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Lost in translation: the German literature on freshwater salinization

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Human activities have globally increased and altered the ion concentration of freshwater ecosystems. The proliferation of potash mines in Germany (especially intense in the early 1900s) constitutes a good example of it. The effluents and runoff coming from potash mines led to extreme salt concentrations (e.g. $72\ g\ l^{-1}$ of total salt content, approx. $149\ mS\ cm^{-1}$) in surrounding rivers and streams, causing ecosystem degradation (e.g. massive algal blooms and fish kills). This promoted scientific research that was mostly published in German, thereby being neglected by the wide scientific community. Here, the findings of the German literature on freshwater salinization are discussed in the light of current knowledge. German studies revealed that at similar ion concentrations potassium (K^+) can be the most toxic ion to freshwater organisms, whereas calcium (Ca^{2+}) could have a toxicity ameliorating effect. Also, they showed that salinization could lead to biodiversity loss, major shifts in the composition of aquatic communities (e.g. dominance of salt-tolerant algae, proliferation of invasive species) and alter organic matter processing. The biological degradation caused by freshwater salinization related to potash mining has important management implications, e.g. it could prevent many European rivers and streams from reaching the good ecological status demanded by the Water Framework Directive. Within this context, German publications show several examples of salinity thresholds and biological indices that could be useful to monitor and regulate salinization (i.e. developing legally enforced salinity and ion-specific standards). They also provide potential management techniques (i.e. brine collection and disposal) and some estimates of the economic costs of freshwater salinization. Overall, the German literature on freshwater salinization provides internationally relevant information that has rarely been cited by the English literature. We suggest that the global editorial and scientific community should take action to make important findings published in non-English literature more widely available.

This article is part of the theme issue 'Salt in freshwaters: causes, ecological consequences and future prospects'.

1. Introduction

The increase in the concentration of dissolved ions (i.e. salinization) in rivers resulting from human activities has long been acknowledged as a water quality problem [1–3]. Also, it was shown to have a negative effect on certain river organisms by early ecological studies [4,5]. However, as Prof. W.D. Williams pointed out in 2001 [6, p. 85]: 'salinisation as a major global geochemical event seems largely to lie outside the consciousness of most water resource managers, conservationists and limnologists if not all'. The number of scientific publications on river salinization has considerably increased since that statement was made; however, it still receives much less attention by policy-makers, water managers, scientists and society at large, than other environmental issues [7]. This should change, because salinization is emerging as one of the top causes of biological degradation of river ecosystems worldwide [8,9].

Figure 1. The mine named 'Güntershall' situated at Wipper River below the city of Sondershausen (Thuringia, Middle Germany). This mine was one of the many potassium mines that were founded in the early 1900s in this region. Its brines were discharged into the Wipper River, causing a strong salinization here [2,3]. Albrecht [25] reported that an accident had happened at one of these factories around 1930. A surveyor, P. Schiemenz, was instructed to investigate whether this incident had damaged the fauna of Wipper River. In the report about his investigations he wrote that he had found many 'small green chironomids' in the surroundings of one of these potash mines. This is the first known report about damage of the aquatic fauna by salinization [25]. Although industrial activities in this mining area have been terminated since the 1990s, salinization owing to the introduction of drainage brines from the residue stockpiles still continues [26]. Picture by an unknown photographer, kindly provided by Mr Hans-Jürgen Schmidt. (Online version in colour.)

Table 1. Types of salinization, their major sources and major ions in Germany.

type of salinization	source of salinization	major ions
primary salinization	Keuper waters (Thuringia, Germany)	Na^+, Ca^{2+}, Cl^-, HCO_3^{2-}, SO_4^{2-}
primary salinization	geogenically salanized waters other than Keuper waters	Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, HCO_3^{2-}, SO_4^{2-}
secondary salinization	potassium mining	K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}
secondary salinization	coal mining	Na^+, K^+, Cl^-, SO_4^{2-}

