Agriculture, Ecosystems and Environment 134 (2009) 277–286

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Water and nitrate exchange between cultivated ecosystems and groundwater in the Rolling Pampas

Silvina I. Portela [a,*], Adrián E. Andriulo [a], Esteban G. Jobbágy [b], María C. Sasal [c]

[a] Estación Experimental Agropecuaria Pergamino, INTA (Instituto Nacional de Tecnología Agropecuaria), Ruta 32 km 4.5, 2700 Pergamino, Buenos Aires, Argentina
[b] Grupo de Estudios Ambientales, IMASL - Universidad Nacional de San Luis and CONICET, Ej. de los Andes 950, 5700 San Luis, Argentina
[c] Estación Experimental Agropecuaria Paraná, INTA, Ruta 11 km 12.5, 3101 Oro Verde, Argentina

ARTICLE INFO

Article history:
Received 21 November 2008
Received in revised form 30 July 2009
Accepted 2 August 2009
Available online 26 August 2009

Keywords:
Water table level
Groundwater hydrology
Evaporative discharge
Nitrate leaching

ABSTRACT

Understanding nitrogen (N) exchange between cultivated ecosystems and groundwater becomes crucial in the Rolling Pampas where high and variable water table levels are accompanied by increasing N-fertilization rates. Field monitoring of crops, soils and groundwater was combined with modeling to evaluate bidirectional flows (from terrestrial ecosystems to aquifers and vice versa) of water and N throughout a 10-year period (1998–2007) of highly variable precipitation (760–1506 mm year^{-1}) and water table depths (6.5 to <1 m). Piezometers at three topographic positions (upland: UP, mid slope: MS, and toe slope: TS; 1740 and 510 m apart) were used to monitor water table depth and phreatic (<14 m), intermediate (35 m) and bottom of the aquifer (45 m) water chemistry. Crop production and soil water and nitrate content were monitored in two agricultural plots (wheat/soybean–corn rotation) where MS and TS piezometers were located. Nitrate concentration in phreatic groundwater was relatively stable and low at UP and MS (<10 mg l^{-1}) but increased sharply at TS (>45 mg l^{-1}) during periods of high water table levels (<3 m deep). Groundwater chloride concentrations increased with depth in piezometers at UP and MS, but showed the opposite trend at TS during periods of high water table levels, suggesting evaporative discharge at this position. The lateral hydraulic gradient (moving energy) between MS and TS ranged from −0.1 to 0.4% and was negatively correlated with water table depth at TS ($R^2 = 0.23$, $p < 0.001$, $n = 79$) indicating that groundwater flow towards TS increased as the water table level rose. A capillary transport model (UPFLOW) suggested that at TS groundwater supplied an important amount of water and solutes to crops with corn obtaining approximately half of its water needs (228–413 mm) and one fourth of its N requirement (38–76 kg ha^{-1}) from groundwater. Water and N supply from groundwater may have explained the higher biomass and grain yield in the lower positions of each plot with regard to the rest of the area. Our results suggest that the Rolling Pampas landscapes can switch from a typical recharge behavior to a recharge–discharge one following extended rainy periods that rise water table levels and hydraulic gradients, favoring water and solute transport towards the lower positions of the landscape and local concentration of solutes by groundwater consumption, simultaneously affecting groundwater quality.

1. Introduction

Biogeochemical exchange between terrestrial ecosystems and groundwater is predominantly unidirectional in most landscapes, where downward water transport from ecosystems to aquifers (recharge) is the only flux connecting them and the primary pathway of nitrogen (N) inputs to groundwater (Galloway et al., 2003). In these situations soil nutrients can be leached and laterally delivered to lower positions of the landscape (and ultimately to streams) via subsurface water flow, driving a horizontal redistribution and local concentration of N along the trajectory of groundwater from recharge to discharge areas (Högberg, 2001; Weiler and McDonnell, 2006).

In landscapes with shallow water tables, however, the exchange between ecosystems and groundwater can be reciprocal, particularly in low topographic positions where groundwater is discharged from soil and groundwater into the atmosphere through direct surface and soil evaporation as well as through transpiration by vegetation (biological discharge). In this situation, soil and groundwater salinity may increase by the upward transport of solutes from groundwater and solute exclusion by roots (Freeze and Cherry, 1979; Salama et al., 1999; Tóth, 1999; Jobbágy and Jackson, 2007).

The Rolling Pampas of Argentina present a smoothly undulating landscape that hosts an array of upland and lowland areas that can

---

* Corresponding author. Tel.: +54 2477 439029; fax: +54 2477 439047.
E-mail address: sportela@pergamino.inta.gov.ar (S.I. Portela).

0167-8809/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.agee.2009.08.001

define contrasting hydrological behaviors in short distances and across subtle elevation differences. Upland zones generally behave as recharge areas generating downward and divergent groundwater flow and hosting salt-free soils. Lowland zones, instead, receive converging flow and their poor groundwater flushing leads to solute enriched waters that ultimately discharge into streams (Sainato et al., 2003). However, recharge/discharge patterns are not a fixed attribute of a landscape position and can change as a result of hydrological and/or ecological changes. For example, the replacement of shallow-rooted grassland by trees with increased water access and transpiration has transformed typical recharge upland areas of the Pampas into biological discharge foci with increasing soil and groundwater salinity (Jobbágy and Jackson, 2004, 2007).

