Hydrobiologia
https://doi.org/10.1007/s10750-022-05063-9

EFFECTS OF CHANGES IN SALINITY

Human activities disrupt the temporal dynamics of salinity in Spanish rivers

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Received: 12 July 2022 / Revised: 7 October 2022 / Accepted: 12 October 2022

Abstract Human activities are not only increasing salinization of rivers, they might also be altering the temporal dynamics of salinity. Here, we assess the effect of human activities on the temporal dynamics of electrical conductivity (EC) in 91 Spanish rivers using daily measures of EC from 2007 to 2011. We expected rivers weakly affected by human activities to have low and constant ECs, whereas rivers strongly affected by human activities should have high and variable ECs throughout the year. We collected information on land use, climate, and geology that could explain the spatiotemporal variation in EC. We identified four groups of rivers with differences in EC trends that covered a gradient of anthropogenic pressure. According to Random Forest analysis, temporal EC patterns were mainly driven by agriculture, but de-icing roads, mining, and wastewater discharges were also important to some extent. Linear regressions showed a moderate relationship between EC variability and precipitation, and a weak relationship to geology. Overall, our results show strong evidence that human activities disrupt the temporal dynamics of EC. This could have strong effects on aquatic

Handling editor: Sidinei M. Thomaz

Guest editors: Erik Jeppesen, Miguel Cañedo-Argüelles, Sally Entrekin, Judit Padisák &S.S.S. Sarma / Effects of induced changes in salinity on inland andcoastal water ecosystems

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10750-022-05063-9.

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biodiversity (e.g., aquatic organisms might not adapt to frequent and unpredictable salinity peaks) and should be incorporated into monitoring and management plans.

Keywords Freshwater salinization · Temporal dynamics · Variability · Agriculture · Precipitation · Water quality

Introduction

Freshwater ecosystems are becoming saltier worldwide due to human activities (i.e., freshwater salinization, FS). Agriculture is the main driver of FS (Thorshlund et al., 2021), but there are others such as mining or the use of salts as de-icing agents in roads (Estevéz et al. 2019; Cañedo-Argüelles, 2020). Overall, FS is a global water quality problem that not only harms biodiversity and ecosystems (Cañedo-Argüelles et al. 2013; Berger et al., 2018; Hintz & Reylea, 2019), but also poses risks to human health (Kaushal, 2016; Cañedo-Argüelles, 2020) and can limit our use of hydric resources (Van Vliet et al., 2017; Thorshlund et al., 2021). The vast majority of studies on FS have focused on short-term laboratory or mesocosm experiments, or on snapshot field studies (Kefford et al., 2003; Horrigan et al., 2007; Birk et al., 2020). Thus, the temporal dynamics of FS have been largely overlooked. The few available studies addressing temporal variability in FS show that human activities can disrupt the natural temporal dynamics of salinity in freshwater ecosystems (Timpano et al., 2018; Niedrist, 2020). We argue that each type of human activity might have a different "temporal signature" (i.e., a characteristic temporal behavior) due to its intrinsic properties.

In agricultural landscapes the temporal dynamics of salinity might depend on the cultivation period and practices (e.g., rainfed vs. irrigated crops). For example, Gardner & Young (1988) showed that salt accumulation in the Colorado River Basin was primarily driven by excess irrigation water from croplands, and that irrigation explained more than a third of the basin salt load. Also, Heimhuber et al. (2019) found that extended dry periods increased salinity due to reduced river discharge and salt accumulation in agricultural regions of the Murray-Darling Basin (Australia). Finally, Leng et al. (2021) found a strong correlation between nutrients and salinity with the discharge of agricultural irrigation water into the Amu Darya and Syr Darya Rivers, in Central Asia. Overall, salinity is strongly driven by irrigation during low-flow periods in agricultural catchments (Crosa et al., 2006; Kulmatov et al., 2020). Therefore, peaks in conductivity are most likely to occur during planting periods, when fertilizer addition and irrigation are maximum. During these periods, the salts that have not been used by the plants are washed into surrounding rivers and streams (Williams, 2001; Anderson et al., 2019). In mining regions where residues are stockpiled (i.e., mine tailings) and surface rocks are exposed to weathering, heavy rain events can wash the salts into surrounding surface waters (Cañedo-Argüelles et al., 2012). This leads to sharp salinity increases that are usually brief and not captured by conventional water quality monitoring programmes (Cañedo-Argüelles et al., 2017; Liu et al., 2021). At the same time, saline effluents generated as a by-product of resource extraction might be disposed directly to surface waters (Cormier et al., 2013b; Vengosh et al., 2014; Sauer et al., 2016; Yusta-García et al., 2017) and diffuse salt pollution can generate from leaks in the waste management infrastructure (Gorostiza & Sauri, 2019). Finally, mining can lead to the salt pollution of groundwaters (Xinwei et al. 2009; Kaushal et al. 2018; Bondu et al. 2021), which can enter rivers and streams at different rates depending on complex geomorphological processes that are difficult to predict (Dahl et al., 2007; Sun & Sun, 2013). In cold regions, salts are often applied to roads to keep them ice-free and ensure road safety and transportation efficiency. For example, salt application has exponentially increased in the US since 1940 (Jackson & Jobbagy, 2005), with around 25 million metric tons of salts applied to roads in 2019 (USGS, 2020). Also, 13.4 tons of sodium chloride are applied annually to each kilometer of roads affected by ice in the Alpine region of Tyrol (Niedrist et al., 2020). Commonly, rivers and streams close to roads in cold regions experience an increase in salinity during early spring (when the snow is melted and flows into the surrounding streams) and during periods of snow-removal from the roads (Crowther & Hynes, 1977; Ruth, 2003; Kaushal et al., 2005; Corsi et al., 2015; Nava et al.,