River salinization can have many different origins [10]. For example, in Australia the substitution of deep-rooted vegetation by crops and pasture has led to reduced evapotranspiration and rising groundwater tables; because groundwaters can be naturally saline, this has produced the accumulation of salts in the soil that are finally flushed into freshwater bodies by surface runoff [11–14]. In North America, road salts [15–17] and coal mining [18–20] are probably the causes of freshwater salinization most widely reported by the English literature. In Europe, potash mining (mainly used for fertilizers) has been shown to greatly increase the salt concentration of rivers. For example, the estimated chloride load increased in the Rhine river from less than 50 kg s^{-1} to more than 300 kg s^{-1} in the 1960s mostly owing mainly to the potash mines in Alsace (although industrial activities also contributed to the high salt load) [1]. In Catalonia (Spain), the impact of potash mines was already revealed during the civil war (1936–39), since the bombings significantly decreased the mining operations leading to lower salt concentrations in rivers [21]. After that, mine operations resumed and grew, currently posing a great risk to riparian vegetation and aquatic organisms [22–24]. In Germany, salinization of running waters is closely tied with the increasing agricultural application of fertilizers in the nineteenth and twentieth centuries. Potassium-containing salt rock was mined to manufacture potassium fertilizers. At several steps of the production process, concentrated brines were generated and disposed into nearby rivers and streams (figure 1). Potash mining was especially intense from 1950s to 1980s and decreased after the German reunification (1990s), when a considerable number of potash mines were closed (mostly in the region of Thuringia) [26,27]. Currently, in addition to potash mining, inputs from (abandoned) coal mines might contribute to river salinization (table 1), especially in Western Germany.

The salt pollution of German rivers by potash mining promoted ecological research, leading to numerous papers

Table 2. Effects of salinization on individuals/populations of different taxa. NEOC, no effect of observed concentration.

reference	organism (group)	indicator value/response metric	threshold value(s)
[28]	*Danio rerio*	salinity [°/oo]	none
[29]	*Gammarids*, *Chironomus plumosus*, *Limnephilus* spec., *Radix auricularia*, *Daphnia spec.*	'NEOC' (no standardized incubation times)	'NEOC' for K^+ (mg l^{-1}): *Gammarids* 200, *Chironomidae* > 700, *Trichoptera* larvae > 1000, snails 400
[3]	*Daphnia* *Chironomus* tadpoles eels	'maximum tolerable concentration' of salt mixtures (K^+ salts, Ca^{2+} salts, Mg^{2+} salts, Na^+ salts)	highest toxicity: K^+ middle toxicity: Ca^{2+}/Mg^{2+} lowest toxicity: Na^+
[30]	fish	blood serum: concentration of K^+; haematocrit value; surface of erythrocytes; condition of inner organs	chronic toxicity: 80 mg l^{-1} K^+
[31]	fish	occurrence of fish mortality	Wipper River: 3000 mg l^{-1} Cl^- Werra River: 6000 mg l^{-1} Cl^- different thresholds are owing to different K^+ concentrations

published in German language. Unfortunately, these papers were largely unnoticed by the wider scientific community. For example, a search (performed the 15 March 2018) of the term 'freshwater salinisation' in the Web of Knowledge provided 1203 results, whereas a search of the equivalent German terms 'Gewässerversalzung' and 'Flussversalzung' provided 0 results. The same search in Google Scholar resulted in 26 700 and 6 results, respectively. Here, we performed a more exhaustive bibliographic search that found 35 papers published between 1911 and 2017. One paper was provided by the Jena University literature collection, the rest came from the first author's personal collection. Only those publications that yielded distinct information were considered here, excluding papers with speculative content. The main findings of these papers are discussed here in the light of recent advances in freshwater salinization. Most data on salinization in German literature are reported as chloride concentration; for readers who are more familiar with electrical conductivity (EC), we converted chloride data into meaningful terms using the following equation:

$$EC[\mu S\ cm^{-1}] = 2.0385 \times Cl^{-}[mg\ l^{-1}] + 2381.456.$$

This equation was derived from long-term EC/chloride data from Wipper River at the sampling location situated at the gauge near the village of Hachelbich (Thuringia, Middle Germany). It allows an approximate calculation of chloride concentrations from conductivity data for carbonatic running waters salanized by brines from the potash industry. The equation was kindly provided by Dr Christian Feld, University of Duisburg Essen (Germany).

