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Impact of irrigation implementation on hydrology and water quality in a small agricultural basin in Spain

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Abstract Irrigation practice has increased considerably recently and will continue to increase to feed a growing population and provide better life standards worldwide. Numerous studies deal with the hydrological impacts of irrigation, but little is known about the temporal evolution of the affected variables. This work assesses the effects on a gully after irrigation was implemented in its hydrological basin (7.38 km^2). Flow, electrical conductivity, nitrate concentration and exported loads of salts and nitrates were recorded in Lerma gully (Zaragoza, Spain) for eight hydrological years (2004–2011), covering the periods before, during and after implementation of irrigation. Non-parametric statistical analysis was applied to understand relationships and trends. The results showed the correlation of irrigation with flow and the load of salts and nitrates exported, although no significant relationship with precipitation was detected. The implementation of irrigation introduced annual trends in flow (3.2 L s^{-1}, +23%), salinity (–0.38 mS cm^{-1}, –9%), and nitrate concentration (5.4 mg L^{-1}, +8%) in the gully. In addition, the annual loads of contaminants exported increased (salts and nitrates, 27.3 Mg km^{-2} $year^{-1}$, +19%, and 263 kg NO_3^--N km^{-2} $year^{-1}$, +27%, respectively). The trends presented a strong seasonal pattern, with higher and more significant trends for the irrigation season. The changes observed were different from those of larger irrigation districts or regional basins, due to the differences in land use and irrigation management. It is important to understand these changes in order to achieve an adequate management of the environment and water resources.

Key words irrigation; trend; salinity; nitrate; contaminant loads; land use

Impact de la mise en œuvre de l'irrigation sur l'hydrologie et la qualité de l'eau dans un petit bassin versant agricole en Espagne

Résumé Récemment, l'utilisation de l'irrigation a considérablement augmenté, et elle va continuer à augmenter pour nourrir une population croissante et fournir un meilleur niveau de de vie à travers le monde. De nombreuses études traitent des impacts hydrologiques de l'irrigation, mais on connait peu de choses sur l'évolution temporelle des variables affectées. Ce travail évalue les effets sur une ravine, après que l'irrigation ait été mise en œuvre sur son bassin hydrologique (7,38 km^2). A cette fin, le débit, la conductivité électrique, la concentration en nitrates et les charges exportées de sels et de nitrates ont été enregistrées sur la ravine de Lerma (Saragosse, Espagne) pendant huit années hydrologiques (2004–2011), allant de la période antérieures à la période postérieure à la mise en œuvre de l'irrigation. Nous avons réalisé une analyse statistique non paramétrique pour comprendre les relations et les tendances. Les résultats ont montré une corrélation entre l'irrigation d'une part, et le débit et les charges exportées de sels et de nitrates d'autre part, mais aucune relation significative avec les précipitations n'a été détectée. La mise en œuvre de l'irrigation a provoqué une évolution du débit (3,2 L s^{-1}, +23%), de la salinité (–0,38 mS cm^{-1}, –9%), et de la concentration en nitrates (5,4 mg L^{-1}, +8%) dans la ravine. En outre, la charge annuelle de polluants exportée a augmenté (27,3 Mg km^{-2} an^{-1}, +19%, pour les sels, et 263 kg NO_3-N km^{-2} an^{-1}, +27%, pour les nitrates). Les tendances présentent une forte saisonnalité, et sont plus fortes et significatives pour la saison d'irrigation. Les changements observés sont différents de ceux de districts d'irrigation plus étendus ou de bassins régionaux, cela étant dû aux différences dans l'utilisation des terres et dans la gestion de l'irrigation. Il est important de comprendre ces changements afin de parvenir à une gestion adéquate de l'environnement et des ressources en eau.

Mots clefs irrigation; tendance; salinité; nitrates; charges de contaminants; utilisation des terres

1 INTRODUCTION

There are many advantages to irrigated agriculture, such as increased production, reliable harvests and regional economic security (Duncan *et al.* 2008). As a consequence, a global increase in irrigated areas has been observed, especially in developing countries where, between 1962 and 1998, irrigated area doubled (Food and Agriculture Organization (FAO 2003a). In Spain, the increase is moderate but significant, with 7% more irrigated area between 1990 and 2009 according to the Spanish environment ministry (*Ministerio de Medio Ambiente y Medio Rural y Marino*; MMARM).

However, irrigation imposes sever pressure on the environment, as it accounts for the consumption of 70% of global water resources (FAO 2003b). Water abstraction for irrigation purposes changes hydrological conditions in dam-regulated rivers (Graf 2006), or overexploited aquifers (Custodio 2002). These pressures impact on water resources not only in a quantitative way, but also qualitatively (Kurunc *et al.* 2005).

The impacts are not only found at the irrigation water withdrawal location, as irrigation return flows can cause hydrological changes in the receiving water bodies. For this reason, organizations such as the US Environmental Protection Agency see irrigated agriculture as the main source of water pollution (US EPA 1992), particularly due to the leaching of salts (Duncan *et al.* 2008) and nitrate (Arauzo *et al.* 2011, Sánchez-Pérez *et al.* 2003), among other pollutants (pesticides, phosphates, etc.).

Several studies exist on the hydrological changes caused by irrigated agriculture. However, these studies were carried out either at such a large scale that the influence of irrigation was masked by other factors (water abstraction, industrial uses, etc.; CHE (2006), or in areas where irrigation had already been implemented (e.g. García-Garizábal and Causapé 2010, Qin *et al.* 2011) without considering the dynamics of irrigation implementation.

The impacts of irrigation are major issues in the development of sustainable basin management strategies. Irrigation affects land use and, therefore, causes hydrological changes in the basin. The responses of the basin to these changes need to be understood (Zhang *et al.* 2011). Despite such an interest, to the best of our knowledge, the study area of this work is the first in which alteration induced by the transformation from rainfed to irrigated agriculture has been assessed, and this was achieved through the monitoring of the hydrological basin during the transition. The research team has studied changes in this study area for approximately ten years and several papers have been published (Abrahão *et al.* 2011a, 2011b, 2011c, Peréz *et al.* 2011). A non-parametric approach is used herein to deal with issues not treated in previous research, such as trends in flow, water quality parameters and exported loads of both salts and nitrates, imposed by irrigation.

Within this framework, the aim of this work is to analyse the effects of a newly-implemented irrigated area on the hydrology of a gully, evaluating relationships between variables, and trends in flow, water quality, and contaminant loads. This objective is consistent with the recommendations of local water authorities (CHE 2006) that suggest the need for increasing knowledge of water bodies with quality problems, in order to create management strategies that will allow to control the quantity and quality of water resources at the basin scale.

