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Preliminary approach to modelling eutrophication – anthropopressure impact on sea water quality

Keywords

excessive nutrients, nutrient pollution, algal blooms, water quality, Baltic Sea, semi-Markov process

Abstract

The chapter is devoted to the problem of eutrophication. Methods and parameters for its assessment are described. Furthermore, the eutrophication of the Baltic Sea is discussed in detailed. Finally, the semi-Markov model of the eutrophication process is proposed, and its characteristics are determined.

1. Introduction

Anthropopressure refers to the collective impact of human activities on the environment. It encompasses various forms of human-induced pressure that affect ecosystems, natural resources, and the overall functioning of the planet. Anthropopressure can have both direct and indirect effects on the environment and can occur at local, regional, and global scales (Ives & Carpenter, 2007). Typical examples of anthropopressure include land use changes involving conversion of natural habitats for agriculture, urbanization, deforestation, and infrastructure development leads to habitat loss, fragmentation, and degradation. These changes can disrupt ecosystems, reduce biodiversity, and alter ecological processes (Hautier et al., 2015). Release of pollutants into the air, water, and soil from industrial activities, transportation, waste disposal, and chemical use has detrimental effects on the environment and human health and therefore it is a kind of anthropopressure. Pollution can contaminate ecosystems, degrade water quality, harm wildlife, and contribute to climate change. The another kind of anthropopressure is extraction of natural resources, such as fossil fuels, minerals, and water, because it can deplete resources, degrade habitats, and disrupt ecosystems. Moreover, unsustainable exploitation of fisheries, forestry, and other natural resources can lead to the depletion of populations, loss of biodiversity, and ecological imbalances. Overfishing, illegal wildlife trade, and unsustainable logging practices are examples of overexploitation (Jackson et al, 2001; Scheffer et al., 2005; ‘t Sas-Rolfes, 2019). Human activities can introduce alien (invasive) species to new ecosystems, which can outcompete native species, disrupt ecological interactions, and cause harm to local biodiversity and ecosystem functioning (Dobrzycka-Krahel, 2023; Dobrzycka-Krahel & Medina-Villar, 2023).

Anthropogenic pressures have also a significant impact on sea water quality, what disrupt ecosystems, affect the health of marine organisms, and compromise water quality. Besides the overfishing and destructive fishing practices, sea water and marine environment pollution with plastic waste (Alimba & Faggio, 2019; Andrady, 2011; Dereszewska et al., 2023) and other debris leads to the accumulation of litter in the ocean as well as the coastal development and the habitat destruction resulting in habitat destruction, loss of biodiversity, and altered hydrodynamics, it includes eutrophication.

Eutrophication is a process in which excessive nutrients, primarily nitrogen and phosphorus, enter a body of water, leading to increased growth of algae and other aquatic plants (Bennett et al., 2001; Galloway et al. 2004; Leach et al., 2012). This ex-

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cess growth, known as an algal bloom, can cause a range of ecological and environmental problems, such as decreased oxygen levels in the water (Sellenr et al., 2003; Hallegraeff, 2003; Sanseverino, 2016). When these plants die, they sink to the bottom and decompose, consuming oxygen in the process. This can lead to a decrease in oxygen levels in the water and the production of toxins that can harm human health and aquatic life, lead to fish kills as well as create *dead zones* where no life can survive (Altieri, 2018; Altieri & Diaz, 2019; Diaz & Rosenberg, 2008). The rise in nutrient levels can occur due to natural factors like erosion, as well as human activities such as agricultural runoff, sewage discharge, and industrial waste. Eutrophication can also cause changes in the physical and chemical properties of water, such as increased water temperature, pH, and turbidity. These changes can further impact the ecosystem and the organisms that rely on it (Burkholder et al., 2007; Chislock et al., 2013; Glibert et al., 2005; Machowski, 2006; Schindler, 2006).

The chapter is organized into 4 parts, this Introduction as Section 1, Sections 2–3 and Conclusion as Section 4. Section 2 is devoted to the problems of eutrophication, methods and parameters of its assessment. Moreover, the eutrophication of the Baltic Sea and monitoring of its water quality is detailed described. In Section 3, the semi-Markov model of eutrophication process is introduced and presented. The possibility of the presented model's applications in the field considered in this chapter is suggested in Conclusion.

