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EFFECT OF WETLANDS ON WATER QUALITY OF AN AGRICULTURAL CATCHMENT IN A SEMI-ARID AREA UNDER LAND USE TRANSFORMATION

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Abstract: The reduction of nutrients and sediments from agricultural runoff by natural wetlands has been commonly accepted, but their role in water quality improvement at the catchment scale has been seldom studied, especially in irrigated catchments. This study aims to elucidate the effect of natural and recently created wetlands on stream water quality after the conversion of a catchment for irrigation purposes. Water quality and morphometrical and vegetation-related variables were measured in 19 wetlands on a 750-ha agricultural catchment under semi-arid conditions in the Ebro basin (NE Spain). A pollution gradient was found, increasing from the wetlands located in the upper catchment to those in the lower catchment. Wetlands with the lowest degree of artificiality, measured as the amount of human created structures (e.g., channel excavation, dikes), and higher plant richness had the poorest water quality, probably because they were in the lower catchment and their water contained more pollutants carried from agricultural and saline soils upstream. Some of these wetlands also had the highest rates of sediment and N-NO_3 retention, in contrast to more artificial wetlands, which exported nutrients and sediments. Less artificial wetlands could also provide ancillary benefits such as biodiversity enhancement or landscape heterogeneity improvement.

Key Words: agricultural landscape, irrigation, nutrients, *Phragmites australis*, salinity, sediments

INTRODUCTION

Wetland management, creation, or restoration for water quality improvement must be considered at the catchment scale to optimize their benefits (Crumpton 2001, Zedler 2003). Significant reductions in the concentration of sediments, nutrients, and other pollutants of the agricultural runoff have been attained by integrating wetlands into agricultural management at the catchment scale (Mander et al. 2000, Trepel and Palmeri 2002, Arheimer et al. 2004, Skagen et al. 2008). Montreuil et al. (2006) found that the presence of valley bottom natural wetlands in an agricultural catchment reduced NO_3 concentrations by 30% to downstream waters.

Johnston et al. (1990) concluded that watersheds with wetlands mainly in the headwaters (versus lower reaches) exhibited increased concentrations of sediments and nutrients because wetlands were not located along the mainstem to intercept them. However, the water quality of agricultural catchment wetlands is determined not only by agricultural practices, but also by environmental factors (geology or soil composition), historic uses (past logging or mining), and landscape features (scale, patch distribution, or special land-uses) (Baron et al. 2002, Carrino-Kyker and Swanson 2007, Smith et al. 2007, Moreno-Mateos et al. 2008). This understanding is particularly relevant to areas in semi-arid regions that were recently converted for irrigation.

Our study aims to identify relationships between wetland characteristics and water quality, and to quantify the effect of wetlands on nutrient and sediment reduction in streams of an irrigated agricultural catchment. This analysis will allow us to provide guidelines for managers who wish to increase the efficiency of existing wetlands to improve water quality.

METHODS

Area of Study

The study was conducted in the Lerma catchment, a 752-ha area located in the center of the Ebro River Basin, NE Spain (Figure 1). The climate is semi-arid and Mediterranean-continental. The average annual temperature is 14°C, and the average annual

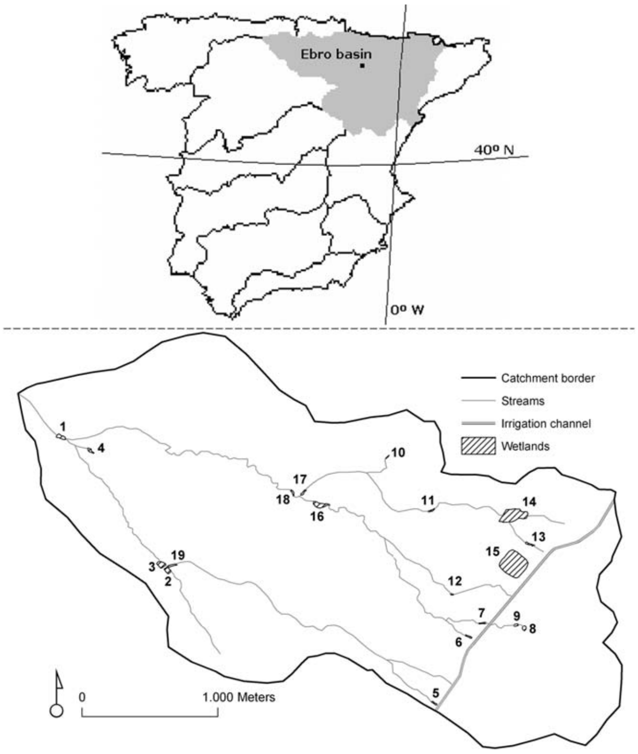

Figure 1. Map of the area of study with the main catchments in the Spanish Iberian Peninsula (top) and the Lerma catchment with selected wetlands (bottom).

