Biodiversity and Conservation
https://doi.org/10.1007/s10531-022-02466-x

ORIGINAL PAPER

An evaluation of freshwater monitoring programs in ILTER nodes and mountain national parks: identifying key variables to monitor global change effects

Francisco J. Peñas[1] · Mario Álvarez-Cabria[1] · Marta Sáinz-Bariáin[2] · María Pilar Mata-Campo[3] · Aaron Pérez-Haase[4] · Marc Ventura[5] · María José Polo-Gómez[6] · Carlos Alonso[7] · Ignacio Granados[8] · Mario Morellón[9] · Carmen Pérez-Martínez[10] · Ángel Rubio-Romero[8] · Presentación Carrillo[10] · Carmen Zamora-Muñoz[11] · María Valladolid-Martín[12] · Lluís Camarero[5] · Esperança Gacia[5] · Mariàngels Puig[5] · Teresa Buchaca[5] · José Barquín[1]

Received: 30 December 2021 / Revised: 22 July 2022 / Accepted: 5 August 2022

Abstract

Identifying and quantifying global change impacts on biotic and abiotic components of ecosystems is critical to promote an effective adaptation that increases the success of conservation strategies. To achieve this goal, global and regional assessment efforts require certain degree of harmonization on local monitoring programs to establish relevant comparisons at different spatio-temporal scales. Otherwise, the lack of harmonization might hinder the detection and assessment on the effects of human impacts. In this work we have compiled information on freshwater monitoring programs located in areas of intensive research and conservation interest: International Long Term Ecological Research (ILTER) nodes and mountain National Parks. We aimed at evaluating the quality and robustness of these programs to assess the impact of global change, addressing from the worldwide to the European and Spanish national scale. Results highlighted that freshwater monitoring programs lack a common strategy to monitor these ecosystems. Even at the continental and national scales, contrasting strategies and level of detail have been historically applied. Water quality, habitat and biodiversity are more commonly monitored than community structure and ecosystem functioning. Monitoring efforts on the Spanish Mountain National parks indicated differences on the targeted aquatic ecosystems. Rivers and lakes received a higher attention, while mires were rarely considered. Our results provide evidence that greater efforts should be directed towards constructing a coordinated strategy to monitor freshwater ecosystems at national, continental, and global scales. This strategy should involve a shared backbone of biophysical and biogeochemical variables for each habitat type on agreed protocols that are implemented across regions and administrative borders. Achieving this will support a substantial advance on the ecological research to

---

Communicated by Ricardo A. Correia.

Extended author information available on the last page of the article

further delineate proper conservation strategies to face the challenges imposed by global change.

Keywords Monitoring · Mountains · Freshwater Ecosystems · Research sites · Conservation areas

Introduction

At the end of the XX century a group of scientists set up the World Climate Research Programme (WCRP) with the aim of determining whether the world climate patterns were changing, and whether the causes were natural (e.g., glaciation-interglaciation periods) or aggravated as a consequence of human activities (see WCRP 1993). After decades of debate, the publication of the first part of the IPCC Sixth Assessment Report (IPCC 2021) has confirmed the unequivocal influence of human action on climate change, showing evidence of intensification and spreading across the planet. In addition, other programs, such as the International Human Dimensions Programme stated that human activity was also the cause of global changes on environmental conditions and on species distribution patterns, coining the term “global change” (Steffen et al. 2001). Global change effects pose a serious threat for the health and functioning of the biosphere (Hoffmann 2021; Malhi et al. 2020) and have important implications for human societies, including the availability of food, energy and water, the increase of environmental hazards, and the occurrence of new pathogens and diseases, among others (Steffen et al. 2004). Understanding how biotic and abiotic components of ecosystems respond to human related changes (e.g., new pollutants, land use and land cover change, climate change, dams, etc.) is paramount to find adaptation strategies for future scenarios (United Nations 2018) and design effective conservation strategies. To achieve this goal, monitoring programs need to be designed and implemented at different spatial and temporal scales to measure and detect abiotic and biotic changes (Parr et al. 2002; Wohner et al. 2019). Several proposals and programs have been developed worldwide for this purpose, with the most relevant being:

- The International Long Term Ecological Research Network (ILTER): composed of hundreds of research sites (i.e., nodes) covering a wide array of ecosystems (marine, continental, freshwater and terrestrial). ILTER focuses on node-based long-term research and monitoring to identify and understand environmental changes across the planet. This network was established in 1993. ILTER nodes have increased drastically in the last decade, reaching 800 nodes in 44 countries in 2016 (Dirnböck et al. 2019).
- The Geo Biodiversity Observation Network (GEO BON): a global social network and community created to coordinate efforts to design and implement national and regional biodiversity monitoring programs with the final aim of supporting decision-makers (Navarro et al. 2017).
- ICP-Waters: The International Co-operative Programme on Assessment and Monitoring of the Effects of Air Pollution on Rivers and Lakes (Kvaeven et al. 2001): Established in 1985, ICP-Waters collects hydrochemichal and biological data from more than 500 sites in more than 20 countries across Europe and North America.

ILTER network could be considered as the largest and most powerful international initiative to understand environmental change across the globe attending to the broad variety of environmental variables that are regularly measured in most of the nodes (climatic, hydrological, biodiversity, socio-economic, etc.). Freshwater ecosystems are particularly vulnerable to global change (Woodward et al. 2010) and hence, they represent priority ecosystems that should be monitored. In this regard, this globally distributed network of long-term biomonitoring and research nodes monitors multiple ecological components that are not currently considered simultaneously in other freshwater monitoring programs (e.g., Water Framework Directive in Europe, the Clean Water Act in the U.S., the National Water Act in South Africa, the National Water Management Strategy of Australia and New Zealand or the Water Act in Canada). For instance, in the European context, the Water Framework Directive (WFD) has been criticized for the overrepresentation of monitoring programs focused on the effect of nutrient or organic pollution (Kelly et al. 2016), while other potential impacts related to global change, such as hydrological and morphological pressures, had much less attention (Carvalho et al. 2019). Moreover, ILTER network covers the monitoring schemes of freshwater ecosystems (lakes, lagoons, big rivers, small streams, wetlands, etc.) of a large variety of characteristics, while the ecosystem typologies covered by the WFD monitoring network is confined in such a way that many water systems are not included, e.g., some wetlands such as mires, river basins < 10 km^2, or tributaries with less than 15 km length. Another strength of ILTER network is related to the metadata documentation system. In this regard, the Drupal Ecological Information Management System (DEIMS; see below) allows to easily search different information and data about nodes, staff and published results (Haase et al. 2016) although some limitations to data accessibility have been underlined (Ondei et al. 2018).

In the context of freshwater ecosystems, those located in mountain areas are recognized as very sensitive and vulnerable to changes in their environmental conditions (Beniston and Stoffel 2013). Mountain areas and their associated ecosystems have been recognized as “sentinels for global change”, as their physical and biological features show patterns of changes that are often more readily identifiable than in any other geographical settings of the globe (Gobi et al. 2014; Zamora et al. 2016). On one hand, altitudinal gradients facilitate space for time climatic change understanding (Michalet et al. 2014) and, on the other, they often have a low human impact due to remoteness that facilitates recording trace impacts (Kollmair et al. 2005). Moreover, the altitudinal gradients characteristic of mountain areas influence other key variables (e.g., temperature or slope) creating unique environments which shape biological communities (Körner 2007). All these characteristics accentuate the fragility and susceptibility of mountain freshwater ecosystems to changes on temperature and precipitation regimes associated with global warming (Schmeller et al. 2018) and changes in land use and land cover (Álvarez-Martínez et al. 2014; Paduel et al. 2016; Pérez-Silos et al. 2021).

On the socioeconomic dimension, mountain aquatic ecosystems are important for human societies as providers of essential natural resources and ecosystem services (energy, food, water, biodiversity, etc.; Barquín et al. 2015; Beniston and Stoffel 2013). As such, they have been historically considered conservation priority areas (Catalan et al. 2017) and about 17% of mountain areas worldwide have a protection figure (e.g., National Park; NP). This percentage supposes the 32% of the continental surface of the world´s protected areas (IUCN Mountain Specialist Group). Mountain systems are protected by environmental legislation worldwide, and different projects have been developed for monitoring the effects of global change on mountain areas at global (e.g., UNESCO GLOCHAMORE Project) and regional scales (e.g., The Eastern Rivers and Mountains Network in the USA; Save the Blue Heart of Europe in the Balkans region).

Despite the efforts carried out to generate common frameworks for the monitoring of freshwater ecosystems, there are still many gaps that need to be filled (e.g. Schmeller et al. 2017). In many cases, data compiled by monitoring programs do not comply with the minimum required design to properly evaluate the effects of global change (Wade 2006). Some of the shortcomings of these programs include: (1) the low periodicity of measurements; (2) the use of contrasting methodologies, and (3) the lack of a common set of essential variables/indicators to identify and quantify the effects of global change (e.g., climate or land use and land cover).

The main objective of the present study is to review and assess the potential of monitoring programs to evaluate the effects of global change on streams, lakes and mires at three spatial scales; (1) worldwide, (2) regional scale (Europe) and (3) local scale (Spain). At the worldwide scale we have analyzed the monitoring programs of 157 river and 150 lakes on the ILTER network; at the regional scale we have analyzed the monitoring programs provided by 28 European mountain NP; at the local scale we have analysed the monitoring programs in the 5 Spanish Iberian mountain NP. Beyond the general objective, this study aims to: (1) identify the set of biotic and abiotic variables measured on different freshwater ecosystems within different programs, and (2) to evaluate the quality of these programs to monitor global change effects according to a set of key variables.

Methods

Worldwide review

We used the DEIMS and dataset registry (DEIMS-SDR) to obtain a global list of ILTER nodes that are included in their Rivers (ILTER-Rivers) or Lakes (ILTER-Lakes) monitoring programs. DEIMS-SDR is a worldwide catalogue of *in situ* observation or experimentation facilities covering all biomes, allowing data associated with each site to be documented and accessible to the public and particularly to scientists (for more details see: Wohner et al. 2019; https://deims.org/). It should be noted this data hub does not contain raw data, but contains metadata associated to the type of variables monitored in each ILTER node. Moreover, the database is rather asymmetrical in the level of detail when describing sampling methods or specific variables monitored in each ILTER node.

