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Toward "good" eutrophication data for marine policies and research: a multi-level quality control framework in EMODnet Chemistry

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The increasing demand for reliable marine data to support environmental policies such as the Marine Strategy Framework Directive (MSFD) in Europe requires harmonized, high-quality datasets that are findable, accessible, interoperable, and reusable (FAIR). This paper presents a multi-level quality control (QC) protocol applied within the European Marine Observation and Data Network (EMODnet) Chemistry initiative, focused on eutrophication parameters (nutrients, chlorophyll, and oxygen) across European marine regions. The approach combines automated and expert-based validation and includes three consecutive QC steps performed by the data originators (Level 1 QC), the data centers (Level 2 QC), and the regional coordinators (Level 3 QC). Particular attention is also given to collecting and maintaining comprehensive metadata associated with the datasets, as well as methodological quality assurance (QA) information. The framework ensures transparent and consistent QC practices across different data providers, improving data comparability and usability. Additional procedures—including cross-parameter checks, derived variable analysis, and region-specific broad range comparisons—are implemented to detect outliers and enhance dataset reliability. The protocol supports the implementation of European marine policies by enabling coherent environmental assessments, and is adaptable to other variables such as ocean acidification and pollution. This work demonstrates the value of expert based, interoperable QC procedures to advance marine data quality and reusability.

KEYWORDS
EMODnet Chemistry, environmental policy support, eutrophication, FAIR data principles, marine data quality

1 Introduction

Marine environmental assessments rely on consistent, high-quality data to evaluate the impacts of human activities and natural processes in the ocean. European and international policy frameworks—such as the Marine Strategy Framework Directive (MSFD), Water Framework Directive (WFD), and regional conventions like the Oslo—Paris Commission (OSPAR), Helsinki Commission (HELCOM), Black Sea Commission, and Barcelona Convention—require data that are comparable across sources as well as validated through transparent and robust procedures.

However, marine data collection often involves heterogeneous methodologies, instruments, and laboratory procedures across regions and institutions. This diversity creates challenges for data integration, comparability, and re-use. In order to guarantee data comparability among different laboratories, harmonized sampling and methodological procedures, together with coherent data management and accurate and transparent quality control are crucial (Berto et al., 2020; Lipizer et al., 2021; Molina Jack et al., 2020). Over the last decades, the European Union and several international initiatives—including SeaDataNet, the European Marine Observation and Data Network (EMODnet), Copernicus Marine Environment Monitoring Service (CMEMS), World Ocean Database (WOD, of the United States National Centres for Environmental Information), International Council for the Exploration of the Sea (ICES)—have made significant efforts to reduce data fragmentation. These initiatives aim to promote the development of the Findable, Accessible, Interoperable and Reusable (FAIR) data principles (Wilkinson et al., 2016) to support informed environmental assessments, policy-making, and scientific research (Giorgetti et al., 2020; Vinci et al., 2017).

A key component of FAIR marine data is the implementation of effective quality control (QC) procedures that aim to guarantee that observations are consistent within a single data set and across a collection of data sets, and that the quality and errors of the data are clear to the user, who has sufficient information to assess its suitability for a specific purpose (UNESCO, 1993). This is particularly important for large-scale data collections that bring together observations from diverse origins—often unknown or partially documented—and covering long temporal ranges. While automatic QC tests are widely adopted and include checks on date/time validity, geolocation, and compliance with global or regional expected value ranges (QARTOD, 2018; SeaDataNet, 2010; US Integrated Ocean Observing System, 2018; Garcia et al., 2024a,b,c; Jaccard et al., 2025), such automated procedures alone are insufficient to ensure the trustworthiness and scientific usability of marine datasets.

Numerous aspects promote interoperability among different and multidisciplinary data infrastructures [e.g., those of the WOD, United Nations Environment Program (UNEP), ICES, and SeaDataNet]. For instance, the adoption of consolidated standards (in terms of metadata profiles, controlled vocabularies, data formats), the availability of detailed and harmonized information on methodological approaches and quality assurance (QA) procedures, and the use of commonly agreed QC protocols and quality flag (QF) scheme developed in a framework of international cooperation.

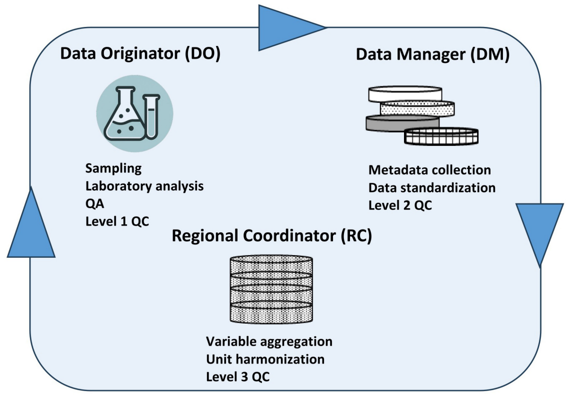

FIGURE 1
Data flow and processing chain involving data originators, data managers, and regional coordinators.

This paper focuses on the framework used by EMODnet Chemistry to QC eutrophication-related parameters (nutrients, chlorophyll, and oxygen) which has been agreed at European scale and adopted in all European regional seas by a large number of National Oceanographic Data Centers (NODC). We present a structured multi-level QC approach that supports transparency and interoperability in marine data management. This approach integrates automated checks, regional expert validation, and comprehensive metadata documentation to ensure the generation of reliable datasets capable of supporting science and policy. It also provides a set of QC procedures that can facilitate the implementation of future automated validation workflows.

The objective of this paper is to describe the methodological structure, practical application, and added value of the protocol. Additionally, we outline key lessons learned and discuss forthcoming steps to extend the QC framework to other marine variables, including those related to acidity and chemical pollution.

