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Hydrosaline balance evolution of an irrigated zone: The case of Lerma basin (Spain, 2004–2020)

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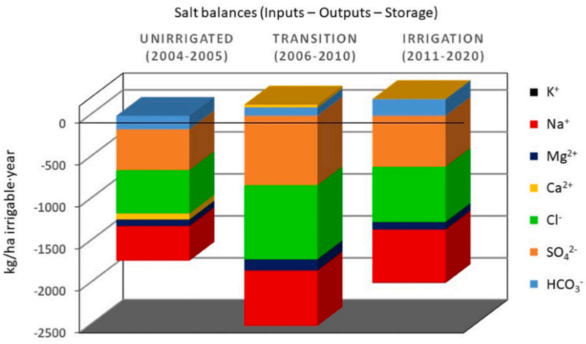
HIGHLIGHTS

- Lerma gully (NE-Spain) evolution since irrigation land transformation
- 2004–2020 hydrosaline balances for main ions
- SO_4^{2-}, Cl^-, Mg^{2+}, Na^+, and K^+ increased while HCO_3^- and Ca^{2+} decreased.
- The implementation of irrigation doubled the mass of exported salts.

GRAPHICAL ABSTRACT



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ABSTRACT

Geologically saline zones with scarce pluviometry are areas susceptible to salinization of their natural drainage. However, the salinization of the receiving water systems can be accelerated with the implementation of irrigation. This work aims to analyze the effects of irrigation on some zones transformed into irrigation land, from the beginning of the process until its complete consolidation. To this end, salt balances are evaluated as a whole and for each significant chemical element. The study zone is the irrigable area of the Lerma basin (Spain), where hydrosaline balances have been carried out since the hydrological year 2004 (before the implementation of irrigation) until 2020 (after the consolidation of irrigation). The implementation of irrigation in the area has doubled the mass of exported salts up to an average of 3177 kg/ha irrigable·year, for the entire study period. 55 % of that amount results from a global mineral dissolution, although this process seems to decrease with time as these minerals are being flushed from the soil. Before irrigation was implemented, the general global dissolution pattern produced more concentration of most ions (SO_4^{2-}, Cl^-, Mg^{2+}, Na^+, and K^+) in the water outputs than in the water inputs. After the implementation of irrigation, there were more water inputs than outputs in the balance and that was shown by the decrease in the dissolved HCO_3^- and Ca^{2+}.These results indicate that the consolidation of irrigation progressively decreases the induced salinization in the water systems that receive the

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irrigation return flows. Further studies are required to expand the general understanding of the process and its effects, quantify the different geochemical processes involved, and identify possible additional environmental issues induced by irrigation.

1. Introduction and objective

The UN estimates (https://www.un.org) that the world population will increase by 2 billion within the next 30 years, from 7.7 to 9.7 billion in 2050 and reaching a peak of 11 billion by 2100. In this context, irrigated agriculture is an indispensable resource to feed the population, as it increases crop productivity and diversity (MAPA, 2018). Although it corresponds to <2.6 % of the Gross Domestic Product (INE, 2018) in Spain, irrigated agriculture is one of the backbones of the country and is strategic to its sustainability.

Nevertheless, agriculture, especially irrigation, significantly affects the quality of the waters receiving the irrigation return flows. Geologically "saline" zones with low pluviometry levels (already prone to salinization of natural drainage) can suffer an acceleration of salinization when irrigation begins.

Among the effects produced by salinity on water resources, the impact on the ecosystems is significant as many species (plants and wildlife) do not tolerate increased salt concentrations (Nielsen et al., 2003; Pinder et al., 2005; Cañedo-Argüelles et al., 2013; Lorenz, 2014; Herbert et al., 2015). The salinity increase can also limit water use for urban supply, irrigation, and even for industries (WHO, 2011; Mateo-Sagasta et al., 2018).

In recent decades, several studies have been carried out to quantify the environmental impact of irrigation regarding the salinization of the systems receiving return irrigation flows (e.g., Causapé et al., 2006). Many of these studies have been developed in the Ebro basin because it presents some areas with high salinity that contribute significantly to the salt content of the surface waters (Alberto and Navas, 1986; Navas, 1991). This is due to the geology of the Ebro basin, which was part of a great interior sea during the Tertiary. In addition, low pluviometry levels in the central zone of the basin and progressive transformation into irrigated agriculture (Alberto et al., 1986) have led to an increasing salinity trend (Lorenzo-González, 2022).

