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Drivers of spatio-temporal patterns of salinity in Spanish rivers: a nationwide assessment

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The salinization of freshwaters is a global water quality problem that leads to the biological degradation of aquatic ecosystems. However, little is known about the spatial extent of freshwater salinization and the relative contribution of each human activity (e.g. agriculture, urbanization, mining or shale-gas extraction). Here, we investigated environmental factors that explain spatio-temporal patterns of water salinity and examined the causes, the extent and the degree of salinization of Spanish rivers. Results showed a strong variation in water salinity among river typologies and between river reaches in good and poor ecological status according to the Water Framework Directive. The variation in water salinity was largely explained by a combination of natural (i.e. climate and geology) and anthropogenic (i.e. land use) factors. By contrast, land use factors as urbanization and agriculture were the main drivers of salinization, which affected more than one quarter of the rivers and streams in Spain, especially those in the most arid regions (central and southern regions) and in the main courses of the largest rivers such as the Ebro, Douro and Tajo rivers. The information provided here can be relevant to set priority regions and actions to ameliorate freshwater salinization.

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

1. Introduction

The salinization of freshwaters has long been recognized as a global water quality problem [1], but its potential effects on biodiversity and freshwater ecosystem integrity have been largely neglected [2]. Strong evidences for the biological degradation of salinized freshwater ecosystems emerged in Australia. There, the substitution of deep-rooted vegetation by pasture led to rising saline groundwater tables, which had lethal and sub-lethal effects on microbes, macrophytes, micro-algae, invertebrates, fishes, amphibians, reptiles, mammals and birds [3,4]. At the same time, water level lowering in the Aral Sea owing to water diversion for irrigation resulted in the lake salinization causing the fisheries collapse [5]. During the last two decades, the potential ecological impacts of freshwater salinization have received increasing attention [6,7], revealing that numerous human activities such as coal mining [8], salt mining [9], shale-gas extraction [10], agriculture [11,12], urbanization [13] or the use of salts as de-icing agents in roads [14], can greatly alter the ion concentration of freshwaters. These investigations have also revealed the role of environmental conditions evidencing that naturally, salinity predominantly originates from the weathering of the catchment [15], which is a

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function of both the geology of the catchment and the climatic conditions (i.e. precipitation). Currently, despite the relative weight of salinity in a multi-stressor context being still uncertain, -salinization could be considered as one of the major causes of biological degradation of rivers and streams [16]. Thus, salinization could prevent many water bodies from achieving the good ecological status demanded by the Water Framework Directive (WFD) in Europe [17] and has important management implications resulting in important economic costs from wastewater treatment and ecosystem restoration [18].

According to available evidence, there is no doubt that freshwater salinization threatens not only aquatic biodiversity, but also ecosystem functioning and services [19,20]. However, there is little robust information on the spatial extent of freshwater salinization and the relative contribution of each human activity is not clear [21]. Current estimates consider that around 20–50% of the freshwater bodies in cultivated areas could be salt affected owing to irrigation [3,22] while approximately 37% of the rivers and streams in the United States could be salinized [21]. Furthermore, the expected increase in water scarcity and desertification in many regions of the world with climate change will increase the extent of salinized rivers and the degree of salinization, exacerbating the biological degradation and the risk to human health [23]. Thus, improving the design and implementation of effective management actions is highly necessary to achieve a sustainable water management [24]. However, management actions are costly, time-consuming and (in most cases) socially controversial and thereby require prioritization. This prioritization should be based on quantifying the spatial extent of freshwater salinization, estimating the relative contribution of each human activity to freshwater salinization and identifying which rivers are the most sensitive owing to their natural environmental conditions.

In this study, we aimed to fill some of these knowledge gaps by examining the causes, the extent and the degree of salinization of Spanish rivers. Spain is a relevant case study because it covers a broad geological gradient and several of the human activities that can lead to freshwater ecosystem salinization constitute primary drivers of the Spanish economy (i.e. agriculture, industrial activity and mining). Further, the United Nations Convention to Combat Desertification expects desertification to increase in arid, semi-arid and dry sub-humid areas, which constitute more than two thirds of the Spanish territory. This aridity poses an elevate risk for the Spanish freshwater ecosystem salinization. We specifically: (i) investigated differences in salinity among river typologies stablished by the Spanish classification of surface water bodies and between river reaches in poor and good ecological status according to the WFD; (ii) explored the environmental factors that explain spatio-temporal patterns of water salinity in Spanish rivers and identified, among these, the factors that can cause water salinization; and (iii) estimated the extent of the Spanish river network salinized and the degree of salinization. Overall, we expected strong differences in salinity among Spanish rivers. We hypothesized that these differences would be largely driven by natural environmental conditions related to climate and geology and that agriculture would cause river salinization since it occupies more than 45% of the Spanish territory.

