Satellite-Based Monitoring of the Algal Communities of Aras Dam Reservoir: Meteorological Dependence Analysis and the Footprint of COVID-19 Pandemic Lockdown on the Eutrophication Status

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Abstract
Aras Dam Lake is a strategic aquatic ecosystem in Iran and there are reports of toxic phytoplankton blooms in this reservoir. This study was performed to determine the effect of meteorological variables on the formation and expansion of toxic phytoplankton communities in Aras dam reservoir. The data of this project have been obtained using field studies and satellite data (MODIS and Sentinel-2). Sampling to determine the composition of phytoplankton communities in the area was carried out seasonally in two time periods from 2003 to 2014, and environmental assessments were also performed based on meteorological and satellite data over an 18-year period (2003–2020). The Chlorophyll-a content was obtained from MODIS and correlated with meteorological data. The statistical analysis showed that the highest coefficient of determination is related to the correlation of chlorophyll-a and Evaporation ($R^2 = 0.86$). Also, the relative root mean square error is equal to 18%, 18.1% and 21.2% for the chlorophyll-a -SST, chlorophyll-a -wind and chlorophyll-a -Evaporation relations, respectively. Moreover, in a supplementary study, correlation between the chlorophyll-a content with selected meteorological variables including evaporation, wind speed and water surface temperature were investigated seasonally. The results showed that the trend of changes in chlorophyll-a content with three considered variables are parabolic functions and chlorophyll-a -Evp ($R^2 = 0.86$, MAPE = 15.2%) model indicates better performance. The results also showed that the eutrophication rate of the reservoir during lockdown period increased in comparison with the same time at pre-pandemic period, which can be related to increase of incoming waste loads in this reservoir.

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Graphical Abstract

Article Highlights

- In the last decade, the development of toxic algal communities and dominance of Microcystis botrys Teiling has been observed in Aras Dam Lake.
- The effect of the main meteorological factors on phytoplankton populations of Aras Dam Lake is evaluated.
- MODIS and Sentinel-2/MSI data were used for satellite monitoring of water chlorophyll content.
- The trend changes of chlorophyll a content with Evaporation, wind speed and Sea Surface Temperature is parabolic functions.
- The changes in water environmental factors and meteorological variables can affect the distribution and diversity of phytoplankton communities.
- The eutrophication rate of the reservoir during COVID-19 pandemic lockdown increased in comparison with the same time at pre-pandemic period.

Keywords Phytoplankton community · COVID-19 · MODIS · Sentinel-2 · Meteorological variables · Microcystis botrys
Introduction

Phytoplankton are the autotrophic microorganisms with unicellular, filamentous, and colonial structure. These microorganisms are a key part of oceans, seas, and freshwater ecosystems. Some phytoplankton populations can release several forms of phycotoxins such as anatoxin, saxatxin, nodularin or microcystins (Yu et al. 2018; Caruana and Amzil 2018; Botana 2007). Microcystins are a class of cyclic heptapeptides produced by freshwater cyanobacteria such as *Microcystis* or some species of other genera including *Oscillatoria*, *Anabaena* and *Nostoc*. *Microcystis* is a freshwater or brackish water taxon, which some of the species are toxic. The most common toxic species within this genus are *M. aeruginosa* and *M. botrys* (Hallegraeff et al. 2003). *Microcystis botrys* Teiling is widely found in freshwater basin ecosystems such as dams, reservoirs and aquaculture ponds (Pham et al. 2015; Dao et al. 2010). This species is also found in slightly brackish waters (Komárek and Anagnostidis 1998; Hallegraeff et al. 2003; Tanabe et al. 2018). It should be noted that this cyanobacteria is one of the main phytoplankton species reported from Aras dam reservoir, as a strategic aquatic ecosystem in Iran, Azerbaijan and Armenia.

Increasing nutrient loading of the reservoirs and lakes coupled with year-round warm weather in recent years has tended to enhance the growth of toxic cyanobacteria and formation of harmful algal blooms (Pham et al. 2015). Blooms of this alga in aquatic ecosystems have ecological and economic importance. Cyanobacteria blooms may cause harmful conditions such as anoxia and the release of various toxins or bioactive peptides in natural habitats (Manach et al. 2018; Bui et al. 2018). Previous studies showed that the development of *Microcystis* communities in aquatic ecosystems and the presence of microcystins in food chain can affect aquatic animals’ health and aquatic production (Lehman et al. 2010). This hepatotoxin accumulates in aquatic animal tissues and disrupts the organs function including the hepatopancreas, heart, gill, kidney, intestine, and gonad (Chen et al. 2017).

Due to the damage caused by these photosynthetic microorganisms in an aquatic ecosystem, the study of factors affecting the formation of these algal blooms is inevitable. In previous studies, the physicochemical properties of water, especially parameters including phosphorus content of water, water column stability, surface water temperature and pH have been introduced as the main factors that were associated with the bloom formation of *Microcystis* (Imai 2009; Jacoby et al. 2000). Meteorological variables, like the physicochemical properties of water, are among the important factors that affect the occurrence of algal blooms (Elliott 2012; Reichwaldt and Ghadouani 2012). In other words, short-term fluctuations of this group of environmental variables are regarded as a determining factor in the occurrence and development of algal communities (Wu et al. 2013). The meteorological variables such as air temperature, rainfall, wind current, sunshine hours, light intensity, relative humidity and number of sunspots are the most important of these parameters (Elliott 2012; Reichwaldt and Ghadouani 2012; Zhang et al. 2012; Aghashariatmadary et al. 2017).