precipitation is 419 mm, but interannual variability is high. The soils are dominated by a mixture of gypsum and clay layers with variable levels of salinity (conductivity = 1–10 mS cm^{-1}) over sandstone bedrock. In 46% of the catchment area, this tertiary structure is covered by a 2–4 m deep gravel layer. These gravel-covered areas were converted into irrigated agricultural fields in 2005, and currently, 90% of them are regularly watered. As a consequence of this conversion, surface water availability has increased substantially, and plant communities are changing. Common reed (*Phragmites australis*), cattail (*Typha latifolia*), other reeds (*Scirpus holoschoenus, S. maritimus,* and *S. lacustris*), and tamarisk (*Tamarix africana*) already existed in wetlands before the conversion to irrigation. These species are now colonizing new valley bottoms and flat areas where water surplus from irrigation is currently available. In many cases, common reed is spreading and dominating the plant communities, as it is more tolerant of water level fluctuations and salinity than the other species (Lissner et al. 1999).

After conversion to irrigation, the amount of water and $N\text{-}NO_3$ increased (Causapé, unpublished data), with water flow increasing from 9 to 15 $l\cdot s^{-1}$ and $N\text{-}NO_3$ exportation increasing fivefold (11 $kg\cdot ha^{-1}\cdot year^{-1}$). In the third year after initiation of irrigation, the average $N\text{-}NO_3$ concentration in the water was 80 $mg\cdot l^{-1}$, well above the 50 $mg\cdot l^{-1}$ limit allowed by the EC (European Communities 2000).

Wetland Characterization

Ten isolated wetlands, defined as those without continuity and not in direct contact with the main stream, but contributing their waters to it, were selected for sampling. Out of these 10, five wetlands (2, 3, 4, 8, and 9) existed naturally before the conversion to irrigation (Figure 2A), four wetlands (1, 14, 15, and 16) were specifically created during the conversion to irrigation (Figure 2B, C), and one (10) formed spontaneously after conversion to irrigation. Out of the four created wetlands, two (1 and 16) were designed to retain sediments and nutrients coming from agricultural run-off, and two others were constructed to regulate the water flow for irrigation. Additionally, three stream reaches covered by wetland vegetation were selected on each of the three main streams in the catchment (n = 9). All nine of these wetlands formed spontaneously in streams and linked flat areas after the water flow increase following conversion to irrigation (Figure 2D).

Morphometric variables were used to characterize the wetlands (Table 1). Area and shape [measured as $2\cdot\sqrt{\Pi\cdot A}\Big/P$, where Π is 3.1416, A is area, and P is perimeter (Forman 1995)] were calculated using ArcGIS 9.2 (ESRI Inc.) and 0.5-m resolution aerial photographs taken in 2003. Water depth was measured at the deepest point of the wetland. To estimate the water flow across the wetland, a salt solution (NaCl) of known concentration and volume was added to the water outflowing the wetland, applying the principle of salt conservation (Comín et al. 2001). To estimate plant cover, the shape and distinguishable plant communities of each wetland was digitized using ArcGIS (ESRI Inc.) and 0.5-m resolution aerial photographs and, later, checked by direct observation of each wetland. The number of species was estimated by direct counting of the total number of aquatic and wetland plant species in each wetland.

Four categorical variables also were used to characterize the wetlands (Table 2). Water extent was defined as the amount of surface water on the wetland estimated by direct visual observation in, at least, half of the sampling visits. Water permanence was estimated by the number of monthly visits over the two year study in which the wetlands had water. Artificiality was estimated as the number of human

Figure 2. A) Natural wetland existing before the conversion to irrigation. B, C) Wetlands created during the conversion to irrigation with the objective of improving water quality. D) Wetland formed spontaneously after the conversion to irrigation.

interventions existing in the wetlands such as: channel excavations, water entering from irrigation, earthen-dike construction, concrete walls, piped outflow, flow regulation, synthetic impervious layers, or rock added for soil stabilization. Only in two cases (14 and 15) there were more than three human interventions. Soils were classified into four categories: mudstone, fine sediment, coarse sediment, and artificial soil (concrete or rock artificially installed).

