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Review

Resilient water quality management: Insights from Japan's environmental quality standards for conserving aquatic life framework

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ABSTRACT

Currently, chemicals and waste are recognized as key drivers of habitat degradation and biodiversity loss in aquatic ecosystems. To ensure vibrant habitats for aquatic species and maintain a sustainable aquatic food supply system, Japan promulgated its *Environmental Quality Standards for the Conservation of Aquatic Life* (EQS-CAL), based on its own aquatic life water quality criteria (ALWQC) derivation method and application mechanism. Here we overview Japan's EQS-CAL framework and highlight their best practices by examining the framework systems and related policies. Key experiences from Japan's EQS-CAL system include: (1) Classifying six types of aquatic organisms according to their adaptability to habitat status; (2) Using a risk-based chemical screening system for three groups of chemical pollutants; (3) Recommending a five-step method for determining ALWQC values based on the most sensitive life stage of the most sensitive species; (4) Applying site-specific implementation mechanisms through a series of Plan-Do-Check-Act loops. This paper offers scientific references for other jurisdictions, aiding in the development of more resilient ALWQC systems that can maintain healthy environments for aquatic life and potentially mitigate ongoing threats to human societies and global aquatic biodiversity.

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1. Introduction

Aquatic organisms form the basic components of the Earth's biodiversity and play a vital role in maintaining the balance and function of ecosystems. However, in 2019, the Intergovernmental Science–Policy Platform on Biodiversity and Ecosystem Services of the United Nations (UN) reported that one million species are threatened with extinction and that many species, including aquatic organisms (e.g., sharks, turtles, amphibians, and fishes), went extinct in recent decades [1]. Aquatic life relies on bodies of water for their survival and reproduction. The discharge of chemicals and waste from anthropogenic activities into aquatic ecosystems (e.g., streams, rivers, lakes, coastal wetlands, estuaries, and seas) can directly contaminate water and sediments, and such contamination affects the organisms living therein, thus disturbing ecosystem functions and services [2,3]. Consequently, water pollution has been recognized as a major threat to aquatic biodiversity in addition to the loss and degradation of habitats, overharvesting, biological invasion, and climate change.

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Abbreviations

ALWQC	Aquatic Life Water Quality Criteria
ALWQG	Aquatic Life Water Quality Guidelines
ALWQS	Aquatic Life Water Quality Standards
A	Aquatic Life A
B	Aquatic Life B
C	Aquatic Life C
DO	Dissolved Oxygen
EC_{50}	Median Effect Concentration
EQS-CAL	Environmental Quality Standards for the Conservation of Aquatic Life
EQSWP	Environmental Quality Standards for Water Pollution
FACR	Final Acute-Chronic Ratio
FAV	Final Acute Value
FCV	Final Chronic Value
FFAV	Food Final Acute Value
FFCV	Food Final Chronic Value
JME	Japan's Ministry of the Environment
LAS	Linear Alkylbenzene Sulfonates
LC_{50}	50% of the Lethal Concentration
LOEC	Lowest Observed Effect Concentration
MATC	Maximum Acceptable Toxic Concentration
NOEC	No Observed Effect Concentration
NP	Nonylphenol
PDCA	Plan-Do-Check-Act
PNECs	Predicted No-Effect Concentrations
PPCPs	Pharmaceuticals and Personal Care Products
SA	Special Aquatic Life A
SB	Special Aquatic Life B
SC	Special Aquatic Life C
SDGs	Sustainable Development Goals
SESs	Social-Ecological Systems
WQC	Water Quality Criteria
WQG	Water Quality Guidelines
WQS	Water Quality Standards

Development Goal 14), it is important to minimize water pollution and ensure that the concentrations of harmful substances remain at or below the health thresholds of aquatic organisms — that is, they should not exceed the predicted no-effect concentrations (PNECs). As susceptibility to chemical contaminants may differ between aquatic species, their effect thresholds on chemicals are likely different. Based on laboratory ecotoxicity tests and epidemiological information, the PNECs of chemical contaminants can be derived from toxicity data using standard protocols, such as the assessment factor approach and the species sensitivity distribution method [4,5]. The derived PNECs can be adjusted with an assessment factor for data uncertainty (e.g., inadequate species representativeness in the species sensitivity distribution). The derived PNECs can then be adopted as environmental quality benchmarks for water quality management, risk assessment, and environmental protection [6,7]. Scientific methods for deriving aquatic life water quality criteria/guidelines (ALWQC/ALWQG) and aquatic life water quality standards (ALWQS) have been developed to determine acceptable levels of various chemical contaminants to protect aquatic life and associated ecosystems [7–9]. The scientific derivation of ALWQC/ALWQG or ALWQS is a risk-based approach. This approach assumes that aquatic ecosystems can withstand a certain level of chemical contaminants without sustaining unacceptable negative changes in biota and ecosystem integrity, given that their concentrations remain below the benchmark thresholds [6]. By benchmarking the measured environmental concentrations of the chemicals of concern against their corresponding ALWQC/ALWQG or ALWQS values, environmental authorities can evaluate the potential ecological risks of certain chemicals to aquatic life [10,11].

Western developed jurisdictions have incorporated environmental quality benchmarks associated with aquatic life into their aquatic environment management systems. Such environmental quality benchmarks are commonly phrased differently by different jurisdictions. For example, the terms ALWQG and ALWQC are interchangeable, as they are mainly used as scientific references for management purposes and are not necessarily legally bound [12–16]. However, ALWQS normally reflects the legally bound safe limits of chemical contaminants set and enacted by national or regional environmental protection agencies as part of their legal basis and regulatory frameworks [17,18]. Moreover, ALWQS are usually implemented considering regional eco-environmental and socio-economic conditions, technical capabilities, protection goals, regulatory compliance, and the combined enhancement of environmental protection and economic growth [19]. This criterion has been adopted by most jurisdictions worldwide to ensure both human and ecosystem health. This is under the One Health concept, which emphasizes the integration of people, animals, and the environment and evaluates their health challenges and interrelations from a holistic perspective [20,21].

Currently, water quality criteria (WQC) research mainly focuses on early development and well-established systems, such as those of the United States and the European Union, while recent development systems in East Asian countries, such as Japan, have been largely ignored. Furthermore, the water hardness level is the most alarming water quality parameter affecting the ALWQC system. Although the substantial of temperature on the toxicity of pollutants to aquatic organisms is clear, the corresponding WQC policies remain understudied. The adaptability of aquatic organisms to temperature-based habitat conditions and variations in toxicity sensitivities across life stages are rarely discussed in research on the ALWQC system. The environmental standard set by the Japanese government — the Environmental Quality Standards for the Conservation of Aquatic Life (EQS-CAL) — pays special attention to protecting aquatic life. However, most studies on this standard involved scattered exploratory research on a single chemical contaminant on a monitoring process that could not accurately reflect the full characteristics of the standards [22–25]. Kataoka et al. provided thorough overviews and data analyses of water quality, national standards, and management policies in Japan but did not cover recent advancements in aquatic organisms and emerging contaminants considered by the EQS-CAL [26–30]. Ishiwatari et al. systematically reviewed Japan's water resource management using data derived from instructive semi-structured interviews and government documents [31]. However, their study hardly analyzed the application and contribution of Japan's EQS-CAL to water quality management and aquatic life conservation in the region. The abovementioned gaps highlight the need for a comprehensive review of Japan's ALWQC system. This study fills this gap by focusing on environmental benchmark tools for Japan's EQS-CAL and protecting aquatic life, which has not received sufficient attention from previous reviews.

Therefore, for this review, more up-to-date relevant documents were collected and reviewed to provide an overview of the EQS-CAL framework in Japan. The results of this in-depth synthesis and analysis are presented in the following sections. The main contributions of this critical review are as follows: (1) This review summarizes the derivation of a methodology for Japan's ALWQC. We unified the underlying implementation and supportive management measures into a single framework to systematically describe how this national standard was established and applied in Japan and how it developed over time (Section 2). (2) This review identifies several key experiences and scientific issues, as they are worthy of consideration in the derivations, applications, and management processes (Section 3). (3) This review conducts in-depth analyses and discussions regarding the lessons learned from Japan's experience. It also explores items related to water quality improvements and aquatic biodiversity conservation practices in Japan and other jurisdictions that can be enhanced from a resilience perspective. We also develop a conceptual framework to illustrate the interactions and dynamics of aquatic ecosystems and aquatic environment management capacity across different scales (Section 4). This review provides a complete perspective and technical guidance for developing and developed jurisdictions to build robust ALWQC research and management systems. It also offers food for thought for scientists and environmental authorities to rethink the resilience and complexity of the currently used ALWQC and ALWQS when coping with the tremendous growth of the amount and diversity of contaminants causing constant changes in aquatic environments.

2. Japan's aquatic environment management framework

As a Pacific Ocean island nation and a top seafood consumer worldwide, aquatic organisms are integral parts of the food supply, livelihoods, and fishery income of the citizens of Japan [32]. The availability and sustainability of healthy aquatic ecosystems are embodied in Japan's traditional culture and local communities. However, around the 1960s, a well-known series of diseases related to anthropogenic releases of toxic chemicals were detected in coastal and riverine areas, including Minamata and Itai-itai diseases caused by organomercury compounds and cadmium salts, respectively [33,34]. Following these tragic incidents, calls from the international community and residents led to changes in Japan's national development policies, with several basic environmental plans and laws launched to tighten environmental protection [35–38]. Japan's environmental quality standards system is a reflection of past incidents. The Environmental Quality Standards for Water Pollution (EQSWP), issued by Japan's Ministry of the Environment, are the principal national standards for surface water bodies to address water-related pollution issues associated with human health and living environments [39]. In the 1980s, a shift occurred in the term from water quality management to water environment management, reflecting a broader vision to address water-related environmental issues [40].

