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Effects of induced changes in salinity on inland and coastal water ecosystems: editor summary

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Freshwater salinization is a global phenomenon that will intensify in the future due to a combination of factors (e.g. Cañedo-Argüelles et al., 2016; Wurtsbaugh et al., 2017; Jeppesen et al., 2020, 2023; Zadereev et al., 2020; Parra et al., 2021; Cunillera-Montcusí et al., 2022). For example, due to climate change the semiarid and arid climate zones will experience much less net precipitation and runoff (Döll & Schmied, 2012; IPCC, 2023), thereby decreasing the salt dilution capacity of rivers and streams. Sea level rise and coastal seawater intrusions will promote freshwater salinisation (Lassiter, 2021), which will be further accelerated by a higher frequency and duration of extreme storms (Paldor & Michael, 2021). Besides, an increase in water abstraction is expected due to a global increase in demand for food to sustain growing human populations (Vörösmarty et al., 2010), thereby altering the salt and water balance of aquatic ecosystems (van Vliet et al., 2017). Finally, human activities that cause salinisation (e.g. resource extraction, transportation, urbanisation, winter deicing, industrial runoff etc.) are expected to intensify

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and expand in the future (Cañedo-Argüelles et al., 2013). All these future predictions, together with the strong negative effects that freshwater salinisation can have on biodiversity, ecosystems and human societies (Cañedo-Argüelles, 2020; Melles et al., 2023) call for action. However, as our knowledge of freshwater salinisation is fragmented, the possibility of taking wise anticipation, mitigation and remediation strategies is uncertain.

Continental waters and estuaries have always been subjected to salinity changes due to natural climate variations. However, the ongoing climate change along with the already experienced extremes and a number of anthropogenic activities have increased their salinity at places and/or increased the amplitude of the salinity changes (Lengyel et al., 2019; B-Béres et al., 2022; Cortez et al., 2022). The collection of papers included in this volume and their location, habitat type, target biota and concept/approach are summarised in Table 1. This special issue of Hydrobiologia provides examples of the effects of changes in salinity and includes 16 contributions, covering a wide range of ecosystems and organisms, based on reviews, experimental, observational and prediction-oriented modelling studies. Papers in this special issue will not cut the Gordian knot, but the guest editors hope that these bits and pieces will bring us closer to overall understanding the role of salinity in aquatic ecosystems and the consequences of modifying natural salinity dynamics.

Estuaries and land–sea interactions

Coastal environments are at the frontline of sea-level rise effects, seawater intrusion and changes in the transportation of energy, matter and organisms along river catchments (Ewel et al. 2001; Levin et al., 2001; IPCC, 2023). Salinisation in these areas results in homogenisation that, in many cases, will exceed the adaptation capacities of biota leading to drastic ecosystem changes. The results from individual papers collected in this volume have shown salinity to be the main driver behind a series of cascading effects that involve biogeochemical cycles and different levels of biological organisation (from individuals to communities).

Seawater intrusion (1),[1] flow-regulated (2) discharges or extreme floods (3) have resulted in the appearance of toxic or potentially toxic dinoflagellates (1, 2) and cyanobacteria (3) in estuaries and their adjacent areas assisted by variations in suspended solids, silica and dissolved inorganic nitrogen. In some cases, such events had socio-economic consequences such as impacts on shrimp and oyster farming (3, 6). Seawater intrusion during a prolonged drought resulting in variations in river discharge had profound effects on the estuarine fish communities by favouring marine stragglers and marine migrants and reducing native freshwater species (4). Damming may lead to the absence of seasonality in fish composition and distribution in downstream waters (5). A long-term (20 years) biological monitoring of nekton occurrence and distribution in a river-fed estuary indicated that spatial variation in species populations was driven by differences in salinity, while seasonal changes were driven by temperature. Freshwater inflow is the primary driver of salinity in estuaries, and as demonstrated, river flow reductions, influenced by climate change, have the potential to markedly alter nekton communities (6).

Changes in hydrology and salinity affect critical habitats such as mangroves, which control sediments, nutrients and organic matter retention. The composition and abundance of the vegetation and the production of litter and roots at 22 mangrove and five wetland sites in two periods were mainly driven by a spatiotemporal gradient of salinity related to river flow and saline intrusions (7). Accordingly, increasing the interstitial and river water values by an average of 10‰ and 16‰ (respectively) led to a decrease in litter and root production and major changes in the composition of various marsh plants and tree species (7). Performance of mangrove-associated key macroalgae can be negatively affected by increased salinity (8) as evidenced by ecophysiological responses of two closely related red algae. Incubation under a range of salinities (5–57 ppt) indicated lower photosynthetic performance at increased salinity for both species, which increased their organic osmolyte

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[1] Numbers in brackets within the text refer to serial number of papers in Table 1.

