water

Review

Multi-Interacting Natural and Anthropogenic Stressors on Freshwater Ecosystems: Their Current Status and Future Prospects for 21st Century

Doru Bănăduc [1,*], Angela Curtean-Bănăduc [2], Sophia Barinova [3], Verónica L. Lozano [4], Sergey Afanasyev [5], Tamara Leite [6], Paulo Branco [6], Daniel F. Gomez Isaza [7], Juergen Geist [8], Aristoteles Tegos [9,10], Snežana B. Simić [11], Horea Olosutean [1] and Kevin Cianfanglione [12,*]

1 Faculty of Sciences, Lucian Blaga University of Sibiu, I. Raţiu Street 5-7, 550012 Sibiu, Romania; mesaje.facultate@yahoo.com
2 Ecotur Sibiu Association, Grădinilor Street 251, 555301 Cisnădioara, Romania; angela.banaduc@gmail.com
3 Institute of Evolution, University of Haifa, Mount Carmel, 199 Abba Khoushi Ave., Haifa 3498838, Israel; sophia@evo.haifa.ac.il
4 Faculty of Natural Sciences, National University of Salta, CCT Salta-Jujuy CONICET, Av. Bolivia 5150, Salta 4400, Argentina; vlozano@ege.fcen.uba.ar
5 Institute of Hydrobiology National Academy of Sciences of Ukraine, Prospect Geroiv Stalingradu 12, 04210 Kyiv, Ukraine; safanasyev@ukr.net
6 Forest Research Centre (CEF), Associate Laboratory TERRA, School of Agriculture, University of Lisbon, Tapada da Ajuda, 1349-017 Lisboa, Portugal; tamaraleite@edu.ulisboa.pt (T.L.); pjbranco@isa.ulisboa.pt (P.B.)
7 Harry Butler Institute, Murdoch University, Murdoch, WA 6150, Australia; daniel.gomezisaza@uq.net.au
8 Aquatic Systems Biology, TUM School of Life Sciences, Technical University of Munich, Muehlenweg 22, 85354 Freising, Germany; geist@tum.de
9 Laboratory of Hydrology and Water Resources Development, School of Civil Engineering, National Technical University of Athens, Heroon Polytechneiou 9, 15780 Zographou, Greece; tegosaris@yahoo.gr
10 Ryan Hanley Ltd. Ireland, 170/173 Ivy Exchange, Granby Pl, Parnell Square W, D01 N938 Dublin, Ireland
11 Department of Biology and Ecology, Faculty of Science, University of Kragujevac, R. Domanovića 12, 34 000 Kragujevac, Serbia; snezana.simic@pmf.kg.ac.rs
12 ICL, Junia, Université Catholique de Lille, 59000 Lille, France
* Correspondence: ad.banaduc@yahoo.com (D.B.); kevin.cianfaglione@univ-catholille.fr (K.C.)

Abstract: The inheritance of historic human-induced disruption and the fierceness of its impact change aquatic ecosystems. This work reviews some of the main stressors on freshwater ecosystems, focusing on their effects, threats, risks, protection, conservation, and management elements. An overview is provided on the water protection linked to freshwater stressors: solar ultraviolet radiation, thermal pollution, nanoparticles, radioactive pollution, salinization, nutrients, sedimentation, drought, extreme floods, fragmentation, pesticides, war and terrorism, algal blooms, invasive aquatic plants, riparian vegetation, and invasive aquatic fish. Altogether, these stressors build an exceptionally composite background of stressors that are continuously changing freshwater ecosystems and diminishing or even destroying their capability to create and maintain ongoing natural healthy products and essential services to humans. Environmental and human civilization sustainability cannot exist without the proper management of freshwater ecosystems all over the planet; this specific management is impossible if the widespread studied stressors are not deeply understood structurally and functionally. Without considering each of these stressors and their synergisms, the Earth's freshwater is doomed in terms of both quantitative and qualitative aspects.

Keywords: freshwater; natural and anthropogenic stressors; threats; risks; management

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1. Introduction, Background, and an Analysis of Necessity

The interrelations and synergies among planetary freshwater and a high variety of natural and anthropogenic stressors are logically expected to be very complex. In terms of scientific research approach coverage, a bibliographical analysis of 2083 research papers of the Web of Science Core Collection dealing with freshwater stressors highlights the status and trends in this knowledge advance, and last but not least, it identifies some structural gaps in the science world's efforts and results in this field of interest (Figure 1).

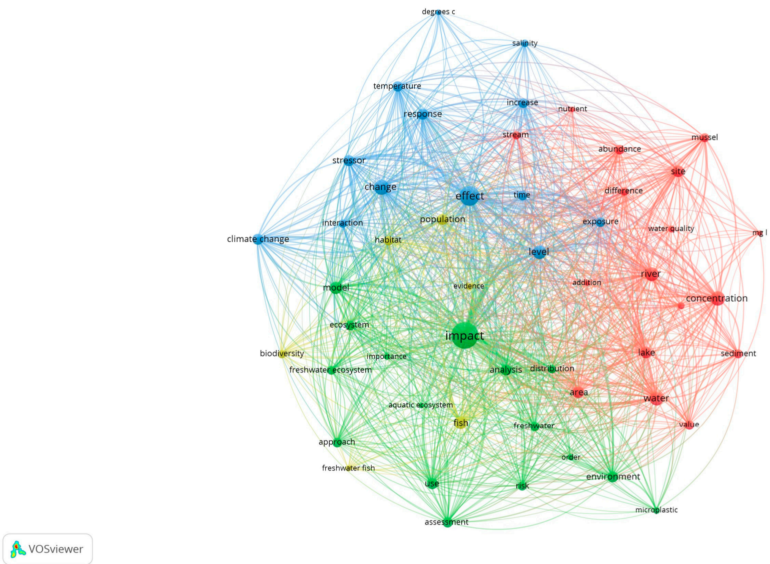

Figure 1. The four interrelated main clusters of freshwater and their stressors and co-occurrence of key terms—network visualization based on 2083 scientific papers published in Web of Science Core Collection. Blue: Articles related to the climate change impact on continental aquatic ecosystems. Green: Articles that analyze methodologies used for water bodies' quality and microplastic impact. Red: Articles that analyze the impact of chemical pollution. Yellow: Articles that analyze the impact of stressors on aquatic biodiversity.

The temporal trend (Figure 2) of the international scientific community's studies reveals that modern research have tried to focus on the interactions among different aquatic ecosystem environments, stressors, exposure, biodiversity, interactions, and risks.

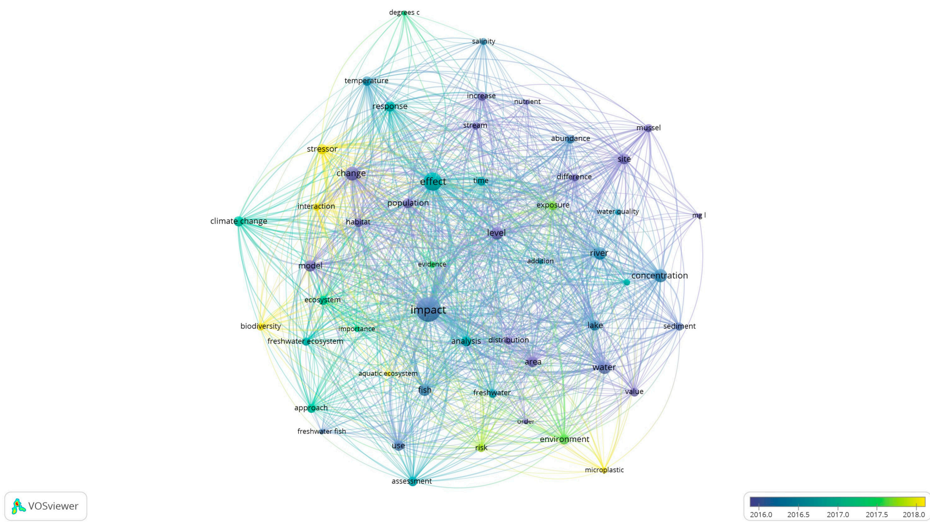

Figure 2. Co-occurrence of targeted key issues—temporal overlay visualization.

The scope of this review is to reveal the importance of the vital freshwater planetary ecosystems' risks associated with some of the main identified natural and anthropogenic stressors. This work's objectives were focused on 16 main natural and anthropogenic stressors, which were identified based on publication result gaps and trend analysis (Figures 3–32) and their characteristics, interrelations, threats, risks, and management.

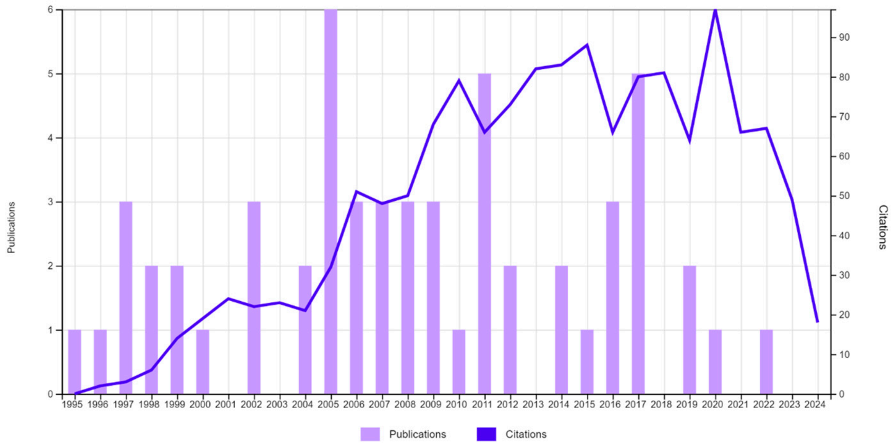

Figure 3. Distribution of articles (56) and citations based on the year of publication (1995–2024)—ultraviolet radiation (worldwide).

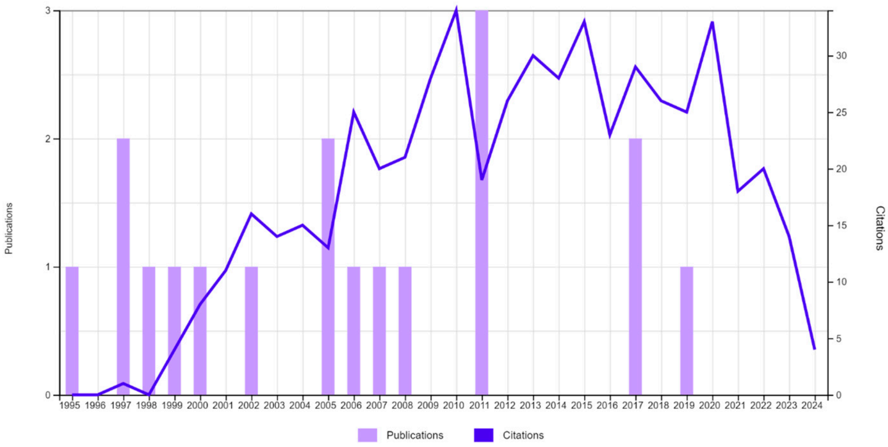

Figure 4. Distribution of articles (18) and citations based on the year of publication (1995–2024)—ultraviolet radiation (Europe).

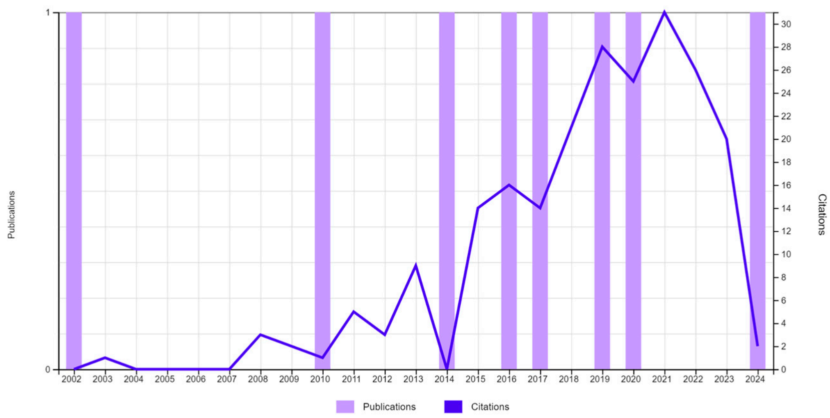

Figure 5. Distribution of articles (8) and citations based on the year of publication (2002–2024)—thermal pollution (globally).

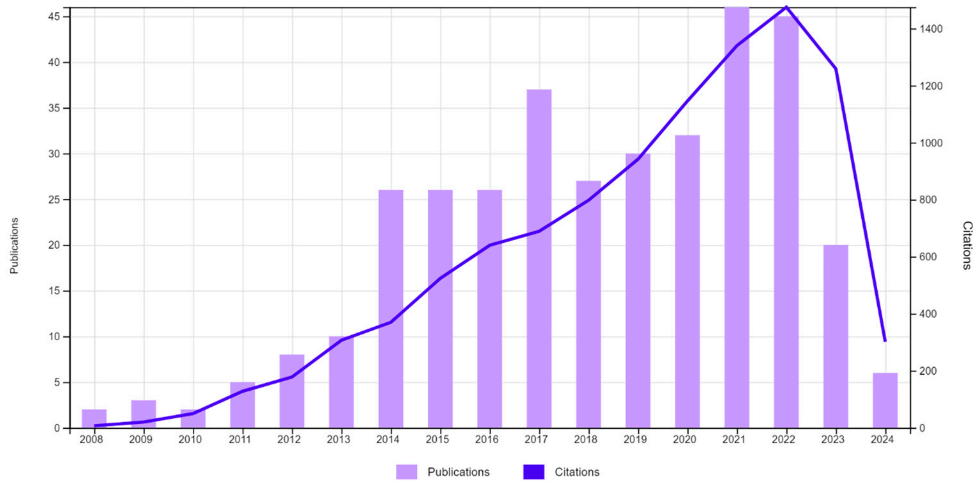

Figure 6. Distribution of articles (351) and citations based on the year of publication (2008–2024)—nanoparticles (worldwide).

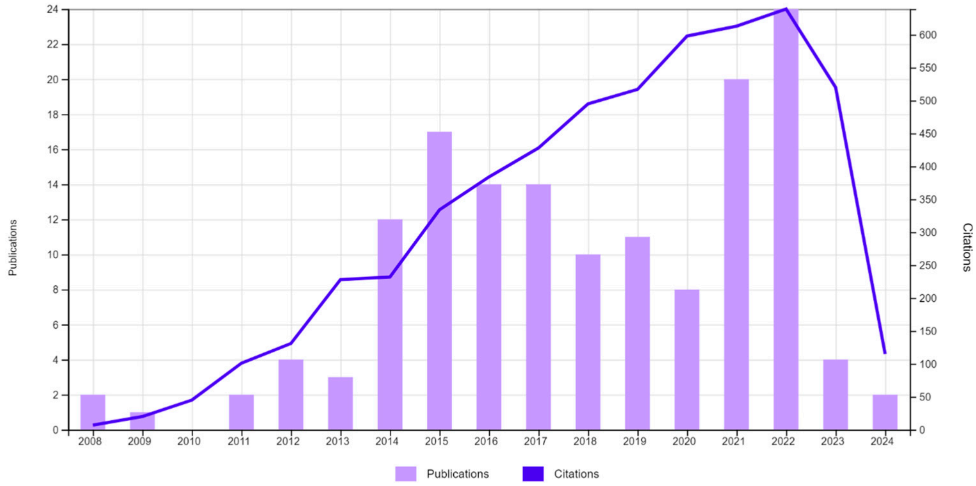

Figure 7. Distribution of articles (148) and citations based on the year of publication (2008–2024)—nanoparticles (Europe).