The database was accessed on the 17 of February 2020 to retrieve information from sites that had an “active” status (i.e., the site is currently being operated) and “freshwater rivers” or “freshwater lakes” were annotated as their GEO-BON biome (Fig. 1). Then, we queried which variables were being monitored in each of the selected list of LTER sites. We filtered out variables that correspond to other biomes (e.g., forest or soil variables) except for atmospheric variables. Then, we classified the obtained list of variables on 5 types (atmospheric, water quality, physical habitat, biological and landscape) and on 32 and 34 subtypes for rivers and lakes, respectively (see Supplementary material Table S1). We only took into account for subsequent analyses the subtype level dropping those variables that were too

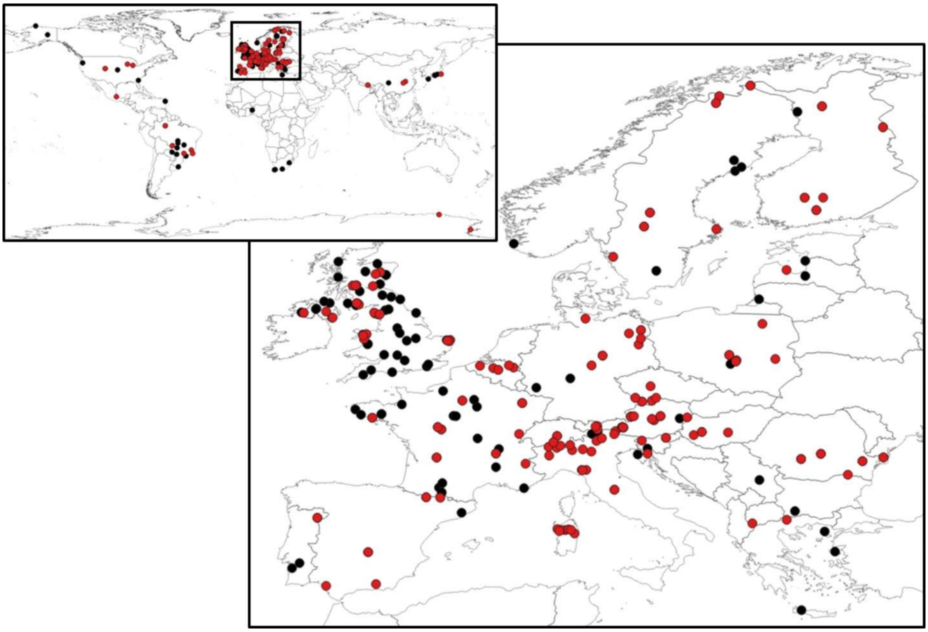


Fig. 1 Worldwide and European distribution of active LTER sites that monitor river (black circles; 157) and lake ecosystems (red circles; 150) included in the DEIMS-SDR database

general and not different to the type level (e.g., “ecosystem parameter” or “atmospheric parameter”).

Monitoring programs at the european level

To assess the monitoring programs carried out on aquatic ecosystems located within European Mountain National Parks (EMNP), we visited the official websites of 51 European countries (including Turkey, Azerbaijan, Armenia and Georgia; Russia was not included) to list all the EMNP. We selected those with altitudes higher than 800 m a.s.l. Following these criteria we identified 113 EMNP, belonging to 27 different countries. Then, we contacted the selected EMNP via e-mail. Moreover, we also contacted different national organisms/agencies responsible for the management of these EMNP (e.g., Environment Ministries), EUROPARC (www.europarc.org) and the Dinarides Parks Net (www.parksdinarides.org). E-mails were sent in October 2019, requesting information on the existing monitoring programs to assess the effect of global change on aquatic ecosystems. Specifically, we asked about the variables being measured, the periodicity of measurements and the type of aquatic ecosystem monitored (lake, river, mire, etc.).

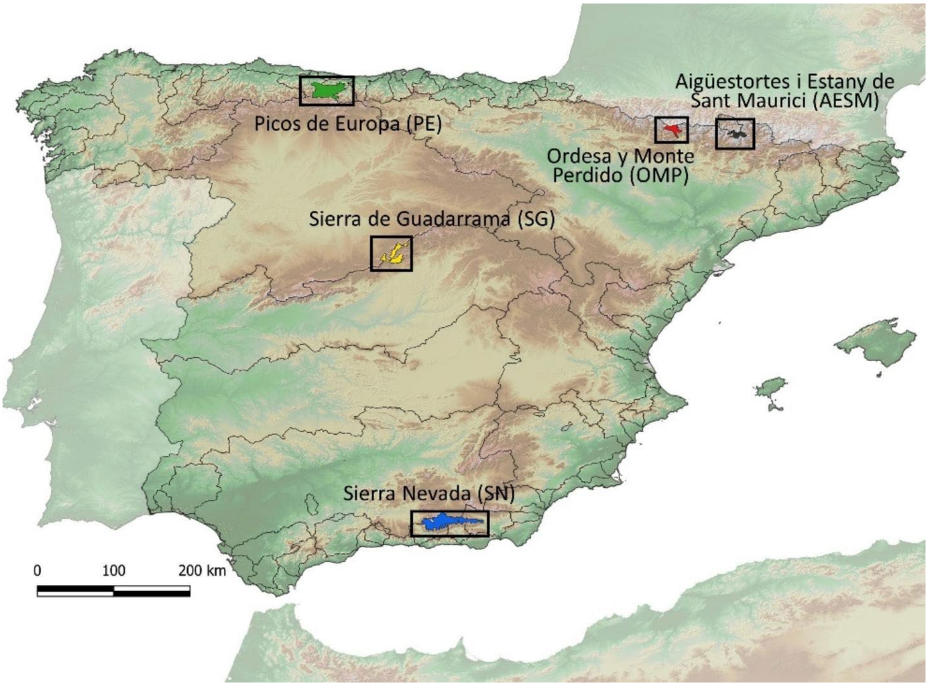


Fig. 2 Location of the five SMNP: Picos de Europa (PE), Ordesa and Monte Perdido (OMP), Aigüestortes i Estany de Sant Maurici (AESM), Sierra de Guadarrama (SG) and Sierra Nevada (SN)

Monitoring programs at the Spanish Mountain National Parks

Working partnership in the Spanish Mountain National Parks

At the most detailed scale, we assessed active or recent monitoring programs carried out in aquatic ecosystem, including rivers, lakes and mires, located within the Iberian Spanish Mountain National Parks (SMNP) network. This network consists in five SMNP (Fig. 2): Picos de Europa (PE), Ordesa y Monte Perdido (OMP), Aigüestortes i Estany de Sant Maurici (AESM), Sierra de Guadarrama (SG) and Sierra Nevada (SN).

We first compiled the information (research and technical reports) developed in these SMNP (2000–2018 period) from the repositories available in the organism that coordinates the management of all the Spanish National Parks (Autonomous Organism of National Parks; Spanish Environmental Ministry). We identified 20 projects and programs dealing with monitoring programs in the five SMNP, which are lead by 22 principal researchers and 12 different institutions. Based on this information we designed a query form to contact via email with researchers and institutions involved in these projects and programs, obtaining an affirmative answer and interest in participating in this consulting process from 18 of them. We further obtained 10 answered online questionnaires where we required information about the spatial and temporal design of the monitoring programs previously identified. Attending to the reviewed bibliography and the questionnaires, we organized the workshop "Synthesis of the monitoring programs of global change in aquatic ecosystems SMNP" on the 4 of December 2017, held in the headquarters of the Autonomous Organism of National Parks in Madrid, Spain. During the workshop, 12 short presentations took place to present the initiatives currently established in different SMNP to monitor global change in aquatic ecosystems, as well as the most relevant results obtained to date. The meeting ended with a round table of synthesis and analysis of the presented results.

The review of this information allowed us to identify a set of 40 environmental and ecological variables (Table 1; Supplementary material Tables S2 to S5) that would be potentially useful to assess and monitor the effect of global change on aquatic ecosystems on SMNP. These 40 variables were classified into 6 different types according to the environmental/ecological attribute they addressed: Climate and Hydrology (10); Water Quality (7); Physical Habitat (9); composition (6) and structure (6) of biological communities and Ecosystem functioning (4). In addition, monitoring programs were evaluated individually attending to the targeted ecosystems: rivers, lakes and mires. We also considered monitoring programs focused on hydrometeorological variables because they are intrinsically related to freshwater ecosystems and global change.

Evaluation of Monitoring Programs

We generated an assessment system based on scores (0–4) for the different relevant characteristics of a monitoring program (Table 2). We provided individual assessments for the monitoring programs in each one of the considered domains (hydrometeorology, rivers, lakes and mires), and taking into account the 5 types of variables described in Table 1 (except for cartography, see below). Specifically, we considered 5 relevant elements for each monitoring program as quality indicators: (1) Cartography; (2) Spatial design of the monitoring program; (3) Length of the historical series; (4) Frequency of the measurement and (5) Percentage of considered variables in relation to the maximum potential variables for each type. These quality elements have been largely highlighted as relevant to design good monitoring programs (e.g., Bartram and Balance 1986; Downes 2002). The cartography was evaluated based on the existence of cartography for river, lakes and mires in each SMNP, while the assessment was not segregated by the type of variable. The spatial monitoring design and the percentage of considered variables was evaluated for each type of variable in each domain. The duration and frequency of the measurements were evaluated independently for each variable (Supplementary material Tables S2 to S5) and the final assessment value was calculated as the average of the values of independent variables by type of variable).

Results

Worldwide review

The LTER-River dataset included 157 nodes and 214 variables to monitor river ecosystems, while LTER-Lake dataset had 150 nodes and 204 variables (see Supplementary material, Table S1). All these monitoring variables could be lumped into 31 major subtypes and 5 major types (Atmospheric, Landscape, Water chemistry, Physical habitat and Biological; Table S1). Only 21% of the LTER-River and 18% of the LTER-Lake nodes measured variables simultaneously in the 5 major variable types, while an extra 25% for river and 20% for

Table 1 Variables and type of variables identified as key indicators of global change in monitoring programs of the five SMNP. We indicated the domains/types of ecosystems in which they can be potentially used; (X) is used to indicate groundwater dependence

TYPE	VARIABLES	Hydro-meteorology	Rivers	Lakes	Mires
Climate and Hydrology	Air temperature, pressure and humidity	X			
	Precipitation	X			
	Solar radiation	X			
	Wind speed and direction	X			
	Soil temperature and humidity	X			X
	Nivology/snowfall	X			
	Permafrost	X			
	Discharge and water level	X	X	X	X
	Water table height	X	(X)	(X)	(X)
	Sediment Budget	X	X	X	X
Water physico-chemistry	Temperature		X	X	X
	pH		X	X	X
	Conductivity		X	X	X
	Suspended Solids		X	X	
	Gas Concentration (O_2, CO_2)		X	X	X
	Nutrients		X	X	X
	Dissolved Organic Mater		X	X	X
Physical Habitat	Hydraulic Characteristics		X	X	X
	Substrate Composition		X	X	X
	Characterization protocols		X		
	Morphology		X	X	X
	Water Level		X	X	X
	Duration of ice cover			X	
	Ice melt time			X	
Community composition	Microbiota and Fungi		X	X	X
	Algae and macrophytes		X	X	X
	Micro- and macroinvertebrates		X	X	X
	Fish		X	X	
	Other vertebrates		X	X	X
	Riparian Plants and Tress		X	X	X
Community structure	Microbiota and Fungi		X	X	X
	Algae and macrophytes		X	X	X
	Micro- and macroinvertebrates		X	X	X
	Fish		X	X	
	Other vertebrates		X	X	X
	Riparian Plants and Trees		X	X	X
Ecosystem functions	Primary Production		X	X	X
	Secondary production		X	X	X
	Fish production		X	X	
	OM decomposition		X	X	X

lakes measured variables in at least 4 of the 5 major variable types. Water temperature and depth where the most represented in monitoring programs in both, LTER-River and Lake (above 55% for river and 45% for lakes nodes; Fig. 3). Then, the most common variables

