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Caspian Sea is eutrophying: the alarming message of satellite data

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Abstract
The competition over extracting the energy resources of the Caspian Sea together with the major anthropogenic changes in the coastal zones have resulted in increased pollution and environmental degradation of the sea. We provide the first evaluation of the spatiotemporal variation of chlorophyll-a (Chl-a) across the Caspian Sea. Using remotely sensed data from 2003 to 2017, we found that the Caspian Sea has suffered from a growing increase in Chl-a, especially in warmer months. The shallow parts of the sea, near Russia and Kazakhstan, especially where the Volga and Terek rivers discharge large nutrient loads (nitrogen- and phosphorus-rich compounds) into the sea, have experienced the highest variations in Chl-a. The Carlson’s trophic state index showed that during the study period, on average, about 12%, 26%, and 62% of the Caspian Sea’s area was eutrophic, mesotrophic, and oligotrophic, respectively. The identified trends reflect an increasing rate of environmental degradation in the Caspian Sea, which has been the subject of conflict among its littoral states that since the collapse of the Soviet Union have remained unable to agree on a legal regime for governing the sea and its resources.

1. Introduction
Caspian Sea is the largest lake in the world by area with no regular connection to open seas except through the Volga–Don canal that connects this aquatic environment to the Sea of Azov and Black Sea [1]. It has a rich biodiversity, provides about 90% of the world’s caviar supply [2, 3], and forms resting regions for ten million migratory birds [4, 5]. Since the sea is landlocked, the pollutants discharged into the sea remain in place and accumulate. As a major oil production site, the Caspian Sea region has been exposed to large pollution loads originated from oil and gas industries [6, 7]. Annually, about one million tons of oil is leaking into the sea [5, 8]. In addition, the rapid urbanization, industrial and agricultural developments in the coastal areas, as well as political and economic competition in using the Caspian Sea resources [9] have further exacerbated the environmental conditions in the sea [10]. Nitrogen- and phosphorus-rich compounds (hereafter referred to as nutrients) are among the concerning Caspian Sea pollutants. The nitrogen and phosphorus released from household wastewaters and caused by the substantial use of agricultural fertilizers in the Caspian Sea basin are transported into the sea through rivers and drainage systems. The Volga, Ural, and Terek rivers carry a wide variety of nutrients that end up in the Caspian Sea [11]. High concentrations of detergents and ammonium have been previously reported in north of the sea [12] (see table S1 (available online at...
This is due to the high concentrations of detergents and nutrients in the rivers that flow into the north Caspian Sea (table S2). According to the United Nations Environment Program [13], respectively, about 886 100 and 104 280 tons of total nitrogen (TN) and total phosphorus (TP), were annually discharged in the sea from rivers, industries, and municipalities within the Caspian Sea basin. The contributions of Russia, Azerbaijan, Iran, Kazakhstan, and Turkmenistan to the discharged TN loads were, respectively, about 91.40%, 3.76%, 3.24%, 1.54%, and 0.06%. In the case of discharged TP loads, the shares of Russia, Iran, Azerbaijan, Turkmenistan, and Kazakhstan were, respectively, about 85.70%, 5.43%, 4.31%, 3.81%, and 0.75%. The resulting nutrient concentrations can potentially reach a level that converts more areas of the sea from oligotrophic (TN and TP concentration less than 0.661 and 0.008 mg L$^{-1}$, respectively) to eutrophic (TN and TP concentration greater than 1.39 and 0.084 mg L$^{-1}$, respectively) and accelerates eutrophication [14,15]. This situation can potentially result in phytoplankton population increase, a good indicator of the nutrients’ enrichment, evidenced by high chlorophyll-a (Chl-a) concentrations across the sea [16].

Few studies have evaluated the spatiotemporal variation of Chl-a in the Caspian Sea [17]. Most of the previous studies have limited coverage in terms of time and space. Nasrollahzadeh et al [14] conducted a study on the trophic status in the southern part of Caspian Sea, Bagheri et al [18] studied phytoplankton distribution in southwest of the sea during 2001–2002. Jamshidi and Bin Abu Bakar [19] investigated the Chl-a distribution in Bandar-e Anzali, a port in the southwest of the sea.

