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Examining global trends of satellite-derived water quality variables in shallow lakes

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ABSTRACT

Lakes are a vital resource for freshwater supply and key sentinels of climate change, and it is projected that global warming will more persistently affect hydrology, nutrient cycling and biodiversity. In this context, shallow lakes are considered particularly sensitive to a changing environment and it is essential to acknowledge their water quality conditions and recent trends to guide effective water resource management and mitigation strategies. The European Space Agency Climate Change Initiative (ESA-CCI) offers globally consistent satellite observations of the Lakes Essential Climate Variable (ECV) including satellite products such as chlorophyll-a (Chl-a), turbidity and surface water temperature (LSWT) for over 2000 lakes during 1992–2020. From this dataset, we extracted a subset of 347 lakes with mean depth $\leq$ 3 m distributed globally to investigate a long-term timeseries (2002–2020) for Chl-a and turbidity. Theil-Sen trend analysis showed that Chl-a did not change significantly in 33 % of lakes, significantly increased in 45 % and decreased in 22 % of the lakes, while turbidity significantly increased in 60 % and decreased in 17 % of lakes. Most lakes with increasing Chl-a and turbidity trends were located in lowland areas, and had relatively large areas (surface area >50 km^2). Further analysis revealed that the majority of lakes showed a concurrent increase in both Chl-a (48 %) and turbidity (50 %) with LSWT, indicating the potential influence of climate warming on lake water quality. A structural equations model-based analysis used for modelling the interactions between climatic, socioeconomic features and water conditions overall showed that Chl-a and turbidity had a concurrent positive increase with population and gross regional product in most lakes. This finding suggests that the impact of human population growth in lake catchments represents an important factor driving pressures on the water quality of shallow lakes.

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1. Introduction

Lakes are a vital freshwater resource, storing around 87 % of liquid surface freshwater on Earth (Messager et al., 2016), they are considered sentinels of climate change and integrators of anthropogenic pressures upon their catchments. Climate change has an important influence on global biodiversity in lakes and has been listed as the third most important driver after invasive species and land-use change (Sala et al., 2000), with projections indicating that the next decades will experience more persistent and stronger effects on lake hydrology and nutrient cycling (Parmesan et al., 2022; Shuvo et al., 2021).

Shallow lakes represent a prominent part of inland waters, providing significant contributions to biodiversity and delivering many ecosystem services linked to sustainable development goals (Janssen et al., 2021). Because of their relatively large surface-to-volume ratios, shallow lakes are more susceptible to environmental change compared to deeper lakes (Feuchtmayr et al., 2009) and anthropogenic pressures can induce a switch from a clear-water, macrophytes dominated to a turbid water state dominated by suspended sediment or phytoplankton. Reversing these changes requires major intervention in shallow lakes due to the close coupling of water quality with internal nutrient loading from sediments (Scheffer et al., 1993).

Having strong interactions between sediments and the overlying water, shallow lakes are also highly sensitive to climate change (Wilhelm and Adrian, 2008), responding more directly to short-term weather variations like storms (Deng et al., 2018), floods or droughts. Warmer conditions can affect lake ecosystems both in their food web structure through the 'trophic cascade' from fish to phytoplankton (Scheffer and Van Nes, 2007), and in changes in catchment hydrology and nutrient inputs to lakes (Straile, 2002). Warming can further enhance internal nutrient loading of shallow lakes through increased remineralization rates (Søndergaard et al., 2003, 2013). Recent results (Beklioğlu et al., 2016) suggesting increased eutrophication and cyanobacterial blooms in shallow lakes, stimulated by increased temperature coupled with hydrological constraints, under future climate scenarios.

For the purpose of researching long-term environmental trends in lakes, satellite remote sensing can be used to observe a variety of indices of ecosystem health and water quality (Tyler et al., 2016; Free et al., 2020). One of the most frequently investigated indicators is phytoplankton biomass, with chlorophyll-a (Chl-a) as a proxy. Satellite observations of Chl-a provide higher temporal resolution compared to in situ measurements, in addition to their ability to integrate signals over a large spatial area of a lake. The spatiotemporal coverage of satellite imagery can, therefore, provide new insights into the dynamic processes of phytoplankton in lakes (Ho et al., 2019). Another important indicator for characterizing water properties, which can greatly influence ecological processes in lakes, is the concentration of total suspended solids (TSS) or water turbidity (Knighton, 2014). Water turbidity is a bio-optical characteristic enhanced by the presence of insoluble organic and inorganic components, such as phytoplankton particles, other microorganisms, detritus, and suspended minerals (Ghirardi et al., 2023). The production of phytoplankton and the living conditions of aquatic plants and animals can be affected by water turbidity, through limiting vertical transmission of light (Moore et al., 1997; Havens, 2003). As a result, understanding spatial and temporal turbidity trends is crucial for assessing the quality of water and its related environmental services. Numerous methods and instruments have been developed throughout time to reliably calculate the Chl-a and TSS

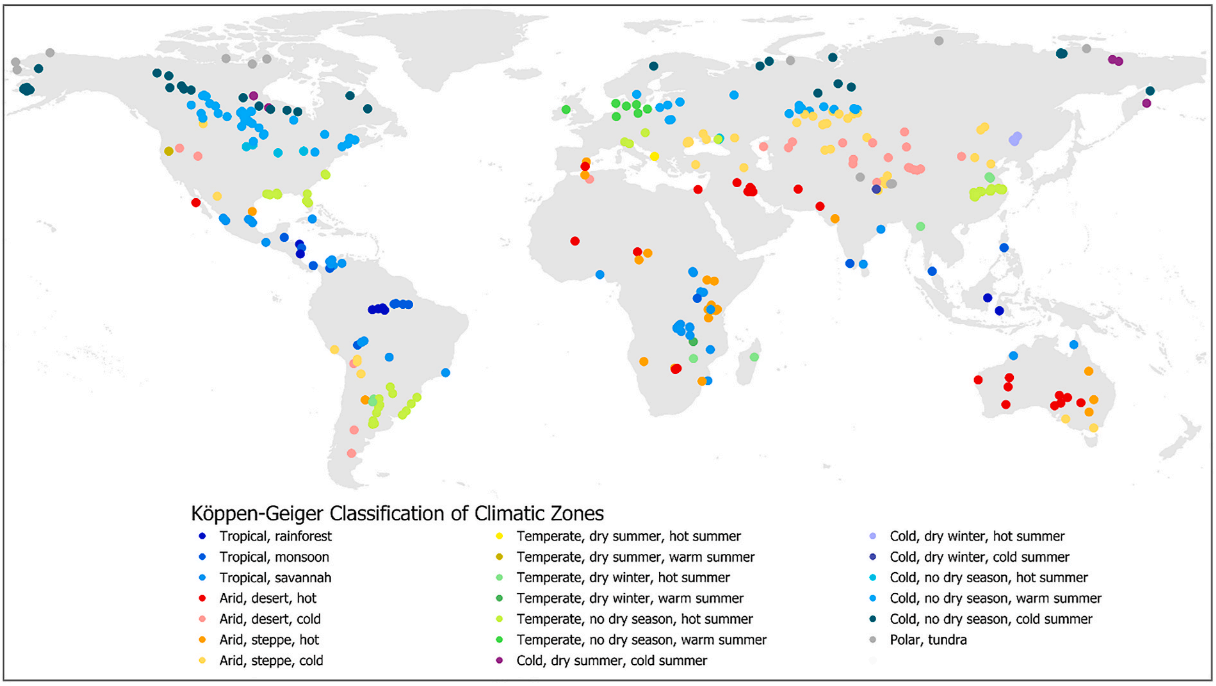

Fig. 1. Map of the shallow lakes included in this study. The colors represent the climatic zone class according to the Köppen-Geiger classification (Peel et al., 2007).

concentration using optical remote sensing data (e.g., Dogliotti et al., 2015; Han et al., 2016; Yang et al., 2017; Balasubramanian et al., 2020; Ogashawara et al., 2022).