In the last three decades the agricultural systems of the Pampas have experienced continuous intensification, with increased cultivation of soybean. Although these changes have been accompanied by a dramatic raise of N-fertilization, the region is still under a negative N balance (fertilization $<$ harvesting exports, Austin et al., 2006) sustained by the mineralization (and reduction) of a rich soil organic matter pool (Michelena et al., 1988; Portela et al., 2006). The exports of N from soils to streams and groundwater under the intensifying agricultural scheme are still modest compared to those reported for intensively cultivated basins of Europe and North America (Mugni et al., 2005). In addition to the low fertilization inputs, the presence of natural riparian vegetation along some streams and the widespread adoption of no till technologies are important factors in preventing N loss through run-off and retaining nutrients from uplands in the sloped areas of the Pampas (Mugni et al., 2005).

The humid climate (mean annual precipitation $\approx$ 1000 mm) combined with the flat regional topography results in relatively shallow water tables across most of the region (Paoli and Giacosi, 2003; Nosetto et al., 2009). Understanding N exchange between crop ecosystems and groundwater becomes a crucial issue given the relatively high and temporally variable levels of groundwater in the region (Hall et al., 1992; Tanco and Kruse, 2001; Viglizzo et al., 2009). Besides being an important control of groundwater quality, this exchange is relevant from the perspective of biogeochemical cycling in cultivated and natural ecosystems. This paper explores water and N exchange between cultivated ecosystems and groundwater across a topographic gradient that represents the typical landscape of the Rolling Pampas throughout a 10-year period in which rainfall and water table levels displayed large fluctuations. Hydrological shifts associated with water table level fluctuations can affect the role of groundwater as a N transport agent in the landscape, altering the vertical direction of N exchange in the crop-soil-groundwater continuum, as well as the horizontal arrangement of recharge and discharge zones. We hypothesize that crop ecosystems in lower landscape positions behave transiently as water and nutrient sinks or sources during periods of high and low water table levels, respectively. Field monitoring of crops, soils and groundwater was combined with modeling of bidirectional flows of water and N to evaluate crop water use from shallow water tables and its effect on groundwater chemistry.

2. Materials and methods

2.1. Study site

We conducted field observations in a typical agricultural farm of the Rolling Pampas (33°36′S; 60°41′W) located in Pergamino (N Buenos Aires Province, Argentina), between 1998 and 2007. The climate is temperate humid without a dry season and with a hot summer (Hall et al., 1992). Mean annual temperature is 16.4 °C and mean annual rainfall for the 1910–2007 period is 975 mm (Agroclimatological network database, INTA). Rainfall in this area is highly variable, with annual totals displaying a coefficient of variation of 21% at Pergamino for the same period. The study area presents a smoothly undulating sedimentary landscape with a general slope of 0.3% towards a main stream, Arroyo del Medio, and average slope length of 1000 m, and is divided into landscape units by tributaries (e.g. El Arbolito) perpendicular to the main stream. Two plots of 83 and 53 ha positioned down the slope towards the main stream were used for data collection (Fig. 1). The soils of these plots and the surrounding uplands are relatively homogeneous, slightly eroded ($<$5 cm loss of A horizon, Michelena et al., 1988) Vertic Argiudolls of the Peyrano series. They have a 10–22 cm deep silty loam A horizon (with 25 and 63% of clay and silt, respectively, and 33 g kg^{-1} of organic matter) and a 63 cm deep strong argillic B_2 horizon (with 50 and 46% of clay and silt, respectively) which does not impede water percolation nor root penetration. Downslope from the experimental plots, soils form highly heterogeneous associations of upland soil types (Peyrano series) intermingled with a varying proportion of alkaline and saline alfisols of the stream sides.

The area lies on the Pampa formation (Pleistocene) of aeolian loessoid sediments with alluvial reworking. This formation hosts the Pampeano aquifer, 20–120-m thick, which encompasses a phreatic aquifer and some deeper semiconfined aquifers. The water is bicarbonate-sodic and its salinity increases towards the discharge zones.

2.2. Crop management

The studied plots host the typical crop rotations of the region involving the sequence soybean–corn, with wheat preceding soybean some years, or otherwise, the soil remaining fallow between the two summer crops (Table 1). Between 1998 and 2001 the stages of the rotation were delayed by 1 year between the two experimental plots, becoming synchronized after 2002. All crops were sown without tillage (and crop residues were left on soil surface after harvest) and sprinkler irrigated during 1998, 1999 and 2000 (with 40–150 mm year^{-1}). Wheat and corn were fertilized with P and N (ammonium phosphate and diammonium phosphate) at seeding, then, wheat was fertilized with N (urea and ammonium nitrate) at tillering and corn at four-leaf stage. Soybean was not fertilized.

