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Modelling the marine eutrophication: A review

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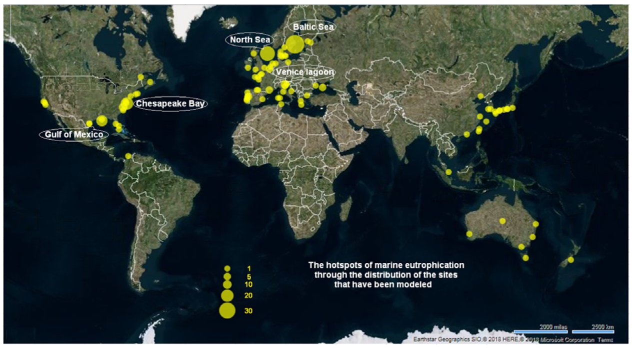
HIGHLIGHTS

- 291 references on marine eutrophication modelling have been analysed.
- 4 batches have been done: estuaries, lagoons, coastal seas, “green tides”.
- The world hotspots of eutrophication are listed, with their main results.
- The evolution of tools, their strengths and weaknesses are described.

GRAPHICAL ABSTRACT



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ABSTRACT

In the frame of a national, joint scientific appraisal, 45 scientific French-speaking experts have been mandated in 2015–2016 by the French ministries of Environment and Agriculture to perform a global review of scientific literature dealing with the eutrophication phenomenon, in freshwater as well as in marine waters. This paper summarizes the main results of this review restricted to a sub-domain, the modelling approach of the marine eutrophication. After recalling the different aims pursued, an overview is given on the historical time course of this modelling effort, its world distribution and the various tools used. Then, the main results obtained are examined, highlighting the specific strengths and weaknesses of the present models. Needs for future improvement are then listed.

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1. Introduction

At the end of the 20th century, the Oslo and Paris Commission (OSPAR) in charge of promoting the good ecological status of West-European coastal seas proposed an operational definition of marine eutrophication (OSPAR, 1997). Eutrophication was then considered as “the result of excessive enrichment of water with nutrients which may cause an increase in the accelerated growth of algae in the water column and higher forms of plants living on the bottom of the sea.” The OSPAR definition pointed out that eutrophication “may result in a range of undesirable disturbances in the marine ecosystem, including a shift in the composition of the flora and fauna which affects habitats and biodiversity, and the depletion of oxygen, causing death of fish and other species.” The most mediated aspects of the marine eutrophication are the mass accumulation of green macroalgae on beaches (the so-called “green tides”) or in lagoons, as well as the intense proliferations of some phytoplanktonic species in coastal seas (the so-called “colored waters”). However, massive kills of fishes and benthic fauna have also revealed the deleterious effects of the invisible anoxia of

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bottom waters, leading to sporadic or permanent "dead zones" in more and more places (Diaz & Rosenberg, 2008). Eutrophication can be a natural process: in inland waters, ageing of a lake over geological time scales induces a slow accumulation of organic material, whereas in some oceanic areas, as off Namibia (Brüchert et al., 2003), intermittent and sudden massive inputs of deep, nutrient rich water upwelled by wind episodes can trigger a high surface production of phytoplankton, which sinks and feeds bottom anaerobic sulphate reducing bacteria. To embrace accumulation of allochtonous organic matter as well as sedimentation of locally produced algal material, (Nixon, 2009) defined eutrophication as an "increase in supply of organic matter". Most of present cases of marine eutrophication are from anthropogenic origin, i.e. caused by recent abnormal man-made inputs of nutrients or organic wastes. The study of many lakes, first affected by anthropogenic eutrophication in the second half of the 20th century, has shown (Vollenweider, 1968) that eutrophication is possible only if the surface mixed layer is sufficiently thin and illuminated to allow a primary production greater than the algal respiration and hence, to ensure a rapid algal growth. The biomass produced can accumulate only if the water body exhibits a residence time of several days, i.e. is sufficiently confined. Eutrophication in lakes revealed to have been mainly triggered by massive anthropogenic inputs of inorganic phosphorus (phosphate). In coastal seas however, ecosystems are naturally open, they show strong continuous gradients extending from the estuaries to the offshore waters. Their high salinities are not in favor of an efficient gaseous nitrogen fixation by cyanobacteria, so that the controlling role of nitrogen may override the phosphorus one. A part of the terrestrial loadings of nutrients is exported into the oceanic waters, gyres of various sizes embedded in the mainstream tidal residual flow provide spatially heterogeneous residence times, whereas oceanic oscillations, such as the North Atlantic Oscillation, can modulate the marine response to nutrient enrichment… This further adds complexity to the marine eutrophication process.

Scientists willing to understand the mechanism of eutrophication as well as public administrations aiming at defining the optimal actions for remediation have used mathematical models to explore hypotheses or remediation scenarios during the four last decades. The need for integrated actions from the watersheds down to the open ocean under a changing climate will probably increase the role of numerical models in tackling the eutrophication problem in the future. What help did the models provide up to now, what cannot they do at this moment, what would we like they should be able to do in the future? This paper tries to answer these questions from the existing literature.

