) 	Rise of water temperature (higher than 25 °C)	Häder et al. (2014), WHO (2017)
Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD)	<ul style="list-style-type: none"> - High water temperature and low level of dissolved oxygen increase the BOD and COD. 	Dissolved oxygen level, high water temperature and organic pollution	Wu et al. (2016), Tampo et al. (2021), Cai et al. (2018)
Suspended Solids and dissolved solids	<ul style="list-style-type: none"> - Pollution increase levels of suspended and dissolved solids, inducing a decrease of phytoplankton biomass, diversity, and can impact the growth of some aquatic organisms 	Quantity of suspended solids, and pollution	WHO (2017), Madhav et al. (2020), Silwal et al. (2021)
Ammonia, nitrate, nitrite	<ul style="list-style-type: none"> - Pollution leads to nutrient enrichment - High concentration can be toxic for the aquatic organisms - It can lead to eutrophication, algae bloom, perturbation of the nitrogen cycle, acidulation water, and reduction of dissolved oxygen 	Pollution, eutrophication, algal bloom	Rabalais and Nixon (2002), Camargo and Alonso (2006), Estevez et al. (2017), Scholz-Starke et al. (2018), Karr et al. (2020)

Table 3 (continued)

Indicators	Potential responses to change	Sources of disruption of ecosystem health	References
Phosphate, phosphorus, orthophosphorus	<ul style="list-style-type: none"> - Pollution leads to nutrient enrichment - High concentration can be toxic for the aquatic organisms - It can lead to eutrophication, algae bloom 	Pollution, eutrophication, algal bloom	Rabalais and Nixon (2002), Estevez et al. (2017), Scholz-Starke et al. (2018), Karr et al. (2020)
Coliforms	<ul style="list-style-type: none"> - High coliform concentrations increase bacterial load, and impact aquatic organism health 	Increased bacterial load, domestic sewage, pollution, anthropic activities	Almeida et al. (2012), Tampo et al. (2021), Wolf et al. (2023)
Diatoms	<ul style="list-style-type: none"> - High sensitivity to environmental changes, organic pollution, and eutrophication - Induce selection pressure, change in abundances, diversity loss, and increase mortality rate in diatoms community 	Water quality, pH change, extreme nutrient concentrations, organic matters and pollution, extreme levels of dissolved oxygen	Dixit et al. (1992), Brown et al. (2004)
Macroinvertebrates	<ul style="list-style-type: none"> - Moderate sensitivity to environmental changes, sensitivity to pollution vary depending on the pollutants, and the species - Induce selection pressure, change in abundances, diversity loss, increase mortality rate, and induce physiological stress 	Water quality (dissolved oxygen, pH...), extreme water temperature, change in conductivity, modification of the habitat, pollution and nutrients enrichment	Willm and Dorris (1968), Reynoldson and Metcalfe-Smith (1992), Verneaux (1994), Brenaman et al. 2000, Barbosa et al. (2001), Lalonde et al. (2016), Wu et al. (2020), Tampo et al. (2021)

Table 3 (continued)

Indicators	Potential responses to change	Sources of disruption of ecosystem health	References
Fish	<ul style="list-style-type: none"> - Moderate sensitivity to environmental changes, sensitivity to pollution vary depending on the pollutants, and the species - Sensitive to habitat changes and environmental contamination - Induce selection pressure, modifications of the diversity, increase mortality rate, and induce modifications of the behavior - High sensitivity to environmental disruption but can vary depending on the species - Induce selection pressure, diversity loss, increase mortality rate and induce physiological stress - High sensitivity to change in water quality and nutrient concentrations can change environment resilience, stress resistance, and sustainability - Induce selection pressure, diversity loss, and increase mortality rate 	<p>Water quality (dissolved oxygen, pH...), high chloride and metal concentrations, extreme water temperature, hydrological perturbations</p>	<p>Moiseenko (2008), Marzin et al. (2012), Karr et al. (2020), Wu et al. (2020), Biswas et al. (2023)</p>
Zooplankton	<ul style="list-style-type: none"> - High sensitivity to environmental disruption but can vary depending on the species - Induce selection pressure, diversity loss, increase mortality rate and induce physiological stress 	<p>Water quality, extreme water temperature, change in salinity, food availability, pollutant concentration, high pollutant toxicity, and eutrophication</p>	<p>Karr et al. (2020), Padovesi-Fonseca (2020), Dey et al. (2023), Machate et al. (2022)</p>
Phytoplankton	<ul style="list-style-type: none"> - High sensitivity to change in water quality and nutrient concentrations can change environment resilience, stress resistance, and sustainability - Induce selection pressure, diversity loss, and increase mortality rate 	<p>Water quality, extreme water temperature, change in water conductivity and channel stability, high biochemical and chemical oxygen demand, and extreme nutrients concentrations</p>	<p>Prygiel (1994), Brown et al. (2004), Moiseenko (2008), Meng et al. (2009), Zhang (2019), Karr et al. (2020)</p>