A complete assessment of the effects of agricultural drainage on water quality should focus on the masses of exported contaminants and their concentrations. The mass of exported salts from irrigated areas is responsible for the degradation of the water systems that receive irrigation return flows (Lecina et al., 2010) – the index called Total Maximum Daily Load (TMDL) is already employed in the USA by regulation agencies (Elshorbagy et al., 2005).

Studies based on hydrosaline balances of hydrological irrigated basins can quantify the mass of exported salts. The difference between inputs and outputs can determine the amount of dissolved or precipitated salts. However, most salt balances of irrigated areas are carried out for specific years and do not include individual balances for the major ions.

The study presented herein aims to go a step further by analyzing the effect of irrigation from the beginning of the transformation process

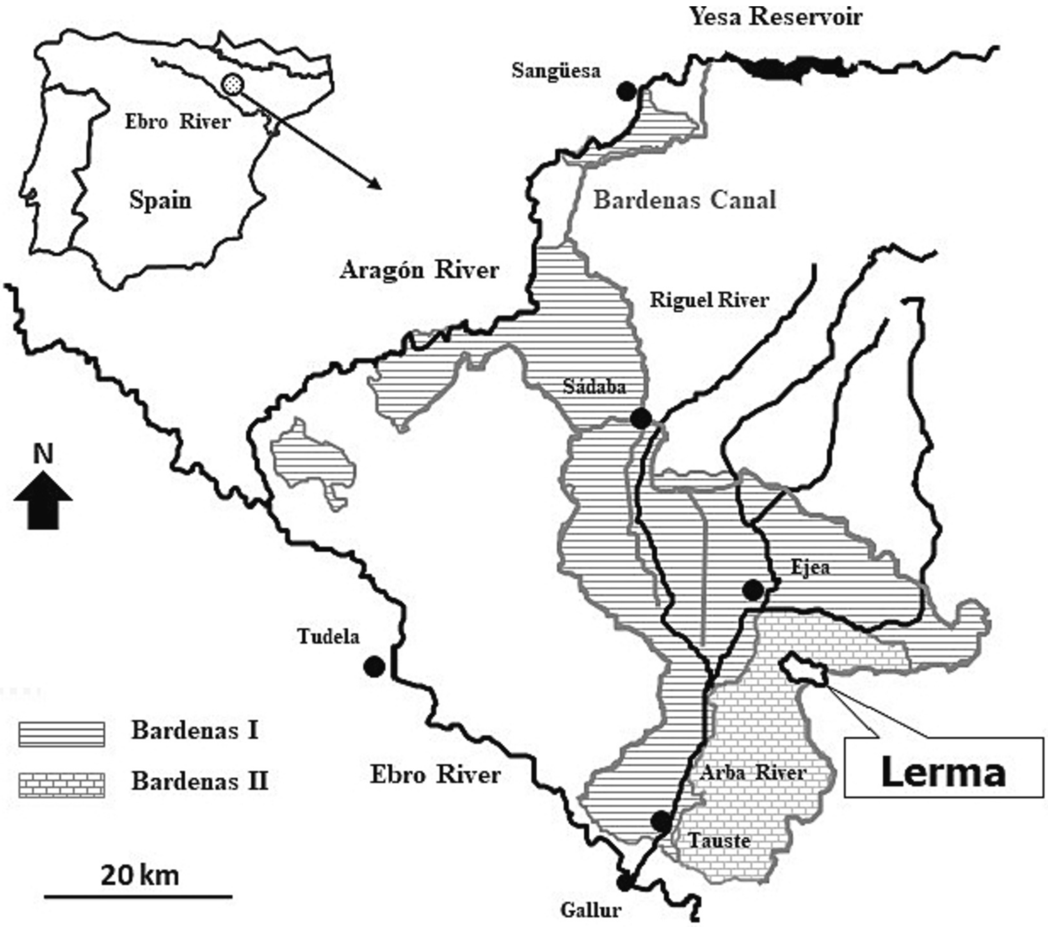

Fig. 1. Geographic location of the Lerma basin.

until the consolidation of the irrigation works (17 years), with a general analysis of salts and individual assessments for the main ions.

2. Study zone and monitoring

The study zone comprehends the hydrological basin of the Lerma gully (Spain), of which 48 % of its surface (352 ha) was included in an irrigation project that covered Sector XII of Bardenas II (Fig. 1).

