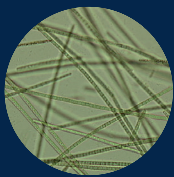
Eutrophication

causes, mechanisms, consequences and predictability



Eutrophication is one of the most common alterations of inland and marine waters. Its best-known manifestations are toxic cyanobacteria blooms in lakes, streams and rivers and proliferations of green macroalgae in coastal areas. These phenomena are generating major disruptions to aquatic ecosystems and have impacts on related goods and services, on human health and on the economic activities of the territories where they occur. In some areas, these environmental crises have become an urgent societal issue, involving a wide variety of stakeholders with contrasting values and interests. The term eutrophication is used by both the scientific community and public policy-makers, and therefore has a myriad of definitions. The introduction by the public authorities of regulations to limit eutrophication is a source of tension and debate on the activities identified as contributing or having contributed decisively to these phenomena.

Debates on the identification of the factors and risk levels of eutrophication, seeking to guide public policies, have led the ministries in charge of the environment and agriculture to ask for a joint scientific appraisal (Expertise Scientifique Collective, or ESCo) to be conducted on the subject. The CNRS, Ifremer, INRA and Irstea were therefore mandated to produce a critical situational analysis on the latest knowledge of the causes, mechanisms, consequences and predictability of eutrophication phenomena. Furthermore, the research institutes were asked to clarify the definition of eutrophication by taking into account operational issues and needs for public action.

1. What is eutrophication? Why and how does it occur?

Definition of eutrophication

The term “eutrophication” is used in the scientific literature to refer to a natural process of increased production of organic materials accompanying the evolution of an aquatic ecosystem over geologic time, until eventually it fills up completely. It can also refer to a process resulting from anthropogenic activities on short time scales (hours, days, months, years). Anthropogenic eutrophication, in its proposed definition based on an analysis of the literature, refers to the **syndrome of an aquatic ecosystem associated with the overproduction of organic material induced by anthropogenic inputs of phosphorus and nitrogen**. Although similar in terms of mechanisms, these two definitions involve processes that do not occur on the same time scales, and therefore have totally different ecological and societal effects. Anthropogenic eutrophication is the focus of societal concerns and is the subject of this joint scientific appraisal. In this definition, concept of syndrome, which is defined as a set of symptoms, is used to overcome the difficulty of summarizing in a few words the multitude of biogeochemical and biological responses triggered by nitrogen and phosphorus inputs.

What are the factors responsible for eutrophication?

The functioning of aquatic ecosystems is governed by dynamic balances. Eutrophication is an imbalance in functioning, triggered by a change in the quantity, relative proportions or chemical forms of nitrogen and phosphorus entering aquatic systems. The nature and intensity of responses also depends on environmental factors: long water residence times, high temperatures and a sufficient amount of light all stimulate eutrophication.

What are the mechanisms of eutrophication?

Both continental and marine water ecosystems share the same general response mechanism to changes in nutrient flows (fig. 1): an increase in nutrient inputs causes an increase in plant biomass, gradually generating a decrease in light penetration in the water column. Aquatic ecosystems thus shift from a system with limited nutrient inputs to a system gradually saturated in nutrients, in which light becomes the new limiting factor. Proliferations of opportunistic plant species, adapted to these new environmental conditions, will then replace the species initially present, inducing changes in the structure and functioning of all the communities (plants, zooplankton, benthic fauna, fish, etc.). These proliferations, or blooms, produce large biomasses. Their degradation by bacteria results in oxygen depletion in the aquatic environment (hypoxia or anoxia: very little or no oxygen), or even toxic emissions (CO_2, H_2S and CH_4). Some proliferations may be toxic.

