



## Review Article

# Water salinity in global salt lakes: Monitoring technologies, spatiotemporal dynamics, and socio-environmental consequences

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## ABSTRACT

Salt lakes represent critical nodes in global hydrological and biogeochemical cycles, accounting for approximately 44% of the total lake water volume worldwide. Water salinity, as a key variable regulating physical, ecological, and chemical processes in salt lakes, plays a decisive role in regional ecological security and the sustainability of water resources. This study presents an interdisciplinary review of the progress in the research topic on the pattern and changes of salt lake water salinity. With the growing prominence of ecological concerns, research on the water salinity of salt lakes has evolved from traditional hydrogeochemical descriptions to an interdisciplinary frontier that integrates the impacts of climate change, ecosystem responses, and remote sensing monitoring. The core driving force behind this transformation stems from the innovation of monitoring technology, that is, from traditional point sampling to a large-scale, long-term dynamic monitoring system centered on satellite remote sensing and machine learning. Synthesized analyses of global records reveal that global salt lakes are predominantly distributed across arid and semi-arid zones in both hemispheres, with the Tibetan Plateau (TP) exhibiting the highest density and heterogeneity of water salinity. Over the past few decades, the changes in water salinity of the global large salt lakes display a significant spatially heterogeneous pattern. Salt lakes in arid regions frequently undergo aggravated salinization driven by agricultural irrigation and aridity, whereas high-altitude salt lakes, particularly on the TP, exhibit a desalination due to increased water volume and glacial melt associated with warming and wetting climate. These changes in salt lake water salinity dynamically reshape food web structures, regulate physical stratification and elemental cycling, and ultimately exert cascading impacts on soil salinization, drinking water safety, and infrastructure across watersheds. Future efforts should focus on integrating multi-source observations from next-generation satellites with hybrid models, to move beyond mere monitoring toward a predictive understanding of water salinity change, allowing us to quantitatively attribute its drivers and forecast its cascading impacts across interconnected socio-ecological systems, from the stability of aquatic food webs and soil health to the long-term resilience of regional water security and critical infrastructure.

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## 1. Introduction

Salt lakes represent a unique component of endorheic surface water systems globally (Wang et al., 2018). Although these lakes cover only 23% of the global lake area, they store up to 44% of the total lake water volume, making them a critical node in both the global hydrological balance and surface salt cycling processes (Messenger et al., 2016; Wurtsbaugh et al., 2017). As typical closed or semi-closed water bodies, salt lakes are characterized by high water salinity, an evaporation-driven hydrological balance, and a highly sensitive response to external water inputs (Messenger et al., 2016). These characteristics constitute distinct hydrological-ecological-geomorphological units in arid and semi-arid regions. In contrast to freshwater lakes, the core ecological and geochemical processes in salt lakes are primarily governed by water salinity. It not only determines the physical structure and ecological carrying capacity of salt lake systems (Hart et al., 2003) but also exerts strong control over microbial community composition (Deng et al., 2017; Yue et al., 2019), nutrient cycling patterns (Mo et al., 2022; Wurtsbaugh et al., 2019), and the formation of chemical sediments (Hammer, 1986; Hong et al., 2011).

As the “lifeline” of salt lake ecosystems, water salinity plays a critical role in sustaining the regional ecosystem health (Saccò et al., 2021; Williams, 2002). Specifically, the environmental impacts of water salinity variation are primarily manifested in three key aspects as follows: First, water salinity acts as an extreme environmental filter for species selection (Lin et al., 2017). On the one hand, as water salinity increases, zooplankton species richness declines significantly, and community composition diverges markedly from that of freshwater systems (Attayde and Bozelli, 1998; Brucet et al., 2009; Jeppesen et al., 1994). On the other hand, these water salinity-driven changes further restructure lake food webs. For instance, a typical three-tier trophic structure observed in freshwater to moderately salt lakes may collapse into a simplified two-tier system under high-salinity conditions (Lin et al., 2017). Secondly, water salinity is a major determinant of vertical

physicochemical stratification in lakes (Colomer et al., 2003). Strongly stratified salt lakes often develop anoxic or reducing conditions at the bottom, which favor the preservation of organic matter (Irwin et al., 1977; Liang et al., 2024). Additionally, water salinity affects elemental solubility and microbial metabolic pathways, thereby profoundly impacting the biogeochemical cycling of key nutrients (Ardón et al., 2013; Jiang et al., 2023). Such as, elevated water salinity has been shown to suppress denitrification while promoting dissimilatory nitrate reduction to ammonium (DNRA), enhancing nitrogen retention in lake systems (Laverman et al., 2007; Rysgaard et al., 1999). Thirdly, in hypersaline environments, water salinity gradients directly govern the precipitation sequence and spatiotemporal distribution of carbonate, sulfate, and chloride minerals (Li et al., 2020). These processes not only shape the sedimentary record of salt lakes but also control the formation and enrichment of strategic saline mineral resources such as lithium and potassium (Lowenstein and Risacher, 2009). Given the central role of water salinity in regulating ecological structure, hydrological processes, biogeochemical cycles, and mineral formation within salt lake systems, establishing efficient monitoring frameworks is essential for supporting sustainable lake management.

In recent years, satellite remote sensing has significantly advanced the monitoring of water salinity, overcoming the limitations of traditional in-situ sampling (Azarafza and Mokhtari, 2013; Pahlevan et al., 2021). High-resolution multispectral imagery from platforms such as the Landsat series and Sentinel-2 enables the detection of water reflectance characteristics, which are strongly correlated with co-varying colored dissolved organic matter (CDOM), thus allowing for indirect salinity estimation (Ansari and Akhoondzadeh, 2020; Bayati and Danesh-Yazdi, 2021; Deng et al., 2024a; Ferdous and Rahman, 2020). Furthermore, by integrating machine learning algorithms such as XGBoost (eXtreme Gradient Boosting) (Jiang et al., 2022; Xu et al., 2024), RF (Random Forest) (Yu et al., 2025), and AdaBoost (Adaptive Boosting) (Borovskaya et al., 2022; Jiang et al., 2024), along with deep learning models like convolutional neural networks (CNNs) (Feizizadeh et al., 2021),

researchers can develop robust retrieval models capable of accurately characterizing the spatiotemporal dynamics of water salinity. In particular, the high spatial resolution (10 m) and short revisit cycle (5 days) of the Sentinel-2 satellite, combined with unmanned aerial vehicle (UAV) platforms for refined local monitoring, provide unprecedented support for tracking salinity fluctuations (Deng et al., 2024b; Jiang et al., 2024; Zeng et al., 2023). The synergistic application of these remote sensing technologies and in-situ sensor networks is significantly enhancing our understanding of the spatiotemporal dynamics and evolutionary patterns of water salinity in salt lakes. For instance, the synergistic application of these technologies has successfully revealed the catastrophic salinization trajectories of the Aral Sea, primarily driven by anthropogenic activities (Ahrorov et al., 2012; Qadir et al., 2026). Furthermore, detailed reconstructions of evolutionary patterns and driving mechanisms have been achieved for representative salt lakes such as the Great Salt Lake (Kintisch, 2022; Mohammed and Tarboton, 2012b; Stephens, 1990), Lake Urmia (Alipour, 2006; Sima et al., 2021), and Lake Qarun (Abdelbaki, 2022), demonstrating the capability of modern remote sensing to characterize complex hydrological dynamics at the scale of individual basins.

However, a significant gap remains in translating these basin-level successes into a coherent global picture. While remote sensing has illuminated the evolutionary trajectories of prominent hotspots, current understanding remains geographically fragmented, lacking a systematic synthesis of these divergent salinity patterns observed worldwide. The sheer number of salt lakes and their vast distribution mean that traditional in-situ measurements are insufficient to capture this spatial heterogeneity. Even though the research field itself has developed rapidly (see the bibliometric analysis in the supplementary material that provides the development trends and keyword changes in this research field), some key knowledge gaps still exist. For example, under advanced observation techniques, how has the modern monitoring framework, centered around remote sensing, evolved in response? What are the global spatial patterns and dynamic trends of water salinity? Why do some salt lakes undergo salinization while others exhibit dilution? Furthermore, as the “lifeline” of lake systems, how do changes in water salinity trigger cascading effects that reshape ecological dynamics, ultimately influencing regional water security, agricultural productivity, and infrastructure stability?

To address these questions, this review focuses on the following aspects: (1) defining the theoretical foundations of salt lake water salinity, including its formation mechanisms and classification systems; (2) evaluating the evolution of monitoring methodologies from traditional sampling to modern remote sensing and machine learning approaches; (3) based the data of salt lake water salinity recorded in the literature, summarizing the global spatial distribution patterns of salt lakes; (4) analyzing the spatiotemporal dynamics and key drivers of water salinity variation, distinguishing between natural factors and anthropogenic influences; and (5) detailing the socio-environmental consequences of spatiotemporal water salinity dynamics. Building upon this foundation, the review aims to provide a theoretical basis and practical insights for the scientific management and ecological protection of salt lake regions.

**Table 1**  
The main chemical types of salt lakes.

Chemical type	Dominant anions	Major cations	Typical characteristics
Carbonate	$\text{CO}_3^{2-}$ , $\text{HCO}_3^-$	$\text{Na}^+$	High alkalinity, high pH (>9)
Sulfate	$\text{SO}_4^{2-}$	$\text{Na}^+$ , $\text{Ca}^{2+}$ , $\text{Mg}^{2+}$	Formation of gypsum or mirabilite, transitional brines
Chloride	$\text{Cl}^-$	$\text{Na}^+$ , $\text{Mg}^{2+}$ , $\text{K}^+$	Terminal evolutionary stage, saturation with halite

## 2. Definition and formation mechanisms of salt lakes

### 2.1. Definition of salt lakes

Water salinity refers to the total concentration of dissolved salts, serving as a critical parameter characterizing water chemistry (Wetzel, 2001; Williams, 1999). Water salinity is typically expressed as the mass of dissolved salts per unit volume or mass of water, commonly measured in grams per liter (g/L), parts per thousand (‰), or Practical Salinity Units (PSU) (Hammer, 1986). From a hydrochemical perspective, the ionic composition determining salinity primarily consists of major cations ( $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ , etc.) and anions ( $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{CO}_3^{2-}$ ,  $\text{HCO}_3^-$ , etc.) (Last and Ginn, 2005). Based on widely accepted limnological and geochemical frameworks (Hammer, 1986; Williams, 1999), salt lakes are generally classified into three major hydrochemical types (Table 1). Chloride-dominated lakes (high  $\text{Cl}^-$ ,  $\text{Na}^+$ /  $\text{Mg}^{2+}$ ) represent highly evolved systems; Sulfate-dominated lakes (high  $\text{SO}_4^{2-}$ ) reflect intermediate evolutionary stages; and Carbonate-dominated lakes (high  $\text{CO}_3^{2-}$ /  $\text{HCO}_3^-$ ) are characterized by high alkalinity (Eugster and Hardie, 1978). However, from an ecological standpoint, water salinity functions as a key factor determining the osmotic environment, directly influencing lake biodiversity and community structure (Velasco et al., 2019; Williams, 1998; Yang et al., 2016).

Currently, with the advancement of interdisciplinary research, water salinity is increasingly viewed as a dynamic variable connecting hydrology, ecology, and climate (Jeppesen et al., 2015b). Notably, water salinity of some large salt lakes exhibits significant spatiotemporal heterogeneity, potentially varying considerably across different seasons or periods within the same lake and diverse regions or landscapes (Castillo-Escrivà et al., 2016). This multi-scale variability necessitates consideration of dynamic characteristics when defining water salinity. Therefore, synthesizing current research progress, salt lake water salinity can be defined as: the total concentration of dissolved inorganic salts in lake water, resulting from the combined effects of watershed geochemical processes, climatic conditions, and human activities. It shapes the structure and function of salt lake ecosystems and exhibits complex spatiotemporal variability in the context of global environmental change (Herbert et al., 2015; Northey et al., 2017).