Water Sampling

Samples of inflow and outflow water were collected from each of the study wetlands, every four months in 2007 and 2008. Calibrated field meters were used to record *in situ* measurements of water temperature, pH, dissolved oxygen (DO), and electrical conductivity (EC). Water samples were collected and filtered (with 0.8-µm mesh precombusted filters) on the day collected, returned to the laboratory, and total dissolved solids (TDS), total suspended solids (TSS), turbidity, alkalinity, Cl^-, Ca^{2+}, Mg^{2+}, Na^+, and K^+ concentrations were measured with standard methods (APHA 1998). One month after the samples were collected, ionic chromatography (APHA 1998) was used to quantify $N\text{-}NO_3$, $N\text{-}NO_2$, $N\text{-}NH_4$, and PO_4 concentrations from frozen ($T = -30°C$) aliquots.

Rates of nutrient retention and export were calculated as the difference between the concentrations measured at the inflow and the concentration of the same parameter measured at the outflow on the same day (corrected for ET). The difference was then interpolated between one visit and the next, then divided by the wetland area. Approximate monthly loading rates were estimated for each wetland by interpolating the instantaneous concentration measured during each sampling visit for the

Table 1. Characteristics of the wetlands located in the studied catchment. The explanation of the values of the categorical variables and the shape formula used are detailed in the Wetland Characterization section.

Wetlands	Area (m^2)	Shape (unitless)	Depth (cm)	Flow ($l \cdot s^{-1}$)	Plant cover (%)	Plant richness (species #)	Water extent	Soil type	Artificiality degree	Water permanence
1	1503	0.78	43	7.06	60	6	5	1	3	5
2	2013	0.91	32	1.82	100	4	4	1	2	5
3	1389	0.89	25	0.80	20	3	4	1	3	2
4	702	0.68	2	0.26	100	4	3	1	1	4
5	384	0.64	7	1.08	100	1	2	4	4	5
6	431	0.62	12	0.59	90	2	1	3	2	4
7	389	0.59	5	0.35	90	3	1	3	2	4
8	741	0.97	6	0.10	50	4	3	2	3	1
9	425	0.86	64	0.10	80	3	4	2	3	1
10	100	0.42	11	1.00	10	2	2	2	2	1
11	420	0.62	6	0.30	100	1	2	3	2	5
12	142	0.64	2	0.61	70	2	4	2	4	4
13	636	0.57	22	0.35	40	2	3	2	4	4
14	13986	0.79	>1000	50.00	0	1	5	1	5	5
15	27795	0.96	>1000	50.00	0	0	5	4	5	5
16	3053	0.68	6	0.22	60	4	4	2	4	4
17	495	0.60	3	0.44	100	5	4	2	1	5
18	471	0.65	7	1.91	50	2	3	3	4	5
19	715	0.62	5	0.99	100	2	3	2	2	5

period between that visit and the next. Then monthly loading rates were summed to obtain approximate annual loading rates, which were averaged for the two years of study.

Statistical Analysis

Water quality variables of wetlands did not exhibit normal distributions (Kolmogorov-Smirnoff test). Kruskal-Wallis tests were performed to test for differences in water quality between inflow and outflow for each wetland. Spearman's correlation analysis of water quality variables was performed and the most representative variables were selected from those highly correlated variables ($p < 0.01$) and used in further analyses. After the correlation analysis, alkalinity, pH, TDS, TSS, Na, N-NO3, and TP were selected. Output concentrations and values for all variables describing wetland water quality were averaged. These variables followed a normal distribution and were analyzed by performing a principal components analysis (PCA). PCA ordination diagrams were created to find potential groupings of wetlands with similar water characteristics.

Table 2. Criteria and values assigned to categorical variables used to characterize wetlands.

Variable	Description	Rank
Water extent	One single channel with water flowing	1
	Two–three channels with water flowing	2
	Water covers < 50% of the wetland	3
	Water covers 50–90% of the wetland	4
	Water covers > 90% of the wetland	5
Water permanence	Water flowing in < 3 visits	1
	Water flowing in 3 to 6 visits	2
	Water flowing in 6 to 12 visits	3
	Water flowing in 12 to 20 visits	4
	Water flowing in > 20 visits	5
Artificiality	Natural wetland without human interventions	1
	One human intervention	2
	Two human interventions	3
	Three human interventions	4
	> Three human interventions	5

Wetland feature variables also did not exhibit normal distributions. Spearman's correlation analysis of wetland feature variables was also conducted to select the most representative variables among those that were highly correlated ($p < 0.01$). After the correlation analysis, area, shape, water extent, richness, artificiality, temporality, flow, and depth were selected. Wetland feature variables were then ranked into five classes in order to use them together with the original categorical variables. Categorical principal components analysis (CATPCA; also called optimal scaling) ordination diagrams of wetland feature variables were obtained that allowed us to delimit groups of wetlands with similar characteristics in the space defined by categorical variables. Cronbach's alpha values close to one represented high model reliability.