The meteorological variables have a key performance, especially when a warning system should be designed to predict the occurrence of algal blooms in drinking water sources and aquaculture ponds (Hu et al. 2009). Field and laboratory methods in algal blooms monitoring and controlling are regarded as difficult and time-consuming and fail in some cases. Therefore, alternative methods allow faster, broader, and more appropriate diagnosis. Algal blooms are detected initially with the help of optical methods because phytoplankton communities strongly affect the optical properties of natural waters and change their color when cell density increases. Thus, remote sensing of water color in aquatic ecosystems such as oceans and measuring the amount and quality of light reflected from the water surface is considered as a useful instrument for evaluating Harmful Algal Blooms (HABs) phenomenon. This method allows the monitoring of coastal waters on a regular and extensive basis and provides the ability to quickly detect the existence of HABs and the extent of their distribution (Schofield et al. 1999). Observing and monitoring the changes of algal blooms in the region are among the strengths of satellite technology. Timely imaging, using computer software, and utilizing meteorological models are among the new instruments used to predict the occurrence of this phenomenon. Generally, the algal blooms are detected in the region based on the images of moderate resolution imaging spectroradiometer (MODIS) sensors and by measuring the temperature of the water surface, chlorophyll-a, and dissolved oxygen. Different types of chlorophyll naturally occur in alga, but chlorophyll-a is predominant in cyanobacterial species (Assunção et al. 2022, Stumpf et al. 2003). It is necessary to mention that peripheral antenna complexes in light-harvesting systems of cyanobacteria lack chlorophyll-b and have other pigments such as phycobilins and carotenoids. Due to the importance of chlorophyll-a as a core antenna in light-harvesting systems of this group of alga, its assessment is used to estimate algal abundance and trophic status in aquatic ecosystems (Papenfus et al. 2020).

Limited information is available on the effect of meteorological variables on the growth of phytoplankton communities in Iran’s strategic water resources. Therefore, one of the main aims of this study is to investigate the effect of environmental conditions, with emphasis on the main meteorological factors, on phytoplankton populations and dominant taxa in Aras dam reservoir using satellite data and field studies. In a more comprehensive study, the impact of meteorological variables on development of phytoplankton communities...
in Aras dam reservoir was assessed over an 18-year period (2003–2020). This research also seeks to address a question that, since the declaration of lockdown in the COVID-19 time period, did the water quality of Aras dam reservoir improved? Therefore, one of the aims this work was to analyze the phytoplankton communities response (using chlorophyll-a concentrations) to environmental and social changes due to the COVID-19 time period in this aquatic ecosystem. We expect that results of present study contribute to a better understanding the behavior of the dominant phytoplankton in aquatic ecosystems for efficient management of water resources, with emphasis on freshwater resources.

Materials and Methods

Study Area and Water Sampling Procedure in Field Study

The Aras is a river in the Caspian Sea basin, between Iran and both Azerbaijan and Armenia. Its maximum capacity is 1350 × 10^6 m^3, mean depth is 20 m., and covering an area of 153 square kilometers (Mohebbi et al. 2015). This freshwater reservoir provides irrigation water in agriculture and is also considered as an important source of urban drinking water in northwestern Iran.

In the present study, water sampling was conducted in two time periods with an interval of 6 years (August 2007–May 2008 and August 2013–May 2014). The statistical method to select the studied sites was randomly by using longitudinal transects. The stations were selected at a distance of at least 50 m from the shore to avoid mixing the sample with benthic species and algal masses accumulated by the wind. Typically, in aquatic habitats with more or less uniform conditions such as lakes, at least three stations are regarded for the study (Mohebbi et al. 2015). In the present study, three stations were considered and sampling was conducted seasonally along the main body of the dam (Fig. 1). The studied sites were chosen in different parts of the lake including dam entrance (Ghanbar Kandi Station), middle of the lake (Secheshme station), and dam exit (Dam crest station). Specifications of sampling stations are shown in Table 1.

In the field study, water sampling was performed seasonally using a Ruttner-type sampler. For this purpose equal water volumes were taken at the water surface, and the three and five meter depths. Water samples of each site which collected from several depths were combined and immediately fixed with 4% formaldehyde solution.

Table 1 Characteristics of sampling sites in Aras dam reservoir

| Site no | Name of sampling site | Longitude   | Latitude    |
|---------|-----------------------|-------------|-------------|
| 1       | Ghanbar Kandi         | 45° 17' 02" E | 39° 10' 32" N |
| 2       | Secheshme             | 45° 18' 27" E | 39° 10' 52" N |
| 3       | Dam Crest             | 45° 22' 14" E | 39° 07' 33" N |

Fig. 1 The Aras dam reservoir and sampling sites locations. (Site 1. Ghanbar kandi, Site 2. Secheshme, Site 3. Dam crest)
Meteorological Variables

The meteorological variables were received from Jolfa synoptic station (latitude 30.25 °N, longitude 56.97 °E) as the nearest station to the sampling sites on a daily scale for 2003–2020 period from the Iran Meteorological Organization. This data included precipitation (mm), air temperature (°C), wind speed (m/s), number of sunshine hours, and evaporation rate (mm/day). The relationship of which with total chlorophyll content of water, water surface temperature, and the frequency of phytoplankton communities were assessed using statistical methods. Data quality control was performed with high accuracy. The influence of meteorological conditions on algal density was investigated by model construction. For this order, multiple stepwise regression analysis was performed and the best subset was selected. The correlation of each meteorological variable and their best subset were tested by Statistica12 and the solver toolbox of Microsoft excel. These tools were used to analyze the relationships between algal density and meteorological variables.