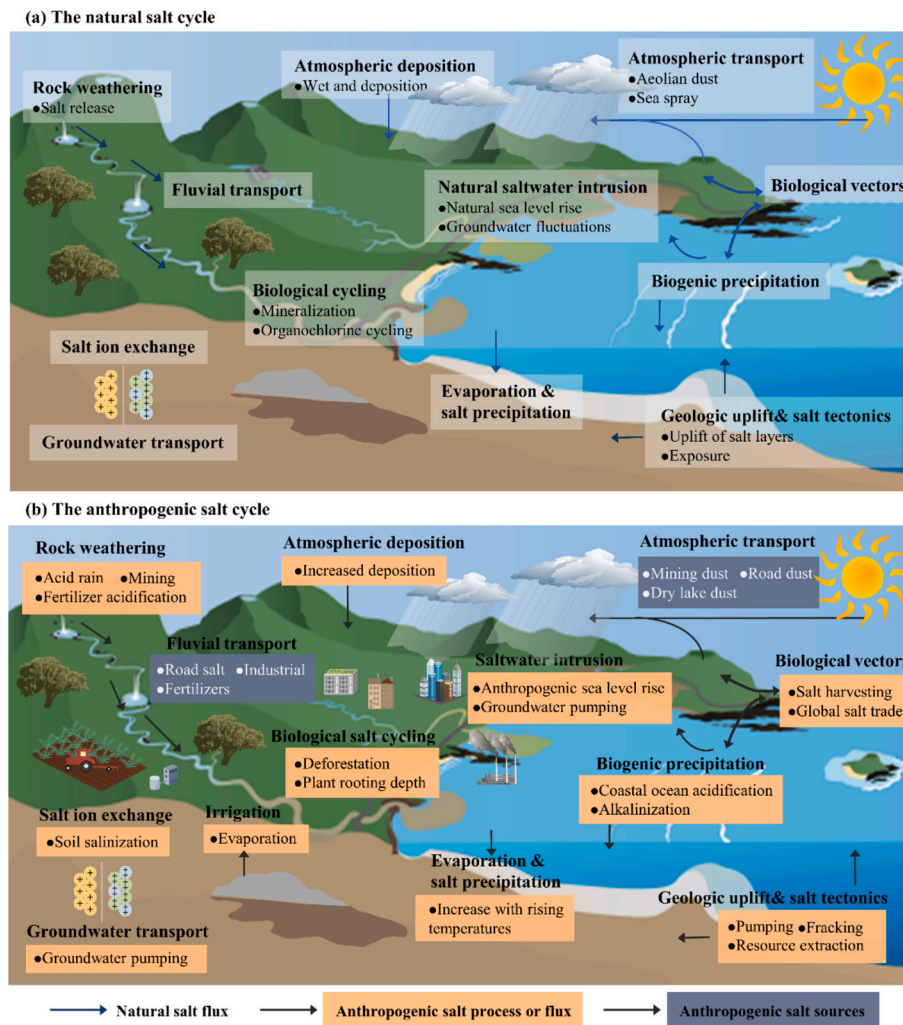
### 2.2. Formation mechanisms of salt lakes

Salt lake formation results from the combined effects of natural salt cycling and human activities, involving complex geological, geomorphological, hydrological, atmospheric, and ecological processes (Fig. 1).

#### 2.2.1. Natural salt cycling and salt lake formation

Under natural conditions, salt lake water salinity is primarily controlled by rock weathering, atmospheric deposition, and evaporation processes (Fig. 1a). Soluble ions released through rock weathering constitute the initial source of lake water salinity, with lakes in different geological settings exhibiting distinct ionic composition signatures (Meybeck, 2003). Furthermore, dust, sea spray, and aerosols transport salts via atmospheric circulation, delivering them to lake surfaces or their watersheds through wet and dry deposition processes (Lovett et al., 2000). Watershed hydrological processes (surface runoff and groundwater recharge) serve as critical pathways connecting salt sources to lakes. Additionally, biological processes also play an important role in lake water salinity formation, as processes such as plant uptake (Chen et al., 2019a; Fritioff et al., 2005), decomposition (Verschuren et al., 2000), and mineralization can regulate the cycling of specific ions (Herbert et al., 2015).

Within lakes, evaporative concentration functions as the direct driver of water salinity increase, particularly prominent in endorheic lakes (Cohen, 2003). Empirical studies have shown that in closed-basin lakes, reductions in lake volume associated with high evaporation-to-precipitation ratios can lead to multi-fold increases in salinity



**Fig. 1.** Schematic diagram of the water salinity cycling mechanism of salt lakes (modified from (Kaushal et al., 2023)). (a) Schematic diagram of the natural salt cycle. (b) A schematic diagram of the salt cycle under human activities. Anthropogenic salt sources exceed natural salt sinks. A wide range of geological, chemical, biological, engineering, and hydrological processes have contributed to the alteration of the global salt cycle by humans.

(Langbein, 1961; Williams, 2002). Correlational research discovered that seasonal freeze-thaw cycles can enhance salt enrichment effects, constituting an important mechanism for water salinity increase in high-elevation lakes (Levy et al., 2011; Nakagawa et al., 2010; Shi et al., 2024). Additionally, natural saline water intrusion and geological tectonic activities can significantly influence lake water salinity at local scales (Stackelberg, 2017).

**2.2.2. Salt cycling and water salinity changes under human influence**

In recent years, human activities and climate change have emerged as the dominant drivers of water salinity changes (Fig. 1b). For instance, anthropogenic sources contribute approximately 13.9% of total dissolved solids (TDS) in U.S. streams from road deicing alone, with agricultural activities adding another 6.7% (Kaushal et al., 2023). In the midwestern and northeastern United States, 44% of lakes exhibit long-term salinization trends, and even just 1% impervious surface coverage around a lake significantly increases its salinization risk, primarily due to the use of road deicing salt (Dugan et al., 2017).

Land use change represents one of the key pathways influencing water salinity. Deforestation and alterations in vegetation root structures significantly disturb watershed biological salt cycling and hydrological processes, thereby increasing salt transport to lakes (Cañedo-Argüelles et al., 2019; Kaushal et al., 2023). Agricultural activities, particularly irrigation, intensify soil salt accumulation through capillary

rise and evaporation(Williams, 2001). Globally, approximately 1 billion hectares of soil are impacted by anthropogenic salinization, largely due to irrigation and fertilizer use (Kaushal et al., 2023). Irrigation return flows can increase groundwater TDS by 3–17 mg/L/yr, directly contributing to lake salinity (Yakirevich et al., 2013). Additionally, urbanization processes exacerbate salinity through multiple pathways: road de-icing salt contributes an average of 7.2–23.2kg/ha/year (Kaushal et al., 2023), household wastewater adds approximately 90,629 mg of Na<sup>+</sup> and 38,768 mg of Cl<sup>-</sup> per person per week to water systems (Tjandraatmadja et al., 2009). Industrial activities, coal and biomass burning, and traffic emissions can also increase mineral dust containing salt ions into the lake system (for example, concentrations within urban dust are 2.4% Ca<sup>2+</sup>, 1.5% K<sup>+</sup>, 1.2% Na<sup>+</sup>, and 0.9% Mg<sup>2+</sup>) (Kakavas and Pandis, 2021).

With the global expansion of human activities, the impact range of salt lake water salinity changes extends beyond areas directly affected by human activities, with even remote lakes facing indirect influences. For example, precipitation pattern alterations and enhanced evaporation due to climate change, along with pollutant deposition from atmospheric transport, can significantly affect salt lake salinity (Dugan et al., 2017).

**2.2.3. Major influencing factors of water salinity of salt lakes**

Lake formation type constitutes a critical factor determining water

(a) Venice system classification (Por, 1972)						Unit: g/L
Freshwater	Oligosaline	Mesosaline	Polysaline	Hypersaline	Brine	
0	0.5	3	18	30	40	
(b) General classification based on salinity values (Hammer, 1986)						
Freshwater	Oligosaline	Polysaline			Hypersaline	
0	0.5	3				30
(c) Ecological dimension classification (Williams, 1998)						
Freshwater ecosystem < 3 g/L High biodiversity, freshwater species		Transitional ecosystem 3 - 20 g/L Salt-tolerant species, specialized taxa		Halophilic ecosystem > 20 g/L Halophilic microorganisms, highly specialized ecosystems		
0		3		20		
(d) Geochemical dimension classification (Eugster and Hardie, 1978)						
Carbonate-type lakes < 10 g/L HCO <sub>3</sub> <sup>-</sup> , Ca <sup>2+</sup> dominance			Sulfate-type lakes 10 - 100 g/L SO <sub>4</sub> <sup>2-</sup> , Na <sup>+</sup> dominance		Chloride-type lakes > 100 g/L Cl <sup>-</sup> , Na <sup>+</sup> dominance	
0			10		100	
(e) Tibetan Plateau water salinity classification based on Records of China's Salt Lakes (Zheng, 2002)						
Freshwater	Oligosaline			Polysaline	Hypersaline	
0	1			35	50	
(f) The classification of water salinity in this review						
Freshwater	Oligosaline	Mesosaline	Polysaline	Hypersaline		
0	1	3	20	50		

**Fig. 2.** Classification standards of salt lake water salinity from different perspectives. (a) Venice system classification. (b) General classification based on salinity values. (c) Ecological dimension classification. (d) Geochemical dimension classification. (e) Tibetan Plateau water salinity classification based on Records of China's Salt Lakes. (f) The classification of water salinity in this review.

salinity pattern and variation characteristics. Endorheic lakes, due to their lack of outflow channels, have water salinity primarily controlled by the dynamic equilibrium between salt inputs and evaporative concentration, rendering them highly sensitive to environmental disturbances (Langbein, 1961; Sheng, 2014). In contrast, exorheic lakes maintain relatively stable and lower water salinity levels through salt removal via outflow discharge (Hammer, 1986). Hydrological connectivity between lakes and surrounding water bodies is considered one of the core factors regulating water salinity variations (Li et al., 2019; Liu and Bao, 2020). A “hydrological connectivity-salinity response” model suggests that stronger connectivity enhances a lake system's capacity to maintain water salinity stability through water exchange (Wurtsbaugh et al., 2017). Furthermore, climatic zone differences profoundly influence water salinity formation processes (Schmitt, 2008). In arid and semi-arid regions, the ratio of evaporation to precipitation has been demonstrated to be the primary predictor of salt lake water salinity changes, whereas in humid climates, geological background and human activity intensity emerge as more critical controlling factors (Wurtsbaugh, 2014). Therefore, understanding the interactions among lake types, climatic conditions, and hydrological connectivity provides an essential foundation for accurately assessing salt lake water salinity dynamics. Additionally, salt lake water salinity changes represent a complex outcome of natural processes and human activities acting in concert, exhibiting significant typological differences and spatiotemporal heterogeneity. Future research should strengthen quantitative analysis of contributions from different salt sources and deepen investigation into synergistic mechanisms between climate change and human activities. Through integration of multi-source monitoring data and development of high-precision simulation models, a more accurate understanding and prediction of global lake salinization processes may be achieved.

### 2.3. Classification standards for salt lakes in water salinity

Water salinity represents an important parameter for classifying lake

types (Carroll and Bohacs, 1999), with different classification standards reflecting the multidimensional characteristics of salt lakes and their critical role in ecosystems (Liang et al., 2024). Synthesizing existing research, salt lake classification systems can be constructed from three interrelated dimensions, as shown in Fig. 2, including the numerical water salinity ranges, ecological-biological significance, and geochemical characteristics.