Bridging the gap in our understanding of the spatiotemporal variation of Chl-a over time and space across the Caspian Sea was the major motivation of this study. Accordingly, this study aimed to: (a) investigate the spatiotemporal variation of Chl-a in the Caspian Sea using the proper orthogonal decomposition (POD) method, a method with limited previous applications in oceanic studies [20, 21]. In this regard, the Chl-a data, provided by the NASA OceanColor, were used by the POD model to capture the dominant spatial patterns and temporal trends of Chl-a concentrations in Caspian Sea from 2003 to 2017. The Oceancolor Chl-a data is collected by the moderate resolution imaging spectroradiometer (MODIS) sensor aboard the Aqua satellite (MODIS-Aqua) with a spatial resolution of 0.1° on a daily basis. Since Chl-a database was incomplete in some grids over the Caspian Sea, the study also developed a proper algorithm to reconstruct the missing values based on the measured data in the neighbor grids; and (b) calculate the trophic status over the Caspian Sea using the Carlson’s trophic state index (TSI) (text S1) [22]; and (c) distinguish the areas that are exposed to the eutrophication or are eutrophic.

The analysis results not only illustrate the spatiotemporal variation of Chl-a over the Caspian Sea, but also provide a general understanding of the sea eutrophication condition caused by the Caspian Sea littoral states that so far have been unable to agree on a legal regime to govern the sea [2, 23].

2. Methods

2.1. Study area

The Caspian Sea, located between the 36° and 47° N latitude and 46° to 54° E longitude, is the remainder of the ancient Thetis Ocean with a water volume, surface area, and water level around 78 000 billion cubic meters (km$^3$), 390 000 km$^2$, and ~27 m below the mean sea level, respectively [17, 24]. Caspian Sea includes nine sub-basins that annually provide about 300 km$^3$ of water to the sea (table S3). The average air temperature over the sea varies from 10 °C in northern parts to 17 °C in southern parts. The sea surface temperature with a north–south ascent gradient varies between 0 °C and 26 °C [25, 26]. Caspian Sea’s salinity, with a north (1 g kg$^{-1}$)-south (13 g kg$^{-1}$) ascent gradient [27], is three times lower than world’s oceans [24]. As a result of varying salinity levels, the diversity of phytoplankton species decrease from the north (shallow section) to the south (deep section) of the sea (text S2) [5].

Azerbaijan, Iran, Kazakhstan, Russia, and Turkmenistan are the five littoral states of the Caspian Sea. With a combined coastline of about 6380 km, these countries house around 11 million people near the Caspian Sea coast, most of whom living in the coastal cities of Azerbaijan and Iran [24, 28] (figure S1). The sea can be divided into three main areas: the north part with a depth of less than 10 m, receiving most of the discharge from the rivers flowing into the Caspian Sea (about 90%); the middle part with inflow from the Kura River; and the south part, connected to the Iranian rivers that provide 4%–5% of the total inflow to the Caspian Sea [25] (figure S1). These three parts with the maximum depth of 20, 788, and 1025 m contain about 0.5%, 40%, and 65.5% of the lake water volume, respectively [25]. About 130 rivers flow into the Caspian Sea including the Volga River that provides about 80% (240 km$^3$ yr$^{-1}$) of the total discharge into the Sea [29]. The other important rivers are Ural (Kazakhstan), Terek (Russia), Kura (Azerbaijan) and Sulak (Russia) that respectively discharge about 12.6, 9.6, 14.0, and 5.6 km$^3$ of water into the sea annually [27, 28].

Caspian Sea is surrounded by urban, industrial, and agricultural areas. The Volga, Terek and Sulak Rivers have shown high concentrations of detergents and ammonium (table S2), attributed to releasing...
domestic sewage into rivers that increase the phytoplankton population and reduce the quality of water. Pollution discharge into the Caspian Sea, resulting from domestic, industrial and agricultural wastewater and oil industries, has affected the marine ecosystem in the past decades. The Volga River’s discharge reported to be the most important source of dichlorodiphenyltrichloroethane among the chlorinated pesticides and hexachlorocyclohexane [30]. The presence of detergents and ammonium was reported in the north part of Caspian Sea (table S1), especially in Volga, Terek and Sulak Rivers (table S2). In general, the north part of the sea has higher productivity than the other parts [24].