2 STUDY AREA AND BACKGROUND

The study area is Lerma gully and its hydrological basin (7.38 km^2), which is located on the left bank of the middle Ebro River Valley, in northeast Spain (Fig. 1). The Ebro basin presents a high level of human interference, with reservoir volumes of 7580 hm^3, and more than 680 000 ha dedicated to irrigated agriculture and other domestic and industrial uses (CHE 2009a). The main use of water is for irrigated agriculture, with more than 6000 hm^3 $year^{-1}$ being extracted. All other uses together do not exceed 1000 hm^3 $year^{-1}$. Environmental problems related to irrigated agriculture, such as salinization and nitrate pollution, are openly recognized by the Ebro Basin Authority (e.g. CHE 2006, 2009b). In particular, the Arba River, one of the Ebro's tributaries and receiver of Lerma gully waters, is the river that presented the highest increase in salinity and nitrate concentrations in the Ebro basin during the period 1975–2004 (CHE 2006). In addition, the Arba River is the only surface water body declared as affected by nitrate pollution by the Ebro Basin Authority (MMARM 2011). Consequently, large areas of the Arba basin, including the Lerma basin, were designated as Nitrate Vulnerable Zones in 2008 by the Regional Government (CAA 2009), according to Spanish legislation and following the European Council Directive 91/676/EEC EC (1991) concerning the protection of waters against pollution by nitrates from agricultural sources.

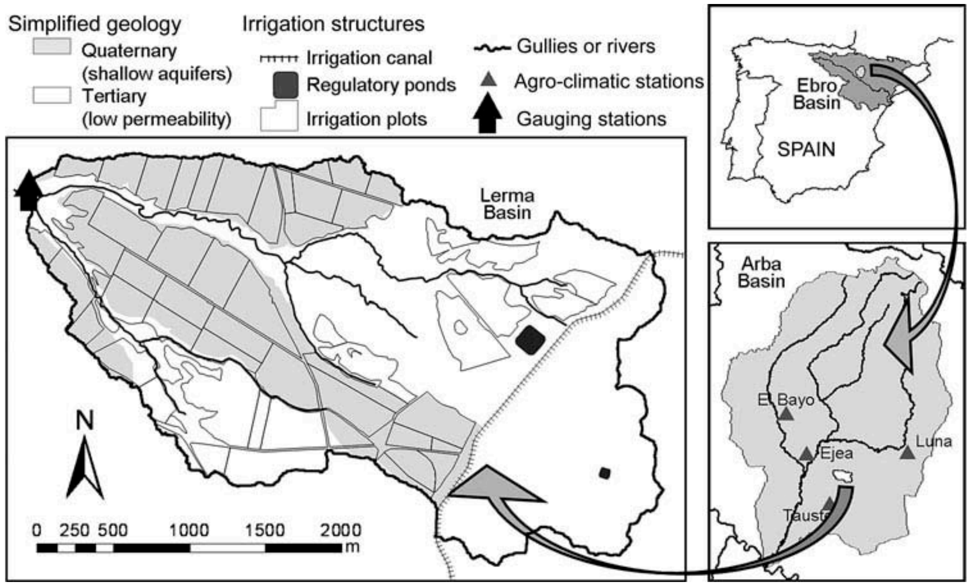

Fig. 1 Location of the Lerma basin within the Arba and Ebro basins (Spain), showing the simplified geology; the irrigation canal, ponds and plots; and the agro-climatic and gauging stations.

The Lerma gully has been monitored for eight hydrological years (2004–2011), covering the transformation of approximately half of its surface (48%) into irrigated land. Previous to our monitoring of Lerma basin, rainfed agriculture was the main land use. In 2003 the implementation of irrigation began with the construction of regulatory pounds and the installation of pipes. The area was not cultivated during this initial construction period (2004–2005). After the main irrigation network was installed, individual farmers equipped their plots for pressurized irrigation, depending on the date of plot assignation or availability of funds. Consequently, the actual irrigated area increased progressively (from 36% in 2006 to 76% in 2007 and 90% in 2008). Since 2009, more than 95% of the projected irrigable area has actually been irrigated.

This region is therefore a valuable location for the evaluation of hydrological changes in terms of environmental issues (flow changes, salts and nitrate pollution) occurring before, during and after implementation of irrigation in the upper sections of hydrological basins (stream order <3, according to Strahler 1952).

2.1 Climate

According to the Spanish national agency of meteorology (AEMET 2010), the study area has a semi-arid Mediterranean climate, with an annual average temperature of 14°C. The coldest months are January and February with monthly mean temperatures lower than 5°C, and the warmer months are July and August, experiencing mean temperatures higher than 23°C, although the maximum temperature can reach 40°C. Historical annual precipitation is 468 mm, with two dry (winter and summer) and two wet (spring and autumn) seasons.

Mean annual rainfall during the study period (1 October 2003–30 September 2011) was 402 ± 113 mm year^{-1} (average ± standard deviation), according to the agro-climatic stations of the integrated irrigation advisory service (*Sociedad Aragonesa de Gestión Agroambiental*; SARGA (2011). A humid hydrological year (2004: 632 mm year^{-1}) and a dry year (2005: 227 mm year^{-1}) were recorded during the implementation period. Under irrigation conditions (2006–2011), mean annual precipitation was closer to average years (ranging between 350 and 444 mm year^{-1}). The average reference evapotranspiration (ET_0), calculated by the Penman-Monteith method (Allen *et al.* 1998), was 1301 ± 61 mm year^{-1}, i.e. three times greater than precipitation, and its coefficient of variation (5%) was less than that of precipitation (28%), which made irrigation essential to achieve productive agriculture.

2.2 Geology

Two geological units are present in the Lerma basin (Fig. 1). Quaternary glacis composed of layers of gravel with a loamy matrix and of maximum thickness 10 m (ITGE 1988) extend over 34% of its area. Soils with good drainage conditions, low salinity and little risk of erosion are found on the Quaternary materials (Calcixerollics Xerochrepts; Soil Survey Staff 1992), which makes these soils preferable for irrigation (Beltrán 1986). The Quaternary glacis overlay Tertiary materials. The Tertiary lutites and marls are interbedded with thin limestone and gypsum layers (ITGE 1988), and generate slow-drainage soils (Typic Xerofluvent; Soil Survey Staff 1992) of high salinity and steeper slopes, which make these areas less suitable for irrigation (Beltrán 1986).