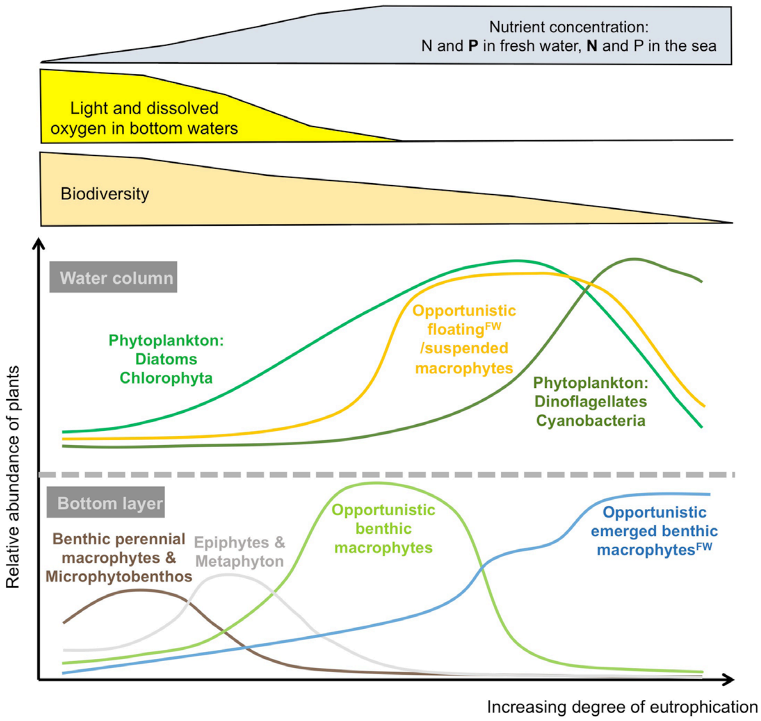


Figure 1. Changes in physico-chemical parameters and in the relative dominance of plants and biodiversity depending on the degree of eutrophication in an aquatic environment. Source: Joint scientific appraisal on eutrophication.

NB: Although marine and freshwater systems do not host the same species, the succession of plant functional types is similar. Schematically, benthic macrophytes capable of tapping nutrients from sediment dominate in nutrient-poor environments. When the environment is enriched, epiphytes, followed by emerging macrophytes, opportunistic floating macrophytes and/or phytoplankton proliferate at the expense of perennial and submerged macrophytes, which no longer have access to light. FW: observable in freshwater only.

What are the manifestations of eutrophication?

Responses generated by a disturbance are initially detectable at the physiological/biochemical level of an individual, then at behavioural or morphological level, and finally at the levels of the populations and communities. The most notable effects of eutrophication are vegetal blooms, sometimes toxic, loss of biodiversity and anoxia, which can lead to the massive death of aquatic organisms. In the bays of large river systems and some lakes, water chestnut (*Trapa natans*), or water ferns such as *Azolla sp.*, for example, have proliferated to the extent of causing hypoxia and anoxia in the environment. In lakes, cyanobacteria which proliferate more commonly in France all include species capable of producing toxins. They belong to the *Microcystis*, *Planktothrix*, *Dolichospermum*, *Aphanizomenon*, *Oscillatoria*, *Lyngbya*, *Nodularia genera*. In coastal environments, the decomposition of opportunistic green macroalgae blooms, mainly of the *Ulva* genus, results in hypoxia and anoxia, causing mass mortality of benthic fauna, a regression of fish nursery areas and health risks through the release of hydrogen sulphide. Excessive proliferation of phytoplankton in coastal seas also causes hypoxia or even anoxia in bottom waters (e.g. Gulf of Mexico, Chesapeake Bay, Baltic Sea). Finally, marine eutrophication can stimulate production of phytoplanktonic toxins, for instance in species of the *Alexandrium*, *Dinophysis* and *Pseudo-nitzschia* genera.

What are the environmental, economic and social impacts inventoried?

Eutrophication poses a threat to the environment, the economy (impact on shellfish production, fishing, tourism, etc.), but also to human health. Attempts to evaluate the monetary impacts of eutrophication have been made over the last decade, mainly in the United States and in the Baltic Sea. These studies indicate a variety of impacts and costs which are quantifiable fairly directly, for instance when cities of hundreds of thousands of people are deprived of drinking water for several days. On the other hand, integrating all the environmental, health and socio-economic impacts in the calculations of indirect effects poses more of a challenge.

