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Identifying the spatial pattern and the drivers of the decline in the eastern English Channel chlorophyll-*a* surface concentration over the last two decades

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ABSTRACT

It has been established from previous studies that chlorophyll-*a* surface concentration has been declining in the eastern English Channel. This decline has been attributed to a decrease in nutrient concentrations in the rivers. However, the decrease in river discharge could also be a cause. In our study, rivers outflows and *in-situ* data have been compared to time series of satellite-derived chlorophyll-*a* concentrations. Dynamic Linear Model has been used to extract the dynamic and seasonally adjusted trends of several environmental variables. The results showed that, for the 1998–2019 period, chlorophyll-*a* levels stayed significantly lower than average and satellite images revealed a coast to offshore gradient. Chlorophyll-*a* concentration of coastal stations appeared to be related to the declining fluxes of phosphate while offshore stations were more related to nitrate-nitrite. Therefore, we can exclude that the climate variability, through river flows alone, has a dominant effect on the decline of chlorophyll-*a* concentration.

1. Introduction

For several decades, European coastal waters have been receiving exceeding amounts of nutrients which has led to a decline in their quality (Vermaat et al., 2008). An increase in the supply of nutrients results in higher phytoplankton production and a greater risk of eutrophication (Nixon, 1995). European directives such as the Water Framework Directive (European Commission, 2000) or the European Marine Strategy Framework Directive (European Commission, 2008) were established to monitor the ecological status of coastal waters and to assess the effect of restoration measures. Regarding the risk of eutrophication, the chlorophyll-*a* concentration was monitored as a core variable related to the phytoplankton biomass. Phytoplankton production and seasonality are primarily controlled by light, nutrient availability and stratification. In most of the temperate marine environments, phytoplankton phenology is dominated by two bloom events (Longhurst, 1995). During winter, when growth is limited by light and water masses are unstable, the phytoplankton biomass is low. Spring blooms start when the increase in daily solar irradiance and increased stratification trigger phytoplankton growth in the upper mixed layer. Autumn blooms occur when and if seasonally increasing vertical mixing renews the supply of nutrients in the euphotic zone before light availability becomes limiting (Findlay et al., 2006). Considerable improvements in the quality of terrestrial waters in terms of nutrients concentrations affect the phytoplankton biomass and its phenology (Desmit et al., 2020): it is particularly true in the case of the eastern English Channel.

The eastern English Channel is also a temperate marine environment but with a well-mixed eutrophic sea (Gentilhomme and Lizon, 1998) and is characterized by a particular hydrological structure called the 'Coastal Flow' structure (Brylinski et al., 1991). In the French part of the eastern Channel, water fluxes stay parallel to the coast due to a frontal area strictly linked to tidal cycles (Brylinski and Lagadeuc, 1990). The area is under the influence of multiple environmental disturbances such as temperature rises (McLean et al., 2019) and nutrient inputs, mainly from

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the Seine and Somme rivers (Thieu et al., 2009), as a result of anthropogenic activities in the watersheds, especially intensive agriculture practices (Garnier et al., 2019). It can be considered that these very eutrophic waters receive the highest levels of nutrient discharge along French coasts (Belin and Soudant, 2018). Thus, several studies have been carried out to assess the impact of anthropogenic inputs to the area. These works have used different types of data, including model outputs, satellite images and *in-situ* data from monitoring networks. Ménesguen et al. (2018) mapped the dilution zones of the plumes of major French rivers, including the Seine and the Somme, for low, medium and high flow regimes respectively, using a hydrodynamic model between 2000 and 2010. These dilution zones went far beyond the mouth of the rivers: for the Seine, for example, they followed the specific hydrological conditions of the French part of the Channel to reach the south of Boulogne, 200 km north. Beyond the exploitation of models, long-term time-series are required to identify shifts resulting from climate change (Koslow and Couture, 2013) or to assess the impact of human actions on nutrient flows. Some works have been based on *in-situ* data series from monitoring networks and satellite imagery. Gailhard et al. (2002) compared the seasonal, inter-annual and spatial variability patterns of 17 sites during the period 1992–2000, but did not assessed possible trends. Hernández-Fariñas et al. (2014) used Dynamic Linear Model (DLM) to model the trends of *in-situ* time series of the different variables monitored by REPHY/Ifremer network (REPHY, 2022). These authors showed an evolution of specific diversity over the last twenty years in the eastern English Channel, in relation to hydroclimatic changes measured by large-scale salinity and temperature data. Romero et al. (2013) and Groetsch et al. (2016) observed a decrease of the mean biomass in western European seas. The decline of the phytoplankton biomass (Romero et al., 2016) is generally attributed to lower phosphate concentrations in rivers, with a decrease close to 75 % between 1970 and 2013 for the Seine River whereas nitrogen is not a limiting factor. These changes in phosphate concentration may affect the phytoplankton biomass and its phenology, but the variability in river flows, with wet and dry periods (driven by climate variability), may also significantly contribute to the variability of nutrient inputs into coastal waters, and therefore to the phytoplankton biomass trend.

Using satellite imagery, maps of temperature variations over the last twenty years (Saulquin and Gohin, 2010) as well as chlorophyll-*a* and turbidity data series for the European marine sub-regions under French responsibility have been established (Gohin, 2011). These maps contributed to a better knowledge of the eastern English Channel and have been widely used to establish its initial state for the Marine Strategy Framework Directive (Gohin et al., 2010) and the following eutrophication status assessment (Devreker and Lefebvre, 2018). These satellite products were validated with data from coastal stations of monitoring networks such as SOMLIT/INSU and REPHY, SRN/Ifremer; they were also compared with observations from instrumented ferries and buoys. Gohin et al. (2019) concluded that the spring phytoplankton bloom (March–April) in the eastern English Channel has not evolved significantly in the last 20 years and the decline of chlorophyll-*a* was mostly from May to September. Recent dry years in Western Europe raised the hypothesis that low river flow was the main driver of low phytoplankton biomass. Previous works have provided a good understanding of the situation in the English Channel for the biomass variable (Gentilhomme and Lizon, 1998; Cappuzzo et al., 2018; Gohin et al., 2019). However, they did not provide a clear explanation of the causes of the decline in chlorophyll-*a* in the area, nor did they allowed the trends to be finely spatialised at a large scale. Finally, the particular hydrology of the area has not been exploited in conjunction with data covering the entire eastern English Channel area.

The aim of this study was to understand how river flows and nutrient inputs impact the chlorophyll-*a* dynamics in the Eastern English Channel and determine which variable was the main driver of its decline over the 1998–2019 period. In particular, we wanted to challenge the assertion that the trend of lower phosphate concentrations found in river flows was controlling the chlorophyll-*a* concentration in coastal waters. To determine the areas of influence of the two main rivers exporting nutrients to the French part of the eastern English Channel, "La Seine" and "La Somme", rivers flows from the French Ministry of Environment, *in-situ* measurements provided by the coastal network REPHY, SRN/Ifremer and satellite data were used. These data constituted time series for about 20 years and included variables such as outflows, nutrients, chlorophyll-*a* and turbidity with a high spatio-temporal resolution. The difficulty in processing these data, particularly in extracting trends, lied in incomplete series with missing data and the presence of exceptional values (Ratmaya et al., 2019). An adapted method was the use of Dynamic Linear Models (West and Harrisson, 1997), which allowed to consider (i) potentially time-varying and non-stationary variables (ii) outliers (iii) irregular sampling frequencies and (iv) missing data. These models were used to extract trends from *in-situ* monitoring time series and then to identify and quantify the changes that occurred. DLM were also applied for each pixel of satellite time series to visualize and still quantify the spatial changes during two decades in the Eastern part of the English Channel.

2. Data and methods

2.1. Study site

The study area (Fig. 1) included central English Channel and eastern English Channel between Cotentin peninsula, to the south-west on the map, and the town of Boulogne, to the north-east, on the French coast, approximately between 49°N/51°N and 1°W/1.5°E. The English Channel is characterized by a macrotidal regime (*e.g.* in the Straits of Dover, during neap and spring tides, tidal range of, respectively, 3 and 9 m) that generates fast tidal currents essentially parallel to the coast and a northeast-flowing tidal residual current from the English Channel to the North Sea (Lefebvre et al., 2011).

Along the French coast, fluvial supplies from the Bay of Seine to Boulogne generate a coastal water mass that drifts nearshore, separated from the open sea by a frontal area (Brylinski and Lagadeuc, 1990). Exchanges between inshore and offshore water masses, inducing the transportation of particles and nutrients, depend basically on the tide and are more notable during the neap than during the spring tide. In the Seine Bay area, the Seine River accounts for up to 80–85 % of the freshwater inflow (Romero et al., 2013) and contributes to >50 % of nitrate inputs and between 60 % and 80 % of phosphate inputs during the 1990–2015 period for the French part of the English Channel (OSPAR Commission, 2014). Besides, the Somme River is important for the eastern Channel, as its bay was known to be an area where the chlorophyll-*a* concentrations were among some of the highest on the French coast (Belin and Soudant, 2018). Hence, data from these two main river outlets were sought and collected.

2.2. Data

According to the availability of satellite and *in-situ* data, the study time window has been set to [1998; 2019].

2.2.1. Outflow and nutrients fluxes

Outflow datasets have been obtained from the public information system, "Banque hydro" (http://hydro.eaufrance.fr/). Measurements were taken at the "Poses" station for the Seine River and at the city of Abbeville for the Somme River. Daily data were extracted from 1998 and 2019. However, the year 2006 was missing for the Seine River.