Satellite Imagery

MODIS Data

In this study, MODIS sensor data of Aqua satellite were used for satellite monitoring of water chlorophyll content on a daily scale for 2003–2020 period. MODIS sensor was utilized in present study due to its appropriate accuracy and greater efficiency of its data with a spatial resolution of 1 km on a daily scale. The data were collected through the ocean color section of US Space Agency (NASA) Website (http://modis.gsfc.nasa.gov). SeaDAS 7.4 (SeaWiFS Data Analysis System) was implemented to extract the data, the output of which included algorithms for estimating chlorophyll-a, sea surface temperature (SST), salinity and the like. SST data can be used to interpret the water surface temperature, and biological activity that happened in the ocean.

Sentinel-2 Data

The high spatial and temporal-resolution observations from the Sentinel-2 MSI were also used in this study. Using Google earth engine (GEE), Surface water region and seasonal chlorophyll-a concentration maps of Aras Dam reservoir extracted based on four bands at 10 m (B03 = 560 nm, B04 = 665 nm, B05 = 704 nm, B08 = 835 nm) of Sentinel-2 Level-2A product with a Collection ID of “COPERNICUS/S2_SR”. Surface water region and chlorophyll-a concentration draw out based on Normalized Difference Water Index (NDWI) and Normalized Difference Chlorophyll Index (NDCI). NDWI index uses green and near infrared bands to determine water bodies. This index can be computed by Eq. 1 (McFeeters 1996).

\[
NDWI = \frac{B03 - B08}{B03 + B08}
\]  

(1)

To achieve the chlorophyll-a (Chl-a) values the model suggested by Watanabe (2019) was used the Eq. 2.

\[
Chl-a = 1093.2 \times NDCI^2 + 283.4 \times NDCI + 25.947
\]  

(2)

In which NDCI = (B05-B04)/(B05 + B04) that is proposed by Mishra and Mishra (2012).

Identification of Phytoplankton Taxa

Taxonomic study of phytoplankton taxa was carried out by morphometric study of them with light microscopy, by

Fig. 2  a Immature colony of *Microcystis botrys*; b Chemical structure of microcystin-LR
preparing semi-permanent slides, and based on Wehr et al. (2002), John et al. (2002), and Komárek and Anagnostidis (1998). The vegetative and reproductive characters used in the taxonomic determination were selected based on specific descriptions of genera and species. The dominant taxon of this aquatic ecosystem or Microcystis botrys was also identified based on key characteristics. The most important diagnostic features of this species are the following: colonies are microscopic and more or less spherical, with cells that are irregularly and very densely aggregated in mucilaginous, spherical groups (Fig. 2); Cells are spherical, with blue-green or greyish content and several aerotopes (Komárek and Anagnostidis 1998).

Enumeration of Phytoplankton

Enumeration of phytoplankton populations was performed according to the procedure described by Andersen (2005). The Utermöhl sedimentation chamber was used for this purpose. For that, water samples were concentrated or diluted depending on the initial cell density, thoroughly mixed by gently shaking the sample bottles and sub-samples were transferred to the 5-mL Utermöhl sedimentation chamber. When the cells have settled to the bottom of the chamber, they were counted and identified using a Nikon TS100 inverted microscope. The number of cells per milliliter (C) was calculated by Eqs. (3) and (4) that is presented by Hötzel and Croome (1999).

\[ C = \text{Cells counted} / \text{Concentration factor, for a concentrated sample} \]  
\[ C = \text{Cells counted} \times \text{Concentration factor, for a diluted sample} \]  

Performance Evaluation Indices

There are various error indicators used to compare and assess the performance of models. In this research, to evaluate the performance of models against measured data, the most-routinely used indices including coefficient of determination \( R^2 \), the Mean Bias Error (MBE), the Mean Absolute Percentage Error (MAPE), the Mean Absolute Error (MAE), the Root Mean Square Error (RMSE) and the Relative Root Mean Square Error (RRMSE) were used. These indices are calculated by Eqs. (5) to (10) as the following.

\[ \text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (O_i - P_i)^2} \]  
\[ MBE = \frac{1}{n} \sum_{i=1}^{n} (O_i - P_i) \]  
\[ R^2 = 1 - \frac{\text{RMSE}^2}{\sigma^2} \]  
\[ \text{MAE} = \frac{1}{n} \sum_{i=1}^{n} |O_i - P_i| \]  
\[ \text{RRMSE} = \frac{\sqrt{\frac{1}{n} \sum_{i=1}^{n} (O_i - P_i)^2}}{\frac{1}{n} \sum_{i=1}^{n} P_i} \times 100 \]  
\[ \text{MAPE} = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{O_i - P_i}{O_i} \right| \times 100 \]  

In which \( P_i \) and \( O_i \) respectively denotes the calculated and observed values of daily global solar radiation, \( \sigma \) is the standard deviation, and \( n \) is the number of the data pairs. The RMSE is an index of random errors that demonstrates some information on the regression short-term efficiency. Knowing the values of MAE and RMSE is important because they indicate the inaccuracy of the considered variables. The values close to 1 in \( R^2 \) show the better perfect fit and performance of the model, which is contrariwise about RMSE and MAE indices. The MAPE is similar to the MAE but each difference between observed and predicted values is divided by the observed data. Moreover, the RRMSE is defined by dividing the RMSE to the observed average values. Different ranges of this index are used to specify the validity of the models such as poor for RRMSE > 30%, fair for 20% < RRMSE < 30%, good for 10% < RRMSE < 20% and excellent for RRMSE < 10% (Deo et al. 2018). The MAPE represents the mean absolute percentage difference between the calculated and observed data.