2. Methodology

(a) Study area

The study area includes the river network of peninsular Spain (66 931 km of rivers). Spanish hydrography is quite diverse as it is determined by the presence of numerous mountain ranges and the climatic conditions and the geological formations that characterize the Iberian Peninsula. The Iberian Peninsula is mostly dominated by a Mediterranean climate (i.e. central, southern and eastern regions), although the north and north-western regions have a temperate climate [25]. Geological formations vary across the territory. Loose or semi-solid materials (gravel, sand and silt) dominate in the valley bottoms of the main rivers and in coastal areas, rocks of carbonated nature in the eastern and southern regions and igneous and metamorphic rocks in the western regions. Given these heterogeneous environmental conditions, the characteristics of the Spanish rivers vary from one region to another. Rivers in northern and northwestern regions are permanent and mighty compared to rivers in the southern and eastern regions. In this area, rivers are characterized by a low flow and severe summer droughts, which in many cases, lead to flow intermittency. Nevertheless, the increase in aridity in the last decades is leading to an increasing extent of the Spanish river network experiencing flow intermittency in space and time, particularly in areas dominated by siliceous sediments. The only exceptions are the large rivers (Ebro, Duero, Guadalquivir and Tajo) since their tributaries originate in the mountain ranges and dampen these climatic effects.

To set the spatial framework for the integration of all the environmental information (water salinity and environmental data), Virtual Watersheds of the Spanish river networks (figure 1) were built using the 'NetMap' platform (http://www.terrainworks.com/) [26]. The Virtual Watersheds were delineated from flow directions inferred from a 5 m Digital Elevation Model (DEM; [27]), re-scaled to 10 m to optimize computational time, and divided in river reaches (1 km of average length).

(b) Data

(i) River typology and ecological status definition

We assigned the river typology and the ecological status of the different river reaches defined in the river network based on the Spanish classification of the surface water bodies included in the official Spanish hydrological plans (2015–2021; Spanish Royal Decree RD 817/2015 on water policy) following the WFD [17]. The ecological status provides a measure of the quality of the structure and functioning of aquatic ecosystems assessed based on a series of biological and chemical indicators in relation to natural conditions defined for each river typology, which comprises rivers with similar environmental characteristics (i.e. elevation, stream size, water temperature, geology). River typology and ecological status information was obtained from the Ministry of Agriculture and Fisheries, Food and Environment digital cartography (www.mapama.gob.es). We used a 500 m buffer to locate and label river typology and ecological status information to our river network in ArcGIS Desktop 10.2.1 [28] based on river type category (except reservoirs). Only the river reaches in our river network with information on river typology and ecological status were considered.

The considered river reaches belonged to 33 of the 36 official river typologies defined for the Spanish rivers (electronic supplementary material, table S1) and their ecological status classification (i.e. high, good, moderate, poor or bad) was lumped in two categories:

(i) good ecological status: high or good ecological status and good chemical status; and
(ii) poor ecological status: any other combination of ecological and chemical status.

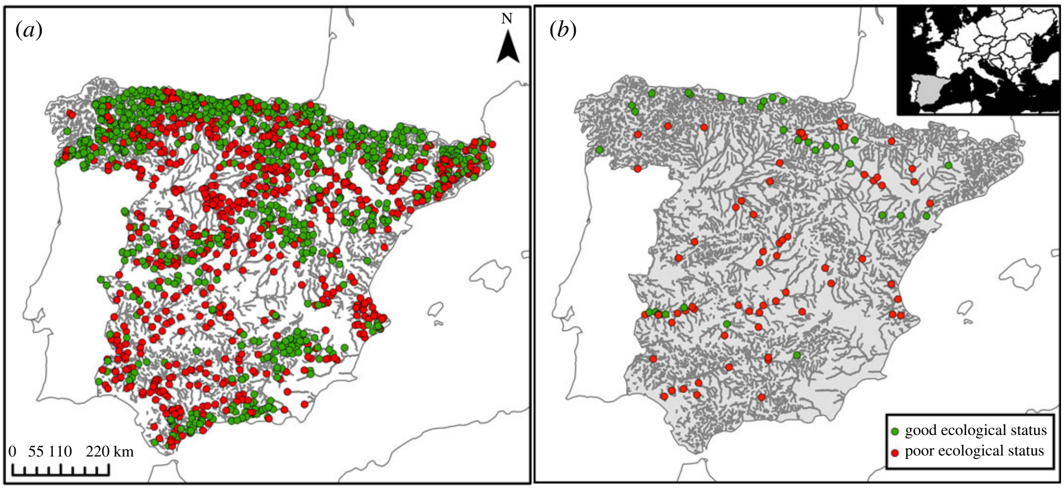

Figure 1. Study area and locations of (*a*) the 1565 water surveys performed by the Hydrographic Confederations and Water Agencies that compose the spatial salinity dataset and (*b*) the 96 SAICA stations that compose the temporal salinity dataset used in this study. Green dots correspond to conductivity measures in river reaches in good ecological status while red dots correspond to conductivity measures in river reaches in poor ecological status.

(ii) Water salinity

Spatial patterns of salinity in Spanish rivers were determined using water electrical conductivity measures obtained from WFD routine surveys and carried out by the Hydrographic Confederations and Water Agencies (i.e. Basque and Catalan Water Agencies). To analyse the most sensitive period throughout the year for salinization [29], we only considered water conductivity measures during low flow season (July-August-September) between the years 2005 and 2014. For each river reach, conductivity measures during this period were averaged. Only river reaches with a mean water conductivity between 0.03 and 5 mS cm^{-1} were considered for subsequent analyses to ensure a reliable dataset. The spatial salinity dataset comprised conductivity measures in 1565 river reaches (figure 1*a*) distributed across the 33 river typologies.

