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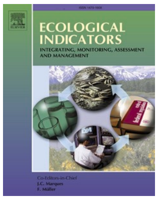

Review

# Diatoms as bioindicators for health assessments of ephemeral freshwater ecosystems: A comprehensive review

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ABSTRACT

Ephemeral waters (EW) are sensitive and vulnerable ecosystems that, although the numerous ecosystem services provided, are poorly investigated and properly managed. Diatoms represent an important biological model largely used in aquatic permanent habitats but underused in ephemeral waters. The aim of this review is to address the knowledge gap, examining the current state of knowledge regarding the health of EW, with a focus on diatoms as bioindicators, specially (i) presenting research trends on EW ecosystem types investigated (ii) analysing the methodological approach, (iii) providing the influence of abiotic factors on the diatom assemblages in EW. A bibliographic search yielded a total of 512 papers. After removing duplicate records, 118 were eliminated. The screening of abstracts resulted in the selection of 48 articles on diatoms and EW since 1982. To avoid discrepancy between terminology we decided to classify the EW found in 3 different categories: Intermittent Running Waters (IRW: rivers, streams, creek, springs), Temporary Large Wetlands (TLW: wetlands, lakes, lagoons) and Temporary Small Waters (TSW: ponds, pools, ventaroles, ditches, thermal waters, troughs, pans). Studies are reported in all continents including Antarctic. IRW are the most investigated ecosystem (n = 683), followed by TSW (239) and TLW (96). Furthermore, studies were mainly conducted on sites located below 1000 m a.s.l. of altitude (n = 27). Studies mainly focus on epilithic diatoms (52 %). Electrical conductivity (80 %), pH (77 %) and water temperature (75 %) are the principal physical–chemical parameters considered. Moreover, electrical conductivity, pH, temperature, nitrate and nitrite resulted the best diatom community drivers. Future research is encouraged (1) to achieve a standardised protocol for monitoring EW using diatoms, (2) to focus on conservation projects for high-altitude temporary waters, and (3) to investigate the main driving forces influencing diatom diversity on EW.

## 1. Introduction

Ephemeral waters (EW) refer to both lentic or lotic ecosystems which water completely or partially stops flowing at any time of the year (Zharov et al., 2020). The presence and duration of EW are influenced by the fluctuating climate and ecological conditions throughout the year (Kulkarni et al., 2019). Abiotic factors like hydrogeological conditions (e.g., substrate type and permeability) and the annual precipitation regime are the main drivers influencing the consistency of these ephemeral ecosystems, while temperature, humidity, and hydroclimatic conditions contribute to the overall dynamic (Madaschi and Díaz-Villanueva, 2021). Despite their global distribution and the multitude of ecosystem services they offer, it is surprising how researchers and society have historically overlooked EW, probably due to their ephemeral existence and limited appeal for tourism and economic activities (Alonso, 2009).

In literature, EW are often identified with different names, lacking a unique nomenclature for these ecosystems. Behind the most common water bodies like ephemeral lakes, ephemeral ponds, intermittent rivers, intermittent streams, ephemeral wetlands there is a wide variety of EW, identified with different terms: ventaroles are Karst cavities in Miocene calcarenite, occasionally flooded (Bologna et al., 1994); vernal pools are

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EW not connected to river systems, but fed by shallow groundwater or by precipitation (Brooks, 2005); riverine pools are EW located in outer channels of rivers, not connected with the principal channel but usually fed by the alluvial water table (Schofield et al., 2018); ditches are part of wetlands created by human activities of natural phenomena, but also trenches occasionally flooded by rain (Al-Khudhairy et al., 2002). The diversity of terminology can lead to confusion regarding the precise definitions of certain terms or how to accurately interpret and compare various types of ecosystems.

EW ecological relevance resides in the support to life they give to biota inhabiting them and the surrounding habitats (Arumugam & Athikesavan, 2021): invertebrates dominate the fauna of EW, in terms of richness, abundance and rare taxa adapted to the natural hydrogeological modifications (Bird et al., 2019), besides uniquely specialised invertebrates (Strachan et al., 2015); birds use EW as a resource for foraging, nesting, bathing and water consumption (de Morais-Junior et al., 2019); moreover, EW represent a biodiversity hotspot for macroinvertebrates, fishes, macrophytes and diatoms supporting unique assemblages of vertebrates and invertebrates (Fritz et al., 2021). Among these, diatoms represent the main inhabitants of EW, due to their ability to colonize different substrates, their ubiquity and the rapid recovery time from the dry periods (Duong et al., 2007).

Furthermore, EW provide habitat and refugia for many species as well as contributing to human needs for freshwater in particular in arid and semiarid landscapes (Higgison et al., 2020). Under global change scenarios and widely anthropogenic pressure, EW threats tend to increase due to population increase, land use changes and declining precipitation (Grzybowski et al., 2019). Intermittent rivers and intermittent streams are among the most dynamic and complex freshwater ecosystems, occupying more than one third of the planet's land surface. However, they are also among the most threatened ecosystems (Karaouzas et al., 2018), for instance from human activities like wastewater treatment (Pascual-Benito et al., 2020) or acidification (Shah et al., 2021); ephemeral ponds are very vulnerable to human activities, due to their special physical and ecological characteristics and especially threatened by agriculture pollution, tourism, fire and water abstractions (Zacharias et al., 2007); ephemeral lagoons are often threatened by mining, pollution, biological disturbances (e.g., introduction of exotic species), and anthropogenically induced climatic and atmospheric changes. Ephemeral wetlands are threatened directly (i.e., agriculture) and indirectly by various human activities and pressures (i.e., reclamations) (Parra et al., 2021).

These ecosystems are very vulnerable to natural drought and anthropogenic water stress, as well as to nutrient enrichment from industrial and urban wastewaters, and organic pollution from agricultural activities. Furthermore, climate change affects mostly this type of ecosystems due to their ephemeral nature (Acuña et al., 2017; Zacharias et al., 2007). Despite significant advances in understanding their hydrology, ecology and management, many scientific and management gaps still remain, particularly in methodological and conceptual fields. This is especially evident regarding the use of ecological indicators for the assessment of the conservation status of EW.

The combined effects of abiotic, in particular anthropogenic (Akhtar et al., 2021; Vanderley et al., 2021; Gutiérrez-Cánovas et al., 2019) stressors on aquatic biotic assemblages, necessitate the use of biological models to assess the threat level to these ecosystems (Dubey et al., 2022).

Several efficient biological models are widely used to evaluate waters ecological status, including fishes, macroinvertebrates, macrophytes, and diatoms (Guerrero-Aguilar et al., 2022; Taurozzi et al., 2023; Marcheggiani et al., 2019;). Among these, benthic diatoms offer distinct advantages over other biological models in most habitats or for different environmental stressors, making them particularly valuable in routine environmental studies (Sharma et al., 2023). Benthic diatoms represent one of the most common biological quality elements (BQEs) used in surface water monitoring, adopted by the European Water Framework Directive 2000/60/EC (WFD) focusing on their advantages as bioindicators (Masouras et al., 2021). Diatoms are ubiquitous, easy to sample, and can be abundant in poor habitats, on hard substrates, or in rivers with high flow velocity where macroinvertebrates, macrophytes and phytoplankton (commonly used in lowland rivers), could be absent. Additionally, owing to their rapid growth rate, benthic diatoms exhibit swift responses to short-term hydrological changes, unlike macroinvertebrates (Pinheiro et al., 2020). However, their morphological and taxonomic identification is challenging and requires specialist expertise (Rimet et al., 2019).

The response of diatoms to multiple stressors in EW has received much less attention, leading to significant uncertainty on how natural and anthropogenic hydrological variation and physico-chemical pollution affect aquatic algae communities (Ganai et al., 2014). Furthermore, the use of diatoms for assessing the conservation status of EW is scarcely widespread. While pollution and water stress can have pronounced and well-documented effects on macroinvertebrate and fish species richness, abundance and community structure (Strungaru et al., 2021; Wheeler et al., 2020), only few studies have addressed this issue using diatoms as the primary tool for evaluating the ecological status of EW.

Given the global distribution of diatoms, their important role as ecological sentinels, and the critical conservation status of EW, this paper reviews and discusses the use of diatoms as bioindicators to assess the conservation status of EW worldwide. To address the knowledge gap, this review examines the current state of knowledge regarding the health of EW, with a focus on diatoms as bioindicators, specially (i) presenting research trends on EW ecosystem types investigated (including year, study area, author's affiliate Country), (ii) analysing the methodological approach (i.e., object of the study, and temporal and spatial effort of sampling), (iii) providing the influence of abiotic factors (i.e., altitude and physical–chemical parameters) on the diatom assemblages in EW.