2. What criteria can one use to characterize the eutrophication of environments?

Indicators of eutrophication are generally classified into indicators of pressure, chemical status and impact (table 1). Pressure and status indicators relate respectively to the identification and quantification of pollutant sources and their concentrations, whereas the impact indicators use the biological responses of the living communities specific to each type of environment. These indicators can be used to link emissions and flows exported by watersheds with the concentrations measured in receiving environments and the biological or ecological status of these environments. While the Marine Strategy Framework Directive has settled on a descriptor dedicated to eutrophication, the Water Framework Directive opted instead for an aggregate vision of the ecological status of water bodies as a result of multiple pressures. The pressures responsible for eutrophication are partly documented in these directives (e.g. nutrient concentrations), but non-linear relations with ecological status sometimes require more in-depth analysis in a number of regions. The interpretation of biological data (macrophytes, phytobenthos, invertebrates, fish) is complex, contained within information on the integrated response of hydrosystems to multiple pressures, and dependent on adapted monitoring methods (frequency, accuracy, etc.).

Indicators	Rivers	Lakes	Transitional waters	Coastal waters	Ocean waters
Pressure indicators					
Nutrient emissions, nutrient load	•	•	•	•	•
Status indicators					
Phosphorus concentrations (total P, ortho-phosphate)	•	•	•	•	•
Nitrogen concentrations (total N, NO_3)	•	•	•	•	•
Impact indicators					
Ecological status (WFD: European Water Framework Directive)	•	•	•	•	
Environmental status (MSFD: Marine Strategy Framework Directive)				•	•
Phytoplankton (chl-a, biovolume)	•	•	•	•	•
Phytoplankton (community composition, harmful and toxic algae)		•		•	•
Secchi depth		•		•	•
Macrophytes (depth of lower growth)		•		•	
Macrophytes (community composition)	•	•	•	•	
Phytobenthos (community composition of benthic algae)	•	•			
Macrozoobenthos (community composition, biomass)	•	•	•	•	•
Oxygen concentration at the bottom		•*	•	•	•

Table 1. Pressure, status and impact indicators of eutrophication in rivers, lakes, transitional waters, coastal and marine waters. * Only for stratified lakes.

Adapted from Ibisch *et al.* 2016, ETC/ICM Technical Report – 2/2016.

3. How is eutrophication changing on a global scale?

Increasing global population growth and the development of urban concentration, agricultural industrialization an specialization of agriculture, including crop-livestock decoupling by means of transport, phosphorus mining and chemical manufacturing process of mineral nitrogen (Haber-Bosch method) have led to an increase in flows and concentrations of nutrients in the environment, and ultimately in aquatic ecosystems. Changes in flows vary from one publication to another based on the approach and the databases used. Based on the latest models deployed globally, outflows to the sea virtually doubled in the 20th century, from 34 to 64 Tg[(1)] N p.a. for nitrogen and from 5 to 9 Tg P p.a. for phosphorus. The contribution of agriculture to these inputs reportedly increased from 20% to 50% for nitrogen, and from 35% to 55% for phosphorus.

Eutrophication phenomena started to be recognized from the beginning of the 20th century near major urban and industrial centres in industrialized countries of the northern hemisphere. Between the 1970s and 1990s, public action in these countries focused on the treatment of industrial and domestic pollution. The drastic reduction in point-source phosphorus pollution as a result of improving wastewater treatment and limiting, then banning phosphates in detergents, led to a gradual decrease in a number of eutrophication phenomena, notably in Lake Erie (United States) and Lake Geneva (France-Swiss).

