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Long-Term Monitoring of Hydrological Dynamics and Phytoplankton Biomass Indicator in Three Shellfish Ecosystems of the English Channel (2000-2024)

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Abstract. This study investigates the long-term monitoring of physico-chemical parameters and biogeochemical cycles in coastal ecosystems, focusing on three stations in Normandy: Blainville-sur-Mer, Saint-Vaast-la-Hougue, and Utah Beach. Over a 24-year period, we analyzed trends in temperature, pH, chlorophyll a concentrations, and nutrient levels, aiming to assess the impacts of climate change and human activities on marine ecosystems. Results show a consistent rise in winter temperatures, particularly since 2013, alongside increasing ocean acidification, especially at Blainville-sur-Mer. These trends suggest potential consequences for planktonic communities and mollusk health. Nutrient analysis revealed significant variations, including high ammonium concentrations on the East coast and a gradual decline in phosphates over the last 15 years, highlighting the influence of anthropogenic activities. The study also identified nutrient limitations, with phosphorus dominating the East coast and nitrogen on the West coast. Our findings emphasize the need for effective nutrient management strategies to mitigate the effects of climate change and human impact, ensuring the sustainability of coastal ecosystems and aquaculture practices. This long-term monitoring is crucial for understanding ecological dynamics and guiding future coastal zone management in the face of global environmental changes.

1. Introduction

Located at the interface between land and ocean, coastal ecosystems are highly productive areas essential for the survival of many marine species (Barbier *et al.*, 2011). However, these environments are under increasing pressure from human activities, such as eutrophication, pollution, and changes to coastal and marine landscapes. These threats affect both benthic and pelagic habitats, thereby disrupting ecological balances (Sala *et al.*, 2000 ; Dudgeon *et al.*, 2006 ; Halpern *et al.*, 2007 ; Barbier *et al.*, 2011 ; Ovaskainen *et al.*, 2019).

Since the 1950s, the widespread use of fertilizers in intensive agricultural practices has led to an increase in nutrient inputs into European coastal waters (Vermaat *et al.*, 2008). Over the decades, numerous programs have been implemented to limit these discharges, but while the effects on phosphorus inputs have been notable (Claussen *et al.*, 2009), nitrogen inputs remain very high (Garnier *et al.*, 2019). These inputs influence not only the concentration of nutrients but also their stoichiometry (Martin *et al.*, 2008 ; Watanabe *et al.*, 2017 ; Meybeck *et al.*, 2018). These imbalances lead to changes in the productivity of phytoplankton communities, which are at the base of the food web, as well as in their composition (Shen, 2001 ; Cadée & Hegeman, 2002 ; Smith, 2006 ; Lefebvre *et al.*, 2011 ; Leruste *et al.*, 2019).

Nutrient inputs, alongside other environmental factors such as light availability, temperature, water residence time, and river discharge, play a critical role in driving phytoplankton blooms (Heisler *et al.*, 2008). These blooms are vital for shellfish ecosystems, serving as an essential food source for farmed bivalves (Sonier *et* al., 2016 ; Filgueira *et al.*, 2016). However, studies have reported a slowdown in primary production, including phytoplankton blooms, due to changing environmental conditions (Romero *et al.*, 2016).

Climate change significantly influences coastal systems through various physical and chemical processes (Kirby *et al.*, 2009). Beyond the well-documented direct effects of rising temperatures on marine organisms (Beaugrand, 2004), warming also affects water stratification, which alters the vertical exchange of nutrients and oxygen (Sarmiento & Gruber, 2006). This can lead to an increased occurrence of hypoxic or anoxic events in coastal waters (Diaz, 2001 ; Selman *et al.*, 2008). Furthermore, atmospheric circulation—through changes in sea level pressure, wind direction, and intensity-impacts oceanic currents, which play a key role in the horizontal transport of nutrients and oxygen in these ecosystems (Cloern, 2001 ; Reid *et al.*, 2003).

Since the early 2000s, the HYDRONOR observatory, dedicated to shellfish water masses, has been established in the Cotentin department. The objective of our study is to track the evolution of hydrobiological parameters in three Normandy shellfish stations: Blainville-sur-Mer, Saint-Vaast-La-Hougue, and Utah Beach, monitored by this observatory. Over 20 years of data have been collected and will be analyzed using advanced statistical tools. These stations make it possible to establish a link between the two SOMLIT stations at Luc-sur-Mer in the Baie de Seine and Roscoff.

2. Material and methods

2.1. Sampling sites and strategies

Three shellfish sampling areas were studied by SMEL between 2000 and 2024 as part of the HYDRONOR observatory. Two of these areas are located in open ecosystems, heavily exploited by oyster farming activities: Saint-Vaast-la-Hougue (named Tocquaise), in the eastern part of the department, and Blainville-sur-Mer, in the western part. The third area, Utah Beach, is located in the enclosed environment of the Baie des Veys, under strong anthropogenic influence (Figure 1).

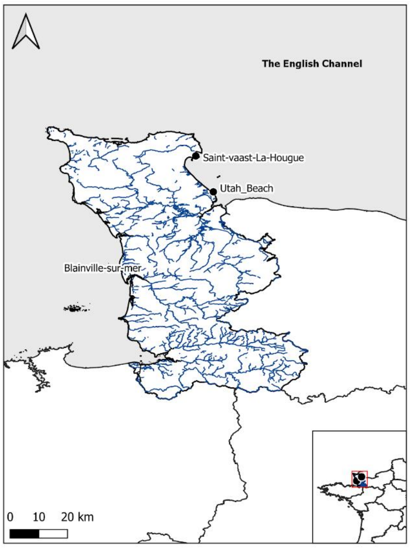

Figure 1: Location of the sampling stations along the French coast in the English Channel (Blainville-sur-mer, Saint-Vaast-La-Hougue, Utah Beach).