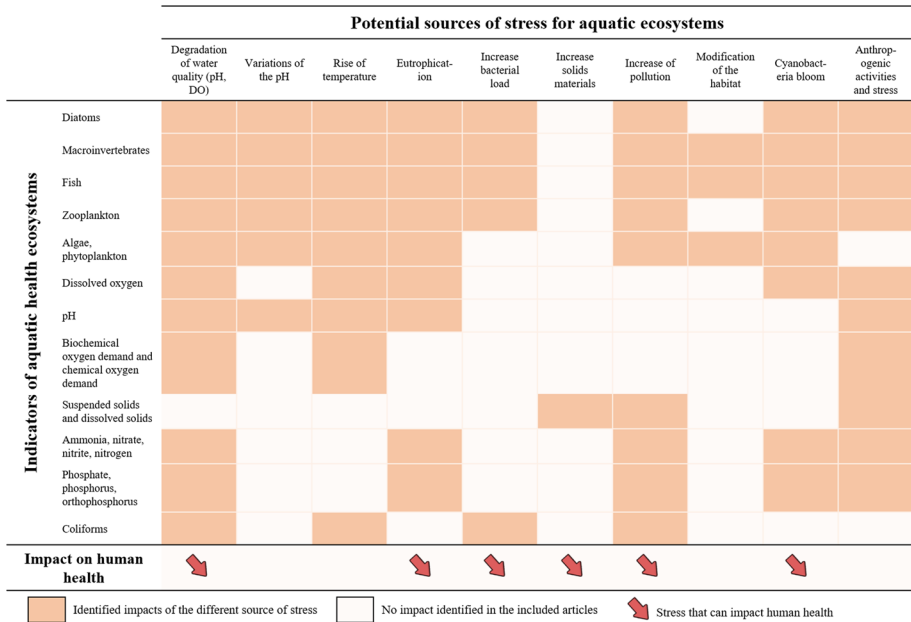


Fig. 3 Crossing external stressors on aquatic ecosystems with their impact indicators and human health. Orange cells indicate a proven positive or negative correlation between the sources of stress and the indicator, based on the literature reviewed. Empty cells indicate an absence of information and verified direct relationship in the reviewed literature (e.g. water temperature only has an indirect impact by changing the visual aspect of the environment or the organisms living in it). Red arrows indicate potentially negative impacts on human health from the changes the indicators are measuring in aquatic ecosystems (see also Table 4)

activities, social and economic isolation, declines in psychological wellbeing, loss of culture and environmental knowledge, and environmental injustice. Other direct impacts are related to damage to human health, such as diseases, allergies, stress, depression, obesity, and immune disorders (Table 4). Based on our assessment, the principal indicators that can have repercussions on human health and well-being are pollutants (e.g. potentially harmful trace elements, microplastics), nutrients (e.g. nitrite), pathogens (e.g. coliforms, cyanotoxins), pathological risk, health of aquatic organisms (e.g. macroinvertebrates, diatoms), and ecosystem services (Table 4).