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2020; Dugan et al., 2020; Niedrist, 2020). Cities generate a large amount of wastewaters that contributes to the salinization of surface waters (Venkatesan et al., 2011) and groundwaters (Li et al., 2021). Salinity attributed to urban areas can be determined by the quantity and type of products used by consumers (Hoekstra, 2015), and the climatic conditions that influence the dilution capacity of rivers and streams (Tiyasha et al., 2020). Also, the efficiency of wastewater treatment plants (WWTP) modulates the salt load of their effluents. For example, Levlin (2014) monitored two WWTP in Stockholm and found no significant reduction in conductivity by the preliminary treatment, and less than a 30% reduction by the activated sludge process (Moyano-Salcedo et al., 2021). Overall, the salt pollution associated with wastewater discharges depends on the WWTP configuration (Gonçalves et al., 2019; Salcedo et al., 2021) and might be highest during the summer, when the dilution capacity of rivers and streams is reduced (Dinçer & Kargi, 2001; Van Vliet & Zwolsman, 2008).

Understanding the temporal dynamics of FS is important because they can affect the structure and functioning of biological communities. For example, Kefford et al. (2007a, b, c) found that the eggs of some freshwater invertebrates were more sensitive to salt pollution than their larval stages. Thus, FS might have a greater effect for macroinvertebrates during oviposition than during larval development or during summer, when many species have emerged from the water. Also, many invertebrates that feed on leaf litter are especially sensitive to salinization (Kefford et al., 2011). This can also have implications for ecosystem functioning, since aquatic invertebrates contribute to carbon cycling through leaf litter decomposition (Canhoto et al., 2021).The aim of this study was to analyze how human activities might disrupt the temporal dynamics of electrical conductivity (EC, a proxy to salinity) in Spanish rivers using long-term data at high temporal resolution. Although previous studies have analyzed long-term salinity trends in rivers (Kaushal et al., 2005; Jiang et al., 2022), this is the first study focusing on the temporal fluctuations of salinity at an interannual scale and a high temporal resolution. We hypothesized that rivers under low human pressure would have low and constant ECs, whereas rivers strongly affected by human activities would have high and variable ECs throughout the year. We expected that the temporal dynamics of EC in Spanish rivers would be mainly driven by (I) agricultural activity, leading to EC peaks during the crops' growing season; (II) mining, leading to high ECs near mine tailings during heavy rainfall events; (III) transportation in cold regions, with high ECs during snowmelt and precipitation events in spring; and (IV) wastewater discharge in urban areas that would lead to maximum ECs during the summer due to low river flows.

Materials and methods

Study area

We studied 13 river catchments covering a wide range of land reliefs (i.e., valleys and mountains) and geological formations (e.g., carbonated rocks the eastern and southern regions and igneous metamorphic and rocks in the western regions) (Morán-Tejeda et al., 2019), and differing in size (from 900 to more than 90 000 km^2) (Estévez et al., 2019). They also covered diverse climatic conditions: the central, southern, and eastern regions present a Mediterranean climate, whereas the northern border is dominated by a temperate oceanic climate (Rivas et al., 2011). Finally, these heterogeneous environmental conditions result in a gradient of hydrological conditions, with some rivers drying during the summer (Peñas & Barquín, 2019; Estévez et al., 2019).

Electrical conductivity measurements

We used daily measures of electrical conductivity (EC) for the period 2007–2011 from 91 stations of the Automatic Water Quality Information System (SAICA, 2020). Using these data, a set of 24 ecologically meaningful conductivity indices (CIs) (Table S1 in Online Resource 1) were calculated based on hydrological indices (Richter et al., 1996; Peñas & Barquín, 2019). These indices were divided into three groups regarding (1) the mean annual and monthly conductivity, (2) the magnitude and duration of annual conductivity extremes, and (3) the timing of extreme conductivity events.

Environmental and human drivers

We selected relevant variables that could drive the change in the temporal dynamics of EC (Table S2 in

Online Resource 1), which were related to land use ($n=8$), geologic characteristics ($n=2$), and anthropogenic pressures ($n=4$). Distance to the nearest mine (P_DMN) and distance to the nearest icy road (P_DIR) were computed in R (R Core Team, 2021) according to the information available from the Spanish National Geographic Institute (2020). To calculate P_DMN, all mines with operating permits were located. Only the mines exploiting ferrous, non-ferrous, precious, non-metallic (e.g., salt), industrial rocks, and coal mines were considered. To calculate P_DIR, areas with a minimum of 30 days of snow were selected. Then, to determine the roads where salt was likely added, the selected areas were intersected with a road map. The intersected roads were checked using information provided by the Spanish General Direction of Traffic (2020). Finally, the distances of each SAICA station to mines (P_DMN) and icy roads (P_DIR) were calculated. The rest of the variables were computed by Estevéz et al. (2019).