The Quaternary materials provide perched aquifers over the low-permeability Tertiary materials. These aquifers are recharged by both precipitation and irrigation water, and drained by springs which feed a network of gullies. The network of gullies crosses Lerma basin from east-southeast to west-northwest. The low permeability of the Tertiary materials ensures a suitable control of the water balance (Casalí *et al.* 2008, 2010).

2.3 Agronomy

Agriculture was the main land use in Lerma basin, covering 48% of the total basin area. Major crops were similar to those in the middle Ebro Valley: maize (46%), winter cereal (19%), vegetables (15%), sunflowers (9%) and others. Sprinkler irrigation was the main system used (>90%), although drip irrigation was also present, mainly for vegetables. Good-quality irrigation water (electrical conductivity ~0.35 mS cm^{-1}; nitrate concentration ~2 mg L^{-1}) came from reservoirs located in a neighbouring basin that are fed with water from the Pyrenees Mountains (northeast Spain). According to Abrahão (2010), irrigation applied to main crops of maize, winter cereal and vegetables averaged 740, 160 and 552 mm $year^{-1}$, respectively. The irrigation volume applied to crops varied depending on water availability in the different years, but the total amount of irrigation for the entire basin increased progressively, stabilizing at approx. 2 hm^3 $year^{-1}$. Regarding nitrogen fertilization, the main applications were conducted for maize (380 kg N ha^{-1} $year^{-1}$), winter cereal (164 kg N ha^{-1} $year^{-1}$) and vegetables (mainly tomatoes, 182 kg N ha^{-1} $year^{-1}$). The fertilizers used depended on the crops and included compound fertilizers, urea and liquid fertilizers (Abrahão *et al.* 2011b).

3 METHODOLOGY

3.1 Data collection

Daily precipitation data (*P*) were obtained from the agro-climatic stations of the integrated irrigation advisory service (SARGA). Data for Lerma basin were obtained by applying the inverse distance squared method (Isaaks and Srivastava 1989) with data from four stations (El Bayo, Ejea, Luna and Tauste) located between 6 and 18 km away (Fig. 1). Daily irrigation data (*I*) measured by flow meters in each plot were provided by the local irrigation authority.

Monitoring of Lerma gully began in October 2003, with the beginning of the work for its transformation (two years before irrigation started). Manual water sampling was performed at a monthly frequency between October 2003 and September 2005. In October 2005, automatic sampling equipment (ISCO 3700) was installed. The automatic sampler was programmed to collect one sample per day. At the same time, a gauging station was installed at a defined section (rectangular thin-plate weir), and water level was registered every 10 min with an electronic limnigraph (Thalimedes, OTT).

The recorded water height data (*h*; m) were transformed to flow (*Q*; m^3 s^{-1}) using gauge rating curves, obtained using the WinFlume software (Whal 2000), as follows:

$$Q = 1.73(h + 0.00347)^{1.624} \text{ for } h \leq 0.5 \quad (1)$$

$$Q = 10.28(h + 0.01125)^{1.725} \text{ for } h > 0.5 \quad (2)$$

The correspondence between water heights and flow was cross-checked by several manual gauging methods, such as the velocity–area method using a wading rod, dilution gauging, and the use of a portable V-notch weir.

Between October 2003 and September 2005 (before installation of the gauging station), flow was estimated using the relationship between flow and precipitation (runoff coefficient of 10.1%) and the form of recession curves during the period when the gauging station was available but the first irrigation season had not commenced (October 2005–March 2006).

Manually or automatically collected samples were taken to the laboratory where the electrical conductivity corrected to 25°C (EC; mS cm^{-1}) and nitrate concentration (NO_3^-; mg L^{-1}) were determined using an Orion-5 Star conductivity meter and a colorimetry Autoanalizer 3 system, respectively.

Seventeen (17) water samples were selected within the range of variation of EC in Lerma gully, for which the concentration of bicarbonate (HCO_3^-; mg L^{-1}) and dry residue (DR; mg L^{-1}) were determined. From these concentrations, the total dissolved solids (TDS; mg L^{-1}) were calculated by (Custodio and Llamas 1983):

$$\mathrm{TDS} = \mathrm{DR} + \tfrac{1}{2}\mathrm{HCO}_3^- \qquad (3)$$

The EC (mS cm^{-1}) was converted into TDS (mg L^{-1}) for each collected sample through:

$$\mathrm{TDS} = 712.22\mathrm{EC} - 104.83 \\ R^2 = 0.99 \quad n = 17 \quad p < 0.01 \qquad (4)$$

Once EC was converted to TDS, the use of both TDS and NO_3^- combined with flow allowed the calculation of: (a) the exported load of salts (SL; Mg km^{-2} $year^{-1}$); and (b) the exported load of nitrate (NL; kg NO_3^--N km^{-2} $year^{-1}$).

3.2 Statistical analysis

Data from hydrological variables have common characteristics, including positive skewness and seasonal patterns. Water resources data analysis methods should recognize these and take them into account to obtain adequate knowledge of the studied system (Helsel and Hirsch 2002).

Rain events cause positive skewness in data, which affects data reliability. In Lerma gully, rain events caused daily discharge volumes to be similar to that of a whole month, modifying considerably the average flow (Fig. 2) and loads of pollutants. The use of medians instead of averages as measures of central tendency reduced the influence of short intense rain events, and permitted a better assessment of irrigation impact (Fig. 2), as medians are known to be more resistant to outliers (Helsel and Hirsch 2002). Consequently, monthly data series were created from the studied variables (P, I, Q, EC, NO_3^-, SL and NL), by taking medians from daily values in those months for which more than one sampling occasion was available (October 2005–September 2011).

The obtained monthly data series were tested for normality (Chi-square and Shapiro-Wilks tests; Statgraphics Plus 5.1). The non-normality of the data series indicated the need to use non-parametric statistical tests, which is recommended instead of the conversion of data sets to normality, and use of parametric tests (Helsel and Hirsch 2002). The use of parametric tests on data sets with a strong seasonal component or correlated variables can result in false positives (Bouza-Deaño *et al.* 2008).