Table 2 Values of relevant elements used as quality indicators to assess the monitoring programs of hydrometeorology, rivers, lakes and mires in five SMNP. GIS: Geographical Information System; AEI: Associated Environmental Information; BA: Before-After; CI: Control Impact; BACI: Before-After Control-Impact

	0	1	2	3	4
Cartography	No data	No digitalized	Digitalized map	GIS database	GIS + AEI
Monitoring design	No data	No Design	Reference Condition	BA or CI	BACI
Historical record	No data	Spot Measures	< 5 years	5–10 years	> 10 years
Measurement frequency	No data	Spot Measures	< 1 campaign/year	1 campaign/year	> 1 campaign/year
%Variables reported	None	1–24,9%	25–49,9%	50–74,9%	75–100%

in LTER-River were water conductivity (55% of sites), suspended solids-turbidity (50%), nutrients (carbon: 50% or nitrogen: 48%) and pH (47%; Fig. 3 A). The biological variables most used in monitoring LTER–River where those related to the diversity of the biological communities (43%), the structure and composition of these communities (35%; mainly benthic macroinvertebrates, 10% of sites) and the water chlorophyll concentration (35%). LTER-Lake presented a slightly lower proportion of nodes in which water chemistry was monitored through conductivity (45%), suspended solids-turbidity (45%), nutrients (carbon: 41% or nitrogen: 37%) and pH (33%; Fig. 3B). Although diversity, community and alkalinity variables ranked a bit higher on importance in lakes than in rivers, their frequency of use in monitoring programs was similar to rivers (45%, 37% and 37%, respectively; Fig. 3). Remarkably, all physical habitat variables (except water depth), phosphorous and oxygen concentration among the water quality variables, and genetic and ecosystem functioning among the biotic variables, are the most underrepresented on LTER-River and LTER-Lake (less than 22% of nodes). Finally, only benthic invertebrate communities and water chlorophyll *a* in rivers and lakes have a reasonable number of sites to construct regional cover assessments, while many other biotic attributes are only collected from ILTER nodes within Europe (see Figure S1 in the supplementary material). Finally, it is important to remark that the DEIMS-SDR dataset did not always include enough detail about the type of variables, organisms/community monitored or the sampling protocols, what made difficult to reach a higher level of detail in our analyses.

Monitoring european mountain aquatic ecosystems

We contacted 113 EMNP (Fig. 4) of which 28 (25%) responded. From these 28, 17 (61%) confirmed that, currently, they are not carrying out any monitoring program to assess the effect of global change on their aquatic ecosystems. The positive responses (11; 39%) were from (Fig. 4):

- Spain. 5 MNP with monitoring programs on different aquatic ecosystems. A detailed description of these programs is included in Sect. 3.3.
- France. 4 MNP with a monitoring program on lakes (Sentinel Lakes Network; www.lacs-sentinelles.fr). This program analyses: water chemistry (2 times/year), chlorophyll concentration and the structure and composition of phytoplankton and zooplankton

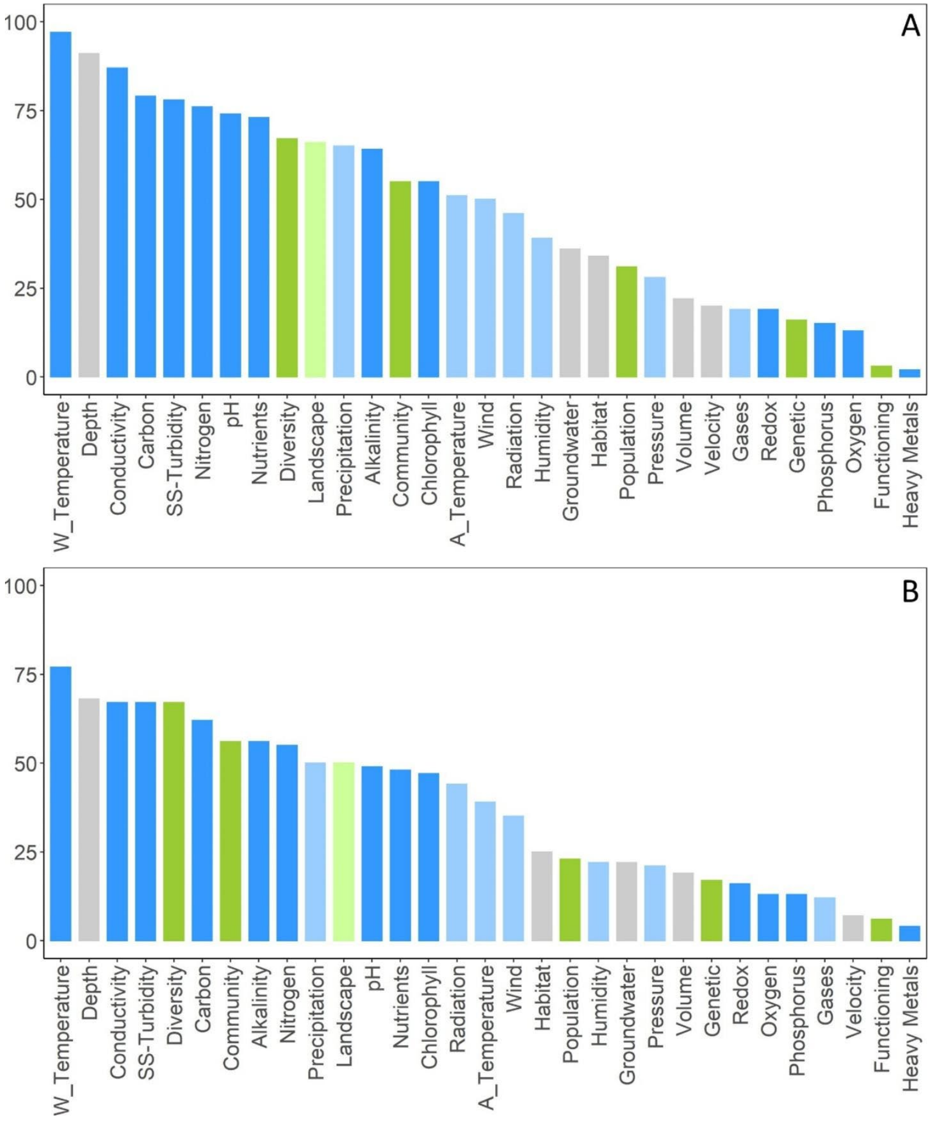
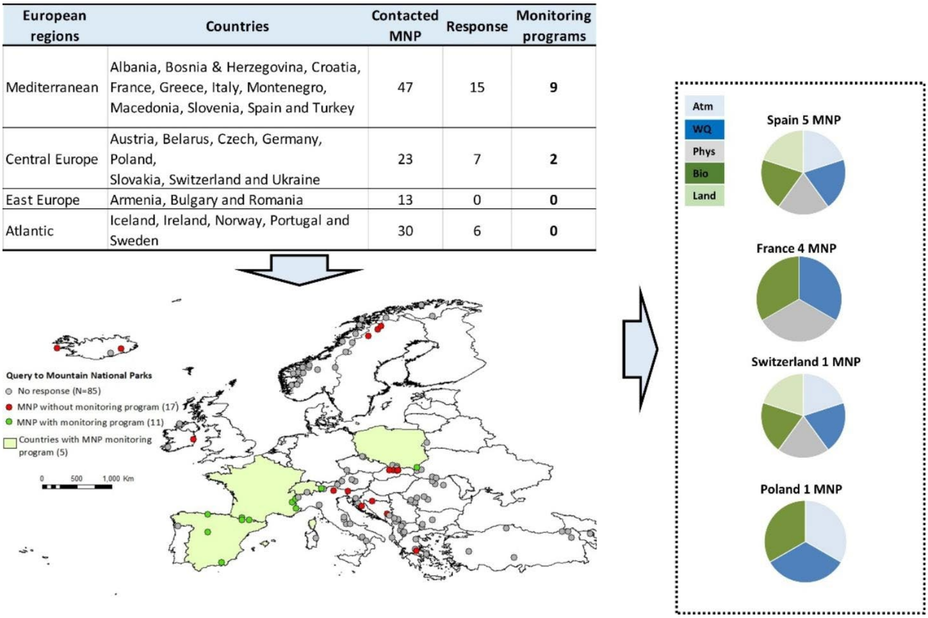


Fig. 3 Number of LTER River (A) and Lake (B) sites that use a given set of variables to monitor ecosystems. Light blue coloured bars are atmospheric variables, deep blue are water quality variables, grey ones are physical aquatic, green are biotic while light green landscape variables

communities. In this case, the environmental conditions and biological communities of these 4 MNP are analyzed following the same protocol, developing a common data base and a standardized long-term monitoring program.

- Switzerland. The only MNP in Switzerland has a complete monitoring program on rivers, lakes and reservoirs. This program includes the analysis of water quantity and quality, the biological communities (invertebrates, fishes, diatoms, etc.), and the physical



European regions	Countries	Contacted MNP	Response	Monitoring programs
Mediterranean	Albania, Bosnia & Herzegovina, Croatia, France, Greece, Italy, Montenegro, Macedonia, Slovenia, Spain and Turkey	47	15	**9**
Central Europe	Austria, Belarus, Czech, Germany, Poland, Slovakia, Switzerland and Ukraine	23	7	**2**
East Europe	Armenia, Bulgary and Romania	13	0	**0**
Atlantic	Iceland, Ireland, Norway, Portugal and Sweden	30	6	**0**

Fig. 4 Location of the 113 mountain National Parks (MNP) contacted in 27 countries of Europe. Number of MNP that responded to our contact and number of MNP that are conducting any monitoring program to assess the effects of global change on aquatic ecosystems. A pie chart indicating the type of variables measured in each country with MNP monitoring programs is also included. Light blue represents atmospheric variables, deep blue water quality variables, grey physical aquatic variables, green biotic variables and light green landscape variables

elements of the ecosystems (e.g., substrate composition and mobilization). For a more detailed description, see Schanz et al. (2012).

- Poland. The Bieszczady MNP has 4 automatic stations monitoring hydrometeorological variables (rainfall, temperature, wind, humidity, etc.; www.imgw.pl). This MNP also has a program of biological surveillance (diatoms, fishes and invertebrates).

Evaluation of monitoring programs at the Spanish Mountain National Parks

The type and quality of cartographic information describing the different type of ecosystems was very similar across the five SMNP. Cartography of rivers consisted of GIS databases representing the hydrographic network with associated environmental information (AEI) in the five SMNP. Differences in the river cartographic information were related to the amount and quality of this AEI. The most basic information included topographic variables (e.g., catchment area, reach slope, elevation), while the most complete AEI database provided geological, land uses and/or climatic information. Cartography of lakes was essentially composed of GIS shapefiles indicating the geographical position and lake perimeter, while in the case of mires, most of the cartographic information consisted only in digitalized maps indicating the location of some of the largest mires.