## 2. Materials and methods

### 2.1. Bibliographic collection

This review follows the PRISMA guidelines for systematic reviews (Page et al., 2021; Moher et al., 2009). Data collection was carried out among peer reviewed international scientific articles via Scopus and Web of Science (without a lower time limit, until 24 March 2024). The review includes only peer reviewed material. For this search, only papers written in English were considered. Obviously, there is the possibility that some reports on this topic have been written in other languages. However, given that English is considered the universal form of communication in science and to uniform the results, articles in languages other than English, books, and other reports have been excluded. The keywords used to select the scientific material on the topic of interest were "diatoms", coupled with "waters", and "freshwaters", and "water basins" and "ponds", and "lakes", and "wetlands", "and "rivers", and "streams", all preceded by the adjectives and synonymous "ephemeral", "temporary" or "intermittent".

"Ephemeral", "temporary" and "intermittent" are used here as synonymous for waters that intermittently has standing water and that, once inundated, holds water long enough on occasion for some species to complete aquatic phases of their life cycle (Blaustein and Schwartz, 2001). A recurrent dry phase is the common feature shared by these ecosystems. However, there is not a unique definition regarding the hydroperiod characteristics in terms of duration and occurrence of the dry phase in the years (Williams et al., 2001). Here, we considered the definition from Wars (1992), considering temporary waters those which have a predictable annual dry phase, usually in the order of 3–8 months, predominantly during summer and autumn. They are also defined as "drying in most years" from Nicolet et al. (2004) adapted from the standard definition used for the UK National Pond Survey (NPS; Pond Action, 1998). Finally, it is important to consider that, according to

Williams (1997)) is difficult to predict the hydroperiod of EW and that, for this reason, there are two different types of EW: those following a seasonal cyclic pattern of dryness and flooding and those which will be flooded unpredictably.

Results were selected for including articles on the detection of epilithic, epiphytic, epipsammic, epipelic and planktonic diatoms, excluding papers on fossil remains of diatoms and paleolimnology. Firstly, duplicate articles were eliminated by a preliminary screening based on the title of articles. Not pertinent articles were excluded after verifying abstracts. Authors considered non-pertinent articles those referring to permanent freshwaters. The manuscript content of the remaining articles was subsequently checked for suitability as a final step. Thereafter, the list of results was obtained.

### 2.2. Collection of information data

Qualitative information were collected from all the articles about the year of publication, the ecosystem type (lakes, ponds, rivers, streams, wetlands…), the study area, the affiliation country of the authors, the topic of investigation and the diatoms type (planktonic, epiphytic, epipelic, epilithic, epipsammic), the study period (month and duration of the study), the global distribution of study sites, the altitude of the study area, and the chemical parameters taken into consideration (Table S2). Information about the study sites and relative coordinates were taken both from the paper body and from supplementary materials, where available.

### 2.3. Statistical analysis

A two sample *t*-test was performed comparing the number of articles and the relatives months involved in sampling for the northern and the southern hemisphere. Data normality and homoscedasticity were tested before performing the two sample *t*-test..

## 3. Results

### 3.1. Research trends on diatom indicators in ephemeral freshwaters

The initial output of the bibliographic research yielded a total of 512 papers. After removing duplicate records, 118 were eliminated. The screening of abstracts resulted in the selection of 48 articles for inclusion in the review (Fig. 1).

#### 3.1.1. Bibliographic search – year of publication

Studies on temporary waters and diatom communities began in 1982 and followed a stable trend until 2012, where the number of papers increased until 2020, reaching a maximum of 7 publications per year (Fig. 1c).

#### 3.1.2. Ephemeral freshwater ecosystem types investigated

Among the reviewed papers, 14 different types of EW were reported to be investigated using diatoms as indicators: lake, pond, river, stream, wetland, pool, spring, trough, ditch, thermal water, creek, lagoon, pan, ventarole. However, some of them are reported to be similar to others from an ecological point of view and are often described by different names, for example pond and pool, or creek and stream, or lake and lagoon (Krishnaraj, 2022). Ponds and wetlands are distinguished primarily by three variables, i.e., depth, surface area and water chemistry: Richardson et al., (2022) described ponds as small (<5 ha) and shallow (<5 m) ecologically distinct type of ecosystem respect to wetlands,

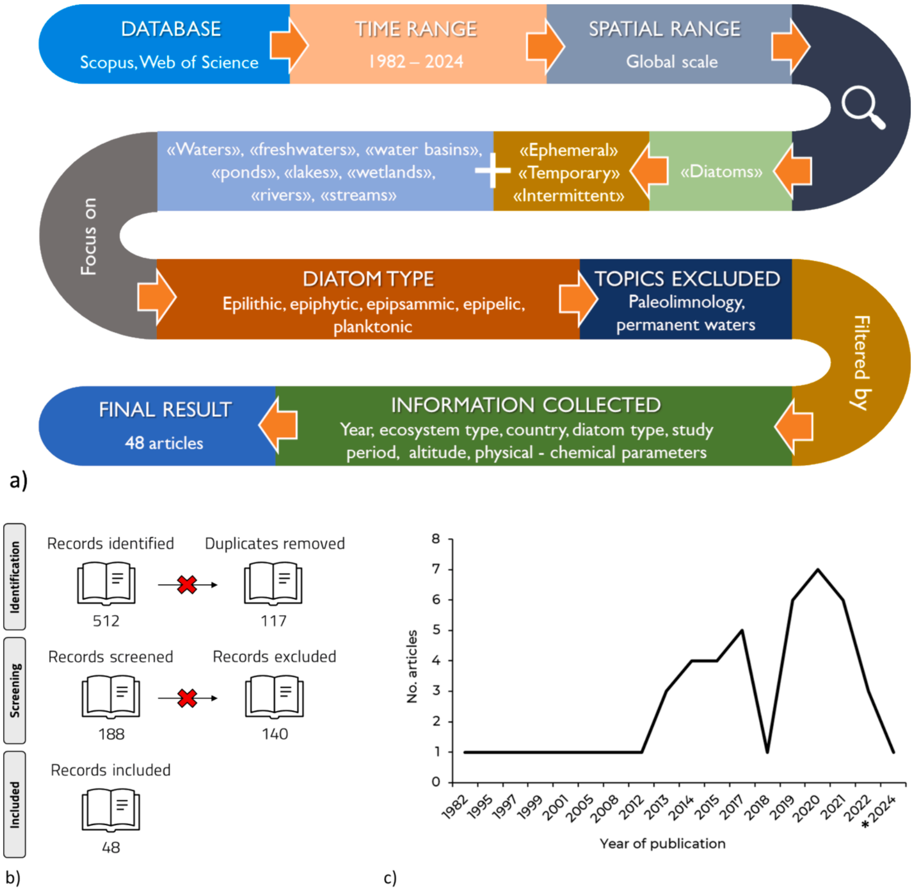

**Fig. 1.** Workflow of the bibliographic research (a), the PRISMA scheme followed for the selection of articles (b) and the temporal trend of literature about EW and diatoms (c). The asterisk (*) highlight that data available for 2024 are considered those until 24 March 2024 (last day of bibliographic research).

considering also chemical parameters like Total Nitrogen (TN) and water chemistry (pH) as important discriminant. Following Xu et al., (2019), wetlands can be considered a subset of lakes. Streams and rivers are distinguished by their flow and their fate: streams don't have mouths that exit into the oceans and seas, and they are more closely linked to wetlands in higher altitudes (Constantz et al., 2016). Instead, rivers are large, flowing bodies of freshwater that usually exit into the sea or ocean, with water sourced from several streams (Merz et al., 2021). Moreover, papers referring to diatoms in marine and brackish waters were not considered in the analysis. To avoid discrepancy between terminology and to simplify the categorization of different types of freshwaters we decided to unify and classify the EW found in 3 different categories: Intermittent Running Waters (IRW: rivers, streams, creek, springs) included in lotic EW ecosystems, Temporary Large Wetlands (TLW: wetlands, lakes, lagoons) and Temporary Small Waters (TSW: ponds, pools, ventaroles, ditches, thermal waters, troughs, pans) included in lentic ones (Fig. 2).

Studies on EW through the analysis of diatom communities are more frequent for IRW (26), followed by TSW (16) and TLW (15) (some papers take into consideration more than one ecosystem type). Considering the lentic-lotic character, studies on EW and diatoms are more frequent for lotic (39) than lentic EW (18).

