



Science
for Public
Policy

When Freshwater Turns Salty

Scientific Challenges and Management
of Aquatic Ecosystems

Coordinated by:

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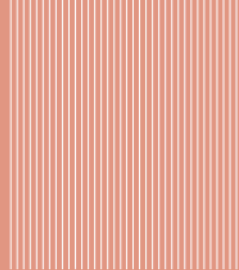
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ONE of the CSIC's functions is to inform, assist and advise public and private entities on science and technology, as stated in article 5 of its Articles of Association. As part of this function, the present report, *When Freshwater Turns Salty. Scientific Challenges and Management of Aquatic Ecosystems*, from the Science for Public Policy collection, is presented as a document aimed at public administrations and society in general. The salinisation of freshwater ecosystems (rivers, lakes, wetlands, etc.) is occurring all over the planet as a result of human activities and is widespread in Spain; it has, however, received little attention. This report explains the main causes of this phenomenon and its impact on ecosystems, the economy and human health. In addition, priority lines of research are discussed and management measures are proposed, including recommendations for improving public policies.

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Salinisation of Inland Aquatic Ecosystems: Causes and Consequences

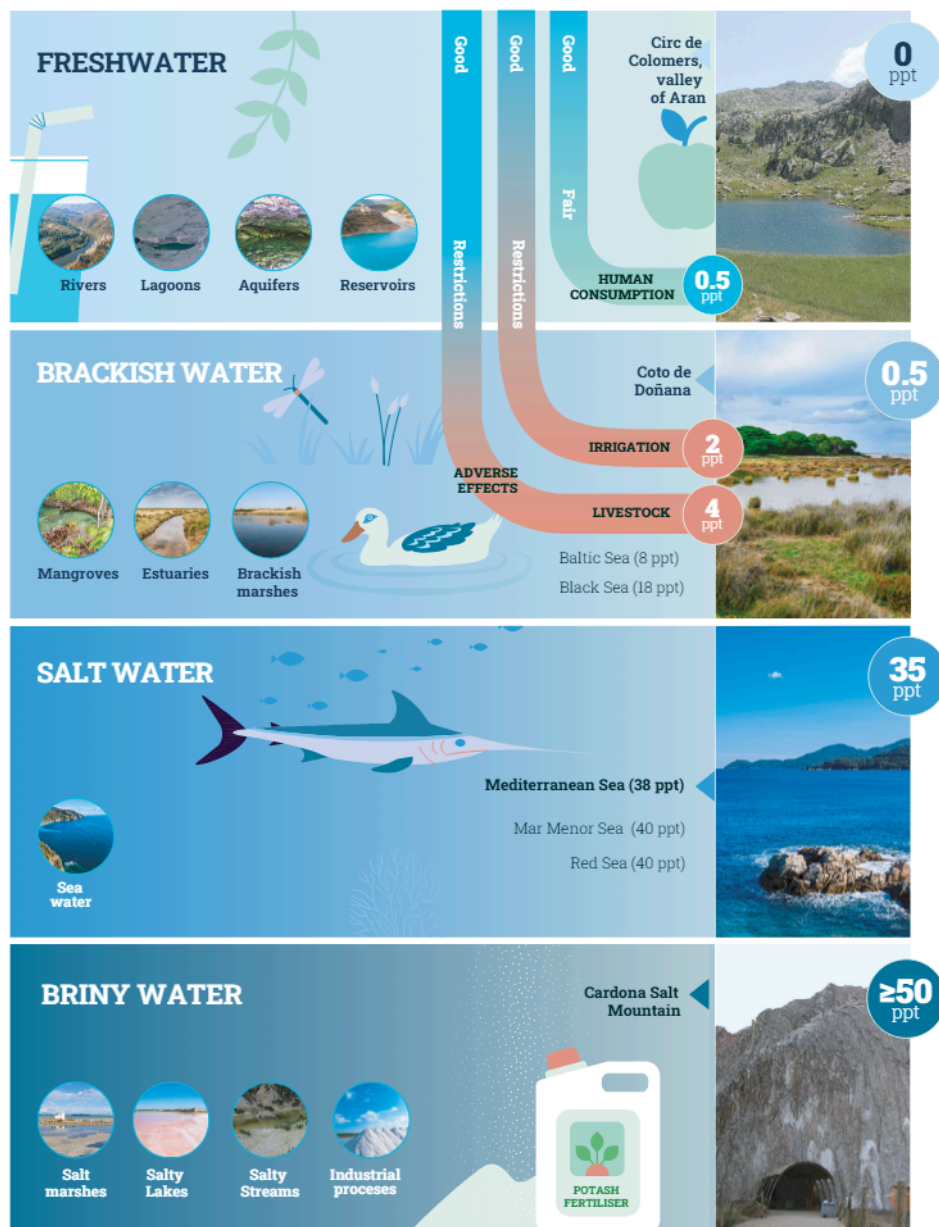
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What is salinisation of inland aquatic ecosystems?

INLAND aquatic ecosystems are those bodies of water that can be found inland: rivers, lakes, wetlands, marshes, etc. With a few exceptions (e.g., the Rambla Salada in Murcia), these ecosystems are freshwater. This means that the water has a very low salt concentration, less than one gram of salt per litre. In any case, even if the concentration is low, it is logical to ask: where do these salts come from? For the most part, they come from the dissolution of rocks that naturally contain salts, and when they come into contact with water, they dissolve. In addition, salt is also transported from the sea to the mainland by wind and breaking waves, as well as by seawater intrusion into coastal aquifers. All this is known as the *salt cycle*.

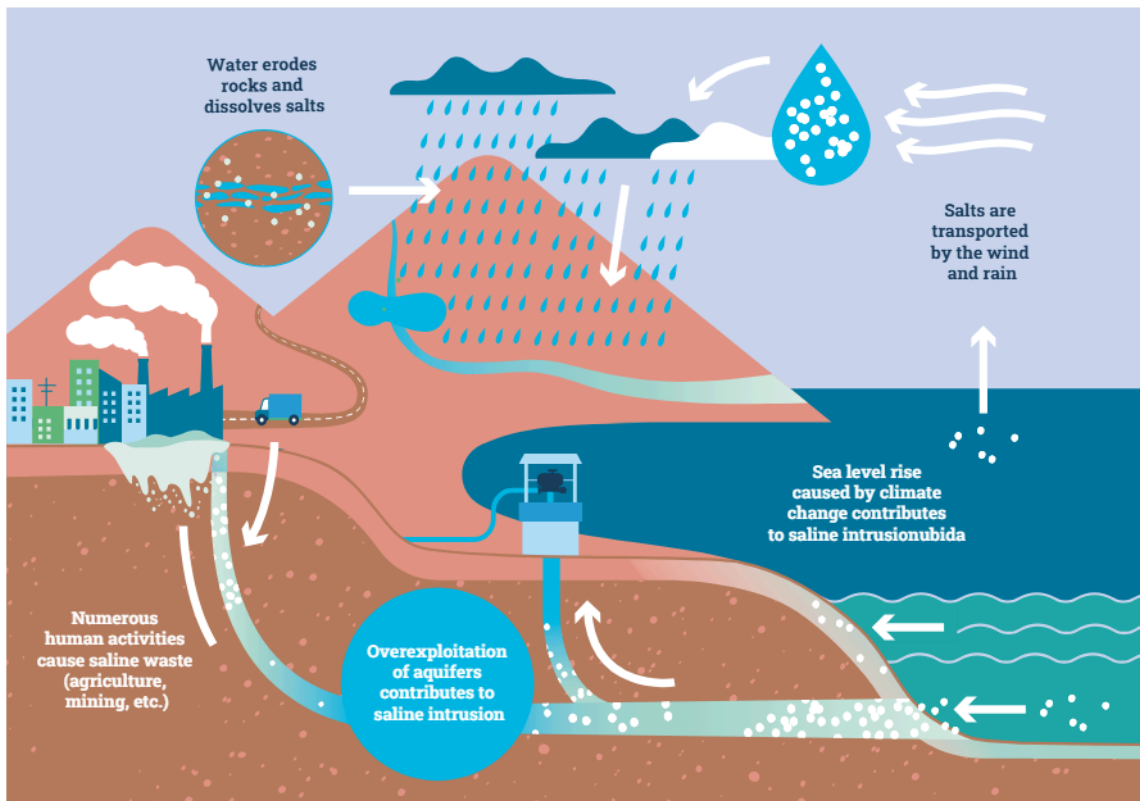
This salt cycle has been severely disrupted by human action since the Industrial Revolution. Urban, agricultural and industrial development has caused a marked increase in salt concentration and a change in the proportion of different ions in inland aquatic ecosystems, a phenomenon known as *aquatic ecosystem salinisation* (AES). AES is a global phenomenon, observed on all continents except Antarctica, with drastic consequences for ecosystems and society. Although there are no exact data on the spatial extent of AES globally, it is currently estimated that one in three freshwater ecosystems may be salinised. For example, in Spain, official data provided by the Hydrographic Confederations estimate that 17,822 km of river sections are salinised, which is 28% of the hydrographic network of our country. This percentage varies according to geographical location. For example, 80% of the rivers in the La Mancha area and the siliceous plains of the Tagus and Guadiana are salinised. There are various human activities responsible for AES. The most relevant based on the information available so far are detailed below.

Figure 1 Classification of waters according to salinity and potential use



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Figure 2 The anthropogenic salt cycle



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1.2.

Causes of aquatic ecosystem salinisation

Agriculture

Agriculture, especially irrigated agriculture, is one of the main causes of AES in the world. In fact, the first major salinisation alerts on our planet (in Western Australia and in the Aral Sea) were caused by agriculture. In the case of Australia, the replacement of tree vegetation with crops and pasture led to increased rainwater infiltration and a rise in the water table. Groundwater was naturally saline, due to dilution of salts contained in the soil. The rise of the groundwater to the surface and its subsequent evaporation created large accumulations of salt in the form of clearly visible white crusts. Runoff from these areas during rainfall led to the salinisation of the surrounding rivers, such as the Murray-Darling Basin. In the case of the Aral Sea, its extension, once the fourth largest on Earth, has been shrinking dramatically since 1960. The decrease in its water volume has resulted in a 100% increase in salinisation. This was due to the combined effect of a loss in salt dilution capacity (the lower the water volume, the higher the salt concentration) and an increase in salt input from the drainage basin as a result of the expansion of irrigated agriculture, mainly cotton crops, in the tributary river basins. This type of agriculture favours salinisation because irrigation water that is not absorbed by plants evaporates, leaving a progressive accumulation of salt that ends up in adjacent aquatic ecosystems. It is estimated that an annual irrigation of 1000 mm with water having a salt content as low as 300 mg per litre adds 300 kg of salt per hectare, depending on leaching (the process by which water washes salts through the soil and carries them to deeper layers or removes them from the soil profile). Added to this is the increase of ions contained in fertilisers used to increase crop productivity. We have clear examples of this phenomenon in Spain, where, according to official data from 2005 from the Ministry of Agriculture, Fisheries and Food about 3% of the 3.4 million hectares of irrigated land in Spain is severely salinized, while 15% is at an escalating risk of salinisation. For example, in the Violada ravine, located in the irrigation area of Monegros (Huesca), high concentrations of ions (especially sulphates) were found in the drainage water.



