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Research article

Climate change and ecological assessment in Europe under the WFD – Hitting moving targets with shifting baselines?

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ABSTRACT

The Water Framework Directive (WFD) sets the fundamental structure for assessing the status of water bodies in the European Union. Its implementation is currently entering its fourth six-year cycle assisted by a total of 38 guidance documents. The principal objective is to ensure good status for surface and ground waters. The functioning of the WFD is based on detecting the impact of human pressures on biological, physico-chemical, or hydromorphological parameters, and reducing these causal pressures through a program of measures to achieve good status. Climate change can exert a significant influence on ecological status by directly altering parameters monitored, pressure interactions, or influencing the effectiveness of programs of measures. Aquatic systems respond holistically to climate change with different pressures having additive, synergistic, or antagonistic interactions. The challenge is how to adapt the framework to manage aquatic systems in the context of climate change while maintaining focus on implementing measures to tackle key pressures. This paper examines potential approaches, including reassignment of waterbody type, quantifying the portion of Ecological Quality Ratio (EQR) driven by climate change, and creating an assessment module of climatic pressures and ecological responses. The overall purpose is to stimulate discussion and explore ways to incorporate climate change into the WFD structure.

1. Introduction

The Water Framework Directive (WFD) published in 2000 sets the fundamental structure for assessing the status of surface and ground waters in the European Union (Council of the European Communities, 2000). Its implementation is currently entering its fourth six-year cycle assisted by a total of 38 guidance documents (European Commission, 2024). The principal objective is to ensure good status for surface and ground waters across the European Union (or good ecological potential for artificial waterbodies such as reservoirs). Its functioning is fundamentally based on a cyclical approach to detecting impact in biological, chemical or hydromorphological parameters, identifying causal pressures and addressing these through a programme of measures to achieve good status. Principal impacts on 145,430 surface waters in 29 countries were attributed to pollution from chemical (38%), nutrients (26%) and organic material (16%) as well as habitat alteration due to morphological (31%) or hydrological (12%) change, whereas 30% had no significant impacts and 10% were of unknown origin (EEA, 2018). The obligation for member states to include biological quality elements (BQE) in assessment was a novel introduction for European legislation in 2000 and stemmed from the aim to preserve the "structure and functioning of aquatic ecosystems". This aim also acknowledged the ability of bio-indicators to capture the effects of a growing list of human pressures, including nutrients, organic pollution, acidification as well as other pollutants and their interactions as well as continued physical habitat alteration (Karr and Chu, 2006). The quality of each BQE measured is expressed as an Ecological Quality Ratio (EQR) that quantifies the deterioration from reference conditions (values close to 1)

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along five classes: high, good, moderate, poor and finally bad status (values close to 0). Member states can use their own assessment metric for each BQE once it is harmonized through an intercalibration exercise (European Commission, 2018; Poikane et al., 2015). This has led to the development of an expanding list of biological methods that currently total 423, which respond separately or in combination to the pressures of eutrophication (370), “general degradation” (244), hydromorphology (160), organic pollution (157), toxic pollution (95) and acidification (34) (Birk et al., 2012; Poikane et al., 2020).

The impact of climate change on aquatic system health has been a focus for several decades, two related aspects of which concern this communication. The first is the impact on ecosystem functioning and integrity and the second concerns the difficulties posed to the continuation of the WFD system of status assessment in use for over 20 years with detailed biological, chemical and hydromorphological monitoring. Climate change can exert a significant influence at important steps of the management cycle altering parameters monitored, pressure interactions, or influencing the effectiveness of programmes of measures.

River temperatures face increases in annual mean values between 1.3 °C and 3.8 °C (van Vliet et al., 2011). Similarly, lakes globally have been estimated to warm by a median value of 2.5 °C with extremes of 5.5 °C possible, also about a quarter of lakes will lose seasonal ice cover and annual mean evaporation rates are projected to rise by 16% by 2100, impacting lake levels and surface water extent (Woolway et al., 2020; Woolway and Merchant, 2019). Increasing water temperature can have a direct physiological response in biota increasing respiration, while the increasingly frequent pattern of heatwaves followed by colder low-pressure systems in Europe can cause metabolic disruption potentially inducing fish kills (Free et al., 2022; Jeppesen et al., 2021; Zhang et al., 2020). In Italian sub-alpine lakes, more stable stratification now means that climate exerts more control on oxygen than trophic status (Rogora et al., 2018). In addition, seasonal mismatch with alteration to the traditional start, length and end of seasons is already altering species phenology resulting in a mismatch between prey and predators, with implications across ecosystems (Moe et al., 2022; Winder and Sommer, 2012).

Changing precipitation patterns including less snowfall and retention will reshape annual hydrographs in Europe (Ranasinghe et al., 2021). Alteration of river flow, also through engineering responses, will have serious consequences on processes such as sediment provision and transport, altering waterbody morphology and physical habitats. This will lead to changes in species composition successively reducing resilience with climate change progression (O’Briain, 2019; Poff et al., 1997). Geochemical parameters and processes will also be increasingly affected by climate change resulting in increasing mineralization and augmenting nutrient export (McAleer et al., 2022; Rustad et al., 2001) which together with changes in land use and hydrology has already been blamed for increasing N export to the Baltic (Räike et al., 2020). Climate change, less acid rain and land-use change have caused brownification of lakes in Europe, in particular in the Northern region (Finstad et al., 2016; Kritzberg, 2017; Lyche Solheim et al., 2024). Flooding or more frequent summer storms can deliver heavy nutrient loads during short time intervals (Kurz, 2000; Sterner et al., 2020) and can cause more storm-overflows in urban wastewater treatment plants, estimated to increase by 37% in volume for a high emissions scenario (Abdellatif et al., 2015). Reduced rainfall and increased evaporation and abstraction during droughts is already leading to increased salinization of lakes such as Trasimeno in Italy (Ludovisi and Gaino, 2010). Droughts and more evaporation will also cause low water level in lakes with deterioration of the littoral zone macrophytes and invertebrates. The reduced lake volume and increased retention time, combined with higher temperature and short-term extreme rainfall bringing in pulses of nutrients increases the risk of cyanobacterial blooms (Ho et al., 2019; Huisman et al., 2018; Paerl and Huisman, 2009; Sterner et al., 2020; Woolway et al., 2022). Sea level rise will also increase salinization inland and has already started to lead to recession in the deep edge of seagrass colonisation in the Mediterranean (Pergent et al., 2015). While many tidal marshes may become sub-tidal by the end of the century (Short et al., 2016).

Aquatic systems respond in a holistic way to climate change with different pressures having additive, synergistic or antagonistic interactions. The major disaster in the river Oder in 2022 was a multifactorial event with the climatic factors of high solar irradiance, drought and low flows likely concentrating existing pressures such as industrial saline discharges and nutrients to promote rapid growth of an invasive brackish algae (*Prymnesium parvum*) the toxins of which killed fish over 100s of kilometers (Bowes et al., 2016; Free et al., 2023; Nordstrom, 2009). Timing is also crucial, for example compounded events like the two successive rainfall events in May 2023 that led to the disastrous flooding in Emilia-Romagna (Italy) caused 12 categories of environmental impact (Arrighi and Domeneghetti, 2023). Warmer temperatures and increasing nutrient loads are a major reason why cyanobacterial blooms are appearing in more lakes (Paerl and Huisman, 2009).

The extent and complexity of the influence of climate change is now starting to complicate the implementation of the WFD, which is structured to detect and remediate the effects of long-standing major pressures such as nutrients, organic substances and hydromorphology. The management approach is largely dependent on pressure-response relationships either defined or assumed (Poikane et al., 2020) and while the influence of climate change may have been present as noise in such relationships, it is now becoming more apparent. The IPCC have defined the term ‘emergence’ for this phenomenon that may refer “to the experience or appearance of novel conditions of a particular climate variable in a given region”. This concept is often expressed as the ratio of the change in a climate variable relative to the amplitude of natural variations of that variable (often termed a ‘signal-to-noise’ ratio, with emergence occurring as a defined threshold of this ratio)” (Arias et al., 2021).