3.2.1 Correlation analysis A correlation matrix was obtained through a rank-based procedure from the P, I, Q, EC, NO_3^-, SL and NL monthly data. Kendall's tau (Helsel and Hirsch 2002) was computed for each pair of variables (called x and y); Kendall's tau is a non-parametric, rank-based, resistant-to-outliers test that measures all monotonic correlations in the data set. Tau (τ) is obtained by sorting the pairs with increasing x and computing:

$$\tau = \frac{(A - B)}{n(n-1)/2} \qquad (5)$$

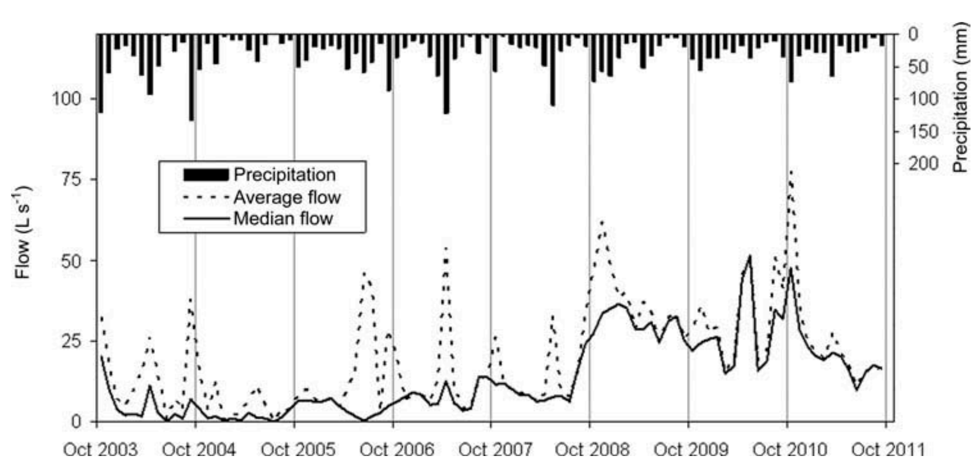

Fig. 2 Monthly precipitation, average flow and median flow in the Lerma basin during hydrological years 2004–2011.

where n is the number of data pairs; A is the number of $y_i < y_j$ for all $i < j$; and B is the number of $y_i > y_j$ for $i < j$; for all $I = 1, \ldots, (n-1)$ and $j = (i+1), \ldots, n$. The correlation matrix allowed the understanding of inter-relationships between the studied variables.

3.2.2 Trend analysis Trend analysis was performed for the variables P, Q, EC, NO_3^-, SL and NL, and detection and estimation of trends was based on the Mann-Kendall test (Mann 1945, Kendall 1975), referred to herein as the M-K test, which is widely applied to trends in hydrological and environmental data (e.g. Stålnacke *et al.* 2003, CHE 2006, Battle *et al.* 2007). The M-K test has the advantages of not assuming any distribution for the data and having similar power to parametric methods (Battle *et al.* 2007). The M-K test determines whether or not a trend is present with an indicator based on the calculation of differences between pairs of successive data (Battle *et al.* 2007):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(C_j - C_i) \tag{6}$$

where:

$$\mathrm{sgn}(C_j - C_i) = \left\{ \begin{array}{lll} 1 & \text{if} & C_j - C_i > 0 \\ 0 & \text{if} & C_j - C_i = 0 \\ -1 & \text{if} & C_j - C_i < 0 \end{array} \right\} \tag{7}$$

and C_i and C_j are the values at different times i and j; with $j > i$ and n the size of the data set. If there is no trend, S is close to zero; thus the trend will be significant when S differs statistically from zero.

Trend estimation is based on the calculation of Sen's slope estimator (Sen 1968) and is obtained by computing the slopes (b_{ij}) for all pairs of successive data:

$$b_{ij} = \frac{C_j - C_i}{t_j - t_i} \tag{8}$$

where C_i and C_j are values of the variable at time t_i and t_j, respectively. Finally, the value of Sen's slope estimator is median of the slope:

$$b = \mathrm{median}\left(b_{ij}\right) \tag{9}$$

As irrigation and fertilization management are seasonal stresses, the Seasonal Kendall test (S-K test; Helsel and Hirsch 2002) was applied to obtain a better understanding of seasonal patterns. The S-K test is a non-parametric test that computes the M-K test for each season (months in our study), and results are combined to obtain an annual trend. This seasonal approach has been used in several hydrological studies (e.g. Lassaleta *et al.* 2009, Lespinas *et al.* 2010, Morán-Tejeda *et al.* 2011).

In addition, the M-K test was applied to different periods within the data set. Tests were performed for the non-irrigated period (2004–2005) and for the irrigated period (2006–2011). Moreover, trends were computed for the transition period (2006–2008), when the irrigation surface was increasing, and the last three years (2009–2011), in which neither irrigation surface nor irrigation volume changed significantly and the irrigated area could be considered as consolidated. No seasonal approach was applied to the different sections of the data set as the S-K test requires a minimal amount of data not reached by the different sections.

Finally, for all estimated trends, a percentage trend value was calculated by dividing the estimated trend by the average value of the variable throughout the period in which the trend was computed.

4 RESULTS AND DISCUSSION

A data summary for the eight hydrological years (2004–2011) of monitoring at Lerma gully is presented in Table 1. Precipitation was the only water input during the non-irrigated stage (2004–2005), contributing 56–59% of the total water entering the basin when irrigation was consolidated. Intermediate values were observed during the period in which irrigation was being implemented. Irrigation volume increased progressively from 2006 and stabilized in 2008, with an annual value of approximately 2 hm^3, when most of the projected surface was actually irrigated.

Water flow in Lerma gully was highly dependent on precipitation during the non-irrigated period and increased after irrigation implementation (Table 1, Fig. 3). Annual flow ranged from 1.1 L s^{-1} (interquartile range, IQR: 3.9 L s^{-1}) in the non-irrigated year, 2005, to 30.8 L s^{-1} (IQR: 9.5 L s^{-1}) in the irrigated year, 2009. Under non-irrigated conditions, Lerma gully was observed to dry up in those seasons when precipitation was scarce. After implementation of irrigation, water flow in the gully evolved from intermittent to perennial (Fig. 3). Scott *et al.* (2011) have reported how some ephemeral lakes

Table 1 Precipitation (P) and irrigation (I) volumes in the Lerma basin; median [inter-quartile range] for flow (Q), electrical conductivity (EC) and nitrate concentration (NO_3^-) in Lerma gully; and salt (SL) and nitrate (NL) exported load; for the hydrological years 2004–2011.