Resource extraction

Mining is a major cause of salinisation for several reasons, such as waste generation and erosion, mainly. Perhaps the clearest and easiest example to understand is that of potash extraction mines (mineral salts, extracted and manufactured, containing water-soluble potassium), such as those in the Bages region (Catalonia, Spain). In these mines, for every part of potash that is extracted, three parts of saline residue are generated, waste which is stored in the open air forming a huge mound (currently about 120 metres high). The salts in this mound are dissolved by rainfall and humidity, and are transported by surface runoff or groundwater to aquatic ecosystems. For example, in the

Detail of the rake shape on the surface of the Vilafruns dump, due to the dissolution of the salt by rainwater. / MONTSALAT



The Cogulló salt waste tip, showing the western slope from the Castellnou mountain range. The image of the Cogulló salt waste mountain, clearly visible from practically the entire centre of Catalonia, strikes the viewer as a large patch of sterility and artificiality located in the Bages plain. / MONTALAT

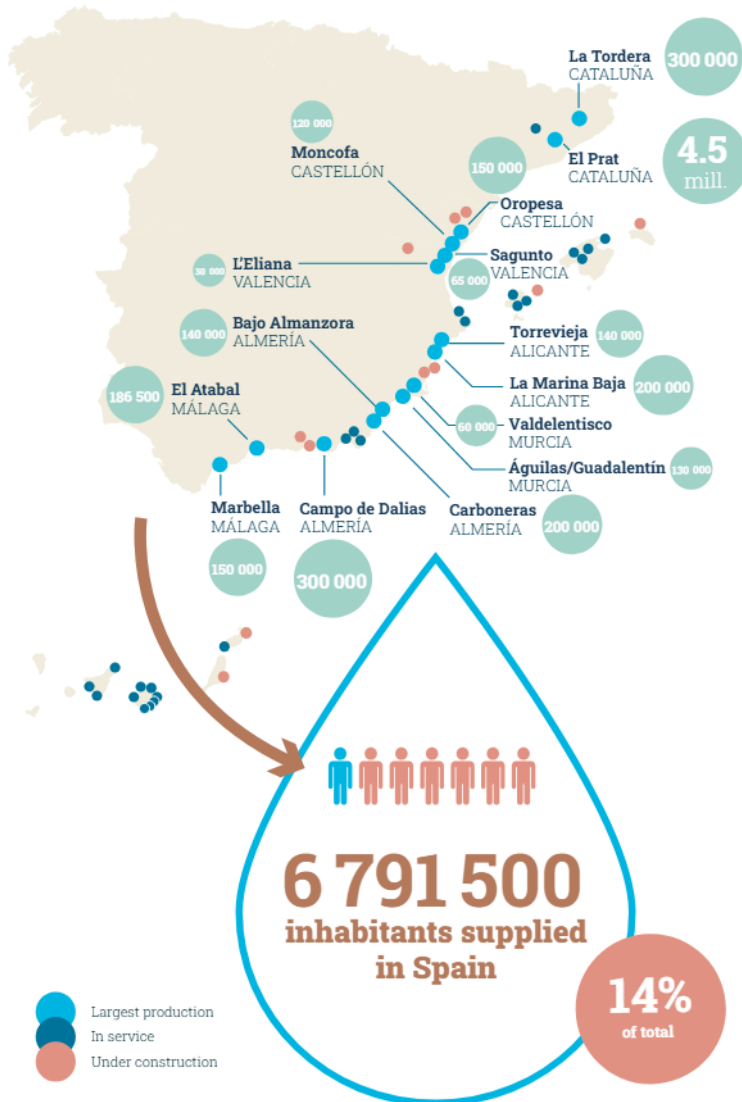
water of the Soldevilla torrent, which receives runoff from the mountain of waste, salinities five times higher than that of seawater have been detected. In an attempt to prevent this, a perimeter channel was designed to collect the runoff and take it to a retention basin. This basin is connected to a buried pipeline more than 30 kilometres long that transports the collected salt to the sea. However, the perimeter channel does not collect all the runoff, and the pipe suffers from corrosion and has broken on numerous occasions, spreading the salinisation problem downstream of the mining area and affecting the agricultural fields of the floodplain of the Llobregat and Soldevilla rivers *per se*. This case is very illustrative of a situation existing in other areas of the world where potash mining has proliferated (for example, in the Werra river basin in Germany). Beyond the particular case of potash mining, the open-pit mining of other materials is a source of salinisation due to the dissolution of salts contained in the exposed rocks. For example, in streams near coal mines in Asturias, significant increases in sulphate levels have been recorded, even after the mines have been abandoned, with a resulting salinity increase in the waters of the receiving aquatic ecosystems.

In addition to mining, oil and gas extraction through hydraulic fracturing is associated with the production of formation water (water that emerges from geological formations during the drilling process) with much higher salinity than seawater. In some regions of the world, such as the Peruvian Amazon, millions of litres of such water have been discharged directly into the river as a result of oil extraction. In other countries (e.g., the United States of America) the direct discharge of formation water is more strictly regulated, but there is still a high risk of contamination associated with accidental discharge and spills or failures in the transport and storage infrastructure. In Spain, extraction by hydraulic fracturing is not permitted, so it does not currently pose an aquatic ecosystem salinisation risk.

Desalination plants

Desalination plants are used to extract salt from seawater or inland aquatic ecosystems with high salt concentrations, for human consumption, river use, mining, etc. This industry generates large quantities of brine (water with a very high concentration of dissolved salt) as waste, which ends up in the oceans or in inland aquatic ecosystems, with devastating effects on organisms, water properties (density, pH, temperature, etc.) and the ecosystem. According to the United Nations University Institute for Water, Environment and Health (UNU-INWEH) report of January 2024, for every litre of desalinated water, 1.5 litres of brine are produced. This report estimates that the desalination industry globally discharges 142 million cubic metres of brine per day. The number of desalination plants has increased exponentially worldwide, particularly in arid countries, and their use is expected to soar in the coming years as global temperatures are rising and droughts are getting worse. Since 2012, the number of desalination plants has almost doubled. Spain, with more than 770 desalination plants, is the fifth largest producer of desalinated water in the world, and the largest in Europe, producing up to 250,000 cubic metres per day. It is also one of the countries generating the highest amount of brine and is therefore more exposed to its impacts. For example, human communities that depend on the resources from ecosystems subject to brine discharges can be severely affected. Although desalination plants in Spain have traditionally been associated with regions such as the Canary Islands, Ceuta, Melilla, the Segura basin, and, to a moderate degree, the Balearic Islands and the Andalusian Mediterranean basins, dependence on desalinated water is spreading to other areas as a result of climate change and increasingly limited access to drinking water. This is the case of Catalonia which, after three years of severe drought, has been forced to invest 467 million euros to build two desalination plants by 2028 with a capacity to treat 80 million cubic metres per year.

Figure 3 Desalination plants in Spain and population supplied with desalinated water





KANSAS DEPARTMENT OF
TRANSPORTATION (USA)

Road de-icing

Salt is widely used during the winter on mountain roads and in cold regions to prevent the formation of ice and to preserve road safety. Salt reduces the melting temperature of water, so that it can be kept in a liquid state at a temperature of about -10°C (even as low as -21°C). This avoids problems with roads freezing during snowfall or rain in winter. Sodium chloride is commonly used because of its readily available, effective, and inexpensive, although there are alternatives such as magnesium chloride or calcium chloride. As roads form impermeable surfaces, the salt applied is eventually transported by rain or melting ice to the surrounding rivers and lakes. This phenom-

enon has been extensively studied in Canada, where it has become a major environmental problem, but is also occurring in Europe (e.g., in the Alpine region). In Spain there are no studies on the salinisation of aquatic ecosystems associated with road de-icing, but recent official data on this practice suggest that a detailed study is needed to assess the extent of the problem. According to the Winter Viability Campaign of the Ministry of Transport, Mobility and Urban Agenda, in the winter of 2021-2022, the consumption of melting agents at national level amounted to 101 995 tonnes of sodium chloride, 133 992 m³ of brine (water with a dissolved salt concentration of more than 5%) and 93 tonnes of calcium chloride.

Industrial activities

There is a wide variety of industrial activities that generate brine and that end up in rivers, sometimes as a direct effluent and sometimes through wastewater treatment plants. For example, salt is used in the textile industry for the manufacture of fabrics, both to separate the organic contaminants from the fibres that will form the fabrics and to standardise the concentrates and favour the correct absorption of the dyes. In Spain, textile colonies were common in basins such as that of the Llobregat river and caused a significant increase in its salinity. Nowadays, textile factories are clustered in other countries such as India and China, where the available data also warn of a salinisation process of the receiving aquatic ecosystems. Salt is also widely used in the meat industry to reduce the water content in meat and sausages, thus helping to inhibit or stop the growth of bacteria. Another example is the paper industry, which uses salt mainly in the form of caustic soda and sodium chlorate. Global pulp production consumed about 6.7 million tonnes of caustic soda and 3.2 million tonnes of sodium chlorate in 2022. There are many other examples of industrial activities that require salt in their production processes. However, there is generally little information on the contribution of industrial activities to the salinisation of aquatic ecosystems, partly because of the non-disclosure policy associated with these activities.