The challenge is therefore adapting the framework to manage aquatic systems in the context of climate change, while maintaining focus on implementing measures to tackle key pressures such as nutrients and hydromorphological modification to achieve the environmental objectives of good or high status and to prevent deterioration. Here we examine the advantages and disadvantages of three potential approaches: i) reassignment of waterbody type (Nõges et al., 2007); ii) identifying the portion of a response metric representing a sensitive biological quality element (e.g. macroinvertebrates, phytoplankton) as attributable to climate change and iii) insertion of a new assessment module based on climate pressure and ecological response. The latter could be considered alongside other modules – either selecting the one with lowest status (the one-out all-out (ooao) approach), or use more nuanced combination methods, or by developing specific new management strategies on how the influence of climate change is included in overall status assignment or programmes of measures. The overall purpose of the paper is to stimulate, orientate and launch discussion, rather than prematurely forward an approach. Care should be taken in addressing the extremely challenging issue of how to manage Europe’s waters over the coming decades. Can the assessment and management framework be adjusted or is a radical redesign needed?

2. Methods

The approach taken is to initially describe possible approaches in basic detail and to also present examples to illustrate and explore aspects of how the approach might be relevant. Development of fully worked solutions or scenarios and their ecological, policy and management implications is outside the scope of this initial work but will be addressed by future research. The approach is largely a conceptual research approach, seeking to develop, configure and integrate relevant ideas into existing policy frameworks to address climate change. These potential solutions are formed based on collective knowledge, existing research and discussion. Typically, such approaches are not dependent on but form the basis for empirical research (Weaver et al., 2023). Therefore, the main products are the proposed approaches to incorporating climate change into the WFD. Of secondary importance are the examples used for illustration and testing of the approaches. An important next step is the gathering of further experiences and ideas across member states subject to diverse climate pressure and environmental conditions to allow critical appraisal and modifications to the approach.

Depending on the region, lakes in Europe can have reduced water levels, typically in summer. In order to examine the presence and change of water in the lakes we used two products from the Global Surface Water layer: the occurrence layer and the occurrence change intensity layer (Pekel et al., 2016). The occurrence layer represents the frequency at which water was present between 1984 to December 2021 expressed as a percentage (0–100%). The occurrence change intensity layer represents change between the periods 1984–1999 and 2000–2021, values of pixels can range from −100% loss to +100% gain and were expressed as average values per lake extent. Density plots showing data distribution were produced to compare among countries and to show change (in the case of data from the occurrence change intensity layer) using ggplot2 (R Core Team, 2019; Wickham, 2016). In order to test for significant changes in lake water extent derived from the occurrence change intensity layer we carried out a *t*-test for zero mean difference per country with Bonferroni correction in R (R Core Team, 2019).

Information on chlorophyll-a concentration was extracted for 36 European lakes from the lakes CCI (Climate Change Initiative) database which provides satellite derived data for over 2000 lakes globally (https://climate.esa.int/en/projects/lakes/). The methods used, data, and additional lake descriptors are available (Carrea et al., 2023; Free et al., 2022). Data on air temperature and precipitation was extracted, including for the climatological normal period of 30 years (1981–2010 inclusive), from ERA5—the 5th generation ECMWF reanalysis for the global climate (https://cds.climate.copernicus.eu/cdsapp#!/home).

Information on Irish river conductivity and macroinvertebrates were obtained from the Irish EPA using a macroinvertebrate EQR based on the national Q-value system which is derived from the categorical relative abundance of macroinvertebrates (Feeley et al., 2020; Toner et al., 2005).

In order to examine the trend in literature focusing on climate change we carried out a bibliographic analysis using the Scopus database from 1990 to 2023 using the co-occurrence in the title, key words or abstract of any of the words lake, river, estuary, transitional water, with climate change. Within these results, we also searched for those mentioning the WFD.

3. Candidate approaches for incorporating climate change into WFD ecological assessment

It is clear that climate change has become of increasing importance in the achievement of water quality objectives. This is evident in the exponential increase in interest of the influence of climate change on surface waters with 50,664 publications detected using the search criteria in the Scopus database, of which 1222 also mentioned the WFD (an average of 2.1% annually from 2001 to 2023 inclusive) (Fig. A1). The approach taken here is to propose three candidate approaches resulting from efforts to develop, configure and integrate relevant ideas into existing policy frameworks to address climate change. Examples are provided to illustrate some core aspects or applications of the approach but an analysis that is comprehensive of the diverse climatic impacts on the various water categories, types and biological, physical, chemical and hydromorphological components is not possible here.

3.1. Reassignment of waterbody type

Surface water bodies are characterised into water body types defined by a set of obligatory (e.g. physical, geological, hydrological) and optional natural descriptors (e.g., water depth, mixing characteristic, background nutrient status) (Council of the European Communities, 2000). A number of these descriptors are climate-sensitive and could therefore result in waterbodies changing from one type to another over time or as a result of extreme events. For example, climate change could lead to reduced flow, which in extreme circumstances could mean a river switches to an intermittent stream type. See Table A1 for a list of typology parameters used (Lyche Solheim et al., 2019) along with estimated sensitivity to climate change taken from revised guidance document No. 24 “River basin management in a changing climate” (European Commission Directorate-General for Environment, 2024). The approach of reassignment of type together with its associated reference conditions is currently recommended by guidance documents European CommissionDirectorate-General for Environment, 2009a,b; 2024). The core idea is that the new type and reference condition will better describe the new climate-driven ‘background’ conditions, allowing the waterbodies to be managed towards achievable (realigned) environmental objectives such as high or good ecological status (Figs. 1 and 2 for current and proposed system). In practical terms a new type could be assigned by either i) moving the water body to an already existing type and simply applying its reference conditions or ii) in the absence of an existing type, a new one could be created necessitating definition of reference conditions and class boundaries (European CommissionDirectorate-General for Environment, 2024). Guidance document 10 suggests methods for establishing reference conditions such as using spatial networks of existing reference sites, historical data, palaeoenvironmental approaches, modelling or expert judgement as a last resort (REFCOND, 2003). Monitoring and updating the conditions from a representative series of reference sites would allow for adaptive management (Nõges et al., 2007).

One of the more straightforward examples of a change in type may result from the fundamental change brought on by the predicted changes in amounts of precipitation spatially and temporally. There is now high confidence that the global water cycle has intensified since at least 1980 with amplified precipitation and evaporation cycles (Arias et al., 2021). Changes are predicted to differ spatially in Europe, with for example, stronger hydrological droughts in the Mediterranean while the Boreal region will have fewer drought traits (Cammalleri et al., 2020). Anthropogenic efforts to adapt to climate change, such as increased abstraction and hydromorphological alterations are likely to add additional pressure on water resources. Fig. 3 shows a recent example from Sentinel 2 satellite image showing declining water levels in Baells reservoir in Cataluña in Spain as a result of extreme drought from 2021 to 2024. The visible reduction in lake extent with significant visible areas of exposed littoral will cause severe disruption to the structure and function of the ecosystem that takes many years to recover. In such systems, climate driven drought and increased demand for water abstraction from reservoirs will mean that an impoverished community of littoral macrophytes and invertebrates can only realistically be expected. A change of type to reflect an increased frequency of littoral desiccation of reservoirs and lakes in the region may theoretically be carried out using the reassignment of waterbody type approach. For reservoirs, ecological potential rather than ecological status is assessed under the WFD with typically lower environmental objectives.