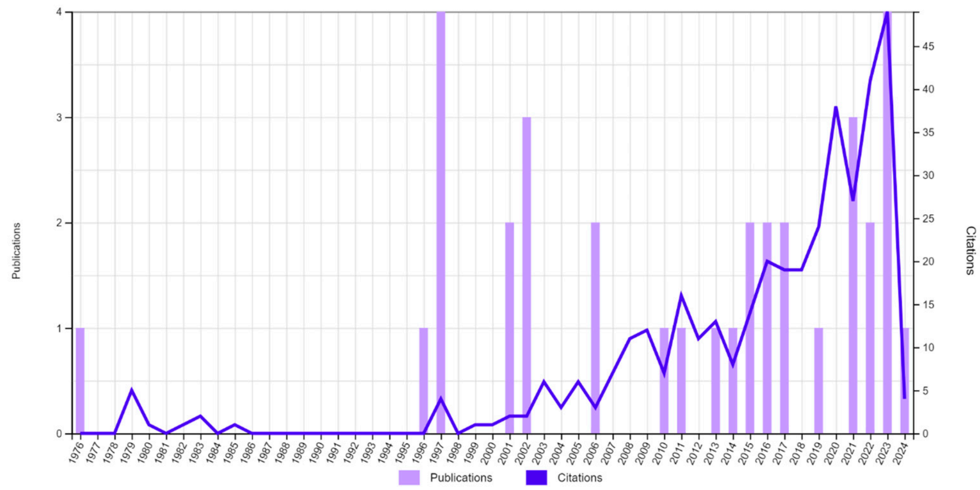

Figure 8. Distribution of articles (34) and citations based on the year of publication (1976–2024)—radioactive pollution (worldwide).

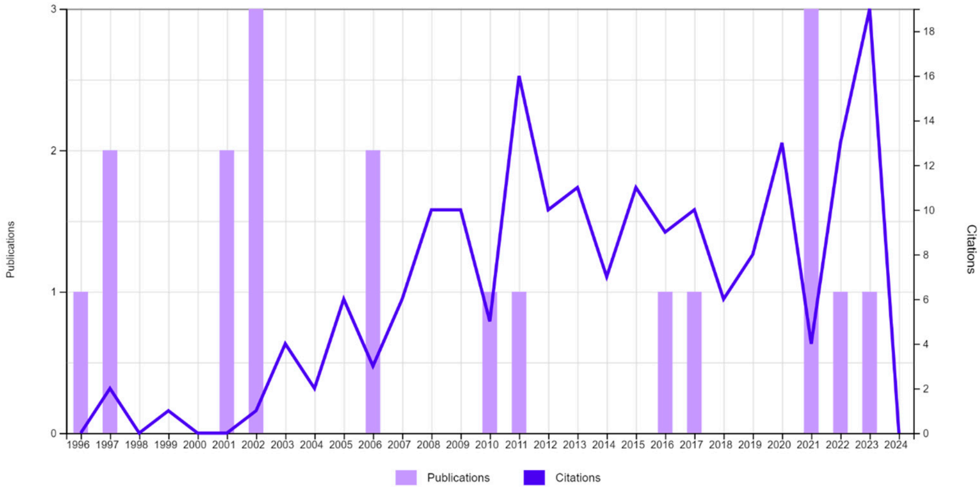

Figure 9. Distribution of articles (19) and citations based on the year of publication (1996–2024)—radioactive pollution (Europe).

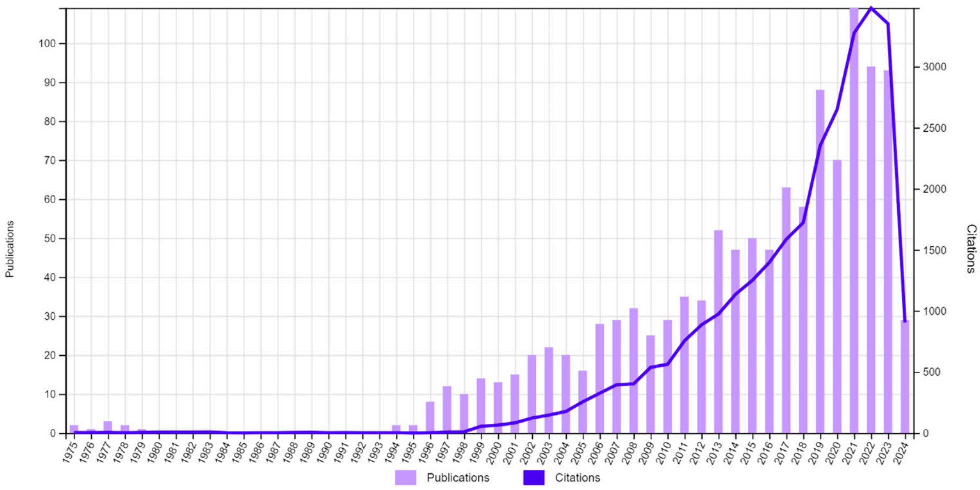

Figure 10. Distribution of articles (1175) and citations based on the year of publication (1975–2024)—salinization (worldwide).

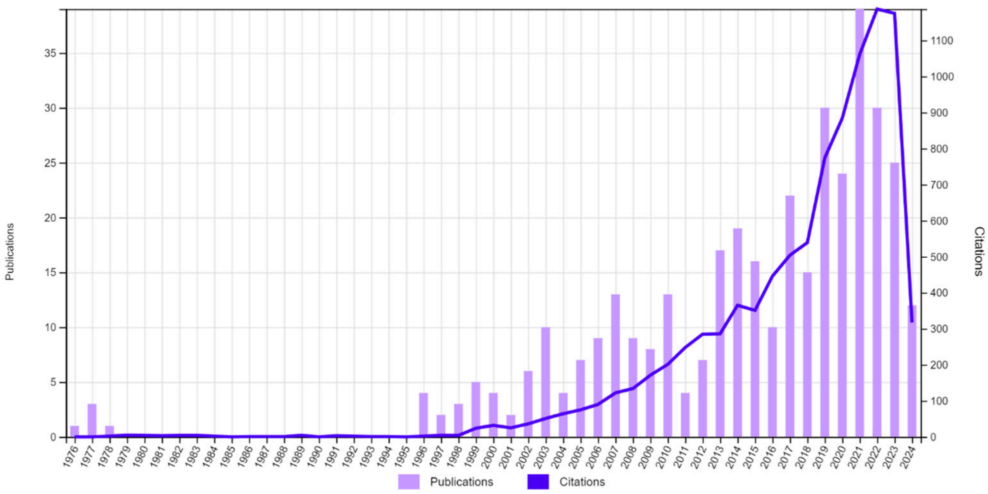

Figure 11. Distribution of articles (374) and citations based on the year of publication (1976–2024)—salinization (Europe).

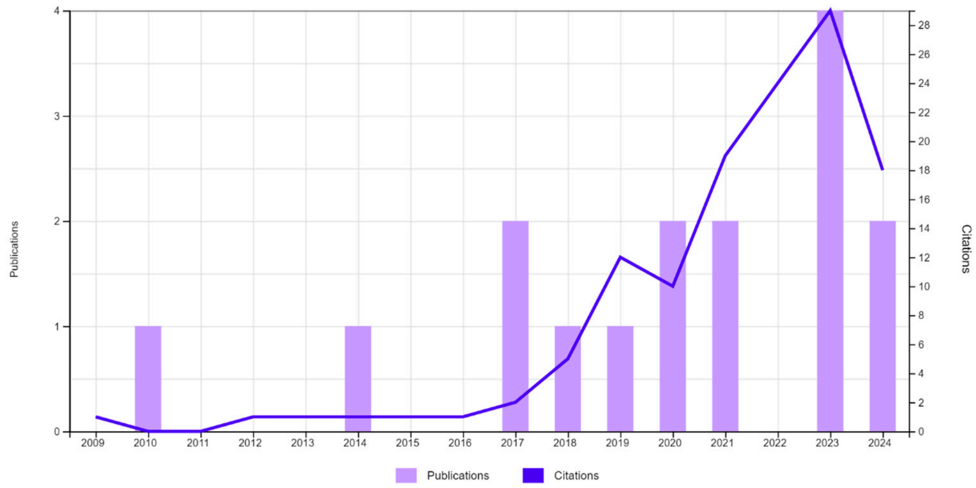

Figure 12. Distribution of articles (16) and citations based on the year of publication (2009–2024)—nutrients (worldwide).

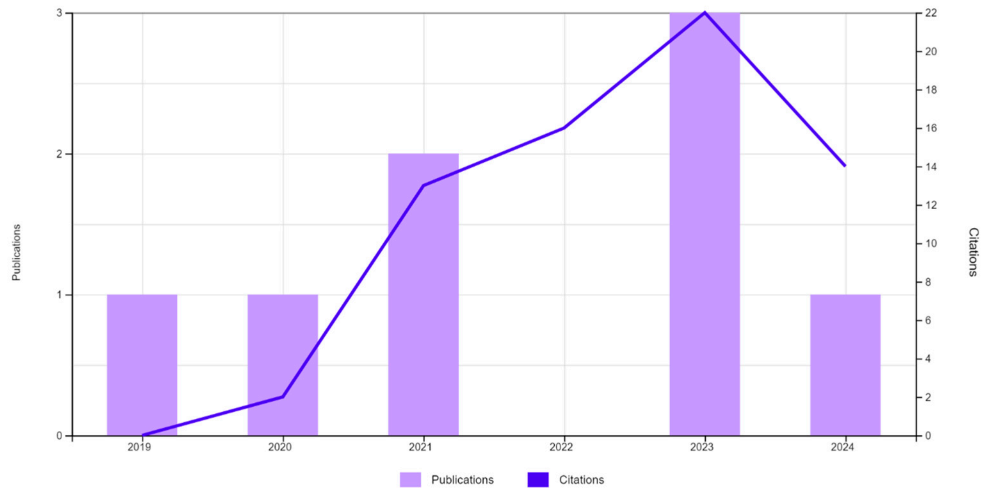

Figure 13. Distribution of articles (8) and citations based on the year of publication (2019–2024)—nutrients (Europe).

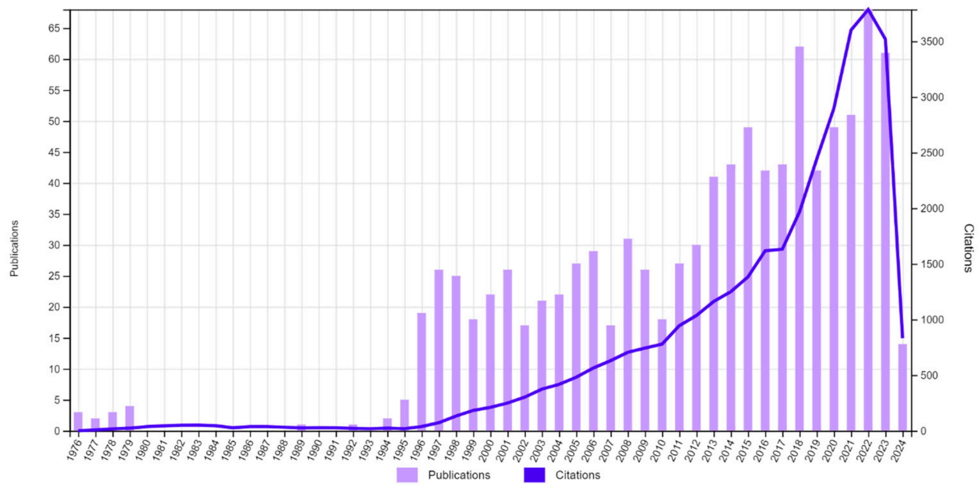

Figure 14. Distribution of articles (987) and citations based on the year of publication (1976–2024)—sediments (global).

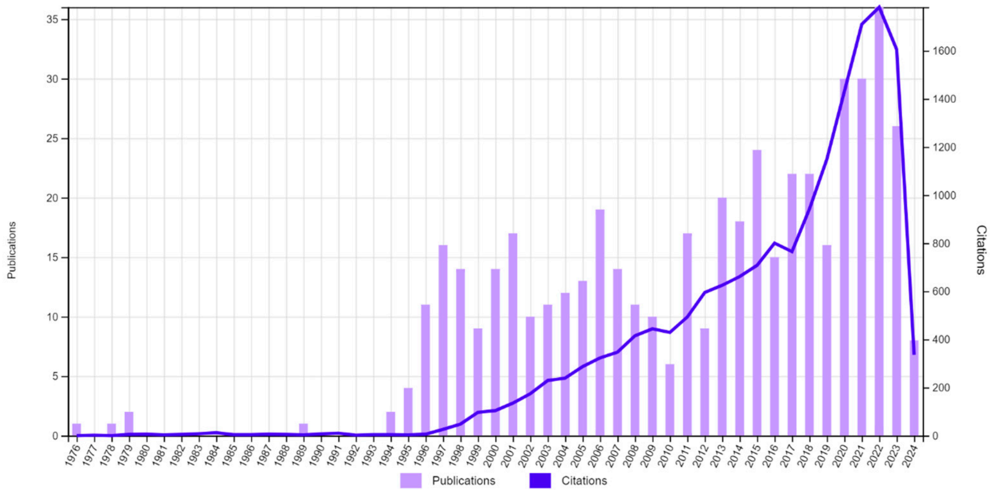

Figure 15. Distribution of articles (491) and citations based on the year of publication (1976–2024)—sediments (Europe).

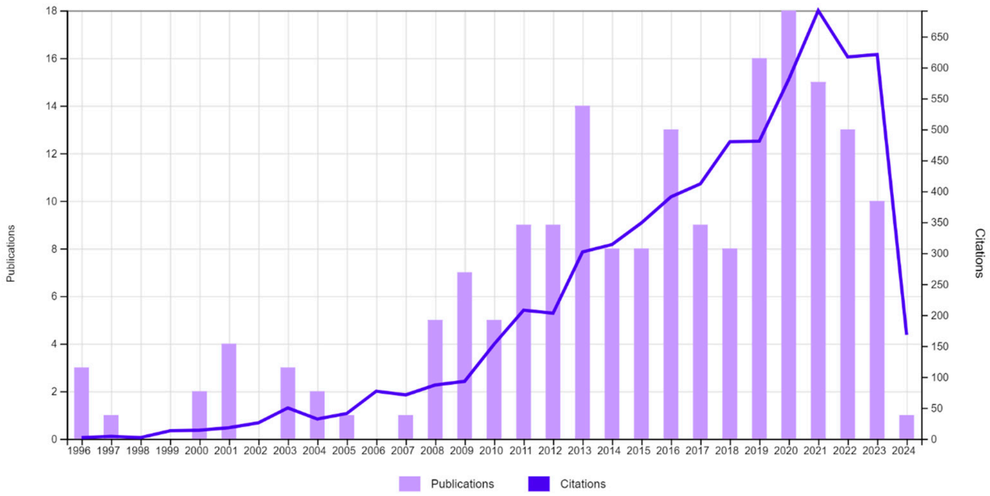

Figure 16. Distribution of articles (185) and citations based on the year of publication (1996–2024)—drought (global).