#### 3.1.3. *Study areas overview*

Overall, 20 countries are reported to be investigated, included Antarctica (Table S1). Obviously, ecological distributions of diatoms are not linked to the political division of countries: however, investigating their distribution among countries make comparisons easier to realize and understand. The papers selected show an important heterogeneity among the countries. The most studied countries are Portugal (9) and Spain (9), followed by South Africa (4), Antarctica (3), Hungary (3) and Italy (3) (Fig. 3). The number of papers varies among continents: Europe (29), Asia (2), Africa (7), North America (3), South America (2), Oceania (2), Antarctica (3). Some geographical regions are taken into consideration more than others, like Balearic Islands, Fuente de Piedra and the Carpathian Basin.

#### 3.1.4. *Author's affiliate country*

Although the majority of studies have been conducted in the same country of the author's affiliate country, there are some exceptions: the researches conducted in Antarctica were performed by researchers from Poland (1) and Czech Republic (2) (see Kochman et al., 2018; Skacelova et al., 2014; Kopalova et al., 2013), a research conducted in Senegal was performed by authors with an affiliation belong to a France research institution (see Beauger et al., 2019) and a research conducted in Mexico was performed by researchers belonging to German research institutions (see Mora et al., 2015). Researchers from Portugal, Spain and Hungary are the most active on the assessment of EW condition through the use of diatoms in their countries, while researchers from Czech Republic are the most involved in studies in Antarctica.

### 3.2. *Methodological approach*

#### 3.2.1. *Topics of investigation: Diatom analysis,substrate type and main aims*

Overall, 5 different types of diatoms were sampled. Epilithic diatoms were the most sampled (52 %), followed by epiphytic (19 %), planktonic (15 %), epipelic (10 %) and epipsammic (4 %) (Fig. 4). In IRW, epilithic diatoms were the most sampled (75 %), followed by epiphytic (11 %), epipsammic (7 %), epipelic (4 %) and planktonic (3 %); in TLW, planktonic (43 %) and epiphytic (43 %) diatoms were the most sampled, followed by epilithic (14 %); in TSW epilithic diatoms were the most sampled (35 %), followed by epiphytic (29 %), epipelic (24 %), epipsammic (6 %), and planktonic (6 %).

Sampling choice is strictly related to the substrate type and substrate availability. Overall, 85 % of the studies used benthic diatoms over planktonic ones. Benthic and planktonic diatoms show different seasonal variations in species richness and, while the former type is affected by spatial processes (Chen et al., 2019; Rimet et al., 2019), the latter type is affected the most by environmental processes (Pan et al., 2020; Bartozek et al., 2019); the use of benthic diatoms as biotic indicator group over planktonic ones is widely spread because they show stronger correlations with environmental factors (Hu et al., 2022). In some cases, due to the shallow depth of the EW considered, differentiation between benthic and planktonic communities could be difficult to recognize. The papers considered performed phytoplankton samplings at 25 or 30 cm deep. Overall, 85 % of the papers reviewed counted up to 400 valves for each slide.

Moreover, the main analysis (81 %) performed emerged is the taxonomic analysis of the diatom assemblages in EW. In most of articles (61 %) the taxonomic analysis was linked to the evaluation of the ecological status of the EW considered (including the environmental variables and environmental stressors); other articles (38 %) focused on the description of the study sites providing a checklist of the diatoms identified; one article (1 %) focused on the geographic variables influencing diatom communities.

The remaining articles (19 %) focused on diatom communities functional analysis (diatom traits). Biological traits represent the functional response of a community to changes in the environment (Wang et al., 2022).

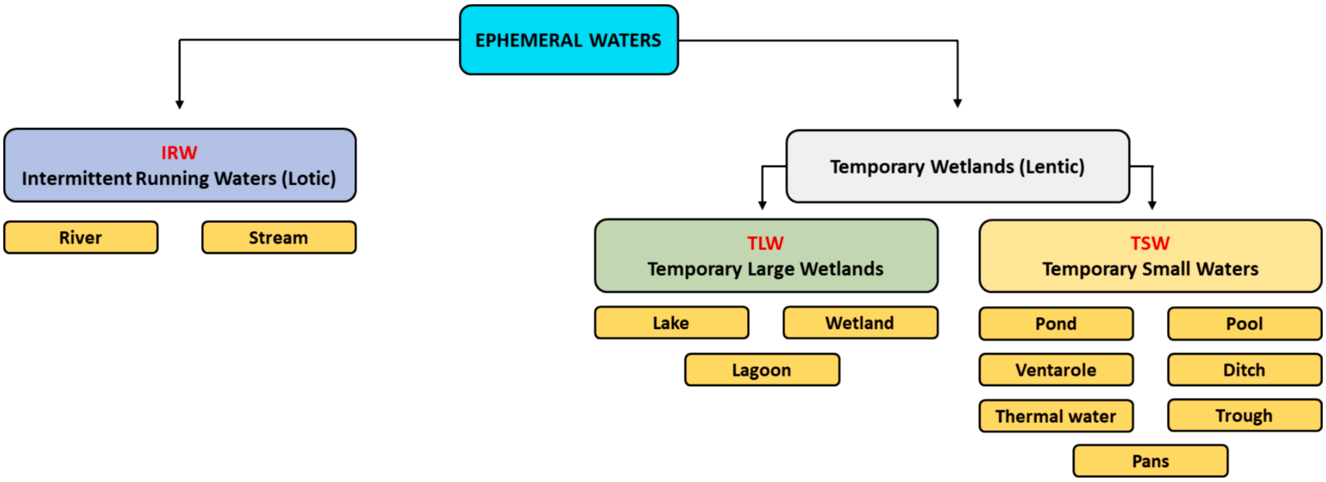

**Fig. 2.** The classification proposed for the EW found.

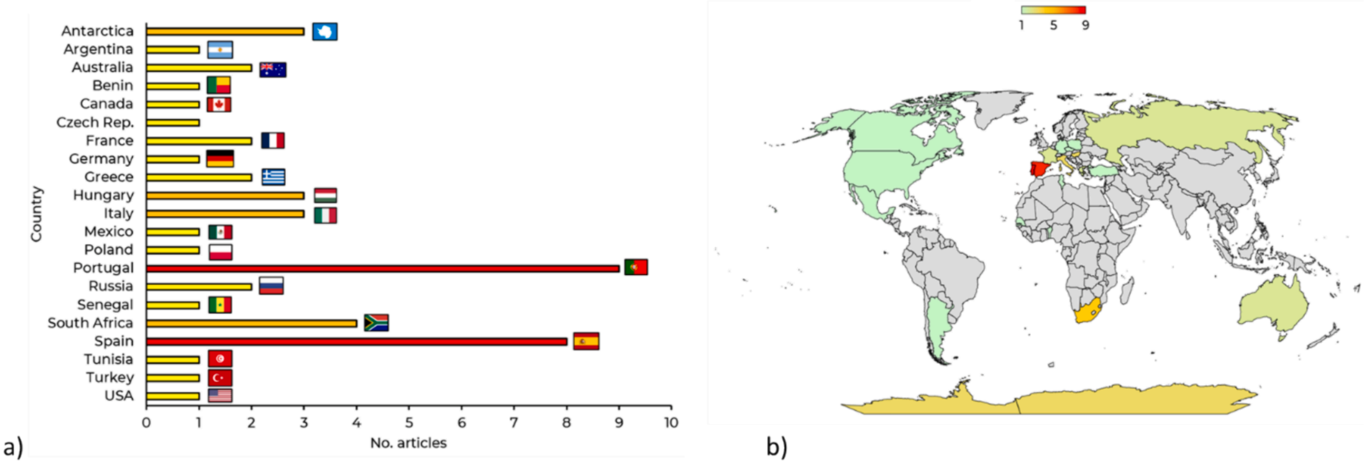

**Fig. 3.** The investigated countries with relative number of studies conducted (a) and the geographical representation of study sites (b) (No. articles = number of articles).