2.3. Groundwater and field measurements

In 1997, 10 temporary wells were constructed to obtain piezometric levels and assess groundwater flow patterns in the landscape (Fig. 1). In 1998, permanent multilevel wells (piezometers) were constructed at three positions of the landscape (1740 and 510 m apart) across the groundwater flow direction: upland (UP), mid (MS) and toe slope (TS) (ground surface at 65.2, 64.7 and 63.9 m above sea level, respectively). At each position three piezometers were installed exploring phreatic, intermediate and bottom of the aquifer waters (screened at 14, 35 and 45 m from ground surface, respectively). Recharge water was characterized in the highest set of multilevel wells (UP), 770 m away from the border of the study plots. A set of multilevel wells at each study plot characterized groundwater in its lowest position (MS and TS).

Water table level was monitored at UP, MS and TS with a portable water level sensor, daily between August 1998 and November 2001, and generally weekly thereafter. The water table level in the wells and the distance between two wells were used to compute the lateral hydraulic gradient. Water samples were extracted every 30–45 days with a stainless steel bailer sampler

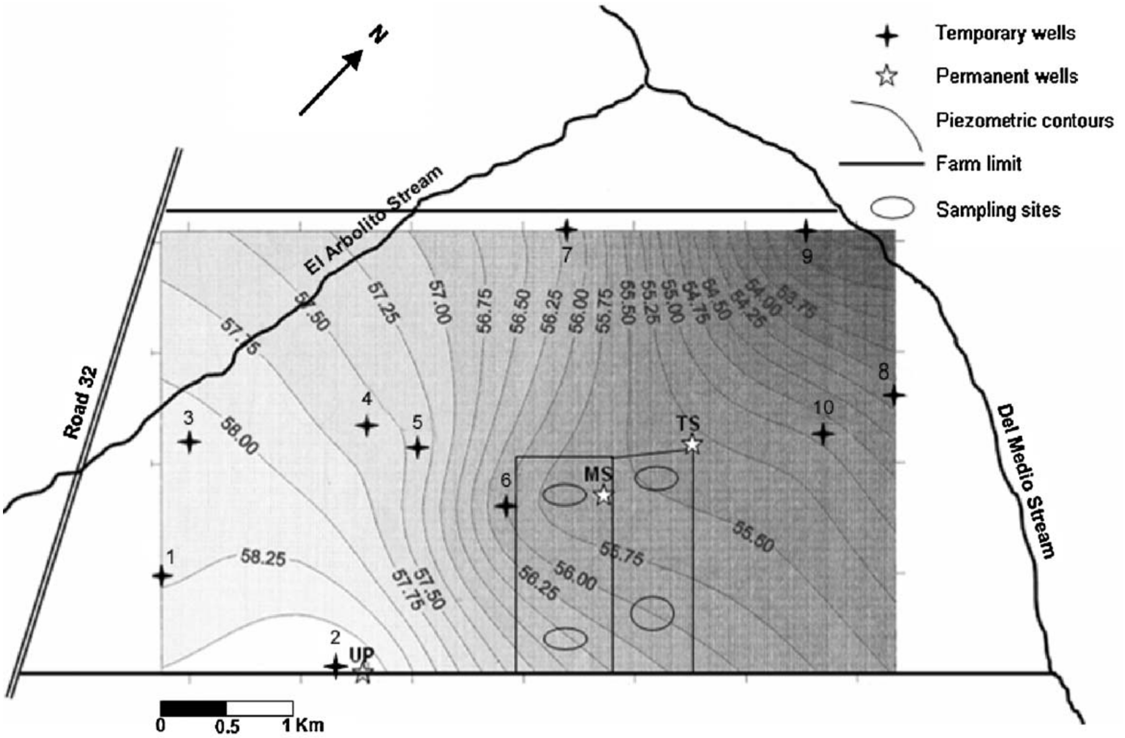

Fig. 1. Field map and experimental set-up. Temporary wells (1–10) were constructed in 1997 to draw the piezometric contours (in m above sea level). Permanent wells were installed at three positions of the landscape across the groundwater flow direction: upland (UP), mid (MS) and toe slope (TS) exploring three groundwater depths (<14, 35 and 45 m).

(12.04, Eijkelkamp, The Netherlands) from each piezometer (three depths at three locations). Piezometers were purged before sample extraction to allow for new water entrance and samples were kept refrigerated in plastic bottles until analyzed. Electrical conductivity (EC) was determined potentiometrically; chloride (Cl^-) was determined by $AgNO_3$ titration and nitrate (NO_3^-) by the colorimetric phenoldisulfonic acid method.