2 Materials

2.1 General data flow and processing chain

The data validation approach adopted within EMODnet Chemistry to produce harmonized, validated and documented datasets for each European sea basin builds upon a distributed network of actors with different expertise and responsibilities: (i) Data Originators (DOs, i.e., scientists involved in sampling and laboratory analysis of marine biogeochemical properties, in charge of QA, and responsible for expert data validation—"Level 1 QC"), (ii) Data Managers (DMs, i.e., data curators in charge of dataset formatting, metadata description and of the delayed mode QC step—"Level 2 QC") and (iii) Regional Coordinators (RCs, data scientists responsible for validating the aggregated collections for each sea basin—"Level 3 QC," Figure 1). This structure ensures comprehensive coverage of the QA/QC process, from *in situ* sampling to regional-level validation.

DOs are responsible for sampling, laboratory analysis, QA procedures, expert-based data QC (Level 1 QC) and provision of detailed methodological information. Expert-based data QC (Level 1 QC) aims to improve dataset internal consistency (IOC/IODE, 1993) through the evaluation of observations by domain experts using scientific knowledge, regional context, and instrument performance. Methodological and QA information is collected via a harmonized questionnaire that was designed based on the metadata requirements of the European Environment Agency (EEA), ICES, UNEP–Mediterranean Action Plan (UNEP-MAP), and NORMAN network (French and Lipizer, 2023). This information is published as open-access in a dedicated Zenodo community (EMODnet Chemistry QC/QA questionnaires community[1] and linked to datasets via persistent digital object identifiers (DOIs) to ensure transparency and traceability. This information is crucial to evaluate data comparability and ultimately to support reliable assessments of marine environmental status.

DMs contribute data to EMODnet through the network of National Oceanographic Data Centers (NODCs[2] and are responsible for managing data and metadata according to standard protocols developed in the framework of SeaDataNet,[3] which involve the use of commonly agreed data and metadata formats, standard controlled vocabularies, and a data validation (QC) procedure (SeaDataNet, 2010; Giorgetti et al., 2020). This data validation (Level 2 QC, Maillard and Fichaut, 2001) is usually carried out in agreement with DOs and includes automated or semi-automated checks of metadata completeness, missing values, outliers, and temporal and spatial consistency, comparison with global and, possibly, regional ranges. All data are retained in the datasets and, as a last step, after applying a set of standard QC checks (Table 1), quality flags (QFs) used in the framework of SeaDataNet (SeaDataNet measurand qualifier flags) and coded by the L20 vocabulary of the National Environment Research Council (NERC) Vocabulary Server (NVS[4] are assigned to data (Table 1).

However, due to differences in expertise in data centers, there is still some level of heterogeneity in the data validation approach, and some parameters do not go through the same steps of Level 2 QC. To address this limit, an additional QC Level is applied by RCs on regional data collections (Level 3 QC), based on the methodology described in Section 4. The following NODCs act as RCs in the data processing chain: Hellenic Centre for Marine Research (HCMR, Greece) for the Mediterranean Sea, National Institute for Marine Research and Development "Grigore Antipa" (NIMRD, Romania) for the Black Sea, Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER, France) for the North-East Atlantic, Danish Centre for Environment and Energy, Aarhus University (AU-DCE, Denmark) for the Greater North Sea, Swedish Meteorological and Hydrological Institute (SMHI, Sweden) for the Baltic Sea, and Institute of Marine Research (IMR, Norway) for the Nordic Seas/Arctic.

1 https://zenodo.org/communities/emodnetchemquestionnaire/)

2 https://iode.org/faq-items/the-mission-of-a-national-oceanographic-data-centre/)

3 https://www.seadatanet.org/

4 https://vocab.nerc.ac.uk/search_nvs/L20/)

2.2 Specificities across countries

The coherence of Level 2 QC among contributing institutions was evaluated through a community survey distributed to 45 institutions from 26 countries formally contributing data to EMODnet (Belgium, Bulgaria, Croatia, Denmark, Estonia, Finland, France, Georgia, Germany, Greece, Ireland, Israel, Italy, Latvia, Montenegro, Norway, Poland, Portugal, Romania, Slovenia, Spain, Sweden, the Netherlands, Turkey, Ukraine, and the United Kingdom). Responses were received from 28 institutions across 23 countries. The survey aimed to evaluate, among other issues, if standard QC checks reported in Table 1 are performed, as well as if additional checks and QFs proposed within EMODnet are adopted (highlighted in blue in Figure 2). The survey also allowed to collect information on additional QC checks implemented within the community in order to share best practices and to possibly improve the overall validation procedures.

Results revealed moderate-to-high alignment on most QC steps (Figure 2). The majority (>50%, green bar) of institutions carry out most of the standard QC steps (6 out of 7) and also adopt additional QF and QC steps (highlighted in blue, Figure 2) proposed within EMODnet Chemistry. Focusing on the comparison with regional values (broad ranges), this is carried out by 17 out of 28 institutions, primarily on dissolved oxygen (64% of respondents) and on some inorganic nutrients (nitrite, nitrate, phosphate and silicate, 54% of respondents, Figure 3a). Conversely, comparison with pre-existing statistics (narrow range) is performed by only 8 out of 28 institutes and mainly concerns nitrate, phosphate, silicate and dissolved oxygen (in >25% of respondents; Figure 3b). According to information collected through the survey, this QC step relies primarily on expert judgment, site-specific historical experience, and statistics generated within individual laboratories, rather than on global and regional ranges and climatologies, as is common practice for the WOD (Garcia et al., 2024a). Reference on the use of regional concentration ranges seems uncommon, and the Mediterranean Sea stands as the most clearly reported case so far (Fichaut et al., 2003). As a result, Level 2 QC validation may entail some degree of arbitrariness and may have limited generalizability.