However, droughts and low water levels are also a feature of the Mediterranean region. Fig. 4 shows the percentage of water occurrence in EU lakes and reservoirs and it is clear that there is typically a lower percentage with many lakes in Spain having a mean occurrence of <20% over the period 1984–2021 (See also Fig. A2). Therefore, it is important to use long-term data to show a change that can be attributed to climate change as distinct from regional climatic patterns. To carry out an initial examination of this we used the occurrence change intensity layer from the global surface water layer database (Pekel et al., 2016) that represents change between the periods 1984–1999 and 2000–2021 where values can range from −100% loss to +100% gain and were expressed as average values per lake. For the lakes and reservoirs used for reporting

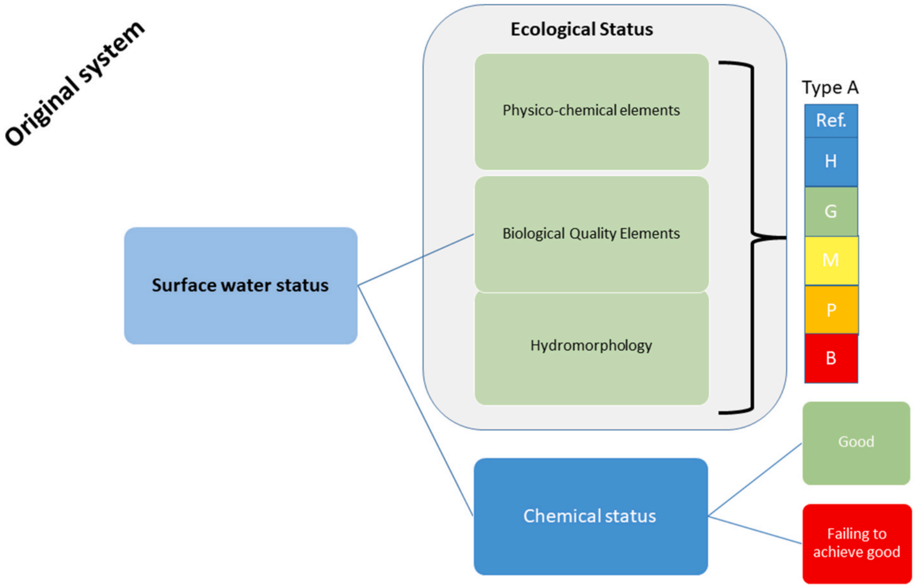

Fig. 1. Original assessment components of the WFD classification system for surface water status.

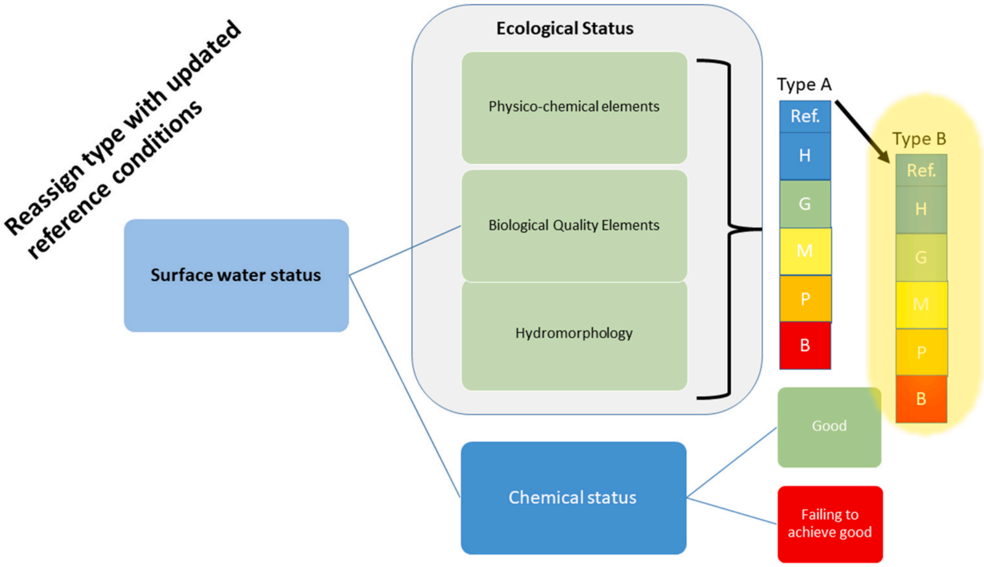

Fig. 2. Reassignment of type and associated reference conditions (yellow oval highlighted) to update assessment components of the WFD system of classification of surface water status in response to climate change. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

in Europe, 6 countries had a significant decrease (FI, HR, IS, LT, LV, PL), 13 had an increase (CY, CZ, DE, DK, EL, ES, FR, HU, IE, IT, NL, NO, SE) while 7 had no significant change (AT, BE, BG, EE, PT, RO, SI) (Fig. 5, Table A2).

3.2. Quantify the portion of EQR driven by climate change

WFD monitoring and assessment systems are designed to incorporate the impact from multiple stressors. The key challenge is to maintain the integrity of these systems in a changing climate. One approach may be to attempt to separate the effects of climate change from other pressures. In particular, the BQEs may be uniquely useful in integrating the net influence of climate change alongside other pressures such as nutrients and hydrology. One possibility is to quantify the decrease in EQR estimated as attributable to climate change and notify this by adding a subscript value to an EQR. For example, a reported EQR of $\mathbf{0.54}_{0.10}$ would indicate that established assessment systems have assigned an EQR of **0.54** (moderate status) but the subscript of **0.10** indicates that climate change is responsible for a decline of 0.10 EQR units (from 0.64 to 0.54) resulting in a change from good to moderate status. Essentially this would be conceptually similar to temperature anomaly maps where deviation from the established normal conditions are reported (Fig. 6).

Such a system could be applied by MS to their waterbodies where the EQR is being altered by climate change. To examine the feasibility of such an approach we considered the example of heatwave events that can increase chlorophyll-a concentration in lakes. We compared the difference between summer chlorophyll-a (June–September inclusive) from a warm year with heatwave events (2018) with a year where summer temperatures were closer to the 30 year average (2017) (Copernicus Climate Change Service, 2021). Chlorophyll-a values were converted to a normalised EQR (NEQR) with a range from 1 to 0 which decreases as chlorophyll-a increases. Fig. 7 shows that during the