2.2. Data preparation

The study used the Level 3 MODIS-Aqua Chl-a data with the resolution of 4 km over the Caspian Sea from January 2003 to December 2017 (available at the NASA Oceancolor website: https://oceancolor.gsfc.nasa.gov/atbd/chlor_a). The recorded data by NASA had some spatial and temporal gaps, especially in the northern parts because of the presence of clouds on different days and at various locations (mainly in the northern part). This made the analysis based on a daily time series infeasible. Instead, mean monthly time series of Chl-a were used. Nevertheless, the monthly Chl-a database still had some missing components in some grids over the sea. To address this issue, an algorithm was developed to reconstruct the missing values. This method is computationally less demanding than the other estimation methods, such as those used by Wang and Liu [31] and Park et al [32]. Starting from the south of the sea, which is generally less cloudy, the proposed algorithm calculated the missing values cell by cell as an average of Chl-a in its adjacent cells. The calculations continued toward the north of the sea and the information of adjacent cells (recorded or reconstructed) were used to fill all data gaps. The extracted Chl-a data over the study area included 24 329 square grids with the resolution of 4 km. Each grid contained Chl-a data for 180 months (15 years), resulting in a 24 329 by 180 matrix with rows representing grids and columns representing months. The reconstructed Chl-a data are given in dataset S1.

2.3. POD application and dominant features extraction

The POD method [33] has been widely used in the field of computational fluid dynamics to project partial differential equations governing low dimensional models [34–36]. Although POD has been usually applied to detailed data simulated by numerical models, few studies have applied this method to data measured experimentally during sampling campaigns [20, 21], such as the data used in this study.

To perform the analysis, the Chl-a data was expressed as a function of time \( t \) and space \( x \), i.e. \( f(x,t) \) where \( i = 1, 2, \ldots, N \). Then, POD was applied to function \( f \) to extract the dominant features of Chl-a that were the space and time dependent components \( \varphi(x) \) and \( \omega(t) \) respectively. These features could exactly regenerate Chl-a as [37]:

\[
f = \sum_{i=1}^{N} \omega_i(t) \varphi_i(x)
\]

The mean square of inner product of function \( f \) and \( \varphi(x) \) was then maximized [36]:

\[
\frac{1}{N} \sum_{i=1}^{N} \left\{ \langle f, \varphi \rangle \right\}^2 \left/ \langle \varphi, \varphi \rangle \right. \}
\]

This maximization was equivalent to solving the following eigen-function problem:

\[
|1 - \lambda \Gamma| = 0
\]

where \( \lambda \) is the identity matrix and \( \Gamma \) is the Hermitian matrix calculated as:

\[
\Gamma_{ij} = (1/N) \int f_i(x)f_j(x)dx
\]

Having calculated eigenvalues \( \delta_i \) and the corresponding eigenvectors \( \tau_{i} \), the space dependent components could be calculated as [36]:

\[
\varphi_i(x) = \sum_{j=1}^{N} \tau_{ij} f_j(x)\varphi_j(x) = \sum_{j=1}^{N} \tau_{ij} f_j(x), \quad \varphi_N(x) = \sum_{j=1}^{N} \tau_{Nj} f_j(x)
\]

By considering the calculated space dependent components, the time dependent components could be also derived as [37]:

\[
\omega_i(t) = \langle f(x,t), \varphi_i(x) \rangle
\]

The eigenvalues decayed so fast that just the features corresponding to the few first eigenvalues represented most of the system’s energy (here, Chl-a variation) [21]. Therefore, the Chl-a variations were investigated using just the few first features as [36]:

\[
f(x,t) \cong \sum_{i=1}^{I} \omega_i(t) \varphi_i(x), \quad I \ll N
\]

where, \( I \) is the number of selected features.