Assessment of the drivers of changes in the temporal dynamics of EC

First, principal components (PCA) and clustering (Lemenkova, 2018) analyses were performed to group the samples according to their CIs. The multicollinearity of CIs was calculated using the Variance Inflation Factor (VIF) function in the R package "car," and the CIs with highly collinearity (VIF > 5) were removed. Then, Random forests (RF) were performed to assess the relative importance of the environmental drivers for explaining the variation in EC within each group using the function "rfsrc" in the package "randomForestSRC" (Ishwaran et al., 2022). ANOVA and Tukey's tests were used to assess the differences in CI between clusters. Then, generalized additive models (GAMs) were used to assess the relationship between EC and the different drivers selected by the RF using the function "gam" in the package "mgcv" (Wood, 2021). The GAMs incorporated independent smooths for each cluster and time step (i.e., each day at which conductivity was measured) and they were built using a default Gaussian distribution. To obtain model diagnostics, we used the "gam.check" and "appraise" functions in the package gratia (Pedersen et al., 2019). We assessed the differences between GAMs (i.e., differences in the temporal behavior of EC between groups) by looking at the confidence intervals. If the difference between the confidence intervals of the fitted smooths between two sets of data (i.e., cluster groups in our study) was non-zero, a strong difference was assumed (Pedersen et al., 2019). Linear regressions between EC and precipitation were built. All the statistical analyses were performed in R (R Core Team, 2021). Finally, the nomenclature proposed by Muff et al. (2022) was used to report the results from statistical analyses in the language of evidence.

Results

The minimum EC was always above 100 µS/cm and the maximum EC value was 5989 µS/cm. Overall, we found a strong decrease in mean EC (R2 = 0.001; *P* value < 0.001) at a rate of 17 µS/cm per year (Fig. S1 in Online Resource 2).

Variations in temporal dynamics of EC among Spanish rivers

Five indices related to the annual coefficient of variation (CVA), twelve to the monthly coefficient of variation (CVM), and ten indices related to the timing of extreme EC events (JMax and JMin) were selected to classify the rivers because of having a VIF lower than 5 (Tables S3, S3a and S3b; Online Resource 1). The first two axes of the PCA (Fig. 1) explained 56.7% of the variance in the different CIs, and the cluster analysis resulted in four groups of stations (SCI1, SCI2, SCI3, and SCI4; Fig. 2). The first axis of the PCA was mainly related to the coefficient of variation of the mean annual EC (CVA) and the coefficient of variation of the mean monthly EC (CVM from month 1 to 12). The groups were arranged along this axis as follows (from positive to negative values): SCI1, SCI4, SCI3, and SCI2. The second axis of the PCA was positively related to the Julian day of annual maximum EC per year (JMax) and negatively to the Julian day of annual minimum EC per year (JMin). All the groups contained stations with both positive and negative values of this axis, but the group SC1 showed the widest dispersion (i.e., a highest temporal variation in EC). SCI1 included 9 stations with the highest mean EC and standard deviation (2500 ± 930 µS/cm); group SCI2 included 37 stations with the lowest mean EC and standard deviation (374 ± 185 µS/cm); group SCI3 included 26 stations with moderate-low

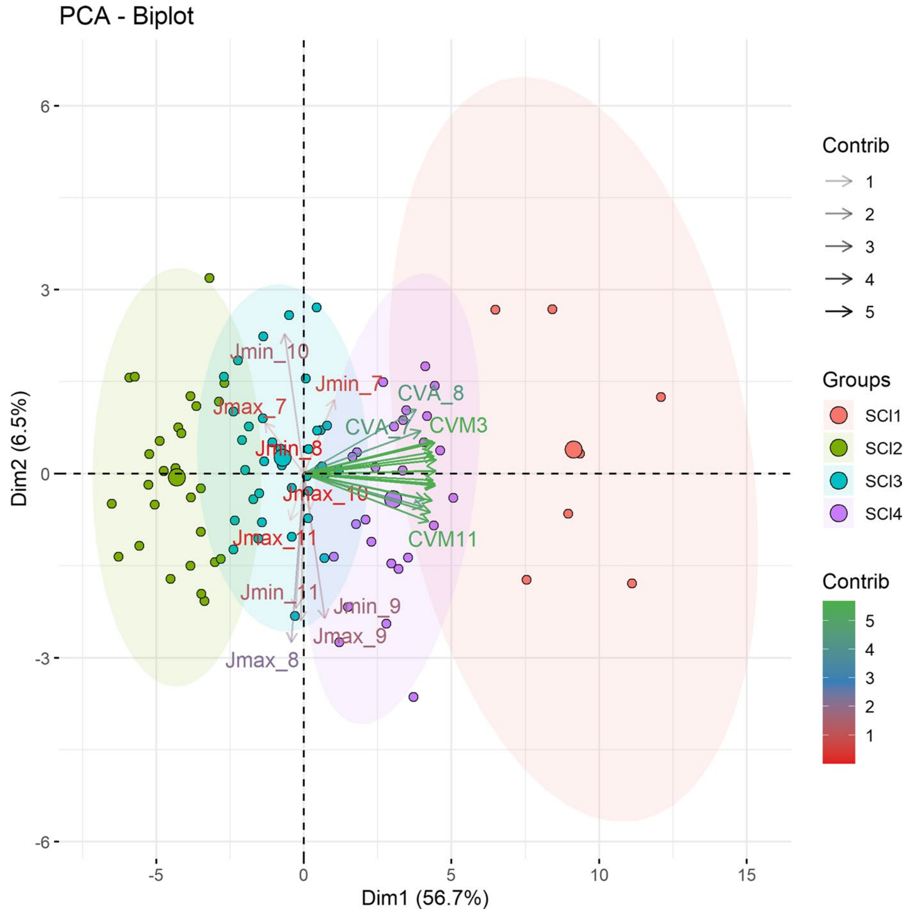


Fig. 1 Plot representing PCA and clustering of Synthetized Conductivity Indices (SCIs). The points and arrows represent the number of SAICA stations by cluster and the CIs, respectively