For the entire French side of the Channel seaboard, from 2000 to 2019, yearly aggregated phosphate and nitrate fluxes data were obtained from the French Ministry of the Environment, and more specifically the Data and Statistical Studies Department (SDeS). SDeS calculated these fluxes from outflow values of the rivers of the French side of the Channel seaboard associated with nutrient concentrations

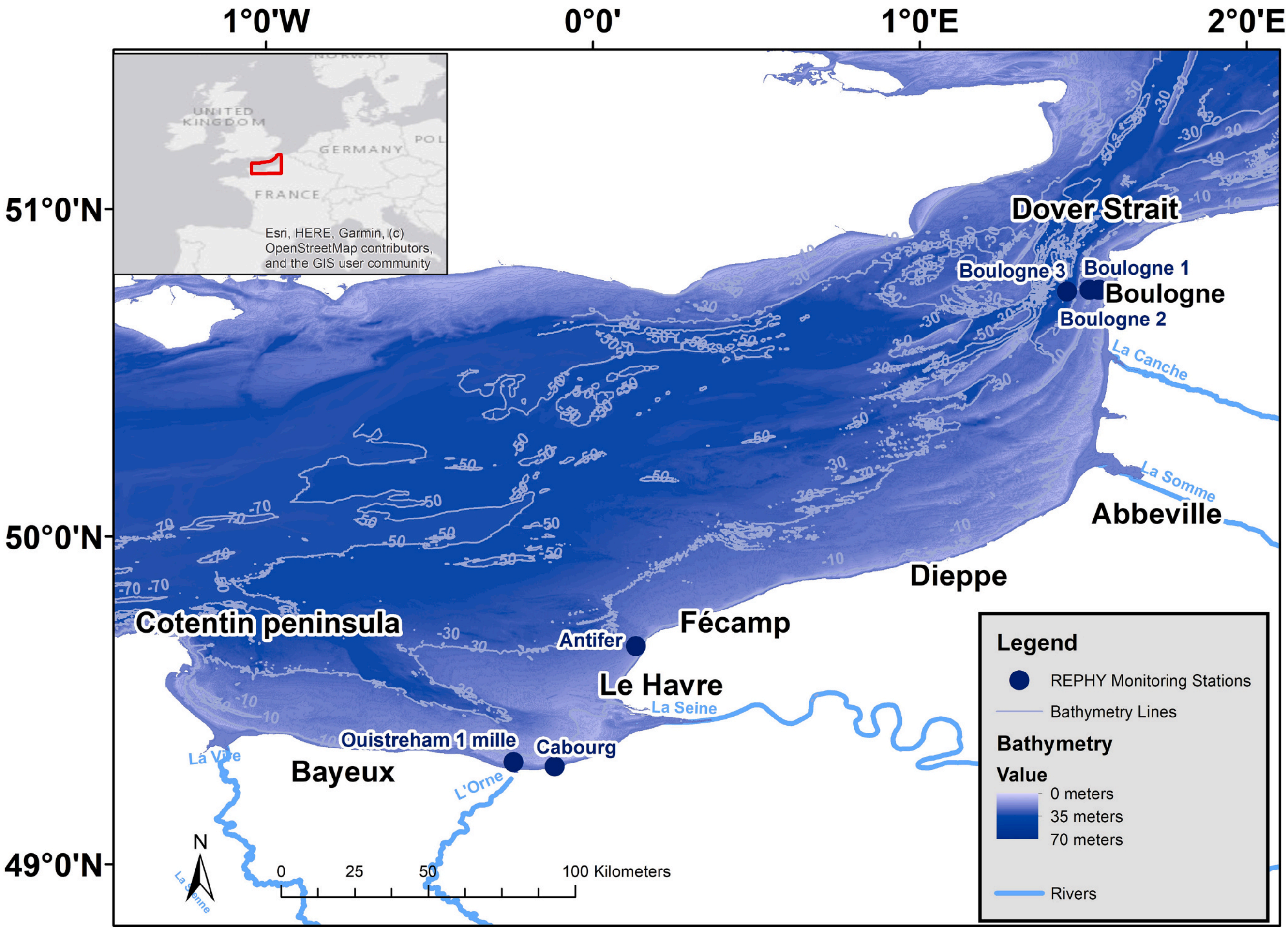

Fig. 1. Study area, central and Eastern English Channel, and *in-situ* REPHY/SRN monitoring stations.

measured in estuarine stations.

2.2.2. *In-situ*

The *in-situ* dataset was provided by the REPHY (REseau d'observation et de surveillance du PHYtoplancton et de l'hydrologie dans les eaux littorales) (REPHY, 2022) and by the SRN (Suivi Régional des Nutriments) monitoring networks (Lefebvre and Devreker, 2022). Based on the length of the available time-series, six monitoring stations were selected for the present study (Fig. 1). Three monitoring stations (*i.e.* "Boulogne 1", "Boulogne 2", "Boulogne 3") are located along a transect offshore the Boulogne harbour. The other three monitoring stations ("Antifer", "Ouistreham 1 mille", "Cabourg") are located south of this area. With the exception of "Antifer", all stations have been used by Gohin (2011). For all sites, samples were taken between 0 and 1 m depth. The sampling frequency in the REPHY, SRN networks is fortnightly (Belin et al., 2019). Chlorophyll-*a* concentrations were obtained successively by spectrophotometry following Aminot and Chaussepied (1983), Van Heukelem and Thomas (2001) and Aminot and Kérouel (2004). Nutrient concentrations, *i.e.* the sum of nitrate and nitrite (NO_3NO_2) and phosphates (PO_4) were determined by flow spectrophotometry (Aminot and Kérouel, 2007). Finally, for the Bay of Seine stations, a known analytical issue induced that nutrient measurements before 2005 could not be used (Table 1).

Table 1
In-situ REPHY monitoring stations selected in the English Channel providing chlorophyll-*a* and nutrients concentrations fortnightly.

Monitoring station name	Location	Time window
Boulogne 1	Coastal Station on the Boulogne transect	1998–2019
Boulogne 2	'Intermediate' Station on the Boulogne transect	
Boulogne 3	Offshore Station on the Boulogne transect	
Antifer Ouistreham 1 mille Cabourg	Bay of Seine	2002–2019 for chlorophyll-*a* 2005–2019 for nutrients

2.2.3. *Satellite data*

Concerning chlorophyll-*a*, SeaWiFS, MERIS, MODIS/AQUA and VIIRS remote-sensing reflectance data were processed by the coastal OC5 algorithm with Look-Up-Tables (LUT) dedicated to each sensor (Gohin et al., 2002; Gohin, 2011). The images used in this study were interpolated from OC5 estimates of chlorophyll-*a* (Saulquin et al., 2019), and are therefore a Level 4 product[1] as per the nomenclature defined by NASA. The interpolation was performed using kriging techniques of daily imagery coming from several sensors and different satellites, which enable the creation of a daily multi-sensor dataset of complete

[1] https://www.earthdata.nasa.gov/engage/open-data-services-and-software/data-information-policy/data-levels.

images over the 1998–2019 period.[2] The spatial resolution of the interpolated images was 0.01° in latitude and 0.015° in longitude (*ca.* 1.2 × 1.2 km^2). Despite possible artefacts on some images, the kriged products are unbiased and the interpolated chlorophyll-*a* showed an excellent relationship with the *in-situ* observations in term of means and 90th percentiles (Saulquin et al., 2011).

Suspended Particulate Matter (SPM), defined as suspended matter not related to dead or live phytoplankton, was determined from reflectance measured in the green wavelength at 550 nm and in the red wavelength at 670 nm. Inorganic SPM was estimated by an inversion of a semi-analytical radiative transfer model considering the theoretical absorption and backscatter coefficients of the medium at 550 and 670 nm. These coefficients were expressed as the sum of the coefficients of pure water, phytoplankton and inorganic SPM, neglecting the specific role of coloured dissolved organic matter. Knowing the coefficients for pure water and chlorophyll-*a*, inorganic SPM was estimated from the total diffusion coefficient related to the observed reflectance in the green (550 nm) and red (670 nm) wavelengths. The algorithm was based on the method described in Gohin et al. (2005).

Time-series were derived from satellite chlorophyll-*a* and SPM images for each pixel of *ca.* 1.44 km^2 and each day.

2.3. Methods

2.3.1. Time-series analysis for outflows, in-situ and satellite data

Time-series analysis needed to define a time unit for which, at most, one measurement was available. Considering that sampling frequencies of *in-situ* variables was fortnightly, the time unit used here was half-month. This frequency was applied also to satellite and outflow data, which were originally collected on a daily basis. This choice has been made to remain as close as possible to the time step of the measurements to minimise the loss of information. The number of seasons considered (24) made the trend analysis more complex and limited by the inter-seasonal heterogeneity it introduced. We therefore decided to correct the data for the seasonal component and not to use a specific statistical test that takes seasonality into account.

Time-series may be affected by outliers, irregular sampling frequencies and missing data, particularly for *in-situ* data. Furthermore, Ratmaya et al. (2019) has shown that seasonality of environment variables may vary with time. According to the *ceteris paribus* principle, it appeared necessary to treat all time series with the same method. In this context, Dynamic Linear Models (DLM) (West and Harrisson, 1997; Harvey et al., 1998) were identified as particularly suitable for environmental data series (Auger-Méthé et al., 2021). The model decomposed the observed time-series as a trend, a seasonal component (*i.e.,* seasonality) and residuals. Hence, all time series have been analysed using DLM with the “dlm” package (Petris, 2010) in R software (R Core Team, 2021). The outliers were identified from the standardized residuals belonging to the highest and lowest 0.35 % of their distribution and they were treated in an appropriate manner; *i.e.*, specific observational variances were estimated for each outlier. Finally, Q–Q plots were used to assess the normality of the standardized residuals, and estimated autocorrelation functions were used to check their independence.

2.3.2. Interannual trend

DLM did not assessed interannual trend. Hence, for each time series, a monotonic linear trend test using a modified non-parametric Mann–Kendall (MK) test (Hamed and Ramachandra Rao, 1998) was performed on raw data deseasonalized with the time varying seasonality estimated by DLM. This trend component was called ‘seasonally adjusted’ further in this paper. When monotonic linear trends were significant (*i.e.* $p < 0.05$), changes were adjusted with Sen's robust line (Sen, 1968) and then calculated from the differences between the beginning and end of the trend seasonally adjusted time series.

2.3.3. Chlorophyll-a relationship with outflows and nutrients

In order to evaluate the independent contributions of nutrients and outflows to the total explained variation in chlorophyll-*a* dynamics, we calculated multiple linear regressions with a hierarchical partitioning of variance (Mac Nally, 2000; Walsh and Mac Nally, 2013) on the *in-situ* seasonally adjusted time series. This method was used to assess an independent explanatory power (*i.e.* % independent contribution) for mean monthly nitrate concentrations, phosphate concentrations and outflows of the Seine River on the dependant variable: chlorophyll-*a* mean monthly concentrations. The explanatory power was expressed as a percentage of the total explained variance. The advantage of hierarchical variance partitioning is that it reduces multicollinearity (Mac Nally, 2002; Heikkinen et al., 2005; Jansson et al., 2014) when the number of explanatory variables is limited to <9 (Olea et al., 2010). These results were completed by 100 randomly sampling from the explanatory variables to test whether the percentages were significantly >0.

2.3.4. Mapping satellite data and trend

2.3.4.1. Definition of productive period. During the spring and summer period, light is no longer a limiting factor for the phytoplankton growth, and nutrient inputs become dominant for the development of the latter. In order to address a more direct link between chlorophyll-*a* production and nutrient flux inputs from rivers, we decided to define and focus on a period called “productive period”. The following process was used to define the most appropriate period. For outflow and chlorophyll-*a*, an arbitrary 6 months length time window was considered. To find the period when outflows and chlorophyll-*a* were best correlated, several pairs of outflow/chlorophyll-*a* periods were formed with starting dates varying between mid-February (*i.e.* half month 4) and mid-May (*i.e.* half month 10). A lag of one month between outflows and chlorophyll-*a* was set to consider the impact of outflows on monitoring locations far from the river mouths. For each year, time window means were computed, and then for each pairs of time window, Pearson correlation coefficient on means were computed. The pair of windows with the highest significant correlation was selected and the productive period was defined as the corresponding chlorophyll-*a* time window.