Results

Evaluation of the Algal Frequency and Biodiversity

In the field study, the biodiversity and frequency of taxa in phytoplankton communities were investigated. Also, different stations were compared in terms of biodiversity and frequency of taxa. The identified taxa in the studied sites belonged to several groups including Chlorophyta, Cyanophyta (Cyanobacteria) and Bacillariophyta (Diatoms). According to the results, dominant taxa in the first time period of study (August 2007–May 2008), varied depending on the season and site location. More precisely, diatoms
were dominant in most studied stations in spring, autumn and winter, while cyanobacterial communities were dominant in summer (Fig 3). However, in middle of the lake or Secheshme station, diatoms were dominant only in winter and cyanobacteria formed dominant communities in warmer seasons of the year. The results also showed that in the second time period of study (August 2013–May 2014), cyanobacteria were the dominant communities in all seasons and
sites. In other words, we saw the dominance of cyanobacterial communities in the second study period instead of diatom communities in Aras dam reservoir. According to the results, cyanobacteria showed a higher cell density in the warm seasons of the year and maximum density is observed in the summer.

It can be said that cyanobacteria and their population changes over time have been very important in this strategic aquatic ecosystem. In other words, the key role of this algal group in long-term environmental changes has been proven in this study. So, the dominant cyanobacterial species and their abundance in studied sites, in a specific period of time, were investigated. According to the results, the dominant cyanobacterial taxa in this lake were *Oscillatoria* and *Microcystis* genera, which eventually changed to *Microcystis botrys* communities in time 2 (August 2013–May 2014). This species is one of the toxic taxa and have a great ecological importance (Fig 2). Comparison between *Microcystis* cell abundance in these two time periods indicates a significant increase of cell abundance in time 2 (August 2013–May 2014). This increase was observed in all seasons and all studied sites (Fig 4).

### Evaluating the Effect of Meteorological Variables and Water Surface Temperature on Chlorophyll Content

In the present study, the amount of chlorophyll-a was regarded as a dependent variable. In addition, water surface temperature and meteorological variables including wind speed, average air temperature, maximum air temperature, precipitation, sunshine hours, and evaporation rate were considered as independent variables. The effects of each independent variable on Chlorophyll content is presented in Table 2. In the Table, the proposed relationships and their statistical error indices are also inserted. Figure 5 shows the comparison between the values of observed chlorophyll-a and calculated from proposed relationships in Table 2. As shown, only the chlorophyll-a -Wind, chlorophyll-a -SST and chlorophyll-a –Evaporation models have little scattering of points around the regression line. The highest scatter

| Table 2 | Statistical analysis indices |
|---------|----------------------------|
| Proposed relationship | RRMSE% | RMSE (mg/m³) | MBE (mg/m³) | $t$ | $R^2$ | MAPE (%) | MAE (mg/m³) |
| Chl-a = 0.49SST + 0.16 | 18.00 | 1.47 | 0.01 | 0.02 | 0.82 | 16.15 | 1.31 |
| Chl-a = 1.96Wind + 3.15 | 18.10 | 1.48 | 0.18 | 0.32 | 0.83 | 14.44 | 1.17 |
| Chl-a = 0.28Tmean + 3.86 | 25.00 | 1.99 | 0.07 | 0.088 | 0.68 | 18.93 | 1.53 |
| Chl-a = 0.267Tmax + 2.41 | 26.00 | 2.10 | -0.005 | 0.006 | 0.64 | 20.16 | 1.63 |
| Chl-a = 0.56Evaporation + 4.24 | 21.20 | 1.72 | -0.09 | 0.146 | 0.76 | 14.72 | 1.19 |
| Chl-a = 1.15SST - 2.20 | 31.00 | 2.49 | -0.04 | 0.042 | 0.50 | 25.70 | 2.08 |
| Chl-a = -8.7Precipitation + 10.40 | 39.00 | 3.16 | -0.05 | 0.04 | 0.20 | 33.42 | 2.70 |
Fig. 5 Scatter plot of observed (satellite derived) versus calculated (model estimation) chlorophyll-a for different proposed relationships in Table 2
Seasonal Trend Analysis of Meteorological Variables and Chlorophyll-a

All meteorological variables used in this study were analyzed for the no-trend (against trend) hypothesis in their seasonal and annual time series. Table 3 summarizes the results of the non-parametric Mann–Kendall (MK) test. As seen in the table, both seasonal and annual series of the four variables precipitation, evaporation, sunshine hours, and wind speed have shown no significant temporal trend in the 5% significance level. The MK test identified the significant positive trends in annual mean air temperature and autumn chlorophyll-a at the 5% significance level. These two variables have not shown any significant trend in other time scales. Due to limited cases of significant trend in data, it can be concluded that the study area has not been undergone the impacts of climate change.