2. Eutrophication

Eutrophication can occur naturally, but it is often caused by human activities, such as agriculture, urbanization, and wastewater treatment (Ansari & Singh,2014; Ansari et al., 2010). When fertilizers, animal manure, or sewage are applied to land or discharged into waterways, the excess nutrients can be carried by runoff or leaching into nearby lakes, rivers, and oceans. The impacts of eutrophication can lead to a range of environmental problems, including oxygen depletion, harmful algal blooms, fish kills, loss of biodiversity, and degradation of aquatic habitats (Burkholder et al., 2007; Chislock et al., 2013; Glibert et al., 2005; Machowski, 2006; Schindler, 2006).

The severity and specific characteristics of eutrophication can vary among different basins based on their geographical location, climate, hydrological conditions, and human activities (Meier et al., 2022). Enclosed and shallow seas, such as the Baltic Sea, can experience eutrophication due to limited water exchange with the open ocean. Nutrient inputs from rivers, atmospheric deposition, and human activities can accumulate in these semi-enclosed basins, leading to eutrophic conditions and ecological imbalance.

Eutrophication is generally considered a negative phenomenon as it can cause significant harm to the ecosystem and human health (Ciu et al, 2021). While there are a few benefits associated with eutrophication, they are generally limited and often outweighed by the negative impacts. Here are a few potential benefits of eutrophication: increased plant growth or primary productivity, and fish production.

The increased availability of nutrients can lead to increased plant growth, which can provide additional food and habitat for some aquatic animals. Eutrophication can increase primary productivity, which is the rate at which energy is transferred from the sun to organic matter through photosynthesis. This can lead to an increase in the overall amount of organic matter in the ecosystem. In some cases, the increased availability of nutrients can lead to an increase in fish production, which can provide economic benefits to local communities.

While these potential benefits of eutrophication may exist, they are often overshadowed by the negative impacts, such as the formation of harmful algal blooms, oxygen depletion, and degraded water quality.

2.1. Monitoring eutrophication

Monitoring eutrophication involves the systematic collection of data on various parameters to assess the nutrient levels, algal growth, water quality, and ecosystem health of aquatic systems. Monitoring programs involve regular sampling of water bodies (Andersen et al., 2006; Conley et al., 2009; Moffat et al., 2010; OECD, 1982).

Nutrient levels is based on their concentrations, including nitrogen and phosphorus compounds, are measured in water samples. Measurement of nutrient concentrations is crucial for assessing eutrophication. Total nitrogen (TN), total phosphorus (TP), nitrate, ammonium, and orthophosphate are commonly measured parameters. These measurements help assess the nutrient loadings and nutrient ratios in the marine environment. It can be done through laboratory analysis using techniques such as colorimetry or spectroscopy. Nutrient samples may be collected at different depths to assess vertical variations. Moreover, ratios of nitrogen to phosphorus (N:P) can provide insights into nutrient limitation and nutrient imbalances in aquatic systems. Deviations from the optimal N:P ratio (usually around 16:1) can indicate nutrient limitation or excessive nutrient availability, both of which can be associated with eutrophication (Aulakh & Malhi, 2005; Jéquier & Constant, 2010; Jørgensen et al., 1981; Zhu et al., 2010).

The assessment of algal biomass can be conducted by measuring chlorophyll-a concentrations in water samples. Chlorophyll-a is a pigment found in algae and provides an indication of algal growth, therefore it is used as an indicator of algal biomass. High chlorophyll-a concentrations often indicate increased algal growth associated with eutrophication. Fluorometry or spectrophotometry are commonly used techniques for chlorophyll-a analysis (Matthews & Odermatt, 2015; Ramaraj et al., 2013; Sadeghian et al., 2018; Singh & Olsen, 2011).