Lastly, the results obtained (Figures 2, 3) also indicate where efforts to improve coherence in data validation are mostly required, such as the need to improve the adoption of the "comparison with pre-existing statistics" and of "cross-parameter checks" which are less in use (Figure 2), but also to increase the number of parameters to be compared with "regional values/broad ranges" and with "pre-existing statistics (Figures 3a, b)."

3 Methods

3.1 Regional quality control approach

To enhance the coherence of data collected within each marine region and originating from multiple institutions, a Level 3 QC procedure has been progressively developed within the EMODnet Chemistry framework (pilot phase 2009–ongoing[5]),

5 https://emodnet.ec.europa.eu/en/chemistry

TABLE 1 Types of standard QC checks, associated quality flag codes and definition (from: Maillard and Fichaut, 2001).

Type of QC check	Quality Flag	Definition
Blank cell	9—Missing value	The data value is missing
Stuck data (constant profile/constant values on the vertical)	4—Bad value (wrong, erroneous)	An obviously erroneous data value
Impossible regional values (min–max, broad range)		
Check vertical stability		
Check for increasing reference (pressure)		
Data point below bottom depth		
Check for spikes	3—Probably bad value (doubtful, questionable)	Data value recognized as unusual during quality control that forms part of a feature that is probably inconsistent with real phenomena
Compare with pre-existing statistics (narrow range)	2—Probably good value (inconsistent with statistics)	Data value that is probably consistent with real phenomena but this is unconfirmed or data value forming part of a malfunction that is considered too small to affect the overall quality of the data object of which it is a part
Correct data	1—Good value (correct)	Good quality data value that is not part of any identified malfunction and has been verified as consistent with real phenomena during the quality control process.
No QC	0—No quality control	No quality control procedures have been applied to the data value

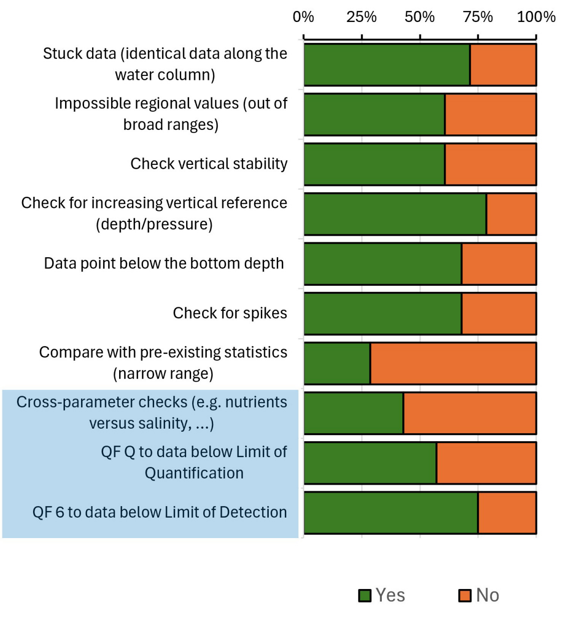

FIGURE 2
Types of QC checks proposed within the EMODnet Chemistry initiative and percentage of institutions carrying out them. QC and QF proposed within EMODnet are highlighted in blue. The bar colors indicate the adoption (green) or not (orange) of the list of QC steps.

with contributions from a dedicated network of marine scientists and data experts. This procedure is applied by RCs to regional datasets and encompasses all QC steps listed in Table 1. The procedure is based on region-specific "broad ranges," adopts a flexible approach for territorial waters (which include coastal and internal waters), and integrates a suite of additional QC checks, including those proposed through community surveys, thereby strengthening the overall validation process.

Regional data collections are retrieved from distributed data centers via an automatic Robot Harvester, configured with predefined spatial and temporal criteria. Once collected, the datasets undergo aggregation—combining heterogeneous descriptions of the same variable (e.g., nitrate in seawater, measured with different protocols or units) into unified, standardized terms—followed by harmonization (conversion to standard units based on EU directives or scientific literature) and validation (Level 3 QC) performed by RCs (Lipizer et al., 2026; Giorgetti et al., 2020). This validation ensures methodological consistency across data sources within each basin and increases the reliability of the regional collections.

Level 3 QC includes visual inspection of spatial and temporal distributions to detect anomalies, cross-parameter comparisons, calculation of derived variables, and verification against basin-specific broad ranges designed to encompass natural variability across seasons and years, which were derived from prior projects, expert knowledge and literature (Belgacem et al., 2021, 2025; Garcia et al., 2024a,b,c; Giorgetti et al., 2005; Manca et al., 2004; Mavropoulou et al., 2020; OSPAR, 2017, 2023; Tugrul et al., 2014; Duarte et al., 2021; HELCOM, 2018; Jaccard et al., 2025). Additional comparisons with existing climatologies (Fichaut et al., 2003; EU-MAST/MEDAR/MEDATLAS II Project, 2001; HELCOM, 2023; OSPAR, 2023) further support the identification of potentially erroneous data.