Table 3 The seasonal and annual trend analysis of meteorological variables using the non-parametric Mann–Kendall test (z and p value indicate the statistic and the corresponding significance level of the Mann–Kendall test)

| Time Scale | Mean air temperature | Precipitation | Evaporation | Sunshine hours | Wind speed | Chlorophyll-a | SST |
|------------|----------------------|---------------|-------------|----------------|------------|---------------|-----|
|            | z  | p value   | z  | p value   | z  | p value   | z  | p value   | z  | p value   |
| Spring     | 1.59 | 0.112     | −1.74 | 0.081     | 0.53 | 0.173     | 0.30 | 0.762     | 0.00 | 1.000     | 0.04 | 1.000     | 1.82 | 0.032     |
| Summer     | 0.68 | 0.495     | −1.44 | 0.150     | 0.00 | 1.000     | −0.30 | 0.762     | −1.82 | 0.069     | −0.30 | 0.750     | 1.14 | 0.596     |
| Autumn     | 0.83 | 0.405     | 0.23 | 0.820     | 1.14 | 0.596     | −0.38 | 0.705     | 0.30 | 0.762     | 2.16 | 0.026     | 0.64 | 0.510     |
| Winter     | 1.59 | 0.112     | 0.00 | 1.000     | −0.30 | 0.762     | 0.00 | 1.000     | 0.34 | 0.725     | 1.29 | 0.263     |
| Annual     | 2.42 | 0.015*    | −1.44 | 0.150     | 1.36 | 0.225     | −0.08 | 0.940     | 0.00 | 1.000     | 0.34 | 0.725     | 1.29 | 0.263     |

aData are unavailable. Winter evaporation is too low to be measured in the study area

*Significant trend in the 5% significance level

Fig. 6 Surface and 3D plot of chlorophyll-a variations with: a Evaporation and Wind speed and b Evaporation and sea surface temperature (2003–2020)
The Effect of Evaporation, Wind Speed and Water Surface Temperature on Chlorophyll-a Content in Long Term Scale

In next step, to examine more accurately development pattern of phytoplankton communities and their relation to selected meteorological variables, correlation between the chlorophyll-a content in the lake with evaporation, wind speed and water surface temperature were investigated seasonally over the period 2003–2020. As seen in Fig. 6, with increasing wind speed and evaporation, the chlorophyll-a content has significantly increased; moreover the lowest amount of chlorophyll-a occurs at low wind speeds and particularly at low values of evaporation. Also, with increasing water surface temperature and evaporation, the chlorophyll-a content has significantly increased; moreover the lowest amount of chlorophyll-a occurs at low temperatures and particularly at low values of evaporation.

According to the results of long term statistical analysis presented in Table 4 and Fig. 7, the trend of changes in chlorophyll-a content with three considered variables are parabolic functions. The Chl-SST model is applicable for range of 8.6 ≤ SST ≤ 30.4, The Chl-Wind is applicable for range of 0.54 ≤ Wind ≤ 4.94 while the Chl-Evp model is applicable for range of 2.63 ≤ Evp ≤ 14.96. As reported in Table 4, the RRMSE of the Chl-Evp model is 18% (good performance), while the rate of this measure for the Chl-SST model is 25% (fair performance) and for the Chl-Wind model is 23% (fair performance). Moreover t, $R^2$ and MAPE indices of three models, Chl-Wind ($t = 0.66$, $R^2 = 0.72$, MAPE = 17.6%), Chl-SST ($t = 0.03$, $R^2 = 0.74$, MAPE = 17.5%) and Chl-Evp ($t = 0.06$, $R^2 = 0.86$, MAPE = 15.2%) indicates better performance of the Chl-Evp model. Therefore, using the measured amount of evaporation, a good estimation of chlorophyll-a content is possible and thus the algal bloom of the study area can be determined (Aras Dam Lake).

Trophic Classification of Reservoir Before and After Lockdown

The satellite based values of chlorophyll-a in Aras dam reservoir were analyzed to investigate the impact of COVID-19 lockdown on algal bloom status in this aquatic ecosystem. For this purpose, the seasonal concentrations of chlorophyll-a compared for two consecutive time period including the average of 17 years before the start of the COVID-19 (2003–2019) and 1 year during the lockdown and restriction period (2020). The comparison of chlorophyll-a levels of water shows that the chlorophyll-a increase in all seasons of 2020 in comparison with the past 17 years seasonal averages (2003–2019). It should be noted that the highest increase in chlorophyll-a concentration in comparison with the 17-year average is related to autumn, which showed a relative percentage deviation (RPD) of 124%. In other words, the chlorophyll-a concentration increased from 7.19 mg.m$^{-3}$ for 17-year average (before lockdown) to 16.08 mg.m$^{-3}$ in autumn 2020 that’s in the pandemic restrictions period (after the partial lockdown). The RPD of chlorophyll-a increased by 21% and 85.5% in spring and winter, respectively and the lowest amount of seasonal chlorophyll-a concentration increase was related to summer by 11.5% during summer 2020 in comparison with a same time of 2003–2018 period (17 years before the COVID-19 pandemic restrictions).