However, the main purpose of previous standards was to protect humans before 2003 [41,42], and they failed to identify the toxicity sensitivities (i.e., effect thresholds) of aquatic organisms toward chemical contaminants. Consequently, the ecosystem health and biological needs of aquatic organisms have been neglected in Japan. In 2003, the EQS-CAL was officially established to provide specialized protection for aquatic life forms with specific derivation methods and applications [43,44]. The EQS-CAL focused on the effects of chemical substances on aquatic organisms and highlighted the adaptability of aquatic life to habitat status. This is due to different species' biological adaptabilities and preferences at different life stages and the trophic levels used as basic characteristics. These newly introduced EQS-CAL are distinct from Japan's previous versions of nationally enforced environmental quality standards, which mainly focus on protecting humans and those of other jurisdictions. The EQS-CAL were designed and derived as ALWQC at the national level and were applied with site-specific targets at the local levels. Local environmental quality standard targets should be stricter than the national standard unless the local capacity to cope with severe pollution situations is very limited [37]. This involves eco-environmental and socio-economic considerations, thus making EQS-CAL suitable for local conditions and prioritizing sites for ecosystem protection. This strategy allows for flexibility and is particularly important for developing nations undergoing rapid economic growth but with limited capacity to address water pollution issues. The EQSWP has been updated 24 times, and long-term positive outcomes in public water bodies have become evident [30].

The current EQSWP sets 40 official standard items consisting of 27 items for human health and 13 for living environments (Table S1 in Supplementary Materials). The latter includes three official items for the protection of aquatic organisms. Like most countries, standards of human health are uniformly applied to surface waters nationwide, while the standards of living environments are classified according to different functions or conditions [30]. The Japanese government has established standards for physicochemical parameters (e.g., pH, dissolved oxygen, and suspended solids particles), biological parameters (e.g., coliform), nutrient parameters (including nitrogen and phosphorus), and chemical contaminants (e.g., total Zn, nonylphenol [NP], and linear alkylbenzene sulfonates [LAS]) that may directly or indirectly threaten aquatic organisms and ecosystems (Fig. S1 in Supplementary Materials).

Based on official information and the findings of this study, a basic framework for Japan's EQS-CAL was developed (Fig. 1). To derive this framework, a systematic literature review was integrated, and desktop analyses of ALWQC derivation methods, site-specific application pathways, and management measures were conducted. This basic framework was constructed according to three main phases.

Phase I: ***Design and derivation***. The EQS-CAL was designed with four core sections: protected species scoping, biological classification, priority chemical screening, and standard value derivation (Fig. 1). The former two sections defined the valuable species to be protected and provided the description of their classification. The latter two sections identified the chemicals of serious concern and presented how their standard values were derived. In this study, the standard values of the EQS-CAL reflect the ALWQC based on scientific evidence [26,43,45]. The results of the biological classification also determined the design of laboratory-based ecotoxicological experiments for generating toxicity data to derive the ALWQC. According to Japan's approach, the biological adaptabilities of aquatic organisms to habitat conditions were highlighted in terms of water temperature, sediment structure, and ecological functions [26]. Along with formal standard items, two groups of chemical contaminants (i.e., monitored and investigated substances) were identified with preventive measures based on their ecological risks, toxicological information, and detection records in Japan's aquatic environments [46,47].

Phase II: ***Applications and adaptations***. When the EQS-CAL were applied to local water bodies, the established standard values were adjusted and tailored to local conditions (Fig. 1). Classified standard values were specified for habitats based on annual monitoring data and detailed field research on local species [29]. Two alternatives could be allowed through either time extensions or interim target values related to pollution status and multiple socio-economic conditions if necessary. In Phases I and II, Plan-Do-Check-Act (PDCA) models were used by local authorities (e.g., prefectures) to ensure appropriate implementation practices [48]. A full PDCA cycle involves a set of complementary measures, including water quality examination,

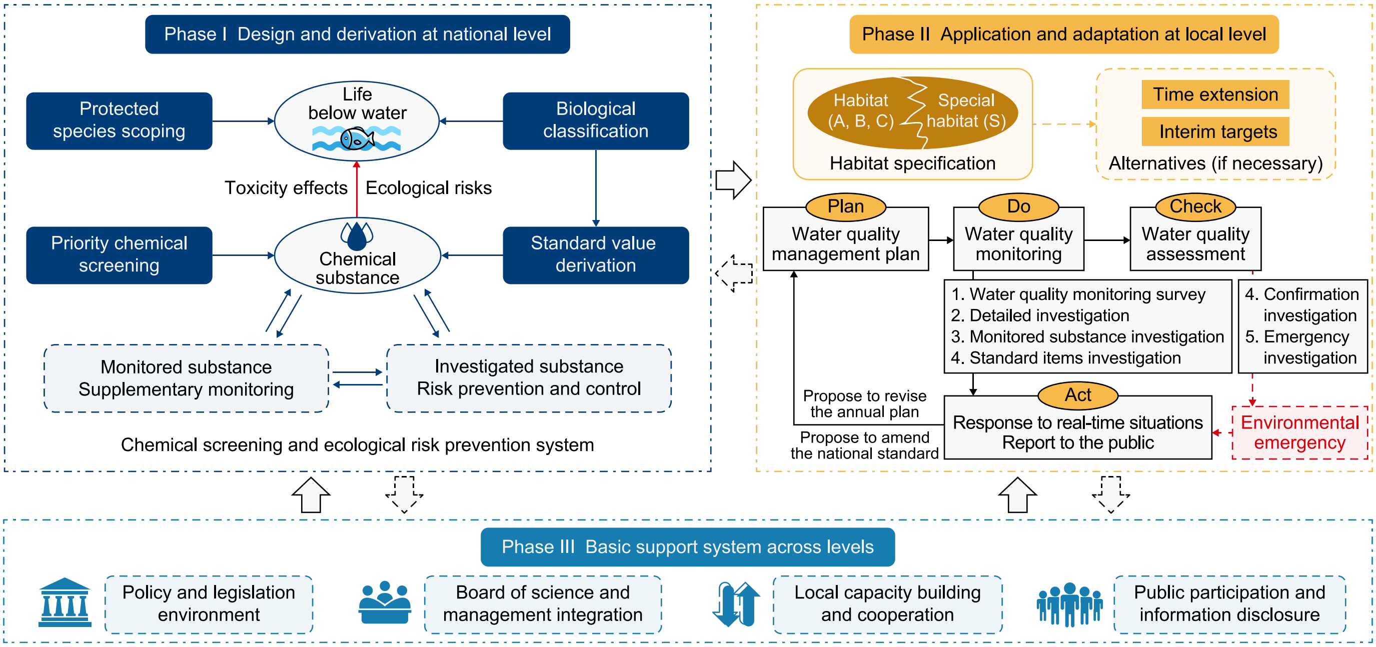


Fig. 1. Conceptual framework demonstrating the establishment, implementation, and management of the Environmental Quality Standards for the Conservation of Aquatic Life (EQS-CAL) system in Japan. Items with dashed frame are optional.

monitoring, assessment, information disclosure, and governmental actions in response to environmental emergencies. Real-time information gathering was conducted throughout this PDCA cycle, and the obtained information was fed back into national standards and annual water environment management plans. Thus, based on practical experiences, decisions could be made regarding whether the plans needed to be revised.

***Phase III*: *Establishing a basic support system associated with environmental policy and management*.** The establishment and implementation of the EQS-CAL were ensured through a concrete support system for water environment management, including (Fig. 1): (1) A constructive policy and legislative environment was considered the prerequisite to build the EQS-CAL at the national level [35–37,39,49]. (2) Institutional support from national and local environmental agencies provided pathways to enable policy mainstreaming and integrate science into environmental policy and management practices [38,50]. (3) Local capacity building was fostered through integrated development and conservation initiatives, which were central to ensuring the implementation of the standards in multiple localities [51]. (4) Information disclosure and public participation practices encouraged people to voice their opinions, and the standard provided a communication and education tool to interpret environmental governance [48,49]. Public engagement has been a core driver of Japan's environmental legislation system, which aims to build and facilitate the establishment and amendment of the EQSWP [52].

3. Key experiences and scientific issues

ALWQC and ALWQS provide critical references for environmental agencies to conduct environmental risk assessments for priority chemical contaminants and maintain healthy living environments for aquatic species worldwide. However, many jurisdictions work with unified guidelines among many water bodies and ecosystems or with fixed lists of chemicals under investigation [6,53]. Such rigid systems do not consider the diversity of site-specific species (e.g., the existence of species with conservation priority), physicochemical characteristics, beneficial uses (e.g., navigation vs. fish farming vs. contact water sports), and socioeconomic statuses. Using universal criteria or standards can easily lead to the under- or overprotection of water bodies with unique properties. Against this background, several key results have been identified and analyzed from the current research and practical experiences related to Japan's EQS-CAL.