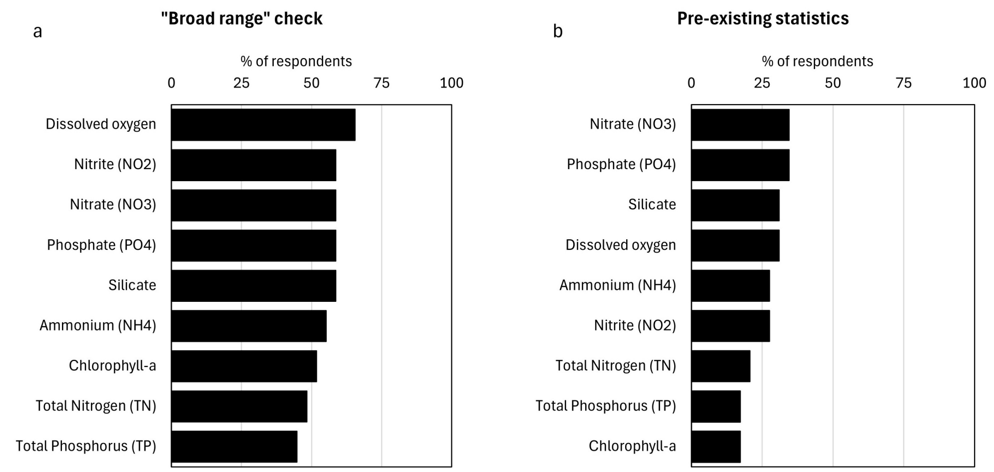

FIGURE 3
Percentage of institutions carrying out a "broad range" check [**(a)** left] and a "pre-existing statistics" check [**(b)**, right] for eutrophication-related parameters.

However, nearshore environments often exhibit higher variability, frequently exceeding literature-based ranges, as a result of continental discharges, land–sea interactions, and sediment resuspension in shallow areas (Lipizer et al., 2012; Grilli et al., 2020; Radach and Pätsch, 2007; Kuss et al., 2020; Yunev et al., 2007). Therefore, the application of broad-range checks to coastal waters should be undertaken with caution.

To support a flexible validation approach in different marine areas (territorial vs. open sea), data have been enriched with metadata indicating the distance of sampling stations from the coast, enabling filtering between territorial [within 12 nautical miles (nm)] and open (beyond 12 nm) areas to support refined validation strategies. The filter was implemented in two steps. First, a joint shapefile was created from the internal and territorial waters features of the Maritime Boundaries Geodatabase, version 11 (Flanders Marine Institute, 2019a,b). Then, a geoprocessing intersection between the stations coordinates and the shapefile allowed the assignment of a location qualification tag, indicating whether each observation was collected within 12 nm, beyond 12 nm, or, in case of trajectory data types (e.g., data collected by thermosalinographer), spanning both zones.

Thanks to the possibility of filtering data at the 12 nm boundary, EMODnet Level 3 QC adopts a more conservative approach when applying broad-range checks to data within 12 nm. In this context, values falling outside expected ranges are not directly flagged as "bad data" (QF 4, Table 1); instead, additional checks are performed to detect potential errors and to support the interpretation of outliers. Importantly, the extent to which these additional checks can be applied strongly depends on data availability and completeness. When sufficient and suitable data are available, these checks may include the calculation of derived variables—such as oxygen saturation, inorganic-to-total nutrient ratios (e.g. DIN:TN, PO_4:TP), nitrate/nitrite differences [(NO_3 + NO_2) − NO_3; NO_3 − NO_2], and N:P ratios—as well as cross-parameter evaluations (e.g., nutrient–salinity relationships). These checks function as alerts that may prompt further investigation or consultation with DOs or regional experts. Derived variables and visual analyses are produced using the freely available software package for the analysis and visualization of oceanographic and meteorological data Ocean Data View (ODV) (Schlitzer, 2026[6]).

The additional QC checks performed in the Level 3 QC procedure are:

1. Evaluate oxygen supersaturation in the upper layer of open waters to assess the reliability of dissolved oxygen data: thresholds are proposed for different depth layers to identify possible erroneous data (Skagseth et al., 2025; Garcia et al., 2024c; Jaccard et al., 2025) (Table 2).
2. Inspect cases where the concentration of the variable "NO_3 plus NO_2" is lower than the NO_3 concentration.
3. Inspect cases where the NO_2 concentration is higher than the NO_3 concentration (assuming that in open water oxygenated marine environments nitrate is higher than nitrite, Gruber, 2008; Garcia et al., 2024b; 2024c).
4. Inspect cases where ratios of inorganic nutrients vs. total nutrients (e.g., PO_4:TP and DIN:TN) are higher than 1.1.
5. Inspect nutrient vs. salinity relationships to identify possible continental (riverine, low-salinity) contributions.
6. Inspect cases where the N:P ratio exceeds ranges reported in the literature (Supplementary material).

When inconsistencies are detected in derived variables (e.g., PO_4:TP > 1.1; Figure 4), the next step is to trace the anomaly to the underlying parameter (e.g., phosphate or TP), ensuring that only the affected variable is flagged. This is achieved by comparing the vertical and temporal distributions of both derived and primary variables to identify the parameter exhibiting anomalous concentrations, and then assign the appropriate QF.

When the anomalous variable cannot be unambiguously identified, all potentially affected parameters are flagged. Negative differences (additional QC Checks 2 and 3) and ratios exceeding

6 https://odv.awi.de/

TABLE 2 Complete list of data QC criteria proposed to produce regional aggregated and harmonized data collections for the European seas by EMODnet Chemistry.

Quality flag	Criteria adopted by EMODnet Chemistry	Introduced by EMODnet Chemistry
Q	Values below or equal to LOQ (limit of quantification)	x
9	Default values used for missing data, such as 9,999 or 999.999	
	Blank cell	
6	Values equal to 0*	x
	Values below or equal to LoD (limit of detection)	x
4	Stuck data (constant profile/constant values)	
	Impossible regional values (min–max, broad range)	
	Check for increasing reference (pressure)	
	Data point below bottom depth	
	Negative values*	x
	Values equal to 0*	x
	Two or more identical consecutive depth values	x
	Nutrients comparison (inorganic nutrients/total nutrients >2)	x
	Data are equal to other variables (same values in different columns corresponding to different variables)	x
3	Check for spikes	
	Only for oxygen saturation: 150% threshold in the upper 10 m, 130% between 10 and 100 m, 115% between 100 and 150 m and 100% below 150 m	x
	Nutrient comparison (NO_3 plus NO_2–NO_3 < 0; NO_3 plus NO_2–NO_2 < 0; NO_3–NO_2 < 0; inorganic nutrients/total nutrients 1.15–2)	x
	Profiles starting with negative values (e.g., from CTD or ARGO): when several negative values are part of vertical profiles, assuming the effect of a negative offset common to the whole profile	x
2	Compare with pre-existing statistics (narrow range)	
	Nutrient comparison (inorganic nutrients/total nutrients 1–115)	x
	Higher than N/P ranges derived from literature review	X**
	Comparison between nutrients and salinity	X**

*Depending on DOs' feedback; X** used as alerts to further investigate data and consult DOs.