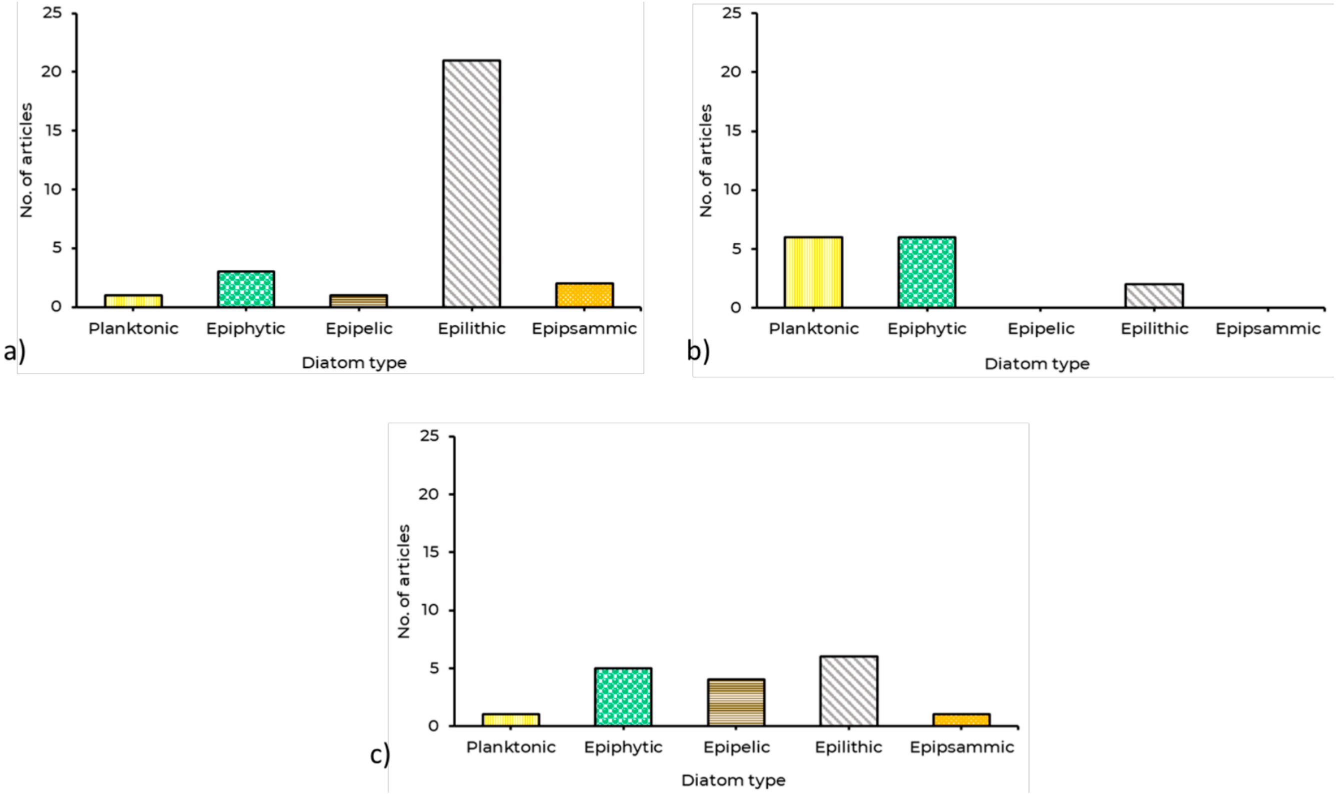

**Fig. 4.** Diatom types and related number of articles divided for Intermittent Running Waters (IRW, a), Temporary Large Wetlands (TLW, b), Temporary Small Waters (TSW, c) (No. articles = number of articles).

### *3.2.2. Temporal effort of sampling*

The reviewed papers show a different distribution of the study periods throughout the year, with a heterogeneity in the studies conducted in the northern hemisphere and a homogeneity in the studies conducted in the southern hemisphere. The *t*-test performed show significant differences ($t = 6.03$, $p < 0.05$) between sampling months in the northern and the southern hemisphere, where March, April and May are the months most involved in this kind of studies in the northern emisphere (Fig. 5a).

Another important aspect to consider in research on EW is the duration of the research in terms of months (Fig. 5b). The reviewed papers showed a similar trend in the selection of samplings duration. Specifically, 28 % of the studies sampled for one month, 14 % for two months, 22 % for three months, while 24 % covered a sampling period of half a year (12 %) or an entire year (12 %).

### *3.2.3. Spatial effort of sampling*

Overall, a total of 1018 temporary water-sites were sampled all over the world; the largest number of sites were considered for IRW (683), followed by TSW (239) and TLW (96) (Table 1).

The highest number of sites were sampled in Spain (317), Portugal (271) and Turkey (100). In IRW, the highest number of sites were sampled in Spain (266), Portugal (214) and Hungary (56); in TLW the highest number of sites were sampled in South Africa (38), Antarctica

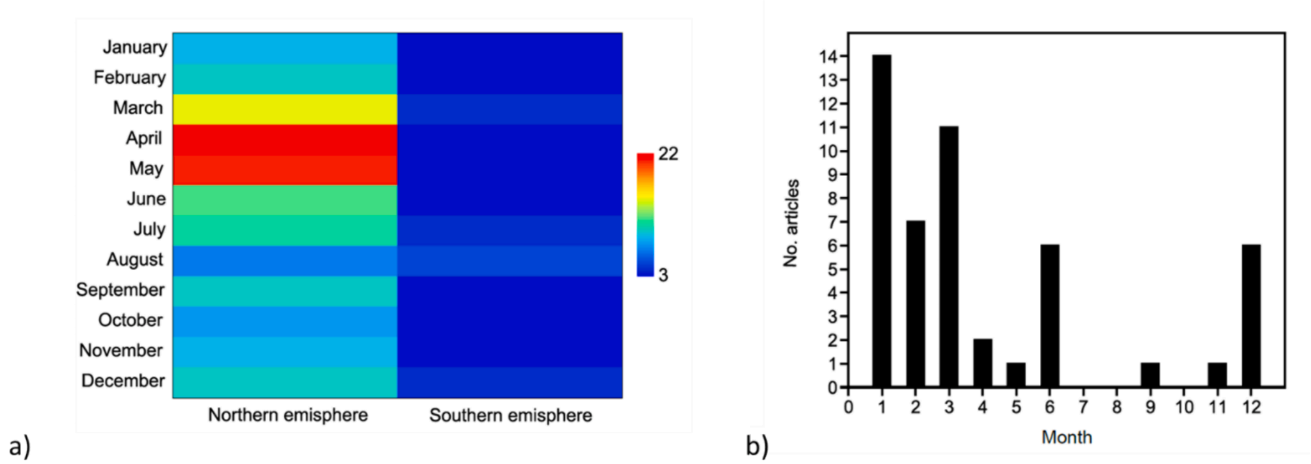

**Fig. 5.** Months coverage by articles (expressed in number) (a) and number of articles and relative number of months of sampling (b) (No. articles = number of articles; No. months = number of months).

**Table 1**
Distribution of study sites among countries and relative number of sites (IRW = Intermittent Running Waters TLW = Temporary Large Wetlands TSW = Temporary Small Waters).

| Country | IRW | TLW | TSW | TOT |
|---|---|---|---|---|
| Antarctica | 8 | 29 | 33 | **40** |
| Argentina | | 4 | | **4** |
| Australia | 23 | | | **23** |
| Benin | | | 78 | **78** |
| Canada | | | 1 | **1** |
| Czech Rep. | | | 4 | **4** |
| France | | 3 | 4 | **7** |
| Germany | 3 | | | **3** |
| Greece | 8 | | | **8** |
| Hungary | 56 | | | **56** |
| Italy | 49 | 2 | | **51** |
| Mexico | 6 | | | **6** |
| Poland | | | 1 | **1** |
| Portugal | 214 | 1 | 2 | **217** |
| Russia | 3 | | 26 | **29** |
| Senegal | | | 1 | **1** |
| South Africa | | 38 | | **38** |
| Spain | 266 | 2 | 49 | **317** |
| Tunisia | | 3 | | **3** |
| Turkey | 47 | 13 | 40 | **100** |
| USA | | 1 | | **1** |
| | **683** | **96** | **239** | **1018** |

(29) and Turkey (13); in TSW the highest number of sites were sampled in Benin (78), Spain (49), Turkey (40) and Antarctica (33) (Fig. 6). As regards the continents, Europe shows the most sampled sites (725), followed by Africa (120), Antarctica (70), Asia (29), Oceania (23), North America (8) and South America (4).

### 3.3. *Influence of abiotic parameters*

#### 3.3.1. *Altitude*

From the analysed literature emerge an altitudinal gradient, of the sampling sites considered. Overall, 47 % of articles refer to sites located on an altitude between 0 and 400 m a.s.l., 13 % refer to sites between 1600 and 2000 m a.s.l., 10 % refer to sites between 400 and 800 m a.s.l., only one site between 1200 and 1600 m a.s.l. and zero sites between 800 and 1200 m a.s.l., while 12 articles don't show any information about the altitude of sampling sites (Fig. 7).

#### 3.3.2. *Physical-chemical parameters*

Ten studies over the 47 total studies didn't take into consideration any physical–chemical parameter of the water bodies. Physical-chemical parameters are taken into consideration in 78 % of the studies. The results of physical–chemical parameters analysis attest that electrical conductivity (37), pH (36) and temperature (35) are the parameters mostly investigated, followed by dissolved oxygen (27), phosphate (26) and nitrate (26) (Fig. 8). Low attention is given to water depth (1), turbidity (4) and chlorophyll *a* (6).