One of the most important state variables for studying the ecological and environmental impacts of climate change is lake surface water temperature (LSWT), through its direct interactions with biogeochemistry and hydrology. Satellite remote sensing has been acknowledged to monitor water surface temperature as a cost-effective alternative to routine field measurements for trend detection especially because it offers consistent measurements on large spatial and temporal scales (Sharaf et al., 2019), and it will play an important role in the next high-level water quality management strategy (Carvalho et al., 2019).

Global-scale analyses provide important insights into the governing patterns of climate change affecting lake biogeochemistry, resilience and potential tipping points (Woolway et al., 2021; Armstrong McKay et al., 2022). Multi-disciplinary datasets including physical and biogeochemical observations are particularly useful to support studies into the potentially complex interactions of lakes with their environment.

The main objective of this study is to assess the medium to long term trends of water quality variables in shallow lakes at the global scale over the last two decades, and to investigate whether water quality changes can be attributed to climatic and socio-economic drivers. Shallow lakes were chosen because of their ecological value and as they are considered among 'the most complex ecologically of standing waters' (Moss et al., 2003). Their ecological functioning greatly differs from that of deeper lakes, and they thus have been generally studied as a lake 'type' acknowledging their unique functioning and response to nutrients and climatic pressures. Additionally, the inversion of reflectance into optical-biogeochemical properties does not generally suffer from incomplete vertical mixing in shallow lakes, meaning that shallow - but optically deep - lakes are very well suited for satellite observations. Since studies on shallow lakes usually focus on singular use cases or are conducted at a regional scale, there is a need of assessing their water quality conditions and long-term trends at a global scale.

The European Space Agency (ESA) Climate Change Initiative (CCI) projects offer globally consistent satellite observations of several Essential Climate Variables (ECVs) as requested by the Global Climate Observing System (GCOS, 2022), including the Lakes ECV. The Lakes_cci project (esa.int) includes the following variables: Lake Water Level (LWL), Lake Water Extent (LWE), Lake Surface Water Temperature (LSWT), Lake Ice Cover (LIC), Lake Ice Thickness (LIT) and Lake Water-Leaving Reflectance (LWLR, which includes chlorophyll-a and turbidity products). The data generated by the project includes satellite products for the period 1992–2020, covering 2024 lakes. From this large dataset, we extracted a subset of 347 shallow lakes defined by their mean depth $\leq$3 m (Moss et al., 2003), distributed globally and covering different climatic and ecological settings, in order to investigate long-term timeseries and trends of water quality variables such as Chl-a and turbidity (Fig. 1). Through our focus on shallow lakes, we were able to test the contribution of global-scale observations to our understanding of long-term change, including the inherent limitations of this dataset and the underlying satellite techniques. The main limitation stems from the spatial resolution constraining our investigation to large shallow lakes. However, this approach grants the advantages of a world-wide analysis using the same instruments and algorithm for all lakes considered during the inspected period, and cost-effectiveness.

2. Material and methods

This study focuses on a total of 347 shallow lakes of mean depth $\leq$3 m (Moss et al., 2003) extracted from the Lakes_cci dataset. On the basis of lake surface area, 17 % of lakes had an area $\leq$20.0 km^2, 24 % between 20.1 and 50.0 km^2, 44 % between 50.1 and 500.0 km^2 and 15 % larger than 500.0 km^2 (Fig. S1 in Supplementary Material).

2.1. Datasets

Satellite-derived data for LSWT, Chl-a, and turbidity were acquired from the Lakes_cci dataset v2.0.2, in NetCDF format (https://climate.esa.int/en/projects/lakes/) offering mean daily bio-physical parameters of lakes with a global grid resolution of 1/120°, covering different periods depending on the variable but overall spanning over 20 years and making use of several satellite missions. In particular, the Lakes_cci LSWT dataset was sourced from the Advanced Along-Track Scanning Radiometer (AATSR), Advanced Very High-Resolution Radiometer (AVHRR), Sea and Land Surface Temperature Radiometer (SLSTR) series, and Moderate Resolution Imaging Spectroradiometer (MODIS) on Terra, while Chl-a, and turbidity data came from the MEdium Resolution Imaging Spectrometer (MERIS) and Ocean and Land Color Instrument (OLCI); notably MERIS covered the 2002–2012 period and OLCI the 2016–2020. The 4-year gap period from 2012 to 2015 was partially integrated with MODIS-Aqua providing Chl-a concentrations for 48 lakes of which only five are shallow. Such a heterogenous satellite dataset posed some challenges regarding the estimation of bio-physical variables, yet the state-of-the-art algorithms both to remove the atmospheric effects and to estimate the lake variables methods have been widely tested in the Lakes_cci framework as reported in Carrea et al. (2023). In brief, the LSWT retrieval was based on four main steps per-pixel, which are the water pixel identification, the application of a radiative transfer model (Saunders et al., 2018), the retrieval of LSWT on the base of optimal estimation and the remapping into a regular grid. LSWT values underwent filtration based on quality levels 4 and 5, which indicate the confidence level of LSWT validity (Carrea et al., 2023). The processing chain for deriving LWLR was based on Calimnos v1.4: Level-1b data were geometrically and radiometrically corrected using AMORGOS and SNAP v.7.0, respectively; water pixels were then identified by Idepix (v7.0) and corrected for atmospheric effects with POLYMER v4.13. To derive Chl-a and turbidity from LWLR, by following a fuzzy classification (Liu et al., 2021), LWLR were clustered based on a set of 13 lake Optical Water Types (OWT) representative of a wide range of water conditions and guiding the choice of the most suited algorithms to specific OWT as described by the tuning techniques in Neil et al. (2019). The mean Chl-a and turbidity values of each lake over time were obtained by also excluding lake areas covered by ice as found in the Lakes_cci LIC product and by considering per-pixel uncertainties lower than 60 % and 70 % for Chl-and turbidity, respectively, as in previous studies (Free et al., 2022; Pinardi et al., 2023). The trophic status of the shallow lakes at the beginning of the time range was computed as the annual mean of Chl-a concentration for the period 2003–2005 while the period 2017–2019 was used to assess the most recent conditions as according to the following classification: oligotrophic <5 mg m^{-3}; mesotrophic from 5 to 12 mg m^{-3}; eutrophic between 12 and 25 mg m^{-3}; hypertrophic >25 mg m^{-3} (Pinardi et al., 2023).