The assessment of the hydrometeorological information also evidenced a good degree of agreement in the extent and quality of the monitoring programs across the SMNP. All meteorological monitoring programs incorporated air temperature, atmospheric pressure and precipitation, while SN, SG and AESM considered the complete set of potential parameters (e.g., additionally, solar radiation, wind speed, soil temperature and humidity, and snowfall; Table 3), although these variables were not included in all the weather stations comprising each network. None of the SMNP considered a specific spatial design to locate the meteorological stations while all of them had series longer than ten years with daily frequency. In the case of hydrology, we also observed similar results, where all the SMNP had daily measurements of discharge and water table height, but without a specific spatial design. It must be pointed out the exception represented by PE where a specific control-impact monitoring design was conducted to locate several flow gauges matching with biological monitoring sites (Table 3; see Álvarez-Cabria et al. 2019 for details). Only SN provided measurements of permafrost, but time-series showed low frequency and duration.

The assessment of the monitoring programs conducted in the 3 types of aquatic ecosystems (rivers, lakes and mires) evidenced that rivers were monitored more intensively than lakes and, especially, than mires. The results highlighted that in all the SMNP the monitoring programs considered water quality, physical habitat and the composition of biological communities (Table 4). Nonetheless, the number of variables covered and the quality of data varied between SMNP. In general, results highlighted that most of the monitoring programs of these three types of variables were designed following the reference condition approach, with the exception of PE (all variables) and SG (Biological communities), where a control-impact design was established. In addition, most of the series had at least between 5 and 10 years and presented a yearly or higher sampling frequency (Table 4). Moreover, all of these monitoring programs considered more than 50% of the identified variables included in the water quality and physical habitat types. By contrast, we observed that a smaller effort has been made to monitor the composition and structure of communities, and especially ecosystem functioning in rivers (Table 4).

Monitoring programs conducted in lakes were especially intense in SN, SG and AESM where the assessment of water quality, physical habitat, community composition and community structure were considered (Table 5). Specifically, monitoring programs in these 3 SMNP measured 75–100% of all the potential variables for water quality and physical habitat and 50–75% for community composition and community structure. Moreover, programs showed a measurement frequency of at least 1 campaign per year, and the time length of the data series was above 10 years in most of the cases. The monitoring design rarely considered a design strategy beyond the reference condition and in many cases, there was no reference to the spatial design. The monitoring program of AESM represented an exception to this rule, and a before after control impact design was implemented in a set of selected lakes. Monitoring ecosystem functioning was very infrequent in most of the SMNP except for SN and AESM. For instance, SN monitored primary production while AESM monitored primary, secondary and fish production (Table 5).

Finally, only 2 SMNP monitored mire ecosystems. In general, these programs were less complete and had lower quality than those in rivers and lakes. AESM had the most complete mire monitoring program. It included 3 types of variables (water quality, physical habitat and biological community composition) but only the 25–50%, 50–75% and 25–50% of all the potential variables were used within each variable type, respectively (Table 6). Mires

Table 3 Assessment of the duration (D) of the historical records, frequency (F) of the measurements, percentage of variables reported and design of programs to monitor the effects of global change in the hydrometeorology in five mountainous Spanish National Parks (Picos de Europa, PE; Ordesa y Monte Perdido, OMP; Aigüestortes i Estany de Sant Maurici, AESM; Sierra de Guadarrama, SG; and Sierra Nevada; SN). In the case of the evaluation of the duration and frequency, the assessment of all the variables within each type while a unique value is reported for the percentage of variables reported and de design of the program. (Values meaning indicated in Table 2)

			PE		OMP		AESM		SG		SN	
TYPE	**ELEMENT**	**VARIABLE**	D	F	D	F	D	F	D	F	D	F
Meteorology	Duration and Frequency	Air temperature, pressure and humidity	4	4	4	4	4	4	4	4	4	4
		Precipitation	4	4	4	4	4	4	4	4	4	4
		Solar radiation					4	4	4	4	4	4
		Wind speed and direction					4	4	4	4	4	4
		Soil temperature and humidity					4	4			4	1
		Nivology/snowfall					2	4	4	4	4	4
	Average assessment of duration and frequency		4	4	4	4	3,7	4	4	4	4	3,5
	% vars. reported		2 (33%)		2 (33%)		4 (100%)		4 (83%)		4 (100%)	
	Design		1		1		1		1		1	
Hydrology	Duration and Frequency	Permafrost									1	1
		Discharge and water level	4	4	4	4	4	4	4	4	4	4
		Water table height	4	4	4	4					4	4
		Sediment Budget					2	4	4	4		
	Average assessment of duration and frequency		4	4	4	4	3	4	4	4	3	3
	% vars. reported		3 (50%)		3 (50%)		3 (50%)		3 (50%)		4 (75%)	
	Design		3		1		1		1		1	

monitoring programs have been usually deployed without a clear spatial design and in most cases they are based on the reference condition approach (physical habitat and community composition in AESM). Most of the time series were shorter than 10 years and the frequency does not reach one measure per year, with the exception of water table regime which is measured once a year (Table 6).

Discussion

This study identified the variables most commonly used in different monitoring programs of freshwater ecosystems at different geographical scales. Looking on river and lake nodes of the ILTER network and on the different MNP considered at the European and National (Spain) spatial scales, we can assert that monitoring of water quality variables is the most widespread approach worldwide (e.g., pH, nutrients, conductivity, etc.). Regarding biological variables, river invertebrates and lake phytoplankton communities were the most common biological assemblages monitored. On the other hand, physical variables of aquatic ecosystems (except water depth) and those related to the adjacent terrestrial landscape are scarcely represented in these monitoring programs, reducing their reliability to evaluate the effect of global change on freshwater ecosystems. The detailed assessment of the monitoring programs conduced in SMNP revealed that their design should be reconsidered, while important discrepancies have also been observed in relation to the quality of the programs and targeted types of variables. This contrasted with the monitoring of meteorological and hydrological variables. In this case, most of the monitoring programs across SMNP notably agreed. Nonetheless, owing to the importance of snowfall and snow accumulation in mountains areas and the potential impact of global change, a larger effort should be done to capture the changes in snow-related variables. Finally, maintaining long term monitoring networks (minimum of 10 years) is a crucial prerequisite to understand the interannual variability and trends of aquatic ecosystems and the potential influence of global change. Thus, long term monitoring designed under a BACI or regional-scale trend analysis will allow a better analysis of the temporal evolution of the affected and control sites. This is paramount to discriminate if the observed variation is generated by the effect of an impact/alteration, or whether the observed changes are more related to the natural ecosystem variability (e.g. dry or wet years).

Worldwide review

The global scale review highlighted that the most widespread variables considered in river and lake monitoring were those related to water quality (mainly: water temperature, conductivity and suspended solids - turbidity) and water depth, while other physical variables were only reported from less than 20% of the ILTER nodes (e.g., water velocity, lake volume, or other physical habitat characteristics). The higher frequency use of water quality variables is not surprising given four main reasons: (1) they respond to changes in the aquatic environment and in the adjacent terrestrial ecosystems (Álvarez-Cabria et al. 2016; Lei et al. 2020); (2) they are easily and inexpensively measurable; (3) they are useful to develop data bases representing pristine conditions (Fonseca and Mendonça-Galvão 2014), and (4) are useful

Table 4 Assessment of the duration (D) of the historical records, frequency (F) of the measurements, percentage of variables reported and design of programs to monitor the effects of global change in rivers in five mountainous Spanish National Parks (Picos de Europa, PE; Ordesa y Monte Perdido, OMP; Aigüestortes i Estany de Sant Maurici, AESM; Sierra de Guadarrama, SG; and Sierra Nevada; SN). In the case of the evaluation of the duration and frequency the assessment of all the variables within each type while a unique value is reported for the percentage of variables reported and de design of the program. (Values meaning indicated in Table 2)

			PE		OMP		AESM		SG		SN	
TYPE	**ELEMENT**	**VARIABLE**	D	F	D	F	D	F	D	F	D	F
Water physico-chemistry	Duration and Frequency	Temperature	3	4	1	1	4	4	4	4	2	4
		pH	3	3	1	1	4	4	4	4	2	4
		Conductivity	3	3	1	1	2	4	4	4	2	4
		Suspended Solids	3	1			2	4				
		Gas Concentration (O_2, CO_2)	3	3	1	1	4	4	4	4	2	4
		Nutrients	3	3			4	4	4	4	2	4
		Dissolved Organic Mater	3	3			4	4			2	4
	Average assessment of duration and frequency		3	3,1	1	1	3,4	4	4	4	2	4
	% vars. reported		4 (100%)		3 (57%)		4 (100%)		3 (71%)		4 (86%)	
	Design		3		2		2		2		2	
Physical Habitat	Duration and Frequency	Hydraulic Properties	2	3	1	1	4	4	4	4	2	4
		Substrate Composition	2	3	1	1	3	4			2	4
		Characterization protocols (RHS, IHF)	1	1			3	4	4	3	2	4
	Average assessment of duration and frequency		1,7	2,3	1	1	3,3	4	4	3,5	2	4
	% vars. reported		4 (100%)		3 (67%)		4 (100%)		3 (67%)		4 (100%)	
	Design		2		1		2		2		2	

Table 4 (continued)

			PE		OMP		AESM		SG		SN	
TYPE	**ELEMENT**	**VARIABLE**	D	F	D	F	D	F	D	F	D	F
Community composition	Duration and Frequency	Microbiota and Fungi	2	3								
		Algae and macrophytes	2	3					1	1	2	4
		Macroinvertebrates	3	3	1	3	4	4	4	4	2	4
		Fish	3	3								
		Other vertebrates										
		Riparian Plants and Tress (QBR)							4	4	2	4
	Average assessment of duration and frequency		2,5	3	1	3	4	4	3	3	2	4
	% vars. reported		3 (67%)		1 (17%)		1 (17%)		3 (50%)		3 (50%)	
	Design		3		1		2		3		2	
Community structure	Duration and Frequency	Microbiota and Fungi	2	3								
		Algae and macrophytes	2	3								
		Macroinvertebrates	2	3			4	4	2	4	2	4
		Fish	2	3								
		Other vertebrates										
		Riparian Plants and Tress (QBR)							4	4	2	4
	Average assessment of duration and frequency		2	3	0	0	4	4	3	4	2	4
	% vars. reported		3 (67%)		0		1 (17%)		2 (33%)		2 (33%)	
	Design		3		0		2		3		2	
Ecosystem functions	Duration and Frequency	Primary Production	2	3								
		Secondary production	2	3								
		Fish production	2	3								
		OM decomposition	2	3								
	Average assessment of duration and frequency		2	3	0	0	0	0	0	0	0	0
	% vars. reported		4 (100)%		0		0		0		0	
	Design		3		0		0		0		0	

Table 5 Assessment of the duration (D) of the historical records, frequency (F) of the measurements, percentage of variables reported and design of programs to monitor the effects of global change in lakes and ponds in five mountainous Spanish National Parks (Picos de Europa, PE; Ordesa y Monte Perdido, OMP; Aigüestortes i Estany de Sant Maurici, AESM; Sierra de Guadarrama, SG; and Sierra Nevada; SN). In the case of the evaluation of the duration and frequency, the assessment of all the variables within each type while a unique value is reported for the percentage of variables reported and de design of the program. (Values meaning indicated in Table 2)