2.2. Sample analysis

Table 1: Analytical Methods for the Determination of Nutrients in seawater samples

Molecule	References	Principe
Ammonium (NH_4^+)	Standard NF T 90-015-2 (January 2000): Water testing – Determination of ammoniacal nitrogen – Spectrophotometric method using indophenol blue	In an alkaline medium ($10.4 < pH < 11.5$), the ammonium ion reacts with phenol and hypochlorite to form monochloramine. This compound, in the presence of nitroprusside as a catalyst, leads to the formation of indophenol blue. The absorption is measured using a spectrophotometer at 630 nm.
Nitrate (NO_3^-) / Nitrite (NO_2^-)	Aminot & Chaussepied, 1983 Bendschneider & Robinson, 1952 Aminot & Kerouel, 2004	The selected method is based on the determination of $NO2^-$ ions obtained through the quantitative reduction of $NO3^-$ ions. In practice, the measurement reflects the sum of the concentrations of both ions, from which the nitrite concentration is deducted separately, without reduction. The reduction is carried out by passing the sample through a cadmium column treated with copper. After nitrate reduction (Griess reaction), measurement is performed based on the determination of nitrite ions. Nitrite ions form a diazo compound with sulfanilamide in an acidic medium ($pH < 2$), which then reacts with N-naphthyl-ethylenediamine to form a pink dye absorbing at 543 nm.
Orthophosphate (PO_4^{3-})	Aminot & Chaussepied, 1983 Murphy & Riley, 1962	Phosphate ions react with ammonium molybdate in the presence of antimony to form a complex that is then reduced by ascorbic acid; this reduced form, with a blue coloration, has a maximum absorption at 885 nm. This blue compound contains phosphorus, molybdenum, and antimony in atomic proportions of 1-12-1. Polyphosphates and organic phosphorus are not measured by this method.
Orthosilicic acid ($Si(OH)_4$)	Aminot & Chaussepied, 1983 Mullin & Riley, 1955 Strickland & Parsons, 1972 Aminot & Kerouel, 2004	The colorimetric determination is based on the formation of a silicomolybdic complex which, after reduction, produces an intense blue coloration. Orthosilicic acid tends to form polymers, of which only the mono- and dimeric forms react with molybdate ions under the conditions of this method, making the term "reactive silicon" more appropriate. Under reaction conditions, colloidal silicates are measured together with dissolved silicates using this method.

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The samples were collected at a depth of 1 meter using a 5L Niskin bottle, twice a month, one hour before or after high tide. Chlorophyll *a* was quantified after filtering three 100 mL samples using fluorimetry. Nutrients were measured via spectrophotometry. Mineral nitrogen was quantified through ammonium (NH_4^+), nitrite (NO_2^-), and nitrate (NO_3^-). Only the assimilable form of phosphorus, orthophosphate (PO_4^{3-}), was quantified, as well as silicates ($Si(OH)_4$). The methods are detailed in Table 1.

Calibration standards were prepared in depleted seawater and validated according to AFNOR XP T90-210 (May 2009), an experimental standard for water quality outlining the protocol for the initial performance evaluation of a method in a laboratory. Physico-chemical parameters (temperature, salinity) were measured in situ using a YSI multi-parameter probe. pH was measured in the laboratory.

To assess the potential limitation of primary production by nutrient availability, the standard molar ratios for dissolved inorganic nitrogen (DIN = ammonium + nitrite + nitrate), phosphate, and silicate were calculated and compared. These ratios were based on the biogenic matter composition described by Redfield *et al.* (1963) and Brzezinski (1985), which is Si:N:P = 16:16:1.

2.3. Data analysis

The entire dataset was analyzed using the R software, with the TTAinterfaceTrendAnalysis package developed by Devreker & Lefebvre (2014).

3. Results

3.1. Evolution of Physico-Chemical Parameters: Rising Winter Temperatures and pH Acidification

Figure 2 presents the monitoring of physico-chemical parameters. The monthly trends across the three stations show a similar pattern regarding temperature. However, the time series reveals a notable increase in winter temperatures. For instance, between 2009 and 2013, the average minimum temperatures at the three stations were around 5°C. In contrast, from 2013 to 2024, these minimum temperatures ranged between 6°C and 8°C across all stations. Significant changes are also observed in pH levels. As illustrated by the time series in Figure 2, pH has become more acidic over time. In the early 2000s, the lowest recorded pH remained above 8.0, whereas by 2024, it has dropped to 7.85. These observations are shared by the mean deviation data presented in Figure 3. Indeed, the red values for temperature indicate so-called "positive" anomalies, representing values above the interannual averages. For pH, the dominance of blue since 2017 reflects its acidification, which is most noticeable in Blainville-sur-mer, on the western coast.