3.1. Scoping of protected species and biological classifications of aquatic organisms

In Japan's EQS-CAL, water bodies are classified into three categories: rivers, lakes (including natural lakes and reservoirs containing more than 10 million m^3 of water, with a retention time of more than four days), and coastal waters [30]. To determine which species to protect, six types of aquatic organisms are classified as follows: aquatic life A (A), special aquatic life A (SA), aquatic life B (B), special aquatic life B (SB), aquatic life C (C), and special aquatic life C (SC). A, B, and C categories are framed according to the biological adaptability of aquatic organisms to habitat conditions, including water temperature and sediment structures. The susceptibility of organisms to essential biological needs (e.g., spawning, breeding, and rearing) during their early life stages is considered, and "special" organisms are correspondingly further derived as SA, SB, and SC (Fig. 2). Similarly, bottom dissolved oxygen is also included in the EQSWP by considering the tolerance of benthic organisms to low oxygen levels (Table S1 in the Supplementary Materials). As protected organisms mainly include fish and shellfish species in this framework, their natural prey organisms have been protected under EQS-CAL standards, considering the primary food chain [43]. During the growth and development of organisms at higher trophic levels, physical changes occurred in their mouthparts and digestive systems that altered their predation behaviors and food preferences (Table S2 in Supplementary Materials). Thus, biological adaptability was established as the

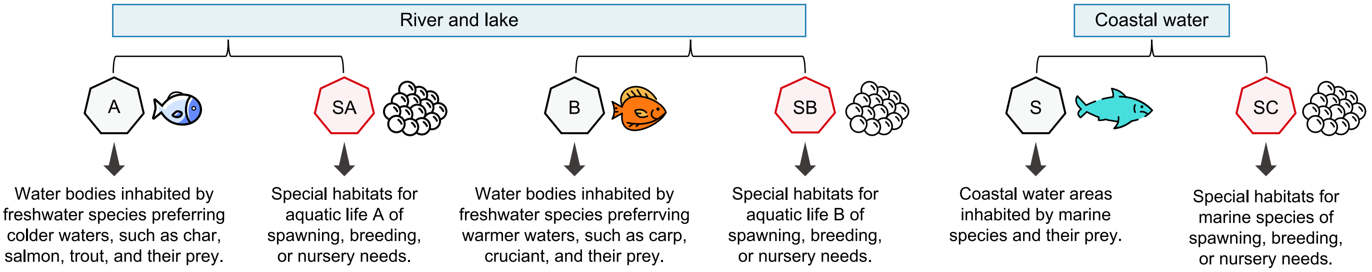


Fig. 2. Schematic diagram of the biological classifications in the EQS-CAL system. According to the biological adaptability of aquatic species to specific habitat conditions, aquatic organisms were classified into six basic types: Aquatic Life A (A), Special Aquatic Life A (SA), Aquatic Life B (B), Special Aquatic Life B (SB), Aquatic Life C (C), and Special Aquatic Life C (SC). The red box indicates special organisms. To avoid confusion, this paper adopts the use of the C/SC notation to differentiate the classification of coastal waters; the original standard expresses this as A/SA, which is the same notation used for freshwater classification.

fundamental concept and characteristic of the EQS-CAL, which is under the following three key factors: (1) species-specific preferences and adaptabilities, (2) location-specific habitat conditions and food webs, and (3) developmental life stages.

Water temperature is considered the most important factor for determining the EQS-CAL's classification scheme. This could be due to the national geographic characteristics and the heterogeneity of Japan's habitats, resulting in large temperature differences spanning up to 23.2 °C among the 47 prefectures of Japan (from Hokkaido to Okinawa) [54]. Aquatic organisms are very sensitive to changes in water temperature and that each species preferably resides within a specific temperature range [55]. Biological compositions and fish preferences differ considerably between warmer and cooler regions or seasons [56]. Thermal heterogeneity can potentially change population distributions and interspecies relationships [57]. Chemical reactions, speciation, and degradation are governed by temperature and the metabolism of aquatic organisms, especially that of ectothermic species. Therefore, it is crucial to determine the relationship between temperature and the toxicity of pollutants to aquatic organisms. Under their optimal temperature for survival, freshwater species typically have the highest resistance to pollutants. The toxicity of pollutants may increase at extreme temperatures. The toxicity of chemicals increases with increasing temperature (within a certain temperature range) [58]. This reaction is partly due to the reduced oxygen solubility in aquatic organisms at elevated temperatures. However, certain aquatic organisms can enter dormancy (i.e., metabolic inhibition) at low temperatures, leading to reduced absorption of chemicals and, thus, reduced chemical toxicity. For example, at 15 °C, the toxicity of ZnO nanoparticles is relatively low because they produce less reactive oxygen species, and copepods enter a dormant state; at 35 °C, the toxicity of ZnO nanoparticles is stronger because, in addition to the thermal stress faced by copepods, they produce an increase in reactive oxygen species and potential physical damage associated with agglomerated particles [59]. Furthermore, for different pollutants, temperature affects the same organism in different ways, and the toxic effects of the same pollutant on different organisms also differ. For example, insects and crustaceans show strong responses to changes in temperature. Temperature has a stronger effect on the biological toxicity of Ag than Cd in invertebrates [60]. Temperature changes could alter chemical properties and species susceptibility to chemical exposure [59,61]. This logic highlights the importance of considering the effect of water temperature on toxicity mechanisms and the derivation of ALWQC values in future research. The effect of temperature fluctuations on aquatic organisms and their habitats and the toxicity of pollutants is becoming increasingly important due to global climate change. Therefore, water temperature should be used as a correction factor in the ALWQC derivation process, and the different temperature sensitivities of different organisms should be considered.

Various fish species also prefer different water temperatures during different life stages. Most juvenile fish prefer warmer and shallower waters, whereas adults prefer deeper and cooler water layers [62]. The habitat locations for spawning, breeding, or nursing have also shown temperature-specific and species-specific features. For example, spawning grounds for Coho salmon (*Oncorhynchus kisutch*) are only present in areas where suitable temperatures (9–12 °C) exist in a river, regardless of whether the locations are upstream or downstream [63]. Indigenous species may adapt to seasonal changes in temperature to a certain extent. Still, they may not adapt well to large temperature fluctuations caused by heat waves or discharges of warm water, such as cooling water from power plants [64]. Therefore, temperature-based classification schemes use biological knowledge to derive and apply ALWQC. Furthermore, as fish's embryonic and larval stages are crucial to their lifecycles, they may be particularly sensitive to environmental changes and pollutants. Typically, fish eggs have a transparent, semi-transparent, or slightly opaque appearance, most pronounced in the yolk sac used for growth and differentiation. During this stage, fish eggs are extremely fragile and susceptible to environmental influences. Throughout the embryonic development process, eggs' fertilization pore and membrane structure also undergo dynamic changes [65]. For example, metal ions may enter fertilized eggs through the egg membrane; once inside the egg, they can disrupt normal egg development, inhibit the synthesis of hatching enzymes, affect the absorption of nutrients by the yolk sac, and reduce the survival rates of fish embryos [66]. In addition, environmental pollutants can induce toxic effects on organisms in early life stages, which differ from those observed in adults. For example, silver nanoparticles infiltrate zebrafish (*Danio rerio*) embryos through passive transportation, thus hindering progress in embryonic growth, causing abnormal larval development, and potentially leading to fatal outcomes [67]. Several chemicals, such as methylmercury chloride, $CdCl_2$, and $PbCl_2$, can induce embryonic deformation in zebrafish by altering the expression levels of thioredoxin1 mRNA, a key player in embryonic development [68]. Acetaminophen, which has recently been detected in various water bodies, may affect the survival of catfish (*Clarias gariepinus*), particularly during the development of their embryos and juveniles [69]. Although there is currently no conclusive evidence proving that compared with later stages, early life stages of organisms are more sensitive to environmental pollutants or other changes, Japan's EQS-CAL has already conducted separate experimental studies on aquatic organisms in their spawning or nurturing stages through their ALWQC research. Strengthening the protection of spawning grounds in practical water environment management remains critical for maintaining aquatic species across generations.

This approach may yield positive results in protecting various aquatic species that rely on multiple habitats throughout their lifetimes. However, despite their centrality in protecting aquatic life, in other jurisdictions, temperature-based classification schemes have not been fully recognized at the national level. For example, a few states and authorized tribes in the United States consider warm-water fish, cold-water fish, and seasonal species in ALWQC applications for several chemical contaminants, including Zn and Fe. The nationally recommended ALWQC also overlook this key point [13].

Nevertheless, developing species-oriented ALWQC for surface water at the national level is a difficult task. Several principal limitations are apparent in Japan's EQS-CAL system regarding biological classifications and the scoping of protected species. First, the EQS-CAL system does not cover a temperature-based classification scheme for marine species. This is due to diverse marine species' wide range of activities, many of which have a large distribution area [26]. However, many chemical contaminants (e.g., Zn, Cu, As, and Hg) occur at concentrations exceeding the ALWQC in certain coastal environments worldwide. The toxicity of these chemicals is temperature dependent, and their negative effects on the growth and development of marine species may be exacerbated under higher temperatures [70,71]. A recent study also identified a significant difference in the chronic toxicity of Fe and Cu between temperate and tropical freshwater species. This difference makes it impossible to protect tropical species by adopting the ALWQC for these metals, mainly derived from temperate species' toxicity data [72].