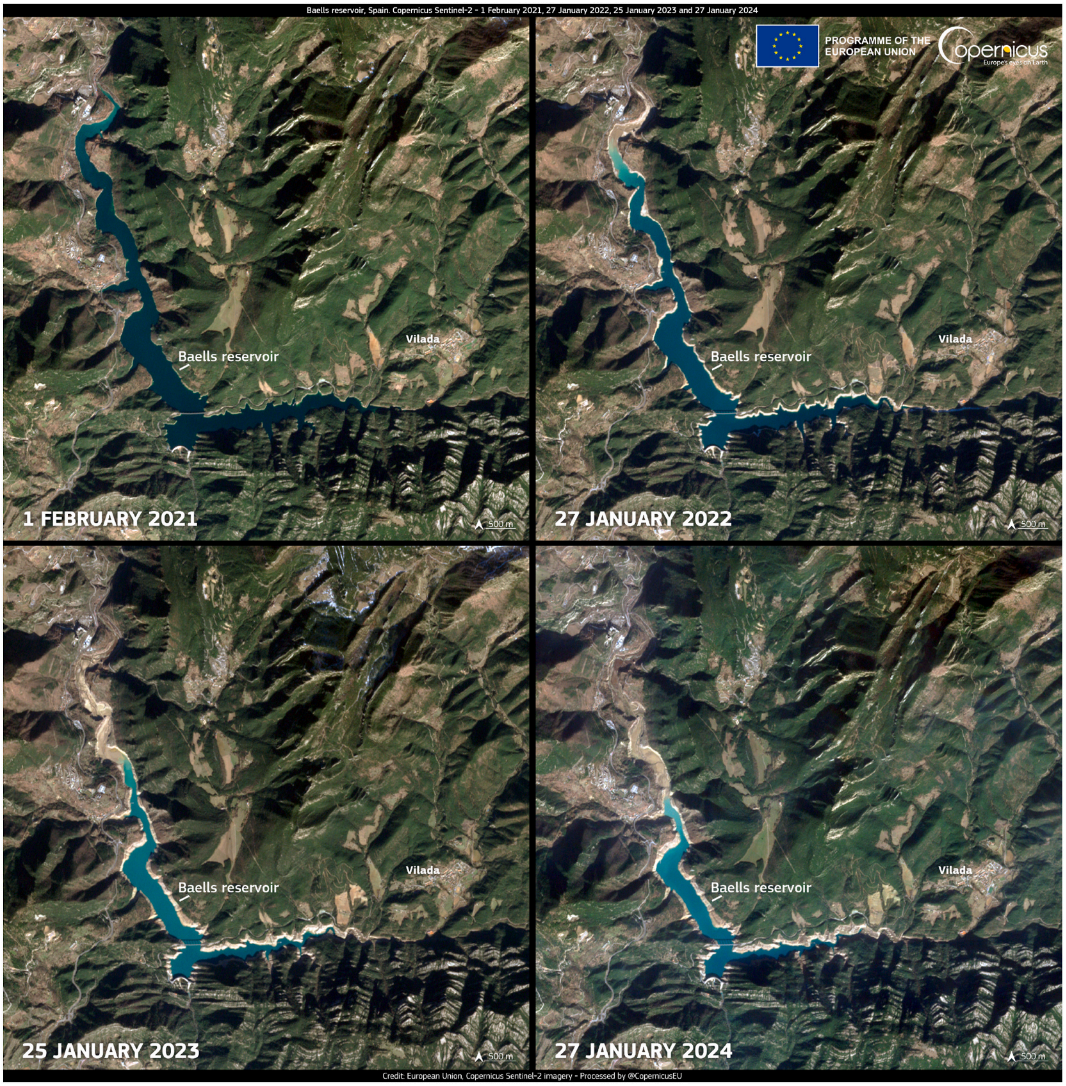

Fig. 3. Copernicus Sentinel 2 image showing declining water levels in Baells reservoir in Cataluña in Spain as a result of extreme drought. Image from https://www.copernicus.eu/en/media/image-day-gallery/severe-drought-cataluna-spain [accessed March 22, 2024].

warmer year 2018 the normalised EQR was lower depending on how much warmer than average it was, with a notable decline in NEQR when temperatures were more than 2 °C warmer. However, in this example only after higher temperatures of 2.5 °C does the smoothed relationship indicate a decline of 0.1 NEQR, equating to half a quality class. As indicated above, reporting would continue to follow established procedure reporting a ‘face-value’ NEQR but the portion of the NEQR estimated to be caused by climate change would be included as a subscript to the value (Fig. 6).

3.3. *Create assessment module of climatic pressures and ecological responses (climate as a supporting element)*

Currently the WFD requires the assessment of supporting parameters to ensure good ecological status or higher. These include nutrients, salinity, acidification, thermal conditions, oxygen, transparency and hydromorphology. The classification of ecological status is required to be carried out using these supporting elements as well as BQEs. Therefore, for example if phosphorus concentrations were deemed not to be supporting good ecological status or higher a waterbody could be classified as below good ecological status and in need of restoration. A similar approach could be applied to climatic factors if they are considered as a dynamic supporting parameter or pressure (Fig. 8). For example, rainfall or drought indicators could be linked to aspects of macroinvertebrate community health in rivers or lakes. Such metrics could be considered in an overall assessment of ecological status. While gradual climatic change, such as warming, may impact ecological quality, so too can sudden climatic events such as floods. We examined the impact of an anomalously high (over 1 in 100) rainfall event in December 2015 in Ireland (Fig. 9A) to see if it led to reduced river macroinvertebrate status (McCarthy et al., 2016). Comparing before (2013) and after (2016) assessment periods found a significant decline in conductivity (Fig. 9B) but not for the ecological quality of macroinvertebrates (Fig. 9C).

4. Discussion

The absence of explicit mention of climate change in the WFD has been regarded as an omission that needs addressing with increasing urgency (Escribano Francés et al., 2017; Wilby et al., 2006). It has been listed as one of the core factors driving development needs of the WFD alongside related factors such as improving diagnosis of drivers of status decline and the understanding of multiple pressure interactions (Carvalho et al., 2019). The construction of a detailed assessment framework with guidance documents, intercalibrated BQEs, thresholds of supporting standards, transposition into national legislation all now

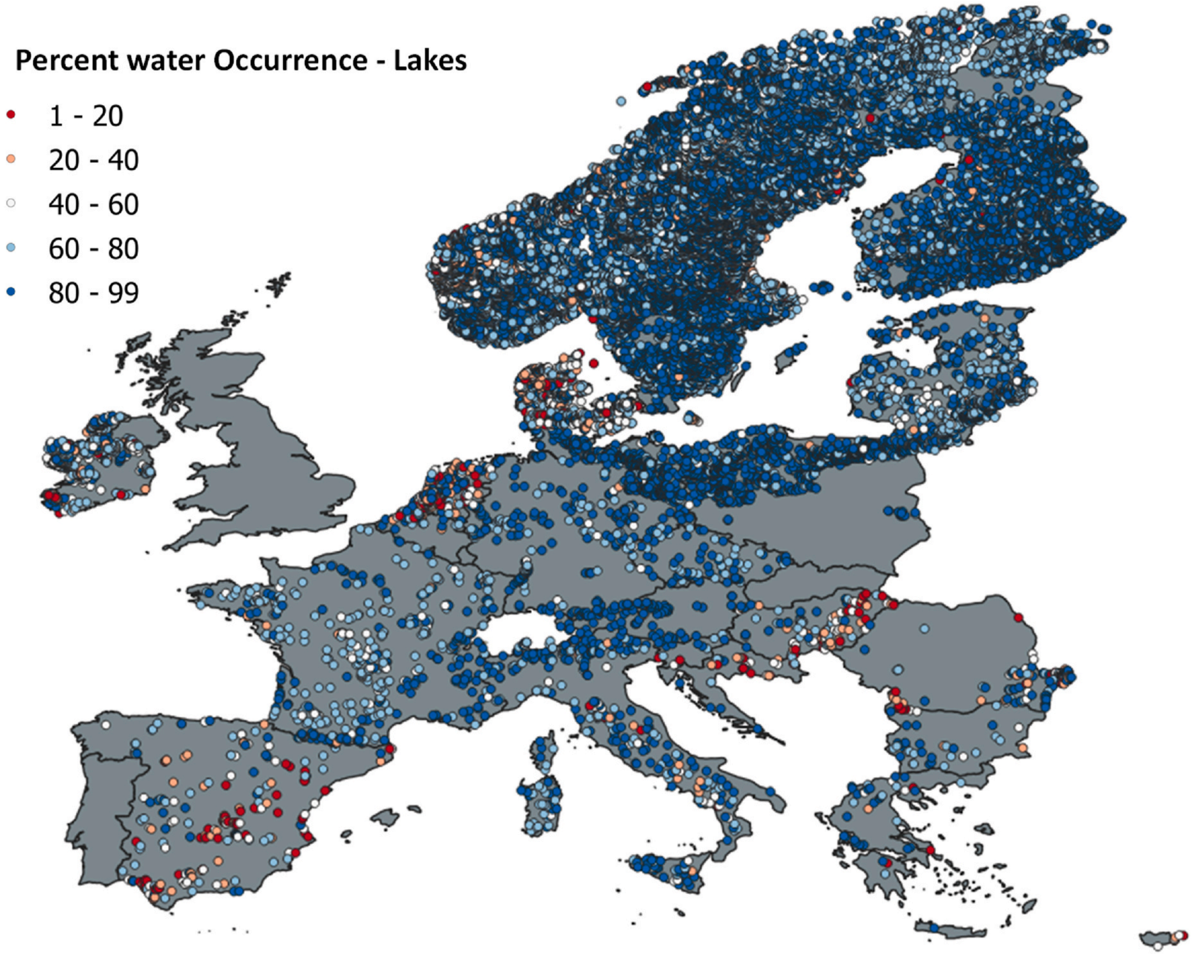

Fig. 4. The average percent of water occurrence in WFD lakes in the European Union (mean occurrence of water between March 1984 to December 2021) extracted from the Global Surface Water layer (Pekel et al., 2016). For each lake, the occurrence was averaged by lake extent.