Classification based on total water salinity values constitutes the most intuitive and widely applied method. Analysis of historical classification system evolution reveals that despite differences in classification standards across different periods, key boundary points maintain certain consistency. The Venice System initially established a systematic water salinity classification framework for estuaries and coastal waters, categorizing water bodies into freshwater (<0.5 g/L), oligosaline (0.5–5 g/L), mesosaline (5–18 g/L), polysaline (18–30 g/L), hypersaline (30–40 g/L), and brine (>40 g/L) (Por, 1972). Subsequently, another classification based on total salinity values divided lakes into freshwater (<0.5 g/L), oligosaline (0.5–3 g/L), polysaline (3–30 g/L), and hypersaline (>30 g/L), a classification system widely adopted in salt lake research (Hammer, 1986). From an ecological perspective, salt lake water salinity classification primarily relies on biological community tolerance and adaptation strategies to salinity. The biologically significant classification criteria established by Williams (1998) identified 3 g/L and 20 g/L as two critical ecological thresholds: sensitive freshwater organisms begin to disappear when water salinity exceeds 3 g/L, while 20 g/L marks the point at which extreme halophilic microorganisms begin to dominate the ecosystem. Hydrogeological classification focuses on the impact of salinity on lake geochemical processes. Based on hydrochemical evolution pathways, lakes are categorized into carbonate-type (<10 g/L), sulfate-type (10–100 g/L), and chloride-type (>100 g/L) lakes (Eugster and Hardie, 1978). This classification reflects the geochemical processes of lake water salinity evolution: bicarbonate and calcium ions dominate the low-salinity stage; with increased evaporative concentration, sulfate and sodium ions gradually predominate; ultimately evolving into high-salinity systems dominated by chloride

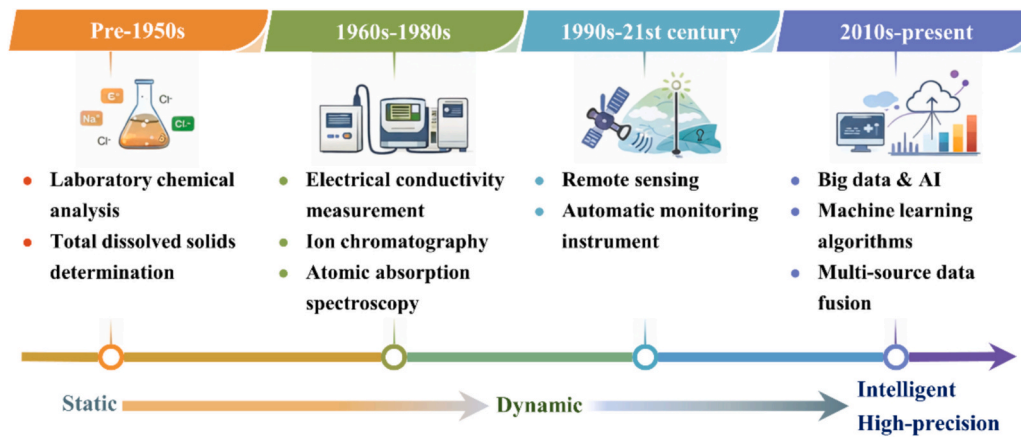


Fig. 3. The evolution timeline of water salinity monitoring technology.

and sodium ions. In addition, Zheng et al. (2002) proposed a water salinity classification system tailored to China's salt lakes in the Records of China's Salt Lakes. This scheme incorporates both the spatial distribution of China's salt lakes and the characteristics of mineral deposition, and categorizes lakes into freshwater (<1 g/L), oligosaline (1–35 g/L), polysaline (35–50 g/L), and hypersaline (>50 g/L) types. Compared to other classification schemes, this system is particularly well-suited for studying lakes on the TP and in arid regions of China, as it better captures the water salinity evolution processes observed in these unique hydro-environmental settings.

Overall, salt lake water salinity classification represents a multidimensional integrated system, reflecting the complexity of lake water salinity and its significance across different disciplinary fields. Therefore, this study adopts a five-level classification system integrating multidisciplinary perspectives: freshwater lakes (<1 g/L), oligosaline lakes (1–3 g/L), mesosaline lakes (3–20 g/L), polysaline lakes (20–50 g/L), and hypersaline lakes (>50 g/L). This classification considers both the continuity of traditional classification systems and reflects threshold effects of salinity on ecosystems, applicable to global-scale lake water salinity research and management.

### 3. Monitoring water salinity of salt lakes

#### 3.1. Overview of monitoring methods of water salinity

The evolution of water salinity monitoring technology exhibits distinct developmental phases, reflecting a systematic transformation from static point sampling to dynamic regional sensing (Ahmed et al., 2020; Deng et al., 2024b). This evolution not only demonstrates the iterative upgrading of measurement techniques but also reflects the deepening research focus from merely measuring water salinity values toward revealing spatiotemporal distribution patterns, hydrological-ecosystem response mechanisms, and lake salinization risk assessment.

As shown in Fig. 3, the first phase (pre-mid-20th century) primarily utilized laboratory chemical analysis, characterizing water salinity

through TDS determination (Hammer, 1986; Langbein, 1961). The second phase (1960s–1980s) was marked by the application of electrical conductivity meters and ion chromatography (IC), which significantly enhanced monitoring efficiency and ionic composition analysis (Drever, 1988; Hem, 1985). The third phase (1990s to early 21st century) featured the emergence of remote sensing and automated monitoring technologies, greatly expanding the spatiotemporal scale of monitoring (Azarafza and Mokhtari, 2013; Wang and Xu, 2008; Williams, 1998). The fourth phase (2010s to present) is characterized by the integration of big data and artificial intelligence technologies. Multi-source data fusion and machine learning algorithms have substantially improved the precision and real-time capability of salinity monitoring (Jiang et al., 2022; Liu et al., 2023; Wang et al., 2020). Currently, water salinity monitoring for salt lakes has formed a comprehensive technical system covering point-area-volume dimensions and integrating field measurement, remote sensing, and simulation approaches. The monitoring methodology has achieved a transition from single parameter determination to multidimensional comprehensive characterization (Chen et al., 2022b; Wagle and Acharya, 2020).

#### 3.2. Traditional methods of water salinity monitoring

Traditional water salinity monitoring methods primarily comprise laboratory analysis and field measurement approaches for salt lakes, constitute the essential foundation for salt lake water salinity research, and provide critical calibration data for remote sensing models (Wetzel, 2001).

##### 3.2.1. Laboratory analysis of water salinity

Laboratory analysis methods represent some of the highest precision techniques in water salinity monitoring, primarily employed for calibrating field measurement data or conducting long-term monitoring (Andrulionis and Zavialov, 2019). As shown in Table 2, common methods include chemical titration, which is highly cost-effective for determining chloride ion concentrations but susceptible to interference

Table 2  
Comparison of water salinity monitoring methods in different laboratories.

Method	Principle	Advantages	Limitations	Typical Application Scenarios
Chemical titration	Determines the chloride ion (Cl <sup>-</sup> ) concentration and convert to calculate the total salinity	Simple, low-cost	Potential interference from other ions (e.g., SO <sub>4</sub> <sup>2-</sup> , CO <sub>3</sub> <sup>2-</sup> )	Suitable for basic water salinity assessment in low salinity salt lakes
IC	Separates and quantifies major cations (Na <sup>+</sup> , K <sup>+</sup> , Ca <sup>2+</sup> , Mg <sup>2+</sup> ) and anions (Cl <sup>-</sup> , SO <sub>4</sub> <sup>2-</sup> ) using ion-exchange columns	High sensitivity and precision; capable of multi-ion detection	High instrument cost, long analysis time, and dependence on laboratory environment	Detailed ionic composition analysis and long-term salinity monitoring in research settings
TDS	Measures total solids remaining after sample evaporation and drying at 105 °C	Simple, fast, requires minimal equipment; effective for overall water quality assessment	Lower precision; susceptible to organic matter, suspended particles, and gases; cannot resolve ionic composition	Rapid assessment of lake water salinity or complementary use in field-lab calibration studies

from other ions (Logan, 2010); and Ion Chromatography (IC), which enables precise separation and quantitative analysis of major cations and anions (Godts et al., 2026). Although IC offers high sensitivity, its application in rapid field monitoring is limited by high costs and equipment requirements. Additionally, TDS determination provides a direct estimation of total dissolved solids through evaporation, though it may be affected by organic matter and suspended particles (Williams and Sherwood, 1994).

### 3.2.2. In-situ measurement of water salinity

In-situ measurement represents the most direct and precise method for salt lake water salinity monitoring, typically employed for high-precision measurements at short time scales and providing calibration data for other monitoring approaches. Currently, common field measurement methods primarily include portable salinity meters, multi-parameter water quality sensors, and profile measurement technologies, with portable salinity meters being the most frequently utilized field monitoring tools. Based on the principle that water's electrical conductivity correlates positively with ionic concentration, water salinity is calculated under 25 °C conditions through the formula (1):

$$TDS(mg/L) = k \times EC(\mu S/cm) \tag{1}$$

where  $k$  represents the conversion coefficient, typically ranging between 0.55 and 0.70 depending on water body characteristics (Hem, 1985), with a value of  $0.64 \pm 0.03$  for typical lake waters. This method features rapid and convenient operation, suitable for water measurements at various depths and regions (Obolewski et al., 2018). However, since water temperature and dissolved mineral types influence the conversion relationship between electrical conductivity and water salinity, this method requires calibration in conjunction with laboratory analysis (Last, 2002). Beyond portable salinity meters, multi-parameter water quality sensors are also widely applied in lake water salinity monitoring. These devices can simultaneously measure multiple water quality parameters, including electrical conductivity, temperature, dissolved oxygen (DO), pH, turbidity, and water salinity (Sarda and Sadgir, 2015; Xu et al., 2024). Compared to portable salinity meters, multi-parameter sensors offer the advantage of continuous automatic monitoring at fixed stations, although they incur higher equipment costs and require regular maintenance to ensure data accuracy (Bhagowati and Ahamad, 2019).

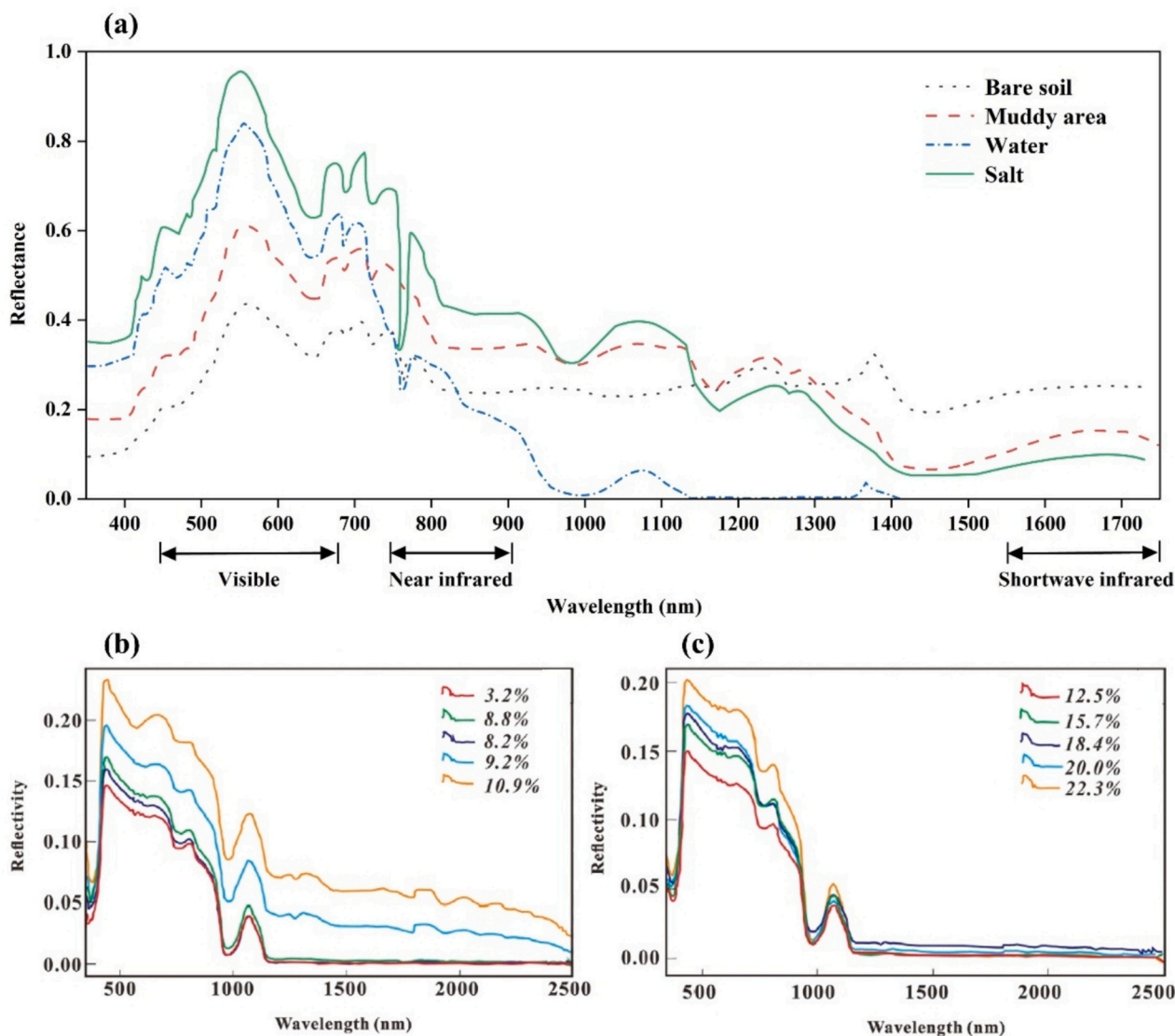


Fig. 4. The reflectivity between the water body of a salt lake and the surrounding ground objects, as well as the reflectivity of the water body under different salinities. (a) It is the spectral reflectance between the water body of a salt lake and the surrounding ground objects. (b) and (c) represent the spectral reflectance under different water salinity.