Since then, a new wave of eutrophication has been spreading, affecting many lakes, reservoirs, rivers and coastal areas around the world. Many iconic places are now subject to recurring eutrophication episodes: the Baltic Sea, the Laurentian Great Lakes, the Chesapeake Bay, the Gulf of Mexico, the Venice Lagoon, a large number of lakes and coastal areas in China, Lake Victoria, the Brittany coast, Mediterranean lagoons, etc. Some of these sites had never been affected before, while others experienced a new eutrophication phenomenon after a previous remission phase. Since the end of the 20th century, public action has been focusing on the issue of non-point pollution of agricultural origin. In industrialized countries, these measures have led to positive developments in freshwater, more so for phosphorus than for nitrogen, while marine eutrophication phenomena do not appear to have diminished since the beginning of the 21st century. At global level, the number and footprint of hypoxic and anoxic zones in the marine environment has tripled since the 1960s. A 2010 census numbered nearly 500 of these areas, with a geographical footprint of 245,000 km². There has also been an increase in the diversity, frequency, size and geographical extent of toxic microalgae blooms in recent decades. Although it is still difficult to extrapolate trends from one region to another, the link between the increase in nutrients inputs and that of toxic blooms is often established.

4. Can the risk of eutrophication be characterized and predicted? If so, how?

An analysis of the literature stresses that a risk analysis framework should combine hydro-biogeochemical transfers and transformations, climate hazards and the ecological vulnerability of receiving systems. These three dimensions are more or less integrated in the modelling.

Transfers, retention and transformation of nitrogen and phosphorus along the land-sea continuum

The risk of eutrophication in an aquatic ecosystem depends partly on nutrient inputs from its watershed via streams and rivers or groundwater that feed it. Nutrient inputs can therefore come from source areas hundreds or even thousands of kilometres away, and their transit time from these areas to the receiving aquatic ecosystems can span decades.

Along the land-sea continuum, phosphorus is mainly retained in soils and sediments (fig. 2). It can be remobilized depending on biological demand, under anoxic conditions, or when sediments are shifted. The entire phosphorus cycle is in solid or liquid form, while the nitrogen cycle has also a gas phase. Nitrogen is more mobile than phosphorus and is transported mainly to groundwater, where it can be stored for decades (fig. 2). In stream, river and lake sediment, in wetlands, nitrates can, to a certain extent, be transformed into gaseous nitrogen by denitrification (natural purification). In soils and sediments, storage of the phosphorus introduced for more than a century by human activity has resulted in there being an excess of phosphorus in relation to nitrogen. These differences between nitrogen and phosphorus in terms of transfer and retention mechanisms and elimination capacity result in differences in the mass ratio between these two elements from the watershed heads and along the land-sea continuum.

These findings also explain why assessments of the retention capacity of phosphorus and of the elimination capacity of nitrogen in a watershed are currently difficult