Monitoring programs often include measurements of parameters that reflect water quality and ecological conditions (OECD, 1982; Tai et al., 2012). These parameters may include dissolved oxygen (DO), pH, temperature, conductivity, turbidity, and transparency (e.g., Secchi disk depth). Field measurements or laboratory analysis may be employed depending on the parameter. DO is a critical parameter for assessing water quality and ecosystem health. Eutrophication can lead to oxygen depletion in water bodies due to increased algal biomass and subsequent decomposition, which consumes oxygen. Thus, low DO levels can have detrimental effects on marine organisms and ecosystems. Moreover, parameters like biochemical oxygen demand (BOD) and chemical oxygen demand (COD) measure the amount of oxygen required for the decomposition of organic matter in water bodies. High BOD and COD values suggest organic pollution and increased oxygen demand associated with eutrophication. Changes in pH and alkalinity can occur as a result of eutrophication. Algal blooms and subsequent decomposition processes can affect water chemistry and alter pH and alkalinity levels. Secchi disk depth is a measure of water transparency or clarity. It is determined by lowering a disk into the water until it is no longer visible, and the depth is recorded. Reduced Secchi disk depth indicates increased turbidity, often caused by algal blooms or suspended particles associated with eutrophication. Biological indicators, such as the presence and abundance of specific algal species like cyanobacteria (blue-green algae) or the composition of macroinvertebrate and fish communities, can provide valuable information about the ecological impacts of eutrophication on aquatic ecosystems (Charles, 1996; Jørgensen et al., 1981; López-López & Sedeño-Díaz, 2015; Persoone & De Pauw, 1979). Biological sampling methods, such as plankton tows or benthic grabs, may be used to collect organisms for analysis.

Monitoring and assessing these parameters over time and in different locations can help identify the presence, severity and trends of eutrophication, guide management strategies, and evaluate the effectiveness of eutrophication mitigation measures. Long-term monitoring programs are crucial to understand the dynamics of eutrophication and track changes over time. Regular and consistent data collection allows for the identification of trends, the evaluation of the effectiveness of mitigation measures, and the assessment of the response of aquatic systems to management actions. Statistical analysis techniques, such as trend analysis, multivariate analysis, or ecological indices, can be employed to interpret the data and identify patterns or changes in nutrient levels, algal growth, and water quality (Anagnostou et al., 2017; Borsuk et al., 2004; Freeman & Skapura, 1991; Karul et al., 2000; Keiner & Brown, 1998; Ménesguen & Lacroix, 2018; Soyupak et al., 1997). These models can also help predict future trends and assess the effectiveness of management measures.

2.2. Eutrophication in the Baltic Sea

The Baltic Sea is one of the most eutrophic sea areas in the world, and eutrophication has been a significant problem in the region for several decades (Andersen et al., 2017). The main sources of nutrient pollution in the Baltic Sea include phosphorus and nitrogen, which come from a range of sources, including industrial and municipal wastewater discharges, agricultural runoff, and atmospheric deposition (Baltic University, 2003). These nutrients fuel the growth of algae, which can cause increased frequency and severity of harmful algal blooms (Fig. 1), oxygen depletion, and changes in the ecosystem structure, namely reduced biodiversity and degraded water quality (Dobrzycka-Krahel & Bogalecka, 2022; HELCOM, 2009, Rönnberg & Bonsdorff, 2004). Additionally, eutrophication can also harm human health by contaminating drinking water supplies and causing skin and respiratory irritation in people who swim in the affected waters.

Figure 1. Satellite picture showing algal blooms in the Baltic Sea (source: Helsinki Commission).

There are several sources of nutrients that contribute to eutrophication in the Baltic Sea. The primary sources of nutrients in the Baltic Sea include: agricultural runoff, wastewater treatment plants, atmospheric deposition, shipping, fish farming and also natural sources (HELCOM, 2009; Ning et al., 2018).

Agricultural activities in the Baltic Sea catchment area are a major source of nutrient pollution, including nitrogen and phosphorus. Fertilizers, animal manure, and other agricultural practices can lead to nutrient runoff into waterways that eventually flow into the Baltic Sea. Nutrient runoff from agricultural fields can be transported to the Baltic Sea via rivers and other waterways, where they can contribute to algal blooms and other negative impacts on water quality (Granstedt et al., 2008; HELCOM. 2021b; Savage et al., 2010).

Municipal and industrial wastewater treatment plants discharge nutrients, such as phosphorus and nitrogen, into the Baltic Sea. This can be a significant source of nutrient pollution, particularly in coastal areas where the water exchange is limited.

Airborne particles containing nitrogen and phosphorus can be transported over long distances and deposited into the Baltic Sea, contributing to nutrient pollution (Bogalecka & Dereszewska, 2022).