Furthermore, trophic classification of reservoir in this time period was studied based on the methodology used by the Environmental Company of S‘ao Paulo (CETESB, 2017). Chlorophyll-a concentration ranges under different trophic conditions of aquatic ecosystems according to this method includes Ultraoligotrophic for Chl - a ≤ 1.17 (mg.m$^{-3}$), Oligotrophic for 1.17 < Chl - a ≤ 3.24 (mg.m$^{-3}$), Mesotrophic for 3.24 < Chl - a ≤ 11.03 (mg.m$^{-3}$), Eutrophic for 11.03 < Chl - a ≤ 30.55 (mg.m$^{-3}$), Supereutrophic for 30.55 < Chl - a ≤ 69.05 (mg.m$^{-3}$) and Hypereutrophic for 69.05 < Chl - a . The trophic classification of Aras dam reservoir according to this index (Fig. 8) indicated that this aquatic ecosystem was classified as Mesotrophic in winter and spring of (2003–2019) and 2020, but an increasing trend in turbidity and Chl-a concentration of reservoir water after the COVID-19 lockdown is noticeable. According to the results, the trophic classification of reservoir in autumn and summer is obviously shift from Mesotrophic in the past 17 years seasonal averages (2003–2019) to the Eutrophic condition in the pandemic restrictions period (2020).

The chlorophyll-a content of Aras dam reservoir was also estimated based on processing the Sentinel 2/MSI images (Fig. 9). According to the achieved maps, the Aras dam reservoir shows relatively high spatio-temporal variations of...
chlorophyll-a over the study time period. When comparing winter 2020 (pre-lockdown) and spring 2020 (through the partial lockdown) maps, reservoir showed a notable increase of mean seasonal chlorophyll-a concentration in spring.

Results showed that the highest chlorophyll-a concentrations occurred through summer 2020 and the lowest in winter 2020. The highest spatio-temporal reduction of chlorophyll-a concentrations was also observed in autumn 2020 that the chlorophyll-a content showing a decreasing trend after the partial lockdown. The results also show that the levels of chlorophyll-a in the winter of 2020 (pre-lockdown) are much lower than in the winter of 2021.

Discussion

Phytoplankton communities and their composition can be considered as an indicator of short and long-term environmental developments in aquatic ecosystems. Long-term environmental protection and maintaining water resources health requires a proper understanding of the factors affecting the development of algal blooms (Wongsai and Luo 2007). Therefore, significant efforts have been made worldwide to identify effective environmental factors for better management of freshwater resources. Although, numerous models have indicated that biotic agents can be considered as the final controllers of phytoplankton abundance in aquatic ecosystems, in another investigations abiotic factors are introduced as the main factors affecting phytoplankton diversity and abundance (Norén et al. 1999; Schabhüttl et al. 2013; Rasconi et al. 2017). Among environmental factors, weather conditions have been suggested as an important factor affecting phytoplankton communities and chlorophyll content of water resources. So, the effect of some meteorological variables on the chlorophyll-a content of Aras Lake Reservoir was investigated in this study. The results indicate a significant increase in total content of chlorophyll-a in the warm seasons of the year. According to the results, meteorological variables such as wind speed, sea surface temperature (SST) and evaporation had major role in expansion of algal communities and total content of chlorophyll-a in studied sites.

It can be said that temperature is the meteorological variable that introduced as an effective factor for phytoplankton's population growth. The effect of this factor on the growth of algal communities can be the result of the impact of temperature on biological mechanisms such as photosynthesis and reproduction. Based on the results, meteorological variables such as wind speed, sea surface temperature (SST) and evaporation had major role in expansion of algal communities and total content of chlorophyll-a in studied sites.

Results of the present study also show a positive correlation between sea surface temperature and chlorophyll-a content of water reservoir (Chl = 0.026SST^2 − 0.53SST + 7.87).

Our results confirm previous reports and importance of temperature in development of some phytoplankton communities and dominance of some species in special environmental conditions (Ke et al. 2006; Abrantes et al. 2008). In recent years, cyanobacteria have been introduced as the
dominant algal communities in the Aras dam lake (Mohebbi et al. 2015). Our observations also showed that cyanobacteria was the dominant phytoplankton group in this aquatic ecosystem and bloom of their toxic specimens, such as Microcystis botrys, has been observed many times in Aras dam lake. The results also show the development of cyanobacterial communities in this aquatic ecosystem, especially in summer and early autumn.

According to previous studies, many cyanobacterial genera grow optimally at 25 °C, and exhibit bloom potentials at relatively high water temperatures (Reynolds 2006; Paerl and Otten 2013). Cyanobacterial bloom is among the most common and serious forms of algal blooms in freshwater ecosystems, and in many cases are harmful to aquatic life (Zamyadi et al. 2012; Bartram and Chorus 1999). The water hypoxia and producing a variety of toxic secondary metabolites are the most important disorders that can be expected from some cyanobacterial blooms in their habitats (Funari & Testai 2008; Paerl and Otten 2013; Patterson and Larsen 1994). In addition, some cyanobacterial blooms such as Microcystis blooms, may have a direct negative impact on diatoms and green algae due to allelopathy (Wang et al. 2016).