2.3.4.2. Definition of wet and dry productive period. All years of the time-series were not equally rainy. In order to consider this factor, we defined “wet” and “dry” years according to river outflows during the productive period. These years have been used to compare the dynamics of chlorophyll-*a* more than ten years apart between years belonging to the same categories. Mean outflow values were calculated for productive period defined as the period between the months of April and October inclusive. “Wet years” were defined as years when the annual mean Seine outflows were above 500 $m^3 \cdot s^{-1}$ (*i.e.* 2001, 2013, 2016) whereas “dry years” years correspond to annual mean Seine outflows below 300 $m^3 \cdot s^{-1}$ (*i.e.* 2003, 2011, 2017) (Supplementary S1).

2.3.4.3. Maps of dry and wet productive periods. Annual maps of chlorophyll-*a* mean concentrations at the scale of the study area for productive period were produced from the satellite dataset, for the whole period [1998–2019]. For all these maps, mean concentrations by pixel were represented using classes based on percentiles calculated over the entire period. Five classes were chosen for the chlorophyll-*a* values: i) below the 50th percentile; ii) between 50th and 70th percentile; iii) between the 70th and 80th percentile; iv) between the 80th and 90th percentile; and v) over the 90th percentile. Percentiles above 50th have been favoured: most of the changes appeared in this range with an

[2] https://sextant.ifremer.fr/Donnees/Catalogue#/metadata/73c61398-3d8a-4387-ad17-047cac1a69aa, Ifremer,2019.

associated spatial gradient from the coast to the offshore area. In addition, monthly mean concentrations maps have been produced for years containing wet or dry productive period. These maps therefore all used the same scale and legend based on these percentiles, with the aim of showing variations in the spatial extent of chlorophyll *a* concentrations over time and making them easy to compare visually.

2.3.4.4. Maps of interannual trends estimated for each pixel. For each pixel, as mentioned above, chlorophyll-*a* time series analysis has been performed. In order to assess interannual variability, changes between beginning and end of the Sen's robust lines were computed, showing the amount of change in chlorophyll-*a* concentrations. These changes were expressed both as percentages and as concentrations ($\mu g \cdot l^{-1}$), with classes based on the five percentiles: below 50th, between 50th and 70th percentile; between the 70th and 80th percentile; between the 80th and 90th percentile; and over the 90th percentile and mapped.

3. Results

3.1. Analysis of river flow time series

Seasonally adjusted trends of mean river flow were estimated by the DLM for the Seine and the Somme (Fig. 2). The Seine river showed punctually high discharges up to >2000 $m^3 \cdot s^{-1}$ (see mean half-month flows between 1st and 15th of February 2001 in supplementary S2) at the beginning of the time series. From 2003 to 2011, values slightly exceeded 1000 $m^3 \cdot s^{-1}$ (see mean half-month flows showed in supplementary S2). After 2010, a new cycle began with increasing flows followed by a decrease again. Over the two decades, an overall decreasing trend was identified: it was driven by the largest flow of the first decade (Fig. 2a). A similar trend was observed for the Somme River although the flow values were an order of magnitude smaller (Fig. 2b for the trend alone; supplementary S2 for trend and mean half-month flows together).

3.2. Analysis of annual nutrients fluxes

For the entire French side of the Channel seaboard, annual nitrogen fluxes showed less variations around 150 $kt \cdot year^{-1}$ and have not decreased in recent years compared to the beginning of the time-series (Fig. 3a). Annual phosphorous fluxes globally decreased from 7 $kt \cdot year^{-1}$ at the beginning of the time series and then since 2014, they stabilized around 3 $kt \cdot year^{-1}$ (Fig. 3b).

3.3. Analysis of in-situ time series: nutrients and chlorophyll-a

The estimated seasonally adjusted trend of the three *in-situ* stations close to the Somme River (Boulogne 1 to 3) showed a continuous decrease in the chlorophyll-*a* concentration since 1998 (Fig. 4). The chlorophyll-*a* concentrations were punctually as high as 25 $\mu g \cdot l^{-1}$ in spring or at the beginning of summer in the first decade but lower than 10 $\mu g \cdot l^{-1}$ at the end of the period (supplementary S4 and S5). This decreasing monotonic trend in chlorophyll-*a* was significant for the two stations closest to the coast (Mann-Kendall test, $p < 0.05$, Table 2). The trends for nitrate + nitrite nutrients at the three stations were very similar to the trend detected for the Somme River flow, with an overall decrease (Fig. 5). Globally, the sum of the nitrate and nitrite concentrations decreased from maximum values of 60 $\mu mol \cdot l^{-1}$ in the early 2000s to 10 $\mu mol \cdot l^{-1}$ in the last decade (supplementary S4 and S5). The decreasing trend in nitrogen was significant for Boulogne 2 and 3 (Mann-Kendall test, $p < 0.05$, Table 2). Phosphate had a significant increasing trend between 2005 and 2007, with a maximum value of 2 $\mu mol \cdot l^{-1}$ followed by a decrease over the last decade, with maximum concentrations reaching 0.6 $\mu mol \cdot l^{-1}$. This decreasing trend in the phosphate concentration was significant for Boulogne 1, which was the closest to the coast (Mann-Kendall test, $p < 0.05$, Table 2).

For *in-situ* stations in the vicinity of the Seine River (Antifer, Ouistreham 1 mille and Cabourg), a significant decrease in chlorophyll-*a* concentrations (Fig. 5) has been observed. These concentrations were as high as 69 $\mu g \cdot l^{-1}$ at the beginning of the first decade but lower than 10 $\mu g \cdot l^{-1}$ at the end of the period (supplementary S4 and S6). However, for the Antifer site, an exceptional value higher than 40 $\mu g \cdot l^{-1}$ was observed in 2018 (supplementary S6). The decreasing trends in chlorophyll-*a* was significant for the three stations (Mann-Kendall test, $p < 0.05$, Table 2). Nitrate + nitrite measurements showed different trends between the three stations with large non-significant variations at Cabourg (Fig. 5), and concentrations ranging from 60 to 140 $\mu mol \cdot l^{-1}$. For phosphate, there was a significant decreasing trend for the three stations (Mann-Kendall test, $p < 0.05$, Table 2). Overall, an 80 % decrease was observed

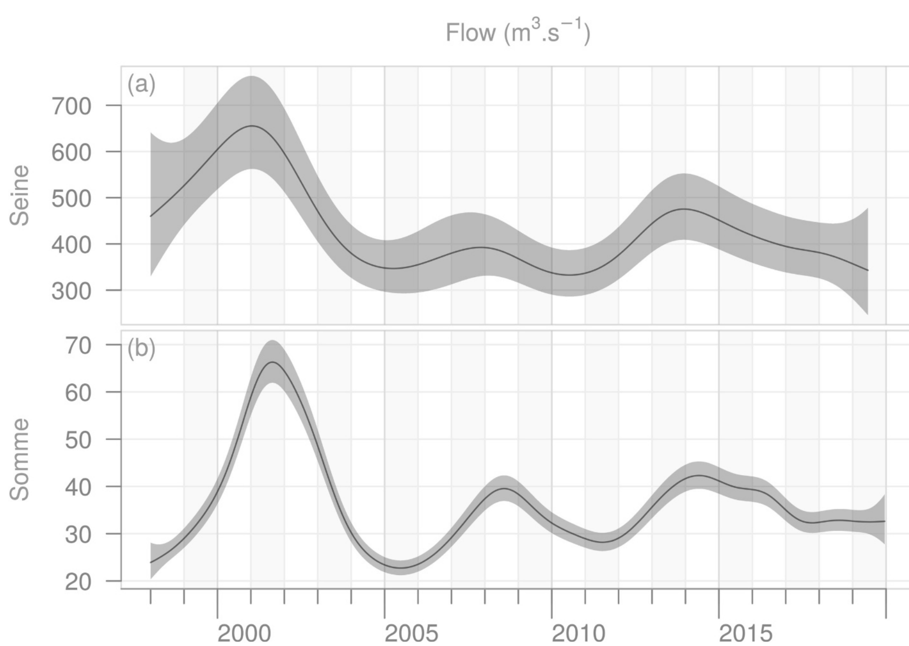

Fig. 2. Long-term trend analysed by DLM of mean half-month flows from the Seine (a) and Somme (b) rivers that have been seasonally adjusted from 1998 to 2019 using DLM. Shaded areas indicate a 90 % confidence interval.

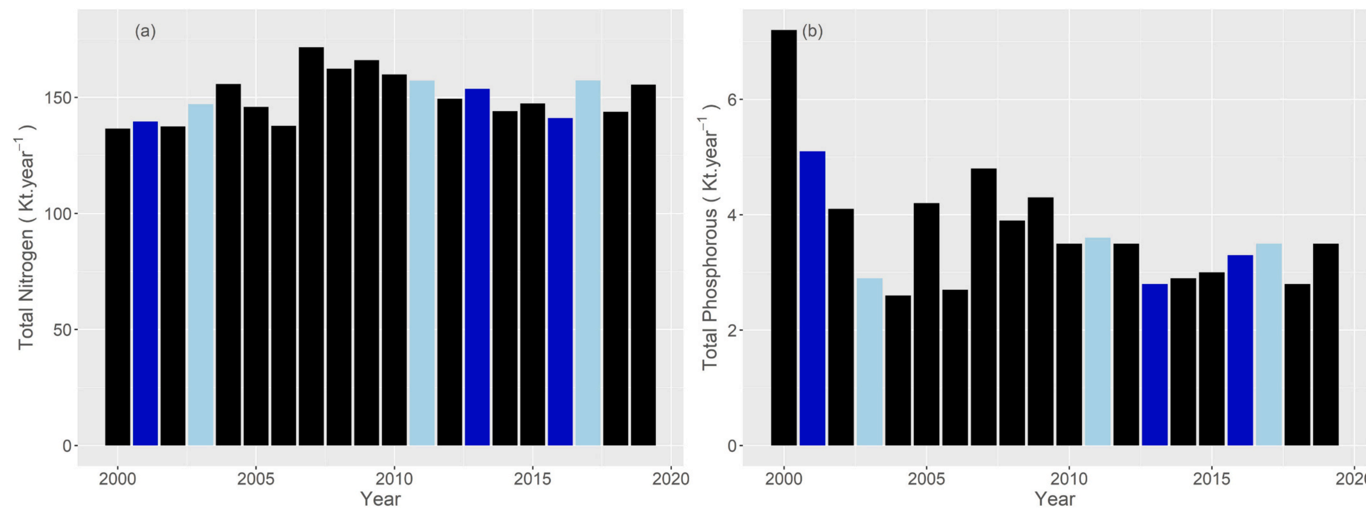

Fig. 3. Annual fluxes (kt·year^{-1}) of total nitrogen (a) and total phosphorous (b) for the French English Channel facade from 2000 to 2019. Dark blue values represent wet years and light blue values represent dry years as defined previously by Seine River outflows. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