Transportation also plays a significant role in the eutrophication of the Baltic Sea. Ships and other vessels that operate in the Baltic Sea can contribute to nutrient pollution through their discharge of sewage and ballast water, which can contain nutrients. Ships emit nitrogen oxides (NO_x) and sulphur dioxide (SO_2), which can contribute to the formation of acid rain and deposition of nutrients in the Baltic Sea.

The production of fish in aquaculture can lead to nutrient pollution through the discharge of fish waste and uneaten feed into the surrounding water.

Natural sources of nutrients, such as sediment and runoff from forests and wetlands, also contribute to nutrient pollution in the Baltic Sea.

Rivers play a significant role in the eutrophication of the Baltic Sea. In the Baltic Sea region, there are several large rivers that are particularly important for nutrient inputs, including the Neva, Daugava, Vistula, and Oder. These rivers transport nutrients from their watersheds to the Baltic Sea, where they can contribute to algal blooms and other negative impacts on water quality (HELCOM, 2021b).

The Baltic Sea receives approximately 570,000 tons of nitrogen and 44,000 tons of phosphorus each year from various sources, including agriculture, urban and industrial runoff, and atmospheric deposition. Eutrophication has caused the formation of several large-scale *dead zones* in the Baltic Sea, where oxygen levels are too low to support most marine life (Conley et al., 2009). These areas cover up to 80,000 km^2 and affect over 60% of the total area of the Baltic Sea. Eutrophication has also led to an increase in the frequency and severity of harmful algal blooms in the Baltic Sea. These blooms can be toxic to marine life and pose a risk to human health through the consumption of contaminated seafood. The economic impacts of eutrophication in the Baltic Sea are estimated to be significant, with the annual cost of eutrophication-related damage ranging from 1.4 billion to 4.4 billion €.

Despite the severity of eutrophication in the Baltic Sea, there have been efforts to reduce nutrient inputs and improve water quality. For example, the Helsinki Commission (HELCOM) established the Baltic Sea Action Plan (HELCOM, 2021a), which aims to reduce nutrient inputs by over 40% from 1990 levels by now.

It is difficult to predict the exact future of eutrophication in the Baltic Sea, as it will depend on various factors such as climate change, land use practices, and nutrient management strategies (Olesen et al., 2019). However, there are some indications of what may happen in the future. Some predictions suggest that eutrophication will continue to worsen in the Baltic Sea in the coming decades. As the planet continues to warm, changes in precipitation patterns and sea surface temperatures could alter nutrient inputs and exacerbate eutrophication in the Baltic Sea. For example, increased rainfall could lead to higher nutrient runoff from agricultural and urban areas, while warming waters could promote the growth of harmful algal blooms. The population of the Baltic Sea region is expected to increase in the coming decades, which could lead to increased nutrient pollution and eutrophication (Reckermann et al., 2022). This is particularly true in urban areas, where increased development and population density could contribute to higher nutrient inputs. Consequently, it could lead to further declines in water quality, reduced biodiversity, and increased risks to human health. On the other hand, some predictions suggest that the situation in the Baltic Sea could improve if nutrient inputs are reduced and the ecosystem is given time to recover. This could lead to improvements in water quality, increased biodiversity, and more sustainable use of the sea's resources. It is worth noting that there is a lot of uncertainty around predictions for eutrophication in the Baltic Sea, as it depends on a wide range of complex and interconnected factors.

To address the role of rivers in eutrophication, it is important to focus on reducing nutrient inputs from upstream sources. This can include promoting sustainable land use practices, such as reducing fertilizer use and promoting soil conservation, as well as upgrading wastewater treatment facilities and improving storm water management practices. Regular monitoring and measurement of nutrient inputs and water quality can also help to track progress and adjust management strategies as needed.

Preventing and mitigating eutrophication in the Baltic Sea requires a combination of some strategies and a comprehensive approach that involves the cooperation among various stakeholders such as government agencies, local communities, businesses, industry and individuals to address the mentioned above sources of nutrient pollution and protect the health of the Baltic Sea and its ecosystems (HELCOM, 2009, 2022). There are some ways to prevent and mitigate eutrophication in the Baltic Sea through restore ecological balance of the affected water body. It involves reducing nutrient inputs from agriculture, shipping and fish farming, improving wastewater treatment, reducing atmospheric deposition, restoration of coastal wetlands, biological, physical and chemical control as well as raising public awareness and education.