(1) Tg: teragramme: correspond to 10^9 kilogrammes

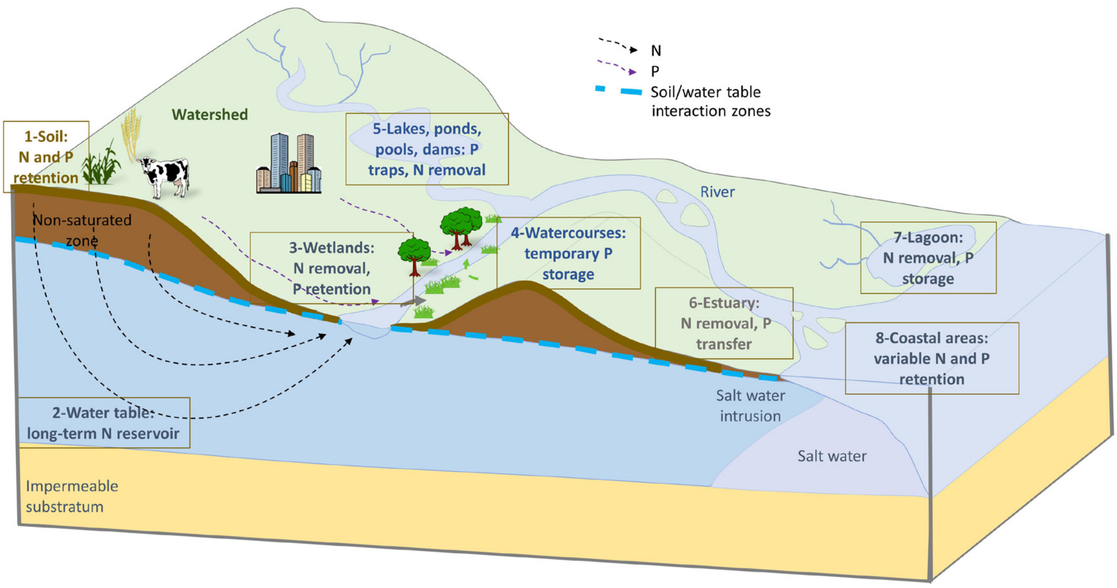


Figure 2. Conceptual diagram of the transfer, retention, and purification zones of nitrogen (N) and phosphorus (P) along the land-sea continuum. Source: Joint scientific appraisal on eutrophication.

to make and highly uncertain. There is a great variability of flows in watershed heads, and it has not been possible yet to establish a clear relation between landscape structures (the spatial arrangement of land use) and the water quality of the rivers that drain them. While the assessment of one or more structures can be performed with the help of a significant amount of equipment and measures, it remains difficult to quantify all landscape configurations. Rates measured at one site cannot be extrapolated to other sites due to the specific hydrological, hydrogeomorphological and biogeochemical characteristics of each site. This creates great spatio-temporal variability in denitrification and phosphorus retention. Nitrogen emission in water is primarily controlled by N surplus and rainfall amount, as it is primarily controlled by landscape connectivity for phosphorus.

Taking account of climate change is essential

The effects of climate change, some of which are already felt, will impact all the mechanisms involved in eutrophication and amplify its symptoms. Plant biomass production, transfers within watersheds, nutrient loads reaching hydrosystems, the physical chemistry of environments, especially oxygen, pH and discharges of phosphorus and metals from benthic sediments, the metabolization of nutrients in aquatic environments, organisms' habitats and their distribution, the dynamics of trophic networks; all of these processes are likely to be modified by forecast climate changes (changes in thermal and water regimes) as well as their interaction with related changes in human activity and terrestrial landscapes. In turn, the benthic physico-chemical reactions involved in hypoxia are likely to contribute to the emission of greenhouse gases (CO_2, CH_4, N_2O). The literature is starting to propose spatialized scenarios of future developments by changing the forcing factors of eutrophication risk analyses. This is an essential step in guiding adaptation actions and scaling efforts to combat eutrophication.

The vulnerability of ecosystems to eutrophication

Each ecosystem is unique and has its own history and dynamics, which in turn are related to local geological, geomorphological, hydrological, ecological and climatic conditions, but also to past and present anthropogenic pressures and their nature, as well as to the sociological and economic contexts in which they have evolved. For instance, there are many possible responses of aquatic ecosystems under constraints of changes in nutrient inputs (fig. 3). This complexity means that the ecological vulnerability of ecosystems is highly unpredictable. Vulnerability therefore needs to be defined by taking into account the entire direct and indirect causal chain that influences the inherent properties of the receiving aquatic ecosystems, in relation to the diversity of local situations and past and present contexts. The idea is