Finally, in order to find subsets of homogeneous wetland groups, tree-classification analyses were performed (De'ath and Fabricius 2000). Two classification trees were obtained, one for wetland features variables and other for water-quality variables. To find the most accurate classification of the studied wetlands, leafs corresponding to $<$ 5% of the observations were pruned from the tree. This reduced the nodes from 42 to 34.

All analysis was performed using SPSS for Windows 15.0 (SPSS Inc.) and/or Canoco 4.5 (Biometrics-Plant Research International).

RESULTS

Wetland Features

Correlation analysis revealed that large wetlands were compact and had extensive surface water (Table 3). Wetlands with a high degree of artificiality had lower plant richness and cover, and they were deeper than more natural wetlands. Also, artificial wetlands had better water quality with lower concentrations of N-NO_3 and Na. Wetlands with high concentrations of Na and N-NO_3 had more plant species.

Artificiality, area, depth, and temporality were removed from the CatPCA because of their high correlation with flow, water extent, and shape. The ordination diagram indicated two main groups of wetlands (Figure 3). The first group (2, 4, 8, 9, 16, and 17) was composed of compactly shaped wetlands with low flow (usually $< 1\ \mathrm{l{\cdot}s^{-1}}$) covered with ($>$ 50%) species-rich vegetation. Wetlands of this group were less artificial, and their flows were more temporary, compared to wetlands included in the second group. The second group (5, 6, 11, 12, 13, 18, and 19) was composed of elongated wetlands that were part of stream reaches with extensive surface water, and were highly covered ($>$ 50%) by homogeneous vegetation. Additionally, they were shallow ($<$ 12 cm) and small ($< 500\ \mathrm{m^2}$).

A small third group was composed of entirely artificial wetlands (14 and 15, one reservoir and one irrigation pond) that were large ($> 10{,}000\ \mathrm{m^2}$), lacked emergent vegetation, had high flows ($> 50\ \mathrm{l\ s^{-1}}$), and were almost always covered with water $>$ 2 m in depth that extended over the entire area. These wetlands were included in the irrigation network as reservoirs. Finally, four wetlands not included in any group exhibited highly specific characteristics. Wetland 1 was compact, deep (60 cm), with very species-rich vegetation, and with surface water over the complete area. Wetland 3 features were less well captured by the variables used in this study. It was sparsely covered by vegetation and possessed surface water over the entire area. Wetland 7 was similar to the wetlands included in the second group, but it had higher plant richness. Wetland 10 appeared shortly after the conversion to irrigation; it was still almost completely unvegetated ($<$ 10%) and had temporary flow. The tree-based classification analysis only showed one splitting level based on water extent, which did not provide relevant information to group wetlands according to their feature variables.

Water Quality

Principal components analysis (Figure 4) of water quality variables showed only one relevant group that separated from the main cloud of points located in the center of the diagram. This group's variance was poorly explained by the analysis. pH and TP were not considered in the interpretation of the ordination diagram because of their low contribution to the total variance explained. Wetlands in this group (5, 13, 14, and 16) had low concentrations of Na (Table 4; except wetland 16, which had $220\ \mathrm{mg{\cdot}l^{-1}}$) and N-$NO_3$ ($\sim 1\ \mathrm{mg{\cdot}l^{-1}}$), but a medium concentration of TDS (Table 4). Wetlands in the separated group showed a high degree of artificiality (Table 1). Wetland 3 was characterized by its extremely high Na concentration ($2000\ \mathrm{mg{\cdot}l^{-1}}$), wetland 9 was isolated for its low N-NO_3 concentration, and wetland 10 for its extremely high TSS and N-NO_3 concentrations (Table 4).

Five main groups were classified through the tree classification model (Figure 5). Groups were numbered from the headwaters (1) to the mouth (5). Group numbers were correlated with both their location within the catchment (the lower the number the higher their location in the catchment) and with

Table 3. Results of the Spearman's correlation analysis for features and water quality variables of the selected wetlands. Significance is provided in brackets (*p < 0.05, **p < 0.01 and ***p < 0.001).