Agricultural practices such as minimizing fertilizer use, planting cover crops, reducing tillage, and implementing best management practices in agriculture, can help reduce nutrient runoff into waterways. The use of buffer strips and wetlands can also help filter out nutrients from agricultural runoff.

Upgrading wastewater treatment plants can help remove nutrients before they are discharged into the Baltic Sea. Technologies such as advanced biological nutrient removal and chemical precipitation can help reduce nutrient levels in treated wastewater.

Reducing emissions of nitrogen oxides (NO_X) and ammonia (NH_3) from industries, power plants, and transport can help reduce the amount of nutrients that are deposited into the Baltic Sea from the air.

Implementing regulations to reduce nutrient discharge from ships, such as requirements for sewage treatment and ballast water management, can help reduce nutrient inputs from shipping. Regulating shipping activities can help to ensure that ships operating in the Baltic Sea comply with environmental standards and best practices. The International Maritime Organization has established regulations, such as the International Convention for the Prevention of Pollution from Ships (IMO, 2022), that aim to reduce the environmental impact of shipping.

Improving aquaculture practices, such as reducing feed waste and improving water management, can help reduce nutrient pollution from fish farming.

Wetlands are effective at filtering nutrients from runoff and can help to reduce nutrient pollution. Restoration of degraded wetlands, as well as the creation of new wetlands, can be a useful tool in mitigating eutrophication.

Biological control methods such as the use of biocontrol agents, e.g. aquatic plants and filter-feeding organisms, can help to remove nutrients from the water and improve water quality. Physical control methods such as dredging, aeration, and artificial mixing can be used to reduce the amount of nutrient-rich sediments and increase oxygen levels. Chemical control methods such as the application of alum or other chemicals to bind phosphorus in the water column can be used to reduce nutrient levels and prevent the growth of harmful algae.

Education programs and raising public awareness about the importance of reducing nutrient inputs into the Baltic Sea can help to reduce nutrient pollution by encouraging changes in behaviour, such as reducing fertilizer use, proper disposal of waste, and avoiding the discharge of waste into the sea.

2.3. Monitoring eutrophication in Baltic Sea

The Baltic Sea region has implemented the SATBALT system (Sustainable Assessment of the Baltic Sea) to monitor eutrophication and assess the environmental status of the Baltic Sea (http://satbaltyk.iopan.gda.pl). The SATBALT system was initiated in 2010. It is designed to support the implementation of the EU Marine Strategy Framework Directive (EU, 2008) and the Baltic Sea Action Plan (HELCOM, 2021a). The system, coordinated by the HELCOM, plays a crucial role in monitoring and managing eutrophication in the Baltic Sea. The program aims to provide a comprehensive understanding of eutrophication and its impacts on the Baltic Sea ecosystem. By providing a harmonized approach to data collection, assessment, and reporting, the system supports decision-making and promote sustainable management as well as the regional efforts to reduce nutrient inputs, improve water quality, and protect the Baltic Sea ecosystem.

The SATBALT system incorporates an integrated monitoring program that involves regular sampling and analysis of various parameters also related to eutrophication in the scope of assessing the environmental status of the Baltic Sea (Fig. 2). There are some key parameters that SATBALT monitors (described in Section 2.1), such as: nutrient concentrations and nutrient ratios, chlorophyll-a, dissolved oxygen, Secchi depth. Additionally, SATBALT monitors benthic conditions, including indicators such as macroalgae coverage, benthic oxygen conditions, and nutrient fluxes in sediments. These parameters provide insights into the impacts of eutrophication on benthic habitats and the functioning of the Baltic Sea ecosystem. SATBALT also monitors the occurrence and dynamics of harmful algal blooms (HABs) in the Baltic Sea. HABs can be associated with eutrophication and can have detrimental effects on water quality, marine life, and human activities.

These parameters, along with other relevant ecological and water quality indicators, provide a comprehensive understanding of eutrophication in the Baltic Sea. By monitoring these parameters, SATBALT helps to assess the environmental status, track changes over time, and guide management strategies to mitigate eutrophication impacts in the region.