Temporal patterns of salinity in Spanish rivers were investigated by using water conductivity data from the Automatic Water Quality Information System (SAICA network, http://www.mapama.gob.es), which provides continuous information of river water quality variables (water level, water temperature, dissolved oxygen concentration, pH and conductivity) at a minimum frequency of 15 min. Mean daily values of these variables from 2007 to 2011 were calculated. Only SAICA stations located on river reaches with a mean daily conductivity between 0.03 and 5 mS cm^{-1} were considered, except when the time series showed that higher or lower conductivity values were common for that river reach. The temporal salinity dataset comprised 96 SAICA stations (figure 1*b*) distributed across 20 of the 33 river typologies.

(iii) Environmental drivers of spatio-temporal water salinity patterns

We selected environmental variables (electronic supplementary material, S1 and table S2) that could drive the spatial patterns of water salinity in Spanish rivers, including topography ($n = 6$), climate ($n = 8$), land uses ($n = 14$) and geology ($n = 14$) variables, and anthropogenic pressures ($n = 3$). We summarized these variables in three different spatial scales of the landscape: river reach (river segment itself), hillslopes adjacent to a river reach (adjacent hillslopes directly draining into an individual river segment) and entire catchment draining to a river reach (all the upstream catchment areas draining into an individual river segment).

In order to have a better explanatory power of the temporal patterns of water salinity, we calculated mean daily values of water level, water temperature, dissolved oxygen concentration and pH from 2007 to 2011. We also calculated, for each day, their maximum (Max), minimum (Min), standard deviation (s.d.) and coefficient of variation (CV) values for the 5, 10, 20 and 40 previous days (electronic supplementary material, table S2).

(c) Data analysis

(i) Variations in water salinity among Spanish rivers

A two-way type III ANOVA was performed to test for differences in water conductivity among river typologies and river reaches in poor and good ecological status. To identify where differences in conductivity between river reaches in poor and good ecological status laid, pairwise comparisons were performed between river reaches in poor and good ecological status within each river typology. Prior to the ANOVA test, data was log-transformed to achieve normal distribution and outliers were removed. Any data more than 1.5 times the interquartile range below the first quartile or above the third quartile were considered outliers. To optimize ANOVA performance, only river typologies which had more than five river reaches in both good and poor ecological status were selected. Thus, the ANOVA test only comprised 20 of the 33 river typologies (electronic supplementary material, table S1).

(ii) Environmental drivers of spatio-temporal water salinity patterns

A Random Forest model (RF; [30]) was used to investigate which were the most important drivers of spatial patterns of water salinity. Mean conductivity during low flow season between the years 2005 and 2014 was established as the dependent variable and spatial variables (topography, climate, land uses, geology and anthropogenic pressures) as potential environmental drivers (i.e. independent variables). The RF analysis model was trained with 75% of the dataset randomly and proportionally selected from 10 groups across the range of conductivity values, estimating the fitted R^2. The predictive accuracy of the model (predicted R^2) was estimated with the remaining 25% of the data. We used the number of predictors divided by 3 as the potential number of variables in each split and the number of trees to grow equalled to 500. We estimated the mean decrease in accuracy (i.e. increase in mean standard error, %IncMSE) to calculate the importance of the predictors in the model results [31] and produced the partial dependence plots showing the effect of each predictor on salinity after taking into account the average effect of all other predictors.

A generalized linear mixed-effect model (GLMM) was used to investigate which were the most important drivers of temporal patterns of water salinity. A stepwise backward selection (i.e. backward elimination of random-effect factors followed by backward elimination of fixed-effect variables) was applied using the step function in 'lmerTest' package. Mean daily conductivity from 2007 to 2011 was established as the dependent variable, the spatial (except climate) and the temporal environmental variables were established as the fixed factors, while the SAICA station, as a random factor. To estimate the importance of the factors in the final model, the percentage of variance explained by each was calculated.

The environmental variables selected for RF and GLMM models were uncorrelated (Spearman's $r < |0.70|$) to avoid collinearity problems. When various variables were correlated (Spearman's $r > |0.70|$), the variable showing the greatest correlation with water conductivity was chosen.

(iii) Extent of the Spanish river network salinized

To estimate the extent of the Spanish river network that was salinized, conductivity was predicted for all the river reaches in the river network (including natural, artificial or highly modified river reaches) based on the spatial RF results. After conductivity was predicted, we identified river reaches that had a high probability of being salinized by comparing, for each river typology, the predicted conductivity in each river reach to the maximum conductivity measured in river reaches in good status excluding outliers (i.e. any data more than 1.5 times above the third quartile). Thereby, for each river reach, we calculated the salinization ratio (SR) as:

$$\mathrm{SR}_{i,t} = \frac{\mathrm{Cond}_{i(\mathrm{Pred},t)}}{\mathrm{maximum\ Cond}_{(\mathrm{Mes},t,\mathrm{good})}},$$

where i is the river reach, t is the river typology and Cond is the water conductivity, which is either measured conductivity (Mes) or predicted conductivity (Pred).