In EW, diatom communities are mainly influenced by electrical conductivity and pH (Novais et al., 2014). Other important abiotic factors are temperature (Celewicz and Goldyn, 2021; Dalkiran et al., 2020; Novais et al., 2020), nitrate (Witteveen et al., 2020; B-Béres et al., 2019; Beauger et al., 2019; Ben Naceur et al., 2013; Macedo et al., 2001), nitrite (Novais et al., 2020; Witteveen et al., 2020; Ben Naceur et al., 2013; Macedo et al., 2001), sodium (Luís et al., 2019; Kovaleva et al., 2014; Novais et al., 2014; Riato et al., 2014, dissolved oxygen (Novais et al., 2020; Karaouzas et al., 2017; Ben Naceur et al., 2013; Macedo et al., 2001), alkalinity (Beauger et al., 2019; Novais et al., 2014; Riato et al., 2014), chloride (Beauger et al., 2019; Kopalová and Van de Vijver, 2013; Riato et al., 2014) and sulphate (González-Paz et al., 2020; Kopalová and Van de Vijver, 2013; Luís et al., 2019), which were generally higher for taxa characteristic of temporary watercourses. In IRW, the main abiotic factors influencing diatom communities are electrical conductivity, pH and nitrate, followed by temperature, nitrite, sulphate e sodium. Similar positive correlations occurred in TLW, with electrical conductivity, pH, temperature, dissolved oxygen, nitrate, and nitrite influencing mostly diatom communities. In TSW, electrical conductivity, pH, temperature, sodium, and chloride result the main abiotic factors influencing diatom communities.

## 4. Discussions

This work represents a complete and global overview about the use of diatoms to evaluate the conservation status of EW. The scientific literature collected for this work includes all the articles based on field data from EW. Lentic EW ecosystems resulted less studied than lotic EW ones. The data we gain and transposed into this review highlight the importance of the temporal and spatial scale at which studies were conducted.

### 4.1. *Ephemeral freshwater ecosystem types*

In the last 25.000 years freshwater ecosystems have undergone a transitional environmental and morphological changes: some lakes dried up, some rivers transformed into small creeks and temporary pools get a permanent shape, while permanent ones translated into ephemeral

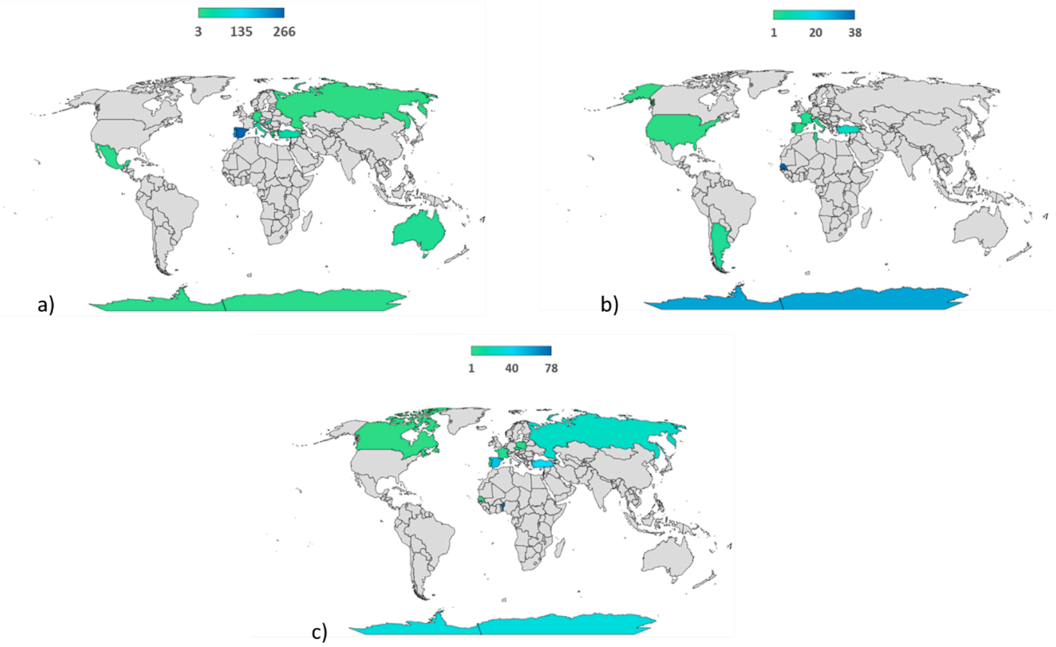

**Fig. 6.** Geographical distribution of study sites expressed in number for Intermittent Running Waters (IRW, a), Temporary Large Wetlands (TLW, b), Temporary Small Waters (TSW, c).

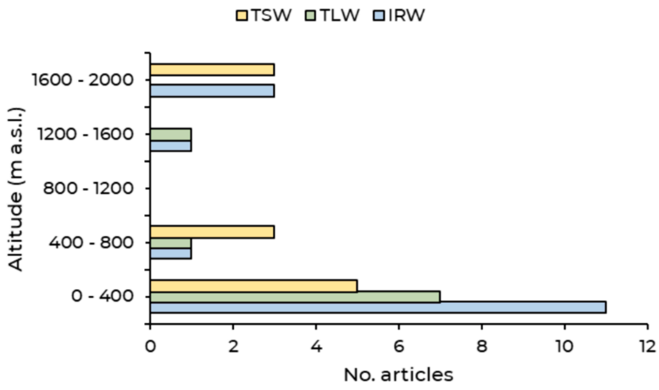

**Fig. 7.** Altitudinal distribution of study sites expressed in number of articles (IRW = Intermittent Running Waters TLW = Temporary Large Wetlands TSW = Temporary Small Waters) (No. articles = number of articles).

(Carpenter et al., 1992). In total, 67 % of literature analysed in this review refers to lotic EW ecosystems, while 33 % refers to lentic EW ecosystems. Historically, millions of humans across the globe depend on rivers and streams for numerous ecosystem services (Mammides, 2020); the ecosystem services provided by rivers and streams can support all the basic necessities for the survival and developmental needs of mankind (Ekka et al., 2020). This led into an important footprint of human on EW, that requested even more conservation projects. The emerging concern about the conservation of freshwater ecosystems through diatoms focused the most on IRW, for the historical reasons overquoted and also because, in literature, there are manuals, indexes and guidelines only referring to these ecosystems, while TLW and TSW conservation methods follow them, with some adaptation.

### 4.2. Global distribution of study sites

According to scientific literature, 55 % of the studies were conducted in the Mediterranean region. Based on our results, Portugal and Spain have the highest number of articles, showing a moderate sensitivity on this topic. South Africa, with its Mediterranean biogeographical region, follows Spain as regards the number of studies: following, there are Antarctica, Italy and Hungary. The results fit with data emerging from continents analyses: in Europe and Africa, both adjoining with the Mediterranean Sea, there is the highest number of sites. Antarctica, where climate change highly affects EW, follows Africa as regards the number of sampling sites, while Asia, the continent with the higher surface area (44.579.000 km$^2$) is only represented by Russia. In North and South America were considered only 12 sites, that is half of the sites considered for Oceania, which surface area is lower than 5 times respect that of the Americas.

Lotic EW sites are mostly studied in the Mediterranean region: 95 % of the stream sites (except for 5 % represented by Australia) and 91 % of the river sites. Lentic waters are less studied. There is a lack of studies about TLW through the use of diatoms as bioindicators: in particular, only 4 % of the sites are wetlands and, about these, more than 80 % are in South Africa. The distribution of TLW sites is highly heterogeneous, covering only three countries: South Africa, Turkey and France; there are no studies focusing on diatoms and TLW in the rest of the world. In addition, the data obtained show that 58 % of the lakes considered are in Antarctica, while only one site has been considered in North America and zero in Asia. According to Alonso (2009), there are numerous TLW in Asia, but they have never been inventoried. Instead, there are no data regarding the number of TLW in North America: this leads to an important gap of information regarding EW and their ecology.

TSW are mostly studied in the Mediterranean region, with 40 % of the study sites, followed by Africa with 33 % of the sites. However, TSW studied in Benin (78) are artificial sites, not referable to natural TSW. TSW, in general, are common ecosystems in the Mediterranean region, but also northern Europe, North America, Australia and South Africa (Zacharias et al., 2007). TSW are of particular concern in Spain, where, in Doñana National Park, most aquatic habitats are temporary (Díaz Paniagua et al., 2010). TSW are very important habitats and resources for people inhabiting rural areas in Africa: they provide numerous ecosystem services and are an important source of water for wild animals, domestic animals and human communities (Zongo et al., 2017).