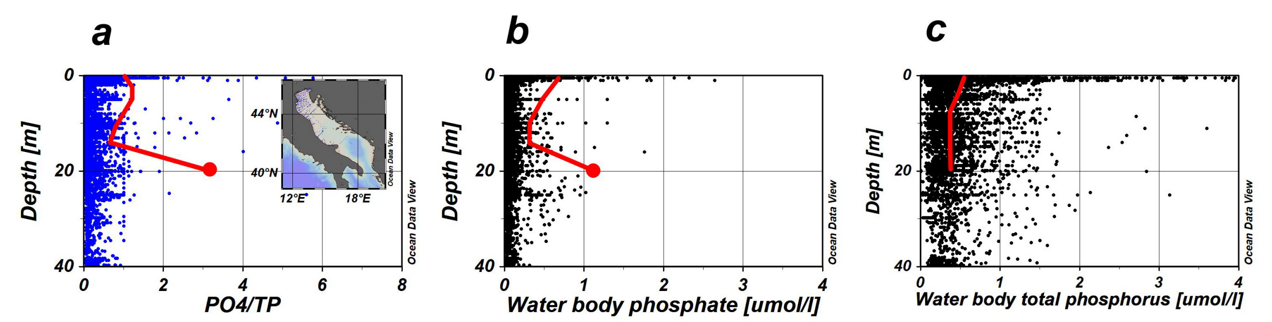

FIGURE 4
Examples of the vertical distribution of the derived variable PO_4:TP [blue dots **(a)**] used to spot probably erroneous data in the original variables [PO_4 **(b)** and TP **(c)**]. The red lines correspond to a vertical profile of PO_4, TP data and derived PO_4:TP.

1.1 (additional QC Check 4) or surpassing values reported in the literature (additional QC Check 6, Supplementary material) are classified as doubtful, assigned a relevant QF (typically QF3, "probably bad"), and reported to DOs and the DM for investigation.

For suspected nutrient outliers (i.e., concentrations exceeding the regional broad ranges) nutrient–salinity relationships (additional QC checks 5) are used to assess whether elevated nutrient concentrations, particularly common in coastal and territorial waters, may reflect continental (freshwater) inputs (Figure 5). An example for the Gulf of Lion (Western Mediterranean) illustrates this approach, whereby nutrient concentrations (Figures 5c–g) exceed the regional broad ranges