2. Methods used to build the inventory

This work has been conducted in 2015–2016, as part of a global review of scientific literature dealing with eutrophication, in fresh inland waters as well as in marine coastal waters. The French Ministry of Ecological and Social Transition (MTES), together with the French Agency for Biodiversity (AFB) and the French Ministry of Agriculture and Food (MAA) mandated the French National Centre for Scientific Research (CNRS), along with three other French public scientific institutes (National Institute for Agronomic Research-INRA, French Institute for Research and Exploitation of the Sea-IFREMER, and Institute for Scientific Research and Technology for Environment and Agriculture-IRSTEA), to coordinate a panel of 45 scientific French-speaking experts which could cover all the different aspects of the eutrophication problem (biogeochemistry, ecology, links with urban and agricultural practices, sociologic impact and legal treatment). This joint scientific appraisal (a so-called French ESCo "**E**xpertise **S**cientifique **Co**llective") should help the public authorities to redefine French regulatory texts dealing with the complex and controversial issue of eutrophication, especially the role played by nitrogenous and phosphorous nutrients in this phenomenon. This will better establish the revision of vulnerable zones in respect of the Nitrate Directive (Directive 91/676/EEC) as well as the implementation of the European directives on the management of aquatic environments, i.e. the Water Framework Directive (WFD, Directive 2000/60/EC), the Marine Strategy Framework Directive (MSFD, Directive 2008/56/EC) and the Urban Waste Water Treatment Directive (UWWTD, 91/271/EEC).

The global appraisal is based on approximately 4000 scientific references. The present subset, dealing only with the modelling of marine eutrophication, is based on 291 references. They result from a first extraction from the Web of Science Core Collection thanks to a bibliographic search equation, followed by the discard of some inappropriate references (e.g. dealing with inland waters) and the addition of some pertinent scientific papers known by the authors, but not selected by the search equation. As the work has been split into four distinct domains (estuaries, lagoons, coastal seas, "green tides"), Table 1 gives for each domain the search equation and the number of papers selected by it, along with the numbers of discarded and added papers. The number of published modelling studies per year (Fig. 1) reveals that the modelling of marine eutrophication is relatively recent, beginning at the end of the 80's. Whereas studies on estuaries and coastal areas had shown a regular increase since 1990, studies on "green tides" as well as on lagoons have kept a weak steady state since the mid 90's. These research papers were published in 76 journals, the 5 most cited being Ecological Modelling (15.8%), Journal of Marine Systems (13.6%), Estuarine Coastal and Shelf Science (9.7%), Marine Ecology Progress Series (5.4%), Hydrobiologia (3.9%), collectively publishing 49.4% of all papers.

3. Aims of the modelling approach

The first aim of the eutrophication models was to help understanding the eutrophication process and to reproduce its main features, i.e. the intense phytoplanktonic blooms (Chan et al., 2002; Kishi & Ikeda, 1986; Dippner, 1993; Baretta et al., 1994; Fennel, 1995; Tett & Walne, 1995; Yanagi et al., 1995; McEwan et al., 1998; Cugier et al., 2005; Tamvakis et al., 2012) or the mass accumulation of ulvaceae (Ménesguen & Salomon, 1988; Bendoricchio et al., 1994; Coffaro & Sfriso, 1997; Martins & Marques, 2002; Lovato et al., 2013; Coffaro & Bocci, 1997; Brush & Nixon, 2010; Trancoso et al., 2005; Silva-Santos et al., 2006), and the possible hypoxia (or anoxia) induced in the bottom waters (Chapelle, 1995; Humborg et al., 2000; Chapelle et al., 1994; Oguz et al., 2000; Grégoire & Lacroix, 2001; Karim et al., 2002; Tuchkovenko & Lonin, 2003; Grégoire et al., 2008; Grégoire & Soetaert, 2010; Evans & Scavia, 2011; Pena et al., 2010; Wan et al., 2012; Große et al., 2017). Because the dynamics of estuaries is strongly controlled by physical drivers (river flow rate, turbidity, haline stratification), the estuarine models have very often been used to assess the respective role of these drivers, especially on the onset of hypoxic conditions (Peterson & Festa, 1984; Cole & Cloern, 1987; Soetaert et al., 1994; Vanderborght et al., 2002; Muylaert et al., 2005; Talke et al., 2009; Nash et al., 2011; Gypens et al., 2013; Gallegos, 2014; O'Boyle et al., 2015; Mathews et al., 2015; Fear et al., 2004; Talke et al., 2009; Robson et al., 2008; Talke et al., 2009; Nash et al., 2011; Arndt et al., 2011; Wang et al., 2013; Liu & de Swart, 2015; O'Boyle et al., 2015; Chen et al., 2014; Chen et al., 2015; Benoit et al., 2006; Bruce et al., 2011b; Hipsey et al., 2013; Cho et al., 2015; Miguez et al., 2001).

Beyond these main aspects, the models have been also used to explore the competition between diverse primary producers: diatoms vs dinoflagellates or Prymnesiophyceae (*Phaeocystis* sp.) as well as diatoms vs cyanobacteria (Petihakis et al., 1999; Guillaud & Ménesguen, 1998; Guillaud et al., 2000; Gypens et al., 2007; van den Berg et al., 1996a; Blauw et al., 2009; Spatharis & Tsirtsis, 2013), *Ulva* vs phanerogams *Zostera* and *Ruppia* (Giusti & Marsili-Libelli, 2005; Cioffi & Gallerano, 2006; Canal-Verges et al., 2014), or macro- vs microalgae (Baird et al., 2003; Madden & Kemp, 1996; Buzzelli et al., 2014; Sohma et al., 2004).

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