2. Effects at the organism/population level

It has been widely proved that increasing salt concentrations over a certain threshold are toxic to freshwater organisms (table 2, [10]). For example, Meinelt & Stüber [28] reported a 60, 50, 10 and 0% survival of zebrafish (*Danio rerio*) larvae exposed to salinities of 2, 4, 8, 16°/oo, respectively, in test solutions prepared from potassium-containg salt rock. However, salt toxicity is not exclusively dependent on total ion concentration, because different ions have different toxicities. For example, Ebeling [29] reported the following toxicity of chloride salts for the aquatic invertebrates Chironomidae and Gammaridae: KCl > MgCl > NaCl. Hirsch [3] found a different toxicity of *Daphnia*, eels, tadpoles and *Chironomus* larvae to Na^+, Mg^{2+}, Ca^{2+} and K^+, with K^+ having the greatest toxicity. Concordantly, in the 1970s Halsband [30,32] found a partial paralysis in rudd (*Scardinius erythrophthalmus*) when exposed to high K^+ concentrations coming from the Weser River and showed toxic responses to chronic exposures to

80 mg K^+ per kg of fish biomass. The greater toxicity of K^+ when compared to other ions (table 2) was later confirmed in the English literature. For example, Mount *et al*. [33] reported that K^+ was the most toxic ion for *Ceriodaphnia dubia*, *Daphnia magna* and fathead minnows (*Pimephales promelas*). At the same time, several studies showed a detoxification effect of Ca^{2+} over other ions [34–36]. This was also later confirmed by other studies published in English [37–39], which suggested that it could be related to reduced epithelial permeability, thus decreasing passive diffusion and the energy required to osmoregulate. Besides the toxicity of individual ions, the proportion of the different anions and cations can be of great importance to aquatic fauna. For example, Ziemann [31] found that the growth of halophile algae was stronger when the relative alkali proportion exceeded that of Ca^{2+} and that differences in ion ratios explained the different threshold values for fish mortality in the Wipper (3 g Cl^- l^{-1}, approx. 8.5 mS cm^{-1}) and Werra (6 g Cl^- l^{-1}, approx. 14.6 mS cm^{-1}) Rivers. Ziemann also found that the alteration of K^+ : Ca^{2+} ratios (which were 2 : 1 in the Wipper River) could determine the distribution of euryhaline diatom species such as *Amphiphora alata*, *Achnanthes brevipes*, *Bacillaria paradoxa*, *Melosira nummuloides* and *Nitzschia sigma*.

The toxicity of salts to freshwater organisms can depend on their previous history of salt exposure [40]. For example, in 1959 Schmitz [41] showed that *Gammarus pulex* individuals coming from a naturally saline creek (salinity = 5.5) were more resistant to salt treatments than individuals coming from a freshwater creek. More recently (2011–2017), intraspecific variations in salinity tolerance have been suggested by some studies [42–44], and progressive (i.e. multi-generational) adaptation to increased salinity (in the form of NaCl) has been documented for *Daphnia* [44,45]. However, other investigations have shown little variation in the salt sensitivity of populations of aquatic insects coming from streams with different background conductivities [46–48] and no evidence that previous salinity exposure could affect salt sensitivity in *Daphnia* [49]. Thus, the existence of intraspecific differences in salt sensitivity according to previous salt exposure is still under debate. Moreover, the mechanisms behind possible acclimation or adaptation to salinization by freshwater organisms remain unclear [45].

3. Effects on aquatic communities

The salt load in German rivers affected by potash mining was extremely high in several cases. For example, in 1989 Buhse [50] reported chloride concentrations of 22.6 (approx. 48.5 mS cm^{-1}) and 40.2 g l^{-1} (approx. 84.3 mS cm^{-1}) and salinities of 40.7 and 72 g l^{-1} in the Werra River and one of its tributaries (the Ulster River), respectively. The same study reported massive algal blooms (*Thalassiosira*, causing oxygen concentrations over 200%) and fish kills since the 1950s. The gill epithelium of the fish was damaged and partially inactivated owing to elevated pH (up to 9.8 by algal removal of carbonic acid for starch synthesis [51]) and free oxygen, especially during hot summers when most fish die-offs occurred. The proliferation of algal blooms by a combination of high nutrient and salt concentrations was also reported by Ziemann [31], specifically for the diatom species *Thalassiosira fluviatilis*, *Cyclotellea meneghiniana* and *Cyclotella nana*. Regarding benthic invertebrates [52], chloride concentrations above background levels can lead to a decrease in rhitral, rheophilic, coarse substrate settling species (with implications for functional feeding groups), a deterioration of the biological condition (e.g. as established by the German Fauna Index [53]) and a general reduction in species numbers (especially Ephemeroptera, Plecoptera and Trichoptera). For example, in 1954 Albrecht [25] reported a significantly lower invertebrate biomass (weight m^{-2}) in salinized sections of the Werra River when compared to non-salinized sections. In cases of extreme salinities, an extensive depletion of aquatic fauna was observed [25,31,54]. Overall, available studies from heavily salt-polluted rivers in Germany confirm that salinization can be among the top causes of biological impairment in freshwater ecosystems [10,55,56].