We considered salinized those river reaches with a SR > 1. In salinized rivers, to estimate the degree of salinization, SR was scaled in the range [0,1] within each river typology. We considered slightly salinized a scaled SR between 0 and 0.25, moderately salinized between 0.25 and 0.50, heavily salinized between 0.5 and 0.75, and extremely salinized between 0.75 and 1. Finally, we estimated the river length salinized in each river typology and in the entire Spanish river network. As four typologies did not have water conductivity measures in river reaches in good status, these analyses were only performed for 29 river typologies, which comprise 96.47% of the river network length (electronic supplementary material, table S1).

(iv) Environmental factors that cause salinization

A generalized linear model (binomial family) with a stepwise forward selection based on Akaike's information criterion [32] was used to identify environmental factors that increased the probability of salinization. The same non-correlated environmental variables selected for the spatial RF were established as independent variables, and not salinized versus salinized classification of river reaches as the dependent variable. The deviance accounted for by the model was calculated following Guisan & Zimmermann 2000 [33].

All statistical analyses were performed in R (v. 3.4.4, R Core Team, 2018), using the following specific packages: 'openxlsx' (v. 4.1.0, [34]), 'caret' (v. 6.0-79, [35]), 'modEvA' (v. 1.3.2, [36]), 'lsmeans' (v. 2.27-62; [37]), 'randomForest' (v. 4.6-14, [38]), 'lme4' (v. 1.1-18-1; [39]) and 'lmerTest' (v. 3.0-1; [40]).

3. Results

(a) Variations in water salinity among Spanish rivers

Measured water conductivity showed a strong variation among Spanish rivers with significant differences among river typologies ($F_{1311,19} = 82.57$, $p < 0.001$). Mineralized rivers in the Mediterranean region such as Tinto and Odiel rivers, heavily mineralized Mediterranean rivers, low altitude mineralized Mediterranean rivers, rivers in the Guadalquivir depression and large Mediterranean river axes were the rivers with the most elevated water conductivity (mean conductivity > 1 mS cm^{-1}; electronic supplementary material, figure S1). By contrast, the rivers with the lowest water conductivity (mean conductivity < 0.2 mS cm^{-1}) were the siliceous and mountainous rivers in northwestern regions such as the humid siliceous mountain rivers, small siliceous Cantabric-Atlantic river axes, siliceous Cantabric-Atlantic rivers, high mountain rivers and Gredos-Béjar Georges (electronic supplementary material, figure S1).

Water conductivity significantly differed between river reaches in good and poor ecological status ($F_{1311,1} = 56.20$, $p < 0.001$), as mean conductivity in river reaches in good ecological status was 0.40 ± 0.01 mS cm^{-1}, whereas in river reaches in poor ecological status mean conductivity was 0.79 ± 0.03 mS cm^{-1}. Water conductivity also differed significantly between river reaches in poor and good ecological status within river typology ($F_{1311,19} = 5.534$, $p < 0.001$). Pairwise comparisons showed that these differences were present in 11 of the 20 typologies (table 1). Water conductivity was more elevated in river reaches in poor ecological status than in river reaches in good ecological status except in high mountain rivers, where river reaches in poor ecological status had a significantly lower conductivity than river reaches in good status (table 1).

(b) Environmental drivers of spatio-temporal water salinity patterns

Thirty three uncorrelated predictor environmental variables were selected for the spatial RF model (figure 2*a*). This model explained 55% of the spatial variation on water conductivity (fitted $R^2 = 0.55$), obtaining a poor fit for high conductivity values (electronic supplementary material, figure S2). According to the %IncMSE (figure 2*a*) mean annual precipitation, mean area occupied by agricultural lands, mean temperature in the hillslopes adjacent to the river reach, average rock hardness, average rock conductivity in the draining catchment, and river reach elevation were the most important drivers. Partial dependence plots showed that conductivity increased with the average percentage of agricultural lands and average rock conductivity in the draining catchment and mean temperature in the adjacent hillslopes, while it declined with average rock hardness and annual precipitation in the draining catchment and river reach elevation. This decline was particularly marked when mean annual precipitation exceeded 500 mm and rock hardness was greater than 3 (electronic supplementary material, figure S3).

From the 36 environmental variables that were selected for the temporal GLMM model (electronic supplementary material, table S2), only 13 were retained in the final model (figure 2*b*). The final model explained 86.1% of temporal variation of water conductivity, being 46.1% explained by the

Table 1. Summary statistics of the pairwise comparisons performed after ANOVA test to identify differences in water salinity between river reaches in poor and good ecological status within each river typology. (Significant *p* values ($p < 0.05$) are given in italics).