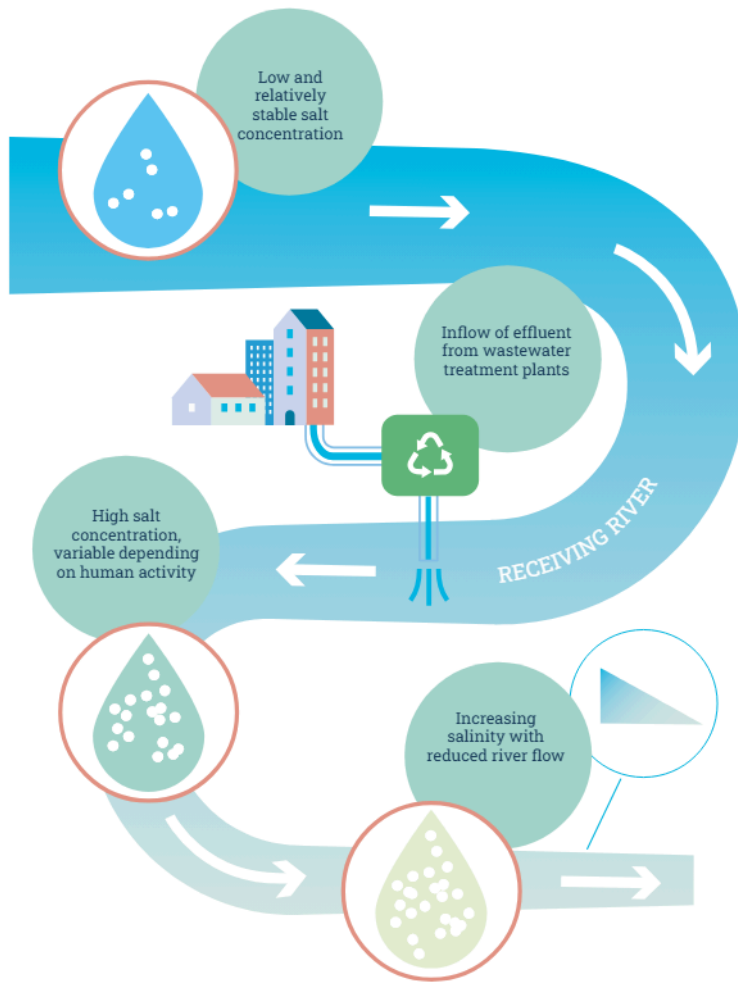


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Urban wastewater

Urban activity is associated with the generation of high-salinity wastewater. Organic matter and urea from human physiological activity are major contributors to this salinity. In addition, some personal hygiene and household care products use salts (e.g., dishwasher salt) to improve their efficiency, so their use also contributes to the salinity of urban wastewater. This water is eventually discharged into receiving aquatic ecosystems, and is therefore one of the causes of AES in urban areas. The richest countries treat 70% of the wastewater they generate, a figure that drops to 38% in middle-income nations and 8% among the poorest, according to a report published by UN-Water and UNESCO in 2018. On average, 63% of urban wastewater is treated in Spain. However, only a fraction of ions is removed in the wastewater treatment process, mainly those associated with organic matter and nitrogenous compounds (e.g., ammonium), while other salts cannot be removed (e.g., chlorides). In this sense, even in high-income countries, treated wastewater is an additional source of salts that are discharged to aquatic ecosystems on an ad hoc basis. These discharges cause abrupt increases in water salinity, although this depends on the degree of dilution of the receiving aquatic ecosystems. However, in populated regions with water shortage, such discharges can increase the conductivity

Figure 4 Increase of salinity in rivers due to inflow of wastewater from wastewater treatment plants



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of rivers by an order of magnitude (e.g., from 100 to more than 1000 microSiemens per centimetre). Finally, it is important to note that urban wastewater discharges not only raise the salinity of receiving aquatic ecosystems, but also modify the temporal dynamics of salinity, as it is partly associated with peak times of daily domestic activity (e.g., at the beginning of the day and before going to bed) or seasonal activity (e.g., in towns with tourist activity).

Marine intrusion and climate change

Marine intrusion is a complex phenomenon resulting from the overexploitation of coastal aquifers, from which water is extracted for human consumption and agricultural and livestock uses, in combination with a lower replenishment of these aquifers, partly associated with a greater demand for water in the river basins. Of the 95 coastal aquifers in Spain, more than half have some form of marine intrusion. For example, in the Llobregat delta, seawater advanced about four kilometres inland between 1960 and 1980, leading the Catalan Water Agency to construct a positive hydraulic barrier by injecting reclaimed water into 14 wells. Marine intrusion in Spain will be exacerbated by climate change, which leads to rising sea levels, decreasing rainfall and increasing number of storms. Rivers that experience reduced flow in their catchments will contribute less water to coastal aquifers, which in turn will be subject to increased saltwater intrusion due to rising sea levels and increased storm surges, leading to salinisation of aquifers, their associated ecosystems (e.g., wetlands) and estuaries. At the same time, existing climate and hydrological models predict a reduction in flow in most of Spain's river basins in the coming decades as a consequence of climate change. Obviously, this is not a problem in Spain only; it is something that occurs in many other parts of the world such as the coast of Bangladesh or the Nile delta.

1.3.

Main consequence for aquatic ecosystems and society

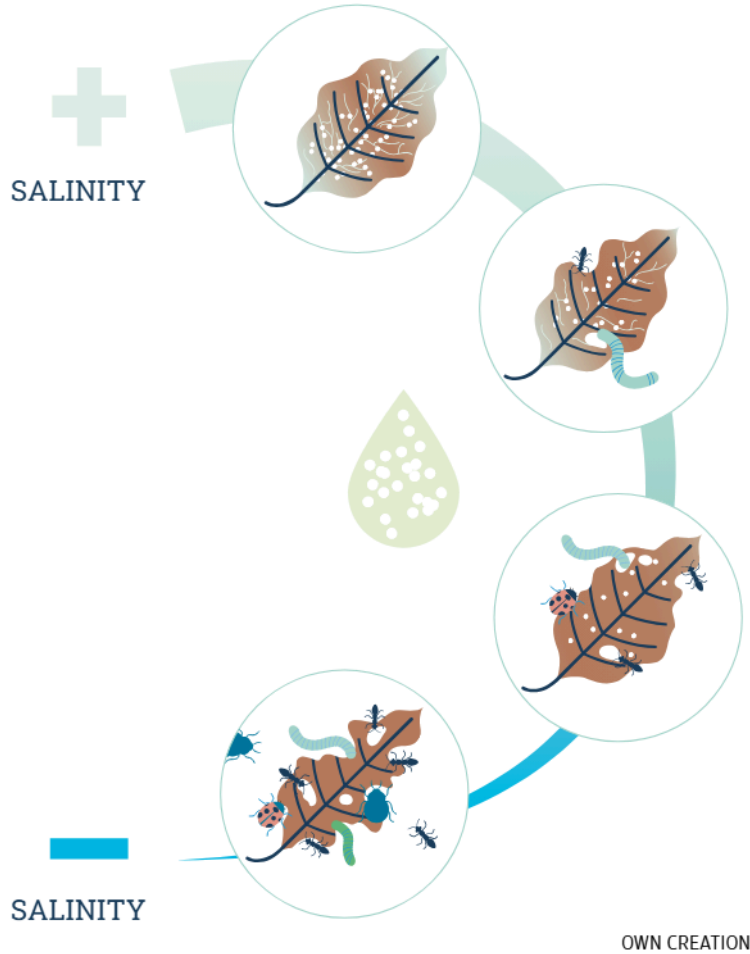
As studies build up on the effect of AES on ecosystems and society, it is becoming increasingly clear that this is a global threat that needs to be urgently addressed. We are still unaware of many of the potential impacts of AES, which are hardly quantified in terms of economic or ecosystem service losses. However, some ecological disasters associated with aquatic ecosystem salinisation have raised social alarm. For example, hundreds of thousands of fish died in the Oder River (the longest river in Poland) in just a few weeks during July and August 2022. This is one of the largest documented ecological disasters in rivers in Europe, and was due to the presence in the water of prymnesin, a toxin generated by the algae *Prymnesium parvum*. This is an estuarine species, adapted to high salinity conditions, which proliferated massively during the summer of 2022 due to high concentrations of salts in the Oder river from mining and agriculture. In Spain, there is still no clear evidence that AES has caused major ecological disasters. However, there are several incidents at the local scale that warn of the need to anticipate and mitigate risks. In the following, we describe the ecological and socio-economic impacts of AES according to the available information, as the identification of these factors is indispensable to be able to propose and implement adequate management strategies. In this regard, it is important to stress that the salinisation of aquatic ecosystems does not only imply an increase in salts, but also a change in the ionic composition of the water. This change depends on the source of the increase in salinity. For example, the use of salt on roads to prevent icing often increases the proportion of chloride in the water of receiving aquatic ecosystems, while agriculture contributes to an increase in the proportion of other ions, such as sulphate. Thus, there is a need to understand the environmental and socio-economic risks associated with different ions and how they are related to the human activities that cause AES.

Consequences for biodiversity and ecosystem functions

Most organisms living in inland aquatic ecosystems (insect larvae, amphibians, fish, etc.) have evolved in freshwater and cannot tolerate high salinity concentration. This is because they need to maintain an osmotic balance, i.e., the concentration of ions (the particles that make up salt) inside the cell must be in balance with that in the body fluids. If the salt concentration in the water increases, it also increases in the body fluids, as the bodies of aquatic species are semi-impermeable. This breaks the osmotic balance and leads to the death of the cell and the individual. To avoid this imbalance, organisms have internal mechanisms that allow them to excrete ions, but this consumes a lot of energy, which would be needed for basic functions such as growth or reproduction. Thus, fish populations in salt-polluted lakes have been found to be smaller than those in non-polluted lakes.

In general terms, salinisation causes a reduction in aquatic biodiversity. As the salt concentration increases, freshwater species (which are the majority) disappear and in the end only a fraction of those able to tolerate high salinity concentrations (e.g., some bacteria, algae, and insect larvae) survive. If the salt concentration becomes extremely high (as has happened, for example, in the Soldevilla stream affected by the Sallent salt mines in Catalonia) the water becomes transparent due to the absence of organisms (including algae). We are immersed in a global crisis in which freshwater species are disappearing at an accelerating rate, much faster than marine and terrestrial species. The disappearance of freshwater biodiversity could have serious consequences for ecosystem functioning, as all species play a role in ecosystems. For example, certain insect larvae are responsible for shredding leaves that fall on river beds. By shredding them, the organic matter contained in the leaves becomes available for other species, thus benefiting the entire ecosystem. It has been shown that these insect larvae are particularly sensitive to salinity, so that when the concentration of salts increases, these organisms disappear and, therefore, the rate of leaf litter decomposition in rivers decreases.

Figure 6 Effects of salinity on leaf litter decomposition in aquatic ecosystems



Consequences for human health

Intake of water with high salt content can pose serious risks to human health. For example, in Bangladesh, there has been a significant increase in the incidence of pre-eclampsia in pregnant women, which can lead to the death of the mother, the baby or both. An increase in hypertension has also been recorded in different parts of the world, associated with an increased incidence of heart disease. Obviously, the health risks associated with direct ingestion of high-salt water are much more prevalent in developing countries where technologically advanced water treatment plants are not available. However, risks also exist in developed countries. For example, in the city of Flint (Michigan, United States of America), from 2014 to the present day, the high salinity of the water, mainly due to the use of melting agents on roads, caused lead to leach out of the pipes in the water distribution network. This lead ended up in the water consumed by the population, with blood lead levels two to three times higher than average in the city's children. This contamination affected between 6,000 and 12,000 children, with effects on their mental health and school performance. Water samples collected from 252 homes by residents themselves indicated that lead levels throughout the city had increased. In addition, nearly 17% of the samples recorded values above the federal action level (15 *parts per billion*, ppb), at which corrective action must be taken. More than 40% of the samples showed lead values above 5 ppb, which researchers considered an indication of a very serious problem. Another example is represented by the Llobregat river, where salts from mining (especially bromine salts) led to the formation of trihalomethanes (THMs), which are volatile chemical compounds generated by the reaction of organic matter with salt. Since 1977, the laboratory of the Sociedad General de Aguas de Barcelona has analysed the presence of THMs in Llobregat river water and found total concentrations frequently higher than 100 micrograms per litre, exceeding the value above the limit established by the US Environmental Protection Agency (EPA). Although the situation improved over time, especially after the construction of a brine trap at the salt mine, the concentration of THMs remained significantly elevated. THMs pose a serious environmental and health risk, as corroborated by epidemiological studies in Barcelona waters linking them to bladder cancer.