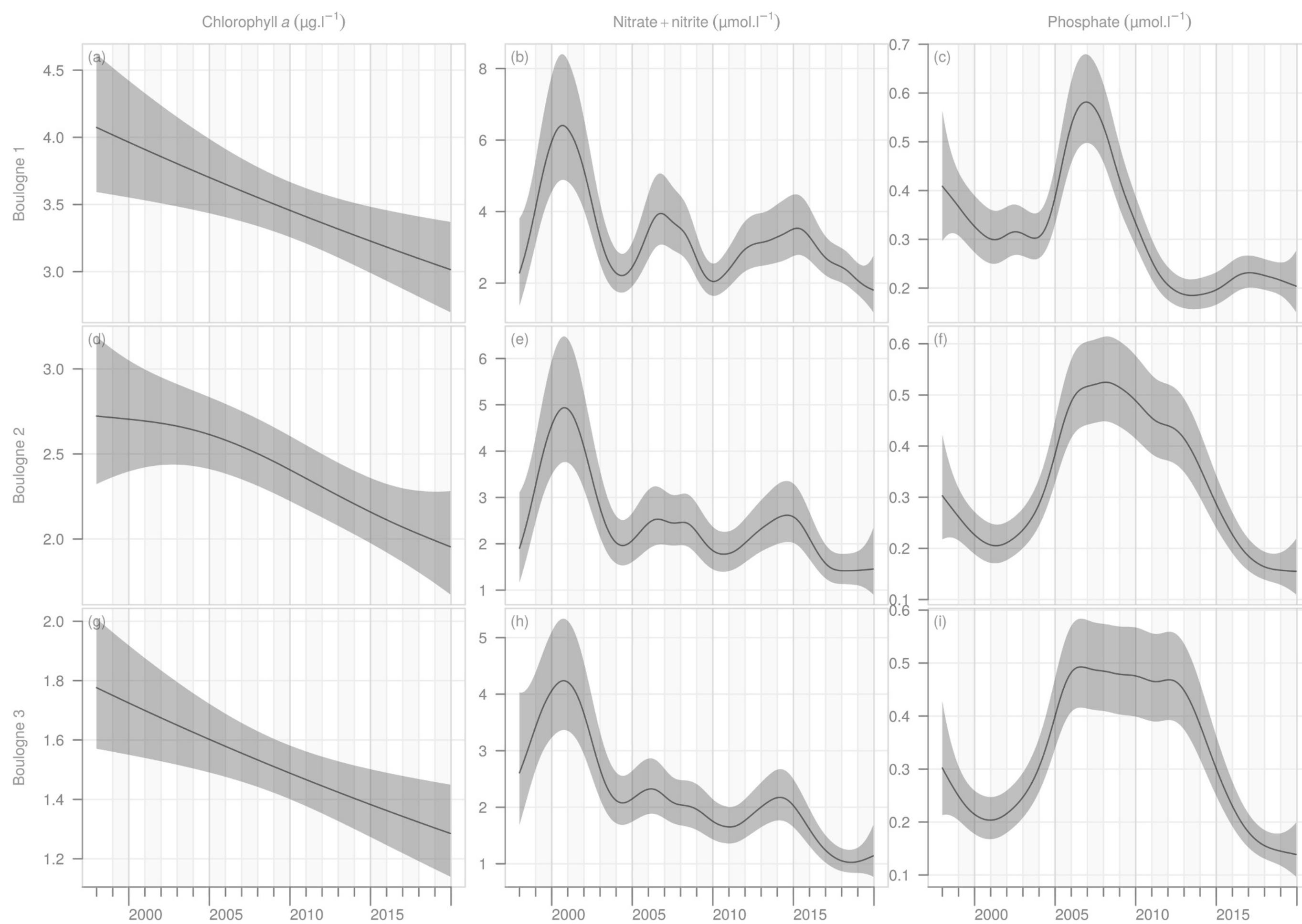

Fig. 4. Long-term trends seasonally adjusted *in-situ* chlorophyll-*a*, nitrate + nitrite and phosphate concentrations from REPHY stations Boulogne 1 (a, b, c), Boulogne 2 (d, e, f) and Boulogne 3 (g, h, i) using a DLM model. Shaded areas indicate a 90 % confidence interval.

in phosphate concentrations from maximum values of 2.3 µmol·l^{-1} in the first decade to 0.9 µmol·l^{-1} at the end of the time-series.

3.4. Explanatory power of outflows and nutrients for in-situ stations on the chlorophyll-a dynamic

The hierarchical partitioning of variance, used to determine the

Table 2
Results of Mann-Kendall test performed on the *in-situ* time-series seasonally adjusted for the selected REPHY, SRN monitoring stations. Variation of chlorophyll-*a* (Chl *a*) and nutrients in % and unit of measure. Years ranges for the trend test are: for Boulogne 1, Boulogne 2 and Boulogne 3 [1998–2019]; for Antifer, Ouistreham 1 mille and Cabourg [2002–2019] for Chl *a* and [2005–2019] for nutrients. Bold values are significant; NS = not significant.

Monitoring stations		Chl *a* (μg·l^{-1})	NO_3NO_2 (μmol·l^{-1})	PO_4 (μmol·l^{-1})
Boulogne 1	Changes (%)	**−0.76 (−19.8 %)**	−0.84 (−25.6 %)	**−0.25 (−59.4 %)**
	p-Value	0.027	NS	<10^{-4}
Boulogne 2	Changes (%)	**−0.71 (−26.3 %)**	**−1.10 (−42.4 %)**	−0.26 (−54.4 %)
	p-Value	0.020	0.003	NS
Boulogne 3	Changes (%)	−0.27 (−17.5 %)	**−1.04 (−46.5 %)**	−0.27 (−17.5 %)
	p-Value	NS	0.016	NS
Antifer	Changes (%)	**−0.34 (−16.7 %)**	**−8.70 (−30.5 %)**	**−0.85 (−81.1 %)**
	p-Value	0.032	<10^{-4}	0.003
Ouistreham 1 mille	Changes (%)	**−1.08 (−34.7 %)**	**5.89 (50 %)**	**−0.75 (−83.3 %)**
	p-Value	0.012	0.042	<10^{-4}
Cabourg	Changes (%)	**−0.93 (−30 %)**	1.46 (9.8 %)	**−0.80 (−82 %)**
	p-Value	0.004	NS	<10^{-4}

proportion of variance explained independently and jointly by each variables revealed that nutrients accounted more of the explained chlorophyll-*a* variations than the river flows (Table 3). For the coastal stations (Boulogne 1, Antifer, Cabourg and Ouistreham), phosphate showed high explanatory power, ranging from 43.6 to 87.4 %. For the offshore stations, Boulogne 2 and Boulogne 3, the explanatory power of phosphate was smaller and even very low for Boulogne 3: <5 % of the total explanatory power. In fact, the sum of nitrate and nitrite concentrations significantly contributed to explain the chlorophyll-*a* concentrations variations for Boulogne 2 and 3, with respectively 62.8 and 71.9

Table 3
Results of the hierarchical partitioning of variance estimated from the multiple regressions between chlorophyll-*a* concentration (dependant variable) and nutrients and river flow (Independent variables) from *in-situ* monitoring stations. Independent explanatory power of independent variables is expressed in % of total explained variance. Years ranges are: for Boulogne 1, Boulogne 2 and Boulogne 3 [1998–2019]; for Antifer Ouistreham 1 mille and Cabourg [2005–2019]. Each result has been tested and has been statistically shown to be >0 (statistical significance in the upper 0.95 confidence interval).

Monitoring stations	Outflows (m^3·s^{-1})	NO_3NO_2 (μmol·l^{-1})	PO_4 (μmol·l^{-1})
Boulogne 1	25.7 %	18.9 %	55.5 %
Boulogne 2	26.0 %	62.8 %	11.2 %
Boulogne 3	23.3 %	71.9 %	4.7 %
Antifer	2.5 %	48.7 %	48.7 %
Ouistreham 1 mille	3.6 %	52.8 %	43.6 %
Cabourg	4.6 %	8.0 %	87.4 %

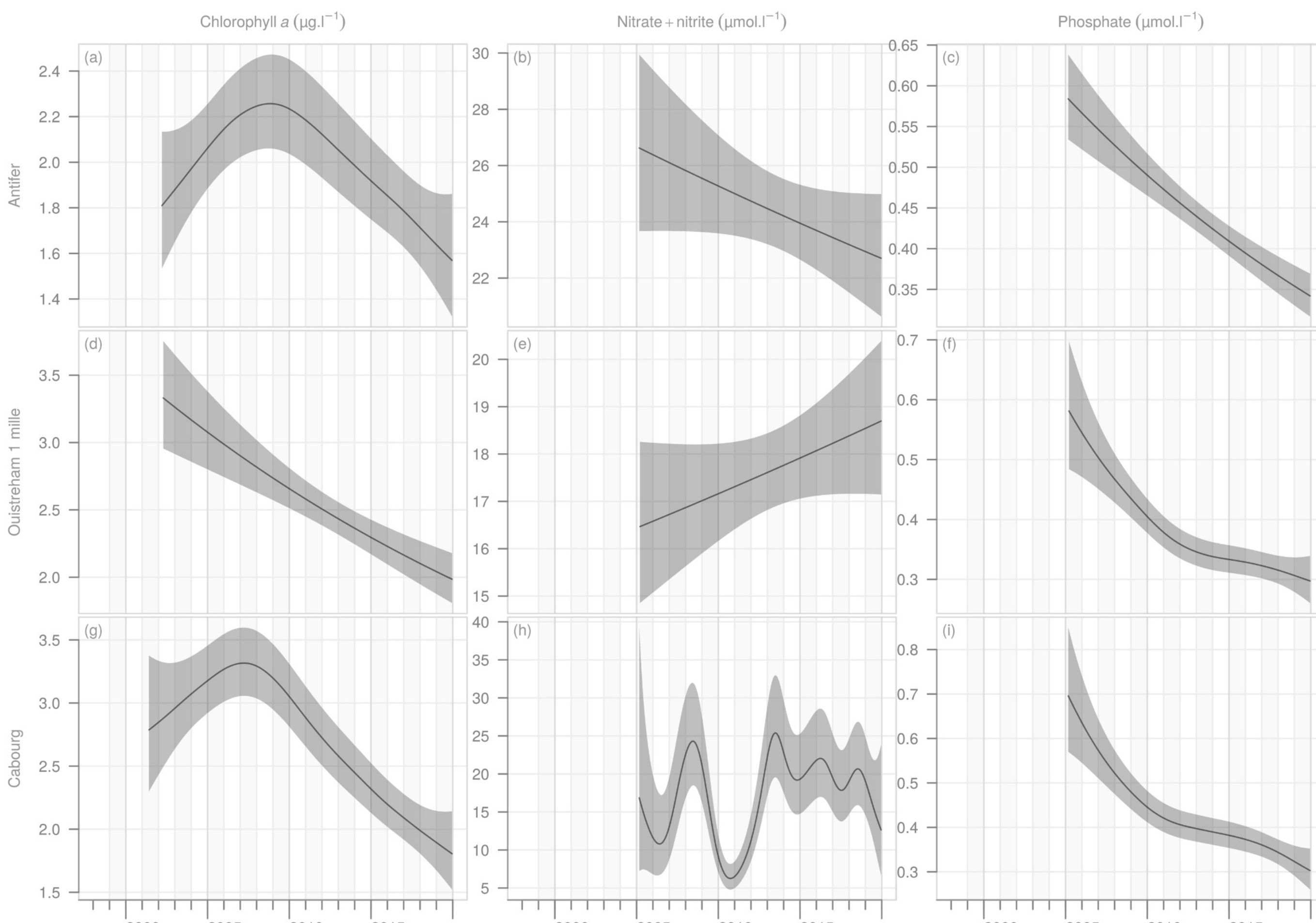

Fig. 5. Long-term trends seasonally adjusted *in-situ* chlorophyll-*a*, nitrate + nitrite and phosphate concentrations from REPHY stations Antifer (a, b, c), Ouistreham 1 mille (d, e, f) and Cabourg (g, h, i) using a DLM model. Shaded areas indicate a 90 % confidence interval.