river typology	estimate	standard error	*t* ratio	*p* value
rivers in Tajo and Guadiana siliceous plains	−0.409	0.095	−4.323	*p* < *0.001*
siliceous rivers in Sierra Morena piedmont	−0.259	0.149	−1.741	0.082
low altitude mineralized Mediterranean rivers	−0.367	0.113	−3.258	*0.001*
rivers of low siliceous Mediterranean mountain	−0.184	0.069	−2.667	*0.008*
mineralized rivers of low Mediterranean mountain	−0.265	0.042	−6.263	*p* < *0.001*
siliceous Mediterranean mountain rivers	−0.193	0.059	−3.271	*0.001*
calcareous Mediterranean mountain river	−0.105	0.036	−2.941	*0.003*
poorly mineralized continental Mediterranean river axes	−0.050	0.067	−0.755	0.450
mineralized continental Mediterranean river axes	−0.119	0.098	−1.212	0.226
large Mediterranean river axes	−0.076	0.120	−0.632	0.528
coastal Mediterranean rivers	−0.123	0.108	−1.130	0.259
siliceous Cantabric—Atlantic rivers	−0.462	0.057	−8.078	*p* < *0.001*
calcareous Cantabric—Atlantic rivers	−0.226	0.122	−1.852	0.064
Gredos—Béjar Georges	−0.063	0.159	−0.395	0.693
humid siliceous mountain rivers	−0.184	0.067	−2.736	*0.006*
humid calcareous mountain rivers	0.028	0.065	0.438	0.661
high mountain rivers	0.344	0.080	4.274	*p* < *0.001*
main siliceous Cantabric—Atlantic river axes	0.018	0.136	0.136	0.892
coastal Cantabric—Atlantic rivers	−0.293	0.116	−2.530	*0.012*
small siliceous Cantabric—Atlantic river axes	−0.346	0.109	−3.182	*0.001*

random factor and 40% by fixed factors. Spatial variables, particularly the area occupied by agricultural land in the draining catchment, the average rock hardness in the draining catchment and the valley width index, were the most influential (figure 2*b*). Temporal variables such as pH, water level, temperature and dissolved oxygen concentration showed a minor importance. The agricultural land in the draining catchment, valley width index, pH, water temperature and dissolved oxygen showed a positive correlation to temporal variations in water conductivity, while the average rock hardness in the draining catchment showed a negative correlation. The different time horizons considered did not show a clear pattern.

(c) Extent of the Spanish river network salinized

The conductivity predicted for the entire river network ranged from 0.04 to 3.21 mS cm^{-1}. The predictive accuracy of the model was 0.58, although it showed a poor fit for high conductivity values (electronic supplementary material, figure S2). Results showed that 17822.41 km of rivers were salinized, which represents 27.60%, of the river network considered in the study (64567.60 km; figure 3). Among the salinized river reaches, 18.82% (12153.67 km) were slightly salinized, 6.87% (4435.74 km) moderately salinized, 1.57% (1010.97 km) heavily salinized and 0.34% (222.03 km) extremely salinized (electronic supplementary material, table S3). However, salinization strongly varied among river typologies. Some typologies showed no or less than 1% salinized stream reaches (i.e. heavily mineralized Mediterranean rivers and poorly mineralized continental Mediterranean river axes), while others had more than 80% of the reaches salinized (i.e. Gredos-Béjar Georges, Manchegan rivers and rivers in Tajo and Guadiana siliceous plains), with more than 10% of river reaches heavily or extremely salinized (10.01%; Manchegan rivers; electronic supplementary material, table S3).

(d) Environmental factors that cause salinization

The generalized linear model explained 28.47% of river salinization. The probability of salinization depended on a large number of environmental variables (30 variables), although the most influential were the land uses of the catchment (table 2). Particularly, the mean percentage of urban areas and agricultural lands in the draining catchment showed a strong positive effect (table 2) on salinization, whereas the percentage of forests (broadleaf and coniferous forests), plantations and shrubs showed a strong negative effect.

4. Discussion

This study shows how natural (i.e. climate and geology) and anthropogenic (i.e. land use) factors drive the spatio-temporal patterns of water salinity in rivers and streams in Spain. Moreover, it provides evidence of the vast extent of river salinization, which affected more than a quarter of the Spanish river network and was mainly caused by urbanization and agriculture.