mean EC and standard deviation (850 ± 268 µS/cm); and group SCI4 included 19 stations with moderate-high mean EC and standard deviation (1300 ± 473 µS/cm). Figure 3 shows the EC variations by SCIs for the study period. In agreement with the PCA analysis, SCI1 showed the highest EC variations, followed by SCI4, SCI3, and SCI2. According to the comparison of GAMs, SCI1 showed strong differences (i.e., confidence intervals in pairwise comparisons for GAMs smooth terms was non-zero) from the rest of the groups in terms of temporal variations in EC (Fig. S2 in Online Resource 2). According to the Random Forest ($R2 = 0.52$), the temporal variation in EC was mainly driven by agriculture (MN_AGR), distance to the nearest icy road (P_DIR) and mining site (P_DMN) in SCI1; distance to the nearest icy road (P_DIR), area occupied by moors, heathland, scrub and shrubs (MN_SSH), agriculture (MN_AGR), and pasture (MN_PAS) in SCI2; mining (P_DMN) and urban areas (MN_UHD) in SCI3; and by pasture cultivation (MN_PAS), agriculture (MN_AGR) and, in some cases, the area occupied by coniferous forest (MN_CNF) in SCI4 (Fig. 4).

According to ANOVA, there was strong evidence of differences between groups (P value < 0.001 in all cases) for several of the drivers analyzed (Fig. 5). SCI1 was the most subjected to human activities, with the highest values of agricultural land, mining, and urban areas, and the lowest values of forest cover and calcareous and siliceous soils. On the opposite extreme of the anthropogenic disturbance gradient, SCI2 and SCI3 were characterized by the highest forest and pasture cover and the lowest urban cover, although SCI2 showed the closest distance to roads affected by snow, and SCI3 showed the closest distance to mining sites. SCI4 presented intermediate values for most drivers. Finally, geological conditions showed a weak relation to temporal EC variations in all SCIs and had the lowest relevance to explain EC variations in SCI1 (the most impacted