entering the fourth six-year management cycle, represents a substantial organization commitment across the EU. In addition, the planned capital investment costs for the measures in the 2nd RBMPs have been estimated as at least EUR 142 billion (European CommissionDirectorate-General for Environment, 2021). This investment by MS needs protecting by finding a way to incorporate climate change into the system to enable continued management in order to allow achievement of environmental objectives. However, the construction of a system with such strongly connected monitoring, reporting and remediation activities backed by legislation also represents a hindrance to adaptive management (Pahl-Wostl, 2007). For example, MS nutrient boundaries have proved difficult to change even if they are too high to support good status in some countries (Nikolaidis et al., 2022; Poikane et al., 2019), notwithstanding the fact that the current setting of nutrient boundaries does not have an explicit consideration of climate change (Crane et al., 2005).

The approach taken here is to propose three candidate approaches resulting from efforts to develop, configure and integrate relevant ideas into existing policy frameworks to address climate change. These approaches have important benefits and drawbacks that are discussed below (with summary in Table 1). It is important that climate change is positioned appropriately into the WFD structure, ideally in a way to improve understanding of monitoring assessments and allow or even contribute to an integrated approach to achieving environmental objectives. It must be avoided that enthusiasm for restoration or preservation of the aquatic resource is weakened by the belief that climate change will inevitably degrade our systems. There is a danger this could be fostered by allowing widespread derogations for member states missing environmental objectives. Derogations do have their place, especially following extreme climatic events and in other circumstances but not in a fatalist framework that does not ensure concerted effort to preserve and restore water quality (European Commission Directorate-General for Environment, 2009b). A hurdle to overcome is the complex and diverse governance across the EU as well as the power of legacy systems to slow the pace of change reducing compliance and achievement of environmental objectives (Rowbottom et al., 2022).

4.1. Reassignment of waterbody type

Reassignment of type together with its associated reference conditions is currently the recommended approach maintained in the revised guidance (European Commission Directorate-General for Environment, 2024; 2009a,b). Reassigning a waterbody's type and reference condition will better describe the new climate-driven 'background' conditions allowing the waterbody to be adaptively managed towards environmental objectives that are realistic in new climatic scenarios (Fig. 2). The concept of reference conditions not being static in time and space is supported by studies of reference sites showing natural variability (Bouleau and Pont, 2015; White and Walker, 1997). The characterization of waterbodies in a river basin district is required to be carried out every 6 years (WFD, Article 5) and would allow a typology change. The example provided was for lakes and reservoirs and was motivated by discussions within an ecological working group on ecological status for the WFD, where some Mediterranean countries stated an obvious point,

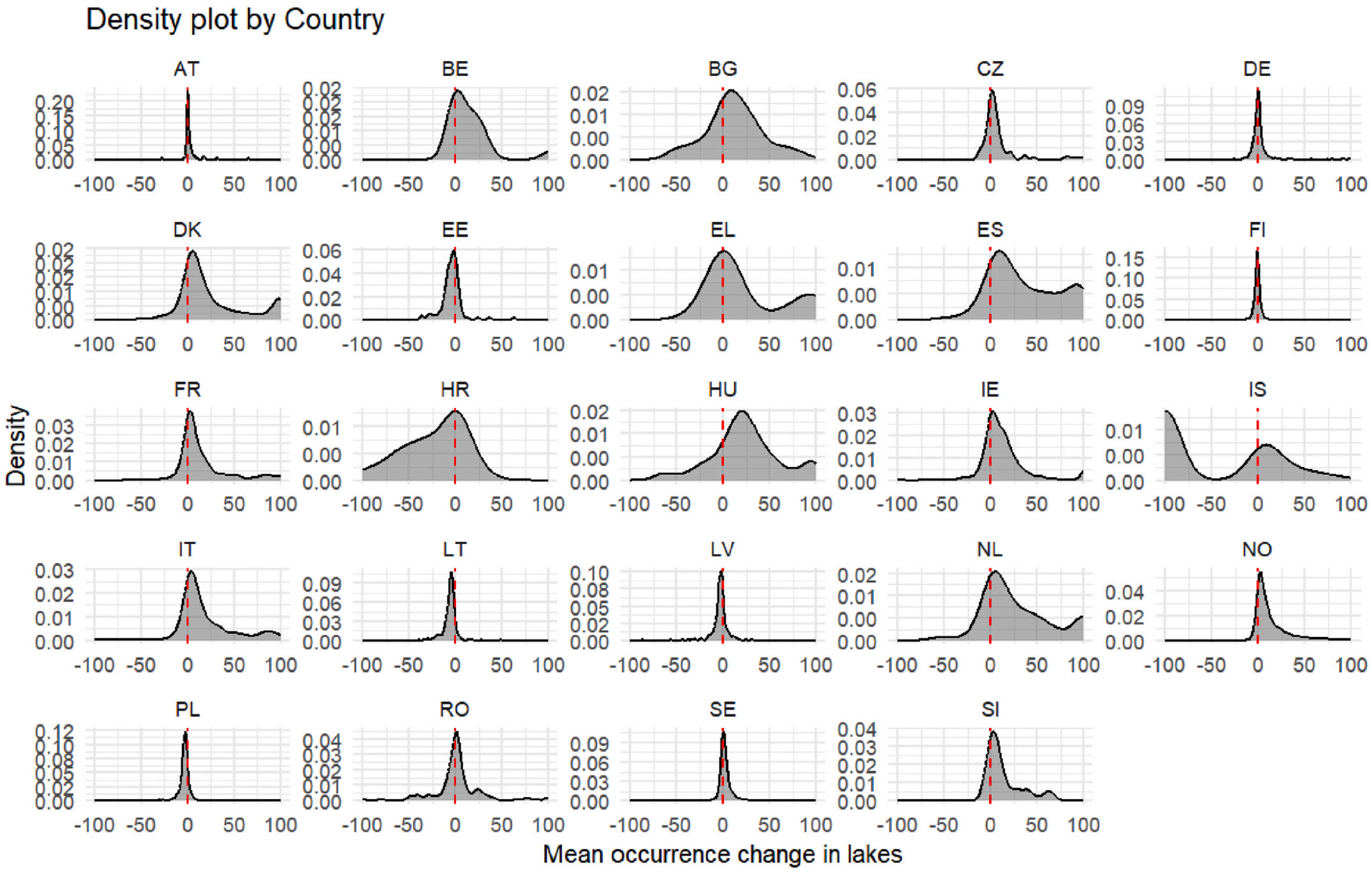

Fig. 5. Density plots showing data distribution by country of mean occurrence change intensity between 1984-1999 and 2000–2021 in WFD lakes in Europe Union extracted from the Global Surface Water layer (Pekel et al., 2016). Red line indicates zero mean change. Only countries with >10 lakes included. The occurrence change intensity layer represents change between the periods 1984–1999 and 2000–2021, values can range from −100% loss to +100% gain and were expressed as average values per lake extent. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