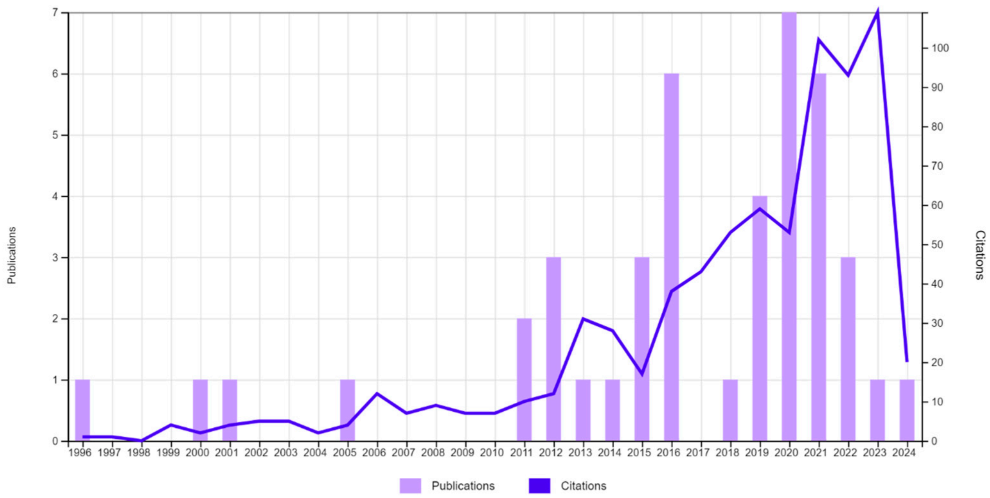

Figure 17. Distribution of articles (43) and citations based on the year of publication (1996–2024)—drought (Europe).

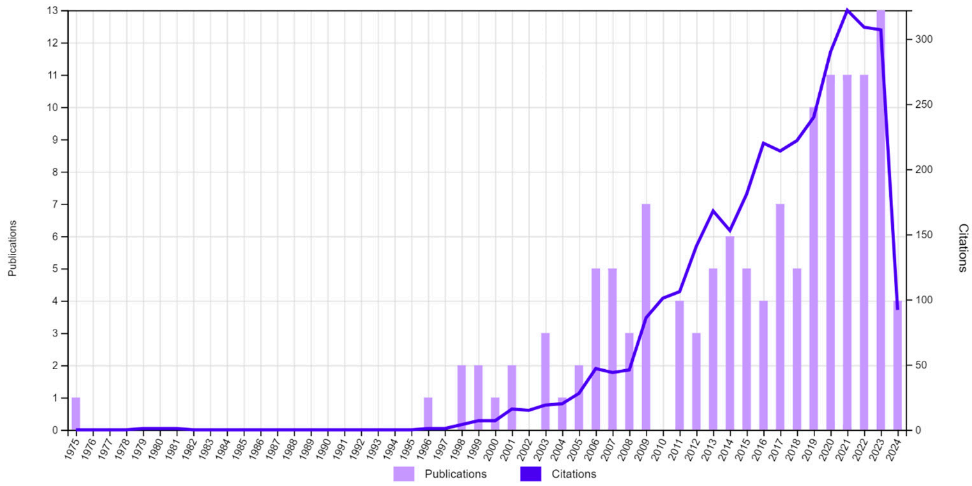

Figure 18. Distribution of articles (134) and citations based on the year of publication (1975–2024)—floods (worldwide).

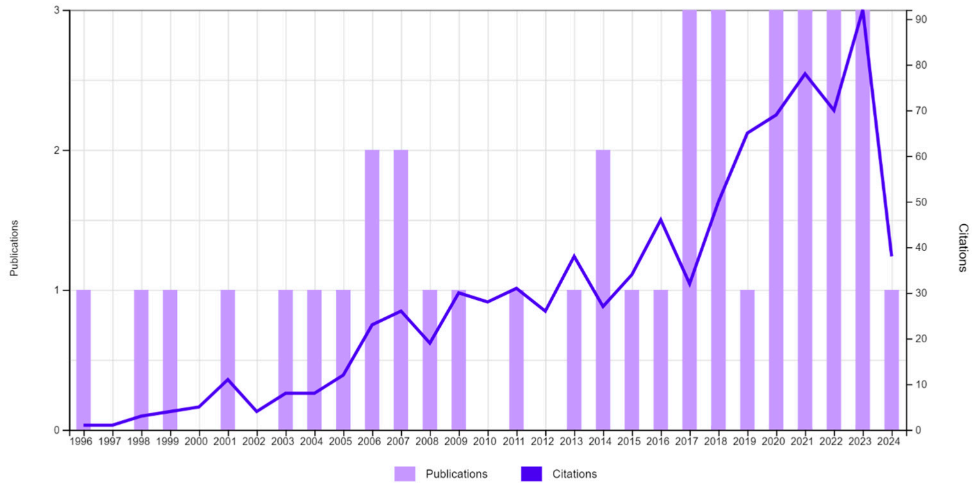

Figure 19. Distribution of articles (39) and citations based on the year of publication (1996–2024)—floods (Europe).

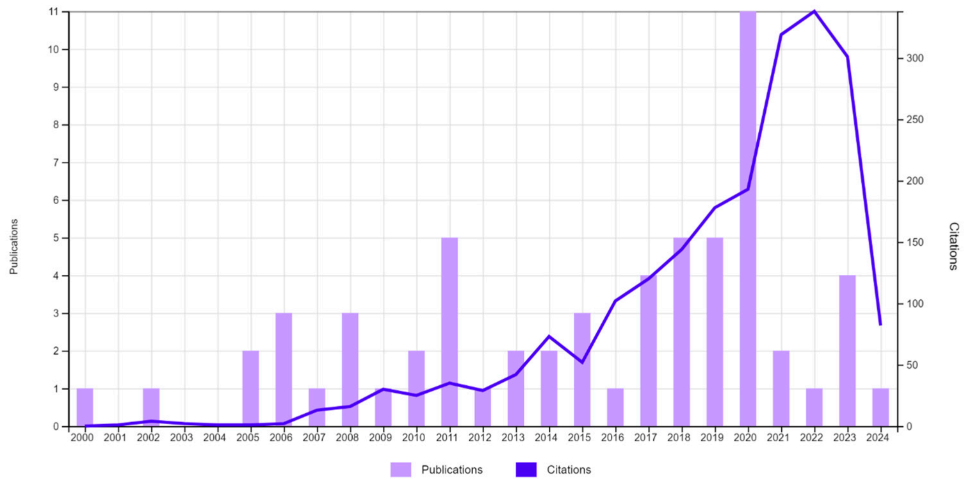

Figure 20. Distribution of articles (61) and citations based on the year of publication (2000–2024)—habitat fragmentation (worldwide).

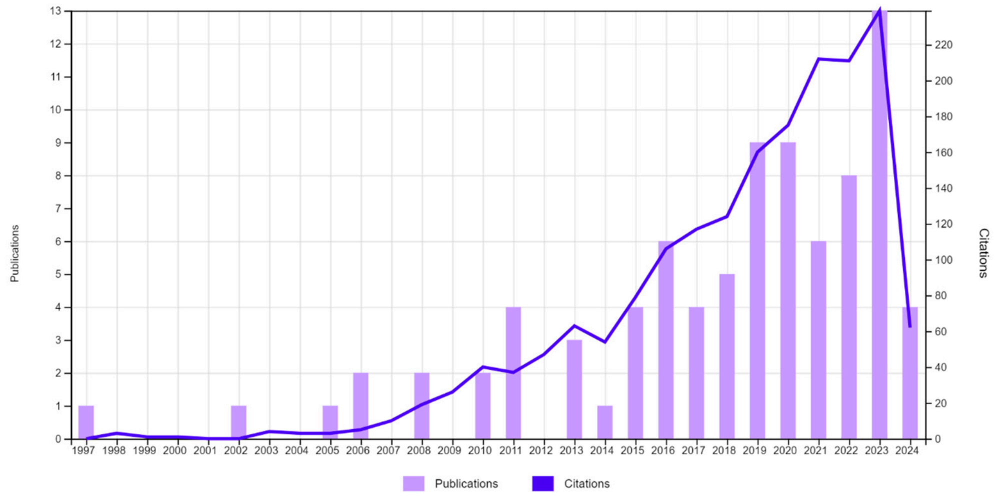

Figure 21. Distribution of articles (25) and citations based on the year of publication (1997–2024)—habitat fragmentation (Europe).

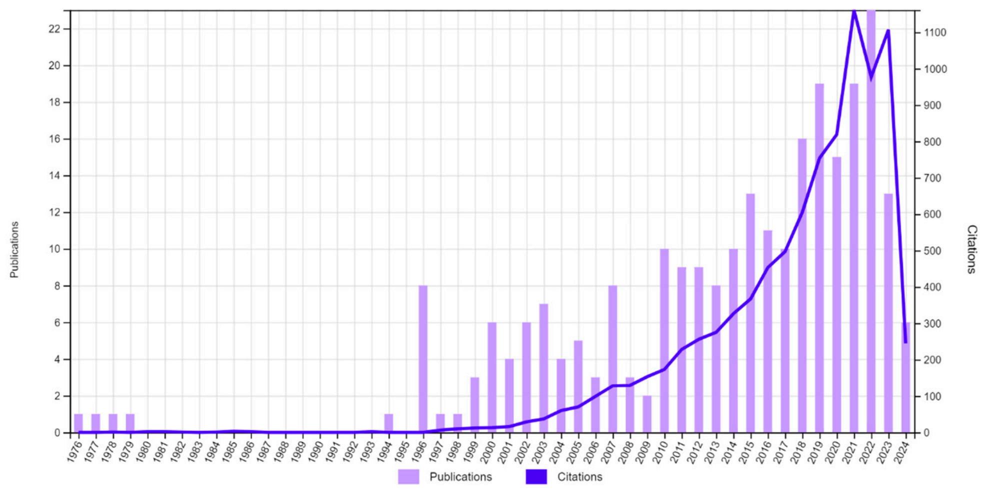

Figure 22. Distribution of articles (257) and citations based on the year of publication (1976–2024)—pesticides (worldwide).

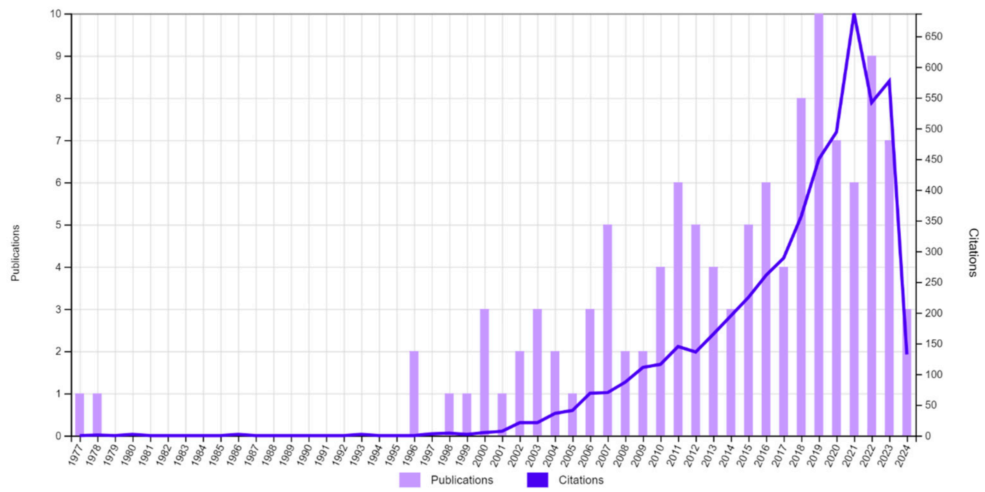

Figure 23. Distribution of articles (117) and citations based on the year of publication (1977–2024)—pesticides (Europe).

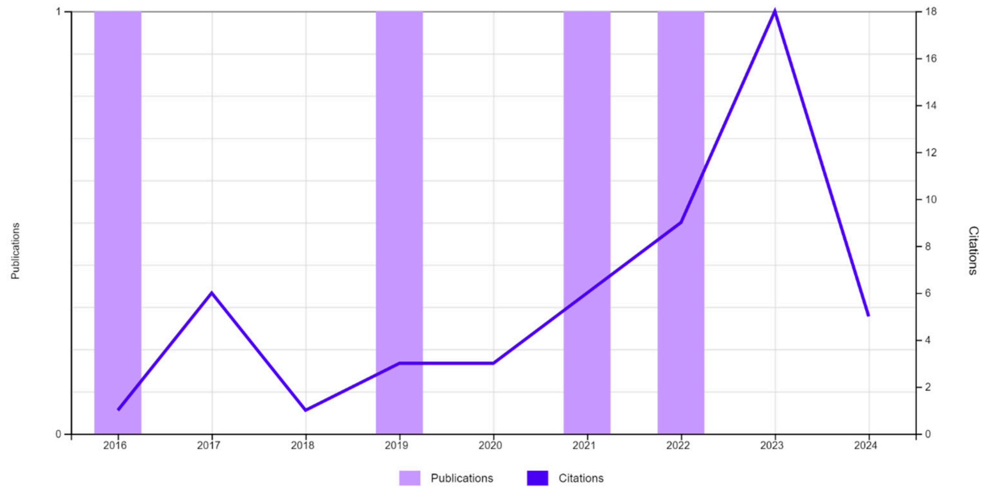

Figure 24. Distribution of articles (4) and citations based on the year of publication (2016–2024)—war and terrorism (worldwide).

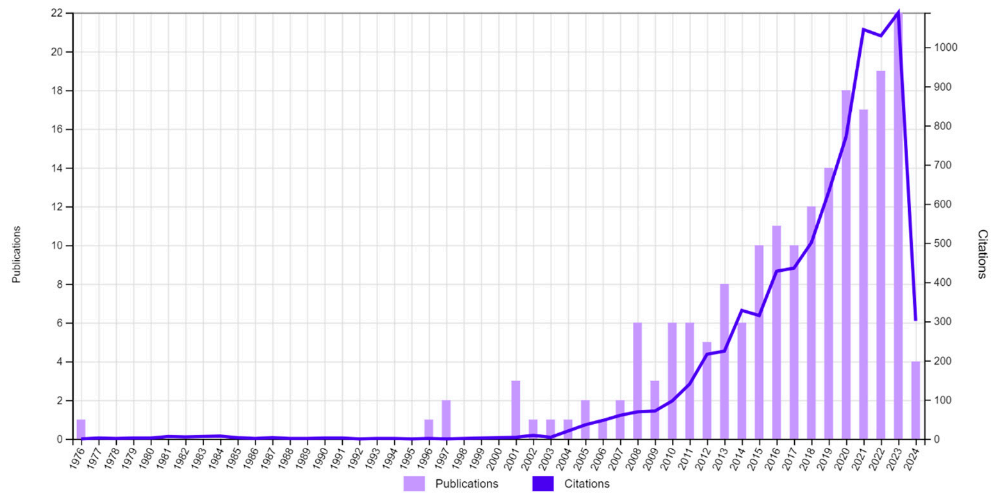

Figure 25. Distribution of articles (192) and citations based on the year of publication (1976–2024)—algal blooms (worldwide).

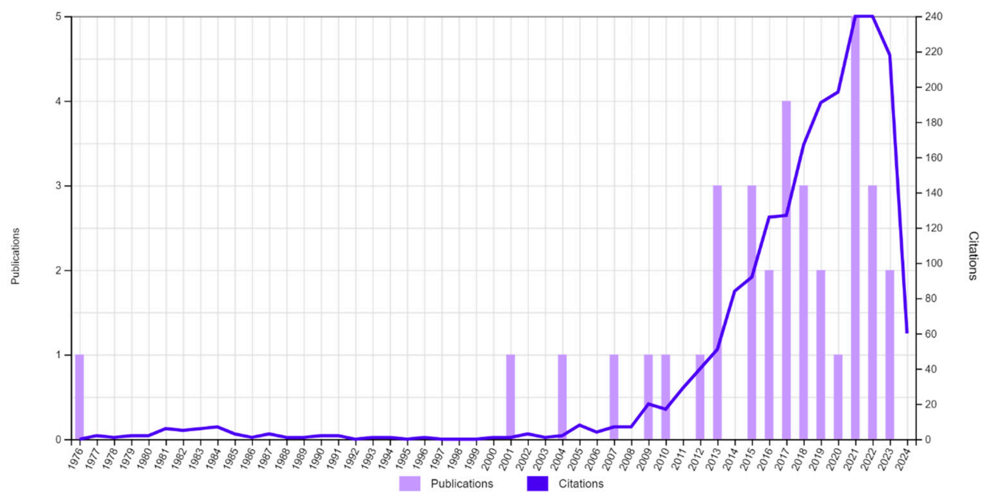

Figure 26. Distribution of articles (35) and citations based on the year of publication (1976–2024)—algal blooms (Europe).