For deep lakes, researchers typically utilize CTD (Conductivity-Temperature-Depth) sensors for profile measurements (Jeppesen et al., 2015a). CTD sensors can measure water salinity, temperature, and pressure at different water depths, thereby revealing vertical stratification characteristics of lake water bodies (Oren, 2011). This approach has provided essential data support for research on lake hydrodynamic processes and water salinity variations (Castañeda and Herrero, 2005).

### 3.3. Remote sensing methods of water salinity monitoring

Remote sensing technology has established new pathways for lake water salinity monitoring, overcoming the spatial and temporal limitations of traditional methods (Chen and Hu, 2017; Deng et al., 2024b).

The theoretical foundation for remote sensing monitoring of lake water salinity is based on the significant differences in reflection, absorption, and scattering characteristics of electromagnetic waves by water bodies with varying salinity levels (Shutko, 2003). The mechanism behind this relationship is primarily indirect; it is not the dissolved salt ions themselves that significantly alter the water's reflectance, but rather their influence on the concentration, composition, and physical state of other optically active components within the water. For example, high water salinity (high ionic strength) neutralizes the negative charges on the surface of fine suspended sediment particles in water, causing them to flocculate into larger particles (Hunter and Liss, 1982). These large particles have a stronger backscattering ability than the original small particles, thereby enhancing the overall reflectivity of the water body.

Field spectral reflectance tests have revealed that salt lake water bodies exhibit markedly higher reflectance in the visible light region (400–700 nm) compared to ordinary water bodies, with distinguishable spectral curve morphologies from surrounding bare soil and muddy areas (Ormeçi and Ekerçin, 2007), as illustrated in Fig. 4a. As water salinity increases, reflectance in visible light and near-infrared regions (400–1000 nm) demonstrates systematic enhancement, with changes most significant in the 500–650 nm and 750–850 nm bands (Shu-fang et al., 2005), as shown in Fig. 4b and c. This quantitative relationship between water salinity and spectral characteristics constitutes the physical basis for remote sensing monitoring, guiding subsequent band selection and algorithm development. Furthermore, it is noteworthy that although salinity-sensitive bands are primarily concentrated in visible light and near-infrared regions, with relatively minor differences in the shortwave infrared region, integrated utilization of multi-band information can significantly improve inversion accuracy (Sagan et al., 2020).

Currently, remote sensing approaches for lake water salinity inversion primarily comprise four methodologies: 1) Indirect inversion based on CDOM. This method leverages the correlation between salinity and CDOM. CDOM primarily originates from terrestrial inputs and biological activities within water bodies, often demonstrating negative correlations with salinity in freshwater-marine transition zones (Ahn et al., 2008; Bai et al., 2013; Liu et al., 2021b; Song et al., 2019), establishing a theoretical foundation for indirect water salinity estimation. However, errors introduced during field data collection and model calibration significantly impact results, resulting in considerable uncertainty for this methodology. Additionally, the relationship between water surface reflectance and CDOM absorption coefficients is only valid when water salinity ranges between 5 g/L and 35 g/L (Bowers and Brett, 2008; Keith et al., 2016; Xu et al., 2024). Consequently, this approach is limited to estuarine and coastal regions with relatively low water salinity.

2) Empirical statistical modeling. This approach was developed in relatively earlier stages and has been applied in multiple typical lakes and estuarine regions (Geiger et al., 2013; Wang and Xu, 2008; Wang and Xu, 2012). Compared to indirect CDOM inversion methods, this approach is more direct; however, spectral characteristics vary across different lake waters, potentially restricting model applicability to specific regions.

3) Machine Learning (ML) algorithms. Algorithms such as XGBoost, RF, and Support Vector Machines (SVM), to establish non-linear mapping relationships between water salinity and multi-band reflectance (Aydin and Sefercik, 2025; Borovskaya et al., 2022; Jalilzadeh and Behzadi, 2019; Smith et al., 2024). The advantage of machine learning methods lies in their exceptional fitting capabilities for non-linear relationships, adaptability to different water body types and environmental conditions, and strong generalization capabilities, overcoming limitations in regional adaptability inherent in traditional empirical statistical models. For example, researchers have applied these machine learning methods for long-term temporal series monitoring of several important salt lakes globally, including Lake Urmia in Iran (Feizizadeh et al., 2021; Raheli et al., 2024) and Qarhan Salt Lake on the TP (Yu et al., 2025), revealing response characteristics of salinity variations to regional climate and human activities. However, machine learning method performance highly depends on training data quality and representativeness, potentially facing challenges in extreme environmental conditions or data-sparse regions.

4) Deep Learning (DL) architectures: Deep neural networks, including CNNs for spatial feature extraction and RNNs (Recurrent Neural Networks)/ (Long Short Term Memory) LSTMs for temporal dynamics (Geiger et al., 2013). Deep learning models overcome the processing difficulties of traditional methods regarding complex interactions among water components through automatic, highly dimensional feature extraction, achieving “end-to-end” salinity inversion (Sagan et al., 2020). CNNs demonstrate excellence in spatial feature extraction, suitable for high-resolution satellite image salinity inversion, while RNNs and LSTMs excel in capturing temporal variation patterns of water salinity (Miller et al., 2024; Mzid et al., 2023; Wai et al., 2022). Although deep learning methods possess powerful expressive capabilities, their “black box” characteristics and computational resource requirements remain challenges requiring resolution in practical applications.

Despite continuous advancements in remote sensing technologies for monitoring water salinity, several critical challenges persist: atmospheric correction significantly impacts inversion accuracy, particularly for salinity-sensitive bands in the visible light spectrum; spectral-salinity relationships vary across different lake types, necessitating calibration specific to each region; and the scarcity of validation data constrains methodological development and accuracy assessment (Ma et al., 2022). Future research should prioritize addressing these key issues, promoting deeper integration of hyperspectral remote sensing with machine learning technologies, and constructing more comprehensive salt lake water salinity monitoring systems. With sensor performance improvements and algorithm optimization, remote sensing monitoring will transition from passive observation to active early warning systems, providing more robust scientific foundations for lake salinization prevention and control.

### 3.4. Future technology development in monitoring water salinity

With continuous scientific and technological advancement, technologies of monitoring water salinity for salt lakes are rapidly evolving toward diversification, intelligence, and integration. Traditional singular monitoring approaches have been progressively replaced by comprehensive monitoring systems, providing robust technical support for precise water environment management. In water salinity and environmental change monitoring, environmental DNA analysis techniques have achieved indirect assessment of water salinity variations through microbial community structure analysis (Yang et al., 2017). In spatial monitoring domains, underwater robotics and unmanned aerial vehicle technologies have addressed limitations of traditional monitoring methods regarding spatial resolution and vertical profiling (Christensen et al., 2022; Vélez-Nicolás et al., 2021; Wang et al., 2024). Advanced underwater unmanned systems can collect three-dimensional data from lake water bodies, acquiring information difficult to obtain

through conventional methods (Mendoza-Chok et al., 2022). In the future, salt lake water salinity monitoring will be founded on the intelligent integration of multiple heterogeneous data sources, combined with knowledge-driven interpretable models.

Specifically, future research should prioritize the development of hybrid salinity inversion and prediction models, which synergize the strengths of process-based physical modeling with the pattern-recognition capabilities of data-driven approaches. Such models are essential for overcoming the regional limitations of traditional approaches and for more accurately quantifying the distinct contributions of various salt sources under evolving climate and human pressures. Crucially, the next generation of satellite missions is poised to revolutionize the data available for these advanced models. For instance, the recently launched SWOT (Surface Water and Ocean Topography) mission can provide unprecedented time-series data on lake surface elevation and area, enabling highly accurate calculations of water volume change, which comprises a critical variable for modeling dilution and concentration processes. Hyperspectral missions like PACE (Plankton, Aerosol, Cloud, Ocean Ecosystem) will allow for more sophisticated optical water-type classifications, helping to disentangle the spectral signature of salinity from other confounding constituents like suspended sediments and dissolved organic matter. Furthermore, upcoming L-band SAR missions such as NISAR will offer an all-weather capability to monitor surrounding land use changes, irrigation extent, and the expansion of salt crusts, providing direct inputs on anthropogenic drivers. Integrating these next-generation observations into a unified modeling framework will ultimately enable a more holistic understanding and a true predictive capability for the future trajectory of these critical, yet vulnerable, ecosystems.

#### 4. The global distribution pattern of salt lakes

The spatial distribution of salt lakes is influenced by multiple factors, including climate, geology, hydrology, and anthropogenic activities, and exhibits marked regional variability at the global scale (Jones et al., 2009). Globally, salt lake water salinity is primarily governed by latitude, climatic zones, topography, and watershed hydrological characteristics. Freshwater lakes dominate in temperate and cold regions, whereas saline and hypersaline lakes are more prevalent in arid and

semi-arid zones (Lowenstein et al., 2017). Hydrologically, this distribution is fundamentally anchored in endorheic basin characteristics. In these closed or semi-closed systems, the lack of outflow channels means that water loss occurs primarily through evaporation. When evaporation exceeds precipitation and inflow, salts continuously accumulate, determining the natural geographical pattern of salt lakes. Currently, the global distribution of salt lakes is concentrated within two major salt lake belts (the Northern Hemisphere Salt Lake Belt, I and the Southern Hemisphere Salt Lake Belt, II) and two additional concentrated lake zones (African Rift Valley lake zones, III and the Southern Victoria Land lake zones in Antarctica, IV) (Eugster and Hardie, 1978; Mianping et al., 2016). As illustrated in Fig. 5, these belts largely coincide with the global distribution of arid and semi-arid climate regions.

The Northern Hemisphere Salt Lake Belt ( $20^{\circ}$ – $50^{\circ}$ N) hosts the world's largest salt lake, the Caspian Sea, which has a vast area of  $377,001 \text{ km}^2$  but a relatively low water salinity of  $12.32 \text{ g/L}$  (Table 3). This belt extends from North America to Central Asia and contains several notable lake clusters. For example, the Great Basin in North America features the Great Salt Lake ( $6478.85 \text{ km}^2$ ) with a water salinity from  $140.00 \text{ g/L}$  to  $300.00 \text{ g/L}$ . Further east, the Iranian Plateau is home to Lake Urmia, which has an area of  $4932.76 \text{ km}^2$  with water salinity levels recorded at  $286.05 \text{ g/L}$ . A particularly important region within this belt is the TP, which hosts the highest density of saline lakes globally. As shown in the inset of Fig. 5, the TP exhibits extreme spatial heterogeneity in salinity, with lakes ranging from slightly saline to hypersaline, reflecting the region's complex terrain and diverse stages of hydrological evolution. This includes large lakes like Qinghai Lake ( $4266.55 \text{ km}^2$ ), which maintains a lower water salinity of  $12.91 \text{ g/L}$ . The Southern Hemisphere Salt Lake Belt ( $15^{\circ}$ – $35^{\circ}$ S) features salt lakes primarily distributed across the Andean Altiplano, southern Africa, and inland Australia. This belt contains some of the world's largest and most saline systems (Deocampo and Jones, 2014). For instance, Australia's Eyre Lake ( $8026.70 \text{ km}^2$ ) is a classic example of a large, hypersaline lake with a water salinity from  $5.00 \text{ g/L}$  to  $322.00 \text{ g/L}$ , making it a global hotspot for saline lake research. The Andean Altiplano is home to the Salar de Uyuni in Bolivia, the world's largest salt flat, covering an immense area of  $10,582.00 \text{ km}^2$ , with water salinity levels recorded between  $291.00$  and  $356.00$  (Table 3).