Both internal factors such as nutrients and water temperature, and external ones such as air temperature, solar radiation, and wind speed and direction can play a significant role in developing the cyanobacterial bloom (Howard 1994). According to available reports, rising water temperature due to climate change lead to cyanobacterial bloom occurrence in temperate and semi-arid regions (Wu et al. 2014; Bui et al. 2018; Zhang et al. 2012; Wagner and Adrian 2009). Elliott (2012) examined the effect of climate change on the freshwater cyanobacteria in some lakes in the United Kingdom, Sudan, and New Zealand. Results of this study showed that the temperature seriously affects the phytoplankton communities, especially cyanobacterial populations. Lehman et al (2017) also confirmed this fact and reported strongly correlation between water temperature, Microcystis cell abundance and microcystin concentration in Sane Francisco Estuary, California.

The dominance of these prokaryotic microorganisms in algal communities has several reasons, including: increase growth rates of cyanobacteria at elevated temperature (O’Neil et al. 2012; Jöhnk et al. 2008); their ability to competitively proliferate at high temperature (Litchman et al. 2010); increased cells and filaments buoyancy due to the presence of gas vesicles that cause cyanobacterial communities to be concentrated in the surface layer of water (You et al. 2018). Previous studies also showed that warming can promote the growth rate and bloom formation of some strains of Microcystis. Bui et al. (2018) confirmed this hypothesis and showed that the biomass of Microcystis tropical species has increased at 31 °C compared to 27 °C. Synergism between temperature and nutrients in eutrophic and hyper-eutrophic lakes, as well as warming-enhanced nutrient loading in this condition can also intensify Microcystis blooms. Increasing temperature and reducing vertical mixing of water also provide more stable environments for this taxa and algal bloom formation (Livingstone 2003). Investigating spatio-temporal diversity of phytoplankton groups in a shallow eutrophic lake from arid regions also indicated that high amounts of nutrients, high temperatures, and heavy rainfall cause spatial changes in phytoplankton communities during the wet season (Jin et al. 2020).

The salinity of water is also an important factor affecting the cell density of phytoplankton in an aquatic ecosystem. Several factors can affect concentration of salts and salinity of water in aquatic ecosystems including: evaporation rate of
water, amount of incoming water and annual rainfall, as well as existence of salt domes. So, decreasing the annual rainfall and increasing evaporation will increase the concentration of water solutes, and it can change the type and abundance of taxa in phytoplankton communities. According to the results of this study and statistical analysis, evaporation is one of the main factors that can affect phytoplankton’s abundance and plays a key role in development of algal blooms in Aras Dam Lake (Table 4). The achieved equation (Chl-a = 0.18Evp² - 2.32Evp + 12.10) indicated that these relation was a

Fig. 9  Aras Dam Lake maps indicating the seasonal average of chlorophyll-a concentration (mg.m⁻³) estimated from Sentinel 2 images
parabolic function of Evaporation (Evp). The simplest function of evaporation is to affect the concentration of solutes in water and to change the species composition in water microflora. In these environmental conditions, algal species with high salinity tolerance have the possibility of survival and further expansion in aquatic ecosystems. Some species of *Microcystis* are resistant to salinity and able to expand into brackish and marine water environments (Robson and Hamilton 2003). According to some available reports, these bloom forming taxa at elevated water temperature and during drought is more successful in competing with other cyanobacteria (Lehman et al. 2017).

Wind is another meteorological factor that can increase the evaporation rate and water salinity. The water trophic status, water stratification and nutrient are also affected by wind speed variations. The water column mixing can accelerate with increasing wind speed and provides the nutrients to the phytoplankton communities (Alcântara et al. 2010; Morais et al. 2010; Liu et al 2014). The achieved equation in our study (Chl-a = 1.32wind² − 4.4wind + 8.94) also indicated that these relation was a parabolic function of wind speed.

In addition to meteorological factors, the water trophic status has been introduced as an important environmental factor affecting cyanobacterial communities. Affan et al (2016) emphasized that natural blooms of *Microcystis* spp. are typically controlled by trophic condition and nutrient concentrations of water. Therefore, by enriching surface water with nutrients, especially phosphate and nitrate compounds, the phytoplankton community shifts towards the dominance of cyanobacteria (Paerl and Huisman 2008; Davis et al. 2009). One of the major sources of nitrate and phosphate pollution in surface water is municipal wastewater and detergents. According to available reports, COVID-19 pandemic restrictions and partial quarantine in urban and rural settings were associated with municipal wastewater loading rates increase into many freshwater ecosystems, and changing phytoplankton communities (Alcântara et al. 2021; Teta et al. 2021; Haghnezar et al. 2022). It is necessary to mention that the periodic algae blooming are strongly related to the increased inlet flows of the residential sewage from the surrounding catchments, and the liquid waste discharge can increase phytoplankton communities’ development (Al-Yamani et al. 2020).

According to some protocols from the world’s scientific communities, hands washing with soap and water during COVID-19 pandemic is the most important and easiest ways to prevent the spread of the disease but this has adverse effects on water and soil health and quality (UNICEF 2020). According to Iran Ministry of Industry and Trade, the production of detergents and the rate of household water consumption increased during lockdown. Haghnezar et al. (2022) showed that the contribution of both municipal wastewater and weathering in water pollution of Zarjoub river located in north of Iran increased from 23 to 50% during the COVID-19 pandemic lockdown. In other study Feizizadeh et al. (2021) showed that the domestic water use in Tabriz increased up to 17.57% during the year 2020 with the maximum increasing in lockdown period in spring 2020 (April-June).