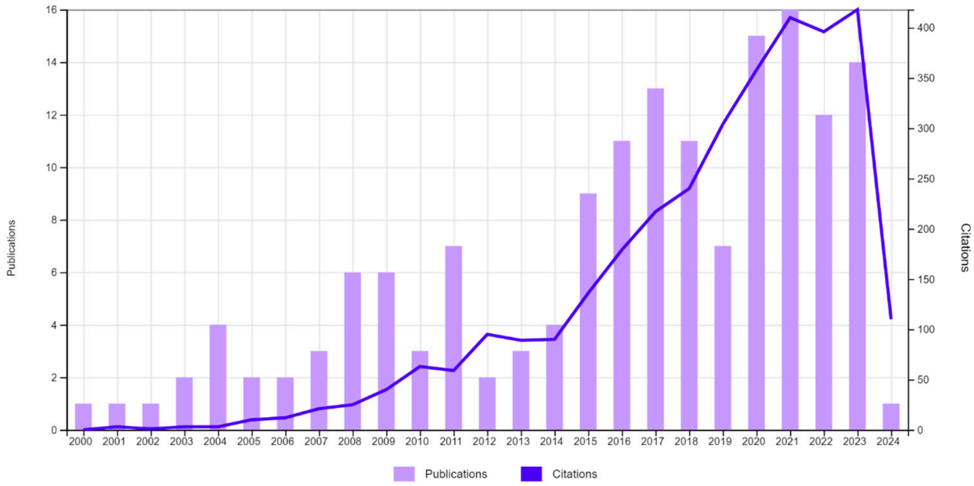

Figure 27. Distribution of articles (164) and citations based on the year of publication (2000–2024)—invasive aquatic plants (worldwide).

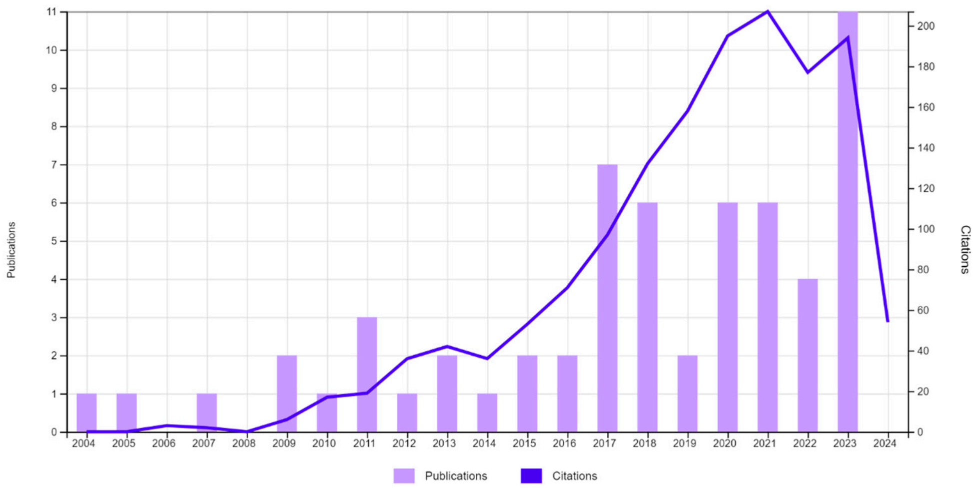

Figure 28. Distribution of articles (59) and citations based on the year of publication (2004–2024)—invasive aquatic plants (Europe).

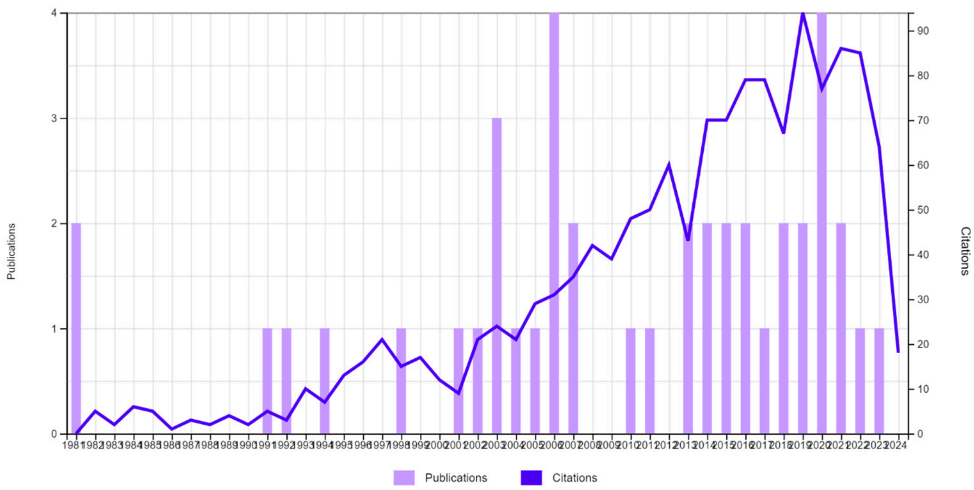

Figure 29. Distribution of articles (42) and citations based on the year of publication (1981–2024)—riverine vegetation (worldwide).

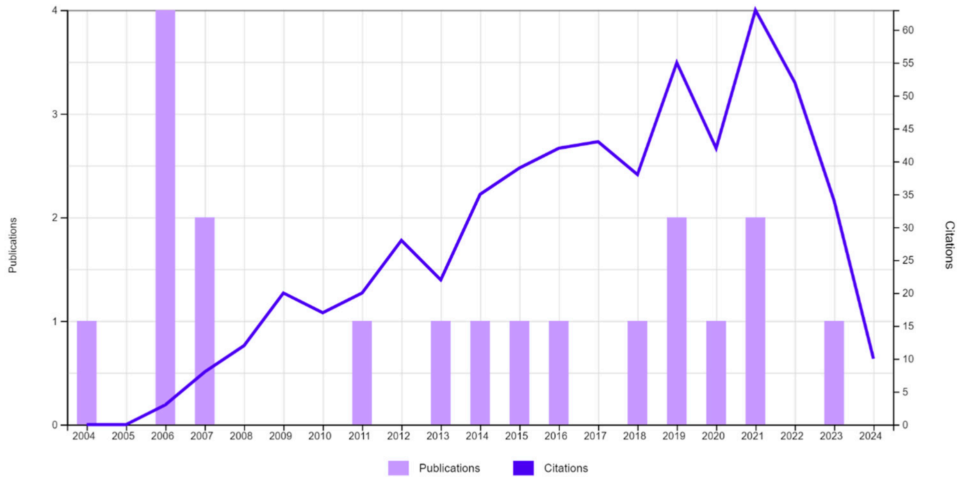

Figure 30. Distribution of articles (19) and citations based on the year of publication (2024–2024)—riverine vegetation (Europe).

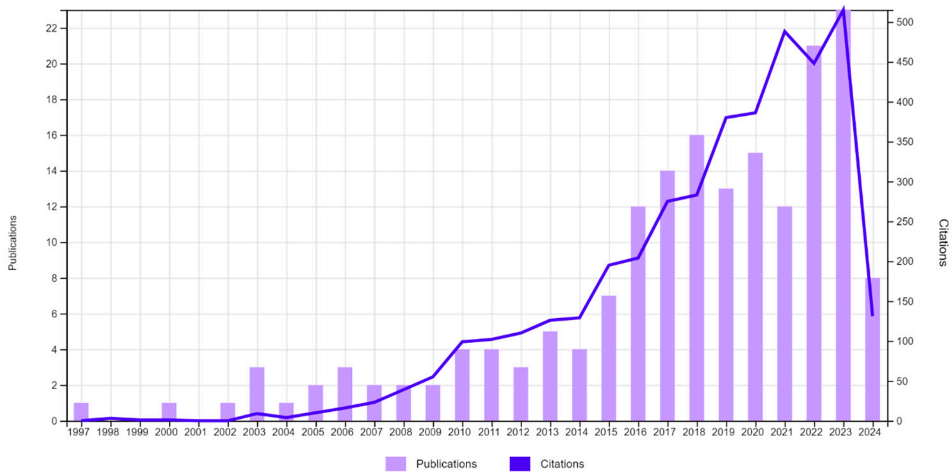

Figure 31. Distribution of articles (179) and citations based on the year of publication (1997–2024)—invasive fish (worldwide).

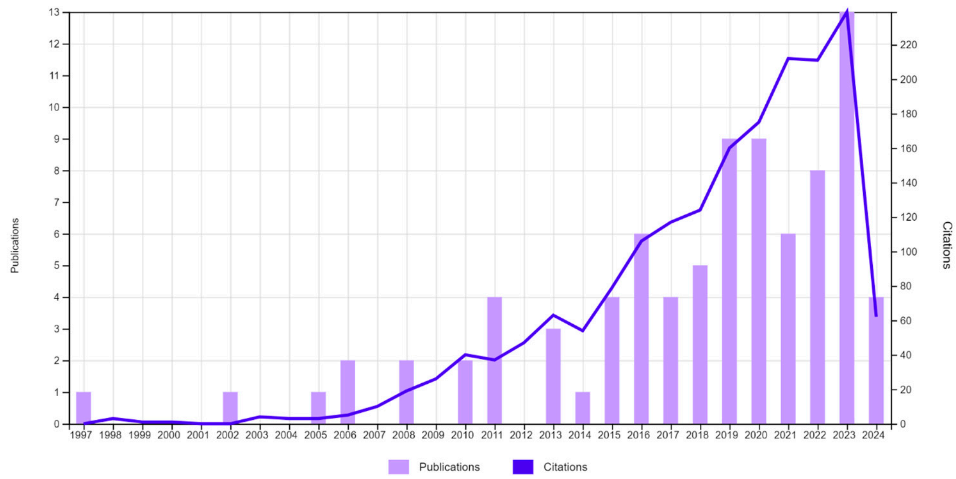

Figure 32. Distribution of articles (85) and citations based on the year of publication (1997–2024)—invasive fish (Europe).

For the bibliographical analysis we used scientific materials published on Web of Science Core Collection, using as search terms “freshwater” in combination with each of the seventeen stressors studied in this review paper. The search specified that the terms should be present either in the title or keywords of the analyzed scientific papers. The results were filtered; only articles, reviews, and proceeding papers were selected.

Water is the key to biological entities' structures, processes, and functions [1,2]. This vital substance for all organisms and ecological systems, fluxes, and circuits is present in large quantities (4.16818183 km^3) on Earth. It varies in its richness: 97.24% in marine areas, 2.14% in icecaps and glaciers, 0.61% in groundwater, 0.009% in freshwater lakes, 0.008% in inland seas, 0.005% in soil, 0.001% in atmosphere, and 0.0001% in rivers [3]. This fact gives the illusion of this resource high availability; however, less than 1% of it is suitable for human needs [4]. The heritage of human-induced disruption and the severity of its present impact greatly distress the structure and function of aquatic habitats [5]; specifically, the growing human population is the main cause of the water shortage and its falling quality, and this growth trend continuing [6,7].

Human-induced environmental change is causing a rise in water temperature, declines in dissolved oxygen content, sea level rises, amplified toxicity from pollution, and habitat degradation and loss, among other changes. These impacts will impose strong pressures on aquatic and semi-aquatic habitats, ecosystems, and their associated resources and services and render future water availability uncertain [8–14].

The proper management of water and related biological and ecological structures and functions, resources, and services can be undertaken at the local, regional, and/or planetary scales. Yet, this may only be accomplished if most threats are approached through an integrated management system to curb human pressures based on state-of-the-art research on freshwater inventory, description, threats, risks, and trends.

In the 20th century, UNESCO began partnerships to cooperate on water-related issues that the Earth is challenged by. The Millennium Development objectives also aim to provide humans with viable access to good-quality water, hygiene, and public health. The Johannesburg Summit proposed that international leaders make safe drinking water and good sanitation available. Have we reached these targets? Are we able to properly manage freshwaters and their associated products and resources? Apart from some local cases, until now, we have failed in this. But do we have the knowledge to adequately manage the many stressors that threaten freshwater ecosystems?

All ecosystems are facing record levels of human-induced stress, pushing them toward global tipping points. Multiple stressors determine these ecosystems' ecological status at continental and global scales [15–19]. Among them, aquatic ecosystems are affected by a wide range of different stressors [20]. This situation raises difficult challenges for academia and decision-makers, who need a solid knowledge base to manage the environmental change crisis. In this review, we highlight some of the natural and anthropogenic stressors in freshwater ecosystems by providing an overview of their status and future prospects in terms of their description, effects, threats, risks, management elements, and freshwater ecosystem protection elements. Specifically, we reviewed, in this respect, the following freshwater ecosystem stressors: solar ultraviolet radiation (1), thermal pollution (2), nanoparticles (3), radioactive pollution (4), salinization (5), nutrients (6), sedimentation (7), drought (8), floods (9), habitat fragmentation (10), pesticides (11), war and terrorism (12), algal blooms (13), invasive aquatic plants (14), riverine plants (15), and invasive aquatic fishes (16). Our review emphasizes some key stressors that influence the quantitative and qualitative features of freshwater ecosystems.

In the context of the global water management challenges, the main idea of our efforts is to manage present and future challenges facing freshwaters to provide appropriate protection to complex ecosystem structures and functions of freshwaters. The key point of this review is to highlight a sequence of individual and categories of environmental stressors with synergistic negative effects, which must be carefully considered for the assessment, monitoring, and management of freshwater ecosystems.

2. Solar Ultraviolet Radiation (UVR)

There has been a fluctuating interest in the impact of the UVR (solar ultraviolet radiation) stressor on freshwater for researchers in recent years both globally (analyses that include countries with both developed and undeveloped scientific networks and financial and human resources) and in Europe (analyses that include countries with preponderant developed scientific networks and financial and human resources), with a significant decrease in interest trends in recent years (Figures 3 and 4). The need for an increase in qualitative and quantitative research efforts is obvious.

Solar radiation influences habitats, organisms, and ecosystems in many different ways depending on its spectral composition [21]. Longer wavelengths (>400 nm) are required for vision in animals and photosynthesis in plants and protists. UV-B radiation (280–320 nm) is harmful to organisms because it damages DNA, biomembranes, and other organelles, whereas UV-A (320–400 nm) can cause damage or stimulate the photo-repair of UV-B damage through photolyases [22].

The UVR effects on organisms depend on diverse levels of exposure, influenced by many factors, including climate change [23]. Climate change is altering the mixing–stratification regimes in the water [24]. These changes are altering key ecosystem services, such as water quality and fishery productivity [25], and impacting biogeochemical cycles, climate-system feedbacks, and biodiversity by inhibiting primary production [26] or rushing the organic matter decomposition through photodegradation, growing the release of greenhouse gases [27]. UVR also alters community structure, distribution and migration patterns, mate choice, foraging, and predator–prey interactions, which ultimately alters trophic interactions and energy transfer efficiency [28]. By contrast, UVR can impact the timing and size of disease outbreaks as it decreases pathogens' infectivity [29] and parasites' fitness [30,31] and reduces their habitat suitability [32,33].