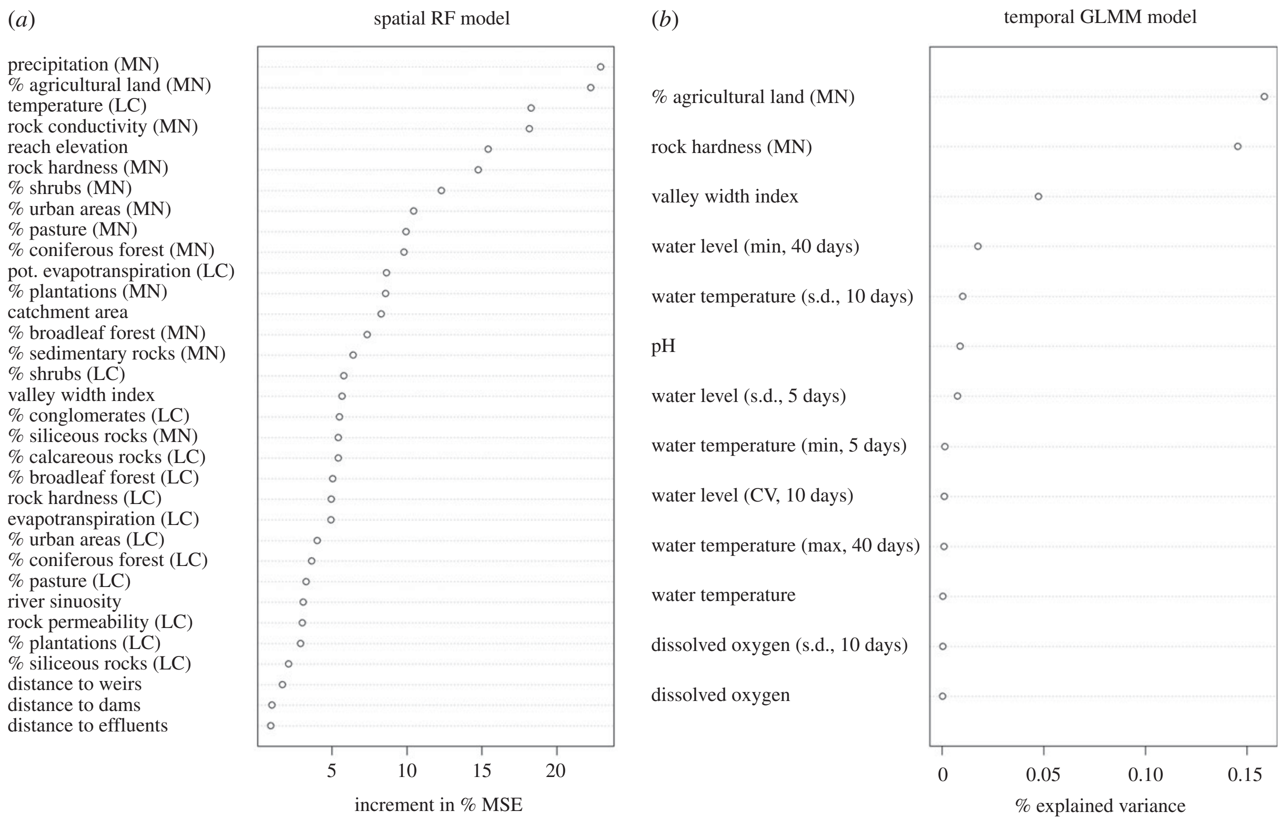

Figure 2. Importance of the environmental factors driving (*a*) spatial and (*b*) temporal patterns of water salinity based on the increase in mean standard error (increment % MSE) and the variance explained by each factor, respectively. MN, in the draining catchment to the river reach; LC, in the hillslopes adjacent to the river reach; Min, minimum value; Max, maximum value; CV, coefficient of variation; s.d., standard deviation of the variable during the 5, 10 or 40 previous days.

(a) Environmental drivers of spatio-temporal water salinity patterns

A combination of natural and anthropogenic factors drove the spatio-temporal patterns of water salinity. Natural factors were associated with catchment geology and climatic conditions. Geological drivers included rock conductivity and hardness. Rock conductivity, which was positively correlated to the area occupied by calcareous rocks, is a measure of the mineral salts contained in catchment soil and informs of the cation exchange between soils and sediments, and river water. Rock hardness, a measure of the erosion resistance of the soil, is related to the susceptibility of substrate to weathering processes (i.e. harder rocks are less susceptible to physical weathering). Precipitation and temperature were the most dominant climatic drivers in our study. Precipitation is, in conjunction with geology, the principal factor responsible for the weathering of the catchment [41]. Moreover, low precipitation and elevated temperature, lead to high evaporation rates (and often water scarcity) and consequently, to the concentration of ions and the increase in water salinity. Thus, geological and climatic factors are commonly considered the main drivers of natural salinity [6,15,42], which involves the accumulation of salts originating from natural sources at a rate unaffected by human activity. Nevertheless, the effect of geology in water salinity is not often considered (but see [43]) and recent studies [44] suggest that weathering processes, which typically occur over long geological time scales, are being accelerated by human activities and are occurring faster over recent decades. This evidences the need for further investigations understanding how natural factors, and particularly geology, determine water salinity within a global change context.

Regarding anthropogenic drivers, agriculture has long been demonstrated to be one of the principal drivers of salinity. Agriculture has been shown to increase the concentration of salts in soils through various pathways: (i) the replacement of deep-rooted vegetation by crops leads to rising groundwater tables that can contain salts, (ii) salts are introduced by irrigation and build up in the soil because of insufficient leaching, and (iii) salts (e.g. potassium) are contained in fertilizers applied to crops [3,21,45]. In all of these situations, the salts might end up in the freshwater ecosystems that surround the crops via surface runoff [46]. Additionally, the water diverted for agriculture irrigation diminishes the dilution capacity of rivers, thereby increasing salt concentration as observed in the Aral Sea [47]. Besides agriculture, river elevation, which was correlated to distance to the river mouth, strongly explained variations in salinity. River elevation could be an indirect indicator of the presence of anthropogenic pressures. Specifically, it might be reflecting the accumulation of human activities such as urbanization, agricultural lands or effluent discharges occurring along the river axes [48–50] and consequently, an elevated salinity in large rivers.