Soil water and NO_3^- contents were characterized at two locations (high and low topographic position) in each plot at sowing and harvest time of each crop (Fig. 1). Three replications were obtained at each position, sampling each soil horizon down to 1 m of depth with a 5-cm-diameter auger. Samples were stored in plastic bags and refrigerated until analyzed. Soil water content was determined on a subsample by the thermogravimetric method; the remaining sample was air dried at room temperature, crushed and sieved through a 2-mm screen for NO_3^- determination. Inorganic N was extracted twice by shaking 20 g of dry soil with 25 ml of 1 M KCl during 30 min and collected by centrifugation (3000 rpm for 15 min) and filtering. Nitrate concentration in the extracts was measured as indicated above for water samples. Soil NO_3^- content (kg ha^{-1}) was calculated as the sum of the products between NO_3^- concentration, horizon thickness (m) and bulk density (kg dm^3) across all soil horizons. Three plant samples were collected at harvest time from a 1 m^2 area at each sampling position for total dry matter production, grain yield and crop N content assessment with Kjeldhal method (Keeney and Nelson, 1982). Soil and plant measurements were used to estimate ecosystem water and N balances and for modeling work.

Table 1
Cropping calendar and fertilization rates for the mid and toe slope plots during the study period. Between cropping periods the soil remained fallow.

Year	Mid slope plot				Toe slope plot			
	Crop	Planting-harvest date	Fertilization (kg ha^{-1})		Crop	Planting-harvest date	Fertilization (kg ha^{-1})	
			N	P_2O_5			N	P_2O_5
1997	Wheat		45	115				
1997/1998	Soybean	na	–	–	Corn	na	na	na
1998/1999	Corn	September 15–March 20	133	46	Soybean	October 20–March 20	–	–
1999/2000	Soybean	November 1–March 31	–	–	Corn	September 4–February 29	120	28
2000					Wheat	June 2–December 1	92	41
2000/2001	Corn	September 3–March 1	105	32	Soybean	December 2–April 28	–	–
2001	Wheat	May 15–November 22	97	41				
2001/2002	Soybean	November 23–April 23	–	–	Corn	October 25–March 4	120	28
2002/2003	Soybean	November 7–April 8	–	–	Soybean	October 26–March 15	–	–
2003/2004	Corn	September 15–March 13	58	33	Corn	September 19–March 16	58	33
2004/2005	Soybean	October 21–March 15	–	–	Soybean	October 21–March 15	–	–
2005	Wheat	June 14–December 10	55	27	Wheat	May 28–December 2	45	29
2005/2006	Soybean	December 11–April 19	–	–	Soybean	December 3–April 11	–	–
2006/2007	Soybean	October 22–March 12	–	–	Soybean	October 21–March 12	–	–
2007	Wheat	May 27–November 30	52	25	Wheat	May 29–November 30	52	25

na: not available.

2.4. Modeling

We used GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) to simulate water percolation and N leaching below the root zone (1 m) at each experimental plot (Leonard et al., 1987) and UPFLOW (Raes and Deproost, 2003; Raes, 2004) to estimate capillary rise of water and salts from groundwater to the root zone. GLEAMS was ran on a daily time step. All the climatic data required (maximum, minimum and dew point temperature, wind speed and solar radiation) were obtained from the weather station at Pergamino Experimental Station of INTA (30 km away from the farm) except for rainfall which was recorded at the farm. Soil physical (texture, bulk density, water content at field capacity and permanent wilting point) and chemical (organic matter, total N, total phosphorus and cation exchange capacity) characterization was performed initially at each plot and crop management practices (rotation, fertilization, irrigation, crop protection, sowing and harvest dates) were represented. The model UPFLOW estimates the upward transport of water and solutes assuming steady state conditions and therefore requires specific environmental conditions valid during the time period considered, we used 10–30-day averages, depending on input data availability. Of the input data required, potential evapotranspiration (ETp) was calculated by GLEAMS using Priestly-Taylor's method, and soil water content, water table depth and EC were directly measured. The root zone depths suggested by the model (1.2 and 0.5 m for corn and soybean, respectively) were used. When the time period between water table depth measurements was more than 30 days we estimated an intermediate value through interpolation. In the case of the high positions of each plot, where there are no wells, water table depths were estimated by adjusting the depths measured at MS and TS according to the piezometric contours determined initially. The model calculates the amount of salt transported from the water table to the root zone by capillary rise assuming that 1 dS m^{-1} of EC is equal to 640 mg salt l^{-1} (Abrol et al., 1988). We estimated N upflow by multiplying the estimated water upflow by the concentration of NO_3-N measured at the phreatic groundwater of each piezometer.

2.5. Statistical analysis

The relationships between water table level and lateral hydraulic gradient, NO_3-N and Cl^- concentrations of phreatic groundwater and grain yield were analyzed through minimum squares linear regression. The relationships between the monthly NO_3-N concentration in percolating water (modeled) and that measured in phreatic groundwater were explored through correlations with variable time lags between the two time series. Chi-Square test was used to determine if the proportion of rainfall that percolated depended upon the land use of a given period (cropping or fallow), and if deep (0.6–1.1) soil NO_3-N concentration at the high and low topographic positions of each plot depended upon water table level.

3. Results

3.1. Description of time series

Throughout ~10 years annual rainfall ranged from 760 to 1506 mm, and water table depth from 6.5 to <1 m below the soil surface (Fig. 2A and B). Our study encompassed a full cycle of groundwater level rise and decline associated to a 3-year period of exceptionally high rainfall from 2000 to 2002 (the highest for the 1910–2007 time series; the 95% cumulative frequency for 3-year periods is 3516 mm and the 2000–2002 period had 4329 mm of rainfall).