Water from the Aragón River (affluent of the Ebro River) is taken, through the Yesa swamp and Bardenas Canal, to irrigate the zone. The water originates from the Pyrenees, and presents low mineralization levels (300 μS/cm). The Arba river (also an affluent of the Ebro) receives the irrigation return flows from the Lerma gully. Under unirrigated conditions, the Lerma gully presented an electrical conductivity at 25 °C (EC) of up to 8000 μS/cm.

In a zone where annual average precipitation (382 mm/year; Merchán, 2015) is less than a third of the potential evapotranspiration (1307 mm/year), irrigation is essential for the development of summer crops (maize, sunflower, vegetables, etc.) and to increase the productivity of winter cereals (wheat, barley, etc.).

The Lerma area has been studied since the beginning of transformation works in 2003 (Moreno-Mateos et al., 2009; Abrahão et al., 2011a,b,c, 2013; Merchán et al., 2013, 2014; Von Gunten et al., 2014; Lorente et al., 2015; Abrahão et al., 2015; Merchán et al., 2015a,b; Von Gunten et al., 2015; Von Gunten et al., 2016; Hurtado et al., 2016; Abrahão et al., 2017; Margalef-Marti et al., 2019; Abrahão et al., 2021). Irrigation was progressively implemented from 2006 (26 % of irrigated area) until 2008 (90 % of irrigated area) when almost the entire irrigable area was effectively under irrigation.

The implemented pressurized irrigation is mainly located on the soils developed on the quaternary glacis, which constitutes 34 % of the area (Calcixerollic Xerochrepts; Soil Survey Staff, 2014) and presents low slopes (<3 %) and low salinity ($EC_{saturated\ extract} < 4$ dS/m). The remaining 66 % of the area are soils developed on the Miocene materials of the Tertiary valley, which is limited by the Lerma gully (Typic Xerofluvent; Soil Survey Staff, 2014). Those soils have pronounced slopes (>10 %) and high salinity ($4\ dS/m < EC_{saturated\ extract} < 8$ dS/m). These tertiary materials correspond to central facies of the lacustrine basin and consist of alternating layers of gypsum, clay, and silt, with brownish and greyish tones and occasional intercalations of thin layers of limestone associated with gypsum.

Merchán et al. (2015a,b) conducted runoff experiments with the study zone soils to verify which geochemical components could reach the waters. The mineralogical composition of the soils was characterized by X-ray diffraction, which indicated the presence of calcite, quartz, and clay minerals in the soils developed on the quaternary glacis. In the case of the soils over the Tertiary, dolomite, gypsum, and halite were also detected. These characteristics were reflected in the results of the runoff tests. In the case of tertiary soils, there was a higher amount of dissolved Na^+ and Cl^-, and when the soils were over gypsum layers, higher concentrations of SO_4^{2-}, Ca^{2+}, and Mg^{2+} were observed. The runoff of soils developed on the quaternary glacis produced much lower ionic concentrations.

Most of the irrigated area is located over the quaternary aquifers, which drains most of the irrigation waters. These waters flow through more saline and impermeable materials of the Tertiary (Fig. 2) before reaching the Lerma gully.

3. Methodology

The general methodology is based on the performance of hydrosaline balances for the irrigable area of the Lerma gully basin. Data obtained from the analysis of the water samples were processed along with thousands of automatic measures of flow and salinity (indirectly determined from EC) in the Lerma gully. The performance of hydrosaline balances and chemical data processing are described next.

3.1. Hydrosaline balances

Hydrosaline balances were carried out for the irrigable area of the Lerma basin from the hydrological year 2004 (October 1, 2003 until September 30, 2004), before irrigation was implemented, until the hydrological year 2020 (October 1, 2019 until September 30, 2020), with the irrigation system already consolidated.

The calculation of the hydrosaline balances was performed with the Irrigation Land Environmental Evaluation Tool (Causapé, 2009; https://jcausape.es/software-emr/). This software calculates balances for the water flows and each of the main ions identified, considering the different water components (water inputs, outputs, and storage). Then, the program assigns the difference between inputs, outputs, and storage (in soils and aquifers) to geochemical processes such as dissolution, precipitation, and possible ionic exchange.