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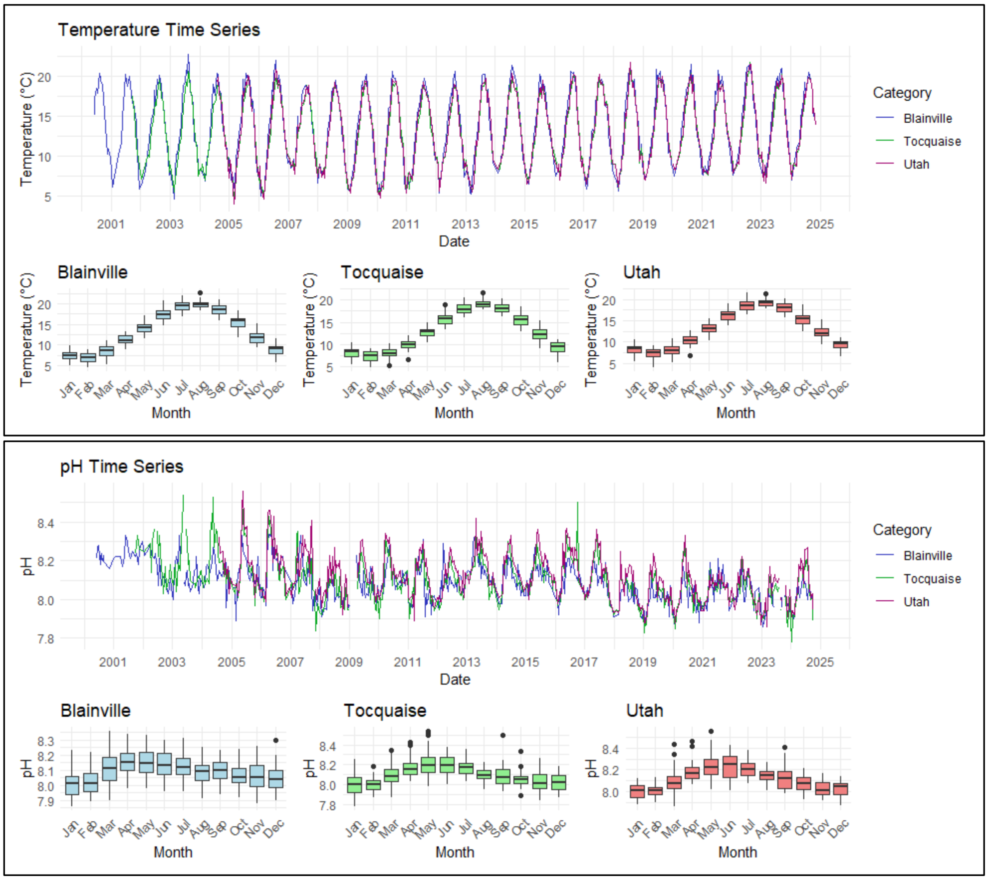

Figure 2: Time Series and Monthly Averages of Temperature (°C) (top) and pH (bottom) Parameters from 2000 to 2024 at Blainville-sur-Mer, Saint-Vaast-la-Hougue (Tocquaise), and Utah Beach.

3.2. Spatial and Temporal Variability of Chlorophyll *a* Concentrations

Chlorophyll *a* concentrations are illustrated in Figure 4. The stations located on the eastern coast, Saint-Vaast-la-Hougue and Utah Beach, exhibit the highest levels, with peaks exceeding 20 µg/L, compared to a maximum of 10 µg/L at Blainville-sur-Mer. On the western coast, the annual bloom is clearly visible, marked by an increase in chlorophyll *a* concentrations every March. In contrast, on the eastern coast, trends are more variable across years, with peaks observed between February and July. Since 2020, a drastic decrease in chlorophyll *a* concentrations has been observed on the eastern coast. This trend is confirmed by Figure 5, which highlights values below the median for this period. Moreover, the predominance of green in the Blainville graph, compared to blue for the other two stations, underscores the differences between the western and eastern coastal ecosystems.

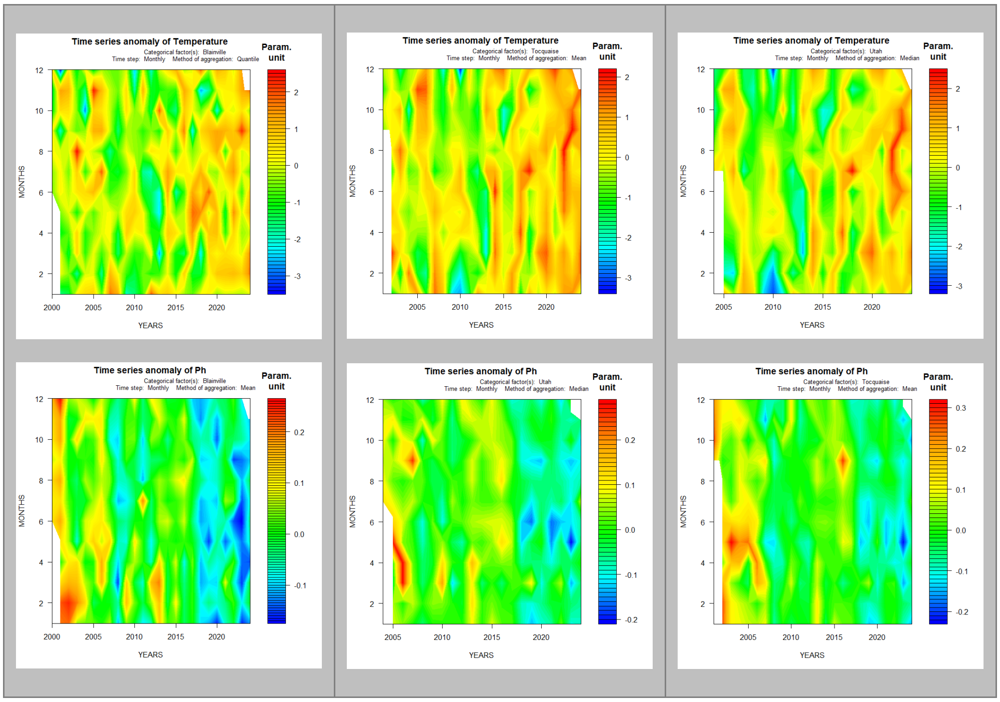

Figure 3: Monitoring of temperature (Top) and pH (Bottom) anomalies for the 3 stations. Anomalies are Calculated as Deviations from the Median (red : positive anomalies / blue : negatives anomalies).