Information on lakes and their catchment areas was gathered from the HydroLAKES and HydroBASINS datasets (https://www.hydrosheds.org/products/hydrolakes). HydroLAKES, available for lakes with a surface area of at least 10 ha, provided attribute details for the 347 lakes studied, encompassing parameters such as surface area, shoreline length, total volume, mean depth, discharge rates, residence time, elevation, and geographical coordinates. Each lake is linked to a sub-basin in the HydroBASINS database via shared IDs. HydroBASINS facilitated the delineation of catchments for the lakes using a level 06 watershed, representing sub-basin boundaries at a global scale (Lehner and Grill, 2013).

Population (Pop) and gross regional product (GRP) at subnational level were obtained from the global DOSE dataset (Database Of Sub-national Economic Output, Wenz et al., 2023) which covers a temporal range from 1960 to 2020 with regional differences for 1661 subnational regions spanning 83 countries. The dataset matches the global administrative boundaries found in the GADM (Global Administrative Areas Database Version 3.6, https://gadm.org/download_country.html). The DOSE v2 dataset further includes annual mean air temperatures (further labelled as T_a or AirTemperature) and annual mean precipitation (P_a, Precipitation) aggregated from the "fifth generation of the ECMWF (European Centre for Medium-range Weather Forecasts) reanalysis of the global climate and weather", ERA5, offering data at 31 km spatial resolution and with an hourly time step (Hersbach et al., 2020).

2.2. Statistical analysis

Theil-Sen trend analysis (Carslaw and Ropkins, 2012, R package openair) was carried out to estimate the slope of LSWT, Chl-a and turbidity. The advantages of this method, also known as Sen's slope or the median slope method, lie in the context of outlier-influenced or non-normally distributed data. This robust approach for trend analysis in environmental data calculates the median of all possible slopes in pairs among the data points, providing a slope estimate less sensitive to outliers compared to traditional linear regression methods. The study period spanned from 2002 to 2020. The non-parametric test outcomes pertain to observed data, which were de-seasonalized (with gap filling), and both annual and seasonal data (December-January-February - DJF; March-April-May - MAM; June-July-August - JJA; September-October-November - SON). Theil-Sen analysis was performed on a reduced number of lakes, 246 lakes for Chl-a and 189 lakes for turbidity, due to data quality or quantity issues, particularly gaps in the timeseries due to insufficient data coverage from satellites based on the filter used to extract the data. Considering the seasonal variation in temperature and precipitation at different latitudes of the globe, the results for seasonal trend of Chl-a and turbidity were presented grouping the lakes by Northern and Southern hemisphere.

In order to investigate the effects of socio-economic and climate variables on shallow lake water quality, tests of the causal hypotheses between their interactions were conducted using structural equation models (SEMs) following the approach of (Gilarranz et al., 2022). First, correlation analyses between water quality parameters (Chl-a, turbidity and LSWT), anthropogenic variables (gross regional product (GRP) and population count), and meteo-climatic parameters (annual average air temperature and precipitation) were performed.

These results were used to form the causal hypotheses between the variables and then tested using SEMs. To implement the SEMs, the piecewise SEM package (v. 2.3.0) in R (v. 4.3.3) was used. Data for LSWT, GRP, population, air temperature and precipitation were

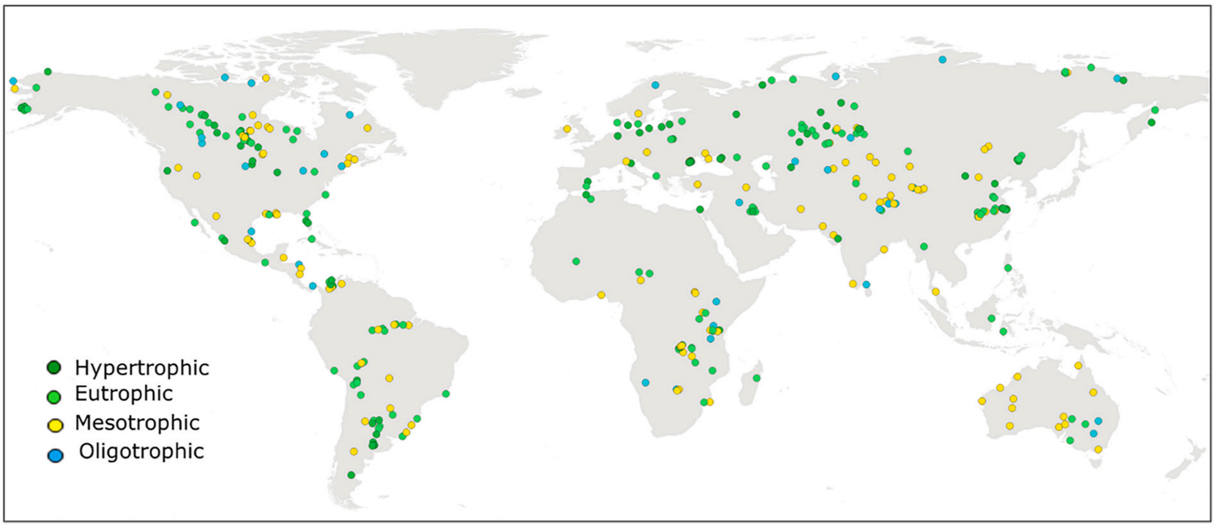

Fig. 2. Map of the lake trophic status based on chlorophyll-a concentration for the period 2003–2005.

normalized using a ln(x+1) transformation. This step aimed to achieve a reduction in skewedness. Furthermore, it reduces variance and contributes to stationarity in preparation for the use of linear models in the SEMs. Two subsets of the data were derived based on the latitudinal distribution of the lakes, resulting in the subset of lakes in the Northern and Southern Hemisphere with 233 and 67 lakes respectively. This reduction in the lake number was due to the mismatches in available data for all parameters.

All statistical tests were performed in R software (R Core Team, 2021).

The workflow of data processing and statistical analysis is summarized in a flow chart reported in Fig. S2 in the Supplementary Material.

3. Results

The geographical distribution of the subset of 347 shallow lakes (Fig. S3 in Supplementary Material) included 12 % in Africa, 24 % in Asia, 19 % in Europe, 5 % in Oceania, 27 % and 13 % in North and South America, respectively.

Regarding lake trophic status calculated at the beginning of the studied period (mean of 2003–2005), lakes were mainly in eutrophic (35 %) and hypertrophic (22 %) conditions, followed by mesotrophic (32 %) and finally oligotrophic (11 %), as shown in Fig. 2.