In agreement with ecotoxicological data (see section above), field studies show clear differences in the sensitivity of aquatic organisms to salt pollution. For example, Coring *et al*. [57] found the following sensitivity of the different biotic components: fish > macrozoobenthos > phytoplankton > macrophytes > diatoms. Regarding diatoms, it is important to consider that planktonic and benthic taxa can show differing salt tolerances [58]. The sensitivity of stream and river communities to salinization can also vary with the catchment geology. For example, calcareous waters have been reported to buffer salt pollution [52], which could be related to the ameliorating effect of water hardness on the toxicity of other ions [37,38]. Overall, the impacts of salinization on community composition seem to follow a salinity threshold pattern (i.e. salt-tolerant species become dominant after a certain salt concentration range is exceeded). For example, salinities of 1.6–2.0 g l^{-1} (corresponding to approx. 0.8 to 1 g Cl^- l^{-1}, approx. 4.0 to 4.4 mS cm^{-1}) led to an extreme situation in the Weser River, characterized by slight salinity changes causing mass developments of a few salt-tolerant algal species [59]. Owing to the threshold pattern, seasonal changes in salinity can greatly modulate community composition. For example, salt-sensitive algal species can dominate in spring when salt dilution by the river is high, whereas they can be outcompeted by halophilous species during the summer when salt concentrations are higher [31]. Shifts in community composition caused by salinity fluctuations can be very fast. For example, Schulz [60] showed that the algal community recovered 6 months after salt pollution ceased in the Urbach creek.

As exotic species tend to be more salt tolerant than their native counterparts, river salinization can promote biological invasions [52,61]. For example, Herbst [62] reported a replacement of the native amphipods *Gammarus pulex* and *G. roeseli* by the invasive *G. trigrinus* when a 1 mS cm^{-1} conductivity threshold was reached. Also, the colonization of Werra River by diatoms was characterized by immigration, fast spreading and mass developments of new species on the one hand, and by a decrease or fluctuations in already existing species on the other hand [63]. For example, the saltwater diatom *M. nummuloides* colonized the Werra River during the 1950s and developed massively during a short time, becoming the most frequent species during the monitoring years 1963 and 1964 [31]. However, not all of the species that reach salinized rivers are able to maintain stable populations there [64]. Heuss [65] found that the aquatic invertebrates that drifted into the Werra River from its tributaries usually died off

Table 3. Threshold chloride concentrations and conductivity values for the transition from good to the moderate status according to the European Water Framework Directive [72]. The thresholds were calculated from monitoring data supplied by the German federal countries (modified from Halle & Müller [73]). LAWA, German Working Group on water issues.

running water type	German stream typology (LAWA-typology)	chloride mg l^{-1} annual mean upper threshold	conductivity $\mu S\ cm^{-1}$ annual mean upper threshold
running waters in the alpine foothills	2.1/3.1/2.2/3.2/4/11	40	600
brooks in the central highlands	5/5.1/5.2/6/6 K/7/11/19	40[a]/50[b]	400[a]/800[b]
small- to mid-sized rivers in the central highlands	9/9.1/9.1 K/19/12	40[a]/50[b]	400[a]/800[b]
large rivers and streams in the central highlands	9.2/10	50	800
brooks in the central plains	11/14/16/18/19	50[a]/70[b]	700[a]/1000[b]
small- to mid-sized rivers in the central plains	12/15/17	60[a]/90[b]	800[a]/1000[b]
large rivers and streams in the central plains	15 g/20	90	1000

[a]Silicious.
[b]Carbonatic waters.

there because they did not tolerate the strong and frequent salinity fluctuations resulting from the mining activity. Also, truly marine algal species occur only seldom in salinized inland waters; with the brown algae *Ectocarpus confervoides* being one of the rare examples [66]. Finally, an investigation on the species sensitivity distributions for maximum salinity tolerance in the river Rhine found no significant differences between native and non-native species [67]. Thus, this is a topic that requires further study.