			PE		OMP		AESM		SG		SN	
TYPE	**ELEMENT**	**VARIABLE**	D	F	D	F	D	F	D	F	D	F
Water physico-chemistry	Duration and Frequency	Temperature	2	3	3	3	4	4	4	4	4	4
		pH	2	3	1	1	4	4	4	4	4	4
		Conductivity	2	3	1	1	4	4	4	4	4	4
		Suspended Solids					4	4				
		Gas Concentration (O_2, CO_2)	2	3			4	4	4	4	4	4
		Nutrients/ions	2	3	3	3	4	4	4	4	4	4
		Dissolved Organic Matter					4	4	3	4	4	4
	Average assessment of duration and frequency		2	3	2	2	4	4	3,8	4	4	4
	% vars. reported		3 (71%)		3 (57%)		4 (100%)		4 (86%)		4 (86%)	
	Design		2		2		4		1		2	
Physical Habitat and morphology	Duration and Frequency	Morphology (surface, depth, volume, shape)	3	1	3	1	4	2			4	4
		Level and regime contributions			3	4	2	4	4	4	4	4
		Duration of Ice cover					4	4	4	3	4	3
		Melt time					4	4	4	3	4	3
	Average assessment of duration and frequency		3	1	3	2,5	3,5	4	4	3,3	4	3,5
	% vars. reported		2 (25%)		3 (50%)		4 (100%)		4 (75%)		4 (100%)	
	Design		1		1		4		1		2	

Table 5 (continued)

			PE		OMP		AESM		SG		SN	
TYPE	**ELEMENT**	**VARIABLE**	D	F	D	F	D	F	D	F	D	F
Community composition	Duration and Frequency	Microbiota and Fungi	2	1	4	1					4	4
		Algae and macrophytes					4	2	4	3	4	4
		Micro and Macroinvertebrates	2	1	4	1	2	3	4	4	4	4
		Fish	2	1	4	1	2	4				
		Other vertebrates	2	1	4	1			4	3		
		Riparian Plants and Trees	2	1	4	1						
	Average assessment of duration and frequency		2	1	4	1	2,7	3	4	3,3	4	4
	% vars. reported		4 (83%)		4 (83%)		3 (50%)		3 (50%)		3 (50%)	
	Design		1		1		4		1		2	
Community structure	Duration and Frequency	Microbiota and Fungi									4	4
		Algae and macrophytes					4	2	4	3	4	4
		Macroinvertebrates					2	3	2	4	4	4
		Fish	-	-			2	4			-	-
		Other vertebrates							4	3		
		Riparian Plants and Trees										
	Average assessment of duration and frequency		0	0	0	0	2,7	3	3,3	3,3	4	4
	% vars. reported		0 (0%)		0 (0%)		3 (50%)		3 (50%)		3 (50%)	
	Design		0		0		3		1		2	
Ecosystem functions	Duration and Frequency	Primary Production					2	4			4	4
		Secondary production					2	3				
		Fish production					2	4				
		OM decomposition										
	Average assessment of duration and frequency		0	0	0	0	2	4	0	0	4	4
	% vars. reported		0 (0%)		0 (0%)		4 (75%)		0 (0%)		2 (25%)	
	Design		0		0		3		1		2	

Table 6 Assessment of the duration (D) of the historical records, frequency (F) of the measurements, percentage of variables reported and design of programs to monitor the effects of global change in mires in five mountainous Spanish National Parks (Picos de Europa, PE; Ordesa y Monte Perdido, OMP; Aigüestortes i Estany de Sant Maurici, AESM; Sierra de Guadarrama, SG; and Sierra Nevada; SN). In the case of the evaluation of the duration and frequency, the assessment of all the variables within each type while a unique value is reported for the percentage of variables reported and de design of the program. (Values meaning indicated in Table 2)

			PE		OMP		AESM		SG		SN	
TYPE	**ELEMENT**	**VARIABLE**	D	F	D	F	D	F	D	F	D	F
Water physico-chemistry	Duration and Frequency	Temperature										
		pH					3	2				
		Conductivity					3	2				
		Gas Concentration (O_2, CO_2)										
		Nutrients/ions					3	2				
		Dissolved Organic Mater										
	Average assessment of duration and frequency		0	0	0	0	3	1	0	0	0	0
	% vars. reported		0 (0%)		0 (0%)		2 (43%)		0 (0%)		0 (0%)	
	Design		0		0		1		0		0	
Physical Habitat	Duration and Frequency	Water table height					3	4	2	1		
		Surface										
	Average assessment of duration and frequency		0	0	0	0	3	4	2	1	0	0
	% vars. reported		0 (0%)		0 (0%)		3 (50%)		3 (50%)		0 (0%)	
	Design		0		0		2		1		0	
Community composition	Duration and Frequency	Microbiota and Fungi										
		Algae and macrophytes					3	2				
		Macroinvertebrates										
		Other vertebrates										
		Riparian Plants and Trees										
	Average assessment of duration and frequency		0	0	0	0	3	2	0	0	0	0
	% vars. reported		0 (0%)		0 (0%)		1 (20%)		0 (0%)		0 (0%)	
	Design		0		0		2		0		0	

Table 6 (continued)

			PE		OMP		AESM		SG		SN	
TYPE	**ELEMENT**	**VARIABLE**	D	F	D	F	D	F	D	F	D	F
Community structure	Duration and Frequency	Microbiota and Fungi										
		Algae and macrophytes										
		Macroinvertebrates										
		Other vertebrates										
		Riparian Plants and Trees										
	Average assessment of duration and frequency		0	0	0	0	0	0	0	0	0	0
	% vars. reported		0 (0%)		0 (0%)		0 (0%)		0 (0%)		0 (0%)	
	Design		0		0		0		0		0	
Ecosystem functions	Duration and Frequency	Primary Production										
		Secondary production										
		OM decomposition										
	Average assessment of duration and frequency		0	0	0	0	0	0	0	0	0	0
	% vars. reported		0 (0%)		0 (0%)		0 (0%)		0 (0%)		0 (0%)	
	Design		0		0		0		0		0	

to assess the divergence between natural and impacted locations (e.g., using reference conditions, CI or BACI designs).

Surprisingly, biological variables were represented only in 40% of the LTER nodes, especially biodiversity and community variables and to a lesser degree, population variables (less than 30% of sites). These results corroborate the findings of Pereira et al. (2013) and Schmeller et al. (2017), who highlighted the lack of harmonized monitoring programs for delivering adequate data on biodiversity change at the global scale. Our results also agreed with Turak et al. (2016), who observed a generalized use of information on freshwater species populations and biological communities for measuring changes in global freshwater biodiversity. By contrast, we have observed that ecosystem functioning variables are the less common biological variables used to monitor changes in freshwater ecosystems.

Quite surprisingly, less than 50% and 40% of the river and lake ILTER nodes, respectively, included more than 3 groups of variables simultaneously. Changes on water or aquatic biodiversity conditions can be associated to environmental changes induced by natural, human or a combination of both elements. Consequently, in many cases the monitoring of water characteristics or biodiversity does not provide enough information to identify the “source of the problem”. In this regard, producing hydro-meteorological (e.g., air temperature, discharge, surface water or groundwater levels) or landscape level information is key to better understand cause-effect relationships (Ervinia et al. 2019).

European Mountain National Parks

Only 4 countries confirmed the implementation of any kind of monitoring program in at least one of their MNP (Spain, France, Poland and Switzerland), while EMNP from the other 9 countries confirmed the absence of monitoring programs. Existing monitoring programs from the 4 EU countries presented contrasting approaches. For example, France assessed several EMNP with the same methods and periodicity. However, the French program only monitored mountain lakes and did not include springs, streams or mires. By contrast, Spanish monitoring programs (SMNP) included rivers, lakes, and mires but they were not monitored consistently across all MNPs, showing different intensities and approaches across locations. These differences complicate comparisons of datasets and analyses of long term trends (see Sect. 4.3 for further details). Differences between both countries, Spain and France, could be related to the politic administration of NP. In France all the NP (9) are managed by the public body *Parcs Nationaux de France*, while in Spain each NP (15) is managed by the regional Government where the Park is located, and therefore, the monitoring programs might differ according to the regional administration. The case of Switzerland is different, with only one MNP (0,4% of country area) concentrating all the monitoring and conservation nationwide efforts. In this regard, Switzerland has implemented a complete monitoring program in the running and standing waters of this MNP. This program takes information from 2 catchments with different water sources (glacier-fed and precipitation-fed) from 2001 to present, including measurements and analysis on water physico-chemical characteristics, biological community structure and composition, atmospheric and weather conditions and variables related to landscape (see Schanz et al. 2012). All this information, compiled in a long-term database, constitutes one of the best in Europe to identify consequences of global change in mountain areas.

The Spanish Mountain National Parks

Monitoring the effects of global change in mountain aquatic ecosystems requires accurate cartographic information (Barquín et al. 2015). The assessment of the available cartographic databases for the five SMNP indicated that there was only sufficient information for rivers, while these databases seemed incomplete for lakes and mires. Moreover, even for rivers, it must be pointed out that a digital hydrographic network derived from a digital elevation model is not sufficient to establish appropriate spatial designs for monitoring. In this case, specific catchment environmental information from different digital sources should be appended to the digital river network. In addition, González-Ferreras and Barquín (2017) evidenced that available river networks still lack a complete representation of the spatial distribution of river channels. In this regard, improving mapping tools and coupling this digital cartography with analytical information is well needed, not only to understand the interactions between large scale environmental modifications and local alterations, but also to avoid significant errors in the water budget calculations and resulting flows (Egüen et al. 2012). Nowadays, global data sets and maps at reasonable resolution are available worldwide (e.g., HydroSHEDS, HydroRIVERS and HydroATLAS (Linke et al. 2019) and HydroLAKES (Messager et al. 2016) for rivers and lakes, respectively. The use of these databases would allow initially filling some information gaps until more specific cartographic products could be developed (but see Benda et al. 2016).

This study highlights the lack of a common national strategy to monitor the biological and ecological impacts in mountain rivers, lakes and mires in Spain. This uncoordinated strategy is prone to generating weaker conclusions in comparison to the possibility of generating a multiple and simultaneous program with a diversity of well-structured datasets (Tydecks et al. 2019). In addition, we found a general weakness related to the lack of adequate spatio-temporal designs, which would be needed to statistically discern changes that can be attributed to global change, natural variability or others (Downes 2002). In most cases the best design does not go beyond the reference condition, while Control-Impact and Before-After/Control-Impact designs would help to discriminate changes caused by global change to those caused by natural variability (Peñas et al. 2016).

Most of the installed meteorological stations in the 5 SMNP (14) measure basic climatic variables such as temperature, precipitation, pressure or air humidity. However, the small number of stations measuring snow-related variables contrasts with the shifts in mountain snowpacks and glacier retreats that have been observed in the last decades in mountain areas (Kneib et al. 2020). Changes on the timing of snow-melting phenology will also affect runoff and the hydrological regime (Beniston and Stoffel 2013), which might further influence mountain freshwater ecosystems. In this context, additional monitoring efforts are paramount to provide insight into the impacts of the snowpack dynamics on mountain freshwater ecosystems. A remarkable example is the Global Monitoring System for Snow in SN (www.uco.es/dfh/snowmed; Polo et al. 2019), with additional instrumentation beyond the standard weather stations to measure snowfall, snow cover area, and specific components of the energy balance.