Year	P (hm^3)	I (hm^3)	Q ($L\ s^{-1}$)	EC ($mS\ cm^{-1}$)	NO_3^- ($mg\ L^{-1}$)	SL ($Mg\ km^{-2}$)	NL ($kg\ NO_3^-$-$N\ km^{-2}$)
2004	4.65	0.00	2.9 [13.9]	5.2 [2.0]	42 [17]	235	561
2005	1.74	0.00	1.1 [3.9]	6.0 [0.7]	78 [25]	98	403
2006	3.39	0.62	4.3 [4.7]	3.7 [1.1]	23 [15]	154	329
2007	2.94	1.59	7.6 [6.1]	4.2 [1.2]	56 [32]	128	568
2008	2.69	2.00	9.4 [5.7]	4.3 [0.4]	86 [22]	176	1068
2009	2.88	2.01	30.8 [9.5]	4.0 [1.6]	87 [12]	404	2707
2010	2.57	2.03	26.5 [17.5]	3.1 [0.4]	71 [20]	259	1936
2011	2.70	2.07	19.6 [8.0]	3.0 [0.4]	85 [15]	198	1763

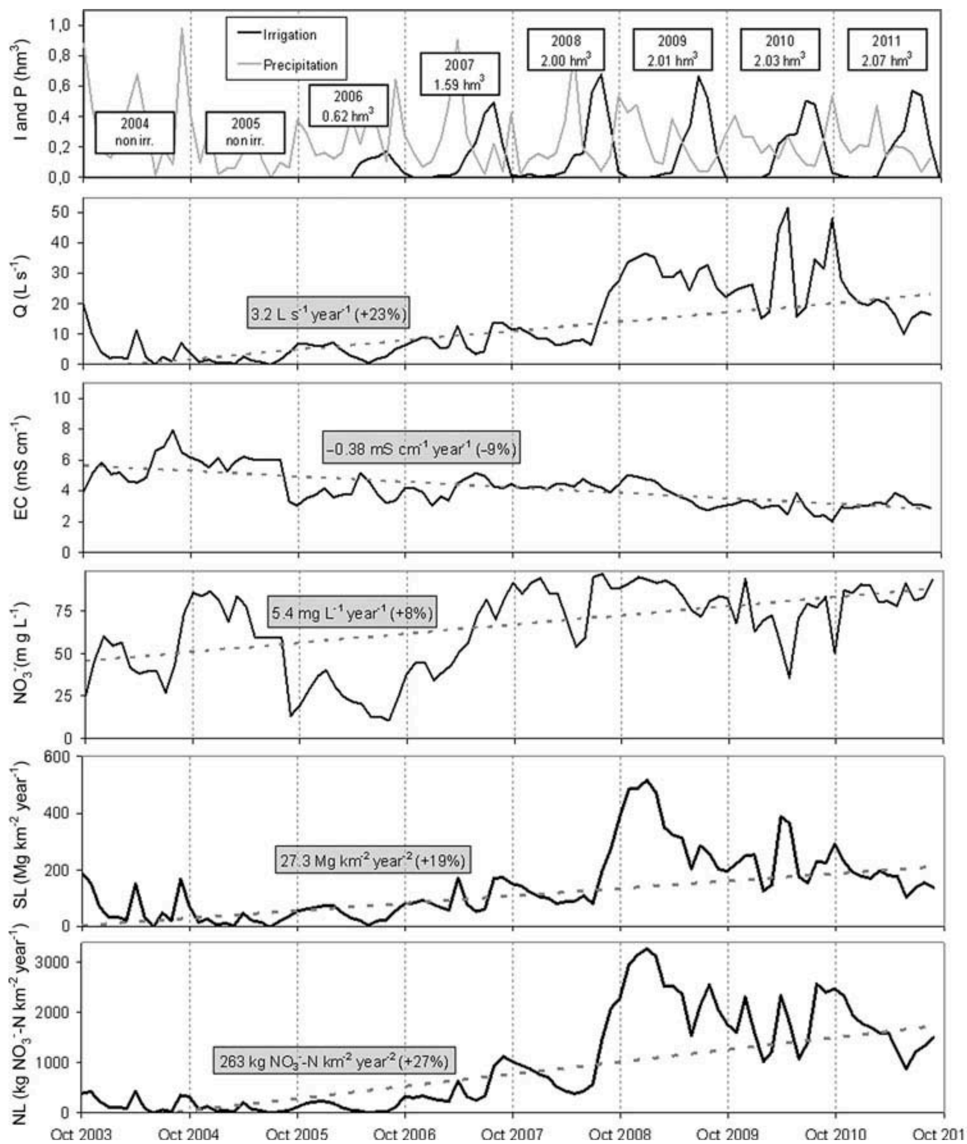

Fig. 3 Monthly precipitation (P) and irrigation volume (I), flow (Q), electrical conductivity (EC), nitrate concentration (NO_3^-), salt load (SL) and nitrate load (NL) at Lerma gully during the hydrological years 2004–2011. Trends (Sen's slope) are shown as broken grey lines.

became perennial as a result of irrigation return flows in the higher reaches of the Aral Sea basin.

Electrical conductivity varied widely, from 6.0 mS cm^{-1} (IQR: 0.7 mS cm^{-1}) in the dry non-irrigated year of 2005 to 3.0 mS cm^{-1} (IQR: 0.4 mS cm^{-1}) in 2011, after six years of irrigation. Intermediate values were observed during the transition to irrigation. Electrical conductivity values during the non-irrigation period are indicative of the high natural salinity of Lerma basin (Beltrán 1986), while lower values at the end of the study period are due to dilution with less-saline irrigation water, and to the flushing of accumulated salts from the surface and upper soil horizons (McNeil and Cox 2007) by irrigation return flows (flow increased while electrical conductivity decreased, Table 1 and Fig. 3).

Nitrate concentrations varied from 23 mg L^{-1} (IQR: 15 mg L^{-1}) during the first irrigated year (2006) to 87 mg L^{-1} (IQR: 12 mg L^{-1}) in the fourth year after irrigation began (2009). Despite no fertilizer applications during 2004 and 2005, nitrate concentrations were 42 mg L^{-1} (IQR: 17 mg L^{-1}) and 78 mg L^{-1} (IQR: 25 mg L^{-1}), respectively. This nitrate concentration is probably a response to fertilizers applied prior to the irrigation implementation, when the basin land use was rainfed agriculture (Irrigation Authority, personal communication), as nitrate leaching in any given year is often dependent on conditions in previous years (Burt *et al.* 2010).

The behaviour of the exported loads of contaminants (both salts and nitrate) was conditioned by the variations observed in flow, although minor differences were attributed to the different processes affecting these solutes. As suggested for flow, exported loads of salts and nitrate were highly dependent on climatic conditions during the non-irrigated period, and increased during the irrigation period. Kyllmar *et al*. (2006) reported that natural factors, such as soil characteristics, hydrogeology and climate, seem to determine the main level of nutrient loads in non-irrigated basins, whereas agricultural management influences the variation in loads around this main level. However, in Lerma basin, irrigation implementation has modified both the main level and the pattern of variation associated with agricultural management (Fig. 3).