% of the total variance, but were also significant independent correlates for Antifer and Ouistreham. The Seine outflows appeared to have the lowest explanatory power compared to nitrate-nitrite and phosphate with percent of total variance explained lower than 5 % for the three monitoring stations at the vicinity of the Seine estuary. The Somme river flow explained *ca.* 25 % of the chlorophyll variations at the three Boulogne stations.

3.5. Time window for productive period maps

The best correlation (Table 4) during summer between outflows and chlorophyll-*a* concentrations coming from the monitoring stations along the Boulogne transect were found between half-months 6 (*i.e.* mid-March) and 18 (*i.e.* mid-September) for outflows and 8 (*i.e.* mid-April) and 20 (*i.e.* mid-October) for chlorophyll-a.

3.6. Spatial distribution of productive period chlorophyll-a for dry versus wet years

Mean chlorophyll-*a* concentrations ranged from <1 $\mu g \cdot l^{-1}$ in the middle of the English Channel, to concentrations higher than 3 $\mu g \cdot l^{-1}$ in coastal areas, mainly near the mouth of the Vire, Orne and Seine rivers, and further north of the Somme and Canche rivers (Fig. 6). The coast-to-offshore gradient was visible, as was the influence of river plumes and the 'Coastal Flow' parallel to the coast. The influence of the Seine River visually extended far north of Le Havre. In the northern part of the English Channel, high concentrations were detected between Dieppe and Abbeville, in shallow areas under the influence of the Somme River.

The spatial distribution of the mean productive period chlorophyll-*a* concentrations is presented in Fig. 7 for wet years (2001, 2013 and 2016) and dry years (2003, 2011 and 2017). Among the wet years, 2001 was by far the wettest year of the study and showed a distribution of chlorophyll-*a* along almost the entire coastline, up to 40 km offshore, with values above 3 $\mu g \cdot l^{-1}$. The 'Coastal Flow' was particularly well defined and remained continuous along the coast. The more recent years of 2013 and 2016 were more comparable in terms of maximum mean outflows (539 $m^3 \cdot s^{-1}$ and 586 $m^3 \cdot s^{-1}$) and showed a much smaller extension than 2001, with localized values above 3 $\mu g \cdot l^{-1}$ at the river mouths and with a discontinuity of the 'Coastal Flow' that stopped near the town of Fécamp.

Among the dry years, 2003 had the highest chlorophyll-*a* values at the river mouths as well as further offshore with a near continuity of the 'Coastal Flow'. In recent years, with low flows values (202 $m^3 \cdot s^{-1}$ for 2011 and 229 $m^3 \cdot s^{-1}$ for 2017) the spatial distribution of chlorophyll-*a* was confined to river mouths. In 2017, few areas had a chlorophyll-*a* concentration that exceeded 3 $\mu g \cdot l^{-1}$ except at the most productive areas of river mouths and the 'Coastal Flow' had almost disappeared.

Table 4
Results of the 4 highest Pearson correlations performed on the *in-situ* chlorophyll-*a* (Chl *a*) time-series for the selected REPHY monitoring stations and Seine River flows for different time windows expressed in half-months (h-m). NS = not significant.

Time windows		Boulogne 1	Boulogne 2	Boulogne 3
Flows starting h-m 5 - Chl *a* starting h-m 7	Correlation	0.46	0.53	0.62
	p-Value	0.02	0.006	0.001
Flows starting h-m 5 - Chl *a* starting h-m 8	Correlation	0.52	0.57	0.62
	p-Value	0.008	0.003	0.006
Flows starting h-m 6 - Chl *a* starting h-m 8	Correlation	**0.52**	**0.57**	**0.63**
	p-Value	**0.007**	**0.003**	**0.001**
Flows starting h-m 7 - Chl *a* h-m 8	Correlation	0.51	0.55	0.6
	p-Value	0.009	0.004	0.001

Overall, irrespective of the river flow, areas of high chlorophyll-*a* concentrations decreased over time, with their spatial extensions decreasing from over 40 km offshore (2001) to 10 km (2017, the most recent dry year).

3.6.1. Seasonal variations of chlorophyll-a for two wet years: 2001 and 2016

The year 2001 had the highest mean annual river flows of the time-series with values for the Seine River as high as 1600 $m^3 \cdot s^{-1}$ in April and above 1000 $m^3 \cdot s^{-1}$ during the first five months of the year. For the Somme River, river flows were above 75 $m^3 \cdot s^{-1}$ during the first six months of the year, with a maximum of 90 $m^3 \cdot s^{-1}$ in April and May. The seasonal dynamics of the two rivers were therefore similar. Spatial distribution maps of chlorophyll-*a* showed low concentrations of chlorophyll-*a* during winter months with an increase beginning in February in the northern part of the study area, at the mouth of the Somme River (Fig. 8). From April, concentrations sharply increased at the mouth of the Seine with large parts of the English Channel showing concentrations above 3 $\mu g \cdot l^{-1}$ in May. An extended spatial distribution of the high chlorophyll-*a* concentrations persisted during the productive period months.

In the last decade, 2016 was the most recent year with the highest mean productive period river discharge (586 $m^3 \cdot s^{-1}$ for the Seine). Peaks of 1450 $m^3 \cdot s^{-1}$ and 58 $m^3 \cdot s^{-1}$ were observed in June for the Seine River and Somme River, respectively. Until March and from October, few areas had monthly average values of chlorophyll-*a* exceeding 1.35 $\mu g \cdot l^{-1}$ (Fig. 9). From April, values increased significantly in the northern part of the study area at the mouth of the Somme and then from May at the mouth of the Seine. The 'Coastal Flow' was continuous in June with mean concentration values higher than 3 $\mu g \cdot l^{-1}$. However, the extent of the chlorophyll-*a* distribution did not encompass the whole Channel as observed in 2001. The 90th percentile values remained limited to coastal areas and the immediate vicinity of the mouth of the Seine and Somme rivers. The extension of the Seine plume did not exceed 23 km in June, whereas the Somme plume reached a maximum of 20 km.

The annual and monthly chlorophyll-*a* mean maps (Figs. 8 and 9) highlighted that the areas with the highest values (>50th percentile class) tended to decrease over time particularly in coastal areas in the north of Le Havre and in the centre of the English Channel. Areas in the bays of Somme and Seine with high chlorophyll-*a* values tended to be severely reduced for recent years.

3.6.2. Spatial distribution of changes in chlorophyll-a concentration

Over the 21 years of this study, a significant decrease in the chlorophyll-*a* concentrations was evidenced in the French part of the English Channel. These trends extracted from the DLM analysis applied to the time series for each pixel were spatialized and quantified (Fig. 10 and supplementary S7). This decrease showed a spatial pattern related to the 'coastal flow'. It was higher in the most productive areas under the influence of the rivers. A spatial gradient could be seen from north to south: between the Cotentin peninsula and Bayeux, the mouth of the Seine and the coastal area from Dieppe to Boulogne where the decrease reached 67 %. Chlorophyll-*a* concentrations were decreasing by at least by 25 % on almost the entire French side of the Channel up to 40 km offshore. The 'Coastal Flow' was also impacted by this decline between Le Havre and Dieppe. In these areas, the mean decrease in chlorophyll-*a* concentration was higher than 0.4 $\mu g \cdot l^{-1}$ (supplementary S7). Although less affected by these changes, the offshore central part of the Channel generally experienced a decline of >15 % over the time period.

4. Discussion

The concentration of chlorophyll-*a*, used as a proxy of phytoplankton biomass can be influenced by a range of factors. These include variables having a direct effect such as light, grazing, interspecific competition, nutrient availability, and variables having an indirect effect such as river