Most river and lake monitoring programs in the five SMNP provided water quality and physical habitat information, and biological data rely mostly on invertebrates community composition (Supplementary material Table S3), ignoring, in other cases, community structure. In this regard, early warning signals on biological communities because of hydrological or thermal regimen changes might be more easily detected as changes in community structure (Carlisle and Hawkins 1998; Whiterod et al. 2015) than as sudden changes such as species replacement. Moreover, the SMNP monitoring programs revealed an underrepresentation of ecological functioning variables. Functioning indicators present some advantages over structural ecosystem components since change in ecosystem process rates can be immediately linked to certain levels of environmental change (Palmer and Ruhi, 2019). For instance, the proliferation of reliable and relatively inexpensive sensors for monitoring dissolved oxygen, and easy-to-use software for the calculation of gross primary production (GPP) and Ecosystem Respiration (ER; Engel et al. 2019) is underpinning a revolution in the use of this kind of indicator (Bernhardt et al. 2018; Smits et al. 2021). These two factors enable scientists to estimate ecosystem metabolism more frequently and in greater detail.

Our study also reveals large differences in the extent and quality of the monitoring programs between rivers, lakes and mires. Results highlighted that monitoring programs in mires were the poorest within the five SMNP. By contrast, our results evidenced a much larger effort to monitoring lakes and rivers than mires in the five SMNP. The rich monitoring networks on lakes existing in three of the SMNP should be remarked. Although mountain lakes are exceptionally susceptible to the effects of global change (Thompson et al. 2009; Alcocer et al. 2021; Zamora and Oliva, 2022s), they appeared underrepresented in monitoring networks many times, given the large amount of resources and effort needed to survey remote lakes (Schaeffer et al. 2013). Moreover, the resources needed for monitoring continuously remote mountain lakes might prevent maintaining the required temporal and spatial resolution of relevant phenomena to capture the effects of global change. On the other hand, there are now larger chances to overcome these drawbacks by Remote Sensing (RS) techniques, as the potentiality of detecting key water quality-, biota-, and functioning-related indicators in lakes is increasing substantially (Dörnhöfer and Oppelt 2016) or by using in-situ sensing systems (Porter et al. 2009). New opportunities raised from the use of RS and novel optical sensors for lakes, might also include the improvement and extend of the monitoring for mires. However, several characteristics of mire ecosystems might challenge the use of these technologies for their surveillance (Gallant 2015).

Recommendations for regional and global assessments

Lessons learnt from the different analysis carried out in this study could help illustrating how the harmonization of local monitoring programs could be improved for comparisons at regional or global scales. This harmonization does not imply that freshwater monitoring programs must converge on a unique monitoring design. The complexity of biodiversity and the idiosyncrasy of each geographical and socioeconomic context make this task unfeasible. Nonetheless, the international scientific community, in coordination with public institutions, should consider a greater effort to agree on a core of ecosystem characteristics and essential variables to be effective in understanding the effects of global change in freshwater ecosystems. In this regard, the comparison of the ILTER nodes information has actually shown that most of the metadata associated to the monitoring programs allows only for the identification of high-level information. Thus, moving beyond the state of the art is rather difficult nowadays. In this regard, we advise that freshwater monitoring programs substantially improve their metadata (e.g. type of community surveyed, habitat sampled, methods and equipment, site selection criteria, survey frequency, date/period of surveys, etc.) so as to find coherences and inconsistencies when trying to build regional or global assessments.

On the other hand, the analysis of monitoring programs at the most local scale and detailed information source (i.e. the SMNP) has identified a key set of variables that could be used as a start to assess the effects of global change in freshwater ecosystems (see Table 1). Thus, one of the first steps towards harmonization is to find a consensus on which of these variables should be consistently measured across aquatic ecosystems at local scales and which might be the targeted biological communities (a bottom-up approach within regions). On a second round, the methodological approach should be clearly defined so as to find a common agreement on the core steps and on how sampling design and temporal frequency should be defined, establishing the minimum conditions for each variable to be comparable across localities. On a third step, the design of the monitoring program (BACI, trend analyses, reference condition approach, etc.) might have importance at the local level (depending on objectives and resources), but is less relevant for regional or global assessments as long as natural and impacted sites are both monitored. For example, a control-impact design with summer surveys on an annual basis using electrofishing and identifying fishes to the lowest possible taxonomic level could be a good start for monitoring trends in fish communities in rivers. This will help to reach a minimum consensus within a region so that the obtained data will be comparable across localities. On a final step, this information could actually be used to inform Essential Biodiversity Variables that summarise the state or trend of the targeted populations, communities or ecosystems for a given region (Pereria et al. 2013). Although, simple in theory these steps have proven to be rather difficult to follow in practice. In this regard, mechanisms for integration of data bases provided for each protected area should be improved so that they can be part of national and international data repositories (e.g., Freshwater Information Platform; Schmidt-Kloiber et al. 2019). Moreover, these efforts should come along with new funding schemes that improve and allow a sustained scientific collaboration at regional and global levels.

Conclusions and future improvements

This is one of the first attempts at accessing the quality of monitoring programs for measuring the effects of global change in freshwater ecosystems. There has been notable progress towards improving monitoring programs in the last decades, however there is still a lack of agreement on what, how and when to measure in order to effectively oversee the effect of global change in freshwater ecosystems. According to our initial expectations, we have found important contrasts among monitoring programs worldwide and, surprisingly, also within those enclosed under the same protection figure in a given country (i.e., SMNP).

Our analysis at the national Spanish scale has evidenced important shortcomings in the monitoring programs that should be solved to increase our understanding on the complex effects of global change and to provide with a stronger body of evidence on current trends and directions at a national level. This evidence is paramount to further design policies and concentrate efforts to design effective adaptation and mitigation actions (e.g., development of blue and green infrastructures networks). In this sense, we have found that specific monitoring designs that allow the application of well-established statistical approaches (e.g., control-impact), grounded in a complete, sound and environmentally-attributed cartography is essential to comply with these objectives. In addition, inclusion of new biological and functional indicators that capture the progressive rates of global change, rather than abrupt changes, are needed within monitoring programs.

All these improvements necessarily lie on a stronger collaboration and coordination between government agencies, research institutions, international scientific initiatives and other stakeholders to maximize efforts in supporting coordinated and joint assessments of freshwater ecosystems. Improving and harmonizing monitoring is paramount to understand the processes, asses the impacts and face the challenges imposed by global change in freshwater ecosystems. This requires the implementation of long-term data bases from different sites, like proposed by ILTER, the standardization of the data collection in the field, like proposed by GEO BON (e.g., Essential Biodiversity Variables; Pereira et al. 2013; Schmeller et al. 2017), as well as an appropriate periodicity of measurements (daily, monthly, annual, etc.; Haase et al. 2018) and a proper statistical design (Downes 2002). In addition, only through a harmonization process built with the consensus of the localities involved in monitoring aquatic ecosystems, can sufficient coherence and consistency be obtained to build regional or global aquatic biodiversity assessments. This effort must therefore grow from the local scale and gain in regional or global vision as new challenges are incorporated to reach higher scale assessments.

Finally, it is remarkable the advances of recent techniques and tools to further improve the monitoring and assessment of ecosystems. This is the case of RS and the programs and services developed for the use/application of this information, like the Copernicus Land Monitoring Service in Europe (https://www.copernicus.eu/en) joined to the open data cube tools needed to manage this information (Giuliani et al. 2019). Remote sensing has long been recognized as having the potential to complement conventional approaches to freshwater monitoring (Bukata 2013), increasingly being used as a complementary source of information to in situ monitoring networks. Regarding in situ monitoring, a continuous or quasi-continuous monitoring of different limnological parameters is possible using autonomous multiprobes and temperature dataloggers. These devices have large data storage capacity, high battery life and sensors which are capable of working unattended from weeks to months (Granados et al. 2020). On the other hand, there has been an increased interest in the use of new molecular techniques to monitor and manage ecosystems (Erickson et al. 2019), which complement traditional approaches to define the structure and composition of biological communities. Even though our results showed an underrepresentation of genetic variables in the ILTER network and they are rarely included as an objective in biodiversity monitoring programs (Turak et al. 2016), the rapid evolution of these techniques (e.g., environmental DNA), could produce a radical change in this tendency (Rees et al. 2014; Pawlosky et al. 2018).

Electronic supplementary material The online version contains supplementary material available at https://doi.org/10.1007/s10531-022-02466-x.

Acknowledgements This study was funded by the European Commission, under the LIFE Nature and Biodiversity program, as part of the project LIFE-DIVAQUA (Proyecto LIFE18 NAT/ES/000121). We also like to thank all the Spanish government agencies and research institutions who provided information, answered the questionnaires and participated in the workshop "Synthesis of the monitoring programs of global change in aquatic ecosystems SMNP: Autonomous Organism of National Parks, MAPAMA-Dir. Gral. Agua, Universidad de Granada, Instituto Universitario de Investigación del Agua, (IdeA-UGR), Universidad Politécnica de Madrid, CISE-P.N. Sierra de Guadarrama, Fundación Biodiversidad, CEAB-CSIC, IGME, MNCN-CSIC, Universidad de Córdoba, Universidad de Barcelona and ICTA-UAB. We also like to thank the 28 European Nation Parks who responded our query. The authors finally thank the support provided by Christoph Wohner in the use of the DEIMS-SDR.

Author contributions M.A-C., F.J.P., M.S.B. and J.B. conceived the study. F.J.P., M.A-C. and J.B. designed and conducted analyses and wrote the first draft. M.A-C., F.J.P., M.S.B., J.B., M.P.M-C., A.P-H., M.J.P-G., I.G., M.M., C.P-M., A.R.R., M.V., P.C., C.Z-M., M.V-M., L.C., E.G., M.P. and T.B. provided monitoring networks data within the SMNP and contributed to additional versions of the manuscript.

Funding This study was carried out with the financial support of the EU LIFE programme, as part of the project LIFE-DIVAQUA (Proyecto LIFE18 NAT/ES/000121). The information showed in this publication only reflects the point of view of the authors. The European Comission and CINEA cannot be held responsible for any use which be made of the information contained here.
Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature.

Data Availability The datasets used to review the monitoring programs at the Global scale conducted in the ILTER nodes that are included in Rivers (ILTER-Rivers) or Lakes (ILTER-Lakes) are available at the DEIMS dataset registry (DEIMS-SDR) (for more details see: Wohner et al. 2019; https://deims.org/). The datasets used to review the monitoring programs at the European scale conducted in the EMNP are available by requesting them via email to the corresponding EMNP. The datasets used to review the monitoring programs at the National scale conducted in the five SMNP are mostly included in this article and it supplementary information file. In addition, meteorological data recorded by the Spanish Global Change Monitoring Network in available at the Meteorological data download web application (https://www.miteco.gob.es/es/red-parques-nacionales/red-seguimiento/acceso-datos.aspx). Further and more detailed information is available from the corresponding author on reasonable request.