Because UVR is a chronic stressor, it is not straightforward to modify or control the stress response. Even though we have a comprehensive understanding of the individual effect of UVR on aquatic ecosystems, we scarcely know how its interaction with other drivers (e.g., temperature, acidification, nutrient inputs, de-oxygenation) could alter the predictions available. The usefulness of data based on single-driver studies in a future scenario of multifaceted planetary change will be limited [34].

The most effective specific strategy to protect life below water from UVR was the implementation of the Montreal Protocol. This implementation, considered the most successful treaty ever, has protected aquatic life by preventing the large increases in UVR that would have occurred due to the Antarctic ozone "hole" (by 20% today, with respect to the 1990s) without the real protection provided by the ozone layer [35].

The impact of UVR on habitats has been greatly increasing eutrophication and browning of water bodies [36,37]. Rising nutrient and organic matter inputs derived from human activities and extreme climate events (i.e., rainfall and wind) are, in many cases, reducing water transparency [38]. Increased water turbidity exerts negative feedback on primary producers because it can limit [39] and inhibit photosynthesis [40]. By contrast, it favors heterotrophic processes, such as respiration, which can trigger anoxia processes that can affect higher trophic levels (e.g., fishes) [41]. These interlinked processes and global-change drivers can not only impair the ecosystems' functioning but also alter the social perception that we have about ecosystems in a negative way and the provision of several ecosystem services (e.g., food supply, drinking water, recreational activities) [42].

It is critical to quantify the costs of multiple perturbations that freshwater ecosystems are facing. A dialogue between governments, natural area managers, and scientists should be promoted to improve and spread knowledge about how anthropogenic activities and changes in land use affect water quality and other ecosystem services and to build commitment. Thus, funding to perform large-scale and long-term experiments designed to test how communities and ecosystems respond to climatically and anthropogenically driven changes is pivotal for providing knowledge-based decisions that support the practices to be developed in future management and conservation plans.

3. Thermal Pollution

The impact of thermal pollution on freshwater has generated an extremely low level of interest for researchers in recent years, both globally and in Europe (eight studies in the studied period, seven of which are in Europe) (Figure 5). The need for both qualitative and quantitative research on these issues is urgent.

The water temperature in the natural environment varies and depends on the region of the planet and on the source of heat, which can be natural (e.g., volcanoes, hot groundwater) or human-made (e.g., thermal and nuclear power plants). The term thermal pollution is applicable only to the second group of sources. Thermal pollution is one type of physical pollution of the natural environment characterized by a periodic or prolonged input of hot or cold waters to the natural water bodies that cause the degradation of water quality by changes in water temperature associated with human activities [43–45].

The water temperature of the water bodies affects not only biological processes but also the growth of aquatic plants and animals [43,46–49]. Cold water pollution suppresses the development of fauna in freshwater [50]. Conversely, warming increases the rate of photosynthesis due to an increasing number of producers up to a temperature of about 32 °C, with temperatures above this temperature beginning to cause mortality and decomposition by aerobic bacteria [51,52]. Water temperature interacts with other abiotic stressors as a driving force for impact. Its effect on ecological processes is due to the complex combined nature of the interaction of stressors [53]. Thermal pollution is a stress factor for aquatic ecosystems and is also capable of exacerbating the effects of anthropogenic pollution. While chemical pollution factors are classified according to their degree of presence in a natural water body, thermal pollution can be measured in a particularly polluted water body but is not classified among other variables [54]. The reaction of an aquatic ecosystem to thermal pollution is assessed by the change in the state of its biotic part [54]. As a result of thermal pollution of water bodies, the production of organic matter in them begins to prevail over destruction, aerobic processes are replaced by anaerobic ones, the sanitary condition of water bodies deteriorates, and significant changes occur in biota [53]. A drop or increase in water temperature in the receiving water body of about 10 degrees or more is likely a value that leads to intense changes in the biotic part of the ecosystem [43,48].

Since the source of thermal pollution is anthropogenic, the intensity of warm or hot water release can be controlled [55]. However, it is impossible to assess the degrees of damage caused as a result to the aquatic ecosystem by measuring the temperature at the inlet of hot water in the reservoir [56] since the distribution of water temperature and the impact in the receiving reservoir has an uneven character [44,47,57]. In this case, the communities structure [58] turns out to be a particularly sensitive link in the ecosystem, and bioindication [59–61] was the most sensitive method for assessing ongoing changes. The innovative methods can lead to positive results in the assessment of the thermal pollution effects on aquatic ecosystems [44,61–65]. It was found that the similarity between thermal pollution and organic pollution impacts [60] can show the parallel in both ecosystem response processes and, therefore, open a new field for thermal influence research [44].

To protect aquatic ecosystems, the United States has an upper temperature limit of 32 °C for surface waters [56] or up to 28 °C according to European Union environmental standards [55]. But, the main thing is to assess the degree of influence of the influx of hot water on the receiving reservoir [66]. The ecosystem can modify its characteristics as the trophic state (e.g. algae or cyanobacteria blooming), the ecosystem's basic structure [61], invasive organisms' events, etc. [47].

The monitoring of species content changes in the natural biota of aquatic ecosystems is important for providing forecasts of future changes, which, together with modeling, can be a part of the biodiversity conservation strategy [50,60,62,66].

An analysis of existing approaches to assessing the thermal impact on freshwater ecosystems has shown that more attention is paid to studies of aquatic animals and plants than to microalgae. The system for indicating thermal exposure (cold or hot) has not yet been sufficiently developed. Research is of a more private or experimental nature, while assessments of the impact of temperature anomalies are made on natural open systems. However, assessment methods are developing quite actively.

If we are not able to manage water temperature, the water quality and quantity could be disturbed more than we anticipate, transforming it into an unsafe environment. The water temperature should be kept within the local and regional natural ranges by full real-time monitoring, automatic alerts, and real-time status reporting of the problematic effluents and their strict technological control by insulation, cooling, etc., at the very points of contact with water bodies.

4. Nanoparticles

There has been a steadily increasing number of articles and citations on nanoparticles (NPs) as stressors that impact freshwater in recognition of its importance globally (investigations that include countries with developed and undeveloped scientific networks and financial and human posibilities) but with a sharp decline in recent years—a trend that needs to be reversed for this area of interest in the future—and in Europe (analyses that comprise countries with preeminent developed scientific networks and financial and human resources) (Figures 6 and 7). The need for increasing both qualitative and quantitative research efforts on these issues is evident.

NPs ranging in size from 1 to 100 nanometers [67], have emerged as a relatively new stressor in freshwater aquatic ecosystems. NPs are composed of various materials, including metals, metal oxides, and polymers. Their unique physical and chemical properties make NPs valuable for a wide range of industrial, commercial, and medical applications such as drug delivery, energy production, and electronics. However, their unique properties make them potentially hazardous to the environment.

Once released into the nature, NPs shows high persistence, undergo major transformation, and display high reactivity with other substances around. These characteristics can lead to harmful effects on ecosystems, both by directly impacting and indirectly influencing the complex ecological interactions within multiple-stressor environments.

The presence of NPs in aquatic environments can exert major impacts on organisms, yielding adverse effects. One such result is the induction of reactive oxygen species (ROS) by NPs, leading to oxidative stress within the tissues of organisms. Also, the accumulation of NPs in diverse organs can cause physical stress and tissue damage. NPs can also affect the food chain in aquatic ecosystems by accruing in tissues and being transferred to larger organisms, causing biomagnification. Furthermore, the delicate balance of aquatic microbiota and enzymatic activity can be disrupted by NPs, further exacerbating the negative repercussions on the health of aquatic organisms and water quality [68].

Concerning management elements, the physicochemical characterization (size, surface area, shape, solubility, aggregation, etc.) and the elucidation of biological effects have been proposed [69]. Effective management should involve assessing and monitoring the sources, fate, and transport of NPs in the freshwater ecosystems. Vale et al. [68] highlighted the importance of assessing the dynamic speciation of NPs in the exposure media and identifying specific endpoints for risk assessment studies. In particular, particle size and shape are important factors to consider when assessing the toxicity of NPs in aquatic environments. For example, smaller Ag-NPs present more severe toxicity to aquatic organisms due to their higher particle-related toxicity caused by small particles and higher ion-related toxicity caused by their high dissolution rate and extent [70].

Protection may include implementing green chemistry practices, promoting the use of alternative materials, and developing sustainable manufacturing processes. Strategies to mitigate the effects of NPs on aquatic organisms include the use of nanoremediation techniques and developing early warning systems for NPs contamination.

One rapidly growing field is focused on nanopesticides. When it comes to assessing their aquatic ecotoxicity, it has been suggested that nanopesticides pose a lower environmental risk compared to conventional pesticides due to reduced drift. However, there is still a scarcity of studies that comprehensively evaluate this risk, particularly in comparison to conventional pesticides on an ecosystem scale [71]. Considering the potential environmental contamination resulting from the use of nanopesticides in food production and the potential risks they may pose to aquatic life, there is an urgent need for comprehensive studies on their ecotoxicity prior to their introduction into the market.

In conclusion, we need to urgently and exhaustively monitor environmental contamination and regulate the use and disposal of NPs, prioritizing the reduction of their release into the environment and developing guidelines for their safe handling.

5. Radioactive Pollution

There is fluctuant evolution in the number of articles on radioactive pollution as a stressor with an impact on freshwater, with a significant interest trend in recent years as a recognition of its importance globally (analyses that include states with both developed and undeveloped research networks and financial and human resources), and in Europe (analyses that include states with preponderant advanced scientific networks and financial and human resources), there has been a fluctuant evolution in the number of articles, with a significant interest trend in latest years (Figures 8 and 9). The need for an increase in both quantitative and qualitative research efforts for these issues is clear.

In the last century, the testing and use of nuclear energy resulted in global contamination by artificial radionuclides [72]. Other sources of the technogeneous radionuclides entering freshwaters consist of mining, refining, and hydrometallurgical processing of the uranium ores; production, processing, and storage of nuclear fuel; operation of nuclear power facilities; production and use of radioactive isotopes; radioactive wastes; and nuclear and radiation incidents, accidents, and disasters [73–75].

The International Atomic Energy Agency (IAEA) identifies natural or technogeneous radioactive contamination as the occurrence of radioactive compounds where their presence is unintended or undesirable or the process gives rise to their presence [76].

Ecosystem response to radiation depends on species' sensitivities and the multitude of direct and indirect pathways by which individual organisms can be affected, including the potential for complex interactions across multiple trophic levels [77,78].

The water bodies located near nuclear power plants are the most vulnerable, as they are subjected to thermal discharge, chemical pollution, eutrophication, mechanical stress, and additional irradiation by artificial radionuclides. The liquid discharges of the most widely used WWER-type reactors contain a wide spectrum of radionuclides, mainly the fission products, first of all, 3H, and radioisotopes of biologically essential elements and their chemical analogs ^{131}I, ^{89}, ^{90}Sr, ^{134}, ^{137}Cs, ^{141}, ^{144}Ce, ^{103}, and ^{106}Ru, among others. The other group of radionuclides comprises products of corrosion of the reactor active zone and the first contour of the heat carrier ^{51}Cr, ^{54}Mn, ^{60}Co, etc. [79,80].

The destructive impact of radiation on the nucleic DNA and other molecular components of organelles, which, depending on the impact intensity and duration, can be irreversibly damaged, is accepted as the main threat of radiation [81–83].

The radiation dose on the organisms, first by the radionuclides contained in water and bottom sediments, is an important integral criterion of the radioactive pollution effect on the aquatic biota [80,84,85]. At this, the organisms are able to concentrate the radionuclides in organs and tissues, which can result in a notable increase in the dose load owing to internal irradiation [86–88]. At the same time, average levels of internal irradiation of aquatic organisms from the radionuclides near nuclear power plants are much lower than irradiation from radionuclides occurring in the environment [79,80].

Despite the relative resistance of aquatic organisms, chronic doses of irradiation can cause damage, mostly mutations, and reduce their vitality, which results in a decrease in the species diversity and changes in the hydrobiocenoses' structure [78,89,90]. The ecosystems' response to the stress impact of the radioactive contamination appears in decades, owing to changes in the structural and functional characteristics of populations and communities of the organisms, as certain irradiation doses can stimulate some species or can be ineffective for others, and suppress radiosensitive species [91,92].

The radioactive contamination of freshwater requires optimization of the complex radioecological monitoring systems, which serve as an "end point" of many biologically hazardous long-living radionuclides, as well as an in-depth study of the nuclear energetics impact on the organisms [93,94]. The radioecological monitoring should include regulated collection and analysis of the primary survey data, prompt detection of the radioactive compounds in the aquatic environment, and informational support for assessment and forecast of risk degree for the aquatic ecosystems as well as for decision-making for the radiation and hydro-ecological safety of the nuclear-cycle enterprises [95].

IAEA is authorized to establish and accept safety standards of radiation protection and provide the application of these standards [96].

The irradiation effects on freshwater ecosystems can be mitigated by chemical, physical, and social countermeasures [97,98]. Computerized systems are under development for management support to identify optimal strategies for the rehabilitation of radionuclide-contaminated aquatic ecosystems and the selection of optimal strategies for freshwater ecosystems with different contamination scenarios [98].

6. Salinization

There has been a constant increase in the number of articles on salinization as a stressor that impacts freshwater, with a low decrease in the interest trend in recent years as a recognition of its importance globally (analyses that include countries with both developed and undeveloped scientific networks and financial and human resources), and in Europe (analyses that include countries with preponderant developed scientific networks and financial and human resources), there has been a constant increase in the number of articles, with a low decrease in the interest trend in recent years (Figures 10 and 11). The need for qualitative and quantitative research efforts on these issues is clear.

Salinization is the increase in inorganic ions in water bodies [99,100]. Primary salinization results from natural processes such as rainfall, rock weathering, seawater intrusion, and aerosol deposits, and secondary salinization is induced by human activities [101]. Anthropogenic salinization is mainly caused by the runoff from irrigation in agriculture, industrial discharges, mining, and salt use in winter on roads [102–104].

The leaching of excess salts increases concentrations of chloride ions and heavy metals in water bodies, which pose a risk to human health and freshwater-related processes [105,106] and can produce temporary yet acute stress on biota [107]. The high salinity levels in rivers create an osmotic pressure on their animals, which can have effects on metabolism, growth, reproduction, and survival [108–111]. Bacterial, fungal, and macroinvertebrate richness can be reduced with salinity increase, altering organic matter decomposition by microorganisms and detritivores and other ecosystem functions affected by the loss of salinity-sensitive taxa [112,113]. For instance, chlorides negatively impact aquatic organisms but favor the phytoplankton, accelerating eutrophication and increasing algal blooms [114]. Freshwater salt retention also reduces benthic organisms' diversity, like bivalves sensitive to salinity [115,116]. Acute stress has negative effects on several aquatic species, mostly fish [117–119]. Fish have diverse ranges of salt tolerance, depending on species, life stage, salt concentration, temperature, and exposure duration. Exposure to high salinity compromises metabolism and influence osmoregulation, and fish development may be impaired [111,120,121]. Short-term effects of salinization stress on fish include behavior modifications [122,123]. Therefore, if freshwater fish populations are exposed to behavioral disruptors such as salinity, there may be severe ecological implications [124]. In contrast, some research suggests some organisms might be less sensitive or have developed a tolerance for high salinity, like *Daphia pulex* [125].