In addition to the two climate-driven salt lake belts, two more

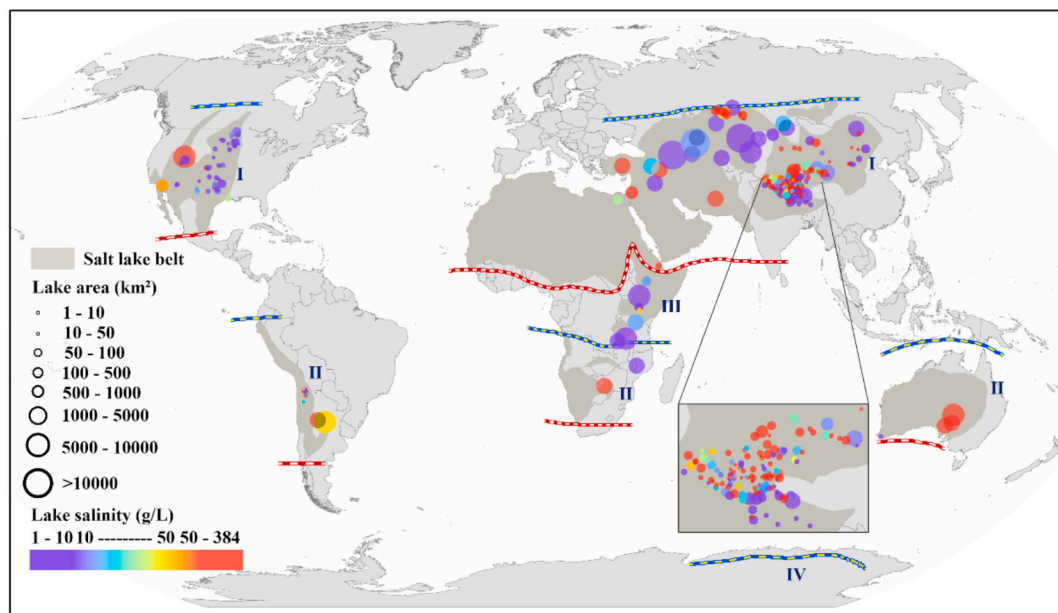
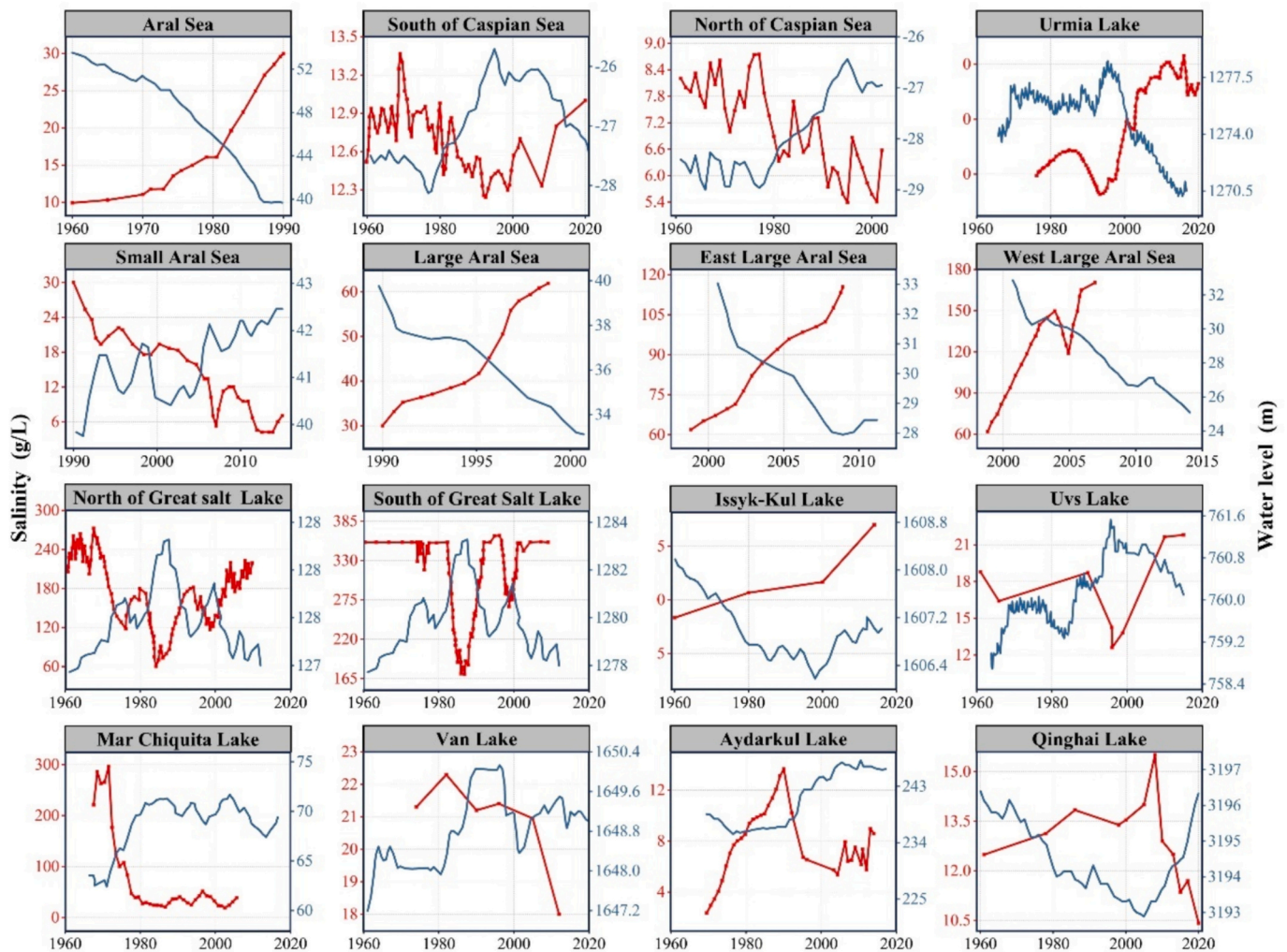


Fig. 5. Based on literature records and in-situ on-site measurements, the spatial distribution of water salinity in 292 ( $>1 \text{ km}^2$ ) terminal salt lakes in the global endorheic drainage area was collected. Region I represents the Northern Hemisphere Saline Lake Belt ( $20^{\circ}$ – $50^{\circ}$ N); Region II represents the Southern Hemisphere Saline Lake Belt ( $15^{\circ}$ – $35^{\circ}$ S); Region III denotes the African Rift Valley lake zones; and Region IV indicates the Southern Victoria Land lake zones in Antarctica.

**Table 3**

Information on salt lakes (> 1000 km<sup>2</sup>) in the global endorheic area. The area is from the attribute data provided in the HydroLAKES dataset (<https://www.hydrosheds.org/products/hydrolakes>). Hydrochemical type refers to the article by Liang et al. (2024).

Lake name	Salinity (g/L)	Monitoring year	Hydrochemical type	Area (km <sup>2</sup> )	Country	References
Caspian Sea	12.32	2008	Sulfate-chloride	377,001.91	Russia	(Jamshidi and Abu Bakar, 2012; Pervov et al., 2003)
Large Aral Sea	>100.00 (West basin large) >150.00 (East basin large)	2013	Carbonate	23,865.91	Uzbekistan	(Andrulionis et al., 2021; Oren et al., 2010)
Balkhash Lake	1.20–3.90	2007	Sulfate-chloride	16,717.89	Kazakhstan	(Sala et al., 2020; Spitsyna and Spitsyna, 2007)
Salar de Uyuni	291.00–356.00	2014	Chloride	10,582.00	Bolivia	(Haferburg et al., 2017; Risacher and Fritz, 1991)
Eyre Lake	5.00–322.00	2006–2007	Carbonate	8026.70	Australia	(Jankowski and Jacobson, 1989; Tweed et al., 2011)
Turkana Lake	2.33	2017	Carbonate	7473.43	Kenya	(Abiy et al., 2024; Liang et al., 2024)
Great Salt Lake	270.00–300.00 (North arm) 140.00–150.00 (South arm)	1960–2010	Chloride	6478.85	U.S.	(Mohammed and Tarboton, 2012a)
Issyk Kul Lake	5.75	2017	Sulfate	6195.93	Kyrgyzstan	(Andrulionis et al., 2023)
Chaka Salt Lake	344.00	2004	Chloride	5856.00	China	(Jiang et al., 2007; Xingqi et al., 2008)
Urmia Lake	286.05	1976–2020	Sulfate-chloride	4932.76	Iran	(Karbassi et al., 2010)
Qinghai Lake	12.91	1961–2020	Chloride	4266.55	China	(Chen et al., 2019b)
Uvs Lake	18.78	2015	Chloride	3600.81	Mongolia	(Shvartsev et al., 2014)
Van Lake	18.00	2012	Carbonate	3568.73	Turkey	(Poyraz and Mutlu, 2020)
Torrens Lake	13.00–249.00	1998	Chloride	3539.20	Australia	(Degens et al., 2012; Timms, 2020)
Alakol Lake	9.00	/	Carbonate	2919.34	Kazakhstan	(Ryanzhin et al., 2015)
Hulun Lake	1.32	1962–2017	Carbonate	2121.43	China	(Gao et al., 2017)
Chany Lake	0.80–6.40	2001	Chloride	1966.57	Russia	(Kipriyanova et al., 2007)
Nam Co	1.26	2010–2011	Chloride	1963.82	China	(Wu et al., 2014)
Tengiz Lake	40.60–54.90	2005	Sulfate	1422.85	Kazakhstan	(Liu et al., 2019)
Khyrgas Lake	7.04	2010	Sulfate-chloride	1383.23	Mongolia	(Shvartsev et al., 2014)



**Fig. 6.** The sequence of water level (blue) and water salinity (red) changes of typical salt lakes in the global endorheic area from 1960 to 2020. The water level data is from the DAHITI dataset (<https://dahiti.dgfi.tum.de/en/products/water-level-altimetry/>). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

geographically distinct saline lake zones exist due to unique geological and environmental conditions. The first is the East African Rift Valley lake system, including lakes in Uganda, Kenya, and Tanzania. Although situated near the equator, this region's lakes are shaped by strong tectonic activity, volcanism, and extreme microclimates (Cooke and Warren, 2023; Smoot and Lowenstein, 1991). This is exemplified by Lake Turkana in Kenya, a large (7473.43 km<sup>2</sup>) carbonate-type lake with a relatively low water salinity of 2.33 g/L, likely influenced by volcanic inputs and a balanced hydrological budget. Despite their number, most lakes here have relatively low water salinity, likely due to unique ionic contributions (e.g., bicarbonate enrichment) from volcanic inputs and relatively balanced hydrological budgets. The second distinct zone lies in Southern Victoria Land in Antarctica, between 71°–73°S, including areas such as the Bunger Hills and Vestfold Hills. Lakes in these polar environments exhibit hypersalinity, extreme cold, and high isolation, making them valuable for research on extremophile life and analogs of extraterrestrial environments (Gibson, 1999). These high-water salinity polar systems represent the fringe limits of ecological tolerance and offer critical insights for astrobiology and global biogeochemistry.

While natural factors dictate the baseline distribution, anthropogenic activities are increasingly reshaping the modern distribution pattern of salt lakes. Large-scale water diversions for agriculture and urbanization directly disrupt the water-salt balance, accelerating lake shrinkage and salinization in semi-arid regions (Foroumandi et al., 2022; Wurtsbaugh et al., 2017). This intervention not only accelerates the shrinkage and salinization of existing lakes but also redefines the boundaries of saline water distribution through secondary salinization processes. Additionally, activities such as mining and the discharge of pollutants further alter the physical structure and ecosystem properties of these lakes. Consequently, the global distribution of salt lakes is transitioning from a pattern controlled purely by natural climate and hydrology to a complex composite system intertwined with human interference.

## 5. Changes and driving mechanisms of water salinity in global salt lakes

### 5.1. Water salinity changes of global typical salt lakes and driving factors

The formation and evolution of global salt lakes result from the integrated effects of climatic conditions, hydrological characteristics, and geological structures. Among these, climatic conditions represent the critical factor determining the water salinity of salt lakes, particularly in arid regions where low precipitation and intense evaporation lead to lake water concentration and elevated water salinity levels (Liang et al., 2024). For instance, numerous lakes in the interior of Australia, subjected to prolonged intense evaporation, have gradually evolved into hypersaline lakes. Additionally, lake hydrological characteristics play significant roles in water salinity variations; endorheic lakes, lacking outflow channels, experience water loss primarily through evaporation, resulting in continuously increasing water salinity, as exemplified by Qinghai Lake and Chaka Salt Lake on the TP (Zhang et al., 2020). Simultaneously, tectonic activities influence spatial distribution patterns of lake water salinity; for example, lakes in the East African Rift Valley, such as Lake Natron, have formed distinctive high-salinity environments due to volcanic activities enriching carbonates and alkaline minerals (Eugster and Hardie, 1978).

Over the past century, particularly in recent decades, many large salt lakes around the world have experienced dramatic changes in water salinity, primarily driven by alterations in lake water balance (i.e., water input vs. evaporative loss). This balance is strongly influenced by both climate change and anthropogenic activities (Wurtsbaugh et al., 2017). In endorheic basin lakes, water level and salinity are typically inversely correlated; declining water levels tend to increase salinity, and vice versa. As shown in Fig. 6, lakes in different regions exhibit distinct water salinity trajectories depending on their dominant driving forces.