3. Modelling eutrophication process

To construct the eutrophication process, the set of ω, $\omega \in N$, kinds of eutrophication parameters is distinguished and these parameters are denoted by $\varepsilon_1, \varepsilon_2, \dots, \varepsilon_\omega$.

This way the set

$$\mathcal{E} = \{\varepsilon_1, \varepsilon_2, \dots, \varepsilon_\omega\}$$

is the set of eutrophication parameters.

These parameters may attain different levels. Namely, the eutrophication parameter ε_i, $i = 1,2,\dots,\omega$, may reach r_i levels

$$\varepsilon_{i1}, \varepsilon_{i2}, \dots, \varepsilon_{ir_i},\ i = 1,2,\dots,\omega,$$

that are called the states of this eutrophication parameter.

The set

$$\varepsilon_i = \{\varepsilon_{i1}, \varepsilon_{i2}, \dots, \varepsilon_{ir_i}\},\ i = 1,2,\dots,\omega,$$

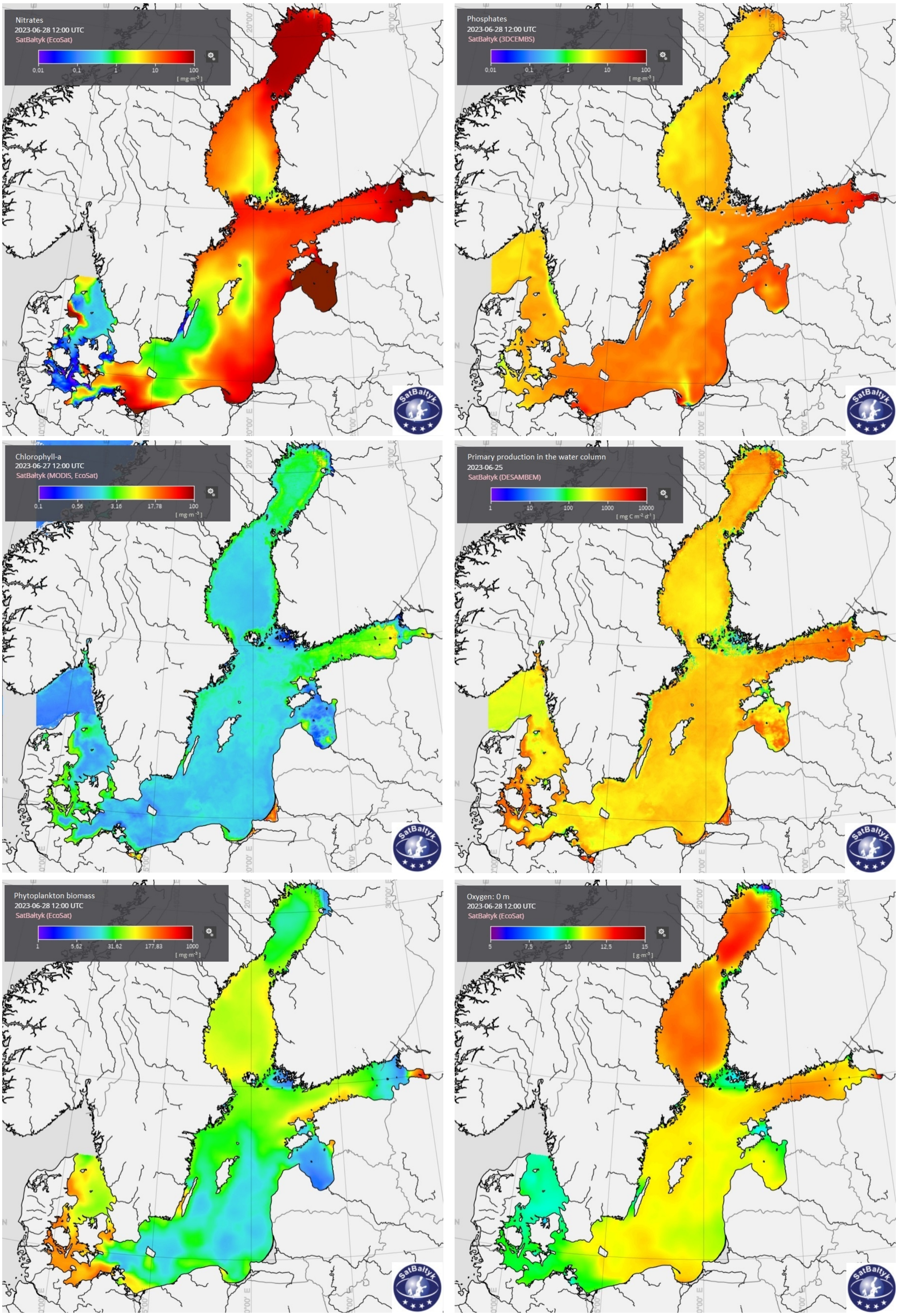

Figure 2. Selected parameters generated from SATBALT (Baltic Sea, 28 June 2023, 12:00 UTC) (source: http://satbaltyk.iopan.gda.pl).

is called the set of states of eutrophication parameter ε_i.

Under these assumptions, the eutrophication process $E(t)$, $t \in \langle 0, +\infty)$ is introduced as a vector

$$E(t) = [\varepsilon_1(t), \varepsilon_2(t), \dots, \varepsilon_\omega(t)],\ t \in \langle 0, +\infty),$$

where

$$\varepsilon_i(t),\ t \in \langle 0, +\infty),\ i = 1,2,\dots,\omega,$$

are the processes of eutrophication parameters defined on the time interval $t \in \langle 0, +\infty)$ and having their values in the eutrophication parameter's state sets ε_i, $i = 1,2,\dots,\omega$.

The vector

$$e_i = [c_1, c_2, \dots, c_\omega], \tag{1}$$

where

$$c_i = \begin{cases} 0, & \text{if a eutrophication parameter } \varepsilon_i \\ & \text{is in the typical range} \\ \varepsilon_{ij}, & \text{if a eutrophication parameter } \varepsilon_i \\ & \text{is in the untypical range} \\ & \varepsilon_{ij}, j = 1,2,\dots r_i \end{cases} \tag{2}$$