The main contributors to the salinization of rivers are humans. There is thus the chance to reduce saline chronic inputs by properly managing land uses and promoting adequate water natural filtering, i.e., riparian forests, and water gathering and treatment, e.g., for the road salts case. Ecosystem-scale experiments, advances in water quality monitoring technology, and models are required to advance and better inform management frameworks for predicting salinization consequences and identifying possible restoration opportunities of freshwater ecosystems [126]. For the chronic input threats, we should add the acute events, like, for example, the well-known case when emergency releases of saline water from chemical plant lagoons led to a complete resetting of all living organisms in the Dniester River for 500 km and triggered the spread of invasive fish species [126].

The management of freshwater secondary salinization must be improved at different scales through mitigation (e.g., source control of main inputs of salt ions, agricultural chemical inputs' regulation, land-use change limitation, backfilling of mine tailings), remediation (e.g., riparian buffer areas care, solutions to clean-up of surface and groundwater, enhanced wastewater treatment), prevention (e.g., eco-friendly alternatives to roads salts), and monitoring (e.g., assessing salt loads to freshwater ecosystems) [127].

Multiple stressors will likely co-occur in nature in addition to increasing salinity, and sequential stressful events may have additive, synergistic, or antagonistic cumulative effects, intensifying or not, the effects of salinity [128–131]. Furthermore, these repercussions of human-driven salinization on river systems could additionally be amplified by climate changes [102,104], as temperatures will rise, and evaporation and dilution capacity of freshwater bodies will be affected [132], augmenting residence time and salt concentration in many water bodies, thus endangering many aquatic species and causing biodiversity loss [133–135]. Extreme salinity may grant competitive advantages to non-native species and produce a community unbalance that may lead to reduced functional community resilience and the failure of ecological processes.

Secondary salinization is increasing vividly across the globe, and climate changes exacerbate it. Salinity stress threatens biodiversity and changes communities. Understanding the impacts on human health and freshwater taxa is critical to predicting the ecosystem impacts of salinization and informing conservation and management decisions. Coordinated management should take place to prevent future pressure on existing freshwaters.

7. Nutrients

There has been a small number of scientific articles on nutrients as stressors and their impact on freshwater (analyses that include nations with both developed and undeveloped scientific networks and financial and human resources), and in Europe (analyses that include nations with preponderant developed scientific networks and financial and human resources), there has been a small number of scientific articles (Figures 12 and 13). The need for these issues to gain attention in the science world is urgent.

Nutrient pollution has emerged as a major stressor in freshwater ecosystems as a direct consequence of the increasing human population and their activities. Nutrient pollution occurs when nutrients, mainly nitrogen and phosphorus, accumulate in water bodies at excess levels. Nutrients are essential to the maintenance of freshwater ecosystem functioning; however, the accelerated and uncontrolled nature of anthropogenic nutrient pollution has led to nutrient levels reaching historically high levels in freshwaters worldwide [136].

Nutrient pollution is the most pervasive threat impacting freshwater ecosystems worldwide. The overuse of agricultural fertilizers, the combustion of fossil fuels, and increasing urban pressures have led to the mass runoff of nutrients into local waterways [135]. Nutrient pollution is expected to worsen with ongoing human development and is predicted to act synergistically with other global threats to endanger aquatic life [137].

Freshwater ecosystems are completely transformed by long-term excess nutrient inputs. Surface plants and cyanobacteria become over-abundant and dominant over other plant forms, which creates low light conditions for underwater organisms [138]. Low levels of oxygen typically trigger mass fish deaths, which further exacerbate environmental problems [139,140]. Water conditions are also disrupted; hypoxic (low oxygen) episodes become frequent, turbidity levels increase, and high nutrient levels disrupt aquatic life [135,138,141].

Nutrient pollution threatens to endanger aquatic habitats unless targeted management strategies are implemented. Management of nutrient pollution should target the source of the pollution that is limiting the application of nitrogen and phosphorus in agriculture and urban settings through strategies such as fertilization management, conservation tillage, and control of water irrigation [142,143]. Key to source control is the application of strict regulations regarding agricultural practices, though enforcement of regulations remains a challenge [134]. Once in the environment, process controls aim to eliminate nutrients before they leach into the receiving water. For instance, buffer zones (e.g., vegetative buffers) along waterways trap and filter excess nutrients from runoff.

Recent decades have seen technological advancements that can treat industrial and domestic effluent as a protection treatment strategy to curb nutrient pollution in freshwaters [144,145]. Among them are water-saving irrigation, ecological ditches, constructed wetlands, and buffer strips, which have successfully been applied to control agricultural runoff [145]. However, no single technology can manage nutrient pollution at all spatial and temporal scales.

Nutrient pollution presents a strong conservation challenge for aquatic fauna. Under the impact of the high levels of nutrients, an overabundance of algal biomass can destabilize food web dynamics [146], and long-term nutrient disturbance can homogenize freshwater communities across local (α diversity) and regional (β diversity) scales that threaten ecological and evolutionary process [146]. Nutrient pollution can also affect aquatic animals through direct toxic effects [147–150].

Conservation strategies have focused on determining minimum ecotoxicological endpoints (e.g., lethal concentrations; LC_{50}; [151]), physiological disruptions [148,152], and also sublethal toxicological effects [141] of nutrients on aquatic organisms.

Nutrient pollution presents a growing risk to freshwater ecosystems. Targeted and holistic management strategies and actions, including source control, process control, and end-treatment processes, are required to control nutrient pollution [153].

8. Sediments

There has been a constant increase in the number of global articles and citations on sediments as stressors with an impact on freshwater (analyses that include countries with both developed and undeveloped scientific networks and financial and human resources), and in Europe (analyses that include countries with preponderant developed scientific networks and financial and human resources), there has been a constant increase in the number of articles and citations (Figures 14 and 15). The need for these issues to gain attention in the science world is urgent.

Changes in land use are growing erosion, which subsequently introduces excessive amounts of fine sediments in some sectors of aquatic ecosystems [154,155]. In general, both increases and decreases in the transport of suspended sediments can be witnessed as a direct consequence of anthropogenic activities. The building of an extremely high number of dams and barriers along the rivers has had the effect of decreasing the river transport of suspended sediments in numerous systems worldwide, causing the erosion of river delta, coastal lagoons, and coastlines. Global climate change resulting in more extreme weather conditions, such as heavy rainfall, as well as structural stream modifications, such as unwise dam construction in rivers, can exacerbate fine sediment accumulation problems, particularly if they involve changes in flow regimes [156].

The stream bed is a crucial habitat for many riverine organisms as a permanent or temporary habitat. This includes multiple target species of conservation, such as gravel-spawning salmonids and early life stages of endangered freshwater mussels [157]. Increased introductions of fine sediment can result in colmation and reduced oxygen supply to the interstitial zone, which increases mortality in fish eggs of gravel-spawning fishes [158,159], decreases juvenile habitat quality for endangered freshwater mussels [157,160], and can even affect microbial community structure and associated ecosystem services [161]. Fine sediment synergistically interacts with other stressors, such as increased temperature and flow alterations, exacerbating the problems, e.g., related to recruitment in gravel-spawning cold-water fishes [162].

Elements of sediment management in river systems include reducing their introduction, e.g., by buffer strips [154], appropriate management of aquaculture systems connected to hydrographical nets of streams and rivers [163,164], as well as the management of flow regime dynamics [156]. The restoration of stream beds by flushing out fine sediments or introducing gravel has been tested, with lower success in central European streams of intensive agricultural land use compared to forest-dominated Scandinavian streams with forested catchments [165,166].

Since, in the past, a much greater management focus has been placed on freshwater quality, nonstop awareness about the extraordinary importance of the stream bed for stream ecosystem functioning, as well as about the factors that can adversely impact this very important type of habitat, is also fundamental. Several species act as ecosystem engineers and directly interact with fine sediment. For instance, the bioturbation resulting from the burrowing behavior of lampreys, different insect larvae, and mussels can all impact the quality of the stream bed [167,168]. On the other hand, filter-feeding species such as mussels can reduce the amount of suspended fine sediments and turbidity [169]. Protection strategies have to take the interaction of fine sediment with other stressors [162] into account. Protection strategies need to consider complete catchments that govern the process of influencing erosion and sedimentation patterns.

Integrative conservation management of streams and rivers and their biodiversity require the inclusion of stream beds as a fundamental habitat [170]. Maintaining the patchiness and habitat heterogeneity in the end is governed by structurally rich habitats [171] since numerous efforts of restoration, such as the introduction of coarse gravel or the washing out of fine sediments, are very laborious and of limited persistence [171]. In light of the climatic change with warmer temperatures, more severe and prolonged droughts, low-flow conditions, and more extreme weather increasing peak erosion, the conservation and restoration challenges related to functional stream beds will increase.

The too often-overlooked stressor of fine sediment pollution needs to be better considered in the management of rivers and streams habitats quality and biodiversity conservation, especially in light of climatic change, which exacerbates the problem of anoxia in this zone.

9. Extreme Drought

There has been a constant globally increase in the number of articles and citations on drought as a stressor that impacts freshwater, with a decrease in the last few years (analyses that include countries with both developed and undeveloped scientific networks and financial and human resources), and in Europe (analyses that include countries with preponderant developed scientific networks and financial and human resources), there has been a constant increase in the number of articles and citations, with a decrease in the last few years in terms of articles but not in terms of the number citations (Figures 16 and 17). The need for these issues to gain attention in the science is urgent.

Meteorological droughts are defined as a period (seasonal, annual, or interannual) of low rainfall relative to the statistical multi-year average for a given location [172,173]. Droughts are a natural characteristic of the hydrological cycle that drives population dynamics and evolutionary processes in freshwater ecosystems [174,175]. Yet, climate warming and human activities are working in tandem to exacerbate drought conditions in freshwaters around the world [175–177]. For one, freshwater ecosystems and the life they support are facing the strain of overextraction and catchment degradation due to the competing needs of human development [178,179]. Freshwater faces the compound risk of climate change, where shifts in precipitation and warmer temperatures mean that some regions are forced to contend with less rainfall than historical norms [172].

In freshwaters, droughts develop as below-average rainfall leads to reduced surface runoff and stream inputs and a loss of soil moisture. Periods of drought may cause water bodies to dry up or be reduced to small pools. The receding water column is typically accompanied by a suite of physicochemical changes, including an increase in water conductivity (salinity), decreasing oxygen levels, a buildup of nutrients, and an increased risk of harmful algal blooms [178,179]. The risks of drought are exacerbated by human alterations to freshwater ecosystems, such as water extraction, sedimentation, and the construction of water barriers (dams, weirs) [178]. Drought conditions create a dangerous cocktail of stressors that can result in a reduced abundance and localized extinction of aquatic life, as well as altered ecosystem functioning [179–181].

Options for mitigating drought impacts are vast [176,182–184] but require a combination of technological and social actions. Technological tools can lessen the impacts of drought on freshwater through improved water conservation, water reuse, and improved water-efficiency devices [184]. Public outreach and strict water conservation policy will be crucial in curtailing extreme drought [182]. For example, policy reforms led to profound changes in public perception of water conservation during Australia's Millennium Drought [185–187]. However, combating the contributions of climate warming to extreme droughts will require intergovernmental actions [185].

Drought protection requires proactive strategies that minimize the impact of man-made alterations to waterways. For example, the restoration of catchments and riverbank zones, maintenance of refuge habitats, and reinstatement of water flow can introduce resilience to freshwaters against increasing drought conditions [178].

Worsening drought conditions pose a significant conservation issue to freshwater ecosystems. Droughts act as a ramp disturbance, meaning that their severity increases with time [188,189]. As such, sensitive species will be lost early in the disturbance, while resistant species could withstand intensifying drought conditions [179,190]. Conservation measures to combat drought will require an understanding of the spatial variation in the severity of drought impacting freshwater habitats [176,190] and the drought sensitivities of regionally important species, coupled with pre-emptive and responsive management actions [180,191], all of which are within the well-known climate change context.

Drought conditions can pose extreme challenges to freshwater. With predictions for longer and more severe droughts, coordinated efforts are required at global, regional, and local levels to ensure the long-term sustainability of freshwater ecosystems.

10. Extreme Floods

There has been a constant globally increase in the number of articles and citations on floods as stressors that impact freshwater (analyses that include states with both developed and undeveloped scientific networks and financial and human resources). By contrast, in Europe (analyses that include states with preponderant developed scientific networks and financial and human resources), it is of low interest, with a small number of articles published annually but a relatively constant increase in the number of citations (Figures 18 and 19). The need for all these complex issues to gain attention in Europe is a necessity.

Extreme fluvial floods are associated with intense natural phenomena resulting in overbank flows in natural river bodies. It is also linked with artificial high flows in strongly modified rivers influenced by the operation of hydropower plants or channelization works to alleviate river water levels. Flooding is the most important environmental parameter in floodplain aquatic environments, and therefore, floodplain wetlands should be considered integrated components of a single dynamic system linked by strong interactions between hydrological and ecological processes [192]. The concept of the flooding pulse was first introduced by Jung et al. [193], defining the flood as a main driving force responsible for the existence, productivity, and interaction of the major biota in river-floodplain systems. Flooding pulses are strongly linked with habitat and organisms' diversity, nutrient and sedimentation life cycles, etc.

The floodplain habitat expansion during flooding creates important spawning, nursery, and foraging areas for many fish species and a variety of other vertebrates. The alteration of the natural flooding regime may substantially impact aquatic ecosystems since it has been observed that reduced summer floods and increased winter flows cause excessive growths of submerged aquatic macrophytes in some rivers regulated by hydropower stations [194]. The effect of flooding in determining fish access to nurseries and food has been well defined [195,196]. The latter has also been investigated in conjunction with the river regulation for quantifying the value of inundated floodplains for breeding and juvenile habitats [197] and whether the fish will remain trapped in isolated floodplain water bodies or are released back into the river system [198].

Another main way that fluvial flooding is linked with biodiversity is associated with the floodplain alluvium since the duration of floods has been the most vital variable driving riparian dynamics. For example, Poiani et al. [199] predicted that the abundance of mature cottonwood would decrease from 40% to about 20% without flooding within a period of about 120 years and would disappear completely in about 450 years. Other studies present similar outcomes as the flow regulation/stabilization below existing dams reduces floodplain size and substantially impacts the riparian ecosystem by altering the trophic structure and reducing the biodiversity, which is highly adapted to the periodic flooding regime and the associated input of nutrients and sediment [200–204].

Assessing the actual connection between extreme flooding and aquatic health is often a challenging task, as a variety of in situ gauges are required to define interconnected study layers [205,206]. Long-term monitoring gauges for multiple abiotic and biotic parameters, as set out above, should be available to provide wise decisions relating to water/environmental exploitation issues.

To manage the negative effects of extreme flooding in the aquatic systems, there is a strong need to provide multidiscipline approaches based on advanced hydrology, hydrodynamics, and environmental modeling in order to investigate optimal strategies for minimizing the flooding impacts on societies and the environment. Integrated engineering solutions must be considered by thoroughly specifying aquatic environmental impacts and, where possible, by promoting environmental wealth as recently proposed by the natural-based approach [207] and also by integrating ecohydrological views within the new major reservoir infrastructure design [208].

Even though the existing and planned hydropower plants have received criticism for unprecedented negative impacts on the downstream riverine environments [209–212], the irreplaceable social value of these types of infrastructure [213] in conjunction with modern and holistic environmental modeling approaches [214] can offer benefits to the aquatic, riverine restoration and maintenance.

The well-defined connection degree of flood flows and riverine ecological components in both unregulated and strongly modified river bodies highlights the importance of setting up detailed integrated modeling approaches based on long-term multiparametric gauges for establishing sustainable scientific solutions, as well as developing reliable and environmentally resilient water infrastructure.