Figure S2 summarizes the estimation procedure followed in this study.
3. Results

3.1. Chl-a data reconstruction

Figures 1(A) and (B), respectively, show the Chl-a data over the Caspian Sea before and after reconstruction for the month of September that included the most missing values during the study period. To evaluate the performance of the reconstruction method, one hundred random cells with available Chl-a data were selected (figure 1(C)). We then applied the reconstruction algorithm to calculate Chl-a concentrations in these cells. Figure S3 shows the real Chl-a data in these hundred cells and the calculated values by the algorithm. The minimum, maximum, and average of absolute relative error were 0.01%, 17.45%, and 4.85%, respectively. These values implied good performance of the applied reconstruction method for Chl-a data over the sea. The applied reconstruction method has some limitations that must be considered when interpreting the results. In areas with higher number of missing Chl-a data, the reconstructed values are associated with higher levels of uncertainty.

3.2. Descriptive statistics

After reconstructing the missing data, the mean, maximum, minimum, and standard deviation (StD) values of Chl-a concentrations were calculated for monthly, seasonal, and annual datasets both temporally and spatially. As shown in figure 2, the monthly, seasonal, and annual time series of Chl-a, averaged over the sea, indicated a gradually increasing trend during the study period. The same trend but with a steeper ascent was observed for the StD of Chl-a values over the sea (figure 2). The investigations of the time series of maximum and minimum Chl-a values over the sea revealed increasing and decreasing trends during the 2003–2017 period, respectively (figure 2).

In general, a gradually increasing trend during the study period is observed for average and maximum values of Chl-a. The same trend but with a steeper ascent is observed for the StD of Chl-a concentrations over the sea (figure 2). The increasing trends for average and maximum values of Chl-a could potentially reflect the increase of nutrients inputs to the sea from natural and anthropogenic pollution sources. Yet, this observation must be further examined by accurate measurements of the nutrient load discharges into the sea. The peak monthly and seasonal mean Chl-a values occurred in August–September and summer, respectively (figures S4 and S5). The monthly and seasonal minimum values of Chl-a mostly occurred during the cold season (figures S4 and S5) when the physical and environmental conditions of Caspian Sea (e.g. light, temperature, and mixing) limit the algae growth [37].

The spatial distributions of monthly mean, maximum, minimum, and StD of Chl-a values, as well as the Chl-a value averaged during the whole study period, are shown in figure 3(A). The northwestern part of the Caspian Sea consists of the deltas of Volga River and Terek River along the Russian coastlines. This part showed the highest Chl-a concentrations during the study period (up to 100 µg l\(^{-1}\)). The coasts of Baku in Azerbaijan and Kendirli Bay in Kazakhstan also showed high concentration of Chl-a (up to 80 µg l\(^{-1}\)), but smaller than the levels observed in the northwestern part. Same as the Baku and Kendirli Bays, the Gulf of Gorgan (also known as Gorgan Bay) on the Iranian side of the Caspian Sea (southeast) also experienced high Chl-a concentrations (up to 85 µg l\(^{-1}\)). This Gulf has a small connection with the Caspian Sea, which should potentially cause a long residence time of water (more than 100 d) and facilitate phytoplankton growth [38–40].

The annual maximum concentration of Chl-a was observed in the Volga River delta and Terek River delta in 2009 (figure 3(B)). Also, the minimum annual Chl-a concentrations were observed in the middle region in 2011 (figure 3(B)). With a large watershed area that mainly consists of vast agricultural and industrial regions, the Volga River contributes to the discharge of large pollution loads (mainly nutrients) into the Caspian Sea (table S2) [25, 29]. This provides a favorable area in the northwestern part of the Caspian Sea for rising Chl-a concentrations.

The spatial distribution of annual maximum and minimum values of Chl-a showed a general decreasing trend from the northwest to the southeast of the Caspian Sea (figure 3(A)). In general, the northern parts of the sea that are exposed to nutrient loads from the Volga and Terek Rivers [28], showed higher Chl-a concentrations. Also, the StD of Chl-a values revealed high variations of this variable over the Caspian Sea with maximum values across the northwest coastlines.

3.3. POD results

Table S4 shows the first ten (out of 180) calculated eigenvalues corresponding to the first ten modes as illustrated in the method section. The conserved system’s energy for the first mode was about 43%. The cumulative conserved energy reached about 65% by the first four modes. The system energy remained during the fifth mode was about 2% and it reduced to less than 0.2% when reaching the tenth mode. Considering the little significance of the mode numbers greater than 4 in explaining the Chl-a variation, it was decided to only use the first four modes to investigate the spatiotemporal variation of Chl-a over the Caspian Sea.