In addition to the risks related to the toxicity of the water we drink, there are indirect and less obvious risks to consider. For example, in Australia, salinisation of wetlands led to the proliferation of the *Aedes camptorhynchus* mosquito, which is a halophilic species and the main vector of the Ross River virus, whose symptoms include joint pain and swelling, muscle pain, fever, fatigue, and rashes. Similarly, although much less studied, salinisation could lead to increased incidence of malaria through the proliferation of vectors, as several species of malaria-transmitting mosquitoes have a preference for brackish water. In addition, salinised landscapes, such as those found in the Aral Sea region, are associated with respiratory conditions, due to increased particulate matter, and with an increased incidence of mental illness. Overall, we have little information on the potential effects of salinisation on human health, but there is sufficient evidence to suggest that the level of risk is high. Consequently, the World Health Organisation has established this issue as a priority for global research.

Economic consequences

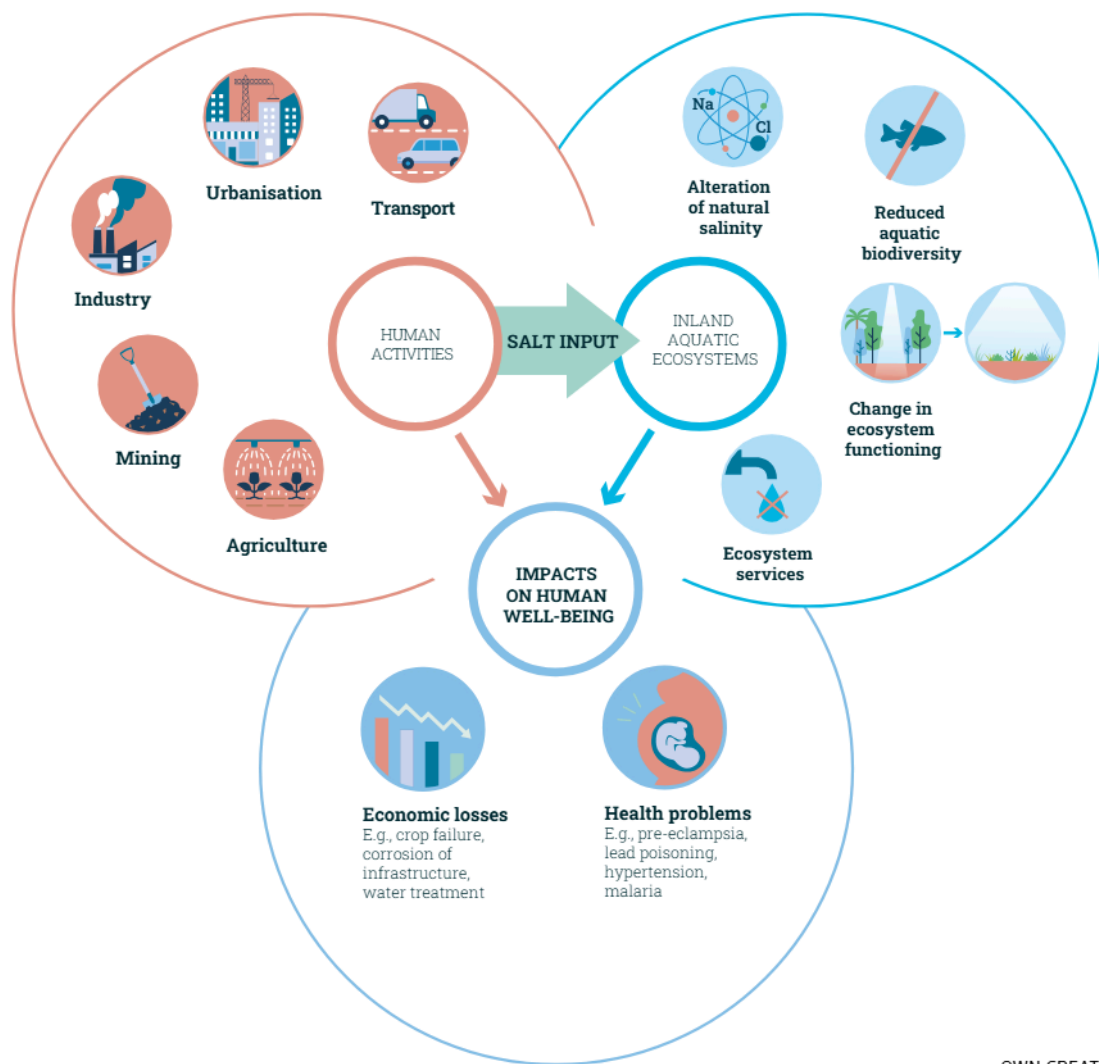
AES has serious economic consequences that are beginning to be quantified. For example, a recent review of the impacts of marine intrusion in Europe concluded that its economic costs range from €577-610 million per year (M€) and are expected to increase significantly with the effects of sea level rise. One of the most obvious economic costs of AES is associated with the repair or replacement of infrastructure damaged by salt corrosion. For example, in Australia, an estimated annual cost of A\$982 million has been estimated (equivalent to €603 million) to repair corrosion of key water distribution infrastructures. There are also obvious costs related to the treatment of water for human consumption, as the concentration of salts should not exceed the limit of 1 gram per litre of water established as safe by the World Health Organisation and ideally should be below 600 milligrams per litre to preserve its palatability. For example, in the Llobregat river in the late 2000s, desalination systems had to be installed, at a cost of €130 million, to remove salts and dissolved solids from the water to make it fit for human consumption. The operation of these water treatment technologies requires an enormous amount of energy. The electrodialysis reversal (EDR)

system at Aigües Ter Llobregat (ATLL) consumes approximately 13 gigawatt-hours (GWh) per year, at a cost of approximately €1.2 million per year.

There are other economic costs associated with AES that are less visible but could be significant. For example, farmers and livestock breeders near the salt mines in Sallent (Catalonia) have reported economic costs associated with crop failure, livestock deaths and the need for drinking water supplies (e.g., through the use of tanker trucks) due to the salinisation of their well water. In this regard, it is important to mention that soil salinisation (closely linked to AES) has immense economic costs as a result of reductions in crop productivity. Recent EU estimates calculate an economic loss of between 141 and 483 euros per tonne produced for crops affected by saline water (e.g., with conductivity of 4 deciSiemens per centimetre). This cost varies according to the type of farming practice, with flood agriculture being the most affected by salinisation, followed by irrigated agriculture.

Finally, it is important to take into account indirect economic costs associated with the loss of benefits obtained from nature (also called *ecosystem services*). In this regard, the most intuitive benefits are those related to the provision of food and water. In the Aral Sea, salinisation led to the collapse of fisheries, which were one of the region's main economic revenues in the late 1950s, with annual production of 50 000 tonnes falling to just 5000 tonnes during the 1990s. However, there are many other benefits we derive from aquatic ecosystems that are affected by AES. For example, freshwater ecosystems play an important role in the retention, transformation and transport of nutrients and in climate control. In this sense, salinisation alters biogeochemical cycles through numerous processes such as desorption of phosphorus from sediment or reduction in litter decomposition and, although this is an issue that has been barely studied, it could lead to an increase in greenhouse gas emissions from aquatic ecosystems into the atmosphere.

Figure 7 Causes and consequences of aquatic ecosystem salinisation



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The CSIC Tackles the Scientific, Economic, and Management Challenges Posed by Salinisation



THE salinisation of inland aquatic ecosystems is a global phenomenon with serious consequences for biodiversity, ecosystem functioning and human well-being. However, salinisation has been relatively understudied compared to other environmental issues. For example, according to the Web of Science, one of the world's leading databases with bibliographic references of scientific content relevant to research, in 1980, about 300 scientific articles were published on metal pollution and as many on pesticide pollution, while articles on salinisation amounted to less than 20. In the 1990s, nutrient pollution became very relevant, but papers on salinisation were still practically non-existent.

However, it is only in the last ten years that salinisation has started to emerge as a line of research of interest and as a subject of study in a multitude of scientific articles, but it has received much less attention than other environmental issues. In this period, around 70 articles per year have been published on salinisation compared to more than 600 related to nutrient pollution. Moreover, research on this environmental problem is fragmented. It has mainly been studied in North America, Australia, and Europe. The studies carried out also show a clear partiality depending on the country where they are carried out. For example, road salt pollution has been studied almost exclusively in Canada and the United States, although we know that it occurs in regions of Europe such as the Alps and the Pyrenees. Similarly, pollution caused by salt mining has almost exclusively been studied in Europe, although we know that there are large salt mines in Canada and different countries in South America.

In short, our knowledge of salinisation is still very limited. The CSIC is working to fill the existing gaps in knowledge about this environmental problem, which can be considered a priority. For example, the World Health Organisation has identified the health risks of salinisation as a priority research issue due to the lack of information and its potential to affect millions of people. There are numerous research challenges ranging from physiological questions of how organisms regulate their internal salt content through cellular processes to questions of how salinisation alters the structure and functioning of ecosystems. There are also many areas yet to be explored in terms of their impact on human health and the economic consequences of the effects of salinisation. This section shows some of the challenges associated with salinisation and the CSIC's significant contribution in addressing the issue.



2.1.

Extended studies and design of management strategies

IN the context of global change, resulting from human activities, inland aquatic ecosystems are subject to factors that alter their structure and functioning. Response to these factors combined is more complex and more difficult to predict than a response triggered by only one of them. Salinisation is not exempt from this complexity, as it encompasses a wide range of chemical compositions and coexists with other environmental problems. This is why there are still many gaps in knowledge about its effects, especially those derived from the interaction between salinisation and other environmental factors. However, the CSIC has international reference groups in the experimental study of these effects and interactions. In the following, we describe different aspects of salinisation that are important for understanding its impact on organisms, feeding interactions between them and communities in inland aquatic ecosystems. These considerations are also relevant for the development of management strategies to mitigate these effects.