Although climatic, geological and land use factors were the main drivers of water salinity, including the seasonal and inter-annual variability of salinity, the poor fit of our spatial models at the highest end of the conductivity range suggests that other important drivers of water salinity might be missing. In this sense, it is important to notice that mining could not be incorporated into this study owing to a lack of detailed and reliable information. Potash and coal mining have been shown to significantly contribute to freshwater salinity [8,51] and, in Spain, streams affected by these type of mines can reach conductivities 3–4 times higher than that of seawater [9]. Thus, not being able to incorporate mining activities

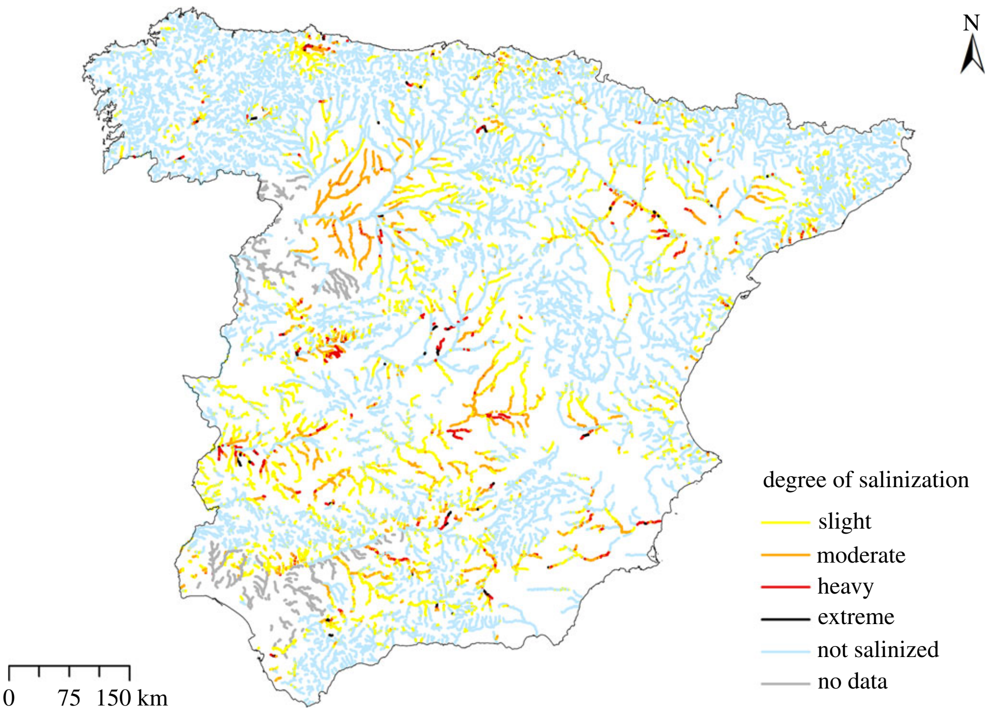

Figure 3. Map evidencing the degree of salinization of Spanish rivers. Light blue lines depict not salinized river reaches, yellow lines, slightly salinized river reaches; orange lines, moderately salinized river reaches; red lines, heavily salinized river reaches and black lines, extremely salinized river reaches. Grey lines represent river reaches in river typologies that were not considered in the analysis owing to the lack of water conductivity measures in river reaches in good ecological status.

might be the reason for our limited capacity to explain the most elevated water salinity values.

(b) Variations in water salinity among Spanish rivers

Spanish rivers showed a strong variation in water salinity, especially among river typologies. River typologies comprise rivers with similar environmental characteristics that are grouped together based on a combination of biogeographic factors such as elevation, stream size, water temperature, geology or geographical position among others [17]. Thus, environmental factors important for establishing river typologies seem to be also important for determining salinity, e.g. mineralized rivers and streams in Mediterranean regions showed the most elevated salinity while siliceous and mountainous rivers in northwestern regions, the lowest salinity.

Results also showed differences in water salinity between river reaches in poor and good ecological status in approximately half of the typologies analyzed. This association between salinity and ecological status might be related to the degradation of biological communities used as biological indicators (i.e. benthic macroinvertebrates, diatoms or phytobenthos) in salinized rivers. Thus, our results suggest that salinization could prevent many rivers and streams from reaching the good ecological status demanded by the WFD; something that was already suggested for German rivers [52]. In spite of this, salinity and specific ion concentrations are largely neglected through the application of the WFD. For example, in Spain, the Royal Decree on water policy (RD 817/2015), which establishes the criteria for monitoring and evaluating the ecological status of surface waters, recommends accounting for water salinity but the only indicator specifically considered for this decree is pH and not conductivity. However, there is no direct relation between pH (i.e. H^+ concentration) and conductivity (i.e. the concentration of all active ions). Further, the absence of differences in salinity between river reaches in good and poor ecological status within some typologies indicates either that rivers are not affected by salinization or that some river reaches in good ecological status are salinized. In this specific case, current indicators of ecological status might not be capturing salinization, probably because some biological indicators might not be sensitive to salinity changes unless they are severe [53]. Hence, these results suggest that water conductivity should be considered in the future as a measure of water quality and incorporated into the required indicators to determine the ecological status of a water body.

(c) Causes, extent and location of river salinization

Despite the numerous environmental factors driving spatio-temporal patterns of water salinity, land uses and particularly, agriculture and urbanization and the absence of forests, plantation and shrubs, emerged as the most important drivers of salinization. Agriculture has been long recognized as a major cause of soil and groundwater salinization [54], which reaches the rivers via surface runoff. Urbanization and its association with salinization has also been well-documented and can be linked to multiple sources such as storm water runoff, de-icing agents and wastewaters [55,56]. Further, although less documented, concrete weathering can substantially contribute to increase the concentration of certain ions in urban rivers and streams [13,44].