1) The decline in water levels, coupled with rapid salinization, creates a vicious cycle of aridification and water exploitation. Rapid salinization represents one of the most pressing challenges faced by large salt lakes in arid regions. A prominent example is the Aral Sea, where catastrophic water level decline since the mid-20th century has led to a dramatic increase in water salinity, from near freshwater levels to hypersaline conditions, triggering an ecological disaster of global concern (Shadkam et al., 2016). A similar case is Lake Urmia in Iran, where intensifying drought and agricultural water use since the late 1990s have led to a persistent decline in water level and a surge in water salinity from 150 g/L to over 300 g/L, nearly collapsing the lake's ecosystem (Sima et al., 2021). Mar Chiquita in Argentina also exhibits a strong inverse relationship between lake level and salinity.

2) Rising water levels and lake dilution: The buffering effect of glacier meltwater. In contrast, some high-latitude or high-altitude lakes exhibit a gradual freshening trend. For instance, Qinghai Lake on the TP has shown increasing water levels since 2005, driven by enhanced precipitation and glacier meltwater inputs. Its water salinity has decreased from 14 g/L to below 12 g/L during the same period. A similar pattern is observed in Lake Issyk-Kul in Central Asia. These cases highlight the short-term buffering role of glacier melt under global warming, mitigating salinity increases by replenishing lake water volumes (Box et al., 2012).

3) Complex patterns and non-linear responses: Hydrogeological and geochemical regulation beyond water balance. Although there is a general negative correlation between water level and salinity, in some lake systems, salinity dynamics are regulated by nonlinear feedback between hydrogeological seepage and geochemical saturation. Firstly, groundwater outflow can buffer salinity rise during lake shrinkage. For instance, in semi-arid terminal lakes like Lake Chad, although evaporation dominates water loss, substantial groundwater seepage exports dissolved salts, preventing hypersalinization despite declining water levels (Pham-Duc et al., 2020). Secondly, geochemical saturation sets an upper limit for salinity. As the lake dries up further, once salinity reaches mineral solubility limits (e.g., gypsum at 140 g/L, halite at 350 g/L), further evaporation leads to salt precipitation rather than concentration increase, resulting in a salinity dynamic change independent of water level decline (McGrath et al., 2025). Additionally, complex basin morphology and connectivity can decouple salinity from water level, as observed in the Caspian Sea, where wind-driven circulation and exchange with Kara-Bogaz-Gol lagoon drive diverging salinity trends between its northern and southern basins. These examples illustrate that salinity dynamics are often governed by hydrogeological export, geochemical saturation, and basin-specific connectivity, resulting in piecewise or threshold-mediated responses rather than monotonic trends.

Overall, water salinity dynamics in large salt lakes are marked by profound spatial heterogeneity. While many follow the “concentration–dilution” model centered on hydrological balance, others are governed by more complex processes involving geochemistry and hydrological exchange. These patterns underscore the diverse sensitivities and nonlinear responses of lakes to external forcing. At the global scale, climate change acts as a “background shaper” by altering regional hydrothermal balances—accelerating evaporation in arid zones and enhancing meltwater inputs in alpine environments. Meanwhile, human activities often serve as decisive forces accelerating lake desiccation and salinization. For example, Lop Nur in China transformed from a vast lake into a salt crust basin due to large-scale irrigation and inter-basin water transfers (Shao et al., 2022). Industrial and mining operations also reshape lake water salinity, such as brine extraction in Salar de Uyuni for lithium production, which disrupts regional hydrochemistry (Hussain et al., 2019). These multiple, interacting drivers shape the disparate “fates” of salt lakes and pose significant challenges for their scientific management and ecological protection.

In general, future trends in water salinity of global salt lakes depend on changes in the global hydrological cycle and the evolution of regional

climate patterns. Against the backdrop of climate warming, arid regions and endorheic lakes may experience further salinization due to enhanced evaporation, while high-latitude and alpine lakes might exhibit decreasing water salinity trends in the short term due to increased glacial meltwater and climate wetting tendency. However, anthropogenic intervention factors, including agricultural irrigation, hydraulic engineering regulation, and mining development, may continue to intensify lake water salinity instability, potentially triggering ecosystem degradation and water resource crises in certain regions. Therefore, future research on lake water salinity requires integration of remote sensing monitoring, numerical simulation, and long-term observational data to thoroughly investigate spatial differences and driving mechanisms of lake water salinity. This approach will enable scientific assessment of lake ecosystem evolutionary trends and provide scientific support for global water resource management and ecological conservation policies.

### 5.2. Water salinity changes of TP salt lake and driving factors

The TP, renowned as the “Earth’s Third Pole”, constitutes the world’s highest plateau and hosts the largest high-altitude lake group (Immerzeel et al., 2010; Wang et al., 2022). These lakes encompass

multiple types, such as inland endorheic lakes, semi-endorheic lakes, freshwater lakes, and saline lakes, forming China’s most significant salt lake distribution region (Mianping et al., 2026). Due to the TP’s distinctive geographical and climatic conditions, e.g., high elevation, cold arid climate, intense solar radiation, and substantial diurnal temperature variations, TP lakes exhibit remarkable regional characteristics in hydrological and chemical properties. Researchers have extensively investigated TP lake water salinity and its variation trends for decades (Liu et al., 2021a). From the 1950s to 1990s, the “Records of China’s Salt Lakes” systematically compiled hydrochemical characteristics of most lakes on the TP region, documenting their water salinity distribution in detail (Zheng, 2002). Subsequently, studies focusing on individual lakes progressively increased, examining lakes such as Qinghai Lake, Pumoyong Co, and Nam Co (Jiang et al., 2007; Mitamura et al., 2003; Murakami et al., 2007; Wang et al., 2013; Zhu et al., 2010). Currently, researchers have gradually expanded to regional-scale studies of lake water salinity changes, employing remote sensing monitoring, field measurements, and numerical simulation methods to systematically evaluate TP lake water salinity trends and their influencing factors (Liu et al., 2023; Liu et al., 2021a; Song et al., 2022). These systematic assessments not only elucidate the spatiotemporal patterns of salinity variation in lakes across the TP, but also reveal, at a regional scale, their

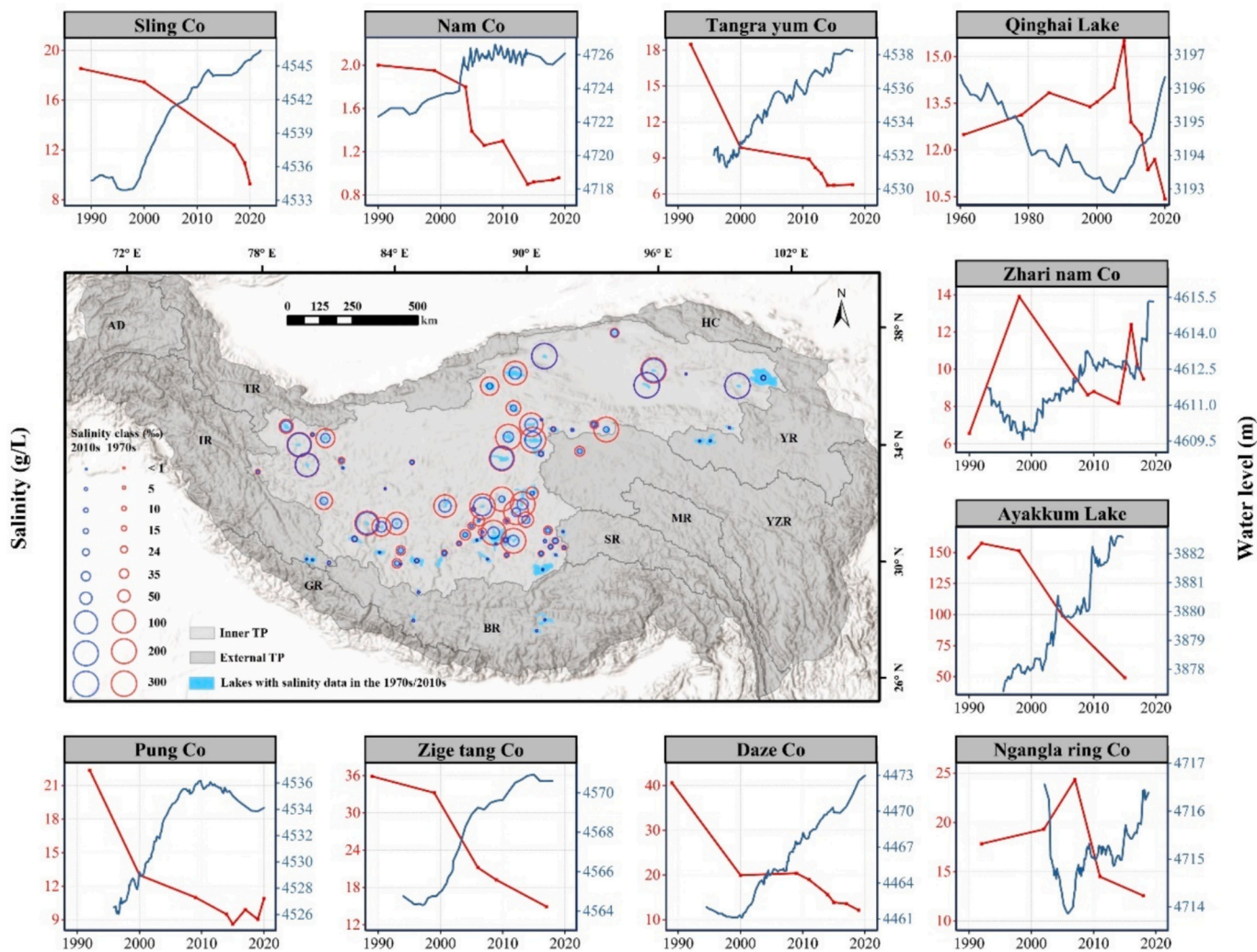


Fig. 7. Comparison of water salinity between the 1970s and 2010s for 83 salt lakes (>50 km<sup>2</sup>) on the Tibetan Plateau (modified from Song et al. (2022)). The sequence of water level (blue) and water salinity (red) changes in typical salt lakes from 1990 to 2020. The water level data is from the DAHITI dataset (<https://dahiti.dgfi.tum.de/en/products/water-level-altimetry/>). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

prominent role as one of the world's major liquid salt reservoirs. Based on the latest estimates of lake water volume (Han et al., 2024), we combined the regional mean water salinity data (Liu et al., 2023; Song et al., 2022; Xu et al., 2024), and roughly estimated the total dissolved salt storage of TP salt lakes to be approximately 44.32 billion tons, occupying a significant position in the global biogeochemical cycle.

In recent years, influenced by global climate change and regional hydrological environment alterations, TP lakes have demonstrated trends contrary to global changes, with generally decreasing water salinity. Analysis based on long-term monitoring data from 1990 to 2020 for nine representative TP lakes indicates that water level fluctuation represents a crucial dynamic factor affecting lake water salinity, with these parameters exhibiting a significant inverse relationship, as show Fig. 7. Water levels in lakes such as Siling Co, Ayakekumu Lake, and Pung Co rose by approximately 12 m, 5 m, and 8 m, respectively, during these 30 years, with corresponding water salinity decreases from 18.54 g/L, 16.01 g/L, and 151.42 g/L to 9.28 g/L, 10.91 g/L, and 49.10 g/L, reflecting the dilution effect from increased water volume. Some lakes, such as Zhari Namco and Nam Co, display more complex variation patterns, suggesting that factors beyond water level and groundwater interactions, evaporation rates, or watershed input changes may also influence salinity dynamics. Post-2000, most lakes exhibited accelerated rates of water level increase and salinity decrease, synchronizing with regional climate change impacts, while response magnitudes of water salinity to water level changes among different lakes may relate to lake basin morphology, initial salinity conditions, and hydrochemical characteristics.

In addition, recent studies analyzing nearly four decades of climatic and limnological data across the TP have identified temperature rise, glacial/permafrost meltwater recharge, and increased precipitation outpacing evaporative losses as the principal drivers behind lake water storage gains and salinity decline (Zhang et al., 2020; Zhu et al., 2025). Between 1986 and 2022, the average salinity of 352 lakes ( $\geq 10 \text{ km}^2$ ) across the region decreased from 48.76 g/L to 23.76 g/L (Liu et al., 2023; Zhu et al., 2025). Over the same period, more than 140 salt lakes transitioned into brackish states, reflecting widespread desalinization (Song et al., 2022). From 2002 to 2022, the mean annual rate of salinity decline was approximately 0.83 g/L per year (Zhu, 2024). This

downward water salinity trend has been particularly pronounced in rapidly expanding lakes in central and northern TP, whereas lakes in the southern region, where surface areas are shrinking, have shown either stable or weakened desalinization patterns. These findings provide a valuable empirical basis for understanding and forecasting how future climate change may alter the ecological and geochemical characteristics of high-altitude lake systems in this climatically sensitive region.