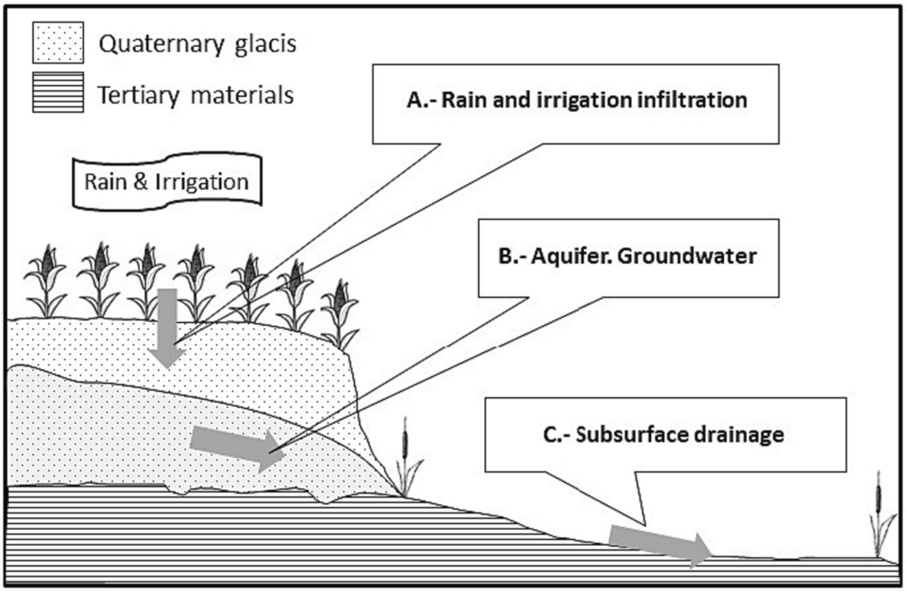

Fig. 2. Conceptual hydrological model (adapted from Merchán et al., 2015a,b).

The methodology proposed by Merchán et al. (2015a,b) for the same study zone was followed herein. The inputs considered in the balance were:

1. Irrigation: measured by the Irrigation Community at the hydrant located on each plot.
2. Rain: measured by pluviometers at the stations of the Agroclimate Information System for Irrigation (in Spanish, SIAR) network; http://oficinaregante.aragon.es/
3. Runoff from unirrigated zones: estimated from the runoff coefficient calculated in unirrigated conditions and then extrapolated to the unirrigated surface using pluviometry data.
4. Leakages of the irrigation channel: measured by the gauging station at the foot of the channel.
5. Direct losses from the Lerma gully due to leaks in the pipe network: determined by decomposition of the hydrograph of the Lerma gully in the periods during which these are detected.

The outputs considered in the balance were:

1. Evapotranspiration: estimated by the EMR software from the daily water balances in the soil of each plot with agroclimate information (crop map, water holding capacity in the soil, reference evapotranspiration, and crop coefficients).
2. Losses due to evaporation and wind drift of sprinkler irrigation systems: estimated by the EMR software from the ratios of relative humidity and wind speed obtained from the SIAR network.
3. Lerma gully drainage: measured by monitoring the flow of the gully.

Finally, the considered water storage included:

1. Aquifers: measured by the difference between the water levels registered by the piezometer network and the effective porosity of the aquifer.
2. Soils: estimated by the software EMR for each plot from the daily water balance in the soil.

During the 17 years of monitoring (2004–2020), most efforts were dedicated to measuring the flow and salinity (EC at 25 °C) at the outlet of the Lerma gully, as these data ultimately provide information on the loads transported from the system. Until September 2005, monthly flow measurements were made along with manual water sampling to determine EC at 25 °C. A gauging station was installed in October of 2005 to obtain more precise data on the variations of the system, including an electronic limnigraph and an automatic water sampler. This enabled daily information on the concentration and mass of exported salts.

Despite the improvement made with the daily sampling, it was not sufficient to detect punctual storm events that could significantly contribute to the overall load of exported salts. In July 2011, the gauging station was equipped with sensors for telemeasurement flow and EC at 25 °C, in 10-minute intervals.

The concentrations of the main ions (HCO_3^-, SO_4^{2-}, Cl^-, Ca^{2+}, Mg^{2+}, Na^+ and K^+) were analyzed in the different water balance components throughout the study period. Data corresponded to 100 samples from the gully, ten from the rainwater, and five from the irrigation water, for which pH and EC at 25 °C were also determined.