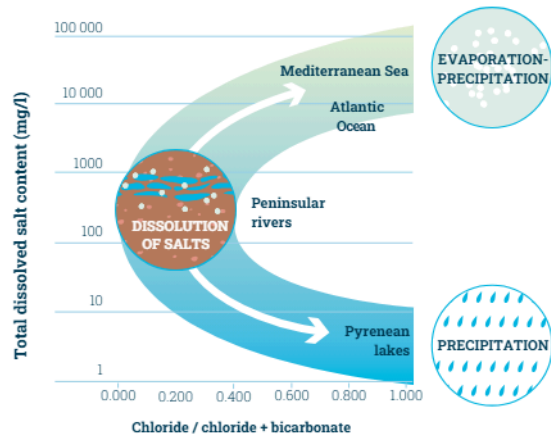
As noted in the introduction, salinisation of inland aquatic ecosystems due to human activity leads not only to an increase in salt content, but also to a variation in the proportion of different ions. This change is relevant, since the harmful effects of salinity on aquatic organisms depend on both the increase in salinity and the type of ions contributing to salinity. Salinisation is therefore associated with a wide variety of “chemical cocktails”, some of which are easy to identify if the origin of their cause is taken into account. Some of these cocktails are briefly described below:

- **Agriculture:** Freshwater salinisation in agricultural areas depends on soil characteristics as the soil releases different ions into runoff water. In addition, the use of fertilisers adds different ions such as sodium, potassium, sulphate, and chloride, which also contribute to salinisation. Pesticides likewise have toxic effects on organisms, although they do not catalyse salinisation.

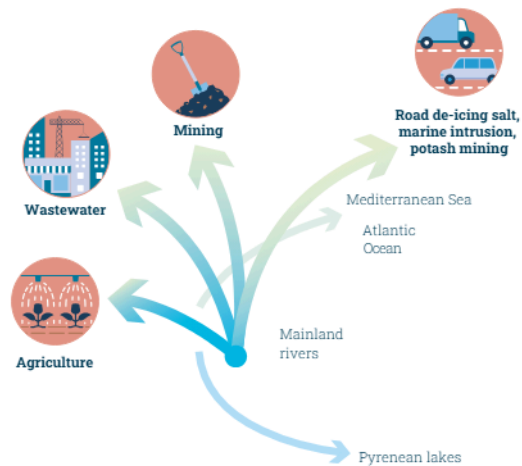
- **Use of salt on roads:** Sodium chloride is the salt most commonly utilised to prevent ice formation, although there are also alternative practices using magnesium chloride or a mixture of salts with organic additives. In addition to these salts, road runoff contains toxic compounds, such as metals and hydrocarbons derived from vehicles, which reach the receiving aquatic ecosystems.
- **Potash mining:** Effluents from potash mines are often dominated by sodium chloride, but concentrations of potassium and magnesium can also be high. In general, these effluents do not contain additional toxic compounds, although some studies have detected the presence of bromide and the formation of trihalomethanes in other mining effluents.
- **Coal mining:** Coal mine effluents are rich in sulphate, carbonate, calcium, and magnesium. These ions often coexist with other chemical elements and metals that are solubilised by exposure to the rocks. In addition, the chemical catalyst in these discharges can be characterised by an acidic pH and therefore has a higher capacity to mobilise metals.
- **Industrial and urban activities:** Although of very different origins (textile, meat industry, metallurgy, paper, pharmaceuticals, etc.), industrial effluents can have high sulphate concentrations. These further combine with urban effluents, which contain a wide range of pollutants, such as organic compounds, pharmaceuticals, plastics, and metals. These discharges contain very complex and diverse chemical cocktails with varying degrees of salinity and toxicity.

Figure 8 Salt content and composition in aquatic ecosystems and natural and anthropogenic factors with an impact on water salinity

Distribution of aquatic ecosystems according to their natural salinity and factors determining salinity



Projection of changes in the saline composition of water in aquatic ecosystems due to different human activities



In view of this wide diversity of chemical cocktails responsible for salinisation, much of the research has focused on experimentally examining the effect of increased salinity derived from sodium chloride (NaCl) on different aspects of aquatic organisms. The CSIC has shown that the effect of salinity on organisms can be modulated by the physical-chemical conditions of the water in aquatic ecosystems. Specifically, the tolerance of freshwater organisms to salinity is greater the lower the temperature and the greater the water hardness (high calcium carbonate concentration). Similarly, salinity has little effect in acidic pH waters (values below 7), while in alkaline pH waters (values above 7) the effect is increased. However, it is to be expected that each chemical cocktail has its specific effects on the organisms and communities of the receiving ecosystems. There is also evidence that the effect may be different if inflows occur acutely (i.e., over a short period of time and usually with high salt concentrations) or chronically (i.e., over a long period of time and usually with low salt concentrations), with the latter causing the most significant alterations.

Indirect effects of salinisation on aquatic ecosystems

Salinisation can cause changes in the concentration of other chemical compounds, which in turn affect aquatic organisms and ecosystems. In this sense, salinisation not only causes direct effects on aquatic organisms, but also indirect effects. For example, CSIC researchers have shown that the increase in salts favours an increase in the alkalinity of the water, which in turn modifies the availability of organic matter, nitrogen and phosphorus, and the biogeochemical processes associated with these elements. This phenomenon has been described as the *salinisation syndrome*.

Apart from this phenomenon, higher salt concentrations have been observed to lead to changes that can indirectly mitigate the effects of other environmental problems, such as reducing the toxicity of metals to organisms. But they can also intensify the effects, such as the mobilisation of heavy metals in runoff water that end up reaching aquatic ecosystems from de-icing salts used on roads.

Other indirect effects of salinisation have been reported in rivers flowing through agricultural areas, where the toxicity of some pesticides is enhanced under high salinity conditions, although studies show that this phenomenon is not widespread. Increased salinity can also contribute to problems caused by eutrophication (excessive nutrient enrichment) of aquatic ecosystems. Saline ions can mobilise organic nitrogen, ammonium, and phosphate adsorbed onto riverbed sediment. Increased nitrogen and phosphorus can cause excess algal production leading to a decrease in oxygen availability, especially at night, negatively affecting macroinvertebrates and fish. In addition, the predominance of these two chemical elements, together with an imbalance in their proportions, can lead to an overgrowth of cyanobacteria. High levels of cyanotoxins have negative consequences on aquatic communities, birds and even the human population. A paradigmatic case of this environmentally devastating indirect effect is the 2022 Oder river catastrophe described in the first part of this report.

These examples highlight the importance of addressing salinisation problems from a broad perspective that goes beyond the direct effect of saline ions on aquatic organisms and their ecosystems. This requires interdisciplinary studies that incorporate different perspectives on the same problem.

This approach must make it possible to anticipate impacts at different levels (chemical, geological, biological) and to address complex ecosystem responses.

Effects derived from the interaction between salinisation and other environmental problems

Salinisation often arises together with many other human-induced alterations (e.g., eutrophication, metal pollution, suspended solids inputs and climate change). We need to establish whether there is an interaction between the different factors involved in these environmental problems and, if so, what kind of effect they produce in order to anticipate their consequences on the structure and function of aquatic ecosystems. The reciprocal action of the factors can cause additive effects (equivalent to the sum of the effects of each factor separately), or an effect greater (synergism) or lesser (antagonism) than that caused by the sum of the effect of each factor.

A research group, with CSIC representation, carried out a compilation of experimental studies focused on examining the effects of salinity and how they vary when combined with other factors involved in environmental problems (temperature, nutrients, metals, pesticides, carbon dioxide, hypoxia, sulphate or pH). The study reported that, among the factors examined, salinity had the highest negative effect on organisms. This result highlights the need for increased management efforts to mitigate the problem of salinisation. It was further found that most studies have focused on the interaction of salinity with water temperature or toxic compounds. The combination of salinity and temperature mostly causes additive effects (54% of the 105 responses examined) on invertebrates and algae. In contrast, the interaction between salinity and toxic compounds produces antagonistic effects mainly on vertebrates.

There is less information on the interaction between salinity and other stress factors, although some combinations are common in Spain (such as in rivers receiving effluent from wastewater treatment plants or affected by drought or water abstraction) and deserve further research. The case of rivers receiving effluent from wastewater treatment plants is a paradigmatic example in the study of effects derived from multiple stress factors (for example, combined with an increase in salinity, temperature, organic matter, nutrients, emerging pollutants and pathogens). Although it is a complex situation and difficult to address experimentally, it would be very interesting to determine whether there is a hierarchy between factors according to the effects they cause, in order to be able to manage this problem more effectively. The CSIC has carried out research on the effects of salinity in combination with high nutrient concentrations. This study shows that the high proportion of salts affects microbial communities in biofilm, the composition of primary producers (dominance of cyanobacteria versus diatoms and filamentous algae) and the richness and diversity of macroinvertebrates. However, this effect decreases under high nutrient concentration conditions (antagonistic interaction). Another study, focused on assessing the effects of drought, analysed the interaction between salinity, water velocity and turbidity. This study found that salinity can enhance the resistance of organisms to desiccation, but aridity can reduce their resistance to salinity. However, more experimental studies are needed to further detail these responses and to see if they are consistent between rivers with different characteristics.

2.2.

Work related to ecological impact

AQUATIC ecosystem salinisation has an enormous ecological impact and affects the different levels of organisation, from individuals to ecosystems, as well as key ecological processes and the interaction between organisms. The effects on biodiversity are manifold; they directly affect the survival of organisms and favour the dispersal and establishment of invasive species, one of the main causes of biodiversity loss worldwide. Salinisation can also have non-lethal effects (i.e., changes in the biological condition without causing immediate death), which can significantly affect the health, behaviour, growth, reproduction and long-term survival capacity of aquatic organisms. The CSIC is working in all these directions.

Impacts on different groups of aquatic organisms

Water salinisation affects a wide range of aquatic organisms, from microorganisms, such as bacteria and algae, to macroorganisms, such as macroinvertebrates, fish, mammals, and aquatic plants. When salinity increases in freshwater ecosystems, the most sensitive species, known as *stenohalines*, which can only survive in a very limited range of salt ratios, often disappear, in contrast to *euryhalines*, which can adapt to a wider range. CSIC research on salinisation covers all the main groups of species that inhabit inland aquatic ecosystems.

Microbial communities are fundamental to the functioning of aquatic ecosystems. Microorganisms regulate nutrient cycling, decompose organic matter, participate in primary production, control greenhouse gases, purify water and sustain the food web, contributing significantly to the resilience and stability of these ecosystems. CSIC researchers have demonstrated changes in the microbial activity of coastal wetland sediments affected by salinisation, going from being dominated by heterotrophic bacteria to archaeal prevalence, which points to fundamental changes in microbial ecosystem functions, with potential implications for organic matter decomposition and greenhouse gas production.