In the future, with intensifying global climate change, hydrological cycle processes on TP lakes may face increasingly complex changes, necessitating strengthened research on water balance and salt migration transformation mechanisms, and the establishment of more comprehensive lake water salinity change prediction models. This research holds important scientific value and practical significance for understanding high-altitude lake ecosystem evolution patterns, assessing regional water resource security, and environmental changes. Particular attention should focus on the differentiated impacts of climate change on water salinity in different lake types and potential resulting ecological and environmental effects, providing scientific foundations for the sustainable development of the TP.

## 6. Impacts of changes in water salinity of salt lakes

Variations in the water salinity of salt lakes are driven by a complex interplay of natural processes, accelerating anthropogenic activities, and climate change. These salinity dynamics exert profound and interconnected impacts across multiple dimensions of lake systems, influencing hydrological processes, water availability, soil structure, and biogeochemical cycles. To provide a holistic overview of these multifaceted consequences, this review presents a conceptual framework that categorizes the impacts into three primary domains (Fig. 8): environmental consequences, ecosystem responses, and socio-economic impacts. The following sections dissect these multidimensional consequences, transitioning from ecological responses to biogeochemical feedbacks, and finally to the broader impacts on human society.

### 6.1. Multifaceted environment consequences

Global variations in water salinity are influenced by natural

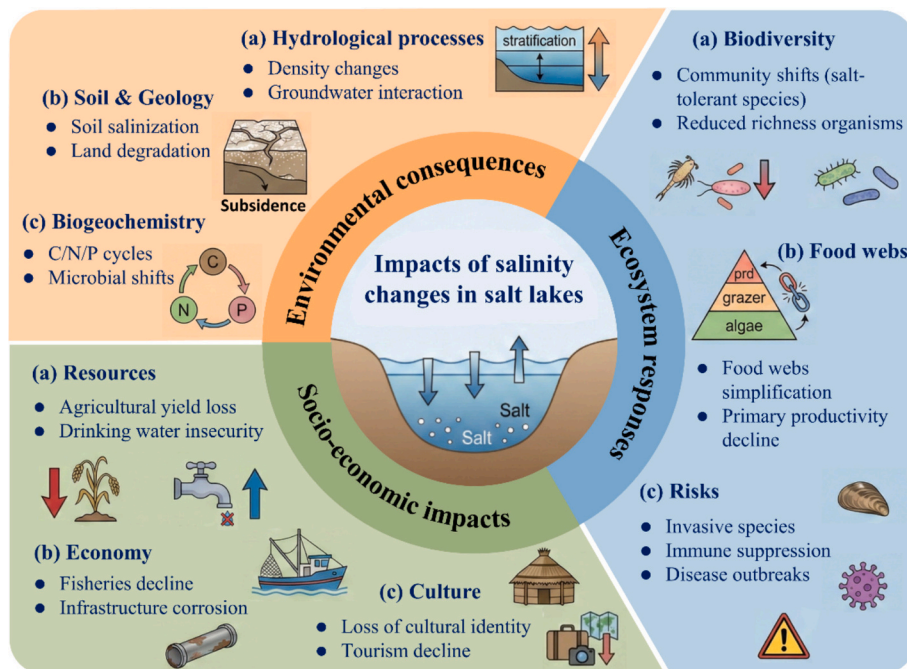


Fig. 8. Conceptual framework of the multifaceted and interconnected impacts of water salinity changes in salt lakes across environmental, ecological, and socio-economic dimensions.

processes, including long-term drivers such as evaporative concentration and tectonic evolution, as well as rapid changes increasingly driven by anthropogenic activities, such as unsustainable irrigation, industrial effluents, resource exploitation, and climate change. These water salinity dynamics exert profound and interconnected impacts on multiple dimensions of lake systems, influencing hydrological processes, water availability, soil structure, geological conditions, and biogeochemical cycles.

#### 6.1.1. Hydrological processes and water resources

Rising water salinity exerts significant impacts on hydrological processes and water resource systems, primarily through alterations in the physical and chemical properties of water (Gleick, 1989). In lakes and rivers, increasing water salinity increases the ionic strength and osmotic pressure of the water column and reduces gas solubility, thereby impacting aquatic respiration and the decomposition of organic matter, which in turn affect vertical mixing, thermal stratification, evaporation, and hydrodynamics (Gell et al., 2007; Hammer, 1986; Williams, 2001). From the perspective of water resources, variations in water salinity are often inextricably linked to lake water level fluctuations (Jeppesen et al., 2015a). Lakes in arid and semi-arid regions, such as the Aral Sea, the Great Salt Lake, and Lake Urmia, are particularly vulnerable to declines in water volume and surface area caused by evaporation, leading to salt concentration and rapid salinity escalation (Jeppesen et al., 2007). This process of “quantity reduction and quality transformation” not only threatens lake ecosystem security but also constrains the sustainable use of freshwater resources (Herbert et al., 2015).

Furthermore, interactions between groundwater and surface water play a critical role in the hydrological cycles of salt lakes (Jolly et al., 2008). These lakes are often terminal points of regional groundwater flow, and the recharge and discharge mechanisms of groundwater substantially influence both lake water salinity and water volume (Costelloe et al., 2009). In-depth investigations of these hydrological linkages, especially through the application of isotope tracing techniques, can provide more accurate insights into the recharge sources, water age, and salt origins of saline lakes, offering a scientific basis for sustainable water management and salinization mitigation strategies (Gomez et al., 2021; Mosaffa et al., 2021).

#### 6.1.2. Soil salinization and geological environment

Water salinity dynamics of salt lakes are closely linked to soil salinization processes in surrounding catchment areas through a bidirectional interaction mechanism. Rengasamy (2006) highlighted the global extent of soil salinization, particularly in arid and semi-arid regions such as Australia. When lake water levels decline and previously submerged lakebeds are exposed, capillary rise and intense surface evaporation can drive the upward migration of salts from deeper soil layers, resulting in soils affected by salinity and subsequent land degradation (Osman and Osman, 2018). Conversely, surface runoff and groundwater flow from saline soils can reintroduce salts into the lake, leading to elevated lake salinity (Salama et al., 1999). This feedback is especially pronounced under conditions of rising groundwater tables or irrigation return flows, where salt-laden water enters the lake system, reinforcing a “salt–water–soil” positive feedback loop.

On a geological scale, salt lake exploitation increasingly impacts regional hydrogeological systems. In the Qaidam Basin of the TP, for instance, prolonged extraction of subsurface brines from lakes such as Qarhan and Chaka has led to notable groundwater table decline, aquifer structure alteration, and even surface subsidence and fault reactivation (Yu et al., 2013). Additionally, improper irrigation practices are a major driver of secondary soil salinization (Mohanavelu et al., 2021). Qadir et al. (2007) emphasized that poor drainage conditions combined with excessive flood irrigation can raise the groundwater table, causing upward movement of deep salts into the root zone and surface layers. This process not only disrupts soil structure but also significantly reduces land productivity.

#### 6.1.3. Biogeochemical cycles

Salt lake water salinity serves as a critical nexus linking physical hydrological changes with ecological responses, and its fluctuations profoundly influence the biogeochemical cycling of key elements such as carbon, nitrogen, and phosphorus (Jiang et al., 2023). Increasing water salinity alters the ionic balance of the water column and affects gas solubility, thereby impacting aquatic respiration and the decomposition of organic matter. Kaushal et al. (2018) introduced the concept of the Freshwater Salinization Syndrome (FSS), highlighting the extensive biogeochemical consequences of salinity variation and framing it as a global environmental threat. This syndrome is not limited to hypersaline endorheic lakes but also affects freshwater ecosystems influenced by anthropogenic activities such as road salt application, mining runoff, agricultural discharge, and urban wastewater inputs (Kaushal et al., 2021; Novotny et al., 2008).

Microorganisms, as primary mediators of carbon, nitrogen, and phosphorus transformations in aquatic systems, are highly sensitive to changes in water salinity (Luo et al., 2019). Elevated water salinity can significantly shift microbial community composition, reduce microbial abundance, and suppress metabolic activities, thereby directly altering nutrient cycling dynamics and overall biogeochemical process rates (Gao et al., 2025; Yue et al., 2019). Specifically, increasing water salinity may inhibit key nitrogen cycle pathways such as nitrification and denitrification, affect phosphorus adsorption in the water, and modify both the composition and bioavailability of dissolved organic carbon (Xia et al., 2019). These alterations in elemental cycling can result in reduced primary productivity, disrupted food web structures, and the onset of secondary environmental problems such as lake eutrophication. Consequently, rising salt lake water salinity not only degrades water quality but also impairs ecosystem functioning, emphasizing the need for integrated water salinity management in lake environments.

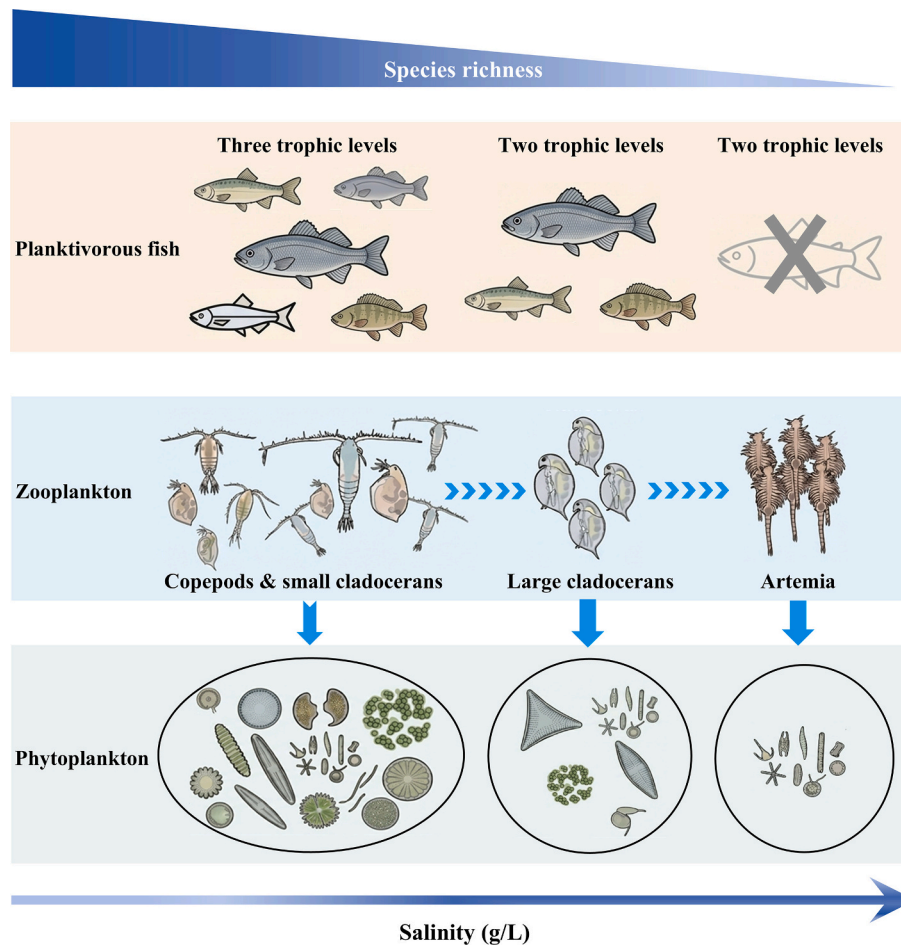
### 6.2. Impacts on salt lake ecosystems

As vital and sensitive aquatic habitats, salt lake ecosystems are highly vulnerable to water salinity. Globally, salinization is profoundly altering lake physicochemical conditions, biological communities, food web structures, and overall ecosystem stability through multiple interacting pathways (Herbert et al., 2015; Hu et al., 2022). These changes are progressively disrupting the dynamic equilibrium of lake ecosystems, revealing their ecological fragility and the limits of their adaptive capacity.