Beyond direct salt toxicity, freshwater salinization can have unexpected consequences for aquatic organisms. For example, Hübner [53] reviewed that salt concentration in the middle and the lower Werra River had achieved such a level that the freezing point of the water was lowered notably. As a consequence, during the cold winter of 1962/1963 eels died in very large numbers, most probably by hypothermia. Also, biochemical cycles might be altered by salt pollution. Ziemann [68] showed a strong degradation delay and inhibition of organic matter degradation by bacteria at $> 10\ g\ Cl^{-}\ l^{-1}$ (approx. 22.8 mS cm^{-1}) and a reduced oxygen consumption by flocculation and sedimentation of organic substances and bacteria. Concordantly, Sauer *et al.* [69] reported decreasing efficiency of leaf litter degradation and phosphorus assimilation by microorganisms with increasing salinity. However, a recent microcosm study [70] showed that trade-offs between growth and sporulation can maintain fungal growth and decomposition at high levels along wide salinity gradients.

4. Management implications

The degradation of river ecosystems caused by salinization has important implications for water management. For example, in Europe the elevated salt concentrations in many rivers [8,71] could prevent them from reaching the good ecological status demanded by the European Water Framework Directive [72]. Halle & Müller [73] suggested that Cl^{-} concentrations as low as $> 0.04–009\ g\ l^{-1}$ could make the achievement of the good ecological condition unlikely in German rivers, although specific thresholds depend on the geology of the catchment (table 3). Other studies on the same dataset used change point analyses to identify that a mean Cl^{-} concentration of around 25 mg l^{-1} marked a shifting point for invertebrate community composition [74,75], with most taxa being negatively affected once concentrations reached 50 mg l^{-1}. However, these values are still under debate: they are not only considerably lower than the toxicity thresholds revealed by laboratory and field studies so far, but they also seem to mismatch the geogenic hydrochemical situation of a number of running waters. For example, the background salt concentration (i.e. salts of natural origin) found in many German rivers exceeds those given by [73]. Thus, further investigations are necessary to evaluate and validate salinity change points for biological organisms and communities. It should also be taken into account that river salinity can experience great temporal fluctuations [23,76] owing to changes in river flow (affecting its dilutions capacity), precipitation (affecting runoff) and salinity point sources (e.g. wastewaters). In this regard, it is clear that biological indices can be useful to monitor freshwater salinization because they integrate temporal fluctuations in environmental parameters [77,78]. However, current biological indices do not seem to properly detect salt pollution [22,23], suggesting that specific salinity indices need to be developed and tested. One example is the Halobion index [79], which classifies diatom assemblages into seven classes according to the ecological range of effect within the salinity spectrum, being able to discriminate between different levels of salt pollution. Also, Halle *et al.* [52] identified so-called orientation values for invertebrates beyond which an achievement of the good condition (European Water Framework Directive, EU WFD) would become unlikely.

For management purposes, it is often helpful to use a classification scheme that allows the grouping of waters of similar salinization. In the 1990s, a number of classifications were proposed [59,80] (table 4). What all these schemes have in common is that they distinguish between 7 degrees of salinization. This is consistent with the former German chemical water quality classification. However, the foundations of the approaches vary strongly, and the classification schemes display considerable differences. For example, the LAWA AK ZVs relied exclusively on chemical parameters, whereas Ziemann [82] used changes in the composition of diatom assemblages while accounting for background water chemistry (silicatic/carbonatic waters).