Wetland characteristics	Water quality						
	Shape	Water extent	Artificiality	Depth	Flow	$N\text{-}NO_3$	Na
Area	0.681(**)	0.694(**)					
Shape		0.632(**)					
Richness			−0.472(*)				0.630(**)
Plant cover			−0.656(**)	−0.558(*)			
Artificiality				0.477(*)		−0.595(**)	−0.604(**)
Temporality					0.622(**)		
Depth					0.479(*)		
$N\text{-}NO_3$							0.751(***)

the concentration of pollutants (the higher the number the higher the concentration of pollutants). Groups one (5, 14, and 15) and two (7, 9, 12, and 13) had low concentrations of pollutants ($N\text{-}NO_3$, TP, Na, and TSS). Furthermore, group one had the lowest Na concentrations of all groups ($< 14\ mg{\cdot}l^{-1}$). All wetlands belonging to groups one and two were located in the upper catchment (Figure 1). Groups three (6, 16, and 17), four (10, 11, 18, and 19), and five (1, 2, 3, and 4) had high TDS concentrations ($> 744\ mg{\cdot}l^{-1}$). Groups three and four also had lower Na concentrations ($< 455\ mg{\cdot}l^{-1}$) than group five, and they separated based on higher $N\text{-}NO_3$ concentration ($> 9\ mg{\cdot}l^{-1}$). Wetlands in groups three and four, with the exception of wetland 6, were in the mid-catchment. Group five had the highest Na concentrations ($> 455\ mg{\cdot}l^{-1}$), particularly wetland 3, whose Na concentration was $> 1394\ mg{\cdot}l^{-1}$. Wetlands in group five were both in the mid and lower catchment.

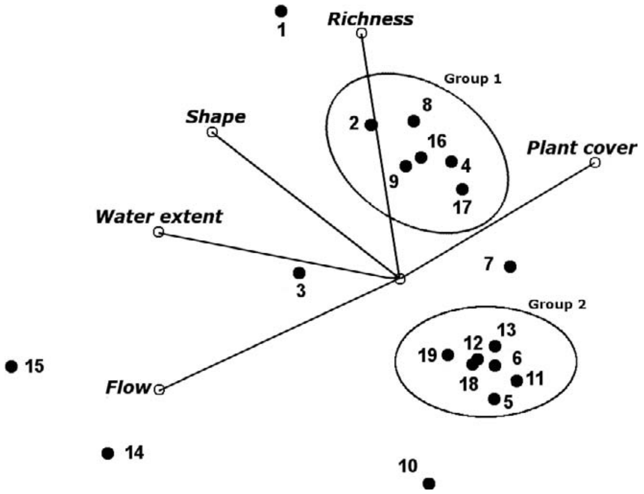

Figure 3. Categorical principal components analysis (optimal scaling) ordination diagram for wetland feature variables (Cronbach's alpha = 0.97). Relevant groups are circled and discussed in the text.

Nutrient Retention

Analysis of water quality between inflow and outflow waters revealed that only five wetlands exhibited significant differences (see also Table 4). Wetland 2 showed a significant decrease in TSS from 28 ± 13 (mean ± sd) $mg{\cdot}l^{-1}$ at inflow to 19 ± 11 $mg{\cdot}l^{-1}$ at outflow. Wetland 3 showed a decrease in total alkalinity (Table 4) and a reduction of $N\text{-}NO_3$, with values ranging from 3 $mg{\cdot}l^{-1}$ at inflow and 0 at outflow to 41 $mg{\cdot}l^{-1}$ at inflow and 3 at outflow, respectively. These findings suggest that there is retention of 725 g $CO_3{\cdot}m^{-2}{\cdot}yr^{-1}$ and 114 g $N{\cdot}m^{-2}{\cdot}yr^{-1}$ by this wetland. In wetland 4, the reduction in $N\text{-}NO_3$ concentration between inflow and outflow waters (Table 4) suggests that 165 g $N{\cdot}m^{-2}\ year^{-1}$ is retained by this wetland. Wetlands 4 and 11 exported 70 and 425 $g{\cdot}m^{-2}{\cdot}yr^{-1}$