#### 6.2.1. Biodiversity and community structure

Increasing water salinity imposes strong physiological and ecological stress on aquatic organisms, affecting osmoregulation and interspecific interactions (Kültz, 2015; Velasco et al., 2019). Herbst (Herbst et al., 2013), in a study of the western Great Basin in the USA, reported a significant decline in invertebrate species richness and abundance under high-salinity conditions, directly illustrating the simplification of community structure in saline environments. Phytoplankton, zooplankton, and benthic microorganisms are particularly sensitive to water salinity changes. Salinity has been identified as a major environmental determinant of salt microeukaryotic community composition (Liu et al., 2022; Mo et al., 2021). Elevated water salinity often drives community shifts toward halotolerant or halophilic taxa, thereby displacing dominant species. For instance, green algae may be replaced by cyanobacteria or euglenoids that tolerate salt, which can significantly alter primary productivity and the basal structure of aquatic food webs (Foflonker et al., 2016; Marden et al., 2013).

At the microbial level, planktonic communities respond acutely to changes in water salinity. Several studies have emphasized that water salinity acts as a primary driver of salt microeukaryotic plankton dynamics (Mo et al., 2021). Serving as the base of aquatic food webs, alterations in the composition and abundance of these microscopic organisms can trigger cascading effects throughout the ecosystem



**Fig. 9.** Conceptual model illustrating changes in trophic structure and zooplankton community composition in response to increasing salinity. Solid arrows indicate top-down effects, while dashed arrows represent shifts in trophic structure and zooplankton composition (modified from Lin et al. (2017) and (Jeppesen et al., 2020)).

(Dildar et al., 2025). High water salinity often leads to reduced microbial diversity and shifts in community composition, favoring halophilic species while suppressing more sensitive taxa (Chen et al., 2022a; Zhong et al., 2019). Such species reassembly not only reshapes ecological niche distributions but also induces trophic cascades that impair overall ecosystem functioning.

#### 6.2.2. Food web and ecosystem functioning

Rising water salinity not only directly affects individual aquatic organisms but also fundamentally reshapes lake food web structure and ecosystem functioning (Vidal et al., 2021). Hammer (1986) observed that under conditions of extreme water salinity, lake food webs typically exhibit simplification, manifesting as reduced species richness, shorter trophic chains, and more direct interactions between predators and prey. Such simplification weakens the system's resistance to external disturbances and diminishes its ecological resilience. A decline in primary productivity is one of the most apparent manifestations of functional change. High water salinity levels suppress phytoplankton photosynthesis and reproduction rates, thereby reducing primary production and constraining the energy base of the entire food web (Golubkov et al., 2018). Hart (2003) further demonstrated that water salinity variation can impair decomposition processes, nutrient transformations, and key microbially mediated biogeochemical cycles, resulting in functional degradation of trophic pathways.

Long-term studies on brackish lakes have shown that salinization alters zooplankton community composition, thereby affecting trophic

interactions and the dynamics between predators and their prey (Bruce et al., 2010; Jeppesen et al., 2007). As shown in Fig. 9, as water salinity increases, zooplankton communities diverge increasingly from those in freshwater systems, with replacements occurring at the species, genus, and even family level (Williams, 1998). For example, large-bodied cladocerans such as *Daphnia* tend to decline, while rotifers, copepods, and small-bodied cladocerans like *Bosmina* and *Chydorus* become dominant (Jeppesen et al., 2014). This community turnover substantially alters the trophic positioning and energy transfer efficiency of zooplankton. With increasing water salinity, some predatory species expand their ecological niches and increase in abundance, intensifying predation pressure on zooplankton communities and accelerating the transition from large-bodied to small-bodied invertebrates (Jensen et al., 2010). As a result, lake food webs under water salinity stress undergo structural transformations not only at the base (primary producers) but also at intermediate (zooplankton) and upper trophic levels (euhaline fish predators) (Zadereev et al., 2022). This food web restructuring directly reflects changes in ecosystem functioning and serves as a critical indicator of ecological impacts caused by water salinity (Lin et al., 2017).

#### 6.2.3. Invasive species and disease transmission

Changes in salt lake water salinity can not only alter ecosystem structure but also increase ecosystem vulnerability to invasive species and aquatic disease outbreaks. Elevated water salinity may weaken the competitive advantage of native species, thereby opening ecological niches for salt-tolerant non-native taxa. Ricciardi and MacIsaac (2011)

noted that under shifting water salinity regimes, invasive species typically restricted to brackish or saline waters can successfully colonize freshwater lakes and even establish dominance, such as certain hard-shelled crustaceans and exotic aquatic plants. Such invasions often occur at the expense of native biodiversity, reducing genetic diversity and undermining the system's regulatory capacity.

Moreover, water salinity has been shown to significantly affect the immune responses and disease susceptibility of aquatic organisms (Dildar et al., 2025; Zhang et al., 2011). Tacchi (Tacchi et al., 2015) found that salinity stress alters the mucosal barriers, metabolic rates, and stress protein expression in aquatic animals, ultimately compromising their resistance to pathogens, including fungi, bacteria, and parasites. For example, zebrafish (*Danio rerio*) exposed to water salinity stress exhibit pronounced physiological and behavioral changes, along with increased sensitivity to infection (Uliano et al., 2010). The impairment of immune function not only raises the risk of individual disease incidence but may also facilitate the spread of pathogens, increasing the likelihood of localized disease outbreaks. Such conditions pose emerging threats to aquatic animal health and further compromise the ecological stability of lake ecosystems under salinization pressure.

### 6.3. Impacts on human society

The socio-economic consequences of lake salinization act as a cascading feedback loop where hydrological and biogeochemical changes precipitate public health crises and economic instability.

Elevated salt lake salinity poses a direct threat to drinking water security and represents one of the most urgent consequences of salinization (Vineis et al., 2011). This threat is compounded by the “Freshwater Salinization Syndrome”, where salinity-driven biogeochemical alterations can mobilize heavy metals and nutrients from sediments, further degrading water quality beyond simple ion concentration. From a public health perspective, chronic consumption of high-salinity water has been strongly linked to increased incidence of hypertension, chronic kidney disease, and cardiovascular disorders (Rosinger et al., 2021; Talukder et al., 2016).

Agricultural, fishery, and aquaculture sectors are also under mounting pressure from water salinity changes in water bodies. In agriculture, salt accumulation in soil induces osmotic stress and ion toxicity, which impair root function and nutrient uptake, ultimately reducing crop yield or causing total crop failure (Majeed and Muhammad, 2019; Yadav et al., 2011). In fisheries and aquaculture, increased water salinity affects the osmoregulatory mechanisms, reproductive cycles, and feeding behavior of fish and crustaceans, leading to lower productivity and economic returns (Agarwal et al., 2024). Critically, these economic losses are deeply intertwined with the ecological simplification described in Section 6.2.2; as primary productivity declines and food webs become shorter, the commercial fish stocks that local communities depend on face systemic collapse. Abisha et al. (2022) noted that under global warming conditions, freshwater aquaculture is increasingly shifting toward salt-tolerant species such as tilapia and tiger shrimp, or adopting saline aquaculture systems. However, such transitions often involve higher initial investment, increased management

complexity, and risks related to local ecosystem adaptation. To quantify these profound economic consequences, we have compiled data from major salt lakes globally (Table 4). The collapse of ecosystem services in regions like the Aral Sea and Lake Urmia has resulted in annual economic losses exceeding billions of US dollars.

Infrastructure systems are also directly impacted by high water salinity levels. Elevated salt concentrations can corrode supply system components, accelerate the degradation of metal and concrete materials, reduce infrastructure lifespan, and increase maintenance frequency. As highlighted in our discussion of soil structure and groundwater, the upward migration of salts not only affects land productivity but also compromises the geological stability of foundations. Studies have shown that cities in salinized regions incur significantly higher infrastructure maintenance costs (Dasgupta et al., 2014). For instance, Environment NSW reported that road maintenance expenditures in salt-affected areas are two to three times higher than in non-salinized regions, while the average replacement cycle of bridges is shortened by 8–10 years (Environment Protection Authority, N.S.W., 2024).

Although often overlooked compared to drinking water or agriculture, the cultural and spiritual consequences of lake salinization are equally critical (Abbas et al., 2024). Lakes are not only ecological entities but also cultural landmarks, repositories of collective memory, and symbols of local identity (Cuerrier et al., 2015). The degradation of these connections is often the final stage of the ecological cascades discussed in Section 6.2; when biodiversity declines, and native species disappear, the cultural services and traditional knowledge associated with these habitats are lost. Rising water salinity that leads to lake shrinkage, water quality degradation, and landscape deterioration undermines these cultural connections. In regions such as the Aral Sea or Salar de Uyuni, salinization has resulted in sharp declines in tourism, abandonment of support infrastructure, and collapse of related economic sectors (Orlovsky et al., 2026). These socio-economic collapses demonstrate that the integrity of human societies in saline regions is fundamentally tethered to the biogeochemical and ecological stability of the lake systems.

## 7. Conclusions

Water salinity of lakes has evolved from a single physicochemical indicator into an interdisciplinary concept that connects hydrology, ecology, and climate change, with its core feature being a high degree of heterogeneity in space. This review systematically synthesizes current knowledge on the spatial distribution, dynamic variations, driving mechanisms, and socio-environmental consequences of water salinity in salt lakes worldwide, and draws the following main conclusions:

- (1) The distribution patterns and salinity dynamics changes of salt lakes are influenced by both natural and human factors. Natural processes (rock weathering, atmospheric deposition, and evaporative concentration) determined the geological origin and baseline salinity, while human activities (agricultural irrigation, land use changes, and urbanization) are becoming the dominant

**Table 4**  
Economic impacts associated with major salt lakes experiencing salinization or shrinkage.

Lake	Country	Major economic impacts	Estimated economic loss	Data source
Lake Urmia	Iran	Loss of 260,000 ha of agricultural land, collapse of fisheries, and public health risks	Millions of dollars	(Feizizadeh et al., 2022)
Aral Sea	Uzbekistan / Kazakhstan	20–30% reduction in agricultural productivity, complete collapse of fisheries, salt-dust storms, and health problems	5.0 billion USD	(Micklin, 2002)
Great Salt Lake	United States	Decline of the brine shrimp industry, reduction in tourism revenue, and associated ecosystem services	1.69–2.17 billion USD	(Abbott et al., 2023; Bioeconomics, 2012; Wurtsbaugh and Sima, 2022)
Lake Chad	Chad / Cameroon / Niger / Nigeria	Up to 90% reduction in lake area, localized salinization, agricultural losses, and intensified social conflicts	/	(Zhao et al., 2023)

driving force for modern salt lake water salinity changes, intensifying the salinization process of global salt lakes.

- (2) The monitoring technology for salt lake water salinity has evolved from traditional in-situ point sampling and laboratory analysis to a large-scale, dynamic monitoring technology system centered on the combination of remote sensing and machine learning, achieving a paradigm shift from static to dynamic and from point to surface.
- (3) The global distribution of salt lakes exhibits distinct climatic zonation, predominantly located in arid and semi-arid belts between 20°–50°N and 15°–35°S. However, water salinity patterns are highly heterogeneous at the regional scale. Based on data from 292 salt lakes, the TP demonstrates both the highest lake density and the most pronounced spatial variation in water salinity. The Altiplano in South America and inland Australia are dominated by hypersaline lakes, whereas lakes in the East African Rift Valley generally exhibit lower water salinity levels, highlighting the critical role of local geological and hydrological processes in shaping salinity patterns.
- (4) An analysis of recent decades of water salinity and lake level records reveals a dual trend of both salinization and desalination in large salt lakes globally, reflecting the combined influence of climate change and human activities. In arid regions, rapid salinization is a dominant trend, exemplified by the Aral Sea and Lake Urmia, where large-scale upstream water diversion for irrigation has dramatically reduced inflows, resulting in soaring water salinity levels and triggering ecological catastrophes. Conversely, high-altitude regions such as the TP exhibit episodic desalination, where increased precipitation and glacier melt, under global warming, temporarily exceed evaporation, leading to lake expansion and diluted water salinity.
- (5) Variations in salt lake water salinity have cascading effects on lakes and their surrounding environments through physical, chemical, and biological pathways. Ecologically, elevated water salinity simplifies food web structures, often causing the disappearance of apex predators and a reduction in trophic complexity. Biogeochemically, water salinity affects water column stratification and nutrient cycling (e.g., nitrogen, phosphorus, and carbon). High water salinity levels can inhibit denitrification while enhancing DNRA processes, altering nutrient retention and ecosystem functioning. Environmentally, water salinity dynamics interact with watershed soil salinization in bidirectional feedback, directly threatening drinking water security, agriculture, and infrastructure resilience.

#### CRediT authorship contribution statement

Pengju Xu: Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft. Chunqiao Song: Conceptualization, Methodology, Funding acquisition, Writing – review & editing.

#### 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

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.earscirev.2026.105487>.

#### Data availability

Data will be made available on request.

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