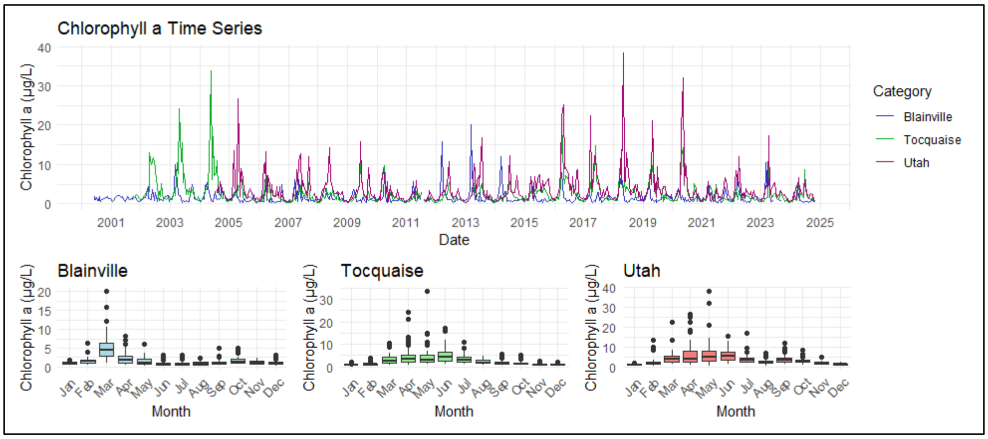

Figure 4: Time Series and Monthly Averages of chlorophyll *a* (µg.L^{-1}) from 2000 to 2024 at Blainville-sur-Mer, Saint-Vaast-la-Hougue (Tocquaise), and Utah Beach.

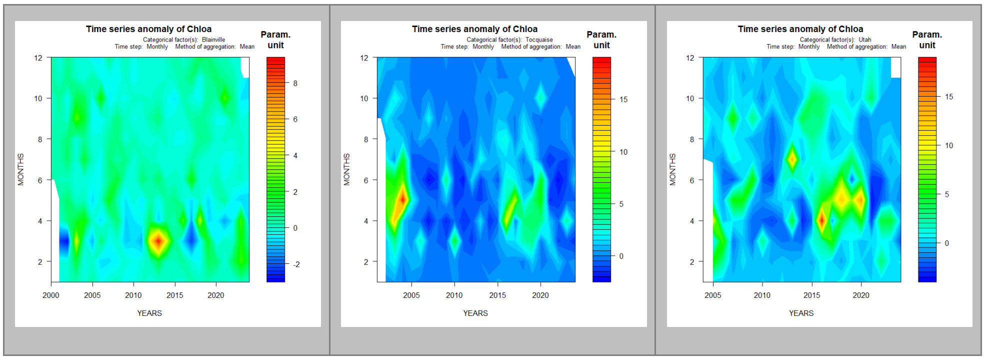

Figure 5: Monitoring of Chorophyll *a* anomalies for the three Stations: Blainville-sur-Mer, Saint-Vaast-la -Hougue (Tocquaise), and Utah Beach. Anomalies are Calculated as Deviations from the Median (red : positive anomalies / dark blue : negatives anomalies).

3.3. Nutrient Salt Dynamics and Seasonal Decomposition

The evolution and trends of nutrient salts are illustrated in Figure 6. Among them, ammonium shows the most marked variations between the stations. Its concentrations mainly increase between September and December, with the highest levels on the East coast, where they can exceed 2 µmol/L.In contrast, on the West coast, represented by Blainville-sur-Mer, the maximum values are closer to 1 µmol/L. Nitrites and nitrates exhibit much more cyclical variations across the three stations, with minimal concentrations in the summer and maximum levels exceeding 20 µmol/L in January, before decreasing in the spring.

On the West coast, although the maximum concentrations are similar to those of the East coast, they decrease more rapidly once the winter peak is reached. As for orthophosphates and silicates, the trends follow a similar pattern to those of nitrates and nitrites: concentrations rise in the autumn, peak in the winter, and decrease in the spring. For phosphate, concentrations rarely exceed 1 µmol/L, while silicates reach nearly 30 µmol/L in winter, especially on the East coast. However, no significant difference was observed between the two coasts for silicates. Finally, the time series for phosphate highlights a gradual decline in concentrations over the past 15 years on both coasts.

The seasonal decomposition of various nutrients and chlorophyll-a, presented in Figure 7, reveals similar trends across the three studied stations over the past 20 years. Chlorophyll-a concentrations decreased progressively until 2010, increased between 2010 and 2015, and then declined again until 2024. Over this period, an overall decrease in chlorophyll-a concentrations was observed, with reductions of 0.2 µg.L^{-1} at Blainville-sur-Mer, 3.0 µg.L^{-1} at Saint-Vaast-la-Hougue, and 2.0 µg.L^{-1} at Utah Beach.For nutrients, a general downward trend was also observed. Between 2000 and 2024, orthophosphate concentrations decreased by 0.3 µmol.L^{-1} at Blainville-sur-Mer, 0.5 µmol.L^{-1} at Saint-Vaast-la-Hougue, and 0.4 µmol.L^{-1} at Utah Beach. Silica recorded decreases of 1.5 µmol.L^{-1}, 2.0 µmol.L^{-1}, and 2.5 µmol.L^{-1} at these respective stations, while ammonium concentrations decreased by 1.5 µmol.L^{-1}, 1.0 µmol.L^{-1}, and 0.4 µmol.L^{-1}. The most significant reductions were observed for nitrates and nitrites, with decreases of 6.0 µmol.L^{-1} at Blainville-sur-Mer and Saint-Vaast-la-Hougue, and 4.0 µmol.L^{-1} at Utah Beach. Finally, it is noteworthy that in 2010, when chlorophyll-a concentrations were at their lowest, nutrient concentrations were not at their minimum, highlighting a distinct dynamic between these parameters.