4.1 Correlation of variables

The application of the Kendall correlation revealed that precipitation did not present significant correlation with the remaining variables (Table 2).

Table 2 Kendall correlation coefficient between monthly values of precipitation (*P*), irrigation (*I*), flow (*Q*), electrical conductivity (EC), nitrate concentration (NO_3^-), salt load (SL) and nitrate load (NL) in the study period. Medians were used to obtain the correlation coefficient, except in the case of *P* and *I*, for which accumulated monthly values were used. Only significant correlations are presented ($p < 0.05$).

	P	*I*	*Q*	EC	NO_3^-	SL	NL
P	1.00	-	-	-	-	-	-
I	-	1.00	0.26	−0.29	-	0.25	0.28
Q	-	-	1.00	−0.48	-	0.84	0.86
EC	-	-	-	1.00	-	−0.36	−0.41
NO_3^-	-	-	-	-	1.00	0.36	0.46
SL	-	-	-	-	-	1.00	0.85
NL	-	-	-	-	-	-	1.00

Irrigation volume was significantly correlated ($p < 0.05$) with all variables except nitrate concentration, showing its influence on the gully's hydrology. The non-correlation of nitrate concentration can be explained by the complexity of the nitrate dynamics, with many influences apart from those of irrigation, such as previous soil conditions and fertilizer management (Burt *et al.* 2010). In fact, no correlation was detected between nitrate concentration and flow in Lerma gully. Irrigation was negatively correlated with EC (–0.29) and positively correlated with *Q*, SL and NL (correlations between 0.25 and 0.28).

A negative correlation coefficient was found between *Q* and EC (–0.48), as a result of the dilution effect (addition of irrigation water). Correlations between *Q* and both SL and NL were the highest (0.84 and 0.86, respectively), showing the important influence of flow on exported loads of contaminants. Antonopoulos *et al.* (2001) also reported a high relationship between discharge and loads, and a low or no relationship between discharge and concentrations. No correlation was found between EC and NO_3^-, indicating that different processes affect each kind of pollution. In fact, EC *vs* SL and NO_3^- *vs* NL presented correlation values of –0.36 and 0.46, respectively. This means that months with higher salt loads were associated with lower salinity in the gully, and months with a higher nitrate load presented higher nitrate concentrations.

Flow presented a greater influence on the exported load of pollutants than water quality, as the correlation coefficients between flow and loads were higher than those between loads and water quality parameters. Similar conclusions on the major importance of flow in exported loads were obtained by

Barros *et al*. (2012), following different approaches in irrigated areas with similar climatic and soil conditions.

4.2 Trend analysis

4.2.1 Seasonal trends Seasonal patterns were observed in the trends of the studied variables (Fig. 4). The S-K test detected significant trends (at least $p < 0.1$) for all months in Q, for nine months in EC (mainly in spring and summer), and for three months (summer) in NO_3^- (Fig. 4). Monthly trends were positive for flow and ranged from 2.2 to 4.6 L s^{-1} $year^{-1}$, with the highest trend for the most irrigated month (August). These trends were equivalent to a relative annual increase in flow from 19 to 31%. However, monthly trends in EC were found to be negative (Fig. 4). Trends for EC ranged from –0.26 to –0.66 mS cm^{-1} $year^{-1}$ (–6 to –16%). Higher and more significant trends were detected for the spring/summer period, i.e. the more irrigated months. Trends detected in nitrate concentration ranged from 4.2 to 6.2 mg L^{-1} $year^{-1}$ (6% to 10%), and were found in June, August and September.

The increasing trends in Q and decreasing trends in EC are responses to water addition as irrigation, as trends in precipitation were not significant during the study period, neither in monthly nor annual values ($p > 0.1$ for all cases). Those months with higher irrigation presented stronger trends. In addition, trends were also detected in months with no irrigation, which can be explained by the effect that shallow aquifers have on the hydrology of the basin (retardation and attenuation of hydrological response). Similar results of seasonal trend patterns were reported for the Arba River and several points of the Ebro basin (Spain) between 1976 and 2004 for flow and dissolved solids (CHE 2006). Those results were linked to irrigated agriculture over large areas of the Ebro basin.

Trends detected in NO_3^- responded to the addition of nitrogen fertilizers coupled with irrigation activity. In the case of NO_3^-, significant trends are only detected for some of the months of the irrigation season, with the highest trend, in June, probably influenced by side-dressing fertilization of maize (Causapé *et al.* 2004), that being the main crop present in the basin. Out of the irrigation season, no monthly trends were detected.

Trends were also detected in the exported load of contaminants. In nine months there was a significant increase in SL, ranging from 21.5 to 36.0 Mg km^{-2} $year^{-2}$ (16% to 34%), while 11 months presented

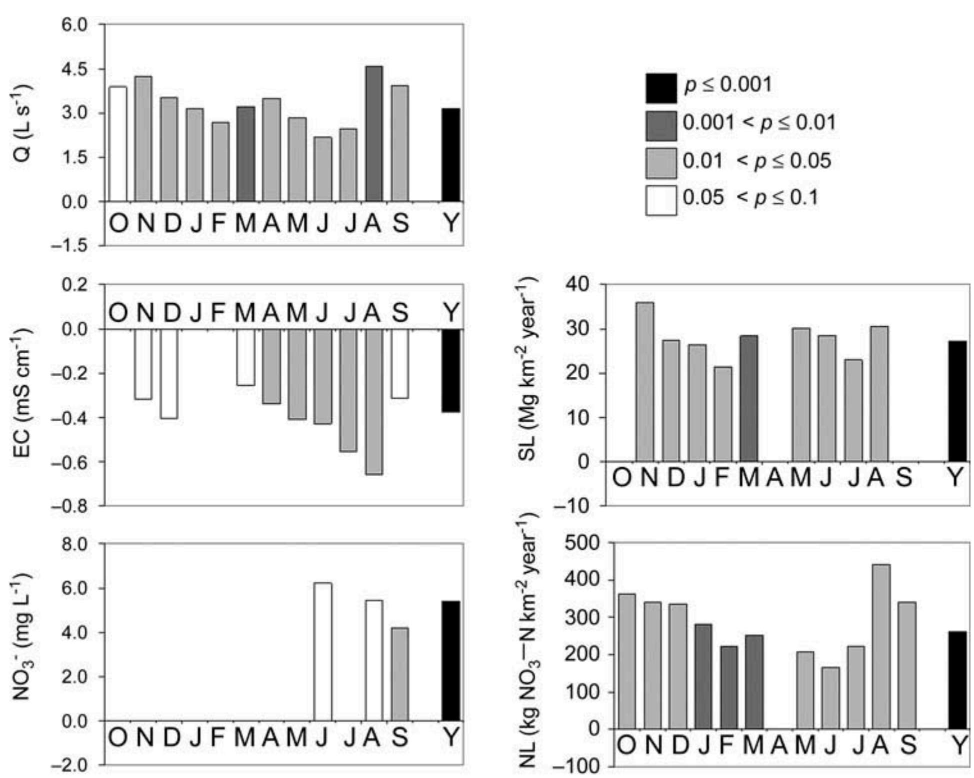

Fig. 4 Monthly (O–S) and annual (Y) trends detected with the S-K test for flow (Q), electrical conductivity (EC), nitrate concentration (NO_3^-), salt load (SL) and nitrate load (NL) at Lerma gully during the hydrological years 2004–2011.