Water table depths at all sites were >3 m most of the time, yet they remained above that depth for 25–28 months (depending on the topographic position of the well) following the period of exceptionally high rainfall, suggesting a strong and well defined hydrological shift during that period. At the end of our study a short rainy period caused another intense shift to high water table levels of shorter duration (4–10 months). The lateral hydraulic gradient (moving energy) between MS and TS ranged from −0.1 to 0.4%, paralleling water table fluctuations (Fig. 2B). Water table depth at TS was negatively correlated with the lateral hydraulic gradient between MS and TS ($R^2 = 0.23$, $p < 0.001$, $n = 79$) indicating that groundwater flow between MS and TS increased as the water table level rose.

The concentration of NO_3-N in phreatic groundwater was relatively stable and low in the UP and MS positions (<10 mg l^{-1}) but increased sharply in the TS position (>45 mg l^{-1}) during periods of high water table levels and lateral hydraulic gradient (Fig. 3). Water table levels and NO_3-N concentrations were positively correlated in this position (TS) ($R^2 = 0.37$, $p < 0.001$, $n = 77$) but not in the higher ones (UP and MS) (Figs. 2 and 4). Noteworthy, the rate of nitrate change with water table level increased and the relationship was tighter during periods of ascending water table level ($b = -5.6$ mg NO_3-N l^{-1} m^{-1} water table depth, $R^2 = 0.55$, $p < 0.001$, $n = 39$) than in periods of descending level ($b = -0.2$ mg NO_3-N l^{-1} m^{-1} water table depth, $R^2 = 0.13$, $p < 0.05$, $n = 40$). Independently from the water table level and landscape position, NO_3-N concentration remained steady at <10 mg l^{-1} deeper in the aquifer (>35 m) throughout the 10 years.

Groundwater Cl^- concentration generally increased with depth at UP, MS and TS positions and towards the lower topographic position (Table 2). However, at TS, the higher concentrations (>3rd quartile) were detected in phreatic groundwater during periods of high water table levels, following a similar pattern to nitrate concentration (Fig. 2).

3.2. Water and nitrogen exchange between soil and groundwater

The total amount of percolated water and leached NO_3-N estimated by GLEAMS throughout the whole study period was similar at the two plots (1673 and 1714 mm and 69 and

Table 2
Groundwater Cl^- concentration (mg l^{-1}) at each topographic position (UP, MS and TS) and groundwater depth (phreatic, mid and bottom of the aquifer).

Topographic position	Groundwater depth	n	Minimum	1st quartile	Median	3rd quartile	Maximum
UP	Phreatic	79	14.2	28.4	34.0	56.7	156.0
	Mid	77	14.2	16.0	28.4	42.5	283.6
	Bottom	79	28.4	53.9	56.7	70.9	205.6
MS	Phreatic	79	14.2	28.4	28.4	51.0	184.3
	Mid	77	17.7	51.0	56.7	70.9	146.0
	Bottom	78	28.4	107.8	113.4	127.6	219.8
TS	Phreatic	78	28.4	85.1	127.6	283.6	510.5
	Mid	77	28.4	141.8	153.1	170.2	248.2
	Bottom	78	14.2	127.6	156.0	170.2	241.1