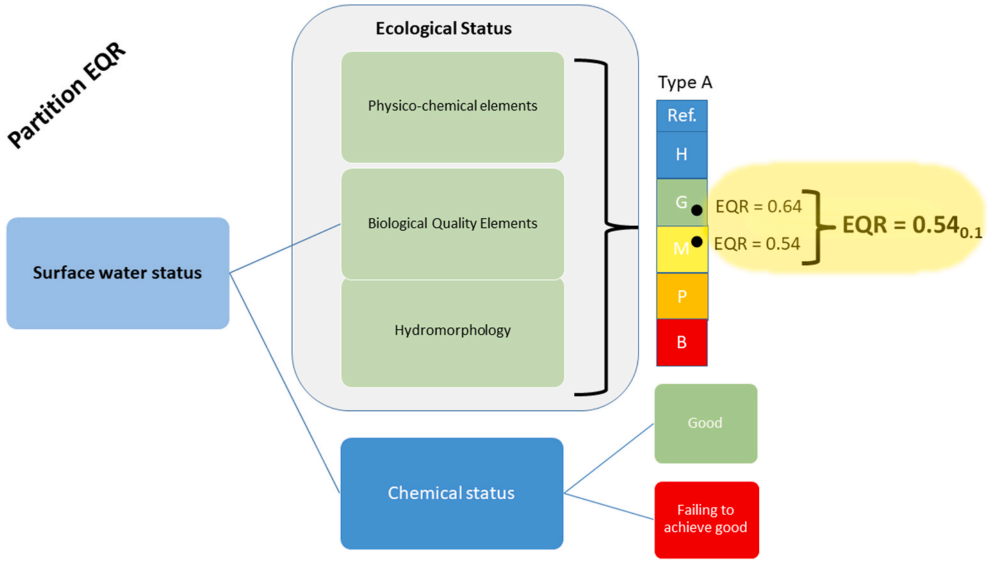

Fig. 6. Partitioning of EQR to quantify the part driven by climate change (yellow oval highlighted) to update assessment components of the WFD classification system for surface water status in response to climate change. The EQR value of 0.54 is the value determined by assessment of the biological quality element and the subscript indicates that climate change has caused a 0.1 decline – in the absence of climate change the EQR would have been 0.64. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

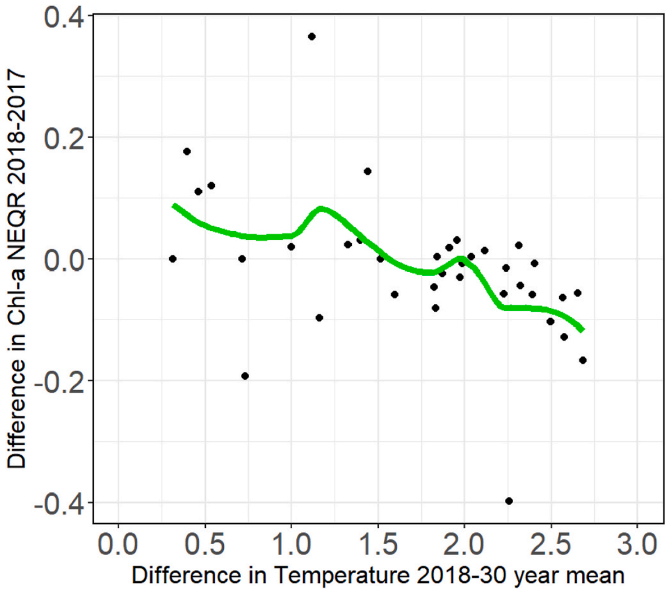

Fig. 7. Difference in chlorophyll-a normalised Ecological Quality Ratio (NEQR) between 2017 and the 2018 against the temperature anomaly (2018-30 year mean) for 36 European lakes. All values June–September inclusive. Loess smoothed line fit to data.

now crystalized by climate change, that policy implementation in this area requires the presence of water as a prerequisite. The drying of reservoir or lake beds also represents a positive feedback for climate change with exposed littoral areas releasing significant carbon dioxide and methane, for example, in the case of Great Salt Lake this amounted to a 7% increase of Utah's anthropogenic greenhouse gas emission (Cobo et al., 2024). The analysis of the variation in water occurrence in the lakes over time was limited in scope. The interpretation of increases or decreases will depend on not only climate change but also on the time periods compared, the morphometry of the lakes with shallow smaller lakes more likely to be dynamic than larger deep lakes with regulation of outflows (e.g. Austria had very little variation over time). Furthermore, analysis by country overlooks the presence of a large climatic gradient in some EU countries (e.g. Italy, France, Norway). It does show that waterbodies are dramatically different across Europe and that some countries had significant increases or decreases in surface extent worthy of further investigation to understand the implications for water management and climate adaptation.

Other examples requiring a change in type could be a river transitioning from permanent flow to a temporary river with altered macroinvertebrate fauna. Another example is brownification of lakes, which is partly due to a wetter climate in Northern Europe causing lakes to change from clear-water lakes to humic lakes (de Wit et al., 2016; Williamson et al., 2015). These have different baseline values as well as target values (good/moderate boundaries) for BQEs and supporting elements (e.g. nutrients and transparency) (Lyche-Solheim et al., 2014; Poikane et al., 2022). For example, isoetid lakes, which often have a rich macrophyte and associated invertebrate fauna, which through climate driven brownification and a reduction in the light climate would transition to a more humic type with substantially lower macrophyte abundance. A loss of functioning would be associated with this through the disruption of the sediment oxygenation and P retention mechanism afforded by isoetid roots (Free et al., 2009; Smolders et al., 2002). The transition from a clear to a humic type also causes changes in the phytoplankton community towards mixotrophic algae and less risk of cyanobacterial blooms but higher risk of another harmful algae (*Gonyostomum semen*) (Hagman et al., 2020; Lyche Solheim et al., 2024). In cases such as these, the new reference conditions would be adopted with management addressing other existing pressures.

There are several drawbacks to this approach including the disruption to the time series for a waterbody with an EQR switching reference conditions and type thereby making assessment less transparent to stakeholders. It also represents an additional complexity for scientists already struggling understand environmental change across multiple combinations of types, methods and classification rules applied in the 27 EU countries (Birk et al., 2012). There is also concern that adjusting type and reference condition may have to be done more than once. Examining the trend since the 1960s in CO_2 increase rate indicates decadal plateaus; potentially making positioning of adjusted reference

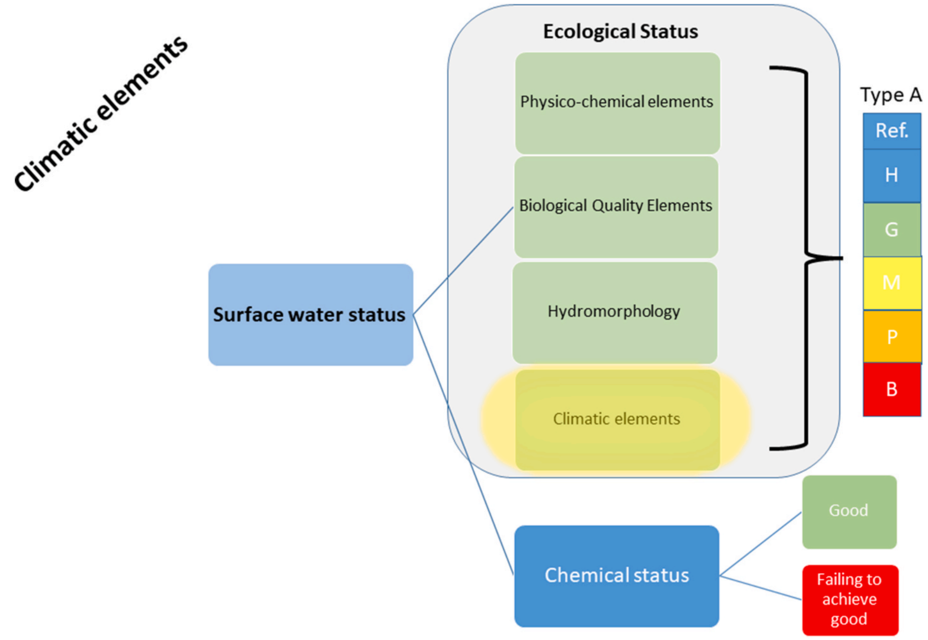

Fig. 8. Incorporation of a climate elements component (yellow oval highlighted) as a new group of supporting parameters to update assessment components of the WFD classification system for surface water status in response to climate change. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