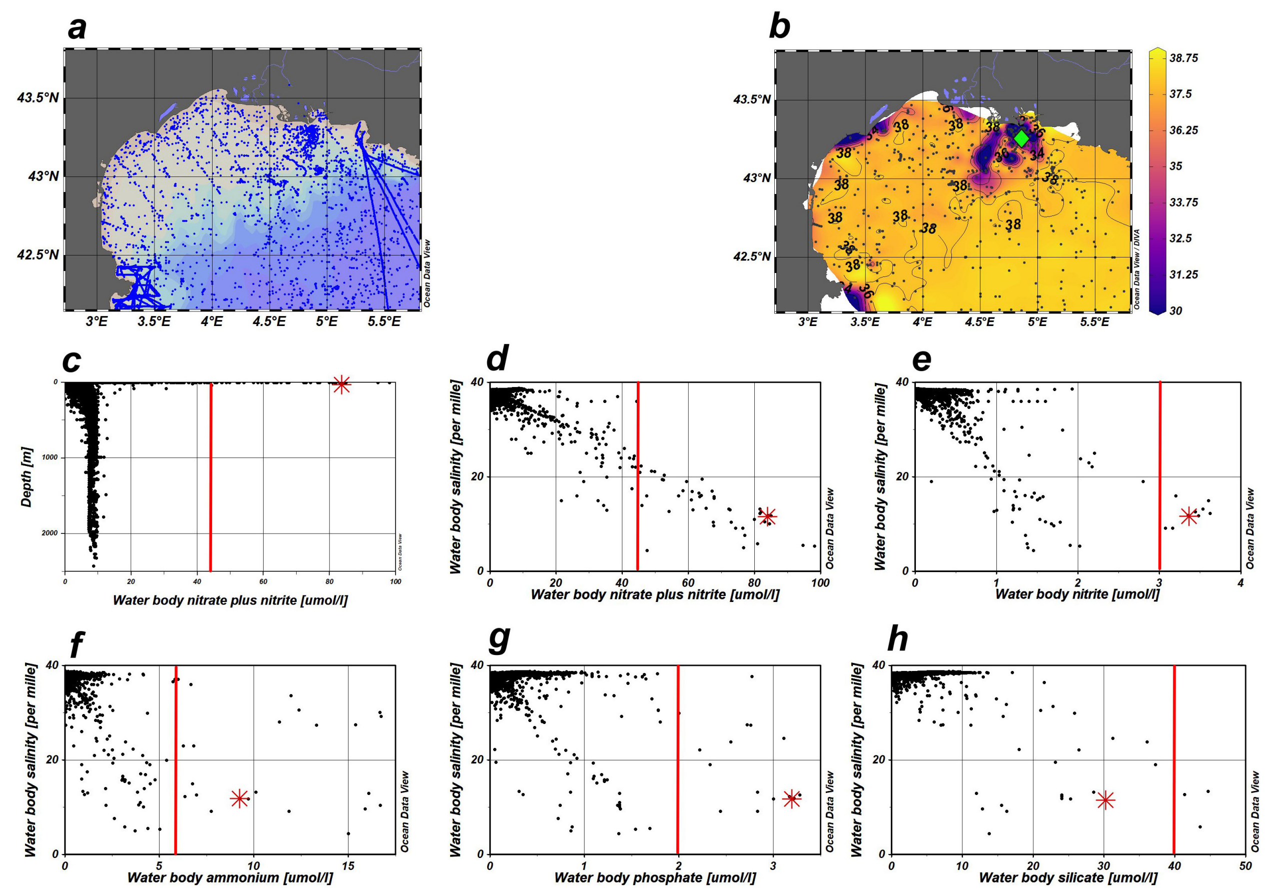

FIGURE 5
Example plots of nitrate + nitrite vs. depth **(c)** and of nutrients [**(d)** nitrate + nitrite, **(e)** nitrite, **(f)** ammonium, **(g)** phosphate, **(h)** silicate] vs. salinity in the Gulf of Lion (Western Mediterranean). Positions of sampling stations are displayed in the map **(a)**. The surface salinity map based on all available data **(b)** is provided as ancillary information to show freshwater dispersion in the area. The thick vertical red lines indicate the "broad range" concentrations used for open waters. The red symbol shows high nutrient concentrations associated with low salinity, measured in the station displayed on the surface salinity map [green diamond **(b)**].

(EU-MAST/MEDAR/MEDATLAS II Project, 2001). However, the distributions of salinity vs. nutrients (Figure 5d: nitrate + nitrite; e: nitrite; f: ammonium; g: phosphate; h: silicate) indicate that the apparently anomalous values (e.g., nitrate+nitrite and silicate) are associated with low-salinity waters. This pattern is consistent with freshwater influence, which is typically accompanied by simultaneous increases in several nutrient species (Figures 5d–h).

As an additional derived variable, the N:P ratio (additional QC checks 6) is proposed to support the identification of possible erroneous data. In oxygenated open-ocean waters, far from continental inputs, the relative proportion of nitrogen to phosphorus is generally considered to remain fairly constant under aerobic conditions because nutrient assimilation and regeneration occur according to stable stoichiometric proportions (Redfield ratio - capital letter N:P = 16:1; Redfield et al., 1963). Although natural variability in nutrient stoichiometry occurs due to differences in nitrogen vs. phosphorus limitation, phytoplankton physiological plasticity, species composition, seasonal succession, and external inputs such as river discharge and upwelling (Ezra et al., 2021; Fransner et al., 2018; Macias et al., 2019; Geider and La Roche, 2002; Klausmeier et al., 2004), deviations in N:P ratios can still provide useful indications of possible data anomalies. In particular, coastal areas influenced by continental inputs may exhibit substantial variability in the N:P ratio across all European sea basins (Lipizer et al., 2011, 1999; Pujo-Pay et al., 2011; Socal et al., 2008; Degobbis et al., 2005; Cociasu et al., 1997; Burson et al., 2016; Ærtebjerg et al., 2003). Based on an extensive literature review, region-specific N:P ranges (provided in the Supplementary material S2) have been identified as reference intervals to support the detection of potentially erroneous nutrient concentrations. These ranges assist in pinpointing anomalies that are subsequently reported to DOs for possible revision of QFs because deviations in the N:P ratio may also arise from characteristic biogeochemical processes occurring in specific areas or seasons. For instance, an elevated N:P ratio often reflects phosphorus depletion, which is common in Mediterranean surface waters (Djaoudi et al., 2018; Ezra et al., 2021), or may derive from concentrations close to or below analytical detection limits.

The overall process of data validation to obtain regional sea data collections produced by EMODnet Chemistry includes expert validation by DOs, the series of QC steps performed by DMs (Table 1) and the additional steps performed by RCs, which have been agreed within the EMODnet Chemistry framework (Table 2). The proposed QF scheme serves as a general guiding rule that aims

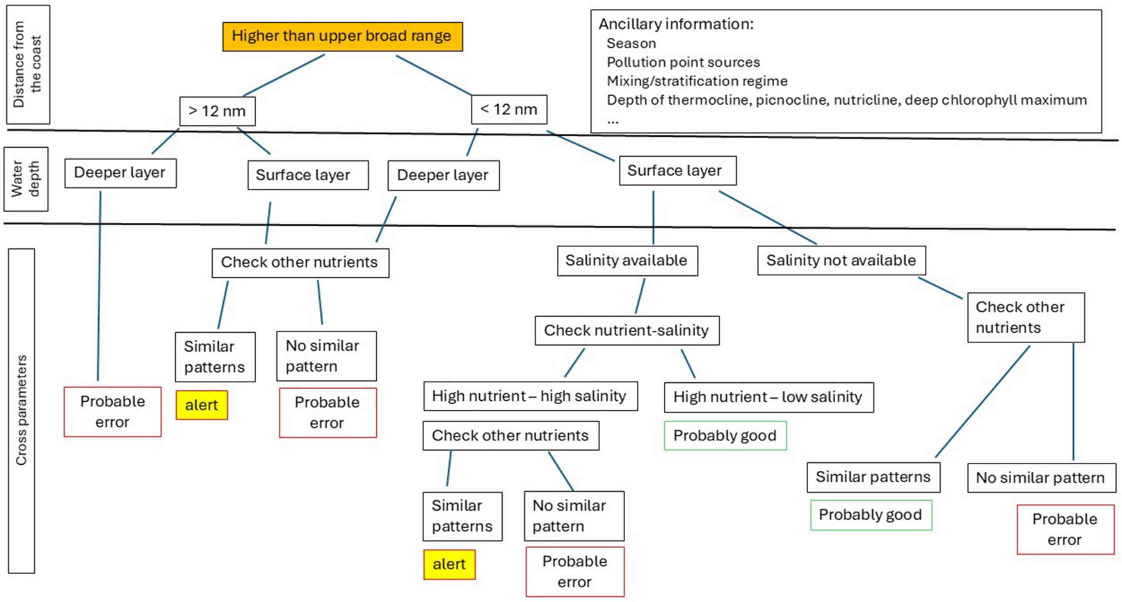

FIGURE 6
Schematic showing QC steps for nutrient concentration data.