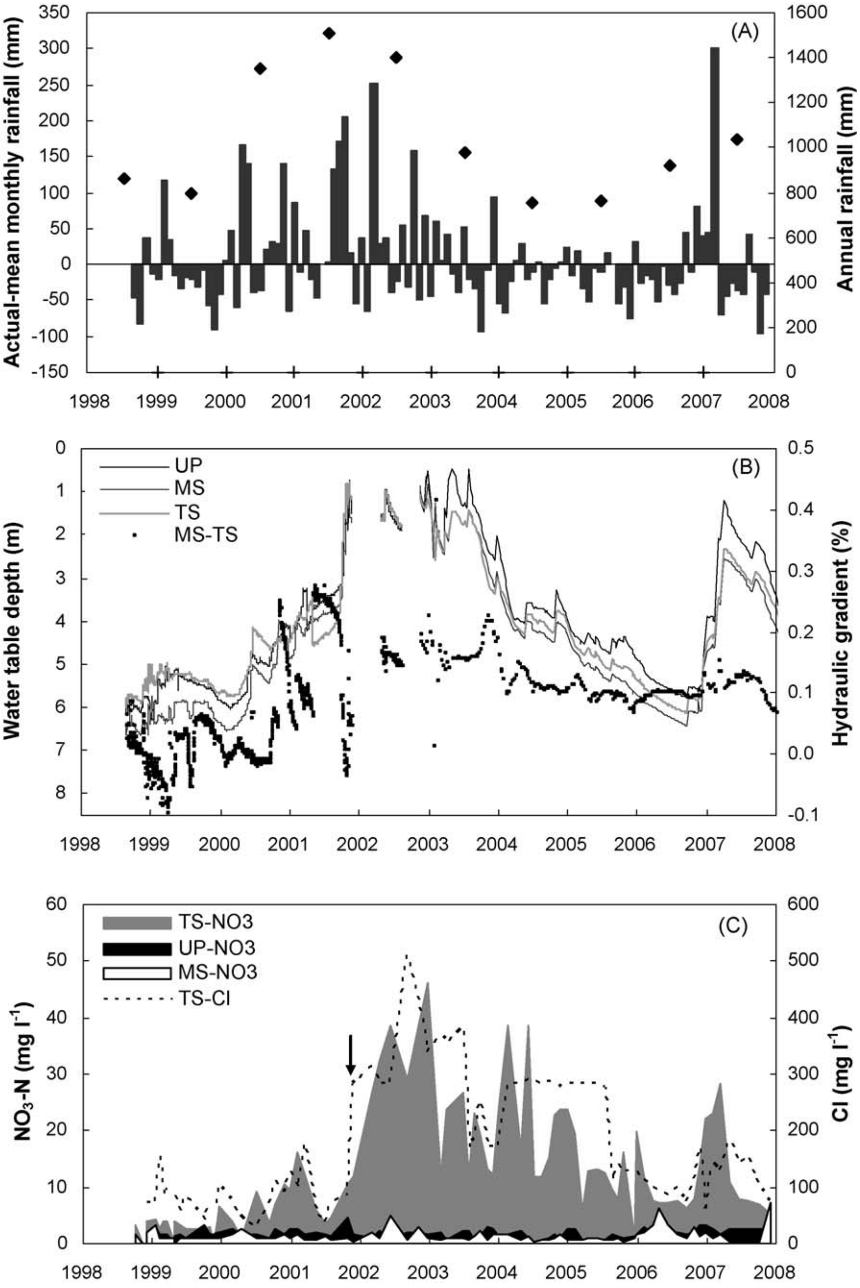

Fig. 2. (A) Annual rainfall (symbols) and difference between actual and long term mean monthly rainfall (bars). (B) Water table depth at three landscape positions: upland (UP), mid (MS) and toe slope (TS) and lateral hydraulic gradient between MS and TS. (C) Phreatic groundwater (<14 m) NO_3-N and Cl^- concentration at the three positions. The arrow indicates the time of maximum ET-induced water upflow from groundwater at TS.

78 kg ha^{-1}), although the temporal distribution and the concentration of leachates varied across plots until 2002, when their crop rotations started to be synchronized (Table 1 and Fig. 5). With more than 400 mm of rainfall, cropping reduced drainage (0–20% of rainfall) compared to fallow (20–40% of rainfall) ($\chi^2 = 14.04$, $p < 0.001$, $n = 25$). However, with less than 400 mm of rainfall there was drainage only when the previous period had had drainage, independently of the presence or absence of crop ($\chi^2 = 9.74$, $p < 0.01$, $n = 19$). Nitrate leaching was better explained by the amount of drainage during cropping ($R^2 = 0.85$, $p < 0.001$, $n = 24$) than during fallow periods ($R^2 = 0.57$, $p < 0.001$, $n = 18$), and N-fertilization rate of crops was not related to leaching losses.

Midslope and toe slope positions showed contrasting relationships between estimates of nitrate concentration in percolating water by GLEAMS and measurements in phreatic groundwater, with MS showing positive correlations at variable time lags and TS showing no association. At MS, when the water table depth was >3 m, monthly mean nitrate concentration in percolating water was best correlated with groundwater concentration measured 8 months later ($R^2 = 0.09$, $p < 0.1$, $n = 36$). When the water table depth was <3 m the best correlation was achieved with a 1-month lag ($R^2 = 0.14$, $p < 0.1$, $n = 26$). These coefficients are low in part due to the absence of drainage on approximately half of the individual months considered in the analysis (55 and 45%, for the >3 and <3 m water table depth periods, respectively), which introduced a large number of zeros that cannot be removed from the (nitrate concentration in percolating water) time series because the observations would result at unequal time intervals. The absence of association between nitrate in percolating water and phreatic groundwater at TS, together with the high concentrations in this

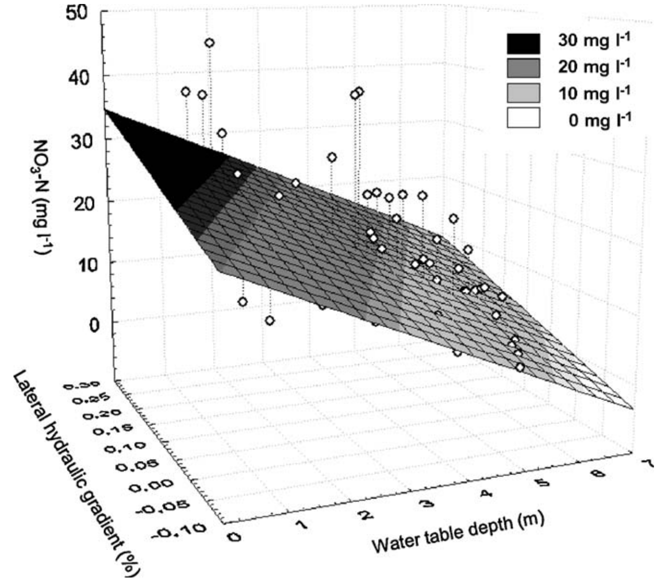

Fig. 3. Phreatic groundwater NO_3-N concentration at TS and its relation with water table depth (m) and lateral hydraulic gradient between MS and TS (%). The model is: NO_3-N (mg l^{-1}) = 25.4–3.7 water table depth (m) + 30.9 lateral hydraulic gradient (%); $R^2 = 0.40$; $p < 0.001$; $n = 75$.