3.1. Trend analysis

Theil-Sen analysis of Chl-a concentration trends showed that de-seasonalized Chl-a trends were non-significant (p-value >0.05) for 82 lakes (33 % of the total number of lakes) while they were significant (p-value <0.05) for 164 lakes, with 110 lakes (45 %) showing a positive trend and 54 lakes (22 %) a negative trend (Fig. 3a).

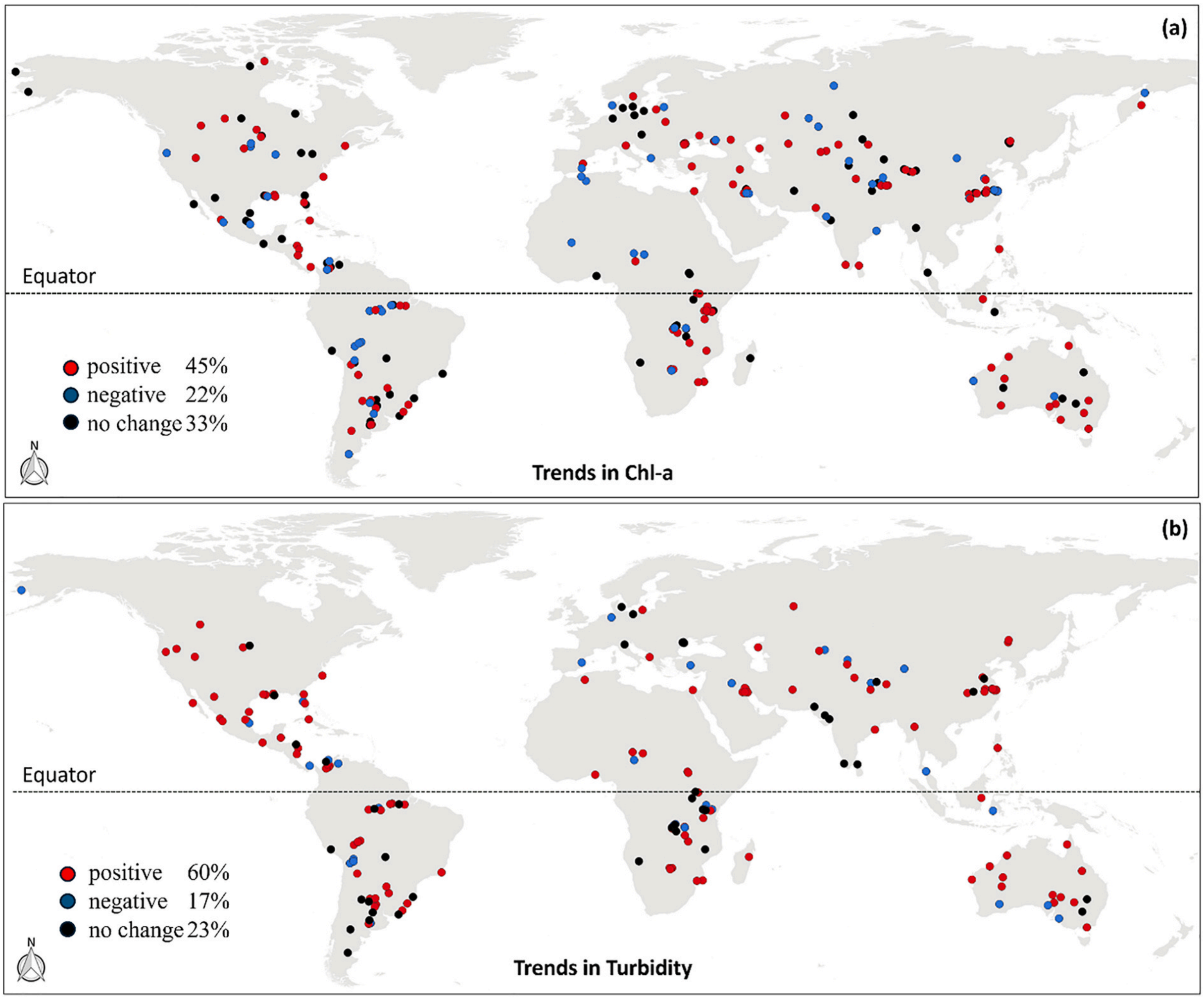

Fig. 3. Maps depicting de-seasonalized trends in (a) chlorophyll-a (Chl-a) and (b) turbidity, among CCI shallow lakes from 2002 to 2020. Red = significant positive trend (p-value <0.05); blue = significant negative trend (p-value <0.05); black = not significant trend (p-value >0.05).

Oceania and Africa had the highest percentage of lakes with a positive Chl-a trend with 65 % and 44 % of cases respectively, while South America had the highest percentage of lakes (28 %) exhibiting a negative Chl-a trend.

Seasonal Chl-a trends (Fig. 4a) revealed that more lakes situated in the Northern Hemisphere exhibited Chl-a increases during summer (JJA) and autumn (SON) seasons (27 % and 23 % of lakes, respectively). In the Southern Hemisphere, more lakes exhibited a Chl-a increase during September-October-November (SON) and during December-January-February (DJF) months (29 % and 24 % of lakes, respectively), although with less confidence due to the smaller sample size (lakes) in this climatic zone.

Theil-Sen analysis of turbidity showed that de-seasonalized trends were non-significant (p-value >0.05) for 43 lakes (23 % of the total number of lakes) while significant (p-value <0.05) for 146 lakes, with 60 % of lakes exhibiting a positive trend and 17 % a