for $i = 1,2,\dots,\omega$, is called eutrophication state. Future, the vectors that cannot occur may be eliminated and the remaining eutrophication states, defined by (1)–(2), are marked by e_k for $k = 1,2,\dots,v$, and the set is formed

$$E = \{e_k, k = 1,2,\dots,v\}, \tag{3}$$

where

$$e_k \neq e_l,\ k \neq l,\ k,l \in \{1,2,\dots,v\}.$$

The set E is called the set of eutrophication states, while v is called the number of eutrophication states.

A function

$$E(t),\ t \in \langle 0, +\infty), \tag{4}$$

having values in the eutrophication states set E is called the eutrophication process.

Next, a semi-Markov model of the eutrophication process $E(t)$, $t \in \langle 0, +\infty)$ is assumed. Its random conditional sojourn time at the eutrophication state e_k while the next transition will be done to the state e_l, $k,l = 1,2,\dots,v$, $k \neq l$ is denoted by θ_{kl}. Thus the eutrophication process $E(t)$, $t \in \langle 0, +\infty)$ is described by the following parameters that can be evaluated by expert or identified statistically using the methods given in (Bogalecka, 2020; Grabski, 2015; Iosifescu, 1980; Kołowrocki, 2014; Kołowrocki & Soszyńska-Budny 2011; Lev'y, 1954; Limnios & Oprisian, 2005; Rice, 2007; Smith, 1955):

- the matrix of probabilities $[p_{kl}]_{v\text{x}v}$ of the eutrophication process $E(t)$, $t \in \langle 0, +\infty)$ transitions between the air pollutant's concentration states e_k and e_l,

  $$p_{kl},\ k,l = 1,2,\dots,v,\ k \neq l \tag{5}$$

  where $\forall k = 1,2,\dots,v$, $p_{kk} = 0$,
- the matrix of mean values $[M_{kl}]_{v\text{x}v}$ of the eutrophication process $E(t)$, $t \in \langle 0, +\infty)$ conditional sojourn times θ_{kl} at the air pollutant's concentration state e_k while its next transition will be done to the state e_l, $k,l = 1,2,\dots,v$, $k \neq l$,