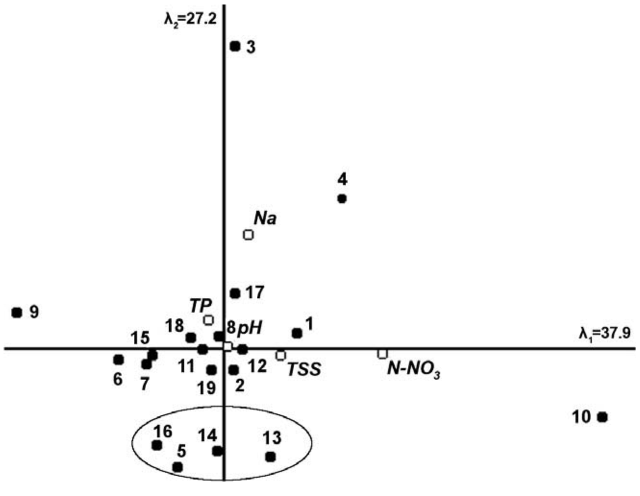

Figure 4. PCA ordination diagram of wetlands (black dots) for water quality variables (open dots). Circled group is discussed in the text.

Table 4. Averaged data of water quality parameters measured at inflow (I) and outflow (O) of studied wetlands. Wetland 15 was an irrigation pond where water was stored without a regular inflow and outflow. Statistically significant differences between the outflow and inflow are marked in bold.

	Alkalinity ($\text{mg}\cdot\text{l}^{-1}$)		Ph		TSS ($\text{mg}\cdot\text{l}^{-1}$)		TDS ($\text{mg}\cdot\text{l}^{-1}$)		Na ($\text{mg}\cdot\text{l}^{-1}$)		NO_3-N ($\text{mg}\cdot\text{l}^{-1}$)		TP ($\text{mg}\cdot\text{l}^{-1}$)	
Wetland	I	O	I	O	I	O	I	O	I	O	I	O	I	O
1	299	299	8.2	8.4	36	19	2348	2451	442	505	52.0	60.0	10.8	9.3
2	340	338	8.2	8.1	**28**	**19**	2681	2545	476	474	31.2	38.4	9.0	8.4
3	**282**	**199**	8.3	8.4	33	33	7498	9554	1519	1985	14.0	1.2	13.5	17.9
4	455	507	8.5	8.9	**29**	**39**	2385	2378	608	613	**57.7**	**29.7**	16.1	17.4
5	150	151	8.0	8.1	30	23	212	219	17	19	2.0	2.1	7.5	4.6
6	253	287	7.8	8.0	11	16	1486	1382	325	290	7.3	5.0	4.1	13.3
7	150	175	8.2	8.2	27	17	321	398	55	61	3.0	1.4	8.8	13.2
8	126	135	7.9	8.0	276	59	496	456	78	70	4.9	1.9	35.2	16.6
9	102	242	7.9	7.5	127	12	586	649	90	100	4.9	0.4	12.4	28.5
10	233	222	8.3	8.3	2410	2095	1436	1388	273	256	93.2	133.4	12.2	7.5
11	244	284	8.1	8.2	**17**	**30**	890	877	137	176	13.6	10.8	53.7	15.0
12	142	143	8.5	8.4	44	47	329	318	67	48	2.8	3.1	11.5	13.5
13	245	227	8.1	8.3	48	49	3760	337	67	48	2.4	1.0	4.4	3.7
14	258	147	8.3	8.3	53	29	441	195	73	11	0.8	1.1	3.8	4.4
15		153		8.2		14		456		31		1.1		33.5
16	239	224	8.3	7.8	37	33	1696	1698	249	269	3.2	1.6	8.4	8.1
17	347	367	8.2	8.4	63	34	1972	1952	408	421	**1.0**	**11.7**	18.7	15.0
18	336	305	8.1	8.1	58	30	2129	2191	418	391	12.9	18.3	15.8	13.1
19	310	307	8.2	8.1	20	19	1854	1841	317	279	30.6	26.4	16.9	12.7

of suspended solids. Wetland 17 released N-NO_3 at the rate of 130 g $\text{N}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$.

DISCUSSION

Natural wetlands (defined in this study as those with a low degree of artificiality) were mainly located in the lower part of the catchment and had the highest concentrations of pollutants. These findings suggest that the wetlands in the catchment are being degraded as a consequence of the conversion to irrigation. In this situation wetlands accumulate pollutants, especially, nutrients and salts. Similar wetland degradation was observed by Koç (2008), who reported accumulation of insoluble salts in wetlands affected by conversion to irrigation in Turkey.