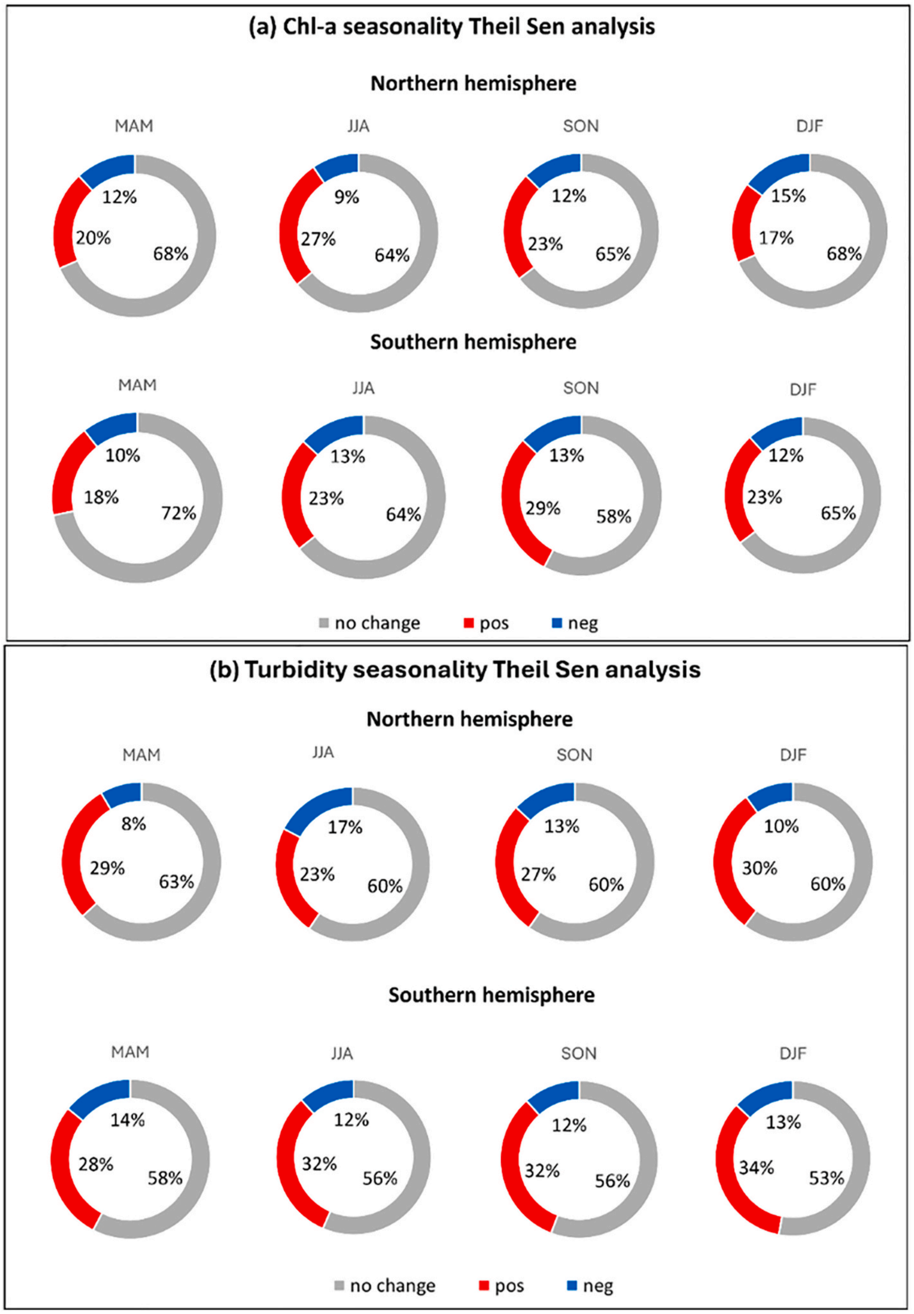

Fig. 4. Seasonal pie charts depicting trends in (a) chlorophyll-a and (b) turbidity, for the shallow lakes in Northern and Southern Hemispheres, during the whole observation period 2002–2020. Neg = significant (p-value <0.05) negative trends; pos = significant (p-value <0.05) positive trends; no change = not significant (p-value >0.05); DJF = December-January-February; MAM = March-April-May; JJA = June-July-August; SON = September-October-November. Trend categories are reported in percentages.

negative trend (Fig. 3b). Further analysis of seasonal trends in turbidity (Fig. 4b) revealed that a larger proportion of lakes in the Northern Hemisphere showed a turbidity increase during winter (DJF; 30 %) and spring (MAM; 28 %) and a higher percentage (33 %) of decreasing trends in summer (JJA). In the Southern Hemisphere the proportions of lakes showing turbidity trends during the annual period were similar, with slightly higher proportions of lakes showing increased turbidity trends during SON (33 %) and December-January-February (34 %) months.

Theil-Sen results for Chl-a and turbidity for each lake in terms of p-values, slopes and intercepts are reported in two tables in the Supplementary Material.

When lakes were related to their morphological properties, obtained from the HydroLAKES dataset, de-seasonalized Chl-a trends show that 56 % of lakes with a significative positive trend were located in lowland areas, 21 % in uplands and 23 % in mountain areas, including 1 % at high altitude (>2500 a.s.l.). Moreover, 60 % of lakes with a significant positive Chl-a trend have a surface area >50 km^2 (with 19 % > 500 km^2) and the 67 % have a relatively short residence time under one year.

De-seasonalized turbidity trends show that 64 % of lakes with a significative positive trend were located in lowlands, 17 % in uplands and 16 % in mountain areas, including four lakes at high altitude (>2500 a.s.l.). Further, 65 % of lakes with a significant turbidity increase have a surface area >50 km^2 (with 15 % > 500 km^2).

To further analyze the directional change in the trophic status of the lakes from the beginning (2003–2005) to the end (2017–2019) of the considered time period, we combined data on Theil-Sen trends in Chl-a for visualization in a Sankey diagram (Fig. 5). For consistency, only those lakes (n = 246) with data adequate to be analyzed by Theil-Sen analysis for Chl-a trends were included.

Overall, most lakes (63 %) did not change trophic status class from the beginning to the end of the considered period, while 23 % of lakes changed to a higher class (i.e., worse quality) and 14 % changed to a lower class (i.e., better quality). When focusing within each trophic class, 71 % of oligotrophic lakes changed to a worse trophic class, 25 % of mesotrophic lakes changed to a worse class and 8 % to a better class. 18 % of eutrophic lakes changed to a worse class while 17 % changed to a better class, and finally 28 % of lakes in the hypereutrophic class changed to a better class.

3.2. Analysis of agreement in trends

Investigating the agreement in trends direction between the optical water quality variables and lake surface water temperature, 64 % of lakes showed concurrent trends of Chl-a and LSWT, of which 48 % were matched-positive (++) and 16 % matched negative (–), while 36 % showed opposite trends between Chl-a and LSWT. Similarly, 61 % of lakes showed concurrent trends in turbidity and LSWT, with 50 % positive and 11 % negative, while 39 % showed inverse trends between turbidity and LSWT. When related to air temperature trends, 67 % of lakes showed a concurrent positive trend with Chl-a and 76 % with turbidity. An overview of these results for all the variables considered is given in Table 1. Correlations between significant trends in Chl-a and turbidity showed that 51 % of lakes had concurrent positive trends, 7 % had negative trends, and 42 % had inverse trends.