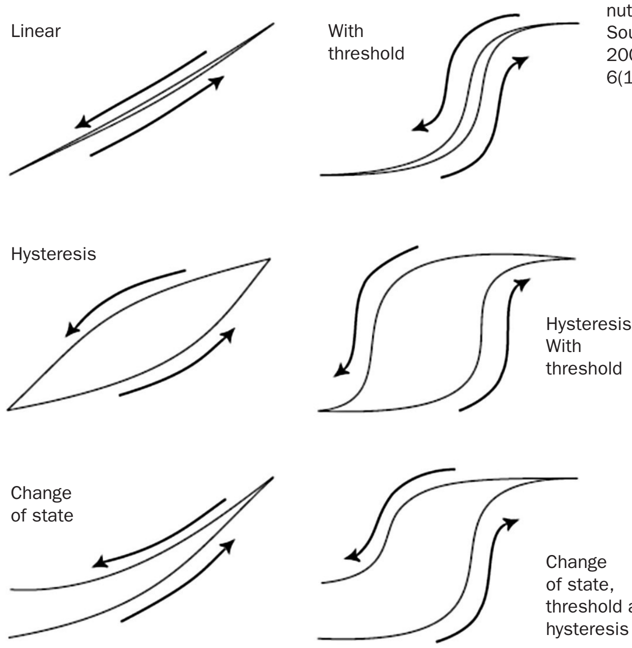


Figure 3. Schematic representation of six hypothetical system response trajectories (in y) following changes in nutrient conditions (in x). Hysteresis refers to the fact that two different status of an ecosystem can be found along an intermediate gradient of nutrient concentrations. Source: Kemp *et al.* 2009, Biogeosciences, 6(12), 2985-3008.

to better understand how some metrics signal significant swings towards eutrophic situations and to identify these swings in the trajectories of situations closely monitored over the long term by interpreting them in functional terms.

Modelling: a tool for understanding ecosystems

Mathematical models of eutrophic ecosystems have been developed to understand and represent ecological dynamics and their coupling with nutrients. Some models have also been used to estimate eutrophication risks, assess the necessary reduction in nutrient inputs and define actions and priority management areas. A first approach is based on the identification and combination of factors of nutrient emissions to aquatic ecosystems. Multi-criteria assessment approaches of the impacts of technical systems (agricultural practices, wastewater treatment plants, etc.), based on the analysis of the life cycle, nitrogen footprint, etc., come within this scope. A second approach is based on so-called statistical models. They seek to provide one or more descriptors of eutrophication based on a number of causal variables measured in the field. A third approach uses equations to represent hydro-biogeochemical and ecological mechanisms and simulates the dynamics of eutrophication. Many eutrophication models combine these three approaches, depending on the availability of data on a specific zone.

Models of nutrient flows from watersheds feed lake and river models, particularly for nitrogen. Lake modelling focuses more particularly on the phosphorus cycle in order to remedy blooms of atmospheric dinitrogen-fixing cyanobacteria. Due to the observed stimulation of non-dinitrogen-fixing cyanobacteria, lake modelling could be similar to that of rivers and coastal waters, which simulates N and P cycles in parallel. Marine eutrophication models identify nitrogen as a main controlling factor and recommend significant reductions in nitrogen river inputs. The transmission of this downstream ecological constraint to river system and watershed models founders on the lack of knowledge about storage compartments (groundwater for N, soil and sediment for P) and their residence times, as well as the geographical complexity of land uses and watershed activities.

Models are commonly used to assess prospective scenarios. That said, replicability remains limited without substantial data on the zone under study, and the uncertainty of the results often receives little evaluation. Very few examples integrate coupling with climate hazard and the ecological vulnerability of aquatic environments. The virtual absence of bioeconomic models makes it even more difficult to use modelling approaches to help towards remediation. Nevertheless, modelling has made it possible to identify gaps in the formalism of some processes that are still insufficiently detailed, in the data necessary for their implementation, and it has undoubtedly highlighted significant elements for reflection to guide management actions.

5. What are the strategies and frameworks to combat eutrophication?

Engineering in aquatic ecosystems: an ad hoc solution

Actions to combat eutrophication in aquatic ecosystems can build on three types of levers: physical levers, which are designed to decrease water residence time or destratify the water column; chemical levers to fight hypoxia by artificially re-oxygenating the environment or to help phosphorus precipitation (addition of lime, aluminium, sulphates, etc.); ecological levers which seek either the eradication of symptoms (use of algaecides), or biomanipulation by introducing species to influence the food web structure. These approaches are costly, and sometimes risky, but they can help regulate a symptom, on a case by case basis, in small spatial areas.