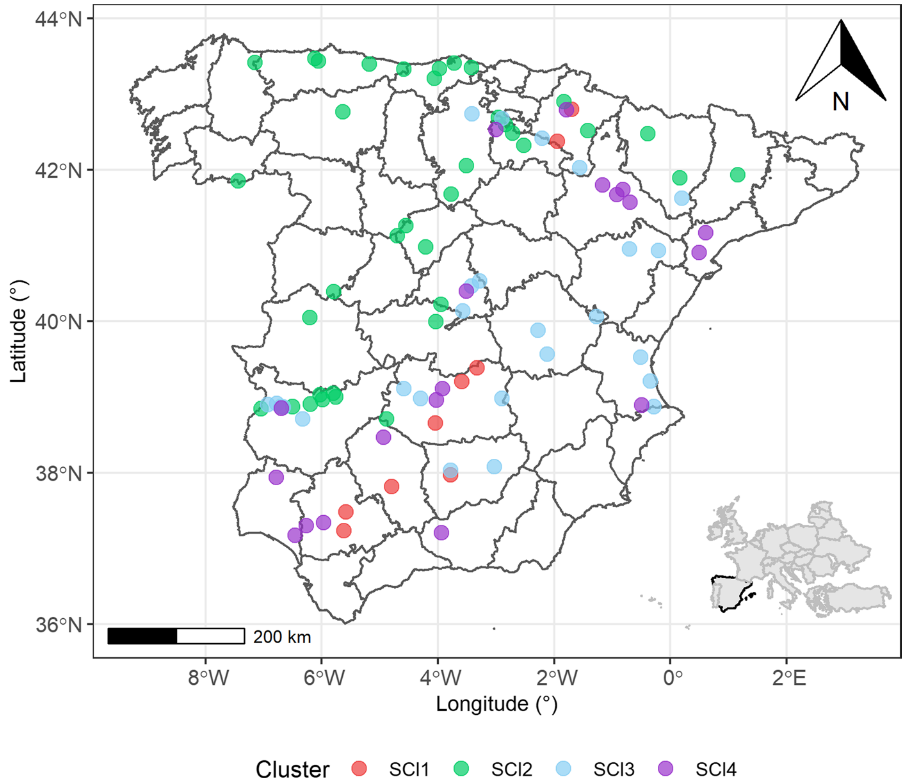


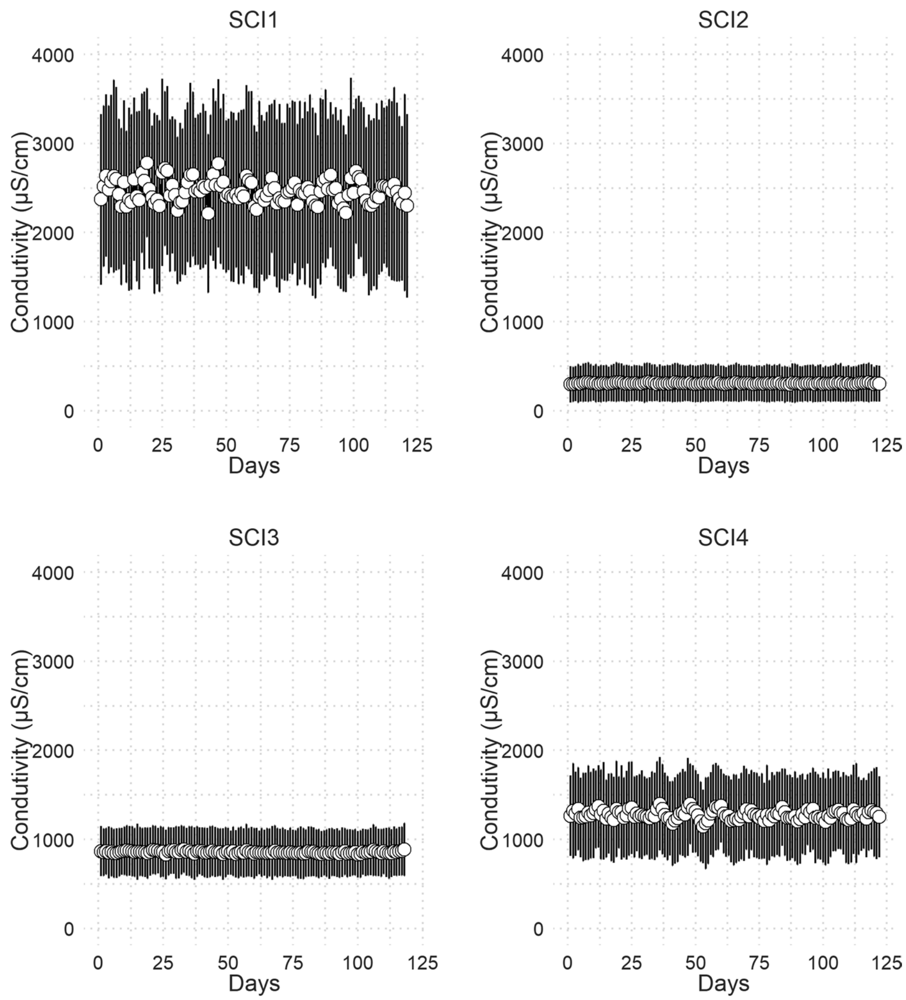
Fig. 2 Geographical map showing a spatial representation of the obtained cluster groups of Synthetized Conductivity Indices (SCIs). The points represent the number of SAICA stations by cluster

by human activities) (Fig. 4). Also, according to the ANOVA test, there was no evidence (P value = 0.738) for differences in EC between calcareous (mean EC = 920 ± 300 µS/cm) and siliceous (mean EC = 800 ± 279 µS/cm) catchments (Fig. S3, Online Resource 2). We found strong positive linear relationships between precipitation and EC during February (P value = 0.012) and November (P value = 0.007) in SCI1. In SCI2, EC was strongly associated with precipitation in March (P value = 0.027), July (P value < 0.001), August (P value < 0.001), October (P value = 0.002), and December (P value < 0.001). In SCI3, EC was strongly related to precipitation in February (P value < 0.001), October (P value = 0.019), and November (P value < 0.001). In SCI4, EC was very strongly related to precipitation in August (P value < 0.001), November (P value < 0.001), and December (P value < 0.035). Finally, EC was strongly related to heavy rainfall events in SCI3 (P value = 0.05), and to low rainfall events (< 10 mm) in SCI1 (P value < 0.019), SC2 (P value < 0.001), and SCI3 (P value < 0.001). The R-squared values of the linear models are shown in Table S4 (Online Resource 1).

Discussion

Overall, we found strong evidence for an amplification of the temporal variability in EC in Spanish rivers due to human activities. The EC was relatively constant along the year in rivers dominated by pasture and forests, whereas it experienced frequent and strong fluctuations in rivers subjected to high human pressure. Also, the group of sites most affected by anthropogenic disturbance (SCI1) showed mean EC values above the current Spanish water quality standards set to protect aquatic ecosystems (1000 µS/cm; Real Decreto 670, 2013) and human health (2500 µS/cm; Real Decreto 140, 2003). This aligns with previous studies showing that water quality standards in Europe are failing to protect aquatic biodiversity from salinization (Schuler et al., 2019; Hintz et al., 2022a, b). Contrary to our expectations, we found that the grouping of sites according to the temporal variability in EC did not respond to unique human drivers, but to a combination of them. Therefore, we cannot claim that each human activity has its own “temporal signature.” This is likely related with regional differences in the human drivers of FS (e.g., different crops

Fig. 3 Plot representing the mean value and variability in conductivity of each group with Synthetized Conductivity Indices (SCIs). The point and the irregular line represent the mean value and standard deviation, respectively



have different growing seasons) and in the natural drivers that modulate natural salinity (e.g., hydrology). Overall, the range of EC values reported in our study matches those reported by previous studies in Spanish rivers (Table S5 in Online Resource 3). We found strong evidence that the EC trends decreased from 2007 to 2011 for the whole set of rivers analyzed. These EC trends could be linked to technology improvements and the increase in the number of wastewater treatment plants (Fuentes et al., 2017; Rufí-Salís et al., 2022; Pompa-Pernía et al., 2022). Although a decrease in EC has also been reported for other regions (Jiang et al., 2022), it is important to notice that many freshwater ecosystems are getting saltier (Kaushal et al., 2005; Dugan et al., 2017) and this trend might be amplified by climate change (Le et al., 2019; Olson, 2019).