According to \(\varphi_1(x)\), the northern parts of the sea have experienced higher variation of Chl-a compared to the other areas (figure 4(A)). More specifically, the northwest areas in the meeting point of Volga River and Terek River showed the highest variation in Chl-a (\(\varphi_1(x) \approx 0.045\)). Also, the middle and south areas showed the lowest Chl-a variations (\(\varphi_1(x) \approx 0.0\)).
except for some parts of the Iranian shorelines in Bandar-e Anzali (Port of Anzali) and Gorgan Bay, and coasts of Baku in Azerbaijan, Kendirli Bay in Kazakhstan, and Turkmenbashi in Turkmenistan. In general, Chl-a variations increase from the south to the north of the Caspian Sea as shown by $\varphi_1(x)$ (figure 4(A)). The spatial component of the second mode ($\varphi_2(x)$) showed large variations of Chl-a in some parts of the west and south of the sea and the Gorgan Bay, located in Iranian shorelines ($\varphi_2(x) \approx 0.025$) that had not fully captured by $\varphi_1(x)$. Based on the obtained results, $\varphi_2(x)$ failed to properly represent large variations of Chl-a in the northwestern parts of the sea except for some small locations where its value went up to $-0.025$ (figure 4(A)). It should be noted that in the POD model, absolute values of the modes (not just positive ones) cause large variations in the objective variables. In addition, major rivers such as Terek River could potentially discharge large nutrient loads to the west coasts of the Caspian Sea that could enhance Chl-a variations in this region as depicted by $\varphi_2(x)$. Same as $\varphi_1(x)$, $\varphi_2(x)$ well reflected high variations of Chl-a in the Terek River delta and Volga River delta ($\varphi_3(x) > -0.06$), and Gorgan Bay ($\varphi_3(x) \approx 0.04$). According to $\varphi_3(x)$, the middle and south regions had the minimum variations of Chl-a ($\varphi_3(x) \approx 0.0$). $\varphi_4(x)$ reflected the high and low variations of Chl-a in the Terek River delta ($\varphi_4(x) > 0.05$ and $\varphi_4(x) < -0.03$) and the middle/south regions of the sea ($\varphi_4(x) \approx 0.0$), respectively.

Figures 4(B) and (C) show the temporal components of the first ($\omega_1(t)$) to the fourth ($\omega_4(t)$), tenth ($\omega_{10}(t)$), and twentieth ($\omega_{20}(t)$) modes. The Mann–Kendall test revealed a significant increasing trend for $\omega_1(t)$ (p-value $\leq 0.05$) that indicates rising Chl-a concentrations during the study period. The first mode captures 43% of the total Chl-a variation in the Caspian Sea. Thus, $\omega_1(t)$ can be considered as a good representative for temporal variation of Chl-a over the sea. Additional screening indicated that the peaks of the $\omega_1(t)$ time series occurred in August and September, shown by red circles in in figure 4(B). The lowest points of the time series correspond to the cold season (December, January, and February), marked by blue circles in figure 4(B). The MK test showed insignificant downward trends for $\omega_2(t)$ and $\omega_3(t)$ (p-value $> 0.05$), and an insignificant upward trend for $\omega_4(t)$ (p-value $> 0.05$). As discussed before, the energy conserved after the few first modes is small. This is indicated in figure 4(C) where the temporal components with higher indices just fluctuate around zero (e.g. $\omega_{20}(t)$).