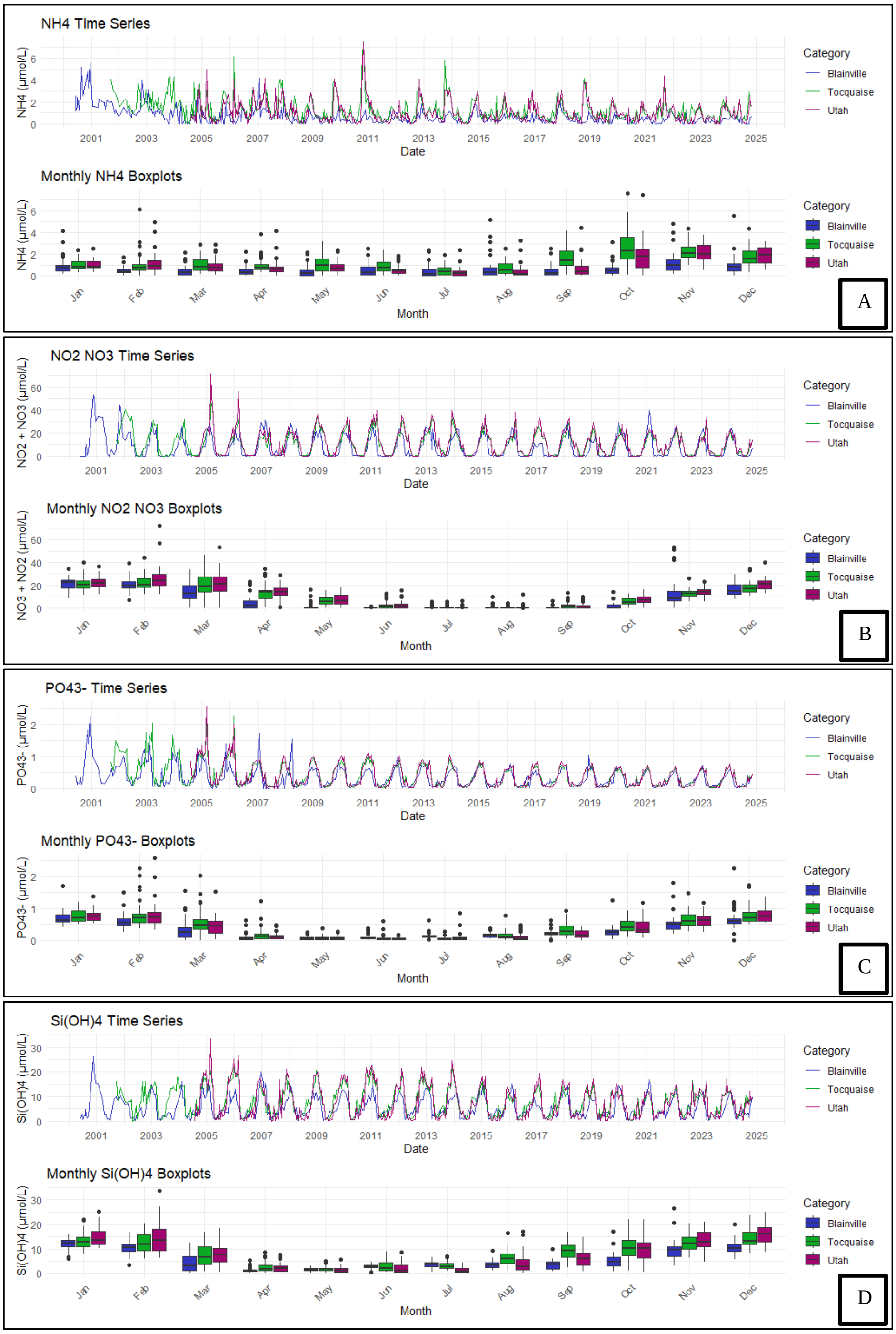

Figure 6: Time series and monthly averages of nutrient concentrations at the three stations (2000-2024): Blainville-sur-Mer, Saint-Vaast-la-Hougue (Tocquaise), and Utah Beach. A: Ammonium (NH_4^+), B: Nitrites and Nitrates (NO_2^-, NO_3^-), C: Orthophosphate (PO_4^{3-}), D: Orthosilicic acid ($Si(OH)_4$).

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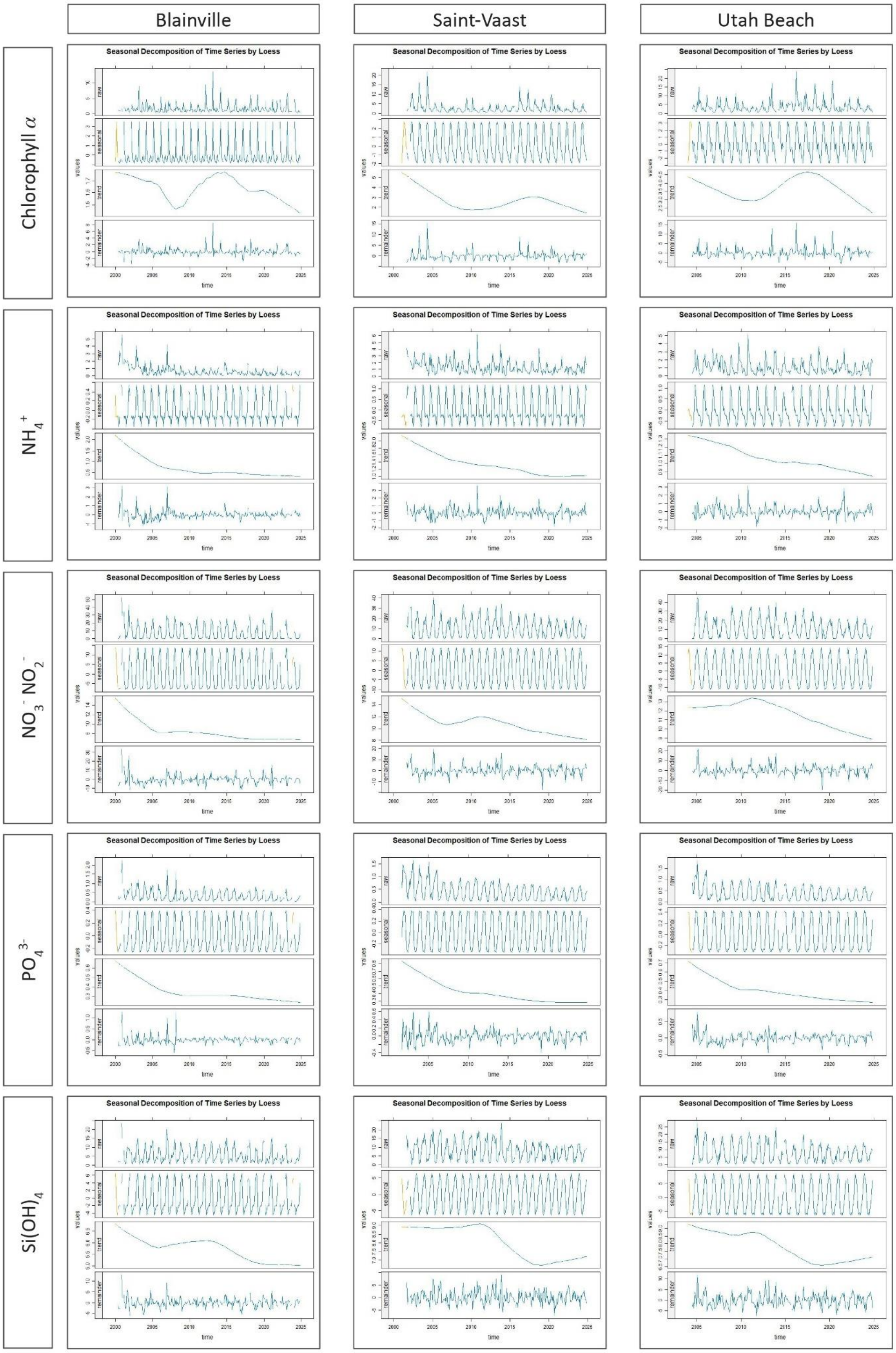