Declarations

Conflict of interest All authors declare that they have no conflicts of interest and no relevant financial or non-financial interests to declare that are relevant to the content of this article.

Consents All authors consent to participate in this work. All authors agreed with the content and consent to publish the research presented in this work. Unfortunately, the author Carmen Zamora Muñoz died on March 2022.

Other statements Animal Research, Plant Reproducibility and Clinical Trials Registration are not applicable in the research presented in this work.

References

Alcocer J, Oseguera LA, Ibarra-Morales D, Escobar E, Garcia-Cid L (2021) Responses of Benthic Macroinvertebrate Communities of Two Tropical, High-Mountain Lakes to Climate Change and Deacidification. Diversity 13(6):243. https://doi.org/10.3390/d13060243

Álvarez-Cabria M, Barquín J, Peñas FJ (2016) Modelling the spatial and seasonal variability of water quality for entire river networks: Relationships with natural and anthropogenic factors. Sci Total Environ 545:152–162. https://doi.org/10.1016/j.scitotenv.2015.12.10

Álvarez-Cabria M, Peñas FJ, Sáinz-Bariáin M, Estévez E, González-Ferreras AM, Pérez-Silos I, Goldenberg A, Hoang M, Rocha-Pompeu C, Silió-Calzada A (2019) Seguimiento del cambio global en los ecosistemas acuáticos del Parque Nacional de los Picos de Europa. Boletín de la Red de Seguimiento del Cambio Global en Parques Nacionales. 7: 8–9

Álvarez-Martínez JM, Suárez-Seoane S, Stoorvogel JJ, Luis Calabuig E (2014) Influence of land use and climate on recent forest expansion: a case study in the Eurosiberian-Mediterranean limit of northwest Spain. J Ecol 102:905–919. https://doi.org/10.1111/1365-2745.12257

Bartram J, Balance R (1986) Water quality monitoring: a practical guide to the design and implementation of freshwater quality studies and monitoring programmes, 381 edn. Chapman and Hall

Barquín J, Benda L, Villa F, Brown LE, Bonada N, Vieites DR, Battin TJ, Olden JD, Hughes SJ, Gray C, Woodward G (2015) Coupling virtual watersheds with ecosystem services assessment: a 21st century platform to support river research and management. WIREs Water 2:609–621. https://doi.org/10.1002/wat2.1106

Benda L, Miller D, Barquín J, McCleary R, Ji Y (2016) Building Virtual Watersheds: A Global Opportunity to Strengthen Resource Management and Conservation. Environ Manage 57:722–739. https://doi.org/10.1007/s00267-015-0634-6

Beniston M, Stoffel M (2013) Assessing the impacts of climatic change on mountain water resources. Sci Total Environ 493:1129–1137. https://doi.org/10.1016/j.scitotenv.2013.11.122

Bernhardt ES, Heffernan JB, Grimm NB, Stanley EH, Harvey JW, Arroita M, Appling AP, Cohen MJ, McDowell WH, Hall RO Jr, Read JS, Roberts BJ, Stet G, Yackulic CB (2018) The metabolic regimes of flowing waters. Limnol Oceanogr 63:S99–S118. https://doi.org/10.1002/lno.10726

Bukata R (2013) Retrospection and introspection on remote sensing of inland water quality: "Like Déjà Vu All Over Again". J Great Lakes Res 39(1):2–5. https://doi.org/10.1016/j.jglr.2013.04.001

Carlisle DM, Hawkins CP (1998) Relationships between Invertebrate Assemblage Structure, 2 Trout Species, and Habitat Structure in Utah Mountain Lakes. J North Am Benthol Soc 17:286–300. https://doi.org/10.2307/1468332

Carvalho L, other 25 co-authors (2019) Protecting and restoring Europe's waters: An analysis of the future development needs of the Water Framework Directive. Sci Total Environ 658:1228–1238. https://doi.org/10.1016/j.scitotenv.2018.12.255

Catalan J, Ninot JM, Aniz MM (2017) The High Mountain Conservation in a Changing World. In: Catalan J, Ninot J, Aniz M (eds) High Mountain Conservation in a Changing World. Advances in Global Change Research, vol 62. Springer, Cham

Downes BJ (2002) Monitoring Ecological Impacts. Concepts and Practice in Flowing Waters. Cambridge University Press, p 452

Egüen M, Aguilar C, Herrero J, Millares A, Polo MJ (2012) On the influence of cell size in physically-based distributed hydrological modelling to assess extreme values in water resource planning. Nat Hazards Earth Syst Sci 12:1573–1582. https://doi.org/10.5194/nhess-12-1573-2012

Engel F, Attermeyer K, Ayala AI, Fischer H, Kirchesch V, Pierson DC, Weyhenmeyer GA (2019) Phytoplankton gross primary production increases along cascading impoundments in a temperate, low-discharge river: Insights from high frequency water quality monitoring. Sci Rep 9:6701. https://doi.org/10.1038/s41598-019-43008-w

Erickson RA, Merkes CM, Mize EL (2019) Sampling Designs for Landscape-level eDNA Monitoring Programs. Integr Environ Assess Manag 15:760–771. https://doi.org/10.1002/ieam.4155

Ervinia A, Huang J, Huang Y, Lin J (2019) Coupled effects of climate variability and land use pattern on surface-water quality: An elasticity perspective and watershed health Indicators. Sci Total Environ, 693:133592. https://doi.org/10.1016/j.scitotenv.2019.133592

Dörnhöfer K, Oppelt N (2016) Remote sensing for lake research and monitoring – Recent advances. Ecol Indic 64:105–122. https://doi.org/10.1016/j.ecolind.2015.12.009

Dirnböck T, Haase P, Mirtl M, Pauw J, Templer PH (2019) Contemporary International Long-Term Ecological Research (ILTER)—from biogeosciences to socio-ecology and biodiversity research. Reg Environ Change 19:309–311. https://doi.org/10.1007/s10113-018-1445-0

Fonseca BM, Mendonça-Galvão L (2014) Pristine aquatic systems in a Long Term Ecological Research (LTER) site of the Brazilian Cerrado. Environ Monit Assess 186:8683–8695. https://doi.org/10.1007/s10661-014-4035-8

Giuliani G, Masó J, Mazzetti P, Nativi S, Zabala A (2019) Paving the Way to Increased Interoperability of Earth Observations Data Cubes. Data: 4 (3) 113. https://doi.org/10.3390/data4030113

González-Ferreras, Barquín J (2017) Mapping the temporary and perennial character of whole rivernetworks. Water Resour Res 53:6709–6724. https://doi.org/10.1002/2017WR020390

Granados I, Toro M, Giralt S, Camacho A, Montes C (2020) Water column changes under ice during different winters in a mid-latitude Mediterranean high mountain lake. Aquat Sci 82(82):30. https://doi.org/10.1007/s00027-020-0699-z

Haase P, Frenzel M, Klotz S, Musche M, Stoll S (2016) The long-term ecological research (LTER) network: Relevance, current status, future perspective and examples from marine, freshwater and terrestrial long-term observation. Ecol Indic 65:1–3. https://doi.org/10.1016/j.ecolind.2016.01.040

Haase P, Tonkin JD, Stefan S, Burkharde B, Frenzel M, Geijzendorffer IR, Häuser D, Klotz S, Kühn I, McDowell WH, Mirtl M, Müller M, Musche M, Penner J, Zacharias S, Schmeller DS (2018) The next generation of site-based long-term ecological monitoring: Linking essential biodiversity variables and ecosystem integrity. Sci Total Environ 613–614:1376–1384. https://doi.org/10.1016/j.scitotenv.2017.08.111

Hoffmann S (2021) Challenges and opportunities of area–based conservation in reaching biodiversity and sustainability goals. Biodivers Conserv. https://doi.org/10.1007/s10531-021-02340-2

IPCC, Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (2021) Climate Change 2021: The Physical Science Basis. Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R and Zhou B (eds.). Cambridge University Press. In Press

IUCN. Terms of Reference. Purpose and Goals.ICUN WCPA Mountain Specialist Group

Kneib M, Cauvy-Fraunié S, Escoffier N, Boix-Canadella M, Horgbya Ã, Battin TJ (2020) Glacier retreat changes diurnal variation intensity and frequency of hydrologic variables in Alpine and Andean streams. J Hydrol 583:124578. https://doi.org/10.1016/j.jhydrol.2020.124578

Kelly MG, Birk S, Willby N, Denys L, Drake S, Kahlert M, Karjalainen MS, Marchetto A, Pitt J, Urbanic G, Poikane S (2016) Redundancy in the ecological assessment of lakes: Are phytoplankton, macrophytes and phytobenthos all necessary? Sci Total Environ 568:594–602. https://doi.org/10.1016/j.scitotenv.2016.02.024

Kvaeven B, Ulstein MJ, Skjelkvåle BL, Raddum GG, Hovind H (2001) ICP Waters — an International Programme for Surface Water Monitoring. Water Air Soil Pollut 130:775–780

Kollmair M, Gurug GS, Hurni K, Maselli D (2005) Mountains: Special places to be protected? An analysis of worldwide nature conservation efforts in mountains. Int J Biodivers Sci Manag 1(4):181–189. https://doi.org/10.1080/17451590509618091

Körner C (2007) The use of ‘altitude’ in ecological research. Trends Ecol Evol 22:569–574. https://doi.org/10.1016/j.tree.2007.09.006

Lei C, Wagner PD, Foher N (2020) Effects of land cover, topography, and soil on stream water quality at multiple spatial and seasonal scales in a German lowland catchment. Ecol Indic 120:1–12. https://doi.org/10.1016/j.ecolind.2020.106940

Linke S, Lehner B, Ouellet-Dallaire C, Ariwi J, Grill G, Anand M, Beames P, Burchard-Levine V, Maxwell S, Moidu H, Tan F, Thieme M (2019) Global hydro-environmental sub-basin and river reach characteristics at high spatial resolution. Sci Data 6:283. https://doi.org/10.1038/s41597-019-0300-6

Malhi Y, Franklin J, Seddon N, Solan M, Turner MG, Field CB, Knowlton N (2020) Climate change and ecosystems: threats, opportunities and solutions. Philos Trans R Soc B 375(1794). https://doi.org/10.1098/rstb.2019.0104

Messager ML, Lehner B, Grill G, Nedeva I, Schmitt O (2016) Estimating the volume and age of water stored in global lakes using a geo-statistical approach. Nat Commun 13603. https://doi.org/10.1038/ncomms13603

Michalet R, Schob C, Lortie CJ, Brooker RW, Callaway RM, Bailey JK (2014) Partitioning net interactions among plants along altitudinal gradients to study community responses to climate change. Funct Ecol 28(1):75–86. https://doi.org/10.1111/1365-2435.12136