### 3.4. Trophic state over the Caspian Sea

Considering the monthly Chl-a concentrations over the Caspian Sea during the study period (2003–2017), the TSI values were separately calculated for all grids. Based on the TSI values, the size of the sea areas under oligotrophic, mesotrophic, and eutrophic conditions were estimated (figures 5(A)–(D)). The monthly TSI values suggest that about 17% and 16% of the Caspian Sea’s area was under the worst trophic condition (eutrophic) in August and September, respectively. The best trophic condition was observed during April to June when more than 70% of sea area was under oligotrophic conditions, reflecting clear water and sufficient oxygen in the water column. The maximum sea area (more than 70%) in the mesotrophic state occurred in September and October (figure 5(A)). Caspian Sea experienced its worst trophic condition at the annual scale in 2014 (during the study period) when about 16% of its area was eutrophic, and 60% and 24% of the sea area had oligotrophic and mesotrophic conditions, respectively. Thereafter, about 14% of the sea area was eutrophic in 2016 (figure 5(B)). According to figure 5(C), the largest eutrophic area occurred during the summer season (about 16%). Also, winter had the smallest eutrophic area (about 4%) (figure 5(C)). By taking the average of the monthly mean Chl-a concentrations in each
grid over the study period, TSI values were calculated to estimate the percentage of the Caspian Sea area under different trophic conditions (figure 5(D)). Results indicate that about 12%, 26%, and 62% of the Caspian Sea areas were, eutrophic, mesotrophic, and oligotrophic, respectively (figure 5(D)).

Figure 6 shows the spatial distribution of the TSI values over the Caspian Sea, calculated for different seasons, years, and the whole study period. Based on the mean annual TSI values, most of the northern part, mainly located in Russian coastlines, were eutrophic during the study period (figure 6(A)). The Volga River and Terek River deltas were eutrophic in all seasons, years, and the whole study period (figure 6), and in all months (figure S6). The southern region was mostly oligotrophic/mesotrophic although some parts of this region had eutrophic conditions, especially in 2005, 2009, and 2010 (figure 6(A)). Baku port and Gorgan Bay were the second and third places (after the Russia coastlines), respectively, that had the worst trophic condition (eutrophic). According to figure 6(A), although
the Iranian coastlines were eutrophic from 2003 to 2010, they became mesotrophic after 2010. The Gara-bogazkol basin in the eastern part of the Caspian Sea was classified as oligotrophic in all investigated time scales. The average value of TSI over the Caspian Sea during the study period suggests that most of the Caspian Sea area had a mesotrophic status (figure 6(B)).

4. Discussion and conclusions

This study investigated the variations of Chl-α, as the most important indicator of eutrophication, over the Caspian Sea, using traditional statistical indices and the POD model based on satellite data. The study results reveal an alarming trend of Chl-α in the Caspian Sea when its Chl-α concentration levels are compared with that in some well-known large and deep lakes around the world such as lakes Superior, Michigan, Huron [41], Malawi [42], and Zürich [43] (table S5). Nevertheless, the world has some other large and deep lakes (we only compared the Caspian Sea to the deep lakes since the eutrophication process influences deep lakes less than shallow lakes [44]) such as lakes Victoria [45] and Winnipeg [46] which have been more eutrophic than Caspian Sea (table S5). However, the findings show the peak of Chl-α concentration usually takes place during warm months. This can be attributed to: (i) upwelling, higher temperature, and light in the
summer season that provides more suitable environment for algae growth. Tuzhilkin and Kosarev [47] also reported upwelling occurrence in the east of the middle parts and southeast of the Caspian Sea that brings nutrient-rich cool waters to the surface with the potential to increase the Chl-α concentration. In addition, Ambrosimov et al [48] reported occasional observation of this phenomenon in summer months; and (ii) discharge of nutrients to the sea from natural and anthropogenic pollution sources. This finding is consistent with the reported observations of Kideys et al [16, 49], Bagheri et al [18], Roohi [50], and Kavak [51] in various parts of the Caspian Sea. Also, the northern parts of the Caspian Sea (which are generally shallower) have higher concentrations of Chl-α (up to 100 µg l⁻¹), due to being exposed to the discharge of nutrients from the Volga and Terek rivers (table S2). Some concerns about large pollution loads discharged to the Caspian Sea from the deltas of these two rivers were reported by
Figure 6. Spatial distribution of the TSI classes over Caspian Sea in (A) an annual time scale and (B) a seasonal time scale over the full study period.