Agriculture was the main variable that differentiated sites with high mean EC and EC variability (SC1 and SCI4) from sites with low-moderate mean EC and EC variability (SCI2 and SCI3). This is in alignment with previous studies at the global (Kaushal et al., 2018; Thorslund et al., 2021) and the Spanish (Estévez et al., 2019) level, which identified agriculture as the main driver of FS. Our study reveals that agriculture is not only increasing the salt concentration of rivers, but also disrupting the natural temporal dynamics of salinity. Although the proximity of icy roads was not as important as agriculture, the ANOVA tests showed very strong evidence for differences between groups according to this variable. So far, road salt pollution of rivers and streams has been almost exclusively studied in Canada and the US (Cunillera-Montcusí et al., 2022). Our results suggest

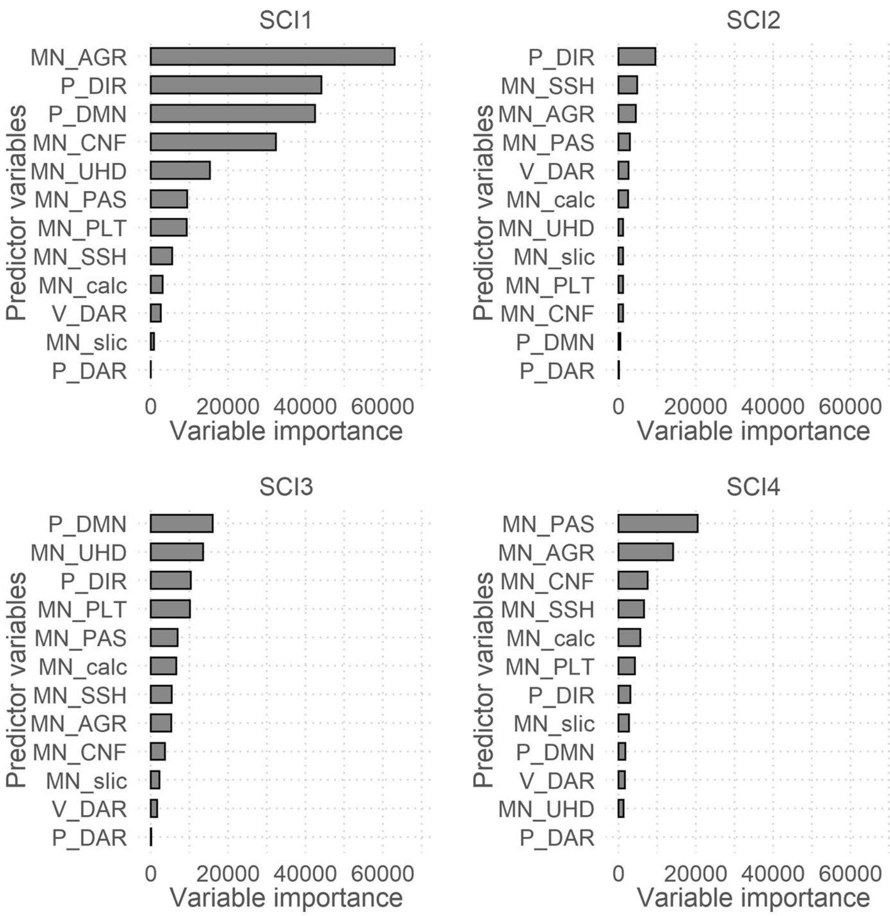


Fig. 4 Random forests (RF) plot representing the relative importance of the environmental drivers for explaining variation in conductivity within each SCIs. P_DMN: Distance to the nearest mining. P_DIR: Distance to the nearest icy road. P_DAR: Distance to the nearest dam upstream. V_DAR: Distance to the nearest effluent discharge upstream. MN_UHD: Area occupied by urban areas in the draining catchment. MN_AGR: Area occupied by agricultural land in the draining catchment. MN_CNF: Area occupied by coniferous forest in the draining catchment. MN_PLT: Area occupied by plantations in the draining catchment. MN_SSH: Area occupied by moors, heathland, scrub, and shrubs in the draining catchment. MN_PAS: Area occupied by pasture in the draining catchment. MN_calc: Area occupied by calcareous rocks in the draining catchment. MN_slic: Area occupied by siliceous rocks in the draining catchment

that this activity is partly responsible for the increase in EC and the alteration of EC dynamics in Spanish rivers, as it has been found for the Alps (Niedrist et al., 2020). Thus, we suggest that road salt pollution of rivers and streams deserves to be further studied in Europe. Despite wastewater treatment plants having a weak effect on EC variability, these also deserve attention due to the potential interacting effect of salinity with other chemical cocktails that compose the so-called freshwater salinization syndrome (Kaushal et al., 2018, 2019, 2021, 2022). Finally, we found weak differences in EC between rivers according to their geological composition. This suggests that human activities are overriding the influence of geology, which is the main driver of changes in salinity in pristine rivers and streams (Meybeck, 2003).