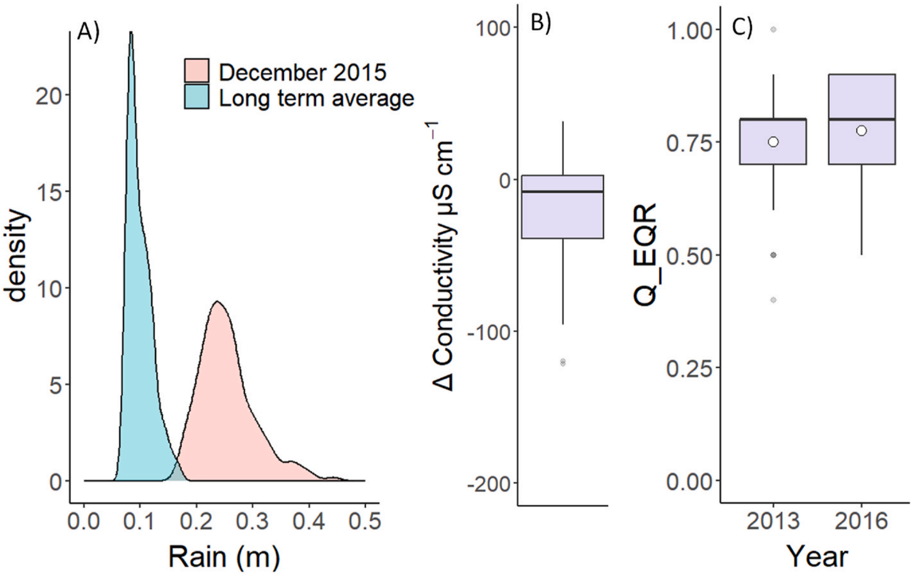

Fig. 9. A) Comparison of long term average rainfall in December with that of December 2015 in Ireland. Differences between 2013 and 2015 for B) conductivity and C) Q_EQR – the ecological quality ratio (derived from the Q value for macroinvertebrates).

conditions a short-term exercise (Fig. A3). While an initial breaching of a resilience threshold due to climate change may result in a new community that could be used as a reference point, the reduction in resilience means that subsequent changes are more likely, with each change being accompanied by a successive reduction in the communities original species (O'Briain, 2019). In addition, the approach may be less useful for countries that have only broad types or generic assessment metrics.

4.2. *Quantify the portion of EQR driven by climate change*

A key benefit of biological monitoring is that it integrates the effect of multiple pressures and their interactions and allows a results-based assessment of the effectiveness of management in the form of preservation or restoration of ecological quality. Apportioning a part of the EQR to the impact of climate change allows focus on the most important part of the assessment system – the ecological response to a complex mix of pressures such as altered hydrology, chemistry and interactions (Fig. 6). Interactions can have important implications with additive, synergistic or antagonistic effects, for example the effect of pollution by fine sediment can be stronger at higher temperatures, but the interaction also depends on nutrient concentrations (Birk et al., 2020; Piggott et al., 2015).

In our example we carried out a simple comparison between a normal year and a year with a recorded heatwave and found that for lakes with temperatures of 2.5 °C above average the EQR declined by 0.1 NEQR units, equating to half a quality class. A similar approach could be applied to compare before and after climatic events or more complex models could be produced to apportion the variation attributable to climate change and this would represent a key scientific challenge of the approach. Twenty years of WFD monitoring has resulted in a wealth of data that could be used to address this, especially when using raw data rather than the reported EQR values (Haase et al., 2023). Long-time series of reference sites are particularly useful in understanding climate change and extracting its influence from other complex drivers (Irz et al., 2024). However, water-bodies that are already impacted by other pressures (such as nutrients and organic pollution) may be more vulnerable to climate change than water-bodies in reference conditions, so climate impacts on reference sites cannot be automatically extrapolated to be valid also for more impacted waters. Simplistic niche-models could also be used for rivers where temperature and solar irradiation are key drivers of cyanobacterial blooms for example (Bowes et al., 2024). In a European context, remote sensing is crucial to providing standardized synoptic data to understand climate driven change at appropriate scale and frequency (Free et al., 2022; Neil et al., 2019).

It would be expected that there would be regional consistency, among similar types, to the climate driven alteration of the EQR. For example, large deep sub-alpine lakes in northern Italy have shown similar shifting seasonal patterns in chlorophyll-a (Free et al., 2021). Some of the benefits of this approach are that it maintains the original EQR while adding additional information as to the climate driven component of it. The approach also makes transparent a member state's estimate of how climate change is influencing a waterbody. It would allow a regional and European analysis of how climate change is affecting aquatic ecology. However, a key drawback is that reference conditions and environmental objectives may no longer be appropriate or achievable under climate change conditions. However, the proportion of EQR attributed to climate change could be useful to inform on the need to increase measures that could counteract the impact of climate change combined with other pressures to achieve good status and maintain ecosystem services. It could also inform on the application of exemptions, in cases where further increases in measures to reduce other pressures are not feasible. Further consideration could also be given to quantifying the influence of climate change on the other individual components of the WFD system for assessing status such as phyico-chemistry and hydromorphology.

4.3. *Including climate as a supporting element*

The WFD six year management cycle focuses on restoring status through established programmes of measures to reduce pressures such as nutrients and hydro-morphological modifications, while the exclusion of climate change as an anthropogenic pressure was due to the absence of mitigation options within this framework (Quevauviller, 2011). However, its exclusion as a pressure from assessment of water quality is generating an increasing gap in the understanding of ecological status decline when climate change is strongly interacting with other pressures (Birk et al., 2020; Spears et al., 2022). Countries that are particularly sensitive to climate change such as Spain with increasing droughts, low flows, higher temperatures and water quality issues that threaten sustainable development have pointed to gaps in policy and implementation suggesting that climate change should be mentioned as

Table 1
Summary of three approaches to incorporate climate change into WFD assessment together with advantages and disadvantages. CC = climate change, POMs = programmes of measures.