Phytoplankton are a group of tiny algae living in water whose primary function is photosynthesis, producing oxygen and converting carbon dioxide into organic matter. This biomass forms the basis of the food web in aquatic ecosystems and is consumed by a variety of organisms, including zooplankton, other invertebrates and small fish. The CSIC has found that increases in chloride concentration above 500 milligrams per litre lead to significant reductions in phytoplankton biomass. It is thought that this problem is probably due to direct toxic effects on water regulation and nutrient uptake by algae. For example, if we add too much salt to a pond, the algae may have trouble maintaining its balance of water and nutrients. This is like a person trying to drink salt water; their body would have difficulty staying hydrated and absorbing the necessary nutrients. Thus, excess salts not only affect the algae, but also the entire aquatic ecosystem that depends on them.

Zooplankton are small animals (mostly crustaceans) that live in the water and act as an intermediate link in the aquatic food web. On the one hand, they feed on phytoplankton, thus controlling primary production, and, at the same time, they are consumed by small fish, fish larvae, and invertebrates. This energy transfer is essential for the survival of many aquatic species. CSIC studies have shown that increased chloride concentration resulting from human activities leads to a drastic reduction in the biomass and average body size of zooplankton, with important consequences for the food web.

Macroinvertebrates act as indicators of water quality, recycle nutrients, form a crucial part of the food web and contribute to the stability and resilience of the ecosystem.

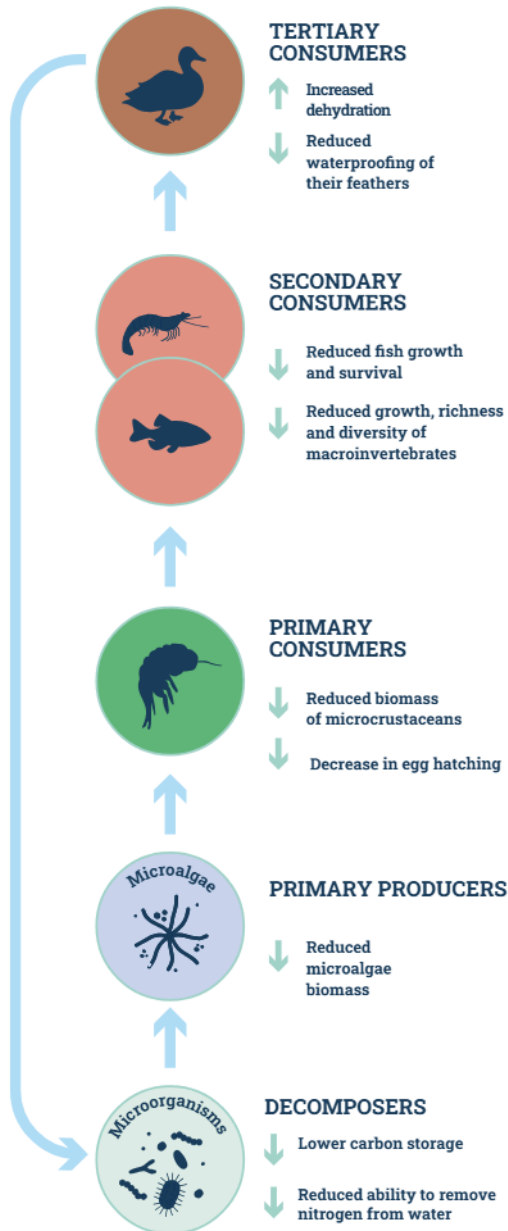
An experimental study under the CSIC's leadership has shown that concentrations of 3000 milligrams per litre can cause significant decreases in macroinvertebrate richness and diversity. These results are crucial for establishing critical thresholds of salt and nutrient concentration in river ecosystems, setting better indicators and developing plans to protect aquatic environments from salinisation.

Waterbirds are essential components of their ecosystems and fulfil numerous key functions, such as the dispersal of organisms, one of the main ecosystem services they provide to society, as demonstrated by numerous research projects carried out by various CSIC groups. They are also excellent bio-indicators of environmental change and very useful for the conservation of other taxonomic groups insofar as they serve as protective umbrellas for biodiversity. In other words, if we protect waterbirds, we can assume that we are protecting a large part of biodiversity. However, climate change and increased salinity are significantly affecting waterbirds in Mediterranean wetlands; on the one hand, through the decline of aquatic plants and invertebrates, and on the other, by affecting their physiology. Increased salinity is a major stressor for birds, which must excrete excess salt when ingesting water during feeding, which, as already mentioned in section 1, entails a considerable energetic cost. In addition, an excess of salt can increase dehydration and affect the waterproof quality of their feathers. CSIC research has shown that salinity is the most important factor influencing the distribution of these birds.

Impacts on the interactions between organisms and food webs

Salinisation affects ecosystem functioning by altering the interactions between aquatic organisms. For example, if salinity reduces populations of algae and aquatic plants, those invertebrates and fish that depend on them will also be affected. This, in turn, will affect birds and other fish-eating animals. These changes may lead to a decline in biodiversity and the loss of important ecosystem services such as water quality and recreation. Detecting these effects in natural environments is complicated, as field studies cannot always isolate salinity from other factors. However, the use of experimental systems, such as mesocosms, allows their study under controlled conditions. Thus, the CSIC is investigating the salinisation of aquatic environments in experimental riverbanks or ponds. For example, studies in Spain have shown that increased salinity affects predator-prey dynamics, altering the abundance and richness of herbivorous invertebrates and, in turn, the biomass of algae. This research illustrates

Figure 9 Effects of salinity on organisms at different trophic levels



This figure illustrates the impacts of salinisation at several trophic levels, from decomposers to tertiary consumers. The trophic levels are arranged vertically and include: decomposers (microorganisms), primary consumers (microalgae), primary producers (microcrustaceans), secondary consumers (fish and macroinvertebrates) and tertiary consumers (waterbirds). The blue arrows represent the energy flows between trophic levels in an ecosystem, starting with decomposers, which recycle dead organic matter and return nutrients to the ecosystem, and primary producers (plants and algae), which capture energy from the sun. This energy is passed to primary consumers (herbivores), then to secondary consumers (carnivores and omnivores) and finally to tertiary consumers (top predators). It is essential to understand how the effects of salinisation affect the structure and dynamics of ecosystems.

OWN CREATION

that, even without immediate mortality, salinity can induce significant stress on predators or prey, which could lead to long-term ecological changes.

Species loss due to salinisation and modification of trophic interactions affects the balance of aquatic ecosystems. The effects of salinisation need to be studied at multiple trophic levels to understand how the responses of aquatic organisms are interconnected. This holistic approach enables the development of more effective strategies to protect and manage these ecosystems in the face of the challenges of environmental change. The CSIC is leading several projects assessing the effects of salinisation on the entire aquatic food web, including microorganisms, algae, crustaceans, and other invertebrates. It has been evidenced that aquatic ecosystems can undergo irreversible changes when trophic interactions are altered. For example, in nutrient-polluted shallow lakes, shifts from a clear water phase dominated by aquatic plants to a turbid water phase dominated by massive algal blooms have been recorded. This was mainly due to the loss of water fleas, small crustaceans that feed on algae. Once the phase change occurs, it is very difficult to reverse it, due to the cascading effects it triggers, hence simply reducing nutrient concentrations is not enough. This new phase of turbid water means a decline in biodiversity and a loss of ecosystem services, such as access to drinking water and recreational benefits, as mentioned above. Some studies suggest that salinity could cause similar phase changes, since key species such as the water flea are highly sensitive to salinity. Anticipating such changes is vital in a context of water scarcity and climate change, which will intensify salinisation.

Impacts on biodiversity through invasive species

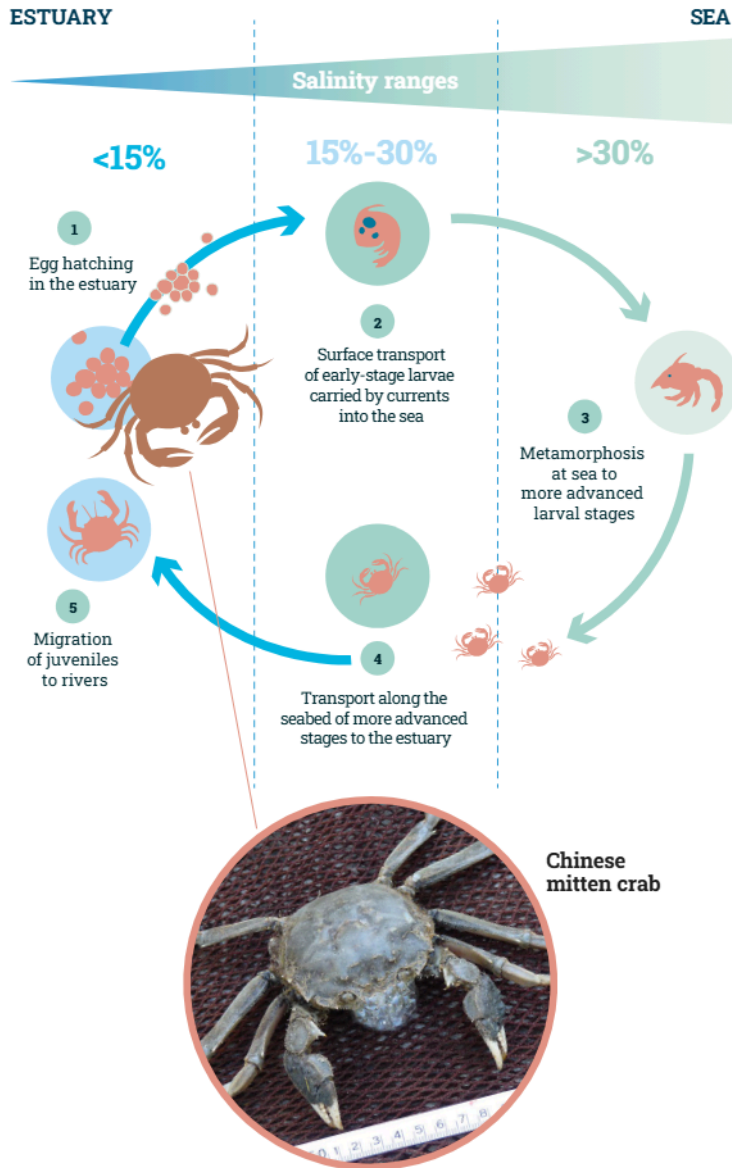
Invasive species represent one of the greatest threats to global biodiversity, compromising the functioning, structure, and stability of ecosystems. They also have devastating effects on ecosystem services and human well-being, with significant economic and public health consequences.