to guarantee a consistent approach at European level. Nevertheless, confirmation by DOs and DMs is mostly required, and in some peculiar environments QFs are applied with flexibility, following expert consultation.

4 Discussion

The multi-level QC protocol implemented in EMODnet Chemistry represents a significant step toward improving consistency in marine data validation across Europe, supporting research, policy, and fostering a culture of data stewardship across disciplines and borders. The overall data QC approach includes collecting detailed methodological and QA information from DOs, enriching standard metadata with this information and adopting the three Level QC carried out by DOs, DMs, and RCs. The adoption of commonly agreed standards for data management and validation as well as the detailed information on the overall process (from *in situ* sampling to data QC) are fundamental for assuring the availability of trusted and reusable data, essential for solid scientific research and the assessment and management of the marine environment, as required by environmental policies. The availability of standardized, detailed information is essential when merging heterogeneous data collected by multiple institutions over long periods of time—such as the data managed by EMODnet—to ensure accurate comparison and interpretation of large, basin-scale datasets.

The EMODnet Chemistry datasets integrate observations collected through monitoring programmes, research cruises, fixed stations, and operational observing systems across European seas. As a result, the spatial and temporal coverage is heterogeneous among regions and parameters. Offshore areas generally benefit from broader spatial and temporal coverage, whereas coastal waters are often characterized by denser but more localized sampling linked to national monitoring activities. Temporal resolution also varies, with some areas supported by long-term monitoring and others by seasonal or episodic observations only. Consequently, the datasets may not equally capture short-term events or long-term trends across all regions. The Level 3 QC procedure partly addresses these limitations by evaluating observations within their regional and environmental context, including the distinction between coastal and open-sea waters.

Observational uncertainty in eutrophication-related variables arises from sampling procedures, laboratory analyses, sensor calibration, and data processing. Since EMODnet Chemistry integrates datasets from multiple institutions and monitoring programmes, uncertainty levels may vary among regions and parameters. The adopted QC/QA framework preserves and links relevant methodological and quality assurance information to the datasets, thereby facilitating users' evaluation of data uncertainty and fitness for purpose. Typical analytical uncertainties reported in monitoring protocols are generally within $\pm 2\%-10\%$ for dissolved inorganic nutrients, $\pm 5\%-15\%$ for chlorophyll-*a*, and $\pm 1\%-5\%$ for dissolved oxygen (Birchill et al., 2019; Jaccard et al., 2025). Observations identified as potentially inconsistent through QC procedures are assigned appropriate quality flags to ensure transparency regarding data reliability and usability.

A key step in data quality control is the comparison of observed values with regional reference ranges (Tables 1, 2; Supplementary material S1). However, several drivers—including climate change, extreme meteo-oceanographic events, marine heatwaves, and policy measures aimed at reducing eutrophication—may alter environmental conditions and limit the applicability of fixed reference ranges, many of which were proposed decades ago. This highlights the need to apply this QC criterion with caution. The issue is particularly relevant in coastal waters which are often subject to high variability driven by continental inputs (e.g., rivers, storm runoff, wastewater), intricate land–sea interactions, and extreme meteorological events (Carstensen et al., 2020; Cociasu et al., 1997; Campanelli et al., 2011), which can result in values exceeding reference ranges. Nevertheless, the compilation of concentration ranges (Supplementary material 1) and N:P ratios (Supplementary material 2) improves transparency in the validation procedure adopted and may support further analysis. In the proposed approach, the possibility to filter internal, coastal and territorial (i.e. within 12 nm) and open waters (i.e., beyond 12 nm) allows the application of different criteria of data QC to different water types. As a consequence, in Level 3 QC regional ranges are used with a precautionary approach to validate coastal and territorial waters, where observations exceeding broad ranges are subject to additional inspection to avoid flagging true environmental signals related to eutrophication or extreme meteo-oceanographic events (Lipizer et al., 2012; Marini et al., 2010; Kuss et al., 2020; Suari et al., 2024) as erroneous data.

At the current stage, the data filtering procedure relies on a "location identifier" tag associated with station metadata rather than on the actual geographic coordinates of the observations. This approach limits the ability to properly filter continuous trajectory-type datasets that may extend across both territorial and open waters. Consequently, such datasets are currently validated together with open-water data (>12 nm). Future efforts should focus on: (i) updating existing ranges (proposed, in some areas, more than 20 years ago and based on less data), (ii) proposing ranges for territorial waters, in order to further support a harmonized and coherent data validation procedure and (iii) facilitating data filtering approaches.

Lastly, the current approach still relies on fixed broad ranges that do not explicitly account for seasonal variability, mixing and stratification regimes, water depth, distance from the coast, or proximity to major anthropogenic and natural nutrient sources (e.g., rivers, wastewater discharges, aquaculture sites), nor for long-term environmental changes affecting seawater biogeochemistry. A major future improvement would therefore involve developing multiple context-specific reference ranges that better incorporate temporal variability and geographic conditions. Furthermore, the integration of spatio-temporal environmental data with interoperable geospatial information available through other EMODnet services (e.g., EMODnet Human Activities, EMODnet Bathymetry,...) could greatly support the interpretation of suspect anomalies and further improve the overall validation process.