Managing phosphorus and nitrogen inputs in aquatic environments is essential

Actions to control flows from watersheds are essential. They must be set in a long-term perspective, in relation with the transfer, retention and elimination mechanisms of nutrients along the land-sea continuum. For example, long transit times partly explain the limited decrease observed in flows of nitrogen, and to a lesser extent of phosphorus, to watershed outlets, despite the efforts made to reduce inputs for several years.

A vast range of objective knowledge currently supports a consensus among scientists to limit both nitrogen and phosphorus inputs to aquatic ecosystems, whether they be point-source or non-point source inputs, of urban, industrial or agricultural origin. Nutrients cycles are not isolated from each other. Measures taken to regulate one element have consequences on other elements, and ultimately on the ecological balance of systems. A joint reduction in N and P inputs is therefore essential to curb eutrophication along the land-sea continuum, even though schematically, the controlling factor shifts from phosphorus in freshwater to nitrogen in marine environments .

Concerning sources of domestic and industrial pollution (non-collective sanitation, collection network and waste water treatment), significant efforts have been made, but there is still room for improvement: reduction at source (household products, diets, etc.), better assessment of the volumes to be treated, especially in areas where the population fluctuates, ramping up of a number of small water treatment plants, specific treatments (urine/faeces, agro-industrial waste, etc.). Nevertheless, the focus is now on agricultural sources, which are significant in developed countries: recycling of effluents in regions with high animal density and high food imports; management of fertilization, taking into account N and P, reasoned by parcel, by crop system (crops and intercrops); preservation or restoration of landscapes, especially land-water interfaces. These three levers must be taken into account in current production systems. However, even if they are taken into account, this will not be enough in some watersheds with highly vulnerable receiving aquatic ecosystems. Agricultural systems and land use must be strongly modified in these zones. Economically realistic and socially acceptable territorial projects, based on targets for very low leakage of nitrogen and phosphorus, will have to be put in place. Synergies between issues related to food, biodiversity, climate, efficiency and resource recycling could also help.

Are regulatory monitoring frameworks well adapted to monitor eutrophication?

Several regulatory texts frame the eutrophication process more or less closely. They are international, European or national in scope, and respond to sometimes different rationales. Several guidelines on uses, dating back to the 1980s and providing a framework for a given field (e.g. the Nitrates Directive and the Urban Waste Water Directive, UWWD), coexist with directives with a more comprehensive objective such as the Water Framework Directive (WFD) and the Marine Strategy Framework Directive (MSFD) in the 2000s. The Nitrates Directive, focused on nitrates from agricultural sources, requires defining the zones that feed waters meeting the following criteria and contributing to pollution as vulnerable zones: waters that have or may have concentration higher than drinking water standards, and waters which have suffered or are at risk of eutrophication. The UWWD frames the collection, treatment and discharges of wastewater, with point source-specific emission standards, but no standards for the receiving environment. The WFD and the MSFD require the implementation of the measures necessary to maintain or achieve the objective of good ecological status in water bodies, notably by a regular characterization of the health state of hydrosystems. With the exception of the MSFD, these directives provide no specific recommendations on eutrophication, which is considered as part of a set of potentially degrading pressures. To each of these texts correspond targeted monitoring systems, which are essentially used to check compliance with standards.

The drinking water standard of 50 mg/L of nitrates, frequently referred to in the regulations, is not adapted to protecting environments from the eutrophication process. Situations of 1 to 3 mg/L are characteristic of zones with very low human pressure; some publications identify a tipping point at barely higher values in the case of early changes in the species composition of communities. It would be interesting to analyze the historical trajectory of the various value guidelines suggested over time and their territorial applications. Transparency on the fundamentals associated with these values and the related educational approach are essential to set threshold value ranges.