a significant trend in NL, ranging from 165 to 442 kg NO_3^--N km^{-2} year^{-2} (25% to 40%). Trend patterns for SL and NL were mainly conditioned by trends in flow (positive trends for most of the months) with slight differences depending on the particular behaviour of each solute. It is interesting to note that, although trends in nitrate concentration were only detected for three months, trends in nitrate loads were detected in 11 months. As mentioned in Section 4.1, nitrate loads were influenced more by water flow than by nitrate concentration, and, therefore, the trends detected in water flow for all months are consistent with the occurrence of trends in NL in almost all months. This fact is important, as management decisions are usually taken considering only concentrations, as indicated by the EC Nitrate Directive (91/676/EEC). Several studies agree that loads, instead of concentration, must be considered in regulations if an adequate assessment of the agricultural impacts regarding nitrogen is to be performed (e.g. Causapé *et al.* 2004, Arauzo *et al.* 2011). In addition, shallow aquifers play an important role in the seasonal impact of irrigation in the study area. The attenuation and retardation of the hydrological response prevents the pollutant loads from reaching receiving body waters in the season when vulnerability is maximum (summer low waters), and loads are distributed throughout the year.

4.2.2 Trends in different periods The trend results under different conditions (non-irrigated, 2004–2005, transformation to irrigation, 2006–2008; and consolidation of irrigation, 2009–2011) are presented in Table 3. For non-irrigated conditions, decreasing trends were detected for *Q*, SL and NL. No trends were detected in the water quality parameters. Trends in the non-irrigated period are related to the decrease in precipitation between 2004 (634 mm) and 2005 (237 mm), as trends were detected in parameters influenced by this variable, i.e. flow, salts load and nitrogen load.

The trend in flow during the irrigated period was 3.8 L s^{-1} year^{-1}, but important differences were observed between the transformation and the consolidation periods, 2.1 and –5.8 L s^{-1} year^{-1}, respectively. The sudden increase in flow observed between 2008 and 2009 (Fig. 3) is responsible for this unusual trend pattern.

A different behaviour was observed between EC and NO_3^- during the irrigation period, when trends were assessed for the different stages of irrigation implementation. Both EC and NO_3^- increased during the transition period; however, EC decreased during the consolidation period while NO_3^- remained stable (Table 3). The EC pattern can be explained by means of both a dilution effect and soil salt leaching caused by irrigation water entering the system. For the first years, EC increased as soluble salts stored in soils and geological materials were leached. After the successive washing out of these salts, EC is now decreasing and is expected to decrease until a new equilibrium in salinization processes is reached. According to Thayalakumaran *et al.* (2007), the time that elapses until new equilibrium states are reached in salt balances varies from less than a year (root zone) to

Table 3 Annual trends detected by the Mann-Kendall test ($p < 0.01$) and quantified by Sen's slope for flow (*Q*), electrical conductivity (EC), nitrate concentration (NO_3^-), salt load (SL) and nitrate load (NL) in Lerma gully during the non-irrigated period (2004–2005) and the irrigated period (2006–2011). The irrigated period is subdivided into the transition (2006–2008) and consolidation (2009–2011) periods.

Variables	Non-irrigated (2004–2005)	Irrigated (2006–2011)	
		Transition (2006–2008)	Consolidation (2009–2011)
Q (L s^{-1} year^{-1})	−1.8	-	3.8
		2.1	−5.8
EC (mS cm^{-1} year^{-1})	-		−0.21
		0.26	−0.44
NO_3^- (mg L^{-1} year^{-1})	-		9.4
		28.1	-
SL (Mg km^{-2} year^{-2})	−28.6		29.3
		29.6	−84.7
NL (kg NO_3^--N km^{-2} year^{-2})	−95		323
		248	−512

thousands of years (regional basin), and will depend on climate. After reviewing several modelling studies, Thayalakumaran *et al.* (2007) suggest that the time required for a small arid basin to reach a new equilibrium in its salt balance is between a hundred and a thousand years.

Nitrate concentration patterns can be explained by the increased use of fertilizers while the irrigation area and volume were increasing, as no fertilizer was applied during 2004–2005. Previous to our monitoring of Lerma gully, the use of fertilizers in rainfed agriculture was a common practice, but was interrupted for a couple of years when work for transformation to irrigation began. The previous fertilization and climatic conditions explain the high nitrate values obtained during the non-irrigated period, which are comparable to those of the irrigated period, especially in the dry year 2005 (precipitation: 237 mm, NO_3^-: 78 mg L^{-1}). High nitrate concentrations have also been reported for dry years by Reynolds and Edwards (1995) and Burt *et al*. (2010) for upland streams and long-term nitrate concentration time series, respectively. By 2006, most of the nitrate stored in the soils and aquifer during rainfed conditions should have been released. At this moment, which coincides with the beginning of irrigation, minimal values in nitrate concentration were recorded. The progressive increase in fertilizer application coupled with irrigation increased the nitrate concentration in the gully. After expansion of irrigation, the amounts of water and fertilizer applied became stable; the hydrological system appears to have reached a new equilibrium regarding nitrate concentration, although it presents a degree of variation as a consequence of the seasonality in irrigation, fertilization and climate. Thus, nitrogen dynamics seem to have a delay in response to input changes at the upper basin scale (river orders <3). This is probably due to water-transit times in soils and groundwater. This delay is, as expected, lower than what was observed at regional basin scales (river orders >7), where delays can reach more than 10 years (Stålnacke *et al.* 2003).

The aforementioned processes affecting flow, salinity and nitrate concentration have consequences for the exported loads of contaminants. Both SL and NL increased during transition and then decreased during consolidation (as a consequence of decrease in flow). However, SL decrease during consolidation was relatively higher than that of NL (Table 3). While SL decreased as a result of both lower flow and EC, NL was only affected by the lower flow, as NO_3^- remained stable during the consolidation period.