Table 4. Water quality classification in relation to chloride concentration according to various authors (after [80]).

level of workload/water quality class	notation by DVWK[a] [59]	Cl^- mg l^{-1} DVWK[a] [59]	notation by NLÖ[b] [81]	Cl^- mg l^{-1} NLÖ[b] [81]	notation by Ziemann [82]	Cl^- mg l^{-1} Ziemann [82] a. silic waters b. carbon waters	notation by LAWA AK ZV[c] [83]	Cl^- mg l^{-1} LAWA AK ZV[c] [83])	SO_4^{2-} mg l^{-1} LAWA AK ZV[c] [83]
I	not or very slightly polluted by salts	0 to $\leq$50	not or very slightly polluted by salts	<200	unpolluted	a. $\leq$ 15 b. $\leq$ 25	geogenic background value	<25	<25
I–II	slightly polluted by salts	50 to $\leq$200	slightly polluted by salts	200 to <400	slightly polluted	a. $\geq$15 to $\leq$50 b. $\geq$25 to $\leq$100	very low pollution	<50	<50
II	moderately polluted by salts	200 to $\leq$400	moderately polluted by salts	400 to <1000	moderately polluted	a. $\geq$50 to $\leq$200 b. $\geq$100 to $\leq$200	moderate pollution	<100	<100
II–III	critically polluted by salts	400 to $\leq$800	critically polluted by salts	1000 to <2500	critically salt-polluted	$\geq$200 to $\leq$600	distinct pollution	<200	<200
III	strongly polluted by salts	800 to $\leq$1500	strongly salanized	2500 to <5000	strongly salt-polluted	$\geq$600 to 1500. . .2000	elevated pollution	<400	<400
III–IV	very strongly polluted by salts	1500 to $\leq$4500	very strongly salanized	5000 to <20 000	very strongly salanized	$\geq$1500. . .2000 to $\leq$3000. . .50000	high pollution	<800	<800
IV	unduely polluted by salts	$\geq$4500	unduely salanized	>20 000	very strongly salanized	$\geq$3000 to 5000	very high pollution	>800	>800

[a]Deutscher Verband für Wasserwirtschaft und Kulturbau (association of German water managers).
[b]Niedersächsisches Landesamt für Ökologie (environmental institute of the German federal country Lower Saxony).
[c]Länder-Arbeitsgemeinschaft Wasser Arbeitskreis Zielvorgaben (working group of the German federal countries who develop hydrochemical targets for waters).

Table 5. Summary of the main findings provided by this literature review and some key English references supporting and/or contradicting each finding.

main finding	references	English literature supporting the finding	English literature contradicting the finding
potassium is the most toxic ion for freshwater fauna	[3,30,31,33]	[33]	Soucek *et al.* [39] found that *Neocloeon triangulifer* was relatively less sensitive to K salts
toxic effect of an ion can be compensated by other ions (antagonism)	[2,34,35]	[37–39]	—
historical salt exposure can enhance the salinity tolerance of freshwater fauna	[40,41]	[42–45]	[46,47,49]
salinization can cause massive fish kills, which are among the most salinity-sensitive freshwater organisms	[31,50,51,53]	—	—
salinization can cause massive algal blooms	[31,59]	—	—
extreme salinization can lead to an extensive depletion of aquatic fauna	[31,53]	[24]	—
salinization can promote biological invasions	[52,62]	[61]	[67]
salinization can cause delay and inhibition of organic matter degradation by bacteria	[68]	[69]	Canhoto *et al.* [70] showed that trade-offs between growth and sporulation can maintain fungal growth and decomposition at high levels along wide salinity gradients

The approach by DVWK [59] is more comprehensive and considers benthic invertebrates, algae and fish.

A central management question in rivers affected by potash mining is how to dispose of brines from potash production. One option that has been taken into consideration on several occasions is the introduction of brines into marine environments through collection systems [84–86]. The idea behind this practice is the assumption that once introduced into the marine environment, brines will distribute rapidly and evenly in a huge volume of seawater. Thereby, no ecosystem damage should occur. However, Michaelis [87] showed that several marine species (e.g. the polyp *Sertularia cupressina*) colonized the tidal brackish waters of the Jade estuary (East Frisian Wadden Sea, German North Sea coast) after brine disposal from the gas industry. Also, the brackish water crab *Bathypreia pilosa*, which had been a widespread species in the Jade estuary, disappeared. It is important to note that potash mining effluents are not exclusively composed of Na^+ and Cl^-, but they can also have high concentrations of other ions such as Mg^{2+} and K^+ [88]. Because, as we have previously discussed, different ions have different toxicities, the potential effects of the alteration of ion ratios in receiving coastal waters should also be evaluated before brines are disposed. Also, salinization can promote ocean acidification by modifying the quality of inorganic and organic carbon transported by rivers [89]. Thus, the potential effects of brine disposal on coastal ecosystems should be investigated to validate this management practice. Moreover, brine collecting systems need to be properly designed and maintained, because they can pose a risk to groundwaters owing to leaks [90].