Temporal changes in EC were very strongly affected by precipitation during some of the studied months. The fact that the months that showed a strong linear relationship between precipitation and EC were different for each group suggests that human activities and climatic drivers interact to modulate the temporal dynamics of salt pollution. For instance, in the case of

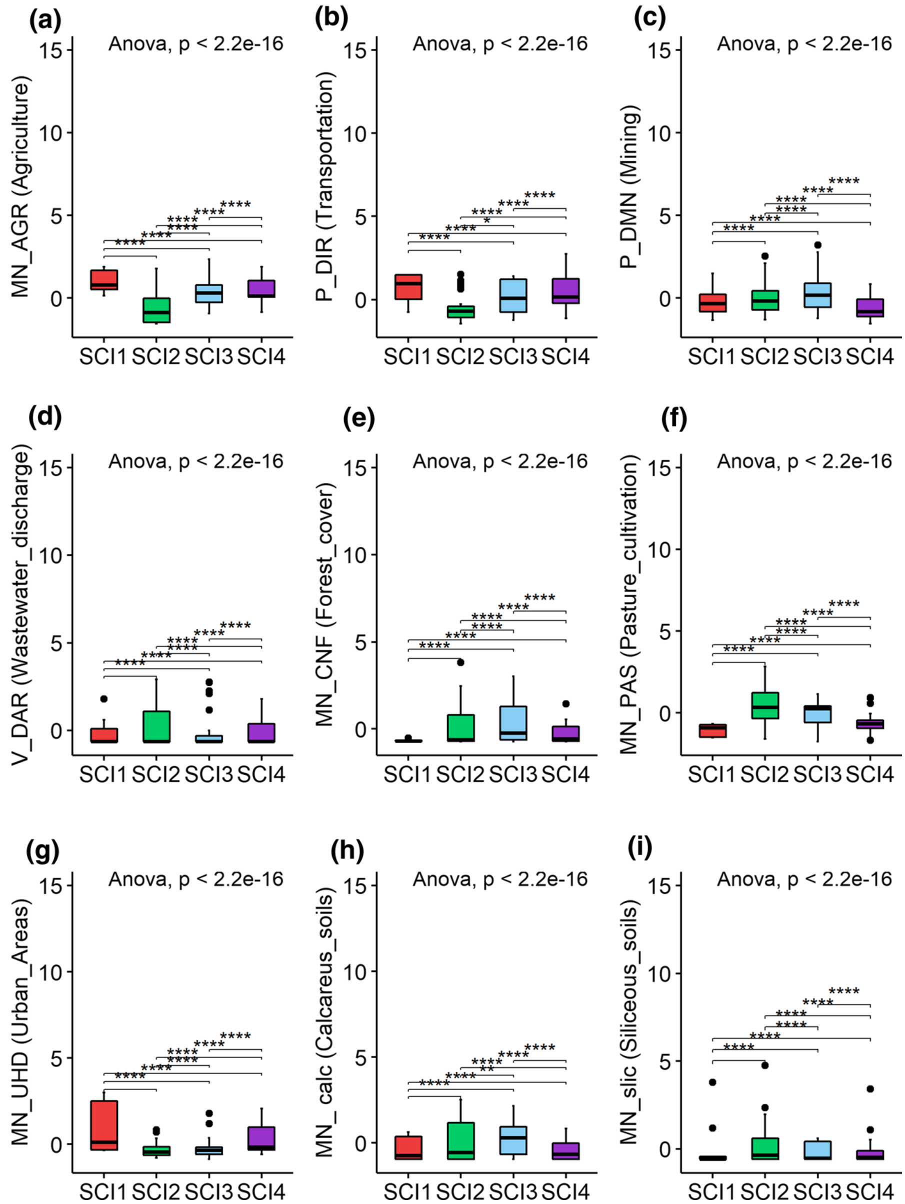


Fig. 5 Results of the relevant environmental variables (according to RF) and differences between SCIs (Standardized Values). **A** MN_AGR: Area occupied by agricultural land in the draining catchment. **B** P_DIR: Distance to the nearest icy road. **C** P_DMN: Distance to the nearest mining. **D** V_DAR: Distance to the nearest effluent discharge upstream. Limitation of 5000 m. **E** MN_CNF: Area occupied by coniferous forest in the draining catchment. **F** MN_PAS: Area occupied by pasture in the draining catchment. **G** MN_UHD: Area occupied by urban areas in the draining catchment. **H** MN_calc: Area occupied by calcareous rocks in the draining catchment. **I** MN_slic: Area occupied by siliceous rocks in the draining catchment