4.2.3 Trends for the entire study period The seasonal Kendall (S-K) test provides an annual trend value taking into account all seasons (Fig. 4). As seen in Fig. 4, the overall trend was very significant for all the variables ($p < 0.001$), even in cases where few seasonal trends were detected as significant. This fact can be explained by the particular case of NO_3^-: although seasonal tests did not detect significant trends for most months (Fig. 4), all the apparent trends were in the same direction, i.e. increasing nitrate concentration with time. These monthly statistics were aggregated when the annual trends were computed (Helsel and Hirsch 2002), and thus the annual trends were significant.

Over the entire study period, the S-K test detected significant trends in Q (3.2 L s^{-1} $year^{-1}$, +23% of annual increase), EC (–0.38 mS cm^{-1} $year^{-1}$, –9%), and NO_3^- (5.4 mg L^{-1} $year^{-1}$, +8%). In addition, positive trends were detected in SL (27.3 Mg km^{-2} $year^{-2}$, +19%) and NL (263 kg NO_3^--N km^{-2} $year^{-2}$, +27%). No trend in precipitation was detected, as occurred in the seasonal test (monthly trends), pointing to irrigation as the factor controlling changes in the gully's hydrology.

The scale of Lerma basin conditioned the prevailing hydrological processes, which were different from those studied in other basins. Thus flow and salinity trends were different from those detected by CHE (2006) at most of the Ebro basin gauging stations for the hydrological years 1976–2004. A decrease in Ebro River flow and an increase in salinity were detected in the aforementioned study, especially in the lower part of the basin. Trends at the Ebro basin scale were explained by the implementation of irrigation in large areas of the basin, including large areas with saline soils. While in Lerma basin the only effect assessed was the incorporation of irrigation return flows, for the whole Ebro basin the effect of abstraction to provide water for irrigation and other uses resulted in less water reaching the rivers, thus decreasing flows and increasing salinity. Decreasing trends have also been reported for flow in other large-scale basins where the irrigated surface had significantly increased (e.g. Great Ruaha River, Tanzania; Kashaigili 2008).

The Arba River presented interesting differences to Lerma gully regarding the trends detected in Q and EC. Contrary to the situation in the Ebro basin, in both the Arba and Lerma basins the water used for irrigation originated from neighbouring basins. However, trends in flow were positive for Lerma basin and negative for Arba basin. In addition, trends in salinity were negative in Lerma basin and positive in Arba basin (CHE 2006). These differences can be explained because the trends detected for the Arba River are a response to an increase in water-use efficiency as a consequence of modernization of irrigation systems and re-use of irrigation return flows (Causapé 2009a, 2009b). In other areas, trends in river water salinity have been related to the proportion of the basin cleared for rainfed agriculture. The greater the area cleared, the higher the trend observed in water salinity, with no trends detected in those river basins without transformation to agriculture (Peck and Hatton 2003). Thus, both rainfed and irrigated agriculture transformation cause increasing trends in streamwater salinity.

Regarding nitrate concentration, Lassaleta *et al.* (2009) also reported significant trends for the period 1981–2005 in four out of 10 sub-basins in the Ebro basin that have experienced change from rainfed to irrigated land over an average of 2.4% of their basin areas, which are minor changes relative to what occurred in Lerma basin (48%). Nitrate concentration trends quantified for the Ebro basin (CHE 2006) were positive (0.91 mg L^{-1} $year^{-1}$ in the Arba River and 0.09–0.21 mg L^{-1} $year^{-1}$ at Ebro River gauging stations), but much lower than those in Lerma gully (5.6 mg L^{-1} $year^{-1}$). These results agree with those of Howden and Burt (2008), who found that detected trends tended to decrease from the headwaters to main rivers in two basins with areas of 208 and 414 km^2 in the south of the UK.

Observed differences between basins are complex to account for, as many influencing factors exist, even if we assume that irrigation has a major role. The main factors are the proportion of irrigated surface (Ebro basin, 9.2%; Arba basin, 25.1%; and Lerma basin, 48%), the rate of land-use change, and the management of irrigation water. Estimated trends were higher in the Lerma basin, as, unlike the Arba or Ebro basins, a high proportion of its surface (48%) was subject to land-use change in a short period of time (2006–2008), which could have a large impact on nitrate concentrations in the short term (Burt 2001).

Trends for loads of pollutants exported were positive and mainly depended on flow conditions, with minor differences as a consequence of the decreasing trend in salinity and the increasing trend in nitrate concentration. According to CHE (2009b), trends in SL and NL in most Ebro basin gauging stations were non-significant or negative. In most cases, as in the Lerma basin, trends in exported loads were conditioned by trends in water flow.

Thus, the impacts of the transformation to irrigation on the hydrology of receiving water bodies will depend on the characteristics of the irrigation project (water withdrawn from the same or a neighbouring basin), climate, hydrological properties of the basin (soils properties, presence of groundwater systems) and agricultural management (rate of fertilizer applications, recent or consolidated irrigation areas). Other uses apart from irrigation add complexity to the assessment of these impacts.

5 CONCLUSIONS

The hydrological dynamics of the Lerma basin have been altered by the incorporation of irrigation return flows. Although rain events imposed great variability on the hydrological response, the effect of irrigation could be isolated to a reasonable degree by the use of non-parametric statistics. No significant relationships were found between precipitation and other hydrological variables of interest. However, significant relationships were found between irrigation volumes and flow and exported loads of salt and nitrate, highlighting irrigation as a controlling factor of the observed changes. Implementation of irrigation imposed significant trends on hydrological variables: (a) increase in flow at Lerma gully, detected both monthly and annually; (b) decrease in salinity and increase of nitrate concentration, mainly in summer months; and (c) increase in exported loads of salts and nitrate, as a consequence of the increase in flow. The detected trends in Q and EC were rather different to those reported in the literature for other irrigation basins, where other processes or land uses interacted with the effects of irrigation. The NO_3^- trend was consistent with that detected at higher scales but with decreasing values downstream, as the influence of other land uses gained relative importance for water quality. Changes in flow mainly controlled the exported mass of pollutants. It is important to continue collecting data in the study area in order to assess the medium- to long-term implications of irrigation implementation.

The results of this study have shown the hydrological changes imposed on a stream as a consequence of the implementation of irrigation in its hydrological basin. The data set generated can also be used for testing hydrological models that simulate the impacts of land-use changes, such as implementation of irrigation. These impacts depend on the characteristics of the irrigation project, the hydrology of the basin and the irrigation and fertilization management, among other factors, which should be taken into account in order to achieve the adequate management of water resources.

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