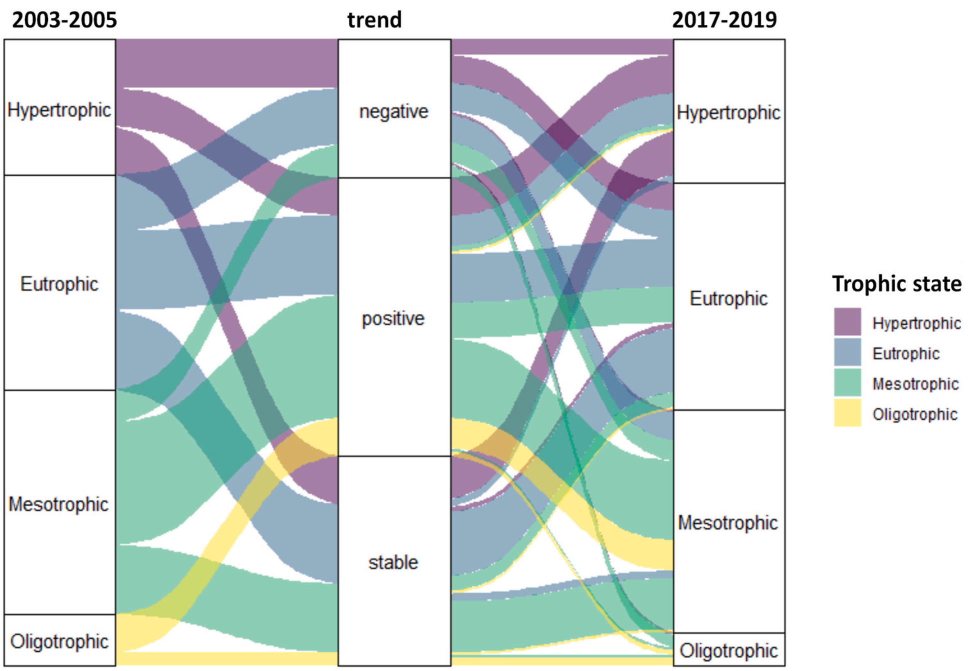

Fig. 5. Sankey diagram visualizing lake trophic classes changes from the beginning (2003–2005; left column) to the end (2017–2019; right column), through chlorophyll-a trends (Theil-Sen Chl-a trends; central column indicates slope direction).

Table 1
Agreement of trends between Chl-a (significant trends, p-value <0.05) and turbidity, LSWT, GRP, population, precipitation and air temperature (upper table); turbidity (significant trends, p-value <0.05) and LSWT, GRP, population, precipitation and air temperature (lower table). Results reported as percentage of lakes (%) with positive (concordant positive), negative (concordant negative) or inverse trends between variables.

	Slope Chl-a vs Slope turbidity	Slope Chl-a vs Slope LSWT	Slope Chl-a vs Slope GRP	Slope Chl-a vs Slope Population	Slope Chl-a vs Slope Precipitation	Slope Chl-a vs Slope Air temperature
Inverse	42 %	36 %	33 %	35 %	49 %	31 %
Negative	7 %	16 %	0 %	1 %	19 %	1 %
Positive	51 %	48 %	67 %	63 %	33 %	67 %
Total	100 %	100 %	100 %	100 %	100 %	100 %

	Slope turbidity vs Slope LSWT	Slope turbidity vs Slope GRP	Slope turbidity vs Slope Population	Slope turbidity vs Slope Precipitation	Slope turbidity vs Slope Air temperature
Inverse	39 %	24 %	22 %	70 %	22 %
Negative	11 %	0 %	2 %	10 %	2 %
Positive	50 %	76 %	76 %	20 %	76 %
Total	100 %	100 %	100 %	100 %	100 %

Regarding agreement of trends in water quality and demographic and economic parameters, Chl-a had a concurrent positive increase with population in 63 % of lakes and with GRP in 67 % of lakes, while turbidity showed a concurrent positive increase with population and with GRP in 76 % of lakes. As population and GRP represent a proxy of anthropogenic pressure on lake catchments, these results may indicate an important factor for water quality changes in these lakes.

3.3. *Structural equation model analysis*

Some of the effects that socio-economic and climate variables might reflect in shallow lake water quality were tested using structural equations models (SEMs). Population (counts) and GRP (Gross Regional Product) were considered as proxies of anthropogenic pressures on lake catchments. Results are presented by graphical representation of the final models with the respective correlation matrices, distinguished in Northern (Fig. 6) and Southern (Fig. 7) Hemisphere. Detail on the SEM analysis is reported in the section "Structural equations modelling" in the Supplementary Material (Figs. S4, S5), with main results highlighted below.

3.4. *Northern hemisphere*

Chlorophyll-a (Chl-a) is directly related to air temperature (T_a; +0.26), turbidity (Turb; −0.10), precipitations (P_a; −0.08) and gross regional product (GRP; +0.06), with population (Pop) as indirectly related through GRP (−0.22). Turbidity is directly related to population (Pop; +0.22) and GRP (−0.17). In the model, air temperature (T_a) is a strong direct predictor for lake surface water temperature (LSWT; +0.78) and precipitation a negative predictor (−0.31).

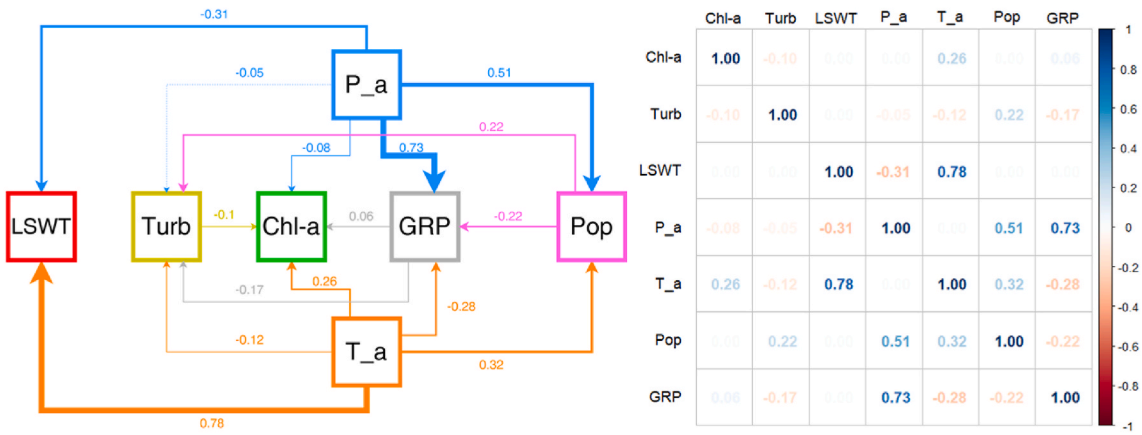

Fig. 6. Graphical representation of the final SEM model (left) and correlation matrix (right) for the Northern Hemisphere. Pop = Population (pink), Turb = Turbidity (yellow), Chl-a = Chlorophyll-a (green), T_a = Air Temperature (orange), LSWT = Lake Surface Water Temperature (red), GRP = Gross Regional Product (grey), P_a = Precipitation (blue). Arrow directions indicate predictor and response, while arrow thickness indicates the level of correlation. Fisher's C = 3.638 with a p-value of 0.725 on 6 degrees of freedom. Directionality was fixed between air temperature and population, Chl-a and turbidity, precipitation and GRP and population.