Navarro LM, Fernández N, Guerra C, Guralnick R, Kissling WD, Londoño MC, Muller-Karger F, Turak E, Balvanera P, Costello MJ, Delavaud A, El Serafy GY, Ferrier S, Geijzendorffer I, Geller GN, Jetz W, Kim ES, Kim H, Martin CS, McGeoch MA, Mwampamba TH, Nel JL, Nicholson E, Pettorelli N, Schaepman ME, Skidmore A, Pinto IS, Vergara S, Vihervaara P, Xu H, Yahara T, Gill M, Pereira HM (2017) Monitoring biodiversity change through effective global coordination. Curr Opin Environ Sustain 29:158–169. https://doi.org/10.1016/j.cosust.2018.02.005

Paduel B, Zhang YL, Li SC, Liu LS, Wu X, Khanal NR (2016) Review of studies on land use and land cover change in Nepal. J Mt Sci 13:643–660. https://doi.org/10.1007/s11629-015-3604-9

Ondei S, Brook WB, Buettel JC (2018) Nature's untold stories: an overview on the availability and type of on-line data on long-term biodiversity monitoring. Biodivers Conserv volume 27:2971–2987. https://doi.org/10.1007/s10531-018-1582-2

Palmer M, Ruhi A (2019) Linkages between flow regime, biota, and ecosystem processes: Implications for river restoration. Science 365:1264. https://doi.org/10.1126/science.aaw2087

Parr TW, Ferretti M, Simpson IC, Forsius M, Kovacs-Lang E (2002) Towards a long-term integrated monitoring programme in Europe: network design in theory and practice. Environ Monit Assess 78:253–290. https://doi.org/10.1023/a:1019934919140

Pereira HM, Ferrier S, Walters M, Geller GN, Jongman RHG, Scholes RJ, Bruford MW, Brummitt N, Butchart SHM, Cardoso AC, Coops NC, Dulloo E, Faith DP, Freyhof J, Gregory RD, Heip C, Höft R, Hurtt G, Jetz W, Karp D, McGeoch MA, Obura D, Onoda Y, Pettorelli N, Reyers B, Sayre R, Scharlemann JPW, Stuart SN, Turak E, Walpole M, Wegmann M (2013) Essential Biodiversity Variables. Science 339:277–278. https://doi.org/10.1126/science.1229931

Peñas FJ, Barquín J, Álvarez C (2016) Assessing hydrologic alteration: evaluation of different alternatives according to data availability. Ecol Indic 60:470–482. https://doi.org/10.1016/j.ecolind.2015.07.021

Pérez-Silos I, Álvarez-Martinez JM, Barquín J (2021) Large-scale afforestation for ecosystem service provisioning: learning from the past to improve the future. Landsc Ecol 36:3329–3343. https://doi.org/10.1007/s10980-021-01306-7

Polo MJ, Herrero J, Pimentel R, Pérez-Palazón MJ (2019) The Guadalfeo Monitoring Network (Sierra Nevada, Spain): 14 years of measurements to understand the complexity of snow dynamics in semiarid regions. Earth Syst Sci Data 11:393–407. https://doi.org/10.5194/essd-11-393-2019

Porter JH, Nagy E, Kratz TK, Hanson P, Collins SL, Arzberger P (2009) New eyes on the world: advanced sensors for ecology. Bioscience 59:385–397. https://doi.org/10.1525/bio.2009.59.5.6

Rees HC, Maddison BC, Middleditch DJ, Patmore JRM, Gough KC (2014) The detection of aquatic animal species using environmental DNA - A review of eDNA as a survey tool in ecology. J Appl Ecol 51:1450–1459. https://doi.org/10.1111/1365-2664.12306

Schaeffer BA, Schaeffer KG, Keith D, Lunetta RS, Conmy R, Gould RW (2013) Barriers to adopting satellite remote sensing for water quality management. Int J Remote Sens 34:21:7534–7544. https://doi.org/10.1080/01431161.2013.823524

Schanz F, Scheurer T, Steiner B (2012) Ergebnisse aus 70 Jahren Gewässerforschung im Schweizerischen Nationalpark. 120 pp

Schmeller DS, Mihoub JB, Bowser A, Arvanitidis C, Costello MJ, Fernandez M, Geller GN, Hobern D, Kissling WD, Regan E, Saarenmaa H, Turak E, Isaac NJB (2017) An operational definition of essential biodiversity variables. Biodivers Conserv 26:2967–2972. https://doi.org/10.1007/s10531-017-1386-9

Schmeller DS, Loyau A, Bao K, Bracke W, Chatzinotas A, De Vleeschouwer F, Friesen J, Gandois L, Hansson SV, Haver M, Le Roux G, Shen J, Teisserenc R, Vredenburg VT (2018) People, pollution and pathogens – Global change impacts in mountain freshwater ecosystems. Sci Total Environ 622–623:756–763. https://doi.org/10.1016/j.scitotenv.2017.12.006

Schmidt-Kloiber A, Bremerich V, De Wever A, Jähnig SC, Martens K, Strackbein J, Tockner K, Hering D (2019) The Freshwater Information Platform: a global online network providing data, tools and resources for science and policy support. Hydrobiologia 838:1–11. https://doi.org/10.1007/s10750-019-03985-5

Smits AP, Gomez NW, Dozier J, Sadro S (2021) Winter Climate and Lake Morphology Control Ice Phenology and Under-Ice Temperature and Oxygen Regimes in Mountain Lakes. J Geophys Res Biogeosci 126. https://doi.org/10.1029/2021JG006277. e2021JG006277

Steffen W, Jäger J, Carson DJ, Bradshaw C (2001) Challenges of a Changing Earth. Proceedings of the Global Change Open Science Conference, Amsterdam, The Netherlands, 10–13 July 2001. ISBN: 978-3-642-19016-2

Steffen W, Andreae MO, Bolin B, Cox PM, Crutzen PJ, Cubasch U, Held H, Nakicenovic N (2004) Abrupt changes: The Achilles' heels of the Earth system. Environ Sci Policy for Sustain Dev 46:8–20. https://doi.org/10.1080/00139150409604375

Thompson R, Ventura M, Camarero L (2009) The climate and weather of mountain and sub-arctic lakes in Europe and their susceptibility to future climate change. Freshw Biol 54:2433–2451

Turak E, Harrison I, Dudgeon D, Abell R, Bush A, Darwall W, Finlayson AM, Ferrier S, Freyhof J, Hermoso V, Juffe-Bignoli D, Linke S, Nel J, Patricio HC, Pittock J, Raghavan R, Revenga C, Simaika JP, De Wever A (2016) Essential Biodiversity Variables for measuring change in global freshwater biodiversity. Biol Conserv 213. https://doi.org/10.1016/j.biocon.2016.09.005

Tydecks L, Ibelings BW, Tockner K (2019) A global survey of freshwater biological field stations. River Res Appl 35:1314–1324. https://doi.org/10.1002/rra.3476

United Nations (2018) UN climate Change Annual Report 2017

Wade JA (2006) Monitoring and modelling the impacts of global change on European freshwater ecosystems. Sci Total Environ 365:1–2. https://doi.org/10.1016/j.scitotenv.2006.02.030

WCRP (1993) Agreement between the World Meteorological Organization, the International Council of Scientific Unions and the Intergovernmental Oceanographic Commission on the World Climate Research Programme: 9

Whiterod NS, Hammer MP, Vilizzi L (2015) Spatial and temporal variability in fish community structure in Mediterranean climate temporary streams. Fundamental and Applied Limnology 187:135–150. https://doi.org/10.1127/fal/2015/0771

Wohner C, Peterseil J, Poursanidis D, Kliment T, Wilson W, Mirtl M, Chrysoulakis N (2019) DEIMS-SDR – A web portal to document research sites and their associated data. Ecol Inf 51:15–24. https://doi.org/10.1016/j.ecoinf.2019.01.005

Woodward G, Perkins DM, Brown LE (2010) Climate change and freshwater ecosystems: impacts across multiple levels of organization. Philos trans R Soc B 365(1549):2093–2106. https://doi.org/10.1098/rstb.2010.0055

Zamora R, Pérez-Luque AJ, Bonet FJ, Barea-Azcón JM, Aspizua R (eds) (2016) Global of Change Impacts in Sierra Nevada: Challenges for Conservation. Consejería de Medio Ambiente y Ordenación del Territorio. Junta de Andalucía, p 208

Zamora R, Oliva M(2022) The landscape of Sierra Nevada: A unique laboratory of global processes. Springer Nature. ISBN: 978-3-030-94218-2

Authors and Affiliations

Francisco J. Peñas[1] · Mario Álvarez-Cabria[1] · Marta Sáinz-Bariáin[2] · María Pilar Mata-Campo[3] · Aaron Pérez-Haase[4] · Marc Ventura[5] · María José Polo-Gómez[6] · Carlos Alonso[7] · Ignacio Granados[8] · Mario Morellón[9] · Carmen Pérez-Martínez[10] · Ángel Rubio-Romero[8] · Presentación Carrillo[10] · Carmen Zamora-Muñoz[11] · María Valladolid-Martín[12] · Lluís Camarero[5] · Esperança Gacia[5] · Mariàngels Puig[5] · Teresa Buchaca[5] · José Barquín[1]

✉ José Barquín
barquinj@unican.es

[1] IHCantabria - Instituto de Hidráulica Ambiental de la Universidad de Cantabria, PCTCAN, C/ Isabel Torres, 15, 39011 Santander, Spain

[2] Centro Oceanográfico de Santander (COST-IEO), CSIC, Calle Severiano Ballesteros 16, 39004 Santander, Spain

[3] Instituto Geológico y Minero de España, CSIC, C/ Ríos Rosas 23, 28003 Madrid, Spain

[4] Institute for Research in Biodiversity (IRBio) and Department of Evolutionary Biology, Ecology and Environmental Sciences, University of Barcelona, Av. Diagonal 643, 08028 Barcelona, Spain

[5] Centre for Advanced Studies of Blanes, Integrative Freshwater Ecology Group (IFE), Spanish Research Council (CEAB-CSIC), Accés a la Cala St. Francesc, 14, Blanes 17300, Girona, Catalonia, Spain

[6] Fluvial Dynamics and Hydrology Research Group, Andalusian Institute for Earth System Research (IISTA), University of Cordoba, Campus de Rabanales, Edif. Leonardo da Vinci, 14014 Córdoba, Spain

[7] Departamento de Sistemas y Recursos Naturales, Universidad Politécnica de Madrid, José Antonio Novais 10, 28040 Madrid, Spain

[8] Centro de Investigación, Seguimiento y Evaluación, Sierra de Guadarrama National Park, 28740 Rascafría, Spain

[9] Departamento de Geodinámica, Estratigrafía y Paleontología, Facultad de Ciencias Geológicas, Universidad Complutense de Madrid, 28040 Madrid, España

[10] Departamento de Ecología Facultad de Ciencias, Instituto Universitario de Investigación del Agua, Universidad de Granada, Campus Fuentenueva, s/n, 18071 Granada, Spain

[11] Departamento de Zoología e Instituto Universitario de Investigación del Agua. Facultad de Ciencias, Universidad de Granada, Campus Fuentenueva s/n, 18071 Granada, Spain

[12] Departamento de Biodiversidad y Biología Evolutiva, Museo Nacional de Ciencias Naturales (MNCN-CSIC), c/ José Gutiérrez Abascal, 2, 28006 Madrid, Spain