The chemical analyses were carried out at the *Centro Tecnológico Agropecuario Cinco Villas*. Alkalinity (HCO_3^-) was analyzed by volumetric titration with acid and potentiometric determination of the final point at pH 4.5. SO_4^{2-} was quantified by spectrophotometry using a turbiditic method with Ba. Cl^- was determined by titration with silver nitrate in the presence of potassium chromate as the indicator (Mohr's method). Ca^{2+}, Mg^{2+}, Na^+, and K^+ were analyzed by atomic absorption spectrophotometry.

3.2. Chemical data processing

Calculating the balances requires information on the ion concentrations within the inputs and outputs of the different hydric components. Table 1 shows the average values of the concentrations analyzed in the waters of the Lerma gully, rainwater, and irrigation water.

The chemical compositions of the remaining balance components were simplified as follows: 1) the concentrations of the waters from the channel and pipelines (leakage) are the same as those measured in the irrigation water; 2) the concentrations of the Lerma gully are considered representative of the inlet flows from the exterior of the irrigable area (similar geology), and 3) the water losses from the sprinkler irrigation due to evapotranspiration, evaporation, and wind drift have been considered free of salts.

The chemical composition of the rain and irrigation waters does not vary much throughout the years. Therefore, the same average values have been considered for all years in both cases (Table 1). However, the salinity of the Lerma gully water is highly variable in time, as observed in the concentrations of the 100 water samples analyzed (Fig. 3). The salinity of the gully is very sensitive to variations caused by storms, leakages, and pipe leaks that might not be reflected in a specific chemical analysis of the water samples. Ideally, the water samples should have been taken every 10 min but as that was impossible, a regression analysis was carried out between electrical conductivity data (EC 25 °C) and the composition of the 100 water samples taken at the gully (Fig. 3). The objective was to convert conductivity data measured every 10 min into a reliable chemical composition. The regressions were statistically significant with a 95 % confidence level ($p < 0.05$) and explained the variability (statistical R^2) in the concentration of most ions.

The values obtained for the concentration of each ion were used to establish annual average values (per hydrological years) representative of the drainage water (final water output) of the irrigable area of Lerma.

4. Results and discussion

4.1. Water balance

Table 2 shows the results of the balances per hydrological year, with annual cumulative data (moving averages) to reflect the temporal evolution but smoothing the variability of a specific year. Years have been grouped into three periods: 1) before the implementation of irrigation (hydrological years 2004–2005); 2) the transition period (hydrological years 2006–2010), and 3) the consolidated irrigation period (hydrological years 2011–2020).

The results indicate that the primary inputs are due to rain (41 %, especially during rainy years), and irrigation (52 %, once the irrigation was consolidated; Table 2). There were lower contributions due to water inputs from the unirrigable area of the gully (5 %), channel leakages (1 %), and leaks/losses from the pipes (0.1 %). Most of the outputs were due to the evapotranspiration (70 %) and the drainage from the Lerma gully (22 %), both of which increased after the implementation of irrigation. Although the water losses due to evaporation and wind drift in sprinkler irrigation systems were <8 %, these were not negligible because they corresponded to 15 % of the water applied to irrigation.

The water storage in the system only contributed 0.7 % to the water balance, significantly lower than the main water balance components. On an annual basis, water storage is important to adjust the balances, but its overall contribution decreases as the balance period widens.

The previous results of the water balances carried out in the Lerma basin since the beginning of its study (in particular the latest one; Merchán et al., 2015a), are in good agreement for the period between 2004 and 2013, with the ones obtained here since the same data and methodology are used. In this paper the continuation of the evaluated period (2014–2020) is presented providing new results for the Lerma irrigated land once consolidated.

Table 1
Number of samples (n°), pH, EC 25 °C, and average concentrations of the main ions in the water of the Lerma gully, rainwater, and irrigation water.