Second, regarding the number of official standard items, no additional chemical substances have been included in the EQS-CAL since 2013 [30]. To strengthen their role in aquatic environment management and environmental protection, it is necessary to incorporate new scientific knowledge to refine the method for deriving ALWQC, advance the standards to cover more priority chemicals and enhance the protection of aquatic life. Apart from integrating water temperature in the ALWQC derivation, it is also worth exploring other core physicochemical parameters to predict the effect thresholds of chemicals under diverse aquatic environmental conditions. Altitude, hardness, dissolved oxygen levels, and dissolved organic carbon levels in geographical and seasonal variations may also be included. In addition, climate change challenges the extent of the adaptability of living species in water bodies under elevated temperatures. These changes are known to affect aquatic life across many trophic levels. Therefore, innovative research on improving the scientific derivation of ALWQC is needed to examine the relationships between potential changes in ALWQC and the different scenarios of predicted changes in water conditions under the influence of climate change [40].

Third, the currently protected aquatic species in Japan were mainly selected according to native statistics of annual catch and biomass levels recorded by fisheries and aquaculture industries [45,73]. Therefore, the EQS-CAL protects commercially valuable fish, shellfish, and their natural prey organisms. This approach seems reasonable when only the taxon-specific sensitivities of fish or shellfish are considered [74]. The original purpose of Japan's ALWQC was to protect the majority of species, which was indirectly achieved through the ALWQC derivation of their prey. To do so, a more explicit protective target may have to be set, similar to the target of protecting 95% of species, as recommended by Australia and New Zealand [16], Canada [14], and the United States [13], as well as most European countries. The target may be modified (e.g., 99% or 90% of species protection) based on the beneficial use or core function of the water body of concern [16]. Furthermore, at the species level, it is necessary to protect rare and endangered species that may be sensitive to chemical and waste pollution, such as the Chinese sturgeon *(Acipenser sinensis)* that lives in or migrates to Japanese waters [3]. At the ecosystem level, the integrity of the ecosystem beyond commercially important fish species must be protected, including ecosystem services and important habitats, such as seagrass beds, wetlands, and coral reefs [75]. Therefore, integrating a broader scope of protected species and ecosystem management practices into the design and derivation of ALWQC will benefit individual species and preserve overall aquatic biodiversity.

3.2. Identifying priority chemical contaminants using a risk-based pollution prevention and control system

The adverse effects of chemical and waste pollution on aquatic ecosystems and the organisms inhabiting them are of great concern [2]. To determine the required preventive steps, a chemical screening system was built into Japan's EQS-CAL system to recognize the potential toxicities, ecological risks, and environmental exposure risks in Japan's surface water (Fig. 3). This process can also help identify priority chemical substances to derive ALWQC and aquatic environment management practices. Priority chemicals are screened based on two principles: (1) whether the chemical substance is currently or has been monitored or regulated nationally or internationally or is recognized as an environmental hazard by experts and (2) whether the chemical substance has been continually detected in domestic water bodies or massively produced/imported/exported in Japan.

In this manner, 797 chemical substances were aggregated in the early stages of the formulation of the EQS-CAL, of which 81 substances were selected as the first batch for ALWQC development (Fig. 3) [43,45]. These 81 selected chemicals were commonly detected in Japanese waters or regulated by international or national environmental agencies. Twenty-six priority chemicals were eventually announced according to their ecological risk assessments and long-term monitoring data (Table S3 in the Supplementary Materials). These priority chemicals had environmental concentrations exceeding the available toxicity values (i.e., effect thresholds) recommended by previous studies [46,47]. However, due to the lack of available toxicity data for local species for most of these 26 chemicals, only nine chemicals were initially selected for ALWQC research [43,45] (Fig. 3). With advancements in scientific knowledge and monitoring techniques, total Zn was finally determined as the first formal EQS-CAL item in 2003, followed by NP in 2012 and LAS in 2013 [27–29].

Notably, Japan only adopted three standard items in the current EQS-CAL system. This short list of priority chemicals is rare compared with the practices of other jurisdictions, which usually provide a long list of toxic and hazardous substances. Their WQCs are made available to the general public in the United States [13], Canada [76], Australia and New Zealand [77], China [19], and many European countries [17]. Chemicals affecting aquatic organisms are not only Zn, NP, and LAS. Therefore, to gain a better understanding of how and why Japan's EQS-CAL system covers only these three standard items, the chemical screening method must be understood as a risk-based pollution prevention and control system (Fig. 3). Along with standard items, there were six other chemicals of concern: chloroform, phenol, formaldehyde, aniline, 2,4-dichlorophenol, and 4-tert-octylphenol, which were identified as “monitored substances” (Table S4 in the Supplementary Materials). They were monitored with available guideline values as a reference for additional monitoring in field water bodies. If monitoring points exceeded the guideline values or continuously exceeded 10% of these values, such monitored substances would be considered in the EQS-CAL system [46]. Another list of chemical substances was identified as “investigated substances”, which initially included 300

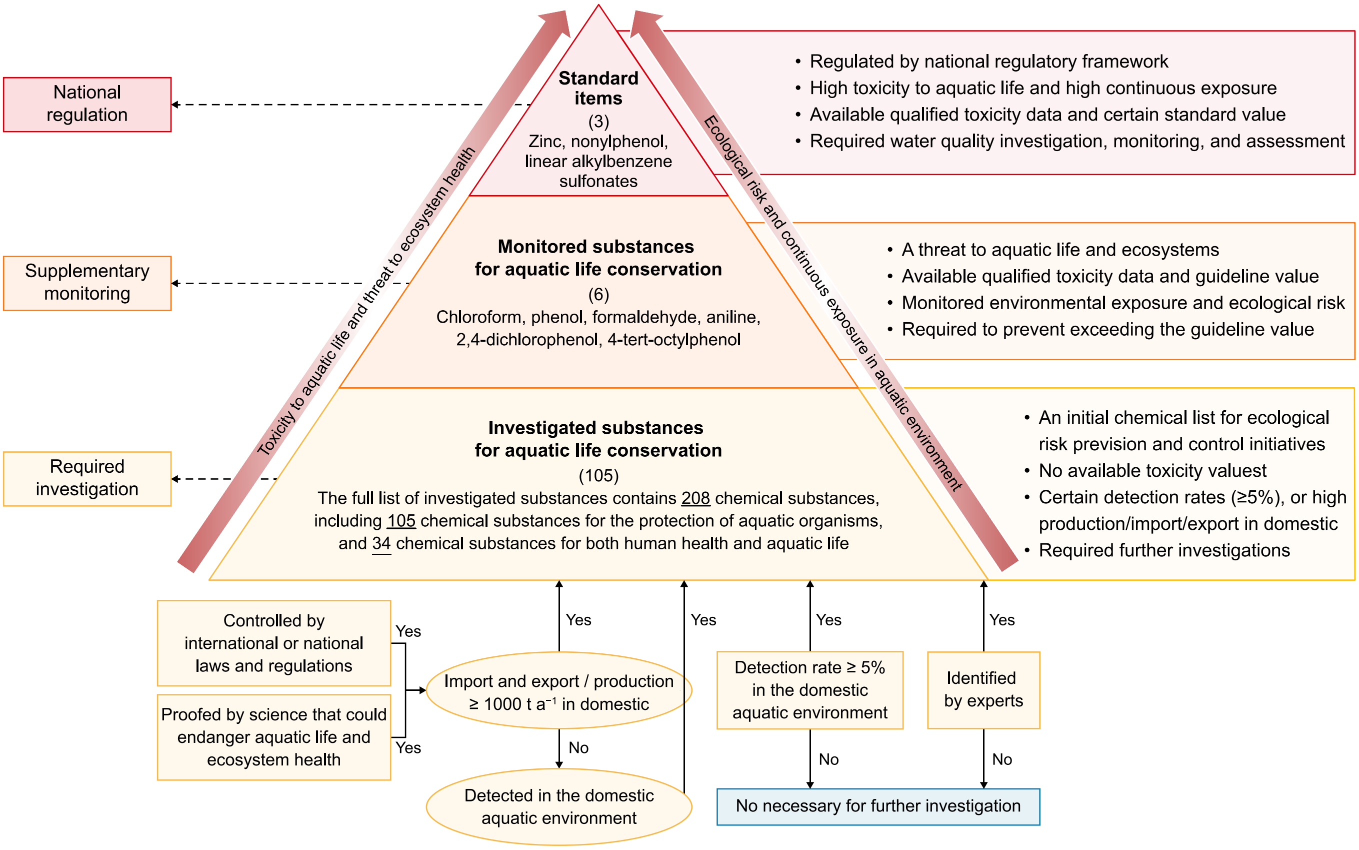


Fig. 3. A risk-based pollution prevention and control system. The hierarchy and interactions between standard items, monitored substances, and investigated substances are shown. The flow chart at the bottom shows a wide range of chemical screenings with certain conditions. The colors red, orange, and yellow represent the potential toxicity levels to aquatic life and ecological risk from high to low, respectively.

substances in 1998 and was fully revised to 208 substances in 2014, with 105 chemicals listed to protect aquatic organisms [47]. These substances are controlled internationally or nationally. If a chemical contaminant had a detection rate exceeding 5% in domestic water bodies, further research and field examinations would be required to identify potential hazards, toxicity data, and test techniques based on individual chemicals (Fig. 3). For example, chemicals such as acetamiprid and ivermectin — the main ingredients of pesticides and disinfectants — have been added to this list because they tend to be related to large domestic production and import–export volumes. Substantial concentrations of perfluorooctane sulfonate and related perfluorinated organic compounds have been found in surface water and fish samples in Tokyo Bay [78]. In 2021, perfluorooctanoic acid and perfluorooctanesulfonic acid were relabeled as monitored substances, and perfluorohexanesulfonic acid was added to derive the value of ALWQC [47]. This system's settings for standard items monitored substances, and investigated substances are dynamic (Fig. 1 I).