Table 1 Serial number (as referred to in the text), geographical location of the study site(s), their habitat type, the focus of the study, target biota a title of the particular papers collected in this special issue

	Geographical location	Habitat type	Focus	Biota	Particular paper
(1)	Itapecuru River Estuary, Brazil	Estuary	Dry season, salinity gradient	Phytoplankton, dinoflagellates	Phytoplankton community dynamics in response to seawater intrusion in a tropical macrotidal river–estuary continuum
(2)	Nearshore region of Florida, USA	Estuary	Flow-regulated discharge	Phytoplankton, dinoflagellates	Algal blooms in a river-dominated estuary and nearshore region of Florida, USA: the influence of regulated discharges from water control structures on hydrologic and nutrient conditions
(3)	Atchafalaya-Vermilion Bay System, Louisiana, USA	Estuary	2019 River flood, social concern	Phytoplankton, incl. HAB cyanobacteria	Flood-driven increases in phytoplankton biomass and cyanobacteria abundance in the western Atchafalaya-Vermilion Bay System, Louisiana
(4)	Estuaries along the Brazilian semiarid coast	Estuary	Prolonged draught	Fish	Prolonged drought influences the taxonomic and functional structure of fish assemblages in estuaries along the Brazilian semiarid coast
(5)	São Francisco River, Brazil	River–estuarine continuum	Damming effect on seasonality	Fish	Composition and distribution of fish assemblages in a tropical river–estuarine continuum
(6)	Apalachicola Bay, northeast Gulf of Mexico	Estuary	Freshwater input	Nekton, oyster	Using long-term ecological monitoring to evaluate how climate and human-induced disturbances impact nekton communities in a Northern Gulf of Mexico estuary
(7)	San Pedro and San Pablo River, Gulf of Mexico	Mangroves, wetlands	Litter and root production	Vegetation	Decreases in mangrove productivity and marsh die-off due to temporary increase in salinity, a case in Mexico

Table 1 (continued)

	Geographical location	Habitat type	Focus	Biota	Particular paper
(8)	Mamanguape River Estuary, Paraíba, Brazil	Estuary	Photosynthesis, osmolith production	Red algae	Photobiological and biochemical responses of mangrove-associated red macroalgae *Bostrychia calliptera* and *Bostrychia montagnei* to short-term salinity stress related to climate change
(9)	Spain	River	Electrical conductivity	N/A	Human activities disrupt the temporal dynamics of electrical conductivity in Spanish rivers
(10)	Ribeira do Candal, Portugal	Low order stream	Leaf litter decomposition	Aquatic fungi	Pulsed vs. chronic salinization effects on microbial-mediated leaf litter decomposition in fresh waters
(11)	Sambhar Lake, India	Hypersaline lake	Desiccation, N and P biogeochemistry	N/A	Lake desiccation drives carbon and nitrogen biogeochemistry of a sub-tropical hypersaline lake
(12)	Florida, USA	Various aquatic environments	Salt tolerance	Macrophytes	Salt-tolerance assessment of aquatic and wetland plants: increased salinity can reshape aquatic vegetation communities
(13)	Garças, Piripiri and Catingosa, Brazil	Lagoons and pools	Drought	Fish, physiological tolerances	Drought drives fish disassembling in a Neotropical coastal plain
(14)	Vejlerne Nature Reserve, Jutland, Denmark	Brackish wetland system	Grazing	Zooplankton	Impact of zooplankton grazing on phytoplankton in north temperate coastal lakes: changes along gradients in salinity and nutrients
(15)	Overall review	Various aquatic environments	Community composition, diversity, invasions	Diatoms	Diatom community response to inland water salinization: a review
(16)	Overall review	Various aquatic environments	Acclimation, ecophysiology, industry	Diatoms	Review of phenotypic response of diatoms to salinization with biotechnological relevances

contents with rising salinity stress. This could have implications for competition, which may depend on their ability to synthetizing osmolytes.

Coastal streams, lakes, wetlands and inland waters

In continental waters, both climate change and human activities are not only increasing the salinity of rivers but also altering its natural temporal dynamic. The exploration of a database of continuous measurements of electric conductivity (EC) in 91 Spanish rivers during a 5 years period shows that trends of EC change are not uniform across rivers (9). The study identified groups of rivers with differences in EC trends that covered a gradient of anthropogenic pressure mainly related to agriculture, although road deicing, mining and wastewater discharges were also important to some extent. Given that the temporal dynamics of EC might have strong effects on aquatic biodiversity (e.g. influencing population dynamics), it should be incorporated into monitoring and management plans.