The data obtained are not only referable to the countries found, but also to those countries which did not appear in the research. For

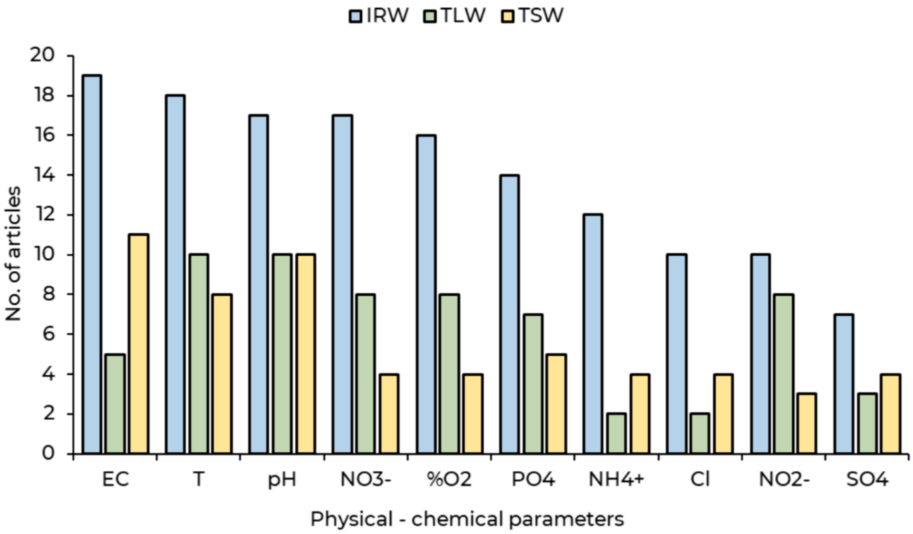

**Fig. 8.** Principal physico-chemical parameters taken during the studies (IRW = Intermittent Running Waters TLW = Temporary Large Wetlands TSW = Temporary Small Waters) (EC = electrical conductivity; T = temperature; No. articles = number of articles).

instance, China is the fourth largest country in the world as regards the surface size (9.596.961 km2) but become the first largest country without any study about diatoms and EW. In China there are over 3000 lakes, over 1500 rivers, while wetlands total area accounts for 10 % of global wetlands and 5.58 % of China's territorial area (Meng et al., 2017). Despite this, no studies have been conducted on EW in China using diatoms, highlighting the negligent scarce use of this biological model. However, the lack of studies could refer to the indexed journals used by the search engine. In this way, it could be possible that some studies were published in other languages and/or published in other platforms not recognized by the search engines used.

Moreover, assessing the reasons for the heterogeneous distribution of study sites between the two hemispheres represents a challenge. One reason could be found in the uneven distribution of EW worldwide. According to our results, most of sites are located outside of the "Torrid Zone", the portion of the Earth between the two "tropics". The high temperatures characterizing the equatorial region could generate higher evaporation rates as described by Trambauer et al (2014) for Africa. Arid and hyper-arid areas in Africa are characterized by a very low evaporation rate. In these conditions, EW hydroperiod often become lower or almost null. Moreover, global threats like climate change, could highly affect the EW hydroperiods: the subtropical zones, considered the most arid zones of the globe, will face decreases in precipitations amounts, affecting the water supply. It's important to consider that landmasses in the northern hemisphere are four times larger than those in the southern hemisphere (Box, 2002). Moreover, the southern hemisphere, unlike the northern one, includes a much wider band of equatorial and subtropical areas where, for the reasons mentioned above, the development of EW is more complex. The temperate zone, much larger in the northern hemisphere, is more suitable for the development of EW (Williams, 2006).

A relevant knowledge gap is that the worldwide description of the ecological status of EW ecosystems using diatoms is lacking. For instance, only 96 TLW over the globe have been studied through the use of diatoms as biological model; furthermore, in larger countries like USA and Canada, showing a cumulative surface area of 19.819.000 km$^2$, only one TLW and one TSW have been studied using diatoms, while zero IRW have been considered.

The largest number of sites considered for the Mediterranean basin can be related to the importance that this biogeographical region has from an ecological point of view: Mediterranean region is considered part of the first 25 Global Biodiversity Hotspots due to its unique biological and ecological diversity (de Figueroa et al., 2013). Moreover, the Water Framework Directive (WFD, 2000/60/EC) recognize diatoms as biological models for the evaluation of the quality of all water bodies at the river-basin level across Europe (Allan et al., 2006). The Europe, with the WFD, is at the forefront as regards the water quality biomonitoring using diatoms, which are particularly successful in detecting eutrophication, organic pollution and acidification. The implementation of the WFD lead also to an increase in the awareness about the importance of water quality assessment by countries all over the world, which started considering adopting similar legislations and assessment methods (Masouras et al., 2021), for instance: in North America, the US is using biomonitoring through the Clean Water Act; in South America, Argentina has developed its own diatom-based indices for assessing water quality (Pampean diatom index); In Australia, phytobenthos has been used for biological quality assessment for many years but without a precise legislative reference; in Asia, with the Asian Pacific Water Summit in 2007, water quality assessment became an ecological priority (Masouras et al., 2021).

### 4.3. *Types of diatoms,sampling methods and substrate selection*

In EW, although occasionally found in the water column as planktonic diatom cells, they are mainly considered benthic diatom species, i. e., attached on substrates such as aquatic plants (epiphytic), stones (epilithic), silt or clay (epipelic), sand (epipsammic), animals (epizoic) or plastics (epiplastic) (Taurozzi et al., 2023; Masouras et al., 2021). Benthic diatom assemblages are often associated with flow intermittency, which can influence variations in the diversity, composition, and trait patterns of diatom communities (Tornés et al., 2021). Moreover, the community structure of benthic diatoms is conditioned by physico-chemical parameters as dissolved oxygen, light, temperature and pH, which in turn may experience strong fluctuations in EW (Novais et al., 2020). With the typical dry periods which characterize EW, the planktonic diatom communities are often lost. Benthic diatoms show physiological adaptation to dryness, which can provide a quick recovery in the wet periods. Moreover, the analysis of benthic diatom assemblages in dry biofilm can be used as an indicator of ecological status during the dry-phase (Novais et al., 2020; Stubbington et al., 2019).

Diatoms can be sampled following different methodologies. Epilithic diatoms can be sampled scrubbing the upper layer of at least five cobble-sized rocks, stones, rocks, artificial substrates, collected at approximately 0.5 m depth (Kennedy and Buckley, 2021; Salmaso et al., 2019), according to European Committee for Standardization guidelines (CEN, 2003). Following Riato and Leira (2020) and Sanal and Demir (2018), epiphytic diatoms can be sampled pooling healthy established submersed macrophyte stems from different individuals of the same species at 5–20 cm below the water surface, placing them into a zip lock bag with a small amount of distilled water and shake for two minutes to dislodge epiphytic diatoms (Zimba and Hopson, 1997). Epipsammic diatoms samplings can be performed pressing a petri dish lid into the top layer of sand to a depth of 5–7 mm and then cleaned of organic material using wet combustion with concentrated sulphuric acid following Bere and Tundisi (2010). Epipelic diatom samplings can be performed scraping sediments as deep as 0.5 cm in plots (Siregar, 2021) or using dissection corers (Hasrini et al., 2023). Planktonic diatoms are usually collected by a vertical net haul using a plankton net with mesh size of 20 μm from 0–30 m depth.

The literature reviewed didn't show important differences between diatom sampling methods among different ephemeral freshwater ecosystems. Most of articles regarding IRW refer to the standard methodology proposed by CEN (2003) for the routine sampling and pretreatment of benthic diatoms from rivers (Kelly et al., 1998):

i. A single substratum should be used at all sites included in a survey;
ii. Areas of the riverbed with naturally occurring moveable hard surfaces (large pebbles, cobbles and boulders) are recommended wherever possible;
iii. A segment of river that has substrata suitable for sampling should be selected: this should be about 10 m in length, but longer lengths may be appropriate, depending upon the physical uniformity of the river and the availability of substrata. Areas of heavy shade should be avoided. Zones of very slow current (approx. $\leq$ 20 cm $s^{-1}$) should be avoided. "Riffles" are preferred, as these tend to have a good variety of natural hard surfaces;
iv. At least five cobbles should be sampled. However, if cobbles are unavailable, then either 5 small boulders or 10 pebbles should be sampled. An area of approximately 10 $cm^2$ or more should be scraped.
v. In case of epiphytic diatoms, sampling should be performed during the flowing phase, from emergent macrophytes growing in the free-flowing parts of the riverbeds (B-Béres et al., 2019).