Figure 7: Seasonal Decomposition of Chlorophyll-a and Nutrients (Ammonium, Nitrate, Nitrite, Orthophosphate, and Silicic Acid) from 2000 to 2024 at Blainville-sur-Mer, Saint-Vaast-la-Hougue, and Utah Beach.

3.4. Stoichiometric Limitations

The variations in macronutrient concentrations described in Figure 6 influenced the stoichiometric ratios. Figure 8, by presenting the Si:N and N:P ratios, delimits six areas that highlight the potentially limiting nutrients in a prioritized order, based on thresholds for biogenic particles defined by Redfield *et al.* (1963) and Brzezinski (1985): Si:N:P = 16:16:1. Data aggregated for the 2000–2024 period reveal two distinct dynamics depending on the observed coastline. At Blainville-sur-Mer, nitrogen was identified as the primary limiting nutrient in 186 observations (Table 2), followed by silica. Conversely, on the eastern coast, phosphorus appears to be the most limiting nutrient in the ecosystem, with 185 and 182 observations for Saint-Vaast-la-Hougue and Utah Beach, respectively.

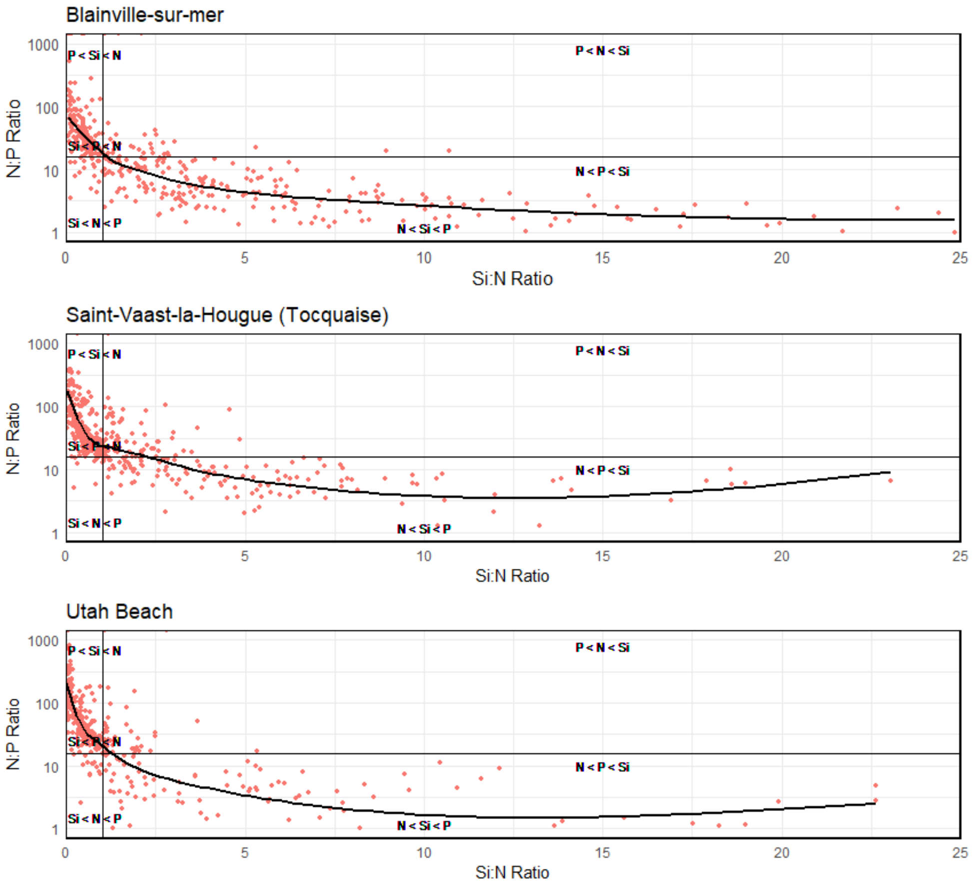

Figure 8: Synthetic graph showing the molar ratios of Si:N:P from 2000 to 2024 at Blainville-sur-Mer, Saint-Vaast-la-Hougue, and Utah Beach. Each region is defined by specific ratios, illustrating the potential limiting nutrient order of priority.

Table 2: Distribution of observations based on the potential limiting nutrient (from most to least limiting) at the three stations (Blainville-sur-Mer, Saint-Vaast-la-Hougue, and Utah Beach) from 2000 to 2024.