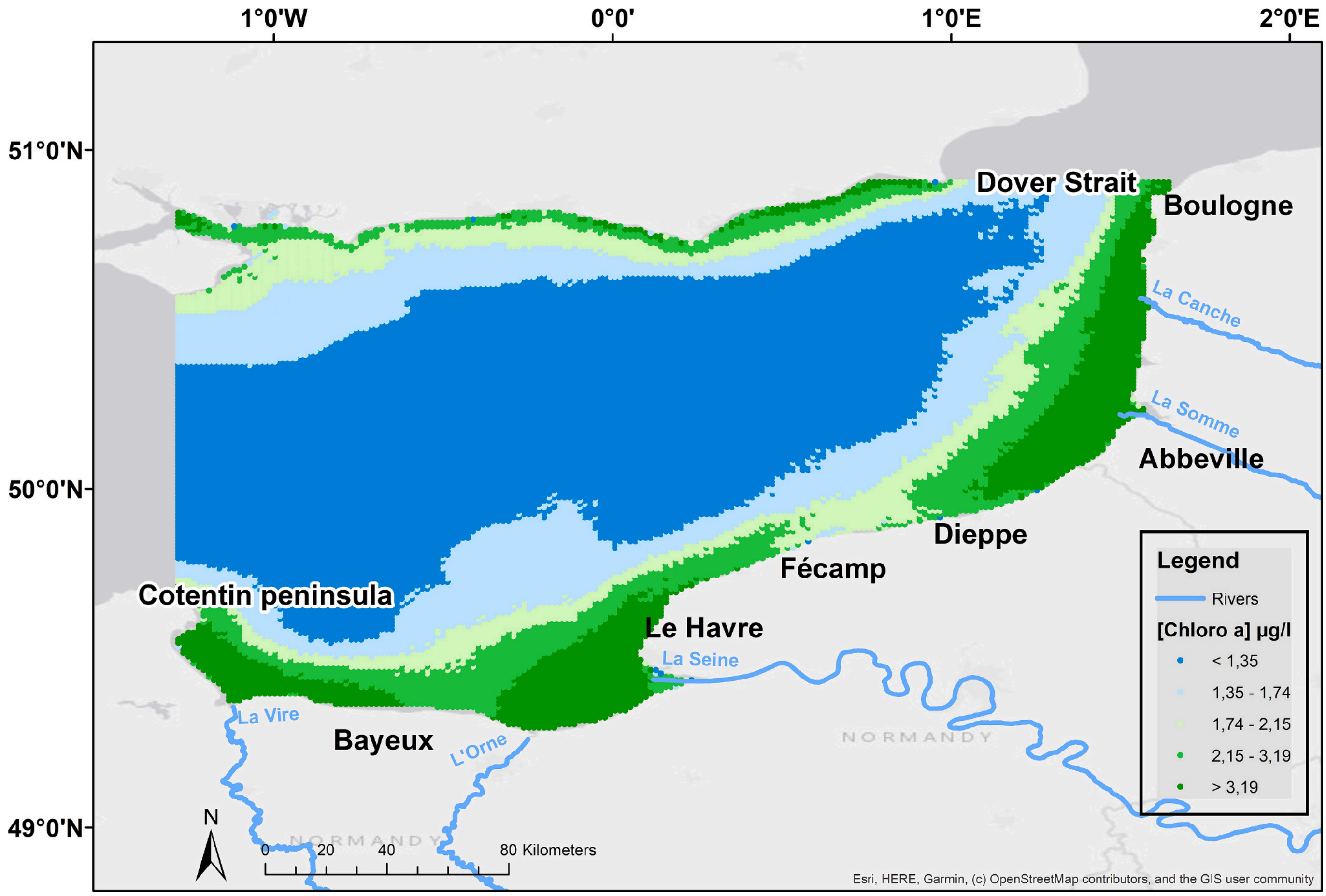

Fig. 6. Spatial distribution during productive period (April to October) of mean chlorophyll-*a* concentrations from 1998 to 2019. Legend classes are based on percentiles calculated on the whole period and defined as i) below the 50th percentile; ii) between 50th and 70th percentile; iii) between the 70th and 80th percentile; iv) between the 80th and 90th percentile; and v) over the 90th percentile.

flow by carrying nutrients and suspended particulate matter into coastal areas or winds which can regulate stratification (Gomez and Souissi, 2007; Hernández-Fariñas et al., 2015). In the English Channel, fluctuations in these variables have the potential to affect the growth and abundance of microalgae, leading to corresponding changes in chlorophyll-*a* concentration. In this study, we analysed these changes during the productive period for which light was supposed not to be a limiting factor and challenged the paradigm stipulating that the decrease of chlorophyll-*a* in the last decades was mainly due to the decrease in nutrients and that river flows played no role. This reduction of nutrients is linked in particular to improvements in the efficiency of wastewater treatment plants, the ban on the use of phosphates in detergents, the increase in the number of people connected to a public sewerage system and, to a lesser extent, the reduction in the use of phosphate fertilizers in agriculture. The analysis of *in-situ* data from monitoring stations confirmed the role of phosphate in the most coastal stations but indicated that the sum of nitrate and nitrite concentrations was also related to the chlorophyll-*a* decrease in offshore stations. The spatial distribution of changes assessed with satellite images time-series confirmed a seaward gradient of chlorophyll-*a* concentration decrease from the coast to offshore.

4.1.1. *Chlorophyll-a decrease in situ coastal stations and changes in the coastal flow*

In this study, decreasing trends of chlorophyll-*a* concentration have been found during two decades over the 1998–2019 period in the Eastern part of the English Channel for *in-situ* monitoring stations and satellite data. For stations close to the coast, a decrease in chlorophyll-*a* was systematically recorded, up to −30 % in the area directly influenced by the Seine River. The decline observed at Boulogne and Cabourg were consistent with the conclusions of Devreker and Lefebvre (2018). A lower decrease was seen further offshore, however it remained within the order of 15 % or more. Spatial distribution maps also showed this coast to offshore gradient as well as its spatial extent, indicating that the strongest decline occurred in the areas directly influenced by the river outflows. In particular, we found this decline in recent wet years and the maps for 2016 with lower and lower values of chlorophyll-*a* in the most productive areas: the Bay of Seine and the Bay of Somme. Changes in the area under the influence of the 'coastal flow' were observed. This coastal flow, characterized by higher chlorophyll concentrations, has a width of *ca.* 3 to 5 miles and corresponds to the movement of water along the coastline, driven with a north-eastward direction by prevailing winds, tides, and ocean currents (Brylinski and Lagadeuc, 1990; Brylinski et al., 1991). The satellite-derived maps of chlorophyll-*a* analysed in this study showed that the coastal flow became less and less visible with years to the point that, for 2016 and 2017, it almost disappeared north of Fécamp regardless of the river flows and "wet" and "dry" characterisation of the years.

4.1.2. *River flow and nutrients: what are the main drivers of the chlorophyll-a concentrations?*

Our study confirmed large and significant decrease in phosphate over the period at the *in-situ* monitoring stations but it also showed

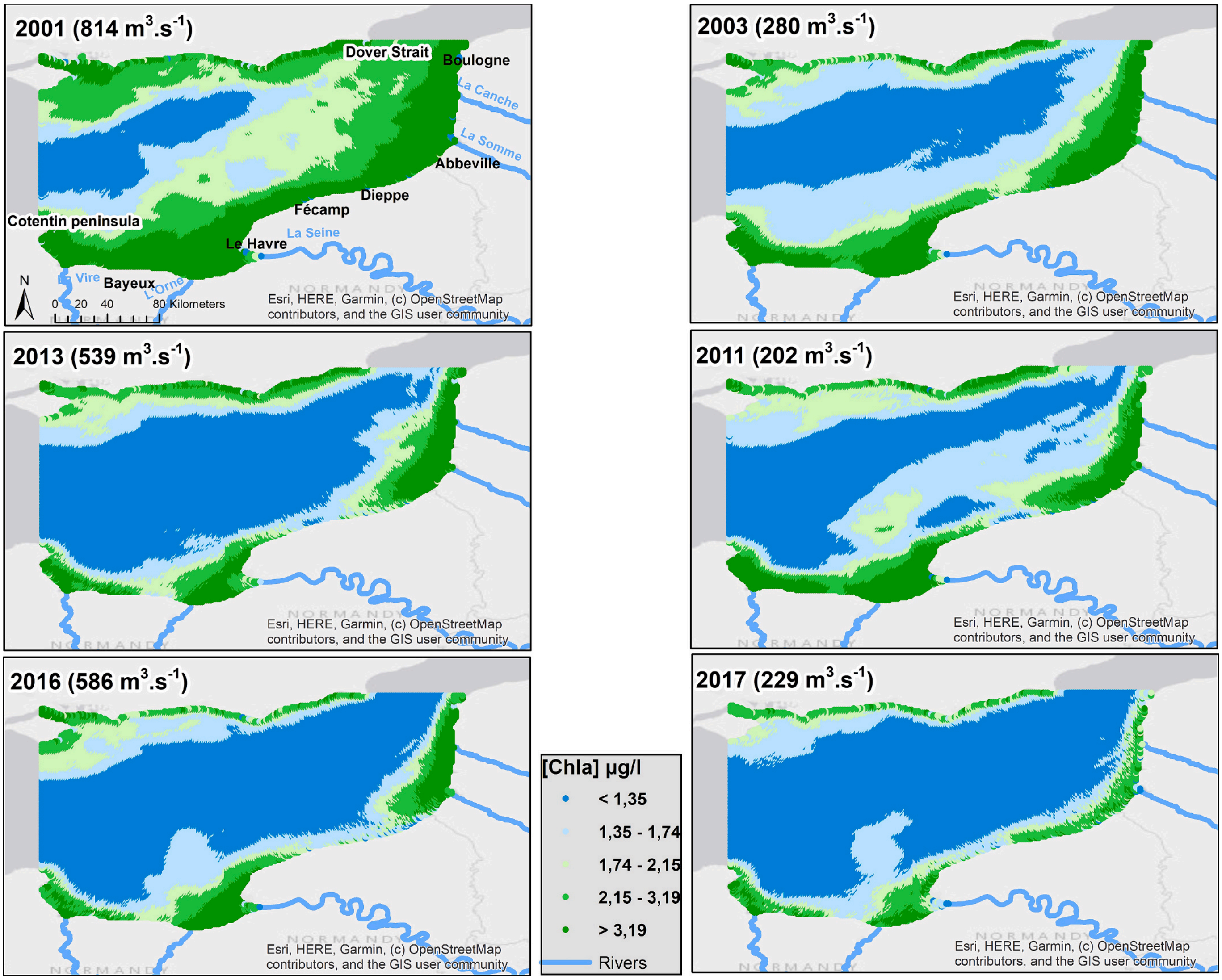

Fig. 7. Spatial distribution of mean chlorophyll-*a* concentrations during the productive period for wet years (left, mean outflows of the Seine) *vs* dry years (right) in $\mu g{\cdot}l^{-1}$ in the eastern English Channel. Mean Outflows of the Seine river are indicated for each map. Legend classes are based on the percentiles calculated on the whole period [1998; 2019] (below 50th percentile; between the 70th and 80th percentile; between the 70th and 80th percentile; between the 80th and 90th percentile; and over the 90th percentile).

significant decrease in the river flow of the Seine and the Somme rivers. These concomitant decreases illustrated the need to quantify the influence of these two drivers on the temporal variations of the chlorophyll-*a* concentration. The hierarchical partitioning of variance indicated that in spite of an overall decrease over the two decades, the flow variations of the Seine river had almost no influence on the variations of chlorophyll-*a* concentrations. It contributed to <5 % of the total explained variance of chlorophyll-*a* for the three *in situ* stations (Antifer, Cabourg, Ouistreham). The pattern was different for the Somme river as it explained 25 % of the chlorophyll variations as an average for the three Boulogne stations. Stations closest to the Seine (Antifer, Ouistreham 1 mille and Cabourg) showed the largest decrease in phosphate, up to -80 %. For these stations, hierarchical partitioning of variance indicated the importance of phosphate but also suggested that for two stations nitrate + nitrite contributed to explain the variations of chlorophyll-*a* concentrations. Nitrate + nitrite displayed idiosyncratic variations at the different *in situ* stations which seemed more dictated by local conditions. In line with these results, Devreker and Lefebvre (2018) reported a stagnation or even an increase in nitrogen fluxes coming from the Somme and the Seine rivers since the 1990s. OSPAR Convention assessed that over this later period, (i) nitrogen flows stagnated without any significant trend except in the northern part of the study area it increased (Artois-Picardie) and (ii) there were significant decreases in phosphate flows throughout the entire area (OSPAR Commission, 2014). Lefebvre et al. (2018) modelled diffuse inputs of nutrients over the last 50 years nitrogen inputs were found highly dependent on hydrology, without however detecting a trend over recent years. Concerning diffuse phosphate, there has been a decreasing trend since the mid-1980s until the early 2000s. Romero et al. (2016) indicated that diffuse sources of nitrate have stabilized in recent years and that polluted aquifers have prolonged discharges in coastal systems, especially during summer. Although atmospheric inputs represent a smaller source of nutrient input than rivers and diffuse inputs, it has been estimated that atmospheric inputs account for up to 20 % of the total nitrogen marine inputs between 1995 and 2008 (Devreker and Lefebvre, 2016). The most recent European Monitoring and Evaluation Program (EDMED) report (OSPAR Commission, 2017) showed a stabilization of these annual atmospheric inputs for our study area since 2007. Anthropogenic nitrogen inputs have therefore not decreased significantly in recent years, they appeared to continue to have an important impact on the dynamic of the primary production for the offshore part of the Eastern English Channel. In our study, nitrate + nitrite significant decrease was detected at Boulogne 2 &