Water	n°	pH	EC 25 °C	HCO_3^-	SO_4^{2-}	Cl^-	Ca^{2+}	Mg^{2+}	Na^+	K^+
			μS/cm	mg/L						
Gully	100	8.2	2318	340.1	337.7	357.6	89.3	69.2	336.4	6.8
Rain	10	5.7	29	11.8	2.3	1.3	3.0	1.1	1.2	0.5
Irrigation	5	8.1	334	161.7	19.3	18.3	48.4	8.0	11.4	1.1

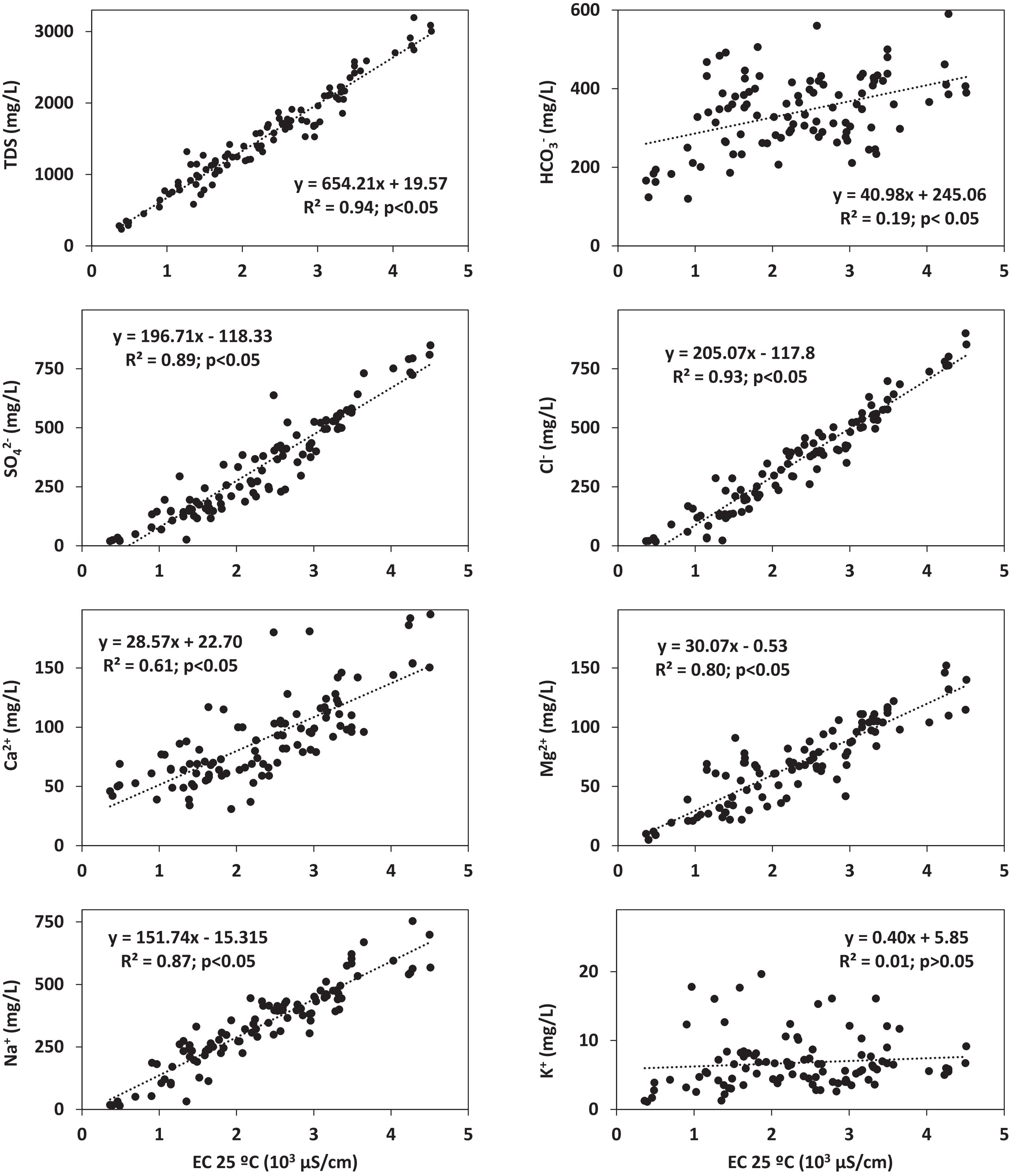

Fig. 3. Regression lines for electrical conductivity at 25 °C (EC 25 °C) and concentration of Total Dissolved Solids (TDS, which includes all the main ions), HCO_3^-, SO_4^{2-}, Cl^-, Ca^{2+}, Mg^{2+}, Na^+, and K^+ in the 100 water samples collected at the Lerma gully.

Table 2

Water balance (accumulated number in bold) at the Lerma basin (2004–2020). In (Rain, Irrigation, Non Irrigation, Leakages, and Losses in the pipes), Out (Evaporation and Wind Drift of Losses in sprinkler irrigation-EWDL, Evapotranspiration-ET, Gully) and Storage (Aquifer & Soil).