Furthermore, this study showed that the interactions between the investigated substances, monitored substances, and established standard items were determined through the reallocation of research and management requirements (Fig. 3). As a result, in Japan, chemical substances were supervised according to the following hierarchy from high to low: standard items > monitored substances > investigated substances. The substance hierarchy corresponds to specific monitoring, investigation, research, and investments requirements. This policy on resource prioritization is essential for countries and regions with limited budgets for environmental protection programs.

However, a national mandatory guideline with only three formal items remains challenging for Japan, given that considerably more contaminants exist in aquatic environments, especially those of emerging concern. The over-concentration of resources may obscure potential hazards or undermine potential threats from various chemical and waste products, such as pharmaceuticals and personal care products, persistent organic pollutants, and endocrine disrupting chemicals. The challenges posed by the presence of trace chemicals in wastewater and their persistence and tendency to bioaccumulate drive the search for effective removal and continuous improvement of wastewater treatment processes [79]. Overly pronounced concerns about “priority” chemicals may result in inadequate supervision of other potentially harmful chemicals [80,81]. Contemporary water quality monitoring methods and ecological risk assessments are constantly updated. For example, nanotechnology enables the manipulation of atoms at the nanoscale, in which nanomembranes are used to soften water and eliminate physical, chemical, and biological water pollutants [82]. However, more research and additional techniques are needed in the face of an increase in newly registered chemical substances and other uncertain threats.

3.3. Derivation methods and protection levels of the ALWQC

The ALWQC are described as safe scientific exposure thresholds of chemical contaminants that do not cause unacceptable toxic effects on organisms or disruptions to the structure and functions of aquatic ecosystems [6,83]. Japan's EQS-CAL system was designed based on this perspective (Fig. 4). The survival of aquatic species and the maintenance of acceptable population levels (i.e., population fitness or population growth) were emphasized to achieve normal reproduction between generations [45]. Under this context, the key points of the derivation method of Japan's ALWQC include (1) maintaining ideal livable environments for aquatic organisms rather than focusing on their ability to survive and tolerate chemical contaminants; (2) ensuring long-term viability rather than short-term maintenance of aquatic organisms by comprehensively considering the toxic effects of the focal chemical on their growth, development, mortality, swimming, mobility, hatching, and reproduction; (3) a preference for the observed long-term chronic toxicity of chemical substances (with endpoints such as the no observed effect concentration and the lowest observed effect concentration) rather than short-term acute toxicity (with endpoints such as the median effect concentration [EC_{50}] and median lethal concentration [LC_{50}]); (4) testing toxicity effects on adult organisms and “special” organisms at early life stages; and (5) conducting independent experiments on aquatic organisms, such as fish and shellfish, including their natural prey organisms, to better understand the impact of chemical exposure on the entire food chain [26].

Based on this review, Japan's method for ALWQC derivation can be summarized as a five-step method (Fig. 4). The individual steps are briefly described as follows.

Step 1 Data collection and screening

Toxicity data were collected from available toxicity tests on native species, focusing on chronic toxicity tests. Data quality was evaluated based on credibility and usability, with experimental designs and toxicity testing methods following commonly used national or international toxicity test guidelines [26–28]. Other data and information were also collected and screened regarding the physicochemical properties of chemicals, water quality parameters, exposure conditions, and information about test species.

Step 2 Grouping for toxicological experiments

To account for the accumulation of toxic chemicals along the food chain, toxicity test organisms were divided into a fish and shellfish group and a food organism group (Fig. 4d). Long-term (chronic) or short-term (acute) toxicity values were obtained. The acute endpoints were the median effect concentration and the median lethal concentration, while the chronic endpoints were the lowest observed effect concentration, maximum allowable toxic concentration, and no observed effect concentration. The toxic effects observed in toxicity experiments included mortality, growth, immobilization, and reproduction. These values were uniformly compared between long-term chronic toxicity tests by estimating the coefficients. The lowest toxicity values were selected as the representative for each test species.

Step 3 Toxicity value estimation

The fish and shellfish group's toxicity values were estimated by the representative toxicity value divided by the species ratio. This approach provides different potential responses to certain chemical substances for different species. The geometric means of the toxicity values from species of the same genus were used for the food organism group, and the lowest food toxicity values were selected as the estimated food toxicity value.

Step 4 Species toxicity sensitivity analysis

The estimated toxicity values from each test group were compared, and the lowest value was selected as the final estimated chronic toxicity value. Species with this lowest value can be

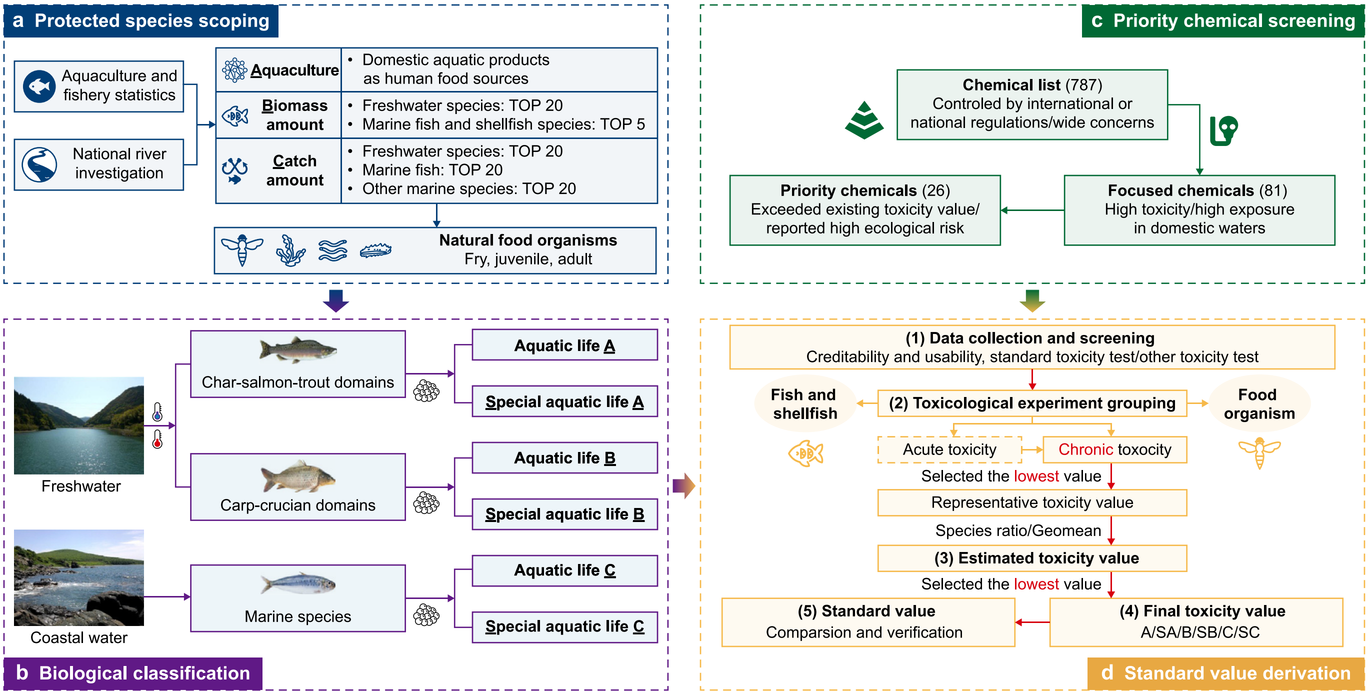


Fig. 4. Integrated diagram of the standard value derivation workflow, including details on protected species scoping (**a**), biological classifications (**b**), priority chemical screening (**c**), and standard value derivation (**d**). Each color block represents the integrity of a key section, and the arrows connect sections in order. Each section's presentation demonstrates a high degree of integration, conciseness, and visualization of information derived from Japan's original technical reports on aquatic life water quality criteria (ALWQC) derivation.

considered the most sensitive species among all tested species in each biological type.

Step 5 Standard value determination

Each biological type's final estimated toxicity values were eventually compared between different life stages. The method was structured to ensure a relatively lower standard value for “special” organisms to obtain higher protection. Standard values were independently proposed using this method for each biological type (A, SA, B, SB, C, and SC), and six proposed standard values were determined for each chemical substance. Holistically, the overall derivation workflow should be reported in a transparent and accessible manner to facilitate review.

Ideally, in light of the above method, the long-term chronic toxicity values of the most sensitive species are selected as the key data source for the standard values for individual chemical substances. They are used to determine the standard value for each biological type (Table 1). This method differs from certain jurisdictions that have adopted “double value” approaches, with a criterion maximum concentration and continuous concentration, to prevent short- and long-term effects. Although Japan's method embraces stricter values, thereby protecting more species, it tends to be problematic. Qualified chronic toxicity data are limited and insufficient for most ALWQC derivations [84]. The underestimation of exposure risks from acute endpoints is also questionable. It appears challenging for Japanese officials to obtain sufficient and qualified toxicity data from each of the two types of aquatic life (fish and shellfish) and their respective natural food organisms at different life stages. This challenge tends to increase both the workload and uncertainty.