Also regarding TLW, the Water Framework Directive guidelines (WFD: European Union, 2000) represent the main reference for the monitoring of the ecological status of water bodies; the principal recommendations from WFD were summarized by King et al. (2006), highlighting that the guidance standard that is already available for rivers (CEN, 2003) was also applicable to TLW:

i. A single substratum should be used at all sites included in a survey;
ii. Epilithic diatoms are preferable to be sampled. At least five cobbles should be sampled, each of them covering an area of approximately 10 $cm^2$ or more. Five stones are sufficient to eliminate major sources of variability within a substratum. This sampling strategy avoids the problem of host specificity or substratum variability associated with macrophytes;
iii. Sampling should be performed preferable in the euphotic zone to avoid differences in diatom communities in function of different depths and consequent light quantity fluctuations. CEN (2003) recommends avoiding heavily shaded areas and selecting sampling stations in open water, with limited surrounding vegetation. Sampling should occur from permanently-submerged substrata within a wadable depth. Sampling within the eulittoral zone at a depth of 30–50 cm would be necessary to avoid exposure and/or movement of the substrata in heavily wave-washed shorelines and reduce the risk of photoinhibition caused by very high irradiance at the lake margins.
iv. Considering natural seasonal and successional dynamics, it is impossible to recommend any single period of the year as the best time for sampling. It is, however, important that both spatial and temporal comparisons are made only on samples collected from the same season in order to minimise these effects;
v. The use of composite samples (made of numerous samples from different microhabitats) can circumvent small scale variation (i.e. on a scale of a few $m^2$).

As reported by King et al. (2006), the overriding concern is to ensure comparability between lakes (or wetlands), which is best achieved by a set of simple guidelines applicable with only slight modification to all water bodies. However, there is considerable natural variability between water bodies. This variability is reflected in the WFD, which requires that ecological targets are 'type specific' (i.e. take the geological and hydromorphological nature of the water body into account). This allows for some flexibility within sampling regimes permitting, for example, the substratum that is sampled to differ between water body types so long as all samples from a single water body type are from the same substratum (King et al., 2006).

Lastly, regarding TSW, sampling activities can be performed referring to TLW guidelines, as suggested by Blanco et al. (2020). Indeed, often can be only subtle differences between TLW and TSW and, as described by the CEN (2003), although the methodologies for evaluating the diatom data vary, the sampling and pre-treatment processes are similar for the different ecosystems considered.

Suggestions from King et al. (2006) are in accordance with our results. All the literature reviewed refer to benthic diatoms. Furthermore, half of the studies mainly focus on epilithic substrates, considering also artificial ones. Stones, rocks and artificial solid substrates are easy to sample, to recognize and to withdraw and usually present in greater number in lotic and lentic waters (Afifah et al., 2021). This type of substrate can also make it easier scraping activities and recognize the green diatoms biofilm, which coloration stands out from the usually grey background of stones. This sampling strategy avoids the problem of host specificity or substratum variability associated with macrophytes (King et al., 2006). Moreover, diatoms are easier to sample on epilithic substrates than in epipelic or epipsammic substrates, which need to be processed before the isolation of diatom communities (Adl et al., 2020). On the other hand, bioassessment methods based on epiphytic diatoms has been proved to be particularly effective for tracking changes in hydrolimnological conditions of floodplain lakes and ponds, in particular temporal ones, because of the high presence of macrophytes in shallow water bodies (Wiklund et al., 2010). Nevertheless, in soft, muddy water bodies where epilithic habitats may be lacking or limited and do not represent a significant component of the phytobenthos, epiphytic samples should be collected (King et al., 2006). In any case, it is important that comparisons between water bodies are based on samples from the same substratum.

The main aims of the literature reviewed confirm the tendency and the large use of diatoms as bioindicators (Srivastava et al., 2016): the assessment of ecological conditions and the main environmental and geographic drivers influencing diatom communities represent the main focus of most of articles. Moreover, taxonomic analysis provides important data about biological diversity, which is generally considered an indicator of the quality of freshwater systems (Leira et al., 2009). Although the use of diatom guilds is limited, it could provide important information and responses to local ecological factors, such as current velocity and resource supply, and geographical connectivity (Jamoneau et al., 2017). Furthermore, explaining diatom distribution by guild rather than straight taxonomic unit would provide much more insights. Ecological guilds can be considered a proxy for describing responses to: (i) different stressors and disturbances (Stenger-Kovács et al., 2013); (ii) environmental and spatial mechanisms (Jamoneau et al., 2017); (iii) changing water regimes (B-Béres et al., 2014); (iv) nutrient and disturbances gradients (Passy, 2007) and its use is encouraged by the authors. The tendency to investigate mainly the ecological status of EW reflect both the underrated nature of EW in terms of scientific attention and the evaluation of the increasingly anthropogenic impacts on these ecosystems (Chiu et al., 2017; Ortega et al., 2014; Zacharias and Zamparas, 2010).

### 4.4. Temporal effort of sampling protocols

The uniqueness of EW dwell in their characteristic dynamic nature, made of an alternance of wet and dry periods (Kulkarni et al., 2019). Despite the limited presence of niches because of the short lifetime of this habitats, restricted water availability forms a unique ecological condition influencing the evolution of an adapted biota community inhabiting them (Gilbert et al., 2021). The duration of hydroperiod length make important the definition of the study period while creating a protocol of analyses.

In the northern hemisphere, most of the studies focus on a temporal interval that goes from March to August, corresponding to the spring and summer seasons. The heterogeneity observed along the studies conducted in the northern hemisphere is compatible with the hydroperiod of EW, that is the most during the spring season (March, April, May): in these months the flow is at its maximum in low and high altitude TSW, because of the snow melting and rain (Pearce, 2018). Moreover, diatoms higher diversity is detectable in –spring and late summer (ISPRA, 2014), where EW flow is at its maximum.

On the contrary, the homogeneity observed for the southern hemisphere can be related to the different environmental features of the continents taken into consideration, in particular Antarctica and Africa, which show the maximum flow during different seasons: summer for the Antarctica (December, January, February) (Boxall et al., 2022), and late autumn/winter (May, June, July, August) for Africa (Ebodé et al., 2020).

Most of sites of the reviewed papers were sampled one month per year: this approach can give an important overview of the ecological situation and the diatom community structure in a precise time, but to give a complete panning of diatom community turnover and evolution over time is fundamental to repeat the samplings for longer periods (Adl et al., 2020). Diatoms spend 14 days to colonize new habitats and to give an exhaustive turnover overview of diatom species along a temporal gradient, sampling should be carried out for almost six or nine months (Taurozzi et al., 2023). However, given the restricted hydroperiod of EW, six months of sampling could be difficult to perform. Diatoms are ubiquitous and present throughout the year, so they can be sampled in all seasons. The greatest diversity of species is found in the periods May-June and September-October, periods with high light intensity and mild temperatures (ISPRA, 2014). The WFD, in the alpine zone, indicates summer as best period to sample diatoms in watercourses; however, the late spring- and early summer months in watercourses of glacial origin should be avoided because the high concentration of suspended solids can strongly alter the diatomic community, while, in the Mediterranean area, it is advisable to carry out sampling in the most suitable period from a biological point of view (ISPRA, 2014). Sampling protocols that cover an entire year can provide a comprehensive characterization of diatom communities. However, EW are characterized by restricted or prolonged dry periods which make impossible in most of cases sampling for 12 months. Moreover, only a few studies encompass a 12-month sampling period, primarily due to the ephemeral nature of EW, which typically allows for sampling periods of 3 or 6 months in most cases. Lastly, it is necessary to highlight that the existing standardized protocols mainly refer to permanent waters. From this emerges the need to investigate the applicable ecosystem health measures that may be transferable to ephemeral systems, as protocols to assess water condition has generally been developed from studies of permanent systems.

### 4.5. Altitudinal gradient

Hydroperiod is a key factor for EW, affecting its nature and the biota related with it (Madaschi and Díaz-Villanueva, 2021). As one ascends a mountain, environmental conditions change, and there are organisms that are commonly well adapted to the local conditions along an altitudinal transect. Literature address 'mountains' as any elevation of land mass from the plains 300 m or over above sea level (Kapos et al., 2000).

Considering abiotic factors influencing diatom communities, there are four primary atmospheric changes associated with altitude: (i) atmospheric temperature, which reduction can bring important implications for humidity; (ii) decreasing total atmospheric pressure and partial pressure of all atmospheric gases (in particular $O_2$ and $CO_2$); (iii) increasing radiation under a cloudless sky, both as incoming solar radiation and outgoing night-time thermal radiation; and (iv) a higher fraction of UV-B radiation at any given total solar radiation (Körner, 2007).