Hydrological year		In										Out						Storage				Balance error[a]	
		Rain		Irrigation		Non Irr.		Leakages		Losses		EWDL		ET		Gully		Aquifer		Soil			
		mm/year										mm/year						mm/year				%	
Unirrigated	2004	632	**632**	0	**0**	71	**71**	9	**9**	0	**0**	0	**0**	335	**335**	136	**136**	–	–	30	**30**	35	**35**
	2005	227	**430**	0	**0**	26	**49**	9	**9**	0	**0**	0	**0**	260	**297**	52	**94**	–	–	−52	**−11**	1	**25**
Transition	2006	444	**434**	181	**60**	51	**50**	9	**9**	0	**0**	27	**9**	467	**354**	144	**110**	–	–	56	**11**	−1	**13**
	2007	406	**427**	467	**162**	45	**48**	9	**9**	0	**0**	72	**25**	691	**438**	124	**114**	–	–	−40	**−1**	9	**12**
	2008	367	**415**	554	**240**	41	**47**	9	**9**	0	**0**	80	**36**	701	**491**	137	**119**	–	–	8	**1**	5	**10**
	2009	380	**409**	576	**296**	44	**46**	9	**9**	2	**0**	87	**44**	751	**534**	342	**156**	−3	**−1**	−17	**−2**	−14	**4**
	2010	307	**395**	582	**337**	37	**45**	9	**9**	13	**2**	90	**51**	669	**554**	294	**176**	−14	**−3**	16	**0**	−11	**1**
Consolidated irrigation	2011	336	**387**	580	**368**	38	**44**	9	**9**	0	**2**	88	**56**	762	**580**	231	**183**	−38	**−7**	−13	**−2**	−7	**0**
	2012	240	**371**	591	**392**	26	**42**	9	**9**	0	**2**	94	**60**	661	**589**	135	**177**	−6	**−7**	7	**−1**	−3	**0**
	2013	480	**382**	544	**407**	57	**44**	9	**9**	0	**1**	71	**61**	760	**606**	291	**189**	37	**−3**	7	**0**	−7	**−1**
	2014	355	**379**	715	**435**	40	**43**	9	**9**	0	**1**	98	**64**	833	**626**	226	**192**	−52	**−7**	7	**1**	1	**−1**
	2015	433	**384**	539	**444**	49	**44**	9	**9**	0	**1**	76	**65**	791	**640**	264	**198**	−16	**−8**	−5	**0**	−7	**−2**
	2016	356	**382**	691	**463**	40	**44**	9	**9**	0	**1**	101	**68**	824	**654**	207	**199**	−13	**−8**	−9	**0**	−1	**−2**
	2017	468	**388**	587	**472**	52	**44**	9	**9**	0	**1**	76	**69**	761	**662**	230	**201**	−4	**−8**	38	**2**	1	**−1**
	2018	452	**392**	553	**477**	51	**45**	9	**9**	0	**1**	69	**69**	739	**667**	307	**208**	−6	**−8**	−34	**0**	−1	**−1**
	2019	352	**390**	573	**483**	47	**45**	9	**9**	0	**1**	136	**73**	701	**669**	260	**211**	−12	**−8**	13	**1**	−11	**−2**
	2020	342	**387**	657	**494**	39	**44**	9	**9**	0	**1**	93	**74**	810	**677**	252	**214**	18	**−7**	−8	**0**	−11	**−3**

[a] Balance error = [(In − Out − Storage) / (In + Out + Storage)] · 200.

Water balances at the irrigable area of the Lerma basin close reasonably well with a −3 % unbalance (last column of Table 2) across the study period. The fact that this water unbalance is minimal for most years indicates that the main components of the water balance have been considered and measured or estimated with adequate precision. This has enabled the assignment of specific concentrations to the dissolved element in each water balance component, to obtain the balances for general salts and their main ions.

4.2. *Salt balances*

Once the water balance has been evaluated and the concentrations of each component have been determined, the next step is to carry out a salt balance. Over the studied years, the total amount of salts exported was, on average, 3177 kg/ha irrigable·year. 42 % originates from irrigation water and 3 % from rainwater. The remainder of exported ions (55 %) must be associated with a mineral dissolution capable of contributing with 1816 kg ions/ha irrigable·year. However, this rate has not been constant throughout the monitoring period and does not correspond exclusively to dissolution processes.