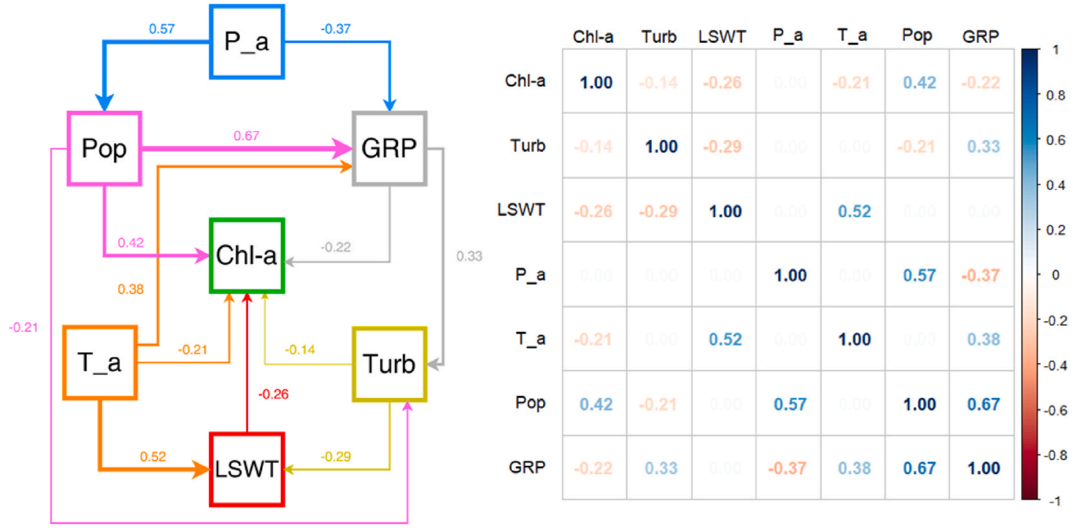

Fig. 7. Graphical representation of the final SEM model (left) and correlation matrix (right) for the Southern Hemisphere. Pop = Population (pink), Turb = Turbidity (yellow), Chl-a = Chlorophyll-a (green), T_a = Air Temperature (orange), LSWT = Lake Surface Water Temperature (red), GRP = Gross Regional Product (grey), P_a = Precipitation (blue). Arrow directions indicate predictor and response, while arrow thickness indicates the level of correlation. Fisher's C = 2.23 with a p-value of 0.973 on 8 degrees of freedom. Directionality was fixed between air temperature and population, Chl-a and turbidity, precipitation and GRP and population.

3.5. *Southern hemisphere*

Chlorophyll-a (Chl-a) is directly related to air temperature (T_a; −0.21), lake surface water temperature (LSWT; −0.26), turbidity (Turb; −0.14), gross regional product (GRP; −0.22) and population (Pop; +0.42). Turbidity is directly related to gross regional product (GRP; +0.33) and indirectly by population through GRP (Pop; +0.67). In the model, air temperature (T_a) is a direct predictor for lake surface water temperature (LSWT; +0.52) and Chl-a (−0.21).

4. Discussion

The results of this study indicate that most of the shallow lakes in our dataset experienced positive trends in turbidity and Chl-a concentration over the last two decades. Although about one third of the total lakes remained relatively stable, the majority of lakes (44 %) experienced increases in Chl-a concentration while a minority (22 %) showed a decrease. In addition, intra-annual variability in trends was observed in both the Northern and Southern Hemispheres, with higher positive proportions in the summer-autumn and spring-summer periods, respectively, following the seasonal growth of primary producers. Most of the lakes with a significative positive trend in Chl-a are located in lowland areas and are large shallow lakes with a surface area >50 km^2. Lakes located in plains or lowland areas are generally subject to more intense agricultural and farming activities, urban development and population aggregation (Solheim et al., 2019; Zhou et al., 2022). Large lakes generally tend to have larger catchments and may thus be affected by a larger human population with diverse activities and pressures, including higher external nutrient loading to the lakes. Lake size was found to be an important factor in influencing the regime of shallow lakes, with large lakes often lacking submerged macrophytes, likely due to wind effects on sediment resuspension (Crisci et al., 2017). The LWE products might also be considered in this context in the near future to assess the dynamics of water extent. As soon as the LWE variable in the Lakes_cci data is extended to cover a longer timeseries and wider global coverage, it could be evaluated as an additional predictor of water quality variables.

A combination of climate warming effects and local anthropogenic pressures on shallow lakes in lowland areas explain the findings of our study, where most lakes experienced deteriorations of their water quality. These findings agree with other studies (Moss et al., 1996; Moss, 1998; Beklioğlu, 2007; Zhou et al., 2022; Meerhoff and Beklioğlu, 2024), stating that during the last decades, increased urbanization, sewage disposal, regulation of wetlands and more intensive farming practices have increased the nutrient loading to many shallow lakes world-wide.

The Chl-a derived trophic status, calculated at the beginning of the study period, revealed that increases in Chl-a concentrations occurred mostly in lakes that were in oligotrophic condition (75 % had Chl-a increases) and that this led to a decline in status for 71 % of oligotrophic lakes. In addition, 54 % of mesotrophic lakes had Chl-a increases, while lower proportions of lakes in higher trophic conditions displayed Chl-a increases. These findings revealed the sensitivity of low productive shallow lakes to environmental changes, either due to increased nutrients input by augmented anthropogenic pressure, or by climate change affecting hydrological processes in lake catchments. The latter could include changes in precipitation regimes leading to more intense runoff as well as higher temperatures affecting lake internal processes such as anoxic microzones and the facilitation of nutrient release from sediments affecting the trophic food web. In large lakes, remotely sensed phytoplankton biomass has been shown to respond to climate warming depending on lake trophic status (Kraemer et al., 2017) and many studies have revealed that global warming might cause significant changes in lake food web structure and community composition (Jeppesen et al., 2010; Brucet et al., 2012; Meerhoff et al., 2012). Internal responses to increased temperatures in shallow lakes include higher internal loading of phosphorus from the sediments (Søndergaard et al., 2003). Some shallow lakes may become temporarily stratified for longer periods due to the rising temperatures, which exacerbates the release of phosphorous from the sediments, promoting primary production and eutrophication.

Turbidity trends revealed that most shallow lakes exhibited a significant positive trend (60 % of lakes) and a smaller part (17 %) a negative trend. Similar to Chl-a, most of the lakes with a positive turbidity trend are located in lowland areas and are relatively large lakes with 65 % having a surface area >50 km^2. Seasonal variability showed a more related increase in turbidity in winter and spring in the Northern Hemisphere, probably following seasonal precipitation, while less variability was found for the Southern Hemisphere where precipitation is distributed differently in the different climatic zones. Changes in catchment hydrodynamics promoted by climate change, via modified precipitation patterns and altered soil conditions, have ultimate impacts on sediment loads and nutrient inputs to lakes. Both empirical and modelling studies indicate that climate warming affects nutrient dynamics through external and internal loading (Jeppesen et al., 2009) and climate change models predict increased occurrence of extreme events (flooding, extended droughts), which will magnify water level fluctuations and hydrological stresses in lakes (Parmesan et al., 2022).