Socio-economic support for remediation

Economic studies helps identify incentive or regulatory instruments susceptible, individually or in suitable combinations, of assisting in decision-making. Existing economic studies show that in many cases, excessively ambitious objectives are not achievable and have led to ineffective programmes, especially in relation to their cost. Targeting instruments spatially is usually more effective than applying generic measures on a broad scale; this raises the question of zoning and of the scale of its definition. Adaptive management, by updating objectives and tools and attempting experiments based on achievable objectives and on a suitable scale, appears the best approach to adopt.

Environmental sociology is currently little developed. In France, the case of green tides is an exception : once eutrophication has gained social visibility it can be more easily studied. The transformation to be implemented in this context is no longer solely perceived as merely bio-physical. Sociological aspects are starting to be taken into account, calling for differentiated approaches depending on the socio-ecosystems and their different spatial scales, and integrating the issues of the various stakeholders in relation to eutrophication.

6. Future areas of investigation

Developing a methodology for analyzing the eutrophication risk

The analytical framework of the risk of eutrophication, which needs to be constructed, must take into account hydro-biogeochemical and climate hazards, as well as the ecological vulnerability of receiving systems. In this sense, the literature identifies various areas for improvement in order to fully leverage the data collected and complete it as necessary: (1) performing regular scientific syntheses (e.g. every 10 years) analyzing both physico-chemical and biological data in their differentiated geographical frameworks, from an integrative and functional perspective; (2) guiding the acquisition of new data to develop modelling approaches, particularly in the continental area, defining and rolling out probabilistic analyses of eutrophication risk; (3) intensifying data acquisition in poorly instrumented zones (e.g. watershed heads, soils and sediments), by increasing the frequency or accuracy of measurements, by measuring variables currently not monitored (e.g. 24-hour cycles, O_2) in order to better qualify the relations between pressures and impacts, as well as response times in various biophysical contexts; (4) developing new data acquisition methods, notably derived from recent technologies (high-frequency, real time, satellite imagery) and participatory science; (5) better exploiting the functional information provided by biological samples: some taxa or ecological properties could deliver more information on trophic malfunctions than at present.

Determining the respective roles of climate and human activity is a central field for research. Modelling can contribute to advancing this work as a complement to long-term observation. Research on the specificity of ecological responses to eutrophication should be strengthened, with the ambition of clearly distinguishing the part related to eutrophication in multi-pressure environments, watershed landscapes and the temporal trajectories of the various nutrient regimes. Sociological studies of public and governance problems are needed at different spatial scales. Research must be carried out on the limits of sector-specific regulatory approaches in terms of effectiveness, enforceability and overlapping, with as a common guideline a better integration of the land-sea continuum and distinctive vulnerability of each type of environment.

Organization and principles of the joint scientific appraisal

The joint scientific appraisal is an institutional expertise project, governed by the national appraisal charter signed by the CNRS, Ifremer, INRA and Irstea. The purpose of a joint scientific appraisal is to provide the public authorities with a base of certified scientific knowledge on which to build a political decision-making process. A joint scientific appraisal consists in collating the international scientific literature on a given topic and extracting points of certainty and uncertainty, knowledge gaps and any questions that are the subject of scientific controversy. This state of knowledge is not intended to provide expert advice or turnkey technical solutions to the issues faced by administrators, but to identify levers for action. The analysis is conducted by a multidisciplinary group of expert researchers from various institutional backgrounds.

40 French and foreign experts were mobilized for the joint scientific appraisal on eutrophication, with skills in the following disciplines: ecology, hydrology, biogeochemistry, biotechnical sciences, social sciences, law, economics, and covering the various types of aquatic ecosystems: lakes, streams, estuaries, marine coastal and offshore environment, as well as the concept of continuum between these systems. The experts' work drew on a bibliographic corpus of around 4,000 references, composed essentially of scientific articles validated by peers, and supplemented, for a number of topics, by technical or scientific reports and legal texts. This exercise culminated with the production of a report compiling the experts' contributions, a synthesis, as well as a symposium, on September 19th, 2017.

Read more: the synthesis, report, and presentation of the results symposium are available here: www.cnrs.fr/inee

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