The results of the salt balances grouped by periods (Table 3) evidence that during the transition period (2006/2010: −2518 kg/ha irrigable of dissolved salts), significant irrigation water inputs produced an increase in the rates of exported salts and a global dissolution process. This behavior contrasts with that observed before irrigation was implemented, which included a very wet year (2004: 632 mm and −2373 kg/ha irrigable of dissolved salts) and a very dry year (2005: 227 mm and −1076 kg/ha irrigable of dissolved salts).

The latest balance of salts carried out in the Lerma basin up to 2013 (Merchán et al., 2015b) was based only on the total dissolved solids but it gave similar results. The work performed here provides a clear improvement as it gives the balances for each ion since the beginning and until the Lerma irrigation land was consolidated.

The consolidation process of irrigation has, nevertheless, caused a decrease in the rate of exported ions. This is interpreted as a decrease in the rate of salt dissolution (2011/2020: −1484 kg/ha irrigable of dissolved salts) due to the constant washing and resulting depletion of available mineral phases.

The general pattern of the global increase in the dissolved contents for most ions (SO_4^{2-}, Cl^-, Mg^{2+}, Na^+, and K^+) is opposite to the behavior observed for HCO_3^- and Ca^{2+} which, before irrigation, presented an increase in the dissolved contents (more outputs than inputs) while, with the consolidation of irrigation, their dissolved contents decreased (more inputs than outputs).

5. Conclusions

Implementing irrigation in the Lerma gully has doubled the mass of exported salts until reaching an average of 3177 kg/ha irrigable·year for the entire study period (2004–2020).

According to data supplied by Causapé et al. (2006), this amount is much lower than the 16 t/ha irrigable·year quantified in flood irrigation areas on gypsum-based soils and 14 t/ha irrigable·year of other irrigated zones, including those with sprinkler irrigation systems, on very saline soils of the Ebro valley. The mass of exported salts of the Lerma gully is, nevertheless, of the same magnitude as other irrigation zones that adopt flood irrigation on non-saline soils (Causapé et al., 2006).

The amount of exported salts is not significantly higher than the natural edaphic salinity of the zone. According to the Salt Contamination Index (SCI) defined by Causapé (2009), the irrigated area at Lerma presents low contamination regarding the load of exported salts (SCI < 2 [t/ha·year]/[dS/m]).

Of the total mass of exported salts at Lerma, 55 % (1816 kg/ha irrigable·year) corresponds to a global process of salt dissolution, with a decreasing trend as the salts in the soil are washed and disappear. This natural process is accelerated by irrigation with low-mineral waters

Table 3

Results of salt balances (Inputs – Outputs – Storage) during the years before implementation of irrigation (2004–2005), transition (2006–2010), and consolidation of irrigation (2011/2020) of the irrigable area of the Lerma basin.

	$\sum$	HCO_3^-	SO_4^{2-}	Cl^-	Ca^{2+}	Mg^{2+}	Na^+	K^+
	kg/ha irrigable·year							
Unirrigated 2004/2005	−1724	−160	−488	−513	−73	−78	−411	−2
Transition 2006/2010	−2518	101	−827	−881	33	−133	−803	−7
Consolidated irrigation 2011/2020	−1484	378	−608	−655	127	−91	−631	−5

from Pyrenean glaciers.

The general pattern of global dissolution followed by most ions (SO_4^{2-}, Cl^-, Mg^{2+}, Na^+, and K^+) is the opposite to the one shown by HCO_3^- and Ca^{2+}. The latter were being incorporated into the waters before the implementation of irrigation and then began to disappear from them.

This study indicated the dissolution of some mineral phases (halite, gypsum, dolomite) and the possible precipitation of others, such as calcite. However, other geochemical processes could occur and have not been detected with hydrosaline balances.

Therefore this study is followed by a companion paper, which is the second part of the study in which geochemical modeling tools are applied to deepen knowledge and quantify the main geochemical processes that intervene in the system.

CRediT authorship contribution statement

Jesús Causapé: Conceptualization, Methodology, Formal Analysis, Investigation, Writing – Original Draft, Visualization, Supervision, Project Administrator.

Ma José Gimeno: Conceptualization, Methodology, Resources, Data Curation, Writing – Review and Editing.

Luis Auque: Conceptualization, Methodology, Resources, Data Curation, Writing – Review and Editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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