agriculture (which was most important in SCI1), daily EC and precipitation were strongly related during August–November, suggesting that salts could build up in the soil during the summer and then enter the rivers as runoff. Concordantly, Merchant et al. (2020) found that EC significantly increased in the Cidacos river (included in our study) during July–November due to crop irrigation. In SCI2, where road-de-icing and wastewater discharge were among the most important predictors according to RF, EC was related to precipitation during winter, spring, and summer. These are the months when there were roads affected by snow, salt could be washed into the rivers due to ice melting and river flows were low, respectively. The potential influence of road salt application on the EC of rivers enclosed in SCI2 aligns with a previous study (Asensio et al., 2017) that found salinized soils 3 m away from roads affected by snow during winter in some of the rivers belonging to this group (Aragon, Araquil, and Arga). Concordantly, in our study, these rivers showed higher mean and standard deviation EC (670 ± 155 µS/cm) than the rest of the rivers belonging to the same group (280 ± 104 µS/cm). In SCI3, which had the greatest impact from mining, EC was strongly related to heavy precipitation in autumn. Heavy rainfalls and flash floods are common in Spain during autumn, especially in the Mediterranean region (Belmonte & Beltrán, 2001; Machado et al., 2011; Camarasa, 2016; Ribas et al., 2020), where important mining areas exist (Spanish National Geographic Institute, 2020). These heavy rain events are associated with EC peaks in mining areas due to the washing of salts that are stockpiled in mine tailings (Cañedo-Argüelles et al., 2012, 2017; Ladrera et al., 2017; Gorostiza & Sauril, 2019). Finally, it is important to take into account that the rivers included in this study are relatively large (mean water level = 0.76 ± 0.97 m), thereby having a high salt dilution capacity (Turunen et al., 2020). Thus, our results need to be taken with caution, as the magnitude of salt pollution and the disruption of the temporal salinity dynamics in smaller rivers and streams might be higher than those reported here. The disruption of the temporal dynamics of EC can have serious consequences for aquatic biodiversity. For example, we found EC peaks higher than 3500 µS/cm in SC1. These EC values are lethal to many riverine organisms according to field studies and laboratory assays (Kefford et al., 2003; Horrigan et al., 2007; Cañedo-Argüelles et al., 2013). However, it is not only the magnitude of the EC peaks that matter, but also their timing. For example, during winter, many macroinvertebrate species are at early development stages, which tend to be more sensitive to salinization than the older stages (Kefford et al., 2004, 2007a, b, c). Also, during summer, many taxa lay their eggs, which might not hatch at high EC (Bailey et al., 2004; Kefford et al., 2007a, b, c; Lawson et al., 2021). Also, the existence of unpredictable and frequent EC peaks along the year could difficult the adaptation of the species to salinization and have deleterious effects on both biodiversity and ecosystems functioning (Cañedo-Argüelles et al., 2014; Oliveira et al., 2021).

Conclusions

This study is the first to analyze how the combination of natural and human drivers (agriculture, mining, wastewater, transportation, and urban areas) influences the temporal dynamics of EC in Spanish rivers. We found strong evidence for a disruption of the temporal dynamics of EC due to human activities during the period study (2007–2011). We obtained four groups (SCI1, SCI2, SCI3, and SCI4) of rivers separated according to EC variability and the timing of extreme EC events. We found different EC patterns throughout the year, with some rivers showing high mean EC and EC variability (SCI1 and SCI4) and others lower and less variable ECs (SCI2 and SCI3). The disruption of the temporal dynamics of EC did not show a clear separation between stations according to the dominance of different human activities. Instead, we found that EC variations were determined by a combination of multiple environmental and human drivers. Agriculture was the main driver of FS, but de-icing roads, mining, and wastewater discharges were also important to some extent. Also, there was very strong evidence for relationships between precipitation and EC that could be related to different human activities (e.g., crop irrigation or road salt application). Overall, our results call for more studies analyzing the ecological implications of increased variability of EC as a result of human activities. According to our results, it seems advisable to measure EC multiple times throughout the year and establish monitoring periodicity according to the human pressures that are operating on rivers and the natural seasonal EC dynamics. For example, in agricultural watersheds dominated by agriculture, information on the timing of pesticide and fertilizer application, irrigation, and harvesting could be very useful to anticipate changes in ECs in the rivers. Also, more studies on the ecological impacts of EC fluctuations are needed to implement effective management responses that protect freshwater biodiversity from salinization.

Acknowledgements AM was supported in part by a doctoral grant from the Ministerio de Ciencia, Tecnología e innovación y Colfuturo (Colombia). MC was supported by a Ramón y Cajal contract funded by the Spanish Ministry of Science and Innovation (RYC2020-029829-I).

Author contributions All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by AJMS, EE, JB, and MC-AI. The first draft of the manuscript was written by AJMS and MC-AI. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript. MC-AI and HS contributed to funding acquisition, and supervision.

Funding Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature. AM was supported in part by a doctoral grant from the Ministerio de Ciencia, Tecnología e innovación y Colfuturo (Colombia). MC was supported by a Ramón y Cajal contract funded by the Spanish Ministry of Science and Innovation (RYC2020-029829-I).

Data availability All data produced from this study are provided in this manuscript (and its supplementary information files). The information on environmental drivers of freshwater salinization was downloaded from Sistema de Información de Ocupación de Suelos de España (SIOSE, https://www.siose.es/usos-de-suelo) and Instituto Geográfico Nacional, Spain (ING, 1 https://www.ign.es/web/ign/portal). Conductivity measurements were downloaded from the Water Quality Information System (SAICA network, http:// www.mapama.gob.es). Other datasets generated (e.g., R scripts) during the current study are available from the corresponding author upon request.

Declarations

Conflict of interest The authors declare there is no conflict of interest.

Ethical approval The research complies with ethical standards.

Consent for publication Not applicable.

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