11. Habitat Fragmentation

There has been a relatively constant increase in the globally number of articles and citations on habitat fragmentation as a stressor that impacts freshwater, with an obvious decrease in the last 3–4 years (analyses that include countries with both developed and undeveloped scientific networks and financial and human resources). By contrast, in Europe (analyses that include countries with preponderant developed scientific networks and financial and human resources), there has been a constant increase in the number of articles and citations (Figures 20 and 21).

Fragmentation can be characterized as the lack of connectedness along the river network. When it is the consequence of human activities, such as the construction of river barriers, it is considered to be one of the most threatening stressors affecting freshwater systems. Fragmentation promotes the isolation of habitat patches or even the separation of a given habitat into smaller isolated habitat patches.

Rivers constitute complex, intricate, and dynamic systems that can be characterized by spatial and temporal fluctuations. These systems have been described as having four classical dimensions: longitudinal—along the river; vertical—between the river channel and the hyporheic zone; lateral—between the river channel and river banks; and temporal—over time [215]. Because habitats relevant for the functioning of the systems and for the life-cycle completion of some species are spatially separated, longitudinal connectivity can be arguably considered the most important. Dams and weirs introduce a breach in the longitudinal connectivity of aquatic systems [216–218], which leads to alterations in habitats and flow patterns that can alter environmental cues [219] and affect the biotic communities [220]. These fragmentation effects have been described across various regions, including North America [221–224], Europe [225,226], Australia [219], Africa [227], and Asia [228,229].

River connectivity is a way of understanding rivers, how these relate and interplay with the spatial components within riverscapes, and how this impacts ecological processes [230]. By the same token, connectivity conservation is a guarantee of ecological processes. To understand to what extent protection should be provided, it is vital to account for classic theories, such as the river continuum concept [231], and for more contemporary hypotheses [232], like the river discontinuum concept [233], network dynamic hypothesis [234], and theory of riverine ecosystem synthesis [235]. The solution to fragmentation along river networks is usually linked with solutions that promote connectivity enhancement at a given barrier when removal is impossible [236]. In this situation, fish passages are probably the most ubiquitous solution that can be used to retrofit existing barriers and serve more than just to fish species, allowing water and sediment movement to be partially restored. Artificial barriers block the communication between spatial elements along river networks. These barriers provide several ecosystem services, such as water storage, agricultural irrigation, energy production, and cultural and scenic values, as well as providing nations with a certain level of energy and water resources security that is currently so appealing [237]. A full understanding is crucial not only for grasping the overall effects of river fragmentation due to different physical barriers on targeted fauna populations but also for devising management strategies to enhance connectivity, aiding in the conservation and management of biodiversity.

Habitat fragmentation is not linearly correlated to the number of barriers present in a system; it is dependent on their features (e.g., height, slope, flow alteration promoted), on the scale of analysis (e.g., river reach, segment, sub-basin, or whole basin), as well as the movement patterns and capability of affected species. River fragmentation by barriers can limit movement and migration along the river, leading to the decline or extinction of numerous native species across Europe [238,239]. Even small obstacles that outnumber bigger barriers may significantly affect flow dynamics, temperature patterns, animal movement, and habitat quality [217,240], potentially altering the composition, structure, and distribution of communities by promoting the loss of genetic diversity, increasing the risk of extinction through demographic, environmental, and genetic uncertainties [216].

The proper management of freshwater systems to maintain a healthy level of connectivity along the network is paramount to fully maintaining ecosystem functioning and allowing the community to be functionally resilient in a time of global changes. The best possible solution to reconnect a system fragmented by the presence of an artificial barrier is to remove it and, by doing so, completely restore longitudinal and lateral connectivity. But, not all barriers can be removed; most, particularly non-obsolete barriers, provide a wide number of ecosystem services and determinants for societal well-being. In such cases, technical as well as nature-based solutions can be applied to existing, non-removable barriers. In these situations, we are enhancing connectivity while maintaining the barrier and its associated ecosystem service provisions. These connectivity enhancements mean that, at least for some species, the connectivity is only partially restored with, at times, severe directional connectivity asymmetries. The maintenance of river connectivity is among the objectives of the Water Framework Directive [241], and the recovery of free-flowing rivers is inscribed in the European Strategy for Biodiversity 2030 [242] as part of the Green Deal's [243] overall architecture.

12. Pesticides

There has been a constant globally increase in the number of articles and citations on pesticides as stressors that impact freshwater, with a significant decrease in the last years (analyses that include states with both developed and undeveloped scientific networks and financial and human resources), in contrast to Europe (analyses that include states with preponderant developed scientific networks and financial and human resources), where there has a been constant increase in the number of articles and citations, with a significant decrease in the last 4–5 years (Figures 22 and 23).

Pesticides, comprising chemicals or mixtures aimed at pest control, including insects, fungi, and weeds, saw an estimated global usage of 3.5 million tons of different active ingredients in agriculture in 2021 [244]. Despite the existence of over 1680 distinct active ingredients [245], the market boasts more than 100,000 different commercial formulations. These pesticides arrive in aquatic ecosystems through drift, runoff, or direct fumigation, leading to the widespread contamination of freshwater ecosystems worldwide [246,247].

A lot of impacts of pesticides on freshwater ecosystems have been documented. Studies have extended from laboratory experiments to complex mesocosm assessments. The obtained outcomes have revealed an extensive range of effects at the species level, including oxidative stress, alterations in behavior, increased mortality, disruption of endocrine systems, and reproductive impairment. These impacts have been observed across various communities, including algae, cyanobacteria, zooplankton, macrophytes, macroinvertebrates, and vertebrates [248]. Comprehensive investigations at the community and ecosystem levels have unveiled alterations through trophic webs, and some pesticides have exhibited biomagnification phenomena. For instance, glyphosate, the most widely used pesticide [249], has been found to selectively enhance the growth of pico-cyanobacteria in the laboratory, mesocosm, and also in field studies [250,251].

A significant challenge in managing pesticide contamination lies in the fact that they are often detected in mixtures. Even individual commercial formulations consist of various mixtures. Co-formulations have been found to increase toxicity, sometimes surpassing that of the active ingredients alone, as evidenced in studies on algae [252]. Furthermore, the common practice of using combined pesticides exacerbates this complexity. Further studies on the impacts of pesticide mixtures at the ecosystem scale are essential to prevent potential underestimations of risks [253].

Most studies have focused on various forms of bioremediation, yet the ecological ramifications of pesticide contamination can be profoundly significant. Existing evidence regarding glyphosate underscores the imperative to intensify proactive measures against contamination [251,254–256]. Mitigating pesticide usage and bolstering safeguards for freshwater bodies stand as paramount challenges of the present.

Strict monitoring and control of pesticide contamination in freshwater bodies are essential for providing early warnings and halting contamination sources. Furthermore, local environmental regulations play a crucial role in formulating protective policies that prevent pollution and promote the transition to more sustainable agricultural practices.

Pesticide contamination stands as one of the most significant stressors on freshwater systems. The presence of highly complex mixtures and various types of impacts have been reported. Avoiding contamination is crucial because persistent ecological impacts continue to be detected despite the environmental persistence of these substances.

13. Terrorism and War

There have been a very small number of articles globally on war and terrorism as stressors that impact freshwater, all of which are outside Europe, despite a present war in our continent. In the new international tense situation, there is an urgent need for this research (Figure 24).

Identification of terrorism and war is important, but until now, there has been no single definition of these terms. For example, contrary to UN resolution 3314, in the Russian Federation, aggression against Ukraine is not called “a war” but a “special military operation" [257]. Terrorism remains undefined beyond a vague sense of "a non-state actor attacking civilian targets to spread fear for some political goal" [258]. Here, we consider that any actions aimed at the destruction of the water management infrastructure, water resource redistribution, or water quality deterioration to achieve political or military goals should be considered water terrorism, which can be considered a multistressor.

The first armed events connected with freshwater resources were mentioned in the Sumerian legend when, over 2500–2400 BC, the Mesopotamian city-states fought over the redistribution of the Tigris and Euphrates Rivers' flow [259]. Recently, water often serves as the subject of the negative impacts caused by war [260,261]. Such a display of water terrorism is well known. Thus, during the Persian Gulf War, Iraq spilled oil into the sea, which later leaked into the desalinization plants in north Saudi Arabia, and in Zambia, the war destroyed the water pipes supplying about 3 million inhabitants [262].

The main impact on population and aquatic ecosystems is caused by the dams' destruction. Their explosions were usual over the Second World War (WWII): the Soviet army exploded the dam on the Dnieper River, the British Royal Air Force bombed the dams on German rivers, the German troops destructed dams in Italy, etc. [262,263].

The terroristic war unleashed by Russia against Ukraine brings new facts on the impacts on the aquatic ecosystems [264–268]. There were five main groups of impacts of this war on these ecosystems delineated: the destruction of the hydrotechnical facilities; water bodies' contamination; destruction and shutdown of the hydropower facilities and disorders of the HPP and NPP cooling ponds regime; navigation issues; and threats to fishery and aquaculture [268,269]. The most drastic display of water terrorism in war was the explosion of the Kakhovka Dam, which had the most catastrophic consequences of our time [270–274].

According to UN prognosis, by the middle of the XXI century, 7 billion persons in 48 states will face a water deficit. Considering climate changes, this increases the risk of wars for water resources [275]. The impact of terroristic actions on freshwater is not reduced to the above-mentioned problems. A complete inventory of the impacts should be carried out on the basis of the waters' monitoring, which comprises biological, physico-chemical, and hydromorphological parameters, and accounts for basin-specific pollutants and compounds to assess the chemical state of the water bodies [276]. The integral assessment of the terroristic actions' impact on the aquatic ecosystems should be realized by the waters' monitoring in view of the revelation of the effects on biota and assessment of the actual ecological state of the modified by war aquatic ecosystems. At this, the monitoring programs should be completed by tasks regarding the collection of information to be used for assessment of the losses of the aquatic ecosystems. The precedents of the UN International Court of Justice's decisions on compensation of environmental losses owing to the hostilities are quite often regarded as just under-received ecological services of the aquatic ecosystems [277].

One of the consequences of the terrible WWII, which affected the aquatic ecosystems as well, consisted of the development of specific international humanitarian legislation, including the Geneva Convention of 1949 and Additional Protocols to it of 1977. Among numerous provisions of these acts, some actually prohibit the use of water and water supply systems as a weapon against the civil population. For example, Article 56 of Protocol I and Article 15 of Protocol II of 1977 of the Geneva Convention prohibit attacks on infrastructure "containing dangerous forces", including explicitly "dams' and 'dykes" if such attacks "may cause the release of dangerous forces and consequent severe losses among the civilian population" [278]. Such a limitation underlies international humanitarian law; however, in our view, the environmental crimes associated with water resources need greater responsibility at the level of international legislation against terrorism.

Last but not least, it is obvious that terrorist activities are triggers for both environmental issues and finally war and associated risks, e.g., the Al-Qaeda pan-Islamist terrorist attack on USA civil targets induced the USA-led coalition—Iraq War—and the Hamas terrorist attacks on Israeli civil targets started the Israel–Hamas-led Palestinian groups War, etc.

14. Algal Blooms

There has been a constant increase in the global number of articles and citations on algal blooms as stressors that impact freshwater (analyses that include countries with both developed and undeveloped scientific networks and financial and human resources), and there has been a constant increase in the number of articles and citations in Europe (analyses that include countries with preponderant developed scientific networks and financial and human resources) (Figures 25 and 26).

In the conditions of global climate change and increasingly intense negative anthropogenic influence, water quality has declined all over the world, and eutrophication of many freshwater ecosystems has been observed more often. Because of the increased concentration of nutrients in the freshwater, there is an overgrowth of algae and cyanobacteria, which are referred to as "Harmful Algal Blooms" (HAB). HAB can be caused by autochthonous, as well as non-native, invasive micro and macro algae and cyanobacteria. In stagnant waters, the bloom of planktonic Cyanobacteria, as well as Dinophyceae, Bacillariophyceae, Euglenophyta, and Chlorophyta, causes a change in the color and smell of the water and the appearance of foam and coatings [279,280]. During the blooming period of green filamentous algae (*Cladophora* sp., *Oedogonium* sp., *Microspora* sp., *Pithophora* sp.), large mats are formed on the bottom or surface of aquatic ecosystems [281,282]. In river and stream systems all over the world, in recent decades, 'blooms' of Bacillariophyceae, primarily the diatom *Didimosphaenia geminata*, have appeared. This periphyton alga forms large 'blooms' in primarily oligotrophic streams and rivers [283,284].

HAB has a negative environmental and socioeconomic impact, and it is a threat to public health [280]. Light and temperature conditions, oxygen, ammonia, and pH concentrations change in the water, which can affect the living conditions of other aquatic or semi-aquatic organisms [284,285]. Different species of cyanobacteria and algae produce different toxins, and they could accumulate in the tissues, cause damage to the tissues and the functioning of certain organ diseases, and cause the death of aquatic organisms, namely fish [286,287].

Due to HAB, there are disruptions in water supply, the use of water for irrigation, as well as for sports and recreational activities [286,288].

General management practices for nuisance algae are divided into two most important categories: nutrient manipulation and direct control techniques [281]. It is also essential to implement effective technologies for the inactivation and removal of toxins [289].

Water quality protection is possible by implementing preventive specific measures: wastewater treatment, proper planning of places where reservoirs are formed, respecting sanitary protection zones, banning or limiting the use of surrounding land for agricultural purposes, creating a buffer zone that will absorb nutrients, implementing anti-erosion measures, maintaining forest zones and macrovegetation, and implementing a good on-site fishing strategy and activities. An important measure is a ban on the transfer of 'blooming algae' by fishing tools, fish translocation, gravel, etc. [279].

The appearance of HAB in the future poses significant challenges for preserving ecological balance, biodiversity, and the intended function of aquatic ecosystems.

The occurrence of HAB in aquatic ecosystems is becoming increasingly common, leading to significant environmental and economic consequences. Besides implementing the mentioned protection measures, it is crucial to enhance our ability to predict and prevent the proliferation of "blooming" cyanobacteria and algae by obtaining detailed and relevant information about their ecology and behavior. Furthermore, it is essential to explore the significant biotechnological potential of non-toxic algae biomass [282].

15. Invasive Aquatic Plants

There has been a constant increase in the global number of articles and citations on invasive aquatic plants as stressors that impact freshwater (analyses that include states with both developed and undeveloped scientific networks and financial and human resources), and there has been a constant increase in the number of articles and citations in Europe (analyses that include states with preponderant developed scientific networks and financial and human resources) (Figures 27 and 28).

Aquatic plants are especially vulnerable to any changes in their environment. Invasive plant species pose severe threats to native wildlife. A total of 75% of all European freshwaters are anthropogenically changed [290].

About 42% of endangered or threatened species are affected by invasive species. Invasive species also threaten human health and the economy. Havel et al. [291] reported that the dispersion of microbes over long distances and infection of new hosts might have consequences for human health. Invasive aquatic species (IAS) reproduce very quickly; reduce the habitats of native plant species; have a negative effect on fish, insects, etc.; and lower the biological diversity of aquatic ecosystems. Many alien aquatic plants strongly negatively affect aquatic ecosystems by blocking rivers [292].

Human activity has dramatically increased IAS's spread rate [293], and global changes accelerate the invasiveness of specific IAS [294].

Biological invasions have become a consequence of globalization [295–297]. *Pistia stratiotes*, an invasive alien species, was introduced to Prilipe, an oxbow in Slovenia. Šajna et al. [298] reported on the successful winter survival of *P. stratiotes* in a natural thermal stream. Climate change and global warming can accelerate such local populations of invasive species as stepping stones for further dispersal [299]. Šajna et al. [300] recently stated that thermally abnormal waters pose an invasion risk for further deliberation.