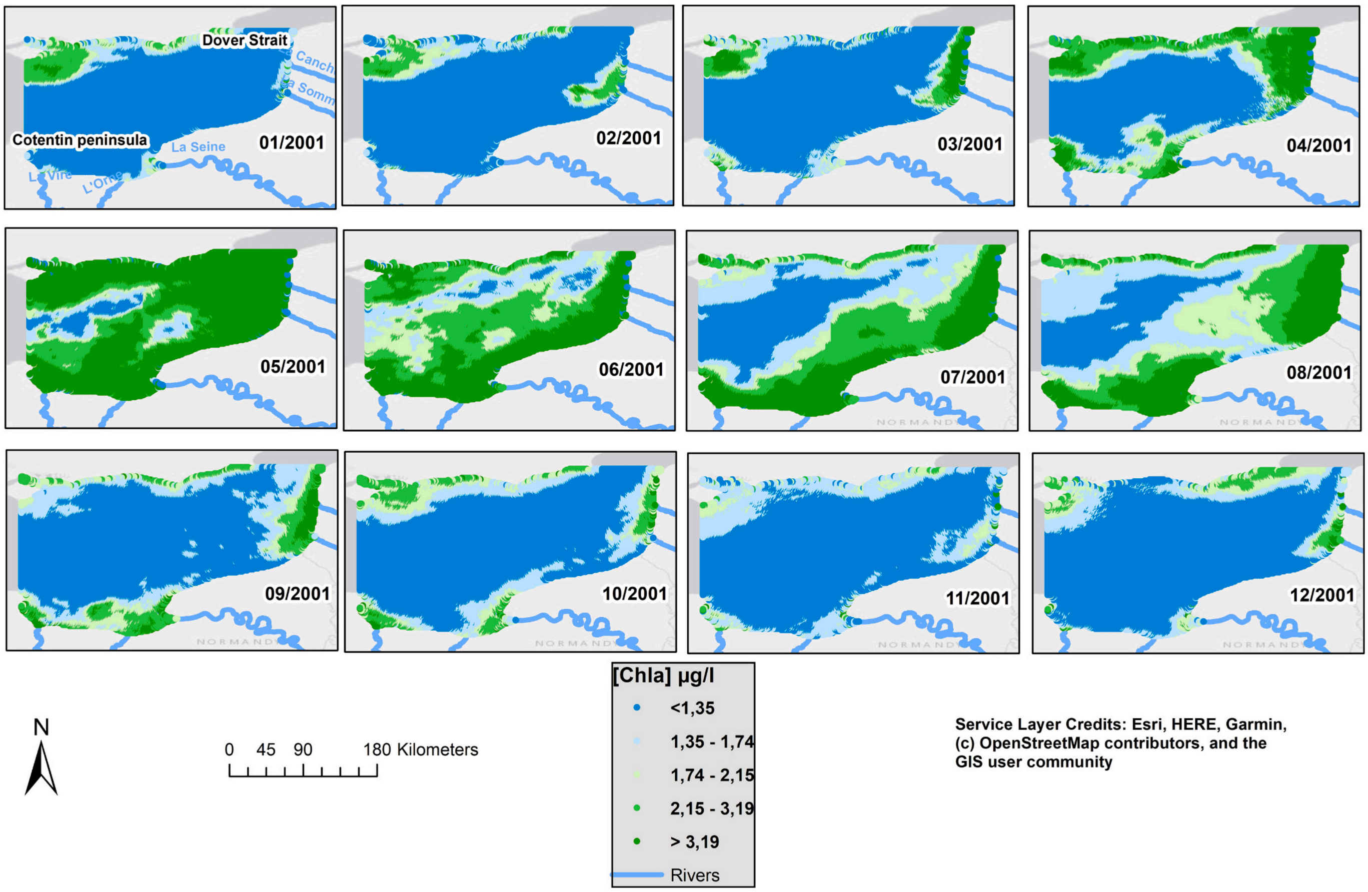

Fig. 8. Seasonal variations in the spatial distribution of monthly mean chlorophyll-*a* concentrations ($\mu g \cdot l^{-1}$) for the wet year 2001 in the eastern English Channel. Legend classes are based on the percentiles calculated on the whole period [1998; 2019] (below 50th percentile; between the 70th and 80th percentile; between the 70th and 80th percentile; between the 80th and 90th percentile; and over the 90th percentile).

3 and Antifer. The hierarchical partitioning of variance revealed a striking spatial pattern for the Boulogne stations. The role of phosphate declined along a coast to offshore gradient to the benefit of nitrogen forms. The explanatory power of phosphate to the variance of chlorophyll-*a* concentrations decreased from 55.5 % for Boulogne 1 (coastal) to 4.7 % for Boulogne 3 (offshore). Simultaneously, nitrate + nitrite explanatory power increased from 18.9 % for Boulogne 1 to 71.9 % for Boulogne 3. This result suggests that, nitrogen can play an important role on the dynamic of chlorophyll-*a* for offshore areas of the Eastern English Channel.

4.1.3. Decrease of chlorophyll-a in the central part of the English Channel and link with global changes

The maps produced from the trends in seasonally adjusted chlorophyll-*a* concentrations quantified a generalised decrease at regional scale, higher for the coastal zone, lower but still detectable in the central part of the English Channel. The area's specific hydrological configuration with the presence of the 'Coastal flow' seemed to isolate the offshore part from the influence of the river outflows. Nevertheless, the central Channel has seen a decrease in chlorophyll-*a* of up to 20 % in some places. In contrast to the coastal area under the influence of river inputs, the decrease in chlorophyll-*a* in the central area could be attributed to other causes and in particular to factors related to global changes. Desmit et al. (2020) showed that increase in sea surface temperature was a significant driver, along with de-eutrophication, of chlorophyll-*a* decline and a shift in the spring bloom. Temperature changes have an impact on stratification which is an important driver of phytoplankton growth. Increased stratification was related to lower phytoplankton production (Holt et al. 2016). Similarly, Lheureux et al. (2021) attributed 20-year changes in different monitored environmental parameters to broad-scale and regional climate changes detected through proxies such as temperature and atmospheric circulation. Using *in-situ* data, they concluded that ecosystem trajectories tended to show increases in temperature and salinity, with decreases in chlorophyll-*a*, nutrients and suspended particulate matter. Cappuzzo et al. (2018) also demonstrated a correlation between the increase in sea surface temperature and the decrease in phytoplankton production in the North Sea. Finally, Richardson and Schoeman (2004) related this increase in temperature to changes in phytoplankton abundance in the North-East Atlantic. Our *in-situ* and flux analysis, coupled with the satellite data analysis and mapping at a larger scale, were in line with the hypothesis that a more global phenomenon was at work and impacted the production of chlorophyll-*a* particularly in the offshore part of the English Channel. Some large-scale processes could be put forward to explain this such as the influence the Atlantic Ocean inputs (Salomon et al., 1993; Pingree and Maddock, 1977), which may be changing or the atmospheric input of nitrogen (Dulière et al., 2019).

4.1.4. Considerations and limitations

DLMs provide a general framework for modelling many environmental time-series (Laine, 2019). They were used in this study to decompose into several components the signal from chlorophyll-*a* measurements and each pixel of satellite images processed by the OC5 algorithm. A strength of this approach was to process *in-situ* and satellite data using the same methodology. The second main interest concerned the treatment of chlorophyll-*a* seasonality, which was variable over time (Ratmaya et al., 2019). We used the trend component and calculated seasonally adjusted chlorophyll-*a* concentrations values for each pixel of

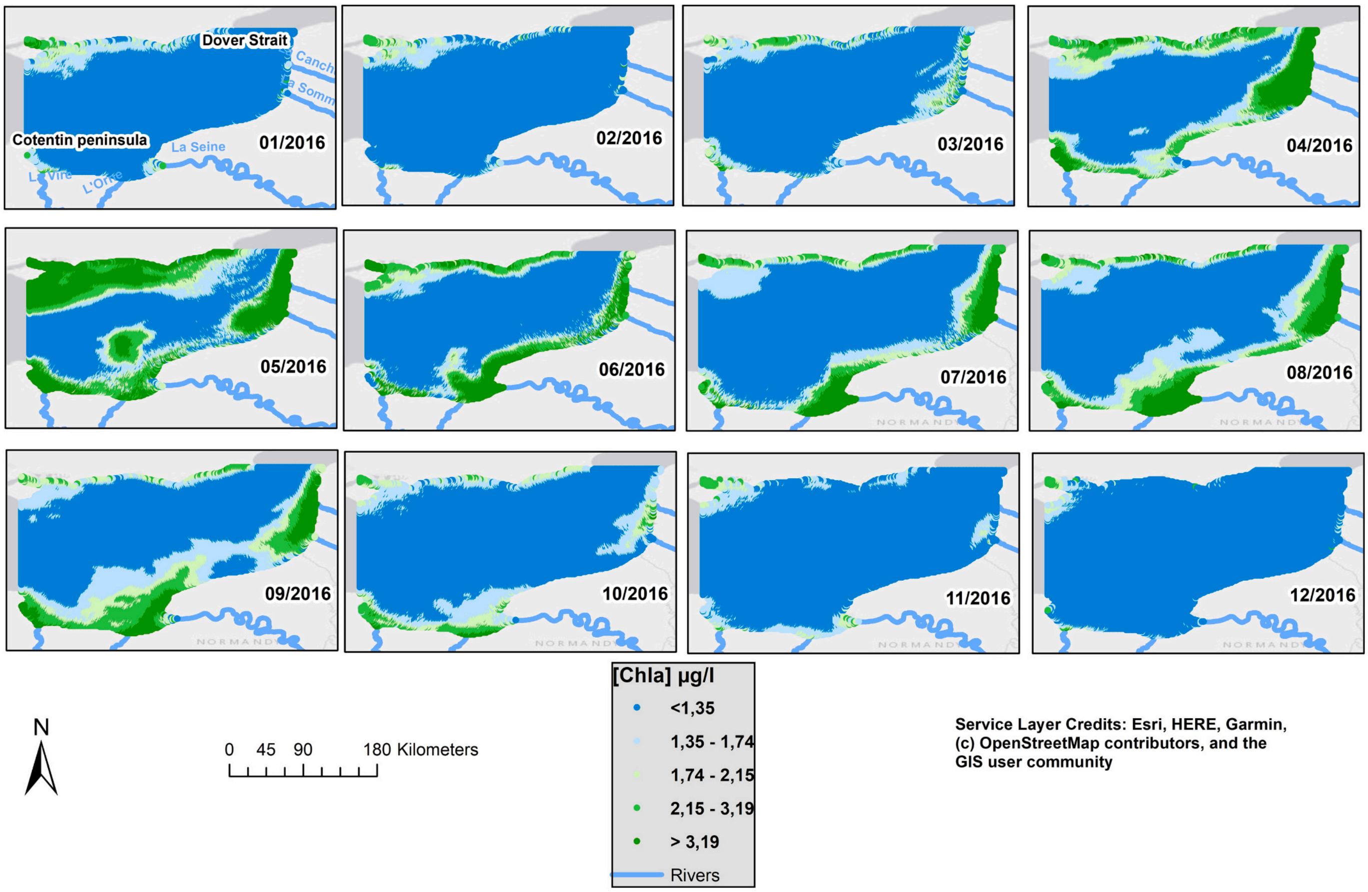

Fig. 9. Seasonal variations in the spatial distribution of monthly mean chlorophyll-*a* concentrations (μg·l^{-1}) for the wet year 2016 in the eastern English Channel. Legend classes are based on the percentiles calculated on the whole period [1998; 2019] (below 50th percentile; between the 70th and 80th percentile; between the 70th and 80th percentile; between the 80th and 90th percentile; and over the 90th percentile).