Sur et al [11], Korshenko and Gul [12] and Kosarev [29]. It must be noted that the surface water circulation along the western and eastern coasts are usually southward and northward, respectively [11]. This circulation pattern in the Caspian Sea could potentially transport nutrient-rich water from Volga and Terek rivers to the south along the western coast as well as nutrient-rich and warm water from the south to the north along the eastern coast. Considering the high contribution of Volga River (about 240 km$^3$ yr$^{-1}$) to total water discharge into the Sea, variation in the river flow can also increase Chl-a concentration in the Caspian Sea [27]. The lowest variation of Chl-a was observed in the middle and southern areas that are far from the pollution plume of Volga, Ural, and Terek Rivers as well as the discharges of nutrient loads from populated areas in southern and middle coastal zones. In addition to the direct impact of pollution loads coming from agricultural and populated coastal zones (e.g. some parts of the Iranian shorelines as well as the coasts of Azerbaijan, Kazakhstan, and Turkmenistan), a long hydraulic residence time could be potentially a reason for the Chl-a variation in some areas such as Gorgan Bay (more than 100 d), in the southeast of Caspian Sea [38, 39]. Nevertheless, the study findings revealed that the Iranian coast moved away from being eutrophic after 2010.

One-third of the system’s energy was unexplained by the first four modes extracted by the POD model. This means that the obtained results did not fully represent the spatial patterns and temporal trends of
Chl-a over the Caspian Sea. For example, the spatial patterns of first four modes did not reflect high variations of Chl-a in the coasts of Baku in Azerbaijan (figure 4(A)). Also, the deep areas of the Caspian Sea (most of the sea area) are far from the coasts and the points of nutrient load discharges—the main stimuli of Chl-a. This may result in large gradients of Chl-a from the coasts to deep areas. Such large gradients could decrease the correlation between Chl-a data over the sea and reduce the suitability of POD model application [52, 53].

The study results reflect the increasing environmental degradation of the Caspian Sea. This can be exacerbated by climate change as well as the increasing economic developments in the Caspian Sea states. Climate change can increase the temperature and decrease precipitation in the region, both having the potential to boost eutrophication condition [54, 55]. Eutrophication would cause biodiversity losses, disrupts food chains, degrades ecosystem services, and accelerates global warming by increasing the emission of greenhouse gases (e.g. methane and nitrous oxide) from the sea [56, 57]. The domination of blue-green algae, deep water anoxia, macrophyte problems, algal scums, toxic byproducts, inverse effects on fishery industry and economic losses, ecosystem service decline, and reduced aesthetic enjoyment are among the other consequences of eutrophication [58, 59]. In addition, the continuation of aggressive urban, industrial, and agricultural developments in the coastal areas, which are accompanied by more water use and diversion, decreases the water discharge and potentially increases the nutrient concentrations in the river inflows to the sea.

The competitive use of Caspian Sea oil and gas resources in the absence an agreeable legal regime for governing the sea and its resources can create additional water quality-related challenges in the future. As the negotiations over the legal governance of this transboundary system continue, it is highly recommended that the Caspian Sea states establish effective measures for pollution control and monitoring. Future studies might consider estimating the contribution of each littoral state to the increasing nutrients in the Caspian Sea.

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Author contributions

A.M. and R.N. conceived the study conceptually and ran both statistical and POD models. R.N. and F.H. reconstructed the Chl-a data. A.H.E. and A.D.M. contributed with explanation of results. K.M. and B.K. supervised the investigation. A.M., R.N. and K.M. wrote the paper with input from all authors.

Data and materials availability

This study used data the Level 3 MODIS-Aqua Chl-a data available on the NASA website: https://oceancolor.gsfc.nasa.gov/atbd/chlor_a. Readers are referred to Dataset S1 to access the reconstructed Chl-a data.

Conflict of interest

The authors declare no conflicts of interest.

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Author contributions

A.M. and R.N. conceived the study conceptually and ran both statistical and POD models. R.N. and F.H. reconstructed the Chl-a data. A.H.E. and A.D.M. contributed with explanation of results. K.M. and B.K. supervised the investigation. A.M., R.N. and K.M. wrote the paper with input from all authors.

Data and materials availability

This study used data the Level 3 MODIS-Aqua Chl-a data available on the NASA website: https://oceancolor.gsfc.nasa.gov/atbd/chlor_a. Readers are referred to Dataset S1 to access the reconstructed Chl-a data.

Conflict of interest

The authors declare no conflicts of interest.

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