Nevertheless, separating the toxicity of fish, shellfish, and food organisms in Japan's ALWQC system is feasible. Evidence indicates that aquatic organisms at different trophic levels exhibit varying sensitivities to metals. For example, organisms at lower trophic levels show relatively higher sensitivity to Zn (plants > vertebrates > crustaceans > invertebrates > fishes). One possible reason is that organisms at higher trophic levels have more developed detoxification mechanisms [83]. By contrast, research has indicated that the toxicity of pollutants can be magnified along the food chain. When pollutants enter the bodies of organisms at higher trophic levels, they accumulate in tissues and organs, further amplifying their toxicity and increasing the threat to organisms at higher trophic levels [85]. Although related studies have not obtained conclusive evidence, integrating the trophic level is essential for future research on the toxicity mechanisms of pollutants and the derivation of ALWQC. Although Japan has started to explore ALWQC studies further from a food chain perspective, the sole focus is on fish bait organisms, which remains relatively simplistic regarding the accumulation effects of pollutants within organisms. In addition to many other national environmental agencies, Japan's derivation method relies on laboratory-driven toxicity data under constant physiochemical conditions. Field/semi-field approaches have become increasingly necessary to complement laboratory-driven ALWQC and facilitate more scientific decision-making processes; this is a common problem in WQC derivation to protect aquatic organisms [6,86].

The ALWQC can be useful for managing the aquatic environment and for species conservation, but only if used appropriately. Existing standard values derived from Japan's current standard may not be sufficiently robust to avoid over- or underprotection of most aquatic life at a certain level (e.g., 95%). For example, the standard value of Zn is 0.03 mg L^{-1} in the EQS-CAL, in which the mayfly *(Epeorus latifolium)* is identified as the most sensitive test species (Table 1). Field studies have shown that 95% of the population can be protected when Zn concentrations of 0.107 mg L^{-1} can be maintained [22]. Slight overprotection has also been found in large benthic populations, with an effect threshold of only 0.1 mg L^{-1} [25,87]. Organisms tested in laboratory studies tend to show higher sensitivities than those in field studies; this seems a common

Table 1
Sensitive species and toxicity data for deriving standard values of the current standard items of the Environmental Quality Standards for the Conservation of Aquatic Life (EQS-CAL) system.

Standard item	Classification	Key test species and toxicity data for standard value derivation[a]					Standard value ($\mu g\ L^{-1}$)[c]
		Scientific name	Test group	Endpoint/Effect[b]	Test period (days)	Concentration value ($\mu g\ L^{-1}$)	
Total zinc	A	*Epeorus latifolium*	Food	NOEC, GRO	28	30	30
	SA	*Epeorus latifolium*	Food	NOEC, GRO	28	30	30
	B	*Epeorus latifolium*	Food	NOEC, GRO	28	30	30
	SB	*Epeorus latifolium*	Food	NOEC, GRO	28	30	30
	C	*Nitzschia closterium*	Food	LC_{50}, REP	4	65	20
	SC	*Strongylocentrotus purpuratus*	Food	LC_{50}, MOR	4	97.2	10
Nonylphenol	A	*Oncorhynchus mykiss*	Fish	LC_{50}, MOR	4	95.1	1
	SA	*Oncorhynchus mykiss*	Fish	NOEC, GRO	91	6	0.6
	B	*Oryzias latipes*	Fish	-	-	-	2
	SB	*Oryzias latipes*	Fish	NOEC, GRO/MOR	43	22	2
	C	*Pagrus major*	Fish	LC_{50}, MOR	4.5	118	1
	SC	*Pagrus major*	Fish	LC_{50}, MOR	2.5	71	0.7
Linear alkylbenzene sulfonates	A	*Oncorhynchus mykiss*	Fish	LC_{50}, MOR	4.5	3000	30
	SA	*Oncorhynchus mykiss*	Fish	NOEC, GRO	57	150	20
	B	*Oryzias latipes*	Fish	LC_{50}, MOR	4.5	4600	50
	SB	*Oryzias latipes*	Fish	NOEC, GRO	40	389	40
	C	*Pagrus major*	Fish	LC_{50}, MOR	4.5	1300	10
	SC	*Pagrus major*	Fish	LC_{50}, MOR	2.5	550	6

[a] Toxicity data and information in this table were collected from original technical studies and official reports.

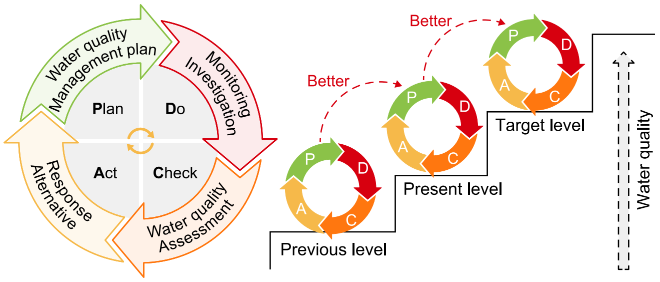
[b] Endpoint: EC_{50}, median effective concentration; LC_{50}, median lethal concentration; LOEC, low observed effect concentration; MATC, maximum allowable toxic concentration; NOEC, No observed effect concentration. Effect: MOR, mortality; GRO, growth; IMM, immobilization; REP, reproduction.

[c] The proposed standard value was derived from the most sensitive species among all test species, ranging from fish and shellfish to their food organisms.

problem with most ALWQC derivation and risk assessment methods [86]. Therefore, the effectiveness of protection through standard values should be validated by field studies and/or other relevant studies. The United States Environmental Protection Agency [88] recommends a criterion continuous concentration for Zn of 0.12 mg L^{-1}, four times higher than the current standard value in Japan. Similarly, the freshwater standard value of NP in Japan is also lower than the value recommended by the United States. The standard values of NP and LAS were also derived from single sensitive species, such as rainbow trout (*Oncorhynchus mykiss*), medaka (*Oryzias latipes*), and red sea bream (*Pagrus major*) (Table 1). This derivation from a single species tends to generate stringent standards that may be too conservative. Such overly conservative standards can lead to overprotection and excessive risk reduction efforts, thus compromising certain stakeholders' needs. It must be admitted that overprotection is certainly a scientifically smarter effort in protecting a range of aquatic life and ecosystems; however, as an environmental management target in less developed areas, it might be unachievable or unacceptable. Therefore, protecting all stakeholders while ensuring a safe environment should be appreciated.

3.4. *Site-specific ALWQC implementation mechanism and basic support system*

The EQS-CAL were established nationally but applied locally for site-specific aquatic environment management. During the implementation phase, the PDCA model was used by individual prefectures to ensure that the EQS-CAL matched the local conditions and responded to any potential changes using unified water quality monitoring, assessments, examinations, and information disclosures (Text S1 in Supplementary Materials). Certain aquatic environment management initiatives are connected by a closed loop, which may enable quick information feedback throughout an overall implementation mechanism. This closed-loop approach also carries reliable references for instant governmental actions in response to environmental emergencies, regional preventive action plans, and national standard amendments. Through replicable loops of the implication mechanism and self-learning processes, both water quality and compliance rates can be continuously improved over time (Fig. 5). As the national government ceased the provision of subsidies to local governments for water quality monitoring in 2005, local governments are required to finance their water quality monitoring [40]. Given the extent required for monitoring and examination processes, underfrequency ratings with fewer monitoring points can be allowed in which continuous compliance levels can be maintained for over three years in Japanese waters and vice versa (Table 2) [48].



A PDCA cycle

An adaptive process

Fig. 5. Conceptual mechanism for continuously improving water quality based on self-learning Plan-Do-Check-Act (PDCA) cycles.

In certain cases, the capacity for water pollution control may deviate from the requirements of national standards. In such cases, the EQS-CAL requires further adjustments for local situations using the two alternative methods: (1) a five-year extension or (2) several interim target values that can be adopted in situations where the pollution status has become too severe to reach the national standard in one step in which local communities rely on large-scale industries that continuously discharge contaminants [30]. The site-specific target of aquatic environmental management tends to be feasible and attainable at the local level. Currently, the compliance rate of the EQS-CAL approaches the achievement level (Table 2). Although a desirable score only implies that the numerical value is within the national standard, water quality improvement outcomes continuously show a current compliance rate of nearly 100% in successfully recovered cases. Moreover, the alternatives could potentially force local capacity building regarding water infrastructure, wastewater treatment techniques, and green industry investment. These actions may enable the standards to become more economically and technically feasible. More importantly, any substantial divergence from the recommended criteria may result in higher risks of harmful chemicals being imposed on aquatic organisms. Optimal models and assessment methods should be identified to avoid ambiguous goals and possible prefectural conflicts because of environmental justice. The government has spent more than 10 years designating 45 water areas within and across Japanese regions and watersheds, but this designation remains a challenging task [29,89]. Based on Japan's practice, this approach is economically feasible for highly disciplined agencies but is a costly and time-consuming option in certain jurisdictions where budgets for environmental protection are tight.