well, suggest that additional mechanisms besides downward water and N transport with its associated lags are controlling groundwater chemistry in this position. These mechanisms are described below.

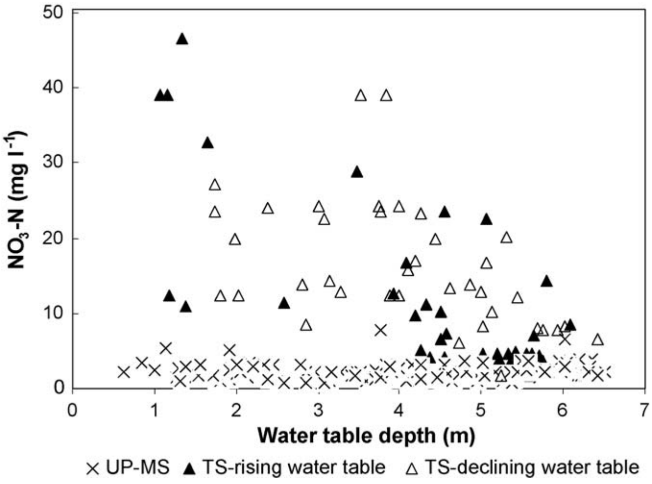

Fig. 4. Phreatic groundwater NO_3-N concentration vs. water table depth at three landscape positions: upland and mid slope (UP–MS) and toe slope (TS). The filled symbols correspond to periods of rising water table level (October 1998–December 2002 and October 2006–May 2007) and the empty symbols to periods of declining water table level (February 2003–September 2006 and June 2007–November 2007).

Groundwater consumption by crops appeared as an important mechanism regulating its chemistry during the periods of high water table levels, as suggested by direct observations and modeling. Between October 2001 and October 2003 the water table remained at <3 m from the soil surface at the three landscape positions (Fig. 2B). During the 2001–2002 summer season the mid slope plot, that drains towards MS, was sown with soybean on

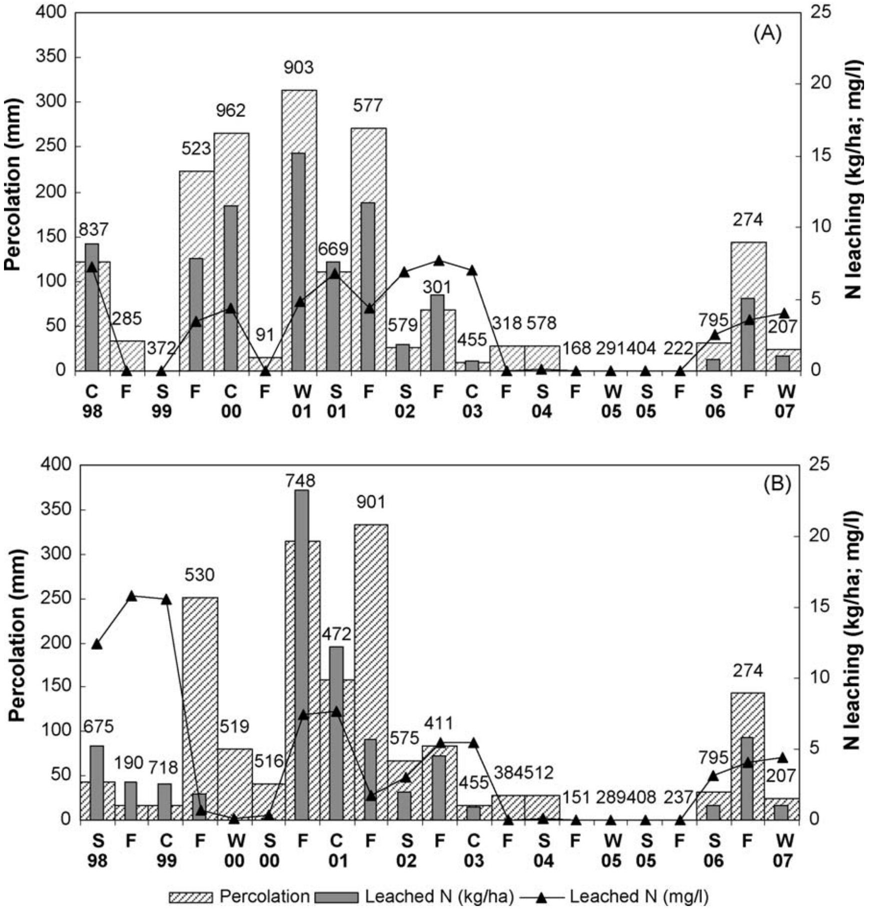

Fig. 5. Simulated water percolation and NO_3-N leaching for each cropping and fallow period (C: corn, S: soybean, W: wheat, F: fallow) at mid slope (A) and toe slope plot (B). Nitrate leaching is expressed as a quantity (kg N ha^{-1}) and as concentration (mg N l^{-1}). The value above each bar corresponds to the amount of rainfall (mm) for that period.