On average, air temperature drops by 5° C per kilometre of altitude (Gonfiantini et al., 2001); hence, across all plant life forms, there is no common altitudinal temperature trend to be expected. In this way, local and/or life form-specific, rather than global, patterns are likely to govern the degree of such departures from ambient conditions (Körner, 2007). Moreover, hydroperiod periods are shifted in mountain and lowland habitats: while precipitations are different in lowlands and highlands, affecting EW in different ways, the impact of snow on mountain habitats must be considered (Wickramagamage, 2016). Winter in mountain translate into presence of snow, ice and low temperatures, EW can be frozen for months, showing a long period of impossibility to be sampled; summer season means high-flow period for high-altitude EW, due to snow melting and following water availability (Lucianetti et al., 2020).

On low-altitude EW, seasons impacts are reversed: in winter EW are at their maximum flow, due to high precipitations and low temperatures and humidity, while during summer they show dry appearance and low flow (Ruiz Sinoga et al., 2011). On average, low altitude EW show a longer hydroperiod than high altitude ones (Eskinazi-Sant'Anna et al., 2020). For instance, in the northern hemisphere, EW on low altitudes can exist from September/October, until the end of May, while during the summer season they usually went dry. On the contrary, high-altitude EW fight a snow cover during winter and spring season and a partial wet period in summer, considering that also in mountain ecosystems, July and August high temperatures can seriously affect EW existence (Padula et al., 2021).

Regarding diatom communities, has been demonstrated that the altitudinal gradient hydrochemistry and different habitat features are the most important factors influencing their distribution than altitude and geographical position, but these factors are inter-correlated and very difficult to separate on their effects (Jüttner et al., 2010). A virtual limit on 2000 m a.s.l. has been described as important for species diversity: areas above and below this boundary show different species and should be considered separately when developing diatom – based monitoring projects (Juttner et al., 2010).

### 4.6. Physico-chemical analyses

Diatoms are important and sensitive bioindicators to assess water quality. The relationship between diatoms and environmental variables is often robust and quantifiable, and the sensitivity of diatom assemblages to environmental conditions did not differ between lotic and lentic habitats (Costa et al., 2022). Therefore, most of literature reviewed consider electrical conductivity, pH, and temperature as main parameters to relate with diatom assemblages. Electrical conductivity is a proxy for water salinity, that is strictly related to qualitative studies of diatom communities (Luostarinen et al., 2023). The total concentration of dissolved salts and the ionic composition of water are known to be important ecological factors influencing diatom distribution (Colla et al., 2022). The difference in salt content between marine and inland waters influence the local distribution of diatom communities and creates an important boundary that only a few diatom species can cross and in only one direction, from marine to freshwater habitat (Potapova, 2011).

Diatoms are found throughout inland waters in habitats spanning the full range of observed temperatures (B-Béres et al., 2022). Inland water temperatures are projected to increase over the coming century, with dramatic consequences for the biota: evidence from the field indicate temperature changes may lead to changes in diatom biogeography (Xiao et al., 2018). Each individual species and even strains within species have their own characteristic temperature performance curve, reflecting evolutionary constraints and past adaptations to its environmental regime; changing in the average temperatures can have heavy repercussions on diatom species assemblages. It is argued that diatom–temperature models are weaker than those developed for salinity, pH (Anderson et al., 2001), but is also clear that higher temperatures negatively affect diatom richness and also the composition of all functional groups (low-profile, high-profile, motile, and planktonic diatoms) (da Silva et al., 2019). Water temperature, which is highly dependent on altitude (Rivera-Rondón and Catalan., 2020), is also strictly related to hydroperiod length of ephemeral waters: air temperature is a key parameter, affecting many aspects of the ecology of aquatic biota (Carosi et al., 2022), increasingly frequent episodes of the early drying up of the ephemeral waters and, as a consequence, influencing the diatom community patterns.

The pH is also related with diatom richness: Wang, Strömgård, and Soininen (2019) surveyed subarctic ponds covering elevations from 10 to 1038 m a.s.l. and documented a unimodal richness–elevation trend, which was best explained by pH. It seems that variation in diatom richness along mountainsides is not only regulated by elevation and associated climatic gradients but may instead be more directly associated with local factors, such as the frequency of disturbances (Jüttner et al., 2010; Teittinen et al., 2016) or pH (Teittinen et al., 2017; Wang et al., 2022). The results of Bennet et al., (2010) suggest that pH can explain a large amount of variability, increasing with decreasing spatial scale: for instance, comparing the lake diatom pH optima in North America and Europe, they found that diatom pH optima were relative similar in the two continents, thus supporting niche conservation.

Comparing data from EW and permanent waters (PW), no differences emerged regarding the abiotic drivers for diatom diversity. In particular, as reported by Blanco (2014), temperature, pH, dissolved oxygen and alkalinity appears as the most important physiographical variable in terms of average variance captured in PW. These data are in accordance with our results, where electrical conductivity, pH, temperature, nitrate, and nitrite are the main abiotic factors influencing diatom communities. Climate has a profound effect on diatom dynamics, affecting diatom communities via its links with nutrient availability and temperatures; moreover, Blanco (2014) provides strong relationship between diatoms and pH in PW, due to the direct physiological influence of pH on diatom, especially in oligotrophic systems. On the other hand, most diatom assemblages appear to be unresponsive to a number of factors related to trophic status (e.g., nitrates, ammonia) in PW (Blanco, 2014). Nutrients also capture important fractions of variability in diatom assemblages across a large range of trophic levels (Blanco et al., 2014). However, the relative importance of nutrients depends on supply rates and on the order in which they are consumed (Blanco, 2014).

Even if diatom richness patterns are difficult to explain, some evidence for general environmental drivers exists. Among the most typical key variables are conductivity, temperature and pH (Benito et al., 2018a; Heino et al., 2010; Stenger-Kovács et al., 2013). Literature gained indicate different responses of diatom functional groups to electrical conductivity, temperature increase, changing in pH, showing the importance of considering ecological differences among functional groups to evaluate the possible consequences of variation in physiochemical variables. Given that abiotic factors are closely linked to the ecosystem considered, it is possible to conclude that diatom communities are strongly influenced by the ecosystem type.

## 5. Conclusions

Ecological and social importance of EW is widely proved and demonstrated. Last few years have seen an increase in conservation consciousness of EW, after many years of lacking approaches. Data from the scientific literature reveal that the assessment of diatom contribution to evaluate the ecological status of EW is poorly exploited, but highly sensitive and specific, providing exhaustive data about environmental alterations. Moreover, considering the large surface of land on earth and the relative surface extension of this type of ecosystems, studies on this topic are largely underrated.

Therefore, researchers are encouraged to engage an increasing data collection on diatom community structure, and on temporal and geographical turnover to their studies to implement the quality of the research. In this regard, chemical analysis of the water matrix can contribute to the characterization of the study site. EW are highly sensitive to climatic seasonal changes, like many diatom species: for this reason, physical–chemical parameters can differ among the seasons and can be highly suitable to associate precise chemical data to diatom species found to have a complete overview of the ecological situation. However, this methodology is based on chemical analysis which requires expensive equipment and generally long procedures. In this regard, the data sets provided here may help researchers conduct further research using metadata analysis in addition to (or by replacing) sampling and chemical analysis. Actually, regarding the application of diatoms in EW management programs recently increased but the lack of studies about high-altitude shallow waters is a further gap because it adds some difficulties in well understand how climate change affects mountain EW.

In conclusion, further investigations should be directed to the following:

- implement the study of EW worldwide using diatoms, which are very suitable bioindicators to evaluate the conservation status of EW;
- create a standardized protocol for EW management coupling data from diatoms and physical–chemical parameters, which could facilitate and enhance research on monitoring and risk assessment of EW;
- determining global threats to EW and harmonise the literature about the use of diatoms as bioindicators, in particular regarding benthic diatoms, which are generally easier to sample and to detect than planktonic ones.

In a world focused on the main themes of nature conservation, like climate change and anthropogenic pollution, the protection of EW is a central theme to investigate. Joint political and social focus on EW is the most important step to look forward to a flawless management of this threatened ecosystems, which ecosystem services provided can help to reach a better living for all mankind.

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## CRediT authorship contribution statement

**Davide Taurozzi:** Writing – review & editing, Writing – original draft, Investigation, Data curation, Conceptualization. **Giulia Cesarini:** Writing – review & editing, Validation. **Massimiliano Scalici:** Writing – review & editing, Validation, Supervision, Resources, Conceptualization.

## Declaration of competing interest

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

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

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