The classification tree showed a gradient of increasing water quality degradation from the wetlands found in the higher reaches of the catchment, fed by water coming from the irrigation channel, to the wetlands located near the mouth, fed with water coming from streams (Figures 1 and 5). This situation could result from two different processes. First, because water travels a greater distance to reach the lower parts of the catchment, it progressively accumulates nutrients, salts, and sediments as it travels down and through the catchment. Second, high evapotranspiration and reduced rainfall can affect salinity-related water variables, increasing salt concentrations in the lower catchment (Whigham and Jordan 2003, Barbier 2005). Wetlands located on the lower catchment are more natural than those in the upper parts. They are also richer in plant species, and surface water usually covers the entire wetland surface. Such was the case for all wetlands displaying a significant decrease in measured pollutants (TSS, alkalinity, and N-NO_3) between the inflow and outflow. This is especially true for wetlands 3 and 4 that removed large amounts of N-NO_3 (114 and 164 g $\text{N}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$, respectively). These rates are comparable to studies elsewhere that report high rates of N removal, e.g., the Mississippi River, United States (57 to 215 g $\text{N}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$, Mitsch et al. 2005), Lake Taihu, China (82 g $\text{N}\cdot\text{m}^{-2}\cdot\text{yr}^{-}$, Jiang et al. 2007), and constructed wetlands, Finland (30 g $\text{N}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$, Koskiaho et al. 2003). Wetland 3 presented high salinity (water EC = 11.5 $\text{mS}\cdot\text{cm}^{-1}$), although this level is still tolerated by common reeds (Lissner et al. 1999). Water inflow with similar EC (14–16 $\text{mS}\cdot\text{cm}^{-1}$) was used by Klomjek et al. (2005) in their experimental wetlands under tropical conditions revealing good retention of sediments, ammonia, and phosphorus by constructed wetlands under saline conditions. Wetland 9 had the best water quality, with an outflow with low Na concentration, neutral pH, and low concentrations of N-NO_3 and TSS. It was a semi-natural wetland constructed