There are numerous examples of how salinisation is promoting the spread of invasive alien species. The case of the Aral Sea is one of the best-known examples of how increased salinity led to a replacement of native fish species by invasive alien species before its complete desiccation. Although the effect of salinisation on invasive success depends on species and context, it is possible to predict to some extent which conditions, life history characteristics or pathways of introduction may be more conducive to establishment and expansion in the face of increased salinity. For example, ballast water (taken onboard by ships for stability) is a primary vector for the introduction of non-native species into coastal waters worldwide. This is of particular importance in Spain, a country which accounts for up to 10% of international maritime traffic, and is most vulnerable to experiencing an increased influx of species under salinisation scenarios. Although only a small part of the transported organisms can settle in freshwater, the increased salinity of these ecosystems could likewise increase their probability of survival and establishment. On the other hand, brackish water species, euryhaline species (with a wide range of salinity tolerance) or diadromous species (migratory species that move through environments of varying salinity throughout their life cycle), are also candidates for extending their distribution ranges in the face of salinisation. In this regard, the monitoring of these species and ways of introduction should be prioritised. The following are some examples of invasive species of high concern in Spain, which meet one or more of the aforementioned characteristics.

Chinese mitten crab (*Eriocheir sinensis*). It is among the hundred most harmful invasive species in the world and is among the twenty worst in Spain (GEIB, Grupo Especialista en Invasiones Biológicas). Originally from the coasts of East Asia, it was first detected in northern Europe at the beginning of the last century, and since then it has spread along the Atlantic coast, reaching Portugal (Tagus river) and Spain (Vigo, Basque Country and Guadalquivir basin). Although its main vector is ballast water or adhesion to the hull of ships, it has also been voluntarily introduced into Spain through illegal trade, as it is a very popular product in the Asian food market.

The Chinese mitten crab is a migratory species. Adults move in autumn-winter from the rivers to the sea, where they reproduce. Larvae and juveniles migrate to the rivers in spring, where they reach adulthood. In this process, larvae undergo ontogenetic changes in their salinity optimum and show a good tolerance (between 15‰ and 30‰) in the early stages. In the intermediate stages they are more dependent on higher salinities (above 30‰); while in the later stages they show higher tolerance to low salinities (below 15‰).

Figure 10 Effect of salinity on the larval development of the Chinese mitten crab



OWN CREATION. Photo Chinese crab: JUAN GARCÍA DE LOMAS

Development to adulthood can occur throughout the entire salinity range. In the Guadalquivir estuary, the presence of the Chinese mitten crab has been a major concern, as a very abundant population was detected in Seville harbour docks a decade ago. This has led to control actions using crab traps, especially during their migration downstream (autumn-winter), preventing them from reaching the sea and, therefore, their reproduction. However, the increase in salinity in the estuary could make it easier for this species to reproduce upstream, complicating control actions. The CSIC, in collaboration with different hydrographic confederations, is working on monitoring actions. Currently (2024), there is a campaign in the Segura basin in search of the Chinese mitten crab and other invasive species (red swamp crayfish, signal crayfish, marbled crayfish, blue crab, and Australian red claw crayfish). The Infraestructura Científico-Técnica Singular de Doñana (ICTS-RBD) [Doñana Unique Scientific-Technical Infrastructure], belonging to the Estación Biológica de Doñana (EBD, CSIC) [Doñana Biological Station], also carries out long-term monitoring of aquatic communities, paying special attention to the Chinese mitten crab, among other invasive species.

The Chinese mitten crab is known to have a huge ecological, economic, and health impact. It affects the biodiversity of invertebrates, macrophytes, algae, and fish through predation and competition, contributing to their local extinction. It alters river banks through its excavating activity, favouring erosion. Not only is the environmental impact alarming, but also the enormous economic costs associated with it. Due to high crab population density, they cause damage to pipes, especially during migration, in aquaculture installations, in fisheries, feeding on commercially relevant species, etc. Although there are still no studies on the subject in Spain, in countries such as Germany, where the species was detected for the first time, annual losses of 80 million euros have been estimated. According to a study by an international group of scientists from Spain, the United States, Germany, the United Kingdom, the Czech Republic, Italy

and France, with the participation of research staff from the Doñana Biological Station, the costs of eradicating invasive crab species have been estimated at \$271 million, although these costs are greatly underestimated. On a health level, the Chinese mitten crab is an intermediate host of the lung parasite *Paragonimus westermani* (trematode known as *lung fluke*), whose final host is mammals, including humans. Infection, caused by consumption of raw or undercooked crabs, results in paragonimiasis, a potentially serious lung disease; allergic reactions and central nervous system disorders have also been reported. In addition to the above, consumption of this crab can affect human health due to its tolerance to high levels of contamination and bioaccumulation of large amounts of pollutants; this, together with poor quality control, makes the Chinese mitten crab unsuitable for human consumption.

Gambusia or eastern mosquitofish (*Gambusia holbrooki*). Like the Chinese mitten crab, the gambusia is one of the 100 most harmful invasive species in the world. It is native to the Atlantic coast of the United States and was deliberately introduced into Spain in the 1920s to control malaria-carrying mosquitoes, from where it spread throughout Europe. In Spain it is one of the most widely represented freshwater fish species, especially in the east and southwest of the Iberian Peninsula and in the Ebro basin. Although the *Gambusia* is a freshwater fish, it is capable of surviving in a wide range of salinities and shows its optimum development in oligohaline waters (between 0.5‰ and 5‰, slightly above what is considered freshwater, less than 0.5‰) or mesohaline waters (between 5‰ and 18‰). In addition to its tolerance to salinity, this species is able to survive in degraded and polluted environments. On the other hand, research by the CSIC has shown a low susceptibility to parasites, one of the main mechanisms explaining the competitive success of invasive species (enemy release hypothesis).

The ecological impact of *Gambusia* on native communities is enormous and profoundly affects ecosystem functioning through cascading effects caused by predation and competition with native species. This fish, barely six centimetres long, is causing the extinction of numerous native fish species, such as the Spanish toothcarp, its congener the Baetican toothcarp (*A. baeticus*), the Valencia toothcarp (*Valencia hispanica*) or the three-spined stickleback (*Gasterosteus aculeatus*). The *Gambusia* also preys on the eggs and larvae of amphibians, causing the decline of their populations, as shown by CSIC research in the case of the southern marbled newt or pygmy marbled newt (*Triturus pygmaeus*), a species endemic to the Iberian Peninsula. It also preys on insect larvae and zooplankton organisms, favouring the proliferation of phytoplankton, increasing turbidity and reducing oxygen in the water. In this way, it contributes to eutrophication, one of the major pollution problems affecting aquatic ecosystems worldwide.



2.3.

Assessments related to human health

As explained in section 1, it is crucial to understand the potential risks of salinisation of inland aquatic ecosystems for human health. In this context, the CSIC can play a key role given that its research addresses a wide range of disciplines and these are often combined to assess different aspects related to human health. One of the most well-known examples of the consequences of salinisation is the presence of **salt dust** in the atmosphere. Air pollution is a serious health problem that causes, according to the WHO, some three million deaths each year, mainly in large cities, where the population is exposed to particulate and gaseous emissions from cars and industry. One source of air pollution is the presence of salt dust. These particles are caused by the drying of water bodies and the exposure of salt precipitates to atmospheric agents (rain, wind, etc.), which facilitates the resuspension and atmospheric transport of salt particles and the exposure of the population to these particles. Salt ions and trace metals are both mobilised in salt dust and contribute to atmospheric pollution. For example, in the Aral Sea, the transport and atmospheric deposition of salt-dust particles and associated pollutants has caused respiratory diseases and cancer of the oesophagus and throat, thus affecting the health of the population in exposed areas. In addition, various diseases such as anaemia, diarrhoea, renal tubular dysfunction and high levels of persistent organic pollutants have been identified in children in the region. The CSIC is developing and leading novel research to identify the physiological mechanisms related to exposure to desert dust (e.g., from the Sahara) and the relationship with heart failure as one of the most important causes of human health problems in the Iberian Peninsula.



In addition, the CSIC is currently undertaking research on the effects of saline intrusion on the Gambia River ecosystem and the local communities dependent on the water quality of this river as a hydrological resource for their livelihood. In this context, there are many challenges to assessing the health effects of salinisation. For example, most of the populations along the river are rural and draw their water directly from wells. If these wells become saline, the available drinking water becomes highly saline. This of course has health consequences. For instance, as mentioned above, pregnant women are at serious risk of developing pre-eclampsia and can die from the disease. The Gambia is also a country with a high incidence of malaria, a disease transmitted by mosquitoes which spend the first part of their lives in water in the form of larvae. Although the predominant species in The Gambia are freshwater species, some species found in neighbouring countries have a preference for brackish water. Therefore, the distribution and abundance of malaria-transmitting mosquitoes could be affected by increased salinisation of inland waters due to saline intrusion.

2.4.

The problem of salinisation for the economy

THERE is little information on the economic costs associated with salinisation. The CSIC is investigating a number of key aspects. For example, water abstraction for agriculture or human consumption in coastal areas increases seawater intrusion, as explained in section 1. This process has serious economic consequences. First, the lower quality and quantity of water available in these aquifers for consumption causes an increase in the price of water. This makes access to this resource conditional on economic status. Secondly, the costs of remedying the problem are often unsustainable. These measures include reducing groundwater pumping (which means less supply for human consumption), artificial recharge of aquifers and the relocation and reduction of wells. Recent CSIC studies have shown that the intensification of greenhouse agriculture in arid areas of the peninsula is leading to the degradation of water resources. Over-extraction of aquifers and marine intrusion are direct consequences of this practice, which is compromising water quality and coastal ecosystems. As a result, biodiversity losses and increased carbon emissions have been reported. Intensification of agricultural production generates even greater dependence and vulnerability in terms of water quality, creating a vicious cycle. The same study has revealed that, in some cases, the salinisation of aquifers leads to reductions of more than a third of the water abstraction capacity (e.g., the region of Campo de Dalías, in the Sierra de Gádor), with associated economic costs in terms of loss of agricultural productivity.

In a context of critically low freshwater reserves, a major problem in some regions of Spain, desalination plants appear as a possible technical solution to supply water to the population. However, desalinating water for human consumption is significantly more expensive than purifying natural freshwater from aquifers, rivers or lakes. It is estimated that using desalinated water for agricultural activities would cost almost ten times more than using water from aquifers. The desalination process involves pre-treatment, reverse osmosis and post-treatment to ensure water quality for different uses. Although costly, desalinated water is a necessary alternative due to the low reservoir levels and prolonged droughts that are affecting productive regions of Spain, such as Catalonia, Andalusia and the Segura basin. An additional problem is that desalination plants not only produce freshwater, but also, as mentioned in section 1, generate brine as a waste product. The CSIC has studied the environmental effects of high-salinity brine discharged from desalination plants on seagrass meadows, such as those of *Posidonia oceanica*, commonly known as Neptune grass or Mediterranean tapeweed, a species endemic to the Mediterranean and of great ecological value, which are highly sensitive to this type of discharge from desalination plants. The loss of these delicate ecosystems has profound economic repercussions on local fisheries, as *Posidonia* meadows are fish nurseries and sources of natural fertilisers, but also has consequences in terms of carbon storage, as pointed out in the National Long-Term Decarbonisation Strategy.

three



Conclusions and Recommendations

Conclusions



Broadly speaking, the waters of inland aquatic ecosystems have a relatively low salt content and a wide variability in the relative proportion of different saline ions. These salts come mainly from the mineralisation and dissolution of rocks, and from drainage and runoff from soils. The organisms that inhabit these ecosystems (insects, amphibians, fish, etc.) are adapted to these natural saline conditions. In recent decades, there has been growing scientific evidence of the increase in salt concentration in inland aquatic ecosystems as a consequence of human activities. The CSIC has made a significant contribution to the highlighting of these trends, identifying the causes and assessing the effects, especially biological and ecological impacts, derived from this increase.