  $$M_{kl} = E[\theta_{kl}] = \int_0^\infty t dH_{kl}(t)$$

  $$= \int_0^\infty t dh_{kl}(t),\ k,l = 1,2,\dots,v,\ k \neq l, \tag{6}$$

  where $\forall k = 1,2,\dots,v$, $M_{kk} = 0$, and where

  $$H_{kl}(t) = P(\theta_{kl} < t),\ t \in \langle 0, +\infty), \tag{7}$$

  for

  $$k,l = 1,2,\dots,v,\ k \neq l,$$

  are the conditional distribution functions of the eutrophication process $E(t)$, $t \in \langle 0, +\infty)$ conditional sojourn times θ_{kl}, $k,l = 1,2,\dots,v$, $k \neq l$, at the states corresponding to conditional density functions

  $$h_{kl}(t) = \frac{dH_{kl}(t)}{dt},\ t \in \langle 0, +\infty), \tag{8}$$

  for

  $$k,l = 1,2,\dots,v,\ k \neq l,$$

- the vector of mean values $[M_k]_{1xv}$ of the eutrophication process $E(t)$, $t \in \langle 0, +\infty)$ unconditional sojourn times θ_k, $k = 1,2,\ldots,v$, at the air pollutant's concentration states

  $$M_k = E[\theta_k] = \sum_{l=1}^{v} p_{kl} M_{kl}, \quad (9)$$

  for

  $$k = 1,2,\ldots,v,$$

  where p_{kl} and M_{kl} are defined by (5) and (6) respectively,
- the vector $[p_k]_{1xv}$ of limit values of transient probabilities

  $$p_k(t) = P(E(t) = e_k), \quad (10)$$

  for

  $$t \in \langle 0, +\infty), k = 1,2,\ldots,v,$$

  of the eutrophication process $E(t)$, $t \in \langle 0, +\infty)$ at the particular states e_k, $k = 1,2,\ldots,v$, where

  $$p_k = \lim_{t\to\infty} p_k(t) = \frac{\pi_k M_k}{\sum_{l=1}^{v} \pi_l M_l} \quad (11)$$

  for

  $$k = 1,2,\ldots,v,$$

  where M_k, $k = 1,2,\ldots,v$, are given by (9), and the probabilities π_k, $k = 1,2,\ldots,v$, satisfy the system of equations

  $$\begin{cases}[\pi_k] = [\pi_k][p_{kl}] \\ \sum_{l=1}^{v} \pi_l = 1\end{cases} \quad (12)$$

  where

  $$[\pi_k] = [\pi_1, \pi_2, \ldots, \pi_v],$$

  and $[p_{kl}]$ is given by (5),
- the vector $[\hat{M}_k]_{1xv}$ of the mean values of the total sojourn times $\hat{\theta}_k$, $k = 1,2,\ldots,v$,

  $$\hat{M}_k = E[\hat{\theta}_k] \cong p_k \theta, \quad (13)$$

  at the particular states e_k, $k = 1,2,\ldots,v$ of the eutrophication process $E(t)$, $t \in \langle 0, +\infty)$ in the fixed time interval $\langle 0, \theta\rangle$, $\theta > 0$, where p_k are given by (11).

4. Conclusion

Eutrophication can have serious environmental consequences and can lead to the degradation of aquatic ecosystems. It is important to monitor and manage nutrient levels in bodies of water to prevent or mitigate eutrophication.

Using the background given in this Section 3 and based on some eutrophication parameters presented in Section 2.1, the proposed eutrophication process can be applied to identify and predict the degree of eutrophication in the exemplary aquatic ecosystem, e.g. the Baltic Sea. In this case, free accessible date from the SATBALT system, presented in Section 2.3, will be used.

To address the problem of eutrophication in the Baltic Sea, a range of measures have been implemented, including nutrient reduction targets for countries in the region, improved wastewater treatment, better agricultural management practices, and efforts to reduce atmospheric deposition of nutrients. However, more work is needed to fully address the problem and protect the health of the Baltic Sea and the people who depend on it.

Monitoring eutrophication requires collaboration among scientists, environmental agencies, and stakeholders. It helps in informing management strategies, evaluating the success of nutrient reduction efforts, and guiding decision-making processes to mitigate eutrophication impacts and protect water quality.

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