	Type change	Partition influence of CC	Climate as a ’supporting parameter’
Summary of approach	Move to existing type or define new type.	EQR is reported using standard approach together with the proportion attributed to CC.	Climate is defined as a supporting parameter. Sites can then fail for climate when it fails to support GES
Advantages	*Allows a framework where realistic management objectives can be achieved in the context of a changed climate. *Recognises that reference conditions are not static over time.	*Allow a continued focus on pressures such as nutrients apart from CC. *Maintains integrity of timeseries. *Allows additional adaption measures to be included to counteract the negative impact of CC on EQR values. *Assessment of the fraction of change driven by CC could provide evidence for exemptions under the WFD. *Allows for transparency in effect of CC and subsequent decision making. *Allows an estimation at European level how CC is affecting aquatic ecology.	*Provides increasingly essential context as to why some waterbodies may fail or decline in status. *Provides accessible and appropriate data for developing a multi-stressor model of status.* Understanding the driver of status failure allows for better planning of POMs including CC adaptation strategies. *A demonstrated failure driven solely by climate on the ooao principle could provide evidence for exemptions under the WFD in cases where additional adaptation measures to counteract CC impacts would not be sufficient to achieve good status. *Many metrics of climatic and weather related stress already exist and are available at appropriate spatial level. Allows for transparency in effect of CC and subsequent decision making.
Disadvantages	*Climate change may continually occur rather than fitting a stage or type change framework. *Difficult to maintain a timeseries on how quality has changed. *Could be interpreted as a de facto lowering of environmental objectives. *May not help countries who use few or one type for assessment. *Masks reality of the impact of CC on ecological status. *Reduces transparency in status and objectives assignment.	*Technically difficult to precisely define.*Original reference conditions may no longer be appropriate. *Environmental objectives may no longer be achievable. *CC may influence nutrient loading or hydromorphology - impacts on a BQE may be indirect and not straightforward.	*Introduces a supporting element that can cause status decline for which remediation may not be feasible. *Confounds typology and supporting parameters. *Interacts with other supporting elements, which makes it difficult to know whether the impact on BQEs are direct (e.g. warming) or indirect through impacts on other supporting QEs (e.g. increasing nutrient loads and concentrations). *Difficult to maintain a timeseries on how quality has changed if a new supporting element is included. * If CC is not considered as a pressure, the PoMs may not be able to include measures to counteract its negative impacts on BQEs and on other supporting elements.

an anthropogenic pressure in WFD revision (Escribano Francés et al., 2017).

One option is to incorporate climate change alongside the group of supporting parameters, which would allow it to be included in assessments similar to nutrients conditions, for example. Current recommendations include a stepwise process of establishing a significant relationship with ecological quality, defining thresholds that correspond to class change, emphasizing the transition point from good to moderate using either linear methods (ranged major axis) or categorical methods (binary logistic regression) (Phillips et al., 2019, 2023). While this approach works for dominant drivers such as total phosphorus for phytoplankton in lakes, it is more likely that climate change parameters mostly act as secondary pressures with important interactions. Adopting a multi-stressor approach to setting boundaries or altering combination classification rules among supporting parameters may be needed rather than the one-out-all-out univariate system currently in use (Caroni et al., 2013). Classification outcomes could be assessed using a confusion matrix approach to manage false negatives and positives appropriately (Phillips et al., 2023, 2024). In addition, most existing BQE metrics have been developed to detect traditional pressures such as nutrients or general degradation and effort would have to be directed to establishing new climate orientated BQE metrics able to detect climate driven shifts in structure and function of ecosystems. An approach to this could include revisiting current metric components to allow greater specificity in response to specified pressures or climate. For example many river macroinvertebrate community based metrics decrease in response to both impacts and drying, while metrics specifically developed using groups of taxa with drought resistant and resilient traits have been found to be better placed to detect specific impacts in rivers susceptible to drying (Stubbington et al., 2022).

One of the key benefits of this approach is that inclusion of climate change as an increasingly important stressor provides essential context as to why some waterbodies may fail to improve their ecological status even if measures to reduce nutrients or hydromorphological pressures have been taken. Other water-bodies may even decline in status due to a combination of climate change and other pressures. In the example from Irish rivers that experienced a high rainfall event, an impact was noted in conductivity being lower but the EQR was not affected. The lower conductivity indicates a dilution effect and the macroinvertebrate EQR may be unaffected because taxa best placed to survive high flows such as Ephemeroptera and Plecoptera are often indicative of higher quality in assessment systems (Feeley et al., 2020). In selecting this example, we expected an impact on the EQR from a >1 in a 100 year extreme rainfall event. We chose to retain this example rather than replace it with another that had a clear ecological impact partly because the removal of negative results creates a bias in reported research (Simundic, 2013). More importantly, a key component of establishing climate as a supporting element would be validation of an EQR response against a climate parameter, in this case if the extreme rainfall does not have an effect on the EQR then no provision for this would be necessary and monitoring and programmes of measures could proceed as before to ensure environmental objectives.

Grouping climate change alongside other pressures may be one of the most intuitive approaches. It also ensures the collection of appropriate data for developing a multi-stressor model of impact on status or on EQR values. Supporting information regarding the climate pressure experienced by a site could be collected as part of the WFD programme but detailed information can also be taken from annual European State of the Climate reports (https://climate.copernicus.eu/ESOTC) or reanalysis datasets (https://climate.copernicus.eu/climate-reanalysis). These provide data and maps on temperature anomaly, soil moisture deficit, river discharge etc. as well as associated documents on heatwaves and floods.

A pressure that signals a failure to provide supporting conditions for good status – such as climate driven low flows would prompt the exploration of targeted measures for mitigation or adaptation at local level. While the success of measures may not be guaranteed with the accelerating progression of climate change, a combination of several measures can still be effective to at least partly counteract the negative impacts. Such solutions include better governance, smart metering, pricing, green infrastructure, natural water retention, enhancing water-efficiency in agriculture and riparian zone management (Costa and Lopes, 2024; Escribano Francés et al., 2017; Kritzberg et al., 2020). However, one of the main reasons for the original exclusion of climate from the WFD was the difficulty in managing it in the context of reaching environmental objectives and some unmanageable impacts and events will require exemptions. Another criticism is that including climatic variables as a pressure confounds their current position as typological parameters. The WFD lists air temperature, precipitation and flow characteristics for rivers as optional typology parameters. However, the WFD already mirrors several typological parameters as supporting parameters (pressures). For example, chloride and salinity for rivers and even background nutrient status for lakes, in these cases what is important is the deviation of a supporting parameter away from reference condition with particular attention regarding values that support good ecological status. Therefore it should not be a conceptual problem to include climatic metrics as supporting parameters and there is a longstanding practice to use metrics that express deviation from normal climatic conditions – for example: 95th percentile flow, temperature anomaly, standardized precipitation index or water scarcity metrics (Vanham et al., 2018; WMO, 2012). Another disadvantage, shared with the approach to changing typology, is that the inclusion of additional climate-related supporting parameters will alter the classification procedures which will make assessment of overall status incompatible with previous assessments from earlier reporting cycles.

4.4. *Final comments*

The objective was to present potential avenues to promote discussion in this area. Often listing the benefits and drawbacks of approaches can help deciding on how to proceed. Identifying some of the desirable characteristics of a solution to better incorporate climate change into the WFD include.

- enables further improvement towards maintaining or achieving environmental objectives,
- enhances understanding and decision making,
- supports and improves transparency
- preserves the time-series so change can be assessed
- allows adaptive management in an uncertain future

The next steps should be to share experiences and examples among countries and redouble research in order to ensure that management and protection of aquatic systems continues. We need science to inform what we can manage and policy to guide implementation but there will also need to be a clear avenue to allow exemptions for what we cannot fix. Finding a path that best enables this in an adaptive management framework is the solution to inserting the missing climate change piece in the WFD jigsaw.

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CRediT authorship contribution statement

Gary Free: Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Sandra Poikane:** Writing – review & editing, Writing – original draft, Conceptualization. **Anne Lyche Solheim:** Writing – review & editing, Writing – original draft, Conceptualization. **Martina Bussettini:** Writing – review & editing, Writing – original draft, Conceptualization. **Catherine Bradley:** Writing – review & editing, Data curation. **Jean Smith:** Writing – review & editing, Data curation. **Rossana Caroni:** Writing – review & editing, Data curation. **Mariano Bresciani:** Writing – review & editing, Data curation. **Monica Pinardi:** Writing – review & editing, Data curation. **Claudia Giardino:** Writing – review & editing, Data curation. **Wouter van de Bund:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of competing interest

The authors declare no competing interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.122884.

Data availability

All data used is available online at the sources listed in the text.

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