It has been shown that this increased amount of salt in inland waters is a global environmental problem resulting from a wide variety of activities (e.g., agriculture, mining, transport, and urbanisation). In Spain, it has been estimated that 28% of the Spanish hydrographic network is salinised.

However, the spatial distribution of the problem is not homogeneous, as it depends on where the causative activities are located. Moreover, each of these activities generates a different type of salt, which can also cause different types of impacts on biodiversity, ecosystem functioning, and human well-being.



Salinisation leads to a decline in aquatic biodiversity, as most species cannot tolerate high salinity ranges. At the same time, many invasive species may be favoured by salinisation and increase their distribution, contributing to the loss of native species. This loss of biodiversity can have severe consequences for ecosystem stability and functioning. For example, the loss of crustaceans may favour algal blooms (some of which can produce toxins), with a consequent reduction in water quality and mass mortality of fish. In addition, changes in ecosystem structure brought about by salinisation (such as alterations in sediment biogeochemical cycles and loss of key habitats) can have unexpected consequences, such as an increasing amount of greenhouse gases being released into the atmosphere.



These structural changes affect human well-being due to the loss of benefits obtained from aquatic ecosystems (e.g., provision of food, feed, and raw materials, climate regulation and recreational uses). At the same time, salinisation carries high risks for human health, as salt intake increases the risk of pre-eclampsia and cardiovascular diseases. In addition, there are indirect health effects such as respiratory disorders associated with salt dust and increased incidence of pathogens associated with changes in the distribution of vectors. On the other hand, the interaction of salt with other compounds in the water supply network

may lead to the ingestion of toxic substances or to an increase in the incidence of cancer. Lastly, the salinisation of inland aquatic ecosystems entails high economic costs associated with the corrosion of infrastructures, water treatment for human consumption and the loss of crop productivity, among others.



We can therefore conclude that the salinisation of aquatic ecosystems is a serious and urgent threat that we need to address through public policies and the implementation of appropriate management measures. Even more so when climate change and increased water demand are expected to amplify this problem. For example, the temperature rise associated with climate change will intensify water evaporation and salt concentration. More frequent extreme hydrological events are also expected, which may contribute to an acute increase in the quantity of salts passing from terrestrial to aquatic ecosystems during heavy rainfall events and to a gradual concentration of salt content during periods of drought. Furthermore, we must bear in mind that the availability of drinking water is one of the greatest challenges for our society in this century, and this depends not only on the quantity of water, but also on its quality. Salinisation goes beyond an increase in salinity; it is associated with changes in the proportions of different ions (chemical cocktails) and the presence of additional toxic compounds such as heavy metals derived from agricultural and industrial activities, which can be highly harmful to organisms. In addition, it

has the potential to interact additively, synergistically or antagonistically with other chemicals or stress factors, such as eutrophication or climate change.



Salinisation affects different levels of ecological organisation - individuals, communities or ecosystems - key ecological processes and interactions between organisms. It severely damages biodiversity, promoting the spread and establishment of invasive species, with devastating effects on ecosystem services and human well-being. From a health perspective, salinisation leads to major problems associated with salt-dust particles, which is a major contributor to air pollution and causes cardiorespiratory diseases and other pathologies. In addition, it affects the epidemiology of serious diseases, modifying the area of distribution of the vectors that transmit them. On the other hand, salinisation has serious economic consequences due to the reduction of water quality and quantity (loss of agricultural production and fishery resources, water purification costs, etc.).

It is therefore essential to approach the problem of salinisation from an inter- disciplinary, broad and holistic perspective, taking into account all its complexity, in order to be able to anticipate the impacts and establish appropriate management measures.

Public policy recommendations

For the political and technical management of public administrations:



Current legislation on the salinisation of inland aquatic ecosystems in Spain is focused on water for human consumption and agriculture (e.g., through Royal Decree 140/2003). In addition, Royal Decree 665/2023 establishes a conductivity limit for declaring contaminated water unfit for agriculture. However, existing legislation is insufficient and inadequate, as it does not guarantee the protection of ecosystems and their biodiversity. In fact, salinisation is completely absent from most environmental standards and strategies, and has been omitted from strategic plans such as the Spanish Government's National Plan for Adaptation to Climate Change.



Conductivity limits to ensure the ecological state of water bodies (rivers, lakes, wetlands, etc.) have been established in the context of the Water Framework Directive. However, it is not clear on the basis of which criteria these limits have been set, and they are generally above the values that we could consider as safe for biodiversity and ecosystem functioning according to the scientific evidence available. Existing legislation and regulations should therefore be revised and appropriate monitoring strategies and tools need to be developed. To this end, we propose the following steps:

1. Decision-making based on scientific evidence and the most up-to-date knowledge possible. Ensure that reference values are based on the best available science and the best understanding of costs and benefits. The participation of stakeholders (e.g., managers, companies, and farmers) is crucial to ensure that agreements are implemented and enforced. This process should be structured to promote communication and social learning between different interest groups to ensure that scientific results are understandable to policy makers, affected stakeholders and the rest of society. Strong integration of natural and social science knowledge will help all parties to understand the risks and opportunities of different protection and recovery options. As scientific evidence will accumulate and our knowledge of salinisation will get better, the development of governance standards and agreements will require an iterative approach over time.
2. Characterisation of the water bodies (aquatic ecosystems) to which the standards will apply. Ion concentrations and composition of freshwater vary naturally due to the underlying geology, proximity to the ocean and hydrology.

Thus, the protection of biodiversity (adapted to the natural salinity of each water body) will require specific limits based on the salinity that can be found under natural conditions.

3. Characterisation of the ionic composition (i.e., concentrations of specific ions and their proportions) of salinised waters associated with each of the human activities contributing to salinisation. In addition, the technical potential for reducing the amount of salt generated, as well as the potential social and economic benefits associated with such a reduction, should be assessed for each activity.
4. Quantification of the potential effects of each kind of saline effluent in the region and identification of toxic-effect thresholds. Quantifying the relationships between aquatic organisms and salinity based on scientific studies allows the identification of vulnerable species that can be used in laboratory tests and monitoring programmes. As with other pollutants, laboratory bioassays (e.g., lethal concentration 50 (LC50) tests) should be combined with mesocosm experiments and field studies to quantify the toxicity of different ions (sodium, potassium, chloride, sulphate, etc.) to a representative set of species (e.g., fish, amphibians and aquatic insects).

For businesses and the private sector:



Parallel to the development of policies and public policy measures, there are different technical solutions to mitigate the impact of salinisation that can be implemented in different contexts. In the following, we detail some options or strategies that can be followed by private stakeholders in different sectors of activity:

1. Agriculture. To reduce salinisation associated with agriculture, more efficient irrigation techniques (e.g., drip irrigation), which only provide the amount of water that each crop needs, are recommended, as well as reducing fertiliser use. If salinisation cannot be prevented, planting salt-tolerant crops may be a good adaptation strategy to guarantee food supply.

2. Mining. Salt pollution from mining could be significantly reduced through *backfilling*, a mining technique that minimises the impact of waste disposal by returning waste to the mines. Likewise, the re-injection of wastewater and the implementation of efficient wastewater treatment facilities could reduce salinity associated with oil and gas extraction operations. Finally, restoration of riparian vegetation and stream floodplains also has the potential to mitigate water salinisation in mining-affected watersheds.
3. Road de-icing. Pre-wetting the asphalt, calibrating de-icing equipment and salt application strategies based on accurate weather forecasts can greatly reduce the salinisation associated with road de-icing. In addition, there are alternatives to salt, such as sand, which instead of melting ice increases the traction of tyres. Another option is beet sugar, which is a biodegradable product. These alternatives should be carefully studied, as they might also generate adverse ecological impacts. For example, sand could reduce the diversity of habitats in the riverbed and beet juice could promote eutrophication.
4. Advanced water treatment. One of the most effective ways of reducing salt concentrations in drinking water systems is reverse osmosis. In this process, water is filtered through a semi-impermeable membrane that retains the salt content. The widespread use of reverse osmosis systems is limited by their high economic cost. In addition, this process generates waste (brine, metals, radionuclides and worn-out membranes) which is complex and expensive to recycle. Another technology available to reduce the salt content of purified water is ion exchange. However, this process can rarely remove multiple contaminants from water at the same time, making it ineffective for treating water containing complex chemical cocktails. Although these two techniques are the most common, there are other techniques still under development (e.g., capacitive deionisation), whose effectiveness has not yet been sufficiently assessed.

For society:



Beyond the actions of public authorities and private players, human activity and lifestyles also have great potential when it comes to addressing salinity as a major environmental problem.



In some ways, the situation with regard to salinisation is similar to that of climate change. Climate also changes naturally, and this has been used by many public and private sectors as an excuse to deny that humans have caused climate change associated with the release of greenhouse gases into the atmosphere. This is why there must be social recognition of this problem.



In the case of salinisation, the increase in salinity resulting from human activities has been irrefutably proven on numerous occasions, with sound scientific evidence. Even so, salinisation is far from being perceived by society as an environmental problem derived from human action. In this context, the CSIC calls on society to bring the salinisation of inland aquatic ecosystems into the public debate, considering the risks it poses to social welfare and public health, and proposing solutions based on social consensus.

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List of Centres



CENTRE	WEB PAGE	E-MAIL
Centro de Estudios Avanzados de Blanes [CEAB, CSIC]	www.ceab.csic.es	direccion.ceab@csic.es
Estación Biológica de Doñana [EBD, CSIC]	www.ebd.csic.es	direccion.ebd@csic.es
Estación Experimental de Aula Dei [EEAD, CSIC]	www.eead.csic.es	direccion.eead@csic.es
Instituto de Diagnóstico Ambiental y Estudios del Agua [IDAEA, CSIC]	www.idaea.csic.es	direccion.idaea@csic.es
Instituto de Productos Naturales y Agrobiología [IPNA, CSIC]	www.ipna.csic.es	direccion.ipna@csic.es
Museo Nacional de Ciencias Naturales [MNCN, CSIC]	www.mncn.csic.es	direccion.mncn@csic.es

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Further Information



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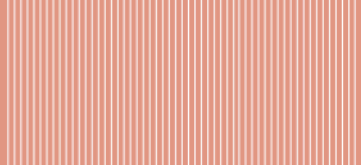
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