This multistep approach has proven particularly robust for eutrophication-related variables, with a lot of knowledge and historical data supporting parameter interdependence and reference thresholds. The set of cross-parameter quality control checks could be further expanded, particularly for variables within the carbonate system (e.g., pH, alkalinity, and dissolved inorganic carbon). However, such an extension would require broader engagement with thematic expert networks (e.g., ICOS, SOCAT, NOAA-OAP, and GLODAP), as well as the development of additional validation criteria. Finally, extending this approach to other parameter groups, such as contaminants, would be highly valuable in order to provide robustly validated datasets capable of supporting marine research and environmental status assessments.

Solid and regular interactions among scientists, data scientists, different types of data users and different data management communities are needed to improve the overall data production process and to continuously upgrade the validation process as new knowledge and new data become available.

Although the proposed approach still relies on some subjective decisions and also requires feedback from experts from different geographic areas and disciplines, it describes a series of multivariate checks (Table 2, Figure 6) that could be considered for designing an automatic or semi-automatic QC approach to be implemented with the aid of machine learning and artificial intelligence (AI) applications.

The logic of the different QC steps must also account for multidimensional sources of spatial and temporal variability, not yet explicitly incorporated into the current framework, which could serve as ancillary information to further support data validation (Figure 6).These include factors such as the distance from the coast, from continental inputs and possible pollution point sources (e.g., waste water discharges, aquaculture sites), water depth, spatial gradients, benthic–pelagic interactions, and the vertical position within the water column.

In addition, temporal variability associated with seasonality in physical and biogeochemical processes (e.g., mixing, stratification, primary and secondary production, respiration), episodic variability driven by extreme meteo-oceanographic events, and long-term trends linked to global change should be explicitly considered.

The management of large, heterogeneous datasets from multiple sources necessitates the use of established automated procedures to ensure rapid, consistent, and standardized data validation. Integrating AI into this process is highly desirable as it can significantly enhance efficiency and scalability (Malde et al., 2020; Tamm and Nikiforova, 2025; Qiu et al., 2025). The inherent complexity of marine ecosystems and the limited understanding of certain biogeochemical interactions make expert judgment indispensable. At the same time, the integration of automated validation procedures represents a significant advancement: routine cases can be efficiently processed, allowing experts to dedicate more time to the most complex and ambiguous measurements. This complementary approach not only enhances the efficiency of the validation process but also reinforces its robustness, ensuring that natural variability is accurately distinguished from genuine measurement errors.

5 Conclusions

Ensuring data quality, transparency, and harmonization is fundamental to support robust marine environmental assessments and policy implementation. The QC methodology described in this work, developed and implemented within the EMODnet Chemistry initiative and commonly adopted for all European seas, demonstrates a concrete, scalable approach to harmonizing eutrophication-related data across diverse European sea basins. The integration of multi-level QC procedures, involving DOs, DMs, and RCs, enhances the comparability, reusability, and trustability of marine datasets, fully aligned with the FAIR principles.

A key contribution of this work lies in its transparent and collaborative process, which combines automatic validation tools with expert-driven checks, cross-parameter assessments, and contextual interpretation based on regional biogeochemical characteristics. The collection of harmonized metadata, methodological details, and QA/QC information is instrumental for enabling consistent and repeatable data validation and for supporting the "collect once—use many times" principle.

The approach outlined here is not static; it is an ongoing process, evolving with increasing data availability and scientific understanding. Future efforts should focus on extending the validation framework to additional variables, such as those related to acidification and chemical pollution. They should also aim to refine the current methodology through the development of context-specific reference ranges that account for seasonal variability and geographic conditions. In this perspective, the integration of spatio-temporal environmental data with interoperable geospatial information available through other EMODnet services could further strengthen the overall validation process. Engagement with thematic expert communities (e.g., ICOS, SOCAT, and NOAA-OAP) will be key for defining robust validation criteria for these parameters.

Finally, while automation and AI offer promising support for scaling up data QC efforts, human expertise remains essential for interpreting complex biogeochemical interactions, especially in dynamic and heterogeneous coastal environments. The synergy between structured QC protocols, scientific judgment, and technological tools will be crucial for building reliable marine data systems capable of underpinning effective research and environmental governance.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found at: EMODnet https://doi.org/10.13120/84b18605-cd31-48cb-ab08-75f2c9595b75; https://doi.org/10.13120/94f43557-d752-49d8-aea5-b24680875b27; https://doi.org/10.13120/0f668667-2cf7-4b3c-9f3e-53a450b2abb2; https://doi.org/10.13120/13d2a552-ee18-49a0-abdf-ac7936bc070f; https://doi.org/10.13120/7aa27f48-c63d-417c-ac82-f18fd33782a4; https://doi.org/10.13120/3171895b-8fa8-4d72-945c-a1bf28dbc708.

Author contributions

MLi: Conceptualization, Methodology, Visualization, Writing – original draft, Writing – review & editing. MM: Methodology, Visualization, Writing – review & editing. LB: Data curation, Writing – review & editing. MF: Writing – review & editing, Methodology. LF: Data curation, Writing – review & editing. JG: Data curation, Writing – review & editing. AI: Data curation, Writing – review & editing. MLa: Data curation, Writing – review & editing. AØ: Data curation, Writing – review & editing. KW: Data curation, Writing – review & editing. AG: Funding acquisition, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/focsu.2026.1835133/full#supplementary-material

SUPPLEMENTARY MATERIAL S1
Broad-range check values in the European sea basins.

SUPPLEMENTARY MATERIAL S2
Review of N:P ratios in the sub-basins of the European Seas.

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