Finally, national development policies and plans require certain water quality levels to protect human health, aquatic organisms, and their shared environments, signifying the One Health concept overall. The economic development mode also plays a crucial role in determining the extent to which the socio-political environment is conducive to enhancing environmental policies and legislation systems. In Japan, the Basic Environment Plan was announced to realize symbiosis between humans and diverse aquatic organisms and the required protection of rich biodiversity, habitat continuity, and biological productivity [38]. This conducive environment policy has ensured that, to date, multiple supports are in place to establish and implement the EQS-CAL system from a national level to a site-specific scale (Text S2 in Supplementary Materials).

4. Integrating resilience thinking into aquatic environment management systems

Rigid management systems of the aquatic environment can lead to an inadequate “one-size-fits-all” approach. Many water bodies have varying biota characteristics, physicochemical conditions, aquatic species, and socio-economic features [6,90]. Rigid management systems may produce a fixed list of priority chemical contaminants with management of universal WQC or water quality standards. However, such a fixed list ignores that the effect threshold of a certain chemical could change in different aquatic environments because of variabilities in physicochemical conditions, biological communities, and exposure pathways. Meeting universal water quality standards may present an unachievable challenge for specific regions because of socio-economic constraints and technological limitations. Considering the constant changes in the aquatic environment and the ongoing development of new synthetic chemical products and component reformulations, this study proposes a conceptual framework for a more resilient aquatic environment management system. The proposed framework addresses the potential limitations of rigid systems for the derivation, application, and management of the ALWQC (Fig. 6).

Table 2
Comparison of water quality monitoring information of the EQS-CAL from 2018 to 2021 in Japan.

Standard items	Rivers				Lakes				Coastal waters			
	Monitoring points		Compliance rate (%)		Monitoring points		Compliance rate (%)		Monitoring points		Compliance rate (%)	
	2018	2021	2018	2021	2018	2021	2018	2021	2018	2021	2018	2021
Total zinc	3562	3473↓	97.9	98.2↑	299	309↑	100	99.1↓	924	924	100	100
Nonylphenol	2481	2543↑	100	100	212	225↑	100	100	577	569↓	100	100
Linear alkylbenzene sulfonates	2433	2499↑	99.6	99.9↑	211	222↑	100	100	588	570↓	100	100

Note: The standard values were evaluated by the annual mean. The national monitoring data can be accessed at: https://www.env.go.jp/water/suiiki/index.html. The arrows indicate either an increase (↑) or a decrease (↓) regarding the number of monitoring points and annual compliance rate.

This framework is described and elaborated on in the following subsection.

4.1. *Theoretical framework for a resilient ALWQC system*

Scientists and environmental authorities have realized the importance of developing a more scientific and robust ALWQC system to protect the aquatic environment and the species inhabiting it. Urban areas, which typically consist of complex production and consumption systems, represent intricate networks that produce substantial amounts of human-made chemicals and waste [91]. Urban areas are commonly closely interconnected with surface water environments. This system needs to be aligned with the diverse needs of stakeholders, periodic priorities, technological advancements, and diverse ecological and socio-economic characteristics across different regions.

Resilience is a commonly used concept to describe a system's adaptability to external disturbances and ongoing changes. This concept emphasizes the stability and flexibility of the system, enabling it to withstand changes while maintaining its structure and functionality [92,93]. In environmental management, a resilient ALWQC system is a cross-scale, interdisciplinary research foundation and management approach that addresses challenges in water pollution and biodiversity loss and adapts to changing contexts. This system integrates dynamic information feedback as a central hub, thus enabling the effective management of the aquatic environment and meeting national policy demands and sustainable development goals. Comprehensive knowledge, understanding, and interdisciplinary thinking about changes and diversities across spatial and temporal scales are crucial to adopting adaptive and resilient ALWQC and ALWQS systems.

A resilient system seeks to establish connections between humans and ecosystems in the context of environmental management. Their linkages and interactions are embodied in complex adaptive cycles known as social-ecological systems (SESs) [94,95]. While ALWQC promotes the interfaces between humans, aquatic organisms, and the environment [90], SESs emphasize the integration of people and ecosystems [96]. Through this integration, a more resilient ALWQC system is proposed that incorporates ecosystem dynamics and management practices (Fig. 6). This system can be perceived as an ALWQC data and information platform that combines diverse social and ecological knowledge systems and has the goals of adapting to changes, responding to information feedback, and facilitating continuous learning to improve the capacity of species conservation and aquatic environment management. Ideally, ALWQC systems should be tailored to local knowledge systems with species- and location-specific features. Temporal—spatial differences and multiple stressors render a rigid system more vulnerable about accommodating such variations and uncertainties. In this context, the authors believe that if the ALWQC and ALWQS systems can be perceived as an SES, cross-scale interactions will emerge when they are applied in real scenarios. The ALWQC are not only a threshold for the concentration—response relationship between aquatic life and chemical substances but also a complex system that integrates considerations of natural diversity and variability of organisms and ecosystems, as well as the socio-economic variety and dynamics originating from human societies.

A resilient system is composed of adaptive cycles across scales. Each level operates at its rhythm, safeguarded by larger and slower

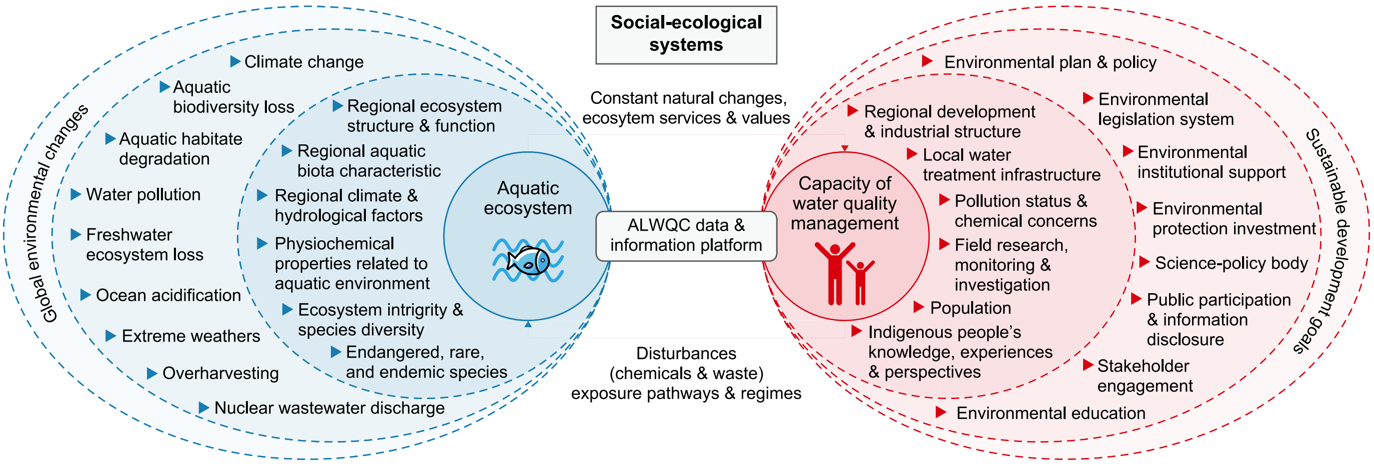


Fig. 6. Conceptual framework of the ALWQC data and information platform based on social-ecological systems. Blue symbols represent ecosystem dynamics, while red symbols represent management practices. The dashed circle represents the boundary of scales, and overlapping circles represent interfaces across scales.

levels yet stimulated by smaller and faster innovation cycles [97]. This interconnected structure (i.e., *panarchy*) allows the system to address ongoing changes by emphasizing the ability to adapt, innovate, and transform into improved configurations [98,99]. This ability may help to distinguish a resilient ALWQC system from existing rigid systems using two key features. First, it encompasses transboundary interactions and feedback between ecological and social components, the outcomes of aquatic ecosystems, and the management capacity across SES contexts. A large-scale interaction can be triggered by a small set of critical small-scale processes [97], which implies the need to expand the analysis to cover a large range of scales [92,96]. As the derivation of ALWQC should be a site-specific tool for localizing specific targets according to the characteristics of aquatic biota [6,53], it is theoretically possible to take local-scale actions (i.e., field/semi-field research, indigenous species, characteristic contaminant identification, and feasible targets for pollution control) on smaller and faster scales, thereby mitigating broader impacts (and vice versa). However, it is important to note that while countries and regions possess the flexibility to make the necessary adjustments, ALWQC may not have all the details of specific locations and situations until the present day. Second, a resilient system is a developing database [100]. A substantial challenge in this regard is to incorporate knowledge and self-learning abilities within the environmental agencies responsible for ALWQC derivation and ALWQS application. Their incorporation can enable these agencies to engage with science and policy bodies at the local, regional, national, and global levels and share up-to-date and interdisciplinary knowledge and outcomes without boundaries.

Resilience reflects the capacity of a system to cope with shocks and undergo changes while retaining its original structure and function [99]. Complex and diverse systems are essential for absorbing disturbances and promoting the stability and transformation of ecosystems [97]. The loss of species from an ecosystem can reduce its complexity and increase its vulnerability to disturbances that could have been absorbed previously. For example, a complex local food web of interactions is more likely to offer alternative food sources, whereas the global loss of biodiversity heightens the vulnerability of the entire ecosystem [96]. To reduce risks and build resilient ALWQC systems, the following actions should be taken: the capacity of an ALWQC system to cope with research uncertainties should be enhanced; field/semi-field toxicity data, physicochemical variables, species diversities, full lifecycles, and ecosystem complexity should be incorporated into experimental design and toxicity prediction models; and the most recent findings from interdisciplinary research fields should be involved (e.g., environmental toxicology, water chemistry, integrative biology, human ecology, development economics, epidemiology, and risk assessment) [7,101]. Considering the needs of different stakeholders, particularly the knowledge and experiences of indigenous people, from the beginning to the end can also enrich the development database and achieve more resilient and diverse systems.