Beyond biological degradation, which could result in diminished ecosystem services [91,92], freshwater salinization can have important economic costs. For example, the annual economic damage (i.e. infrastructure corrosion) caused by the salt load of the Weser River was estimated 81 million Deutsche Mark (DM) (around 41.4 million euros) for the year 1992, and up to 1981 compensation payments of 414.5 million DM (around 212 million euros) were necessary owing to salt introductions into the Werra and Weser Rivers [59]. Concordantly, infrastructure damage amounted $700 million per year in the Border Rivers catchment, Australia [93]. Moreover, salinization can make river water unpalatable and even unsafe [21,94], thus resulting in high economic costs associated with improved water treatment through reverse osmosis [95].

5. Conclusion

Overall, it is clear that freshwater salinization can significantly affect aquatic biodiversity and human welfare through ecosystem degradation, economic costs and risk to human health. Rivers and streams impacted by potash mining in Germany constitute a great example of this. German authors found that K^+ was the most toxic ion to freshwater fauna, whereas calcium could ameliorate the toxicity of other ions (table 3). This is in agreement with several studies published in English, although Soucek *et al.* [39]

showed that the the mayfly *Neocloeon triangulifer* was relatively less sensitive to K^+ salts than it was to other salts such as NaCl, $MgSO_4$ and Na_2SO_4. Thus, more studies on specific ion toxicity and salt combinations are needed [7], as well as on the transport mechanisms of each ion [96]. Interestingly, we found some German papers suggesting that populations historically exposed to elevated salt concentrations could be more tolerant to salinization [40,41]. This is a controversial topic, because there are papers both supporting and rejecting this hypothesis (table 5). Further studies, ideally combining laboratory and field data, will be required to assess the importance of historical salt exposure in determining intraspecific variations on salt sensitivity. The German literature reviewed here also revealed drastic changes in biological communities exposed to severe salinization, such as massive algal blooms and fish kills. These are events that had been previously unnoticed by the English literature, probably because the very high salt loads registered in German rivers polluted by potash mines (e.g. $40.2\ g\ l^{-1}$ of Cl^-, approx. $84.3\ mS\ cm^{-1}$) have rarely been reported elsewhere (but see [24]). However, it should be noted that freshwater salinization is being neglected in many parts of the world such as Africa, Asia and South America [10], where these very high concentrations could be reached, posing a risk to freshwater biodiversity. The changes in community composition included the facilitation of biological invasions, which has been confirmed by English studies, although Verbrugge *et al*. [67] found no differences in the salinity sensitivity of native and non-native mollusc species in the river Rhine. Finally, we show that salinization can have potential impacts on ecosystems functioning, because Ziemann [68] found that increased salinity delayed the degradation of organic matter by bacteria. This is also a very interesting finding that deserves to be further studied, because it has been both confirmed and rejected by the English literature (table 5).

In addition to these findings, the German literature that we consulted includes some conductivity and salinity values above which there would be damage to biodiversity that would probably prevent rivers from reaching the good ecological status demanded by the European Framework Directive. It also provides economic estimates for damage caused by freshwater salinization. These kinds of estimates are unusual and can be very useful for building social awareness. Overall, we can conclude that the findings summarized in this paper are relevant and timely (even if some of them are more than 100 years old). However, the German publications reviewed here have barely been cited by the English literature, even when reporting similar results. This makes us think about the probable significant amount of scientific findings that have been and are still being published in the non-English literature (e.g. Brazilian, Chinese, German, Russian, Spanish) and could be internationally relevant. Maybe the global editorial and scientific community should take action to make these findings widely available [97].

Data accessibility. This article has no additional data.

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