the satellite imagery. This methodology allowed to work on the whole time series without seasonal effects. The spatialization of these series provided a global view of the eastern English Channel regarding the evolution of chlorophyll-*a* in both relative (Fig. 10) and quantitative terms (supplementary S7). It revealed spatial patterns with a clear distinction between the coast under the influence of the rivers and the central zone of the Channel under the influence of more global phenomena. A limitation of our approach is that we did not consider changes in the phytoplankton community structure (Hernández-Fariñas et al., 2014). A decrease in chlorophyll-*a* could also be associated with changes in phytoplankton communities. The North Atlantic Oscillation (NAO) has been described as a key driver of ecological variations through direct, indirect or integrated effects at individual and population levels, in terms of recruitment, abundance, growth, rate, distribution, phenology, species assemblage and survival (Hallett et al., 2004; Drinkwater et al., 2010). These changes in the phytoplankton community impacted the concentration of chlorophyll-*a*. The presence and distribution of ecological niches remained dependent on several environmental parameters linked to seasonal changes: diatoms were dominant in nutrient-rich waters, whereas dinoflagellates and the other family taxa were associated to less nutrient-rich waters and summer conditions (Karasiewicz and Lefebvre, 2022). This affinity of taxa to environmental conditions and their spatial distribution, in relation to the results of our study on this coast-wide gradient, should be explored. The dominant phytoplankton genera in the area were *Phaeocystis* and *Chaetoceros* (Belin et al., 2019) with a succession of strong seasonal blooms of *Phaeocystis* (Lefebvre and Delpech, 2004). Alvera-Azcarate et al. (2021) observed from satellite imagery that the typical spring bloom in the Greater North Sea happened earlier each year, with about 1 month difference between 1998 and 2020. Therefore, spring blooms could have been affected enough to be partly the cause of the drastic drop in chlorophyll-*a* observed in the coastal zone.

Although this study has partially addressed the subject, the analysis of the changes in SPM concentrations should be further explored to understand its impact on the temporal dynamic of chlorophyll-*a*. The spatial distribution of SPM (supplementary S3) showed values over 3.4 g.m^3 in the coastal zone while they stayed very low offshore. Although SPM could partly explain the decrease in chlorophyll-*a* in the coastal area (Cappuzzo et al., 2018), it likely did not play a role in the central part of the Eastern English Channel. In addition, SPM values during winter months preceding the spring bloom did not show a clear trend in the period (Alvera-Azcarate et al., 2021).

In this area, the relationship found in this study between nitrate + nitrite and chlorophyll-*a*, should be nuanced in the light of seasonal aspects and in particular the evolution of the Redfield ratio (Redfield et al., 1963). Seasonality is fundamental in the area and this ratio can change significantly over time (Ward et al., 2011). Lheureux et al. (2021) exhibited for some of *in-situ* stations (*i.e.* "Boulogne 1", "Boulogne 2", "Boulogne 3") an overall changes towards a decrease of the nitrogen and silicate nutrients, corresponding to an increase of silicate/nitrogen and silicate/phosphorous ratios. It cannot be excluded that changes in these ratios for nitrogen, phosphorus, but also silicates not considered in this work, contributed to limiting the growth of phytoplankton.

5. Conclusion

The chlorophyll-*a* concentration in the eastern English Channel has

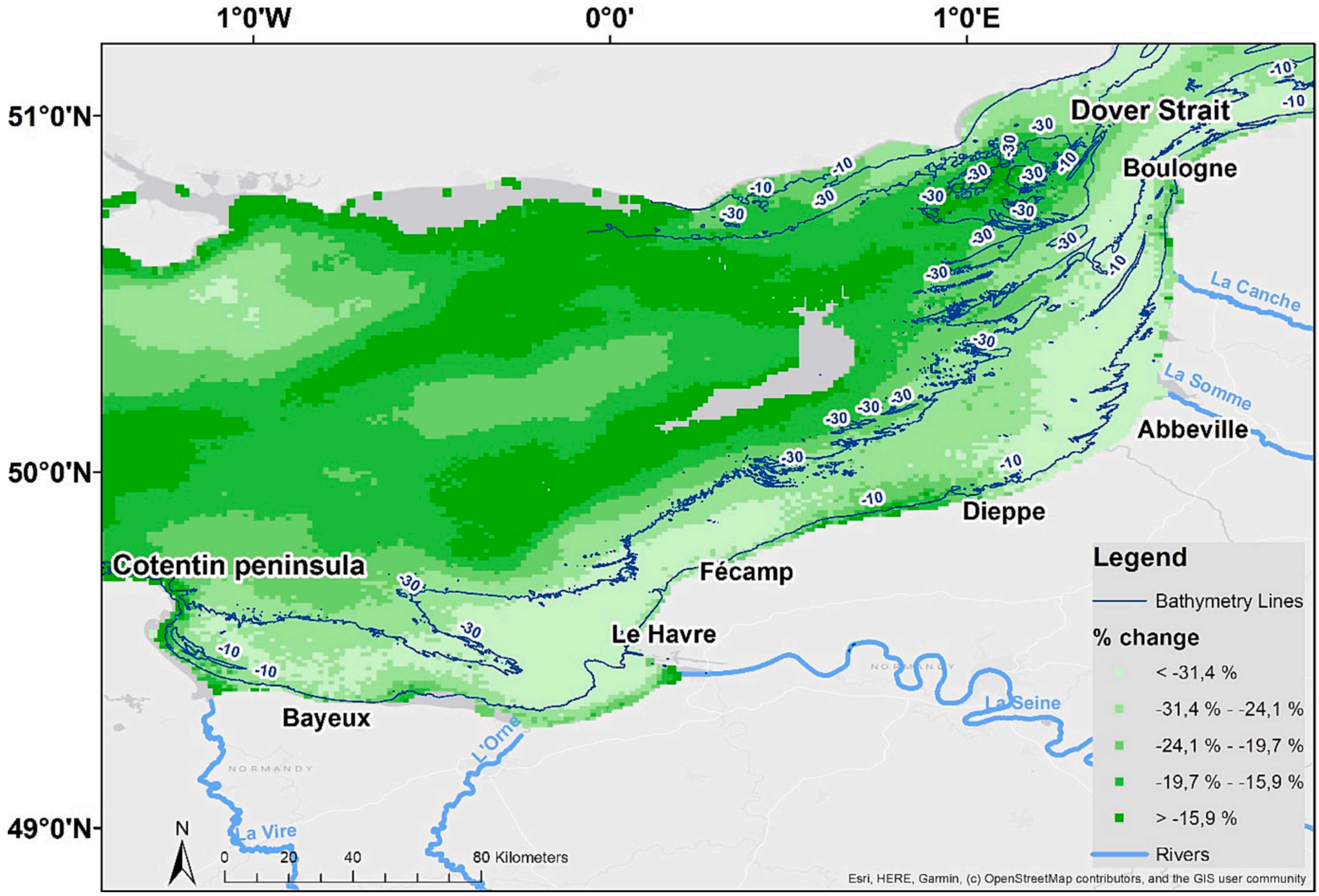

Fig. 10. Changes in chlorophyll-*a* concentration (expressed in percent change) from 1998 to 2019 estimated for each pixel of the time series using the DLM trends. The grey central offshore area to the north of Fécamp is where the linear fitted trend was not significant. Legend classes are based on the percentiles calculated on the whole period (below 50th percentile; between the 70th and 80th percentile; between the 70th and 80th percentile; between the 80th and 90th percentile; and over the 90th percentile).

undergone a significant decline over the last two decades. This decline showed a spatial pattern, with a strong decrease in the areas directly influenced by rivers and a lower but still significant decrease in the area further offshore. This study has shown that nutrients were the main driver of the trends in chlorophyll-*a* concentration in coastal stations close to the Seine estuary and that the variations in river flow did not play a significant role. For the Boulogne stations, the decrease in river flow though lower than the role of nutrients could not be discarded as an explanatory factor. The decline of phosphate is having a significant role in the decrease of chlorophyll-*a* but nitrogen could also contribute to the observed variance of chlorophyll-*a* in particular for offshore stations. The situation appeared therefore to be more complex in the offshore area. During the productive period, the offshore area was probably subject to hydrological and climate drivers other than anthropogenic inputs. The influence of climate change cannot be excluded, with an impact on the species composition of the phytoplankton community, associated with the decrease in chlorophyll-*a*. A perspective to this study could be to map phytoplankton community changes using for example the PHYSAT classification method (Alvain et al., 2008) and relate them to the decrease of chlorophyll-*a* in order to link this phenomenon to global changes. On the other hand, DLMs generated a great deal of information that deserves to be more fully exploited. Indeed, this study only considered the trend component. Another perspective would be to use the seasonal component of DLM, which could be classified in order to find patterns of chlorophyll-*a* phenology and evaluate their change over time. Finally, the calculation of trends and the associated methodologies could provide information of the long-term changes of marine sub-regions, and water bodies under the jurisdiction of EU Directives (European Commission, 2000; European Commission, 2008). This could set a global context and complement the water quality assessments currently carried out on shorter time scales by European regulations.

CRediT authorship contribution statement

Antoine Huguet: Conceptualization, Methodology, Software, Writing – original draft, Writing – review & editing. **Laurent Barillé:** Conceptualization, Methodology, Supervision, Validation, Writing – review & editing. **Dominique Soudant:** Methodology, Software, Supervision, Writing – review & editing. **Pierre Petitgas:** Methodology, Writing – review & editing, Validation. **Francis Gohin:** Methodology, Writing – review & editing. **Alain Lefebvre:** Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2023.115870.

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