Correlation of trend slopes between water quality variables and lake surface water temperature revealed that 48 % of lakes showed a concurrent increase of Chl-a and LSWT, while 36 % showed an inverse trend. Similarly, 50 % of lakes showed a concurrent increase in turbidity and LSWT, while 39 % showed an inverse trend. When related to air temperature trends, 67 % of lakes showed a concurrent positive trend with Chl-a and the 76 % with turbidity. With most lakes showing a concurrent positive trend between both Chl-a and turbidity and LSWT, our results indicate that climate warming is likely to promote lake primary production. However, a considerable number of lakes showed an inverse trend, indicating that water temperature changes can be associated with either increased or decreased lake productivity. Our findings are in agreement with other studies, showing that climate warming can increase or decrease lake phytoplankton biomass depending on whether warming is affecting productivity directly or indirectly through food webs (Kraemer et al., 2017). Although it is acknowledged that shallow lakes are particularly sensitive to climate change, how changing temperature might affect the competitive balance between phytoplankton and submerged macrophytes is still under debate, with studies often delivering inconclusive results, because the influences of temperature alone cannot be easily separated by lake biogeographical history. In an attempt to remove the biogeographical effect, experimental studies using mesocosm systems have been run in lakes across Europe, showing a stronger tendency for phytoplankton dominance with decreasing latitude (Moss et al., 2004), mainly owing to greater fish predation on zooplankton grazer communities (Feuchtmayr et al., 2009). Moreover, other mesocosm studies in shallow Mediterranean lakes have revealed that systems switched from macrophytes to phytoplankton dominance at lower nutrient concentrations than in similar studies conducted in North European lakes (Romo et al., 2004). However, there is still uncertainty as to how future temperatures will influence structure and function of shallow lakes (Feuchtmayr et al., 2009) as the persistence of other pressures on lake catchments such as eutrophication, urbanization and nutrient pollution all contribute to the overall impact on shallow lake ecosystems.

Regarding agreement of trends in water quality and demographic and socio-economic parameters in our subset of shallow lakes, overall Chl-a and turbidity had a concurrent positive increase with population and GRP for most lakes indicating that the impact of human population growth on lake catchment represents an important pressure on lake water quality. However, about one third of the lakes had discordant relationships, either indicating that the human population might have a more complicated interrelationship and be less related to lake water quality or that lake management and conservation of water quality in a part of shallow lakes have been effective in the last decades.

In order to investigate further interactions and potential drivers of Chl-a in our subset of shallow lakes, we ran a SEM analysis including as predictors demographic (population) and socio-economic (GRP) data to detect whether water quality changes were directly or indirectly linked to human global drivers. In the Southern Hemisphere, population was directly and positively related to Chl-a (+0.42) and GRP to turbidity (+0.33), while in the Northern Hemisphere population was indirectly related to Chl-a through GRP (with pop vs GRP -0.22) and directly related to turbidity (+0.22). The relationships found likely reflect differences in population dynamics in the two hemispheres, with the Southern including countries experiencing population expansion that might increase anthropogenic pressures on lake catchments and ultimately on Chl-a, while the Northern included countries with more stable populations, thus becoming a secondary factor for lake Chl-a. Moreover, relationships between GRP and lake variables might be more consistent in the Northern Hemisphere with, in general more economic stability, while in the Southern Hemisphere they are more difficult to interpret owing to the high economic fluctuations and political instability for many countries (i.e., South America and Africa).

The SEM analysis further showed how the effects of precipitation were positively correlated with population in both hemispheres, and with GRP in the Northern Hemisphere. This underlines, unintentionally, the linkages between water (precipitation), human population and economic prosperity (GRP), however the SEM analysis indicated that this in turn leads to negative impacts on lake Chl-a or turbidity influencing their increase. This highlights the unsustainable management of the water resource despite its vital role and our dependence on it. This, coupled with loss of oligotrophic lakes, the Earth's most precious lakes, means that we must reevaluate our relationship with water and better manage the resource to sustain life and stop the persistent eutrophication urgently, as this is still the most widely spread pressure on shallow lakes associated with anthropogenic activity in lake catchments (Meerhoff et al., 2022).

In conclusion, the presented approach confirmed the advantage of satellite remote sensing for investigating indicators of water quality (i.e., Chl-a and turbidity) at high temporal frequency, over a large spatial coverage during the last 20 years. The availability of validated and consistent data on lake variables (e.g. LSWT, LIC, Chl-a and turbidity) offer unique opportunities to observe global processes. This can be considered a success in the face of the many barriers and limitations to using satellite data. These include the inherent limitations such as spatial resolution, which limits the study to large shallow lakes, the presence of clouds, that increases the possibility of missing key events such as algal blooms and the usual persistent challenges (e.g. errors due to atmospheric correction). Other key areas where improvement in needed include the use of gap filling techniques to improve the spatial and temporal coverage and the use of uncertainty provided for each of the Lakes-cci products for including lakes in climate modelling.

This is one of the first studies (e.g., Free et al., 2022) to examine trends in turbidity and Chl-a and changes in lake trophic status over a 20-year period in a valuable sample of globally distributed shallow lakes. Our work fits well within the current scientific understanding where the main expectation for shallow lakes is the additive or synergistic effect of eutrophication (e.g., anthropogenic pressure, agriculture) with climate change (i.e., warming) (Meerhoff and Beklioğlu, 2024 and references therein). In further studies, the integration of satellite-derived data with in-situ or modelled data to fill data gaps and nutrient concentration data would help to better identify the relative importance of the major pressures driving recent water quality changes in shallow lakes globally.

CRediT authorship contribution statement

Rossana Caroni: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Anna Joelle Greife:** Writing – original draft, Methodology, Formal analysis, Data curation. **Mariano Bresciani:** Writing – review & editing, Resources, Methodology, Conceptualization. **Claudia Giardino:** Writing – review & editing, Resources, Conceptualization. **Giulio Tellina:** Formal analysis, Data curation. **Laura Carrea:** Writing – review & editing, Data curation. **Xiaohan Liu:** Writing – review & editing, Data curation. **Stefan Simis:** Writing – review & editing. **Clément Albergel:** Writing – review & editing. **Monica Pinardi:** Writing – review & editing, Writing – original draft, Resources, Conceptualization.

Ethical Statement for Solid State Ionics

Hereby, I/Monica Pinardi/consciously assure that for the manuscript/*Investigating global trends of the Essential Climate Variables for shallow lakes from multi-disciplinary satellite observation*/the following is fulfilled.

1) This material is the authors' own original work, which has not been previously published elsewhere.
2) The paper is not currently being considered for publication elsewhere.
3) The paper reflects the authors' own research and analysis in a truthful and complete manner.
4) The paper properly credits the meaningful contributions of co-authors and co-researchers.
5) The results are appropriately placed in the context of prior and existing research.
6) All sources used are properly disclosed (correct citation). Literally copying of text must be indicated as such by using quotation marks and giving proper reference.
7) All authors have been personally and actively involved in substantial work leading to the paper, and will take public responsibility for its content.

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I agree with the above statements and declare that this submission follows the policies of Solid State Ionics as outlined in the Guide for Authors and in the Ethical Statement.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Claudia Giardino reports financial support was provided by European Space Agency. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rsase.2025.101565.

Data availability

Data will be made available on request.

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