Hundreds of non-native organisms are introduced to different parts of the world every year, but not all become invasive. However, for different reasons, most do not survive in the newly invaded environment. Some non-native organisms cannot adapt to the new environment or have a population that is too small to reproduce successfully.

Lind et al. [301] reported that the effects of climate change may lead to an increased abundance and distribution of emergent and floating species and a lowered abundance and distribution of submerged macrophytes, which are most sensitive to global changes. The same authors also claimed that an increase in invasive species would probably occur at high latitudes while not at high altitudes. It makes lakes at higher altitudes in tropical areas hotspots for future conservation measures to protect endemic macrophyte species.

Climate change will cause frequent extreme events of heavy precipitation and drought, impacting hydrological conditions in riverine ecosystems, like flow velocity and evapotranspiration, which will cause drought or runoff due to heavy rainfall [297].

There are several mechanisms with which we can try to stop the spread of IAS, such as lowering the water level, shading, manual and mechanical removal, and measures to reduce the input of nutrients into water bodies, but none of the methods are completely successful.

The spread of IAS is hard to prevent. However, we can limit their spread in various ways. It is important not to remove riparian vegetation, as empty corridors along water bodies are quickly occupied by IAS. It is also important to educate and make people aware of the negative effects of IAS on the aquatic ecosystem.

We will not preserve IAS, but we can take advantage of their positive characteristics. The introduction and large dispersion of miscellaneous non-native species is predominantly detrimental to invaded ecosystems. However, the study provides an example of the positive effects of non-native Eurasian Watermilfoil, *Myriophyllum spicatum* [299]. Kourantidou et al. [300] also stated in their recent review that IAS has potentially beneficial roles. It was also reported that IAS's competitive success depends on environmental conditions [302].

We cannot prevent the spreading of IAS to new areas in the world. With increasing globalization and climate change, their occurrence will be even greater. Therefore, it is crucial to make people aware so that they do not intentionally introduce non-native organisms into nature.

16. Riverine Vegetation

There has been a constant increase in the number of articles and citations on riverine vegetation as a stressor that impacts freshwater, with big fluctuations and a significant decrease in interest in the last 3–4 years (analyses that include countries with both developed and undeveloped scientific networks and financial and human resources). There has been a relatively small number of articles published annually and a significant deflection in interest in the last 3–4 years (Figures 29 and 30).

These plant formations and environments are both essential for the hydrogeological balance of water bodies, for ecosystem functionality, and for biodiversity, ensuring protection from hydrogeological catastrophes, environmental connectivity, and ecological dynamics.

In general, freshwater bodies' bank vegetation is dominated by the presence of azonal vegetation, from the most hydrophilic to the mesic portions. There are also particular cases in which even the most xeric vegetation can contribute to forming communities in riparian environments like, for example, high banks or under other extreme draining conditions.

Riverine environments and related vegetation, in any case, represent important values and provide services, goods, and ecosystem functionality of primary importance, which are essential for the good functioning and for the protection from hydrogeological catastrophes. Naturally, the riverine vegetation follows a gradient from the minor bed to the major riverbed, according to the variations in the topographic conditions and moisture. The characteristics of riverine vegetation also depend on other factors that can lead to further differences, such as the variation of salinity, temperature, precipitations, organic and mineral substances concentration, deposition/erosion, etc. [303–306]. The anthropogenic-induced effects (fragmentation, deterioration, pollution, urbanization, etc.) generally have modified or eliminated natural habitats' functions, negatively influencing also the connected ecosystems. This led to an increase in the related risk of natural catastrophes, especially in a scenario of global and local socio-economic and climate changes.

The riverine habitats and vegetation expression have been the most impacted by human activities during history. The banks have been artificialized, canalized, narrowed, rectified, walled up, and reclaimed to obtain greater spaces to be used for agriculture, farming, pastures, fishing, hunting, industrial, and trade goals or for urbanistic purposes (residential, industrial, navigation, portual facilities, etc.). The vegetation in these habitats is often seen as a pest, as something to be eliminated, or in a way that needs strict and strong control. Riverine vegetation is too often seen as dirt that needs to be cleaned up or as a danger that needs to be eliminated. This ends up negatively influencing the stability of the banks of waterways, destroying very important environments and their ecotones, undermining biodiversity, destroying ecological continuity and functionality, increasing land and water management costs, increasing environmental risks, etc. The artificialization of riverine habitats represents a significant degradation of the natural vegetation types, plants aging, fluctuation, regeneration, biological successions, and dead wood cycle, and it influences feeding, nesting, refuge, roost, passage habitats for insects, fishes, reptiles, amphibians, birds, and mammals [307,308].

Many riverine environments that are today widely considered by people as green or natural have instead been greatly altered over time, although they look green, pleasant, or not urbanized [309–311]. This happened not only in large lowlands rivers but also in small rivulets and streams up to the mountains [312].

In the hydraulic management of water bodies and forests, it has too often been thought to ensure the greatest quantity of water flows downstream rivers and streams in the shortest possible time. This ended up reducing water body suface, simplifinge their natural complexity, transforming their functioning and changing their forms, altering the processes of erosion/deposition to the point of creating problems such as the beaches' retreat, siltation of wetlands, or other hydrogeological problems, as well as causing drought and water scarcity. Urbanization has also increased the risks related to flooding. Today, we should rethink this logic and, to the contrary, favor the diversification and the re-naturalization of these areas. We must not only think about the banks or riverbed conditions, but we should pay attention to the whole catchment basin, promoting the vegetation cover (in particular forests), which allows for greater precipitation absorption together with better water redistribution, just as we should encourage or re-establish water storage areas. To ensure the water flow, rather than continuing or promoting the systematic elimination of the woody vegetation on the waterbody banks, with the fallen wood into the rivers, it would be necessary, for example, to rethink the bridge system, avoiding pylons in the rivers, and rethink the management of the banks restoring spaces, forms variability, and functionality of the narrowed/deepened water bodies that are now forced to be artificialized water canals or reservoirs. We should rethink the riverine spaces to leave more green surfaces and more variable forms where vegetation can express itself as freely and as much as possible. Even the water expansion areas must be rethought to be not simple artificial expansion pools but as possible floodable heterogenous wetland habitats as they could have been in the past, before land reclamation and other human interventions. We should rethink artificial water expansion areas as possible natural areas for biodiversity conservation, to be used as wetland vegetation refugia, and to foster ecological connectivity, thinking of spaces where vegetation and ecosystems can develop autonomous dynamics without necessarily being forced or determined by man.

Today, alongside the restoration of those riverine portions, we should also pay attention to artificialized springs and fountains, which remain important historical, architectural, and cultural landmarks. We should rethink those waterpoint areas, considering the ecological function that these waterpoints should perform in the landscape. In that way, we should recreate wetlands, swamps, and mesic forests using the water that flows out of these managed water points, with the possible related potential vegetation communities and related ecosystems. In that way, we can also encourage the communities of animals and plants that live inside those fountains and that are strongly threatened by cleaning or maintenance operations carried out by the users or by the offices in charge, in line with what should also be carried out with different water bodies. We should pay even more specific attention to wet cave environments from tourist management modifications.

17. Fish

There has been a relatively constant increase in the global number of scientific articles and their citations, including in European countries, on invasive fish species as stressors with an impact on freshwater (analyses that include countries with both developed and undeveloped scientific networks and financial and human resources) (Figures 31 and 32).

Fish are aquatic, craniate, and gill-bearing, such as hagfish, lampreys, cartilaginous, and bony fish, and are naturally mostly ectothermic and relatively abundant in most bodies of water in nearly all aquatic environments, exhibiting greater species diversity than any other group of aquatic vertebrates. In spite of the fact that fish are ecological keystones for aquatic environments, ecological indicators, and important resources for humans [312–320], some of them can sometimes be undesirable.

Fish can be considered in some circumstances as stressors for their ecosystems and human health.

With a growing world population, over-industrialization, extensive and intensive agriculture development, transport extension and intensity, land-use changes, and wars, aquatic life is susceptible to the harmful effects of agrochemicals, different poisons, heavy metals and non-metals, phytotoxins, microbial toxins, genotoxins, and other contaminants [321–324]. Fish under environmental pollution induces toxicokinetics, biotransformations, bioaccumulation, or multi-transgenerational effects [325]. Also, the biological uptake and transport vectors for different anthropogenic substances negatively affect both the environment and human health [326,327].

General and specific freshwater ecosystems' complex point and non-point pollution phenomena that impact the fish, too [300], which became stressors for the environment and human health, can be managed in an integrated way only at the watershed level [328–331].

Non-native fishes are frequently used to enhance aquaculture and fisheries; some of them will become aggressively invasive, producing adverse ecological effects [332]. Aquatic ecosystems, especially those already disturbed by human activities, appear to be particularly vulnerable to alien and invasive organisms [333]. All these organisms, including fish, can be, in some circumstances, major environmental stressors, impacting native species, habitats, and ecosystems through predation and competition for resources; spreading other organisms and diseases, ultimately disrupting the environment by reducing water quality; contributing to erosion; increasing nutrient levels; etc. [334–336].

In this multifaceted context, very complex management actions may be needed to minimize their naturalization, dispersal and impacts. These actions include eradication attempts from specific waters or well-defined spatial areas, population control by suppression (e.g., through removal programs), and containment of existing populations to prevent their further spread. These remedial actions have generally only been undertaken across large spatial areas in developed countries, but the experience suggests fundamental scarce selective removal methods that target the non-native fish species only [337].

A well-balanced ecological status of the ichthyofauna is not possible in disturbed ecosystems and vice versa [338,339].

Consequently, all the needed conservation issues have to be targeted in an integrated manner, not only for the ecologically healthy ichthyofauna but also for their habitats and ecosystems.

The pollution-related larger and more complex circumstance should be necessarily approached in an integrative local, regional, and international crosborders context. In terms of alien and invasive species, almost all fish species are difficult to control once established, but biological control offers some hope in controlling widespread water pest species.

18. Discussion

The issue of environmental stressors on freshwater ecosystems is extremely vast and encompasses a multitude of aspects worldwide.

This work deals with seventeen major stressors from a planetary scale perspective, dealing with their description, induced effects, threats and risks, management, protection, and conservation-related elements.

The present review, even if not exhaustive due to the vastness of the addressed subjected evidence, shows that we are dealing with a wide spectrum of sources that can cause stress on freshwater ecosystems. As could be concluded, agriculture, industry, energy production, transport, and urbanization are the main drivers of the negative effects on freshwater ecosystems, but in changing classic perspectives of the observations, we found that relatively less frequent events, such as, for example, terrorist actions and war, can have effects at least as harmful. Moreover, indirect factors, such as climate changes, can act as vectors amplifying the effects of the aforementioned activities, just as combined actions of these can generate effects of much greater magnitude or can constitute the inflection point of triggering the stress mechanism on the freshwater ecosystems.

Additionally, multiple stressors with cumulative and/or synergistic effects can act on the same freshwater ecosystem with much more significant effects, given the easily formed connection between phenomena from the same spectrum. Thus, for example, the discharge of thermal waters can create conducive conditions for the development of algal blooms, which, in turn, decrease the amount of dissolved oxygen in the water and could favor the spread of invasive fish species, some adapted to conditions with less dissolved oxygen, but more sensible to parasites, etc. In this context, habitat fragmentation can contribute to the confinement in areas with limited extension of algal blooms, not allowing the dispersion of algae over a large area and increasing local-level effects. Thermally polluted waters can favor the spread of invasive aquatic plant species, especially those with higher temperature preferences (such as some species used by aquarists, for example). Military activities can lead to the production of warmer waters, can lead to local increases in radioactivity, and can be responsible for the discharge of nanoparticles into water bodies, in addition to more obvious effects such as intentionally caused floods. Drought periods can lead to the concentration of nutrients in the water, which, in turn, can be the starting point for algal blooms, with the previously discussed effects. Drought can also lead to increased salinity, and floods lead to large quantities of fine sediments being transported into the water, affecting their sharing in the basin and influencing the species that depend on stream beds as their habitat.

The examples of these stressors single and/or interrelated negative effects can infinitely continue as the review highlighted.

Attempting a classification, we can conclude that actions with a stress effect on water bodies can be categorized into three major groups: (1) adding content, (2) disturbing the natural characteristics or normal functions of the water body, and (3) disturbing biological components or processes.

In the first category, we include the addition of waters with different temperatures, altering the local temperature, the discharge of nanoparticles, and chemical and radioactive pollution, all three based on the introduction of unnatural elements into the aquatic circuit. Traditionally, it is assumed that this first category would be the most important.

The second category includes a larger number of stressors: increased salinity, extreme floods and droughts, disturbance of fine sediments, and the increase or concentration of nutrient quantities—factors that, in addition to the way they influence each other, as discussed earlier, have extremely long-lasting, if not permanent, effects on the affected ecosystems, often requiring more complex and costly reparative interventions than those in the first category. Of course, the first category and the second category of stressors can interact and produce cumulative and synergistic effects.

Regarding the last category, it includes algal blooms, invasive or potentially dominant aquatic species, and biocoenotic destructuring, whose effects are among the most serious at the ecosystem level, disturbing the entire structure of the ecosystem and causing effects that are often difficult to reverse. All three categories of stressors can interact and produce cumulative and synergistic effects.

From each stressor perspective, and more than that, from the stressor interactions and the interrelated perspective, it is important to analyze the trajectory of cause—type of influence and effects—and, last but not least, potential solutions specific to each situation.

In relation to the causes, it is important to identify whether we are talking about a direct cause of an impact, or an indirect cause, whether it is solvable through a quick/medium/long period and simple/complex intervention, or whether its effects can no longer be removed by external interventions. Likewise, the type of influence is of similar importance, being necessary to distinguish between direct and indirect, chronic, and acute influences in order to be able to evaluate the impact and propose solutions. In this context, it is necessary to estimate whether the effects of a certain phenomenon are, in principle, quantifiable, given that the reparative intervention on an unquantifiable event is much more difficult.

19. Conclusions

The health of the aquatic ecosystems is a key point where assessments and monitoring of the impact of various stress factors intersect, but these factors themselves, which destabilize biodiversity and ecosystem structure and functions, have been studied to varying degrees. Thus, in the future, it will be productive not only to strengthen the study of individual stressors but also to evaluate their cumulative, additive, and synergistic effects through mathematical modeling and accurate predictions.

The stressors' influence on freshwater is often combined, and the factors are triggered in a cascade, causing effects on one another, leading to irreversible effects that are costly to counteract in many situations.

To meet the challenges regarding the multi-interacting natural and anthropogenic stressors' effects on freshwater ecosystems, unified systematic and comprehensive frameworks are needed to identify key questions and for data collection to build ecological conceptual models based on which a proper assessment, monitoring, analysis, and management can be achieved.

Climate change, especially global warming, has an aggravating effect on most of these stressors, making the issue of protecting freshwater bodies even more difficult.

In a context where freshwater resources are of utmost importance to human society, protecting them against a large and complex number of stressors becomes a very difficult endeavor, requiring complex solutions, especially in situations where the effect of some factors is chronic and can only be controlled or maintained at a certain level and not completely or partially eliminated.

As a result, the protection of freshwater ecosystems must be considered in conjunction with the protection of other important ecosystems, whose indirect role in regulating natural processes as fundamental for freshwater, but not only.

Integrated theoretical and applied holistic approaches concepts should be strengthened in a more focused research direction and, last but not least, reliably transferred from a pure scientific niche family of works in an emergent day-by-day tendency of practical in situ freshwater ecosystems sustainable management.

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