Discussion

Here, we reviewed indicators and indices used in the assessment of aquatic ecosystem health and assessed their potential to evaluate human health risks and their well-being. We found that only a few studies approached the notion of ecosystem health in relation to human health (Angermeier et al. 2021), despite the known diverse direct and indirect impacts aquatic ecosystems have on human well-being. None of the studies and indices listed in this review use or include parasites or vectors of infectious diseases in the assessment of ecosystems, even though they can be sources of risk for human health. Those impacts can involve physical, psychological, or socio-cultural elements of human health

Table 4 Impacts of aquatic ecosystem parameters on human well-being and health

Source of modification of aquatic ecosystems	Impact on human health and well-being	References
Alkalinity and Hardness	- Impacts the taste of drinking water	Silwal et al. 2021
High chloride concentration in ingested water	- Risk of asthma, hypertension, renal stones, or gastrointestinal disorders	Silwal et al. 2021
Coliforms, waterborne pathogens, toxic aquatic fungi and parasites	- Increase of the risk of infections and gastroenteritis	Gibson 2014, Conn 2014, Adlard et al. 2015, Magwaza et al. 2017, McNinch et al. 2009
Cyanobacteria and cyanotoxins	- Change in water color, taste and smell Neurotoxins: interruption of respiratory functions or death	Mez et al. 1998, Zanchette and Oliveira-Filho 2013, Codd et al. 1999
Environmental microbiome	- Microcystins: fever, gastroenteritis, dysfunctions of the liver or liver cancer - Hepatotoxins: risk of cancers - Dermatotoxins: skin irritation - Can impact the human respiratory microbiome, intestinal microbiome, skin microbiome and the immune system	Sandifer et al. 2015, Adamovsky et al. 2018
Potentially harmful trace elements (mercury, arsenic, lead...)	- Risk of abortion, congenital malformation, gastrointestinal disorders, dysfunctions of organs, chronic diseases, or cancers	Mouly et al. 2012, Wu et al. 2013, McNinch et al. 2009, Singh and Kalamdhad 2011
Microplastics	- Can impact the nervous system, the respiratory system, digestive system, and can be responsible for infertility, obesity or cancers	Sharma and Chatterjee 2017, Elizalde-Velasquez and Gómez-Oliván 2021
Micropollutants (Persistent Organic Pollutants (POPs), Polycyclic Aromatic Hydrocarbons (PAHs), pesticides, herbicides, biocides...)	- Potential disruption of the endocrine functions, the immune system or the nervous system, or risk of cancers	Kim and Zoh 2016, Knap et al. 2002
Increase of nitrate or nitrite	- Impact oxygen transport and can induce Methaemoglobinemia or impact respiratory functions	Gupta et al. 2017, Silwal et al. 2021
Total dissolved solids	- Impact nervous system, and induce gastrointestinal irritations	Gupta et al. 2017
“bad” overall water quality	- Can lead to skin disease, diarrhea, gastric problems, or respiratory illness	Halder and Islam 2015

Table 4 (continued)

Source of modification of aquatic ecosystems	Impact on human health and well-being	References
Ecosystem services	<ul style="list-style-type: none"> - Provision of resources, water, food... - Provide cultural services, recreational activities, cultural and scientific development, improve psychological and physiological health, social interactions, moods and behavior 	Limburg 2009, Sandifer et al. 2015
Biodiversity of the ecosystem	<ul style="list-style-type: none"> - Prevention and reduction of diseases outbreaks, and control of infectious diseases 	Sandifer et al. 2015, Grizzetti et al. 2016, Pongsiri and Roman 2007

(*POPs* Persistent Organic Pollutants, *PAHs* Polycyclic Aromatic Hydrocarbons, pesticides, herbicides, biocides...)

Some stress factors have not been shown to have a direct impact on human health. For example, the pH and alkalinity of water has no direct impact on human health, but may impact human well-being through the taste. Only repeated and excessive consumption of water with a very acid or very alkaline pH may have an impact on human health (Silwal et al. 2021)

and well-being. Moreover, only a few studies, mainly in North America, have examined the cumulative effects of various stressors on aquatic ecosystem health (Dube et al. 2006; Crain et al. 2008). Based on our review, we suggest that an adaptation of bioindicators (e.g. phytoplankton, macroinvertebrates), physicochemical parameters, and chemical compounds already in use is needed to widen their application to the assessment of the impact of ecosystems on human well-being.

The main indicators used in biological indices and physicochemical indices found in the literature have been described through the few indices cited. For example, in biological indices, indicators are mainly based on taxonomic metrics such as the richness, abundance or taxonomic composition, or on parameters of sensitivity or tolerance to disturbance, or the presence and ratio of native and non-native species (Birk et al. 2012, Poikane et al. 2015, Poikane et al. 2020). These parameters used in the different available indices are largely overlapping. The main physicochemical indicators used to assess aquatic ecosystems, either via an index or calculated separately, were also analyzed here.