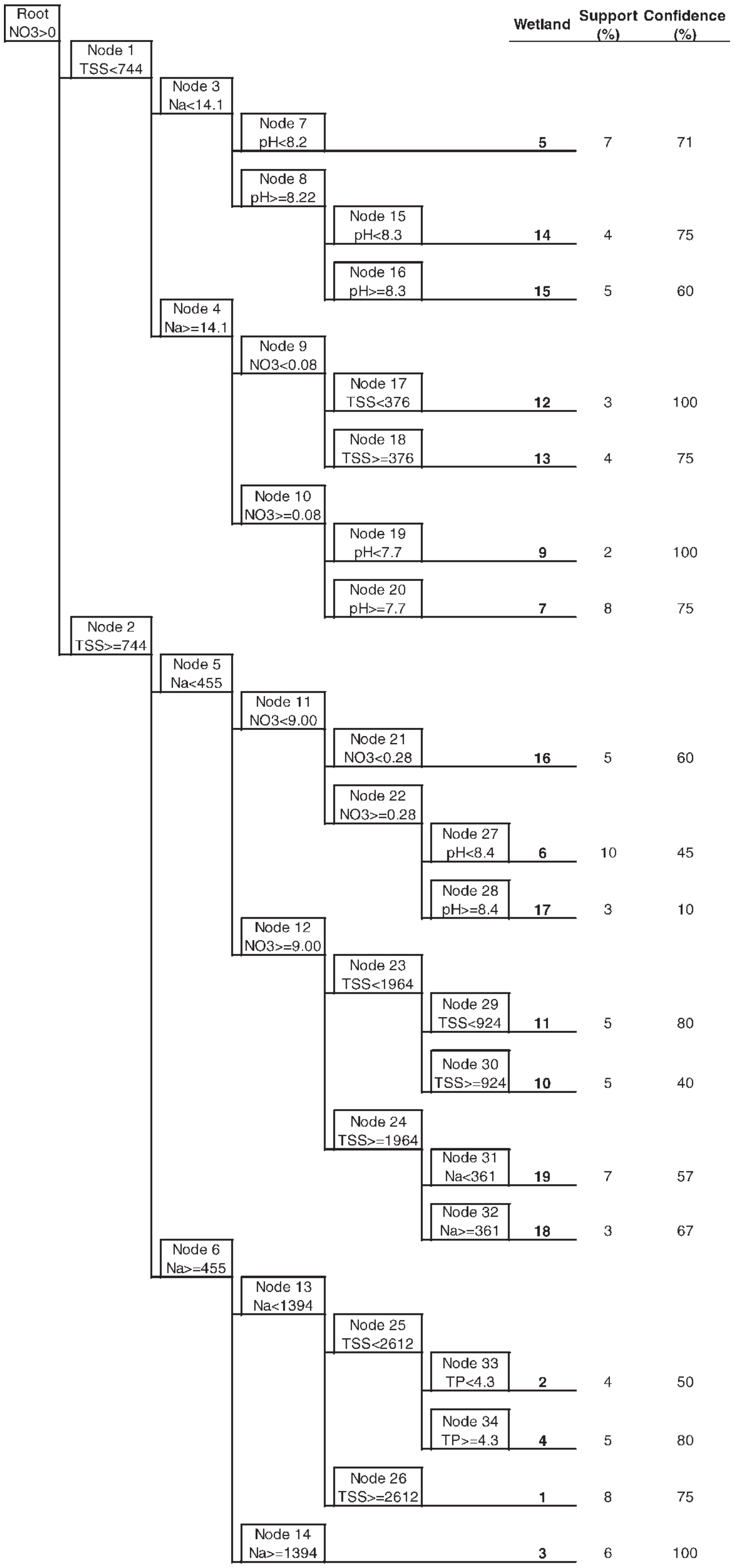

Figure 5. Tree-based classification model for hydrochemical parameters measured in water samples collected at all the studied wetlands. Support is the % of training data for which the left-hand side of the rule applied is true. Confidence is the % of records for which the right-hand side is true, out of the training records for which the left-hand side of the rule applied is true.

more than 100 years ago and fed by storm water. In this case, water is stored for long periods, and providing time for sediments to precipitate and N-NO_3 to be assimilated by vegetation.

Wetlands in the higher parts of the catchment (included in groups 1 and 2, according to the classification tree) were closer to the irrigation channel, the main water supplier in the catchment. Wetlands in group 1 were directly fed by the irrigation channel, and in group 2, water flows a short distance (< 100 m) to reach the wetlands. Because water flows for such a short distance (and time), inflow to these wetlands had lower concentrations of pollutants than wetlands further downstream. These upstream wetlands had a higher degree of artificiality (typically presenting concrete components, tiles, or dug streams) than wetlands in the lower catchment. An extreme case was observed in wetlands 14 and 15, which were completely artificial (regulated flow, impervious surface, water inflowing directly from the channel, piped outflow, and concrete structures) and were a part of the irrigation network.

Export of pollutants was observed in wetlands located in the higher parts of the catchment: wetland 11 exported 425 $g \cdot m^{-2} \cdot yr^{-1}$ of dissolved solids and wetland 17 exported 130 $g\ N \cdot m^{-2} \cdot yr^{-1}$, as N-$NO_3$. Knox et al. (2008) found that degraded, channelized wetlands had lower retention rates and higher export of nutrients and sediments compared to natural reference wetlands in areas affected by agricultural irrigation. Johnston et al. (1990) suggested that the location of wetlands in the landscape has a substantial effect on nutrients and sediments in receiving waters downstream. They found that wetlands in the lower part of the catchment, because they are better positioned to intercept water and pollutants, are more effective for removing pollutants than wetlands in the upper part of the catchment. Our results support Johnston et al's findings as water in the upper part of the catchment had much lower concentration of nutrients and solids than wetlands located in the lower part of the catchment. Also, because of their high degree of artificiality, wetlands in the upper catchment were less able to provide additional benefits such as biodiversity enhancement. An extreme case was wetland 15, an irrigation pond with an impervious layer that prevents vegetation establishment and is surrounded by a concrete structure.

CONCLUSIONS

A gradient in water quality degradation existed in wetlands from the catchment headwaters, where water coming from the irrigation channel had the lowest concentration of pollutants (NO_3, TP, Na, and TDS), to the catchment mouth, where wetlands had the highest concentration of pollutants. Paradoxically, wetlands in the lower catchment were more natural than those in the upper parts; they had greater plant diversity, larger extent of surface water, and less artificial features. Also, some of them removed sediments and nutrients from agricultural runoff.

Wetlands with artificial features located in the upper catchment did not reduce pollutant concentrations in the water, and they had fewer features that supported biodiversity and other ancillary benefits such as landscape heterogeneity (Hammer 1992, Comin et al. 2001). In the future, optimization of existing wetlands in the catchment could provide a cost-effective and simple way to reduce nutrient levels in the water and increase biodiversity in degraded agricultural ecosystems where irrigation is implemented. Efforts should focus initially on wetlands in the upper part (i.e., headwaters), where water quality is still high to avoid the progressive accumulation of pollutants as water travels downward through the catchment.

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