4.2. *Lessons learned from Japan's practice*

Japan's EQS-CAL system is relatively adaptive and flexible, adopting a species- and site-specific approach. Japan's experiences have demonstrated several experiences regarding the concept of resilience as follows: (1) Depending on the capacity of aquatic environment management, considerations of ecological adaptability concerning exposure regimes, biological preferences and tolerance, organism development, and interspecific relationships can be adopted in the design and derivation of ALWQC at the national level [26]. (2) Japan's ALWQC system was applied by designating specific types of water habitats based on a combination of multiple field data and information (i.e., species diversity, temperature, location of spawning areas, monitoring data of certain contaminants, fishery jurisdictions, artificial facilities, and conservation and release activities). (3) The chemical screening and ecological risk prevention system was developed from local monitoring data, regional industrial structure to domestic consumption, and the global ecological risks of certain chemicals. (4) The PDCA model was adopted at the local level because it enables fast information feedback, which enhances the flexibility (e.g., the use of interim targets and extension) of the ALWQC application and facilitates the amendment of the national-level standard. (5) A multi-level network of supporting institutions and public engagement is in place to build and apply Japan's ALWQC system nationally and locally. This approach can also be understood as an example of adaptive governance. Japan has greatly benefited from this approach, and so have other jurisdictions. Table 3 shows the lessons learned from Japan's experiences in building ALWQC systems. This knowledge can help enhance the adaptability of a holistic aquatic environment management system to meet the challenges of an ever-changing world.

Although challenges are associated with the ALWQC methodology and resilience approaches, they are favored tools for disclosing the complexity of the environment. Resilience is not a new concept in environmental research and management, but it has not yet been fully explored and has not been applied to aquatic environment management about ALWQC systems. This is the first study to propose a conceptual framework for integrating resilience thinking into ALWQC systems. The proposed framework and the discussion of Japan's experiences highlight the potential value of a resilient approach in enhancing the connectivity, adaptivity, and self-learning abilities of the most popular environmental management tool. This study can assist environmental organizations and authorities in solving complex problems and generating a wider range of useful outcomes.

5. Conclusion

This study provides a comprehensive overview of Japan's ALWQC system and proposes a practical and adaptable ALWQC framework. Japan's ALWQC system prioritizes the adaptability of aquatic organisms to their habitat conditions, resulting in identifying six biological types to derive ALWQC values. Among these, the significance of fish temperature preferences is the primary basis for biological type classification within the system, which may offer a more logical and effective means for protecting species. Regarding the screening procedures for chemical compounds, Japan officially lists only three standard items (Zn, NP, and LAS), but its robust screening system includes numerous supplementary items for monitoring and over a hundred additional items for further examination. The derivation method for ALWQC values in Japan is based on the toxicity of the most sensitive species. It also considers the adaptability of different species, the specific vulnerabilities of organisms at early life stages, and their natural prey organisms. Although this approach may increase the workload of experimental research, it is a meticulous and essential process. Furthermore, by integrating key elements (e.g., water quality management plans, monitoring, assessment, and responses), Japan has established a foundational support system for implementation and management, thus ensuring the ongoing improvement of water quality. However, Japan needs to continuously research emerging pollutants and newly registered chemicals to update its ALWQC system in the future. The range of protected species should encompass various categories of organisms present in the ecosystem. This includes commercially valuable fish and shellfish species, as well as

Table 3
Applying resilience and interdisciplinary thinking to aquatic environment management and aquatic species conservation in Japan and other jurisdictions.

Key experiences	Scientific issues of the aquatic life water quality criteria (ALWQC) derivations and applications in Japan	Potential applications to aquatic environment management and aquatic biodiversity conservation in Japan and other jurisdictions	Interdisciplinary research fields	Resilience-based considerations
Protected species scoping	a) Only considering “beneficial species”, i.e., fishery resources. b) Only primary food organisms, i.e., prey organisms, are considered.	a) Extend a broader coverage of protection, i.e., ecological value. b) Consider regional food webs and the complexity of ecosystems.	One Health approach Hydrobiology Epidemiology	Ecosystem complexity Vulnerability
Biological classification	a) Unified classification scheme in freshwater ecosystems and unclassified marine species. b) Water temperature tends to be the decisive factor. c) Unclear effect mechanisms of the physicochemical factors on biological preferences and chemical toxicity. d) Costly and time-consuming.	a) Consider the difference between aquatic ecosystems' hydrological conditions and biological resources (e.g., streams, rivers, lakes, coastal wetlands, estuaries, and seas). b) Consider the variability and adaptability of aquatic species to habitat status in the early design and establishment of ALWQC. c) Consider multiple physicochemical factors in the derivation of ALWQC. d) Organise toxicity tests through life history and provide “special” protection for special needs (e.g., spawning, breeding, and rearing).	Integrative biology Food chains	Biological adaptivity *Panarchy*
Priority chemical screening	a) Only three official standard items. b) Overly concentrated in a very short list of chemicals. c) Technology constraints exist in monitoring and testing.	a) Build dynamic chemical screening systems for different levels of potential ecotoxicity and ecological risks. b) Prioritize certain chemicals according to domestic consumption and socioeconomic conditions. c) Adjust the resources of examination and monitoring (e.g., the number of monitoring points) based on field situations.	Ecological risk assessment Command and control policy	Hierarchy Dynamics
Standard value derivation	a) Overly dependent on laboratory toxicity data, and the final standard values were obtained from single-species laboratory tests. b) Insufficient qualified chronic data and employment of acute-to-chronic ratios (ACRs) may not be appropriate. c) The most sensitive species received the highest concern, thus leading to their slight over-protection. d) Test species selection ignored the diverse composition of ecosystems. e) Lack of up-to-date scientific findings.	a) Develop independent ALWQC derivation methods apart from the protection of human health. b) Emphasize the resilience of ecosystems and adopt risk-based approaches to allow acceptable levels of chemical contaminants. c) Develop models to predict the toxicity to fulfill the acquisition of qualified toxicity data, particularly the long-term reproductive toxicity of emerging pollutants. d) Consider differences in water conditions between laboratory shelter and field habitat by organizing field/semi-field research. e) Build a national toxicity database based on local species and consider collaborative datasets for long-distance migratory aquatic species that move across jurisdictions.	Risk-based approaches Ecotoxicology Water chemistry	Disturbance absorption Interdisciplinary environment Developing a database
Site-specific application	a) Very detailed examinations require long-term action, while implementation and management are delayed. b) The permit for a five-year extension and interim values is vague and potentially causes ambiguous goals and prefectural conflicts. c) Increased financial pressure on local environmental conservation.	a) Connect water quality monitoring, assessment, examinations, and annual plans to enable fast information transfer and quick response to environmental emergencies. b) Adopt adaptive strategies with clear permits and technical guidelines regarding cost-benefit analyses at the local level. c) Establish local knowledge systems and consider the needs of different stakeholders, especially the voices of indigenous people. d) Strengthen the cohesion of ALWQC to local standards, regulations, and rules for aquatic environment management and species conservation.	PDCA models Analytical chemistry Cost-benefit analysis Human ecology	Social-ecological systems (SESs) Self-learning Knowledge integration Adaptive management
Supportive management system	a) The priority of protecting aquatic life and the environment remains lower than the priority of human health. b) Information disclosure is relatively lagging and monolingual.	a) Build a supportive environment for ALWQC. b) Enhance the integration of science and policy bodies. c) Largely engage stakeholders among environmental agencies, science groups, local communities, fishers, enterprises, business groups, wastewater treatment plants, and NGOs/NFOs.	Development economics Public participation	Pathway diversity Adaptive governance

species of ecological value, such as endangered species. Therefore, it is necessary to refine the temperature-based classification scheme based on the toxicity mechanisms of pollutants in organisms and appropriately consider other water chemical conditions. Deriving protection levels from an ecosystem perspective may be more reliable than relying on a limited number of test species. Nevertheless, the lessons learned from Japan's experiences in building ALWQC systems can benefit other jurisdictions aiming to achieve a more resilient water quality management system for ALWQC derivation and application. These lessons can also enhance the capacity to address increasing water pollutants and environmental changes.

CRediT authorship contribution statement

Zihan Xu: Writing - Original Draft, Visualization, Methodology, Formal Analysis, Data Curation, Conceptualization. **Ying Wang:** Writing - Review & Editing, Visualization, Conceptualization, Validation. **Li Xie:** Writing - Review & Editing, Validation, Investigation. **Di Shi:** Writing - Review & Editing, Investigation. **Jia He:** Investigation. **Yanqing Chen:** Writing - Review & Editing. **Chenglian Feng:** Writing - Review & Editing. **John P. Giesy:** Writing - Review & Editing. **Kenneth M.Y. Leung:** Writing - Review & Editing, Supervision. **Fengchang Wu:** Writing - Review & Editing, Supervision, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

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