Salinity changes, especially in streams and rivers, can be chronic or appear as pulsed contamination depending on the driver of salinisation. These scenarios might have different implications for ecosystems according to theoretical differences between stress and disturbance (Sveen et al., 2023). Comparing effects of chronic/pulsed salt addition at similar ionic concentrations on microbial-mediated litter decomposition, mass loss of oak leaf litter was consistently depressed by salinisation with stronger effects at the highest concentrations, independently from the pattern of salt addition, however with differences in response variables (10). For example, at high salt concentrations, chronic salt exposure was more deleterious than pulsed inputs to microbial activity, reproductive output and fungal richness, but with no effects on fungal biomass. Overall, the effective salt concentration to alter fungal activity is greater in the case of acute salinisation, as the intervals between salt pulses seem to facilitate a total or partial recovery of microbial functions (10).

Saline lakes are among the most threatened ecosystems in the world, and they have experienced severe reductions in their surface area due to climate change and human-induced perturbations like water diversion and extraction (Stenger-Kovács et al., 2014; Pálmai et al., 2020). One of the studies included in this volume (11) focused on a hypersaline lake and its adjacently located reservoir and salt pans by using stable isotopes. The study shows that desiccation alters N and C biogeochemistry along with nitrification and mineralization rates in lake sediments, favouring the appearance of potentially toxic N_2 fixing cyanobacteria.

Experiments in the 0.2–20 ppt salinity range with aquatic vegetation samples from Brazilian wetlands concluded that salinisation provides an empty niche for invasion of non-native species, thus increasing the opportunity of invasion by salt-tolerant non-native species (12). Also, in lentic environments of a drying coastal plain of Southeast Brazil, a comparison between stenohaline (i.e. narrow salinity tolerance ranges) and euryhaline (i.e. wide salinity tolerance ranges) fish species showed non-random patterns of community composition. Species replacement was promoted by environmental heterogeneity, with parameters related to desiccation (salinity and depth) affecting euryhaline species co-occurrence. Together, these results revealed group-dependent responses to drought according to physiological tolerances (13).

Salinity has both direct and indirect effect on zooplankton, the latter due to variations in the predation by fish and macroinvertebrates with top-down implications for the grazing on phytoplankton. Zooplankton grazing at similar nutrient levels is generally regarded as lower in brackish than in freshwater lakes not only because of intensive predation by fish and mysids—but experimental evidence supporting this view is lacking. Short-term zooplankton grazing experiments in bottles were conducted with water from 12 Danish brackish lakes covering a large gradient in salinity (0.3–17.4 ppt) as well as from mesocosms conducted in the same area with various salinities (0.5–12 ppt), two nutrient levels and low fish density (14). Grazing was generally low in the lakes, even when they were dominated by edible phytoplankton, and nutrient addition led to a major increase in phytoplankton biomass. By contrast, grazing was significant in most of the mesocosms, particularly at high nutrient levels and salinities of 8 ppt or below where *Daphnia* dominated. Thus, grazing by zooplankton can be high in brackish lakes with a salinity up to 8 ppt at low fish densities, but the realised grazing in the lakes was overall low, which the authors attributed to high predation on zooplankton.

Both conductivity and ion composition are highly important variables shaping diatom communities, a distinguished indicator group in environmental monitoring systems. Secondary (human induced) salinisation can mask regional differences in diatom assemblages. The increasing conductivity along a wide conductivity scale decreases the alpha-diversity (15). In harmony with (12), salinisation induces the spread and invasion of marine and brackish diatoms into inland freshwaters as well as that of freshwater species tolerating elevated conductivity and/or needing specific ions. Applicable diatom indices are available to assess the level of salinisation. However, future models predicting ecological consequences of salinisation are scarce and sometimes contradictory. At ecophysiological level (16), salt stress can significantly affect the photosynthetic activities, pigment contents, growth rate, metabolism and toxin synthesis of diatoms. The acclimation capability of diatoms is apparent: they can adjust turgor pressure and ion homeostasis and produce compatible solutes for osmoprotection by applying various biochemical pathways and complementary mechanisms. However, knowledge about their molecular background and long-term adaptation is completely missing. Various morphological changes can also be attributed to changes in salinity. Abnormal forms may indicate extreme and complex effects of salinity and collateral stress factors.

Conclusion

In a recent overview, Cunillera-Montcusí et al. (2022) pointed out that the understanding of the impacts of salinisation is limited from both ecological and evolutionary perspectives. Thus, there is limited focus on the functional, spatial and trophic consequences of freshwater salinisation, only a few long-term studies exist, and there is a severe geographical bias as most of the studies have been conducted in only a handful of regions and/or ecosystems. This special issue provides new information from less studied regions and ecosystems, mainly observational studies, cross-system analyses and medium-sized experimental studies. Overall, the studies show that salinity is a key driver of biodiversity and ecosystem functioning in both inland freshwaters and estuaries, and the modification of natural salinity dynamics by humans might have undesired consequences such as biological invasions or harmful algal blooms. We encourage further observational studies and large-scale experiments (temporal and spatial) as well as comprehensive cross-system analyses, paleolimnology and modelling to bring the understanding of salinisation on aquatic ecosystem up to the level of the knowledge of the effects of other stressors, such as nutrients or metal pollution.

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