	Blainville-sur-mer	**Saint-Vaast-la-Hougue**	**Utah Beach**	**Total**
P<Si<N	100	185	182	467
Si<P<N	101	107	95	303
N<Si<P	186	90	75	351
N<P<Si	48	41	34	123
Si<N<P	19	8	15	42
n	454	431	401	1286

4. Discussion

The results of this study highlight the importance of conducting long-term monitoring at specific sites to better understand intra- and inter-annual variations in the biogeochemical cycles of nutrients and the evolution of physico-chemical parameters.

4.1. Coastal Ecosystems and Climate Change

The three studied sites, located in the Normandy region, show a progressive increase in winter temperatures over the past decade (Figures 2, Figure 3). This finding aligns with observations made at other monitoring points in the English Channel (Cornes *et al.*, 2023 ; Kassem & Thompson, 2023 ; McEvoy *et al.*, 2023 ; Hubert *et al.*, 2024 ; Neven *et al.*, 2024). While our data indicate an average rise of 1°C over 12 years for the three stations, studies conducted along the southern coast of England report an increase ranging from 0.42°C to 0.76°C per decade (Kassem & Thompson, 2023). In France, Hubert *et al.* (2024) reported a similar warming trend, estimated at +1.063°C over 11 years. Moreover, the year 2022 was marked by an exceptional heatwave, recorded by Simon *et al.* (2023), with particularly high summer temperatures (Guinaldo *et al.*, 2023 ; Hubert *et al.*, 2024). This phenomenon was also observed within our monitoring network. However, natural temperature oscillations, such as the Atlantic Multidecadal Oscillation (AMO; Kerr, 2000), also affect conditions in the English Channel (Edwards *et al.*, 2013 ; Auber *et al.*, 2017).

The warming of coastal waters may lead to significant changes in marine ecosystems, particularly by altering the composition and biomass of phytoplankton communities (Richardson & Schoeman, 2004), zooplankton (Neven *et al.*, 2024), and fish populations (Auber *et al.*, 2017 ; Maltby *et al.*, 2020). These changes could have major repercussions on the dynamics of coastal ecosystems and the services they provide. Another major factor threatening marine ecosystems is ocean acidification. Observations and modeling studies indicate a global decrease in ocean pH by 0.02 units per decade, with a projected drop of up to -0.7 units by 2100 due to the dissolution of atmospheric CO_2 into the oceans (Calderira & Wickett, 2003 ; Bates, 2007 ; Santana *et al.*, 2007 ; Olafsson *et al.*, 2009 ; Lauvset *et al.*, 2015). Such acidification will have significant consequences, including altering the structure of marine communities (Fabry *et al.*, 2008), disrupting nutrient cycles (Hutchins *et al.*, 2009), reducing productivity (Riebesell *et al.*, 2007), and impacting carbon fluxes (Schulz *et al.*, 2008).

Data from the HYDRONOR observatory reveal an average acidification over 24 years of -0.2 units in Blainville-sur-Mer, -0.25 units in Saint-Vaast-la-Hougue, and -0.15 units in Utah Beach. These values significantly exceed previously predicted levels, highlighting the urgency of better understanding these phenomena. Long-term monitoring of coastal ecosystems is crucial to understanding the effects of climate change, particularly in shellfish farming areas where bivalves, vulnerable due to their calcareous shells, are heavily impacted by acidification (Doney *et al.*, 2020). However, coastal zones present specific challenges due to their high daily, seasonal, and interannual variability. This complexity, influenced by factors such as riverine inputs, climatic conditions, and anthropogenic pressures, makes identifying climate change-related trends more difficult (Kapsenberg *et al.*, 2017; Reimer *et al.*, 2017 ; Chen & Hu, 2019).

4.2. Ecological Contrasts between the West and East Coasts of Cotentin

Our findings highlight two distinct ecological dynamics between the West and East coasts of Cotentin. The West coast, represented by the Blainville-sur-Mer station, is characterized by an open environment where processes appear to "dilute," leading to consistent and regular seasonal trends. As shown in Figure 4, chlorophyll *a* peaks occur systematically in March, with variations mainly limited to the amplitude of phytoplankton blooms. In contrast, the East coast exhibits much less predictable and highly variable trends from year to year. Regarding nutrient salts, although maximum concentrations are similar between the two coasts (except for ammonium, Figure 6), these peaks are short-lived on the West coast.

We hypothesize that this "dilution" of processes on the West coast is linked to its open environment, with greater exchange with the English Channel and the Atlantic Ocean. Conversely, the East coast, influenced by the proximity of bays and riverine inputs (Figure 1), experiences more intense and irregular phenomena. A notable difference lies in the limiting elements: the West coast is primarily nitrogen-deficient, whereas the East coast is limited by phosphorus and silica (Figure 8). These observations contrast with studies conducted in the English Channel, which generally report a nitrogen surplus due to agricultural activities and riverine inputs (Ménesguen *et al.*, 2019 ; Romero *et al.*, 2019 ; Yan *et al.*, 2021 ; Yan *et al.*, 2022).

Differences between the ecosystems of the East and West coasts of the Cotentin Peninsula have already been highlighted in previous studies. Lefebvre et al. (2009a; 2009b) found that the diet of oysters on the West coast was primarily based on phytoplankton (*i.e.*, pelagic), whereas on the East coast, the animals consumed a mix of benthic and pelagic sources.

4.3. Phytoplankton Communities in Transition

Since the 1980s, European policies have aimed to reduce nitrate and, more specifically, phosphate inputs (Claussen *et al.*, 2009). Long-term data analysis shows that phytoplankton availability is closely linked to the hydrographic and hydrological conditions of the area studied (Loebl *et al.*, 2009). Thus, the decline in riverine nutrient inputs is directly correlated with decreasing chlorophyll *a* concentrations, as illustrated in Figure 7. Regardless of the site studied, a decrease in ammonium, nitrate, nitrite, phosphate, and silicate concentrations in the water column has been observed over the past decade (Figure 7). This reduction in nutrients is accompanied by a widespread decline in chlorophyll *a* levels across the region since the early 2000s (Goberville *et al.*, 2010; Gohin *et al.*, 2019).