Considering the changing pattern of detergents production and consumption during COVID-19 pandemic and according to proven impact of these compounds on algal communities, in this study the effect of COVID-19 pandemic restrictions and partial lockdown on algal bloom development was investigated in Aras Reservoir. To this purpose, we analyzed the mean seasonal concentrations of MODIS derived chlorophyll-a for 2018–2020 years in Aras Dam Lake. The Aras Reservoir is a transboundary river basin flows from Turkey to the Caspian Sea along the international borders between Iran, Azerbaijan and Armenia (Khosnoodmotlagh et al. 2020). This international river supplies daily water use include drinking, agriculture and industry of eight million people and receives part of the region’s domestic, municipal and agricultural sewage. In present study, we analyzed the mean seasonal concentrations of MODIS derived chlorophyll-a for 2018–2020 years in Aras Dam Lake. According to the results, an increasing trend in turbidity and Chl-a concentration of reservoir water after the COVID-19 lockdown was noticeable.

Since March 2020, partial lockdown was performed due to the coronavirus pandemic and population were restricted to their homes and stop common daily activities such as agricultural, commercial and entertainment activities. These limitations reduced insecticides, herbicides, and fungicides consumption that used in farms, reduced activity of fishers, reduced chemical effluents of factories and the rate of tourism transportation (Teta et al. 2021). The cutout of discharges from industries, aquatic transport systems and tourism, accelerated the growth of phytoplankton communities because of the removal of stress posed by toxic pollution from point and nonpoint sources. It should be noted that the negative effect of these pollutants on the algal communities has been reported in previous studies (Staley et al. 2015).

According to the Iranian Ministry of Health report, by noon of May 25, 2022 the total number of people infected with the COVID-19 reached 7,230,882 and the number of deaths reached 141,293. Due to the high rate of the outbreak, lockdown, and minor restrictions were imposed across the country. It should be noted that while partial lockdown and minor restrictions were imposed across Iran, in many countries of the world there was full nationwide quarantine and severe restrictions. The comparison between the images from spring of 2020 and spring 2021 showed that there was a significant increase in the Chl-a concentration in reservoir during lockdown (spring 2020) (Fig. 9). Similar conditions were reported by Alcantara et al. (2021). They indicate that...
During the lockdown, cyanobacteria blooms in the water surface increased due to the increasing discharge of domestic sewage. It is worth noting that domestic wastewater is an important source of nitrate and phosphate pollutants in aquatic ecosystems.

During the lockdown period, the highest amount of increase occurred in autumn that the chlorophyll-a concentration increased from 7.19 mg.m\(^{-3}\) for 17-year average (before lockdown) to 16.08 mg.m\(^{-3}\) in autumn 2020 that’s immediately after the partial lockdown period and health care and detergent entry into surface streams continue. As well, the chlorophyll-a concentration increased from 14.09 mg.m\(^{-3}\) for 17-year average to 15.70 mg.m\(^{-3}\) (during lockdown) in summer. The results revealed that the seasonal development of algal communities in Aras dam reservoir increased. In addition, according to the mentioned CET-ESB (2017) ranges, calculated trophic status of Aras dam reservoir showed that the eutrophication during lockdown period especially in summer and autumn 2020 increased in comparison with the same seasons at the past 17 years seasonal averages of pre-pandemic period (2003–2019). Part of this increase, can be due to COVID-19 restrictions and lockdown. In other words, this increase can be due to the increase of incoming sanitary sewers loads and major nutrition for algal bloom and reduction of the load of pollution sources’ stress induced by human activities such as industrial sewage, water transport system, and tourism.

The chlorophyll-a concentration estimated by sentinel 2 showed the development of phytoplankton communities in the reservoir. The comparison between the image from spring of 2020 (during lockdown period) and spring 2021 (one year after lockdown) indicated that there was an obvious reduction of chlorophyll-a concentrations in the spring of 2021 (Fig. 9). In other words, phytoplankton blooms increased during the lockdown that can be due to the cutout the discharge from the stress sources in aquatic ecosystems such as water transport systems, tourism and industries and reduce the load of pollution sources’ stress. A same effect has been reported by Alcantara (2021). With respect to the shift of the cyanobacteria blooms to the potentially toxic species in this reservoir and increasing of the residential water supply during the COVID-19 pandemic period, there are a major concern about the public and environmental health.

**Conclusion**

Today, environmental pollution, their sources, and the methods of controlling pollution in nature play a significant role in leading research paths. Algal bloom in aquatic ecosystems has been introduced as one of the most harmful and important environmental phenomena in recent decades. The results obtained from this study elucidated the correlation between the chlorophyll-a content with selected meteorological variables including evaporation, wind speed and water surface temperature. The results also showed that sea surface temperature and evaporation in the summer usually cause cyanobacteria to bloom in Aras dam reservoir. Also in this research the dam reservoir changes of trophic states during Covid-19 pandemic was analyzed. Results showed that the algal blooming increased under the influence of conditions caused by social, industrial and commercial restrictions in comparison with the same period in Aras dam reservoir. In addition results indicated that the eutrophication during COVID-19 lockdown period increased in comparison with the same time at pre-pandemic period due to the increase of incoming sanitary sewers loads and major nutrition for algal bloom of the time at pre-lockdown reservoir.

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**Declarations**

**Conflict of Interest** All authors declare that they have no conflict of interest.

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