The most suitable and pertinent bioindicators are the ones with a sensitive and fast response to environmental modifications to evaluate the state of the ecosystem over the long term (Adams and Greeley 2000, Roley et al. 2014). Among sensitive bioindicators, diatoms and other phytoplankton species (e.g. cyanobacteria, Sentenac et al. 2023) appear highly suitable, owing to their short development cycle, sensitivity to environmental conditions, organic pollution, and eutrophication, and their rapid response rate (Brown et al. 2004). Monitoring cyanobacteria, indicators of ecosystem degradation (Mateo et al. 2015), has the additional advantage, that they can also inform about the potential presence of potentially harmful cyanotoxins (Sentenac et al. 2023). Toxins can affect humans through oral infection, skin or inhalation during recreational activities, or ingestion of contaminated water or organisms. The human morbidities associated with cyanotoxins are varied including fever, skin irritation, disruption of the gastrointestinal system, and in very rare and severe cases increased risk of cancer (Dash et al. 2015; Christensen and Khan 2020). Their impacts are multiple from disruptions of ecosystem services like water treatment, recreational activities, or economic loss, to the production of hazardous toxins for animals and humans (Mez et al. 1998; Zanchett and Oliveira-Filho 2013). However, there is a lack of standardized methods and experts for phytoplankton identification which makes such indices difficult to use and not always suitable. A metataxonomic approach targeting diatoms and cyanobacteria might be an advance, but currently available 16S and 18S primers have limited taxonomic resolution (Sentenac et al. 2023) and call for new targeted primer development.

Phytoplankton monitoring indicators should be supplemented by data on macroinvertebrates and fish. They are less sensitive to environmental changes, but easier to identify, while time-consuming to collect (Verneaux 1994, Barbosa et al. 2001). Macroinvertebrate and fish indices can be useful to study the long-term evolution of ecosystems and constitute stable communities and are hence complementary to phytoplankton and zooplankton approaches. Both species groups indicate degradation of water quality, eutrophication, increase in bacterial load and pollution and cyanobacteria blooms, all impacting negatively on human health.

Physico-chemical metrics are easy to use and interpret, and can easily be comparable from different environments if there is a reference state. We identified dissolved oxygen, pH, biochemical oxygen demand, suspended solids, and nutrients as the most useful metrics of aquatic ecosystem health linked to human health risks. They indicate degradation of water quality, eutrophication, and human-induced stress, increasing the risk for human health.

Finally, organic and inorganic contaminants, such as pesticides and heavy metals, are an ever-increasing health issue, even in remote areas (Machate et al. 2022, 2023). Only eight indices in our review used data on organic and inorganic pollution. The quantitative assessment of the concentrations and the presence of organic molecules and of inorganic heavy metal trace elements is generally costly and many molecules are not readily detectable with current sampling and analytical techniques. A broad assessment of environmental contamination would ask for a consequent budget, while more sporadic assessments would not allow to analyze background contamination levels. For example, even in low concentrations of ng/l, two molecules, diazinon and permethrin, crustacean species are affected in remote mountain lakes due to their high toxicity (Machate et al. 2022). In those lakes, the period of exposure to the pesticides and their peak concentrations remain unknown and would not have been detected with sporadic sampling. A broad environmental contaminant monitoring would be needed to allow for a robust analysis of health risks for wildlife, animals, and humans. For the moment, there is a lack of studies on the combined impact of organic and inorganic micropollutants on the health of aquatic ecosystems.

Various indices have been developed to assess the health of aquatic ecosystems over the past decades, but linking them up to human health risks has been insufficient done. Setting up an integrative method with several indices is important. We here have outlined that biodiversity monitoring of diatoms, cyanobacteria, macroinvertebrates and fish, needs to be complemented by environmental monitoring of physicochemical parameters, including nutrients, organic and inorganic pollutants, and pathogens to assess ecosystem health and resulting benefits and risks for human health (Fig. 3). While the water framework directive (WFD, Directive 2000/60/EC) is an important policy tool, which provided a unified set of EU-wide applicable indicators on drinking water, a set of more specified indices and indicators for assessing aquatic ecosystem health, such as the one proposed here, are needed for the assessment of existing and emerging human health risks across the European continent.

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Data availability No datasets were generated or analysed during the current study.

Declarations

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