These environmental changes naturally impact planktonic communities. In regions such as the central North Atlantic Ocean, the North Sea, and the Baltic Sea, an increase in certain dinoflagellate populations has been observed (Leterme *et al*., 2005; Klais *et al*., 2011; Zhai *et al*., 2013). Similar trends have been reported in the English Channel, where some diatom species are declining while dinoflagellate communities have been expanding since the 2000s (Hernandez-Farinãs *et al*., 2014). Moreover, in the western English Channel, monitoring efforts have highlighted the growing importance of pico- and nanoplankton communities in primary production (Barnes *et al*., 2015). Although their biomass is relatively low compared to microphytoplankton, these communities exhibit high productivity and significant photosynthetic efficiency (Barnes *et al*., 2014).

Picoplankton biomass remains relatively stable in terms of production and plays a significant role in productivity within oligotrophic gyres (Maranon *et al*., 2001; Uitz *et al*., 2010; Moreno-Ostos *et al*., 2011). Meanwhile, nanoplankton appears to be the primary contributor to primary production in coastal areas (Hirata *et al*., 2009).

These shifts can be explained by changes in N:P stoichiometric ratios and the forms of available nitrogen, which influence the structure of phytoplankton communities (Donald *et al*., 2013; Glibert *et al*., 2014). Based on Glibert's (2016) work and his phytoplankton mandala (Figure 9), it is possible to hypothesize two contrasting dynamics. On the west coast, the coastal ecosystem is characterized by nitrogen deficiency, with nitrate and nitrite as the dominant nitrogen forms, which could favor a regenerative phytoplankton community with a high abundance of diatoms. In contrast, the east coast is nitrogen-enriched, with significant ammonium concentrations, potentially leading to an ecosystem dominated by picophytoplankton and cyanobacteria.

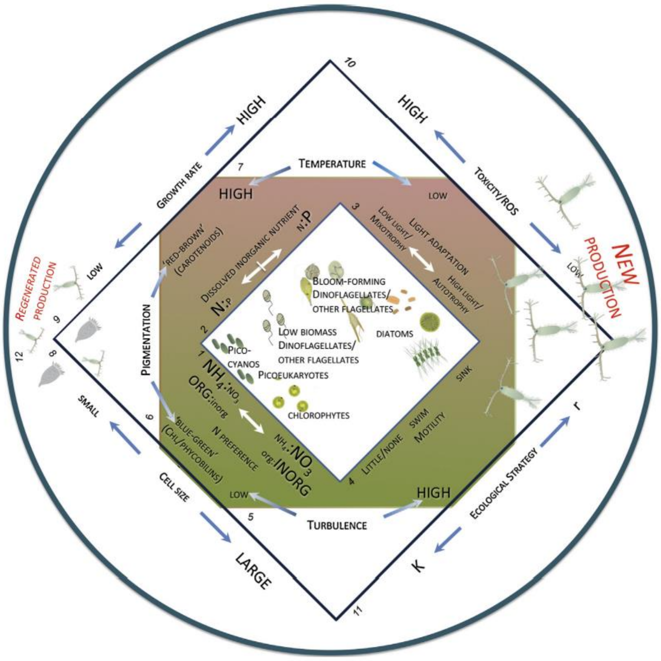

Figure 9: Revised phytoplankton mandala. Phytoplankton functional types are depicted along 12 axes (shown by the small numbers in the corner of each axis. All responses within relative space are representative and not meant to imply that all species or individuals within a given response surface will respond similarly. Icons of the organisms are from the University of Maryland Center for Environmental Science Integration and Application Network symbol library. From Glibert *et al*., 2016.

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5. Conclusion

This study provides valuable insights into the long-term trends of hydrobiological parameters in Normandy's shellfish ecosystems, emphasizing the significant impacts of both human activity and climate change. Our analysis highlights a consistent increase in winter temperatures and a gradual acidification of pH levels across all three monitoring stations (Blainville-sur-Mer, Saint-Vaast-la-Hougue, and Utah Beach) from 2000 to 2024. These changes align with broader trends observed in the English Channel and suggest a shift in the environmental conditions that could affect the ecological balance of coastal habitats.

The observed variations in chlorophyll *a* concentrations and nutrient dynamics reveal complex interactions between nutrient availability, primary production, and the potential limitations of different nutrients across seasons. Notably, nitrogen was identified as the primary limiting nutrient in the western region, while phosphorus dominated as the limiting factor in the eastern stations. These findings have important implications for managing nutrient inputs and maintaining the health of coastal ecosystems, particularly in the context of ongoing eutrophication.

Furthermore, the study underscores the importance of sustained, site-specific monitoring to capture the intricate and evolving dynamics of coastal environments. The long-term dataset from the HYDRONOR observatory has proven essential in understanding how climatic shifts, such as increased temperatures, influence phytoplankton blooms and nutrient cycling. This research provides a crucial foundation for future efforts to mitigate the impacts of climate change and anthropogenic pressures on coastal ecosystems, particularly those supporting critical industries like shellfish farming. As the region faces rising temperatures and ongoing nutrient imbalances, adaptive management strategies will be key to preserving the resilience of these vital ecosystems.

6. Data and code availability

The hydrobiological dataset from the HYDRONOR Observatory is openly accessible on Zenodo at the following DOI: https://doi.org/10.5281/zenodo.15058835 (SMEL - Synergie Mer & Littoral, 2024). Additionally, the R package **TTAinterfaceTrendAnalysis**, designed for trend analysis, is available for consultation and download directly from the CRAN website: https://cran.r-project.org/web/packages/TTAinterfaceTrendAnalysis/index.html.

7. Author contribution

JS wrote the paper. JB and SP coordinate the ecological monitoring of the HYDRONOR observatory. SP developed all the methodologies and has conducted all laboratory analyses since 2000.

8. Competing interests

The authors declare that they have no conflict of interest.

9. Acknowledgements

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