The percentage of salinized rivers and streams in Spain exceeded 25%. This percentage is similar, although slightly lower, to those reported for North America by Kaushal and colleagues [21], who found that 37% of streams and rivers were salinized and Olson [57], who recently estimated that 34% of

Table 2. Summary statistics of the most parsimonious generalized linear model performed to identify environmental factors that cause salinization. (Significant *p* values ($p < 0.05$) are given in italics).

environmental variable	estimate	standard error	*p* value
(intercept)	3.911	0.281	*<0.001*
% agricultural land (MN)	1.824	0.158	*<0.001*
% pasture (MN)	0.134	0.173	0.437
reach elevation	−0.002	<0.001	*<0.001*
catchment area	<0.001	<0.001	*<0.001*
precipitation (MN)	−0.002	<0.001	*<0.001*
% urban areas (MN)	2.958	0.380	*<0.001*
rock conductivity (MN)	−0.370	0.018	*<0.001*
valley width index	0.013	0.001	*<0.001*
% conglomerates (LC)	0.617	0.038	*<0.001*
distance to effluents	<0.001	<0.001	*<0.001*
% pasture (LC)	0.835	0.059	*<0.001*
% coniferous forest (MN)	−3.443	0.197	*<0.001*
% shrubs (MN)	−3.689	0.193	*<0.001*
% shrubs (LC)	1.025	0.068	*<0.001*
temperature (LC)	−0.074	0.009	*<0.001*
% siliceous rocks (LC)	−0.134	0.063	*0.033*
% urban areas (LC)	0.890	0.119	*<0.001*
% broadleaf forest (MN)	−1.964	0.173	*<0.001*
% plantations (MN)	−2.395	0.263	*<0.001*
rock permeability (LC)	0.163	0.021	*<0.001*
river sinuosity	0.337	0.054	*<0.001*
% sedimentary rocks (MN)	−0.962	0.117	*<0.001*
rock hardness (MN)	−0.144	0.032	*<0.001*
% plantations (LC)	0.606	0.134	*<0.001*
% siliceous rocks (MN)	−0.413	0.071	*<0.001*
distance to weirs	<0.001	<0.001	*<0.001*
% calcareous rocks (LC)	0.265	0.057	*<0.001*
% coniferous forest (LC)	−0.322	0.104	*0.002*
rock hardness (LC)	−0.051	0.017	*0.002*
distance to dams	<0.001	<0.001	*0.002*

streams have had water conductivity increased by more than 50% above natural background levels. Nevertheless, the percentage of salinized rivers obtained in our study may probably be underestimated given that the predicted conductivity was considerably lower than the measured conductivity at the highest values of conductivity, and river reaches with a conductivity of more than 5 mS cm^{-1} were not considered and most corresponded to river reaches in poor ecological status with a high probability of being salinized.

The most salinized rivers were located in central and southern regions of Spain (figure 3). The presence of more salinized rivers in these regions could be related to a more intensive agriculture than in northern regions. However, it needs to be considered that central and southern regions are characterized by a semi-arid and arid Mediterranean climate and irrigation agriculture dominates over rain-fed agriculture. Irrigation agriculture not only introduces more salts to the rivers but also diminishes their dilution capacity (i.e. water diversion), exacerbating the already limited dilution capacity of rivers arid regions. Hence, climatic conditions, although indirectly, seem to be key determinants of river salinization together with agriculture and urbanization. Concordantly, these regions show the highest risk of desertification (Spanish Ministry of Agriculture and Fisheries, Food and Environment; [58]). Although soil salinization and desertification have been shown to be tightly linked through water scarcity and soil erosion [59], interactions between desertification and freshwater salinization had rarely been reported. The elevated number of rivers salinized in regions in risk of desertification suggests that river salinization should be considered for future scenarios of global desertification [60], especially within a context of water scarcity, since this is determined by both the quality (i.e. salinized waters might not be suitable for human uses; [61]) and availability of water. Moreover, results also showed that large rivers can be salinized despite their high dilution capacity. This is the case of the Ebro, Douro and Tajo rivers, the largest rivers in Spain. The main causes of salinization in these rivers have been related to the discharge of wastewaters from cities and industries [16], the discharge of irrigation return flows [12] and the flow reduction caused by dams [62]. This, once more, points to the accumulation of a large number of anthropogenic pressures in the main axes of the largest rivers [48,49] as potential drivers of river salinization. In these rivers, where multiple pressures are present, a more mechanistic understanding of the salinization causes could be provided by the use of stable isotopes and hydrological measures and models [63].

5. Conclusions

Our results show that human activities may be causing a drastic increase in the salinity of rivers and streams in Spain and leading to the salination of more than a quarter of the river network. These activities particularly threaten rivers where numerous anthropogenic activities accumulate (i.e. large rivers) and rivers with a limited capacity to buffer salt-rich effluents such as rivers in arid and semi-arid climatic regions. Given the increase in the effects of climate change such as desertification and water scarcity, further investigations identifying the most sensitive regions for freshwater ecosystem salinization are highly needed to prioritize management actions.

Data accessibility. Data available from the Dryad Digital Repository at: http://dx.doi.org/10.5061/dryad.5m3338v [64].

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