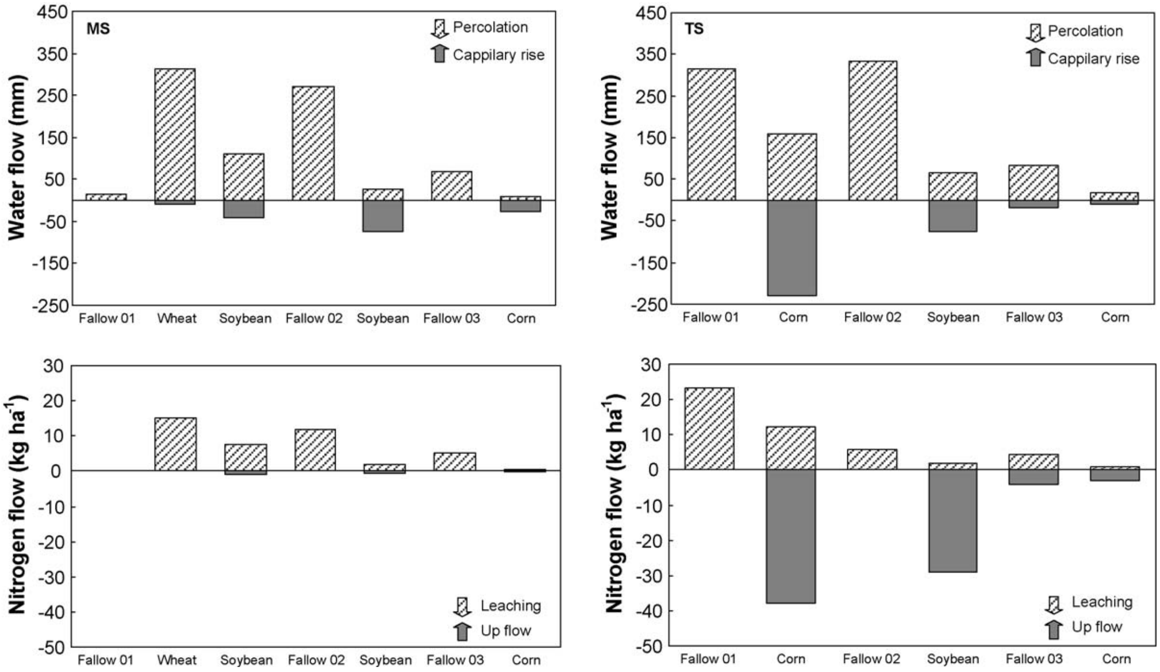

Fig. 6. Water and N exchange between soil and shallow groundwater at mid slope (MS) (left panels) and toe slope (TS) (right panels) landscape positions. Water percolation and N leaching were estimated with GLEAMS and capillary rise of water and N was calculated with UPFLOW.

November 23 (immediately after wheat) while the toe slope plot, that drains towards TS, was sown with corn 1 month earlier. The UPFLOW model suggested that the shallower water table depth at TS compared to MS (1.0 m vs. 1.5 m) and the deeper rooting system of corn compared to soybean (1.2 m vs. 0.5 m) caused more ET-induced capillary rise from groundwater at TS than at MS (228–413 mm vs. 42 mm) (Fig. 6). Additionally, the higher salt concentration of groundwater at TS (likely leached from recharge areas) resulted in a 3–9-fold upward transport of salt relative to MS. For example, during October 2001, a capillary flow of 0.5 mm day^{-1} "lifted" 5.2 and 1.6 kg salts ha^{-1} day^{-1} from groundwater at TS and MS, respectively.

We estimated that during the 2001–2002 growing season, corn at TS induced the upflow of 38–76 kg N ha^{-1} while soybean at MS received less than 1 kg N ha^{-1} (Fig. 6 and Table 4). During the 2002–2003 growing season, when soybean occupied both plots and ET-induced capillary rise was 75 mm at TS and MS (Table 3) the upward N transport was 29 and 0.7 kg N ha^{-1} at TS and MS, respectively. Groundwater consumption at the capillary fringe likely increased salt concentration in the soil profiles, and these salts eventually reached groundwater, raising its salinity after they were leached by subsequent rains or reached by rising water table levels, explaining the observed patterns of EC at TS (Table 3).

Soil NO_3-N content at 0.6–1.1 m depth was higher (mean value of 14.4 kg ha^{-1}) and more variable (range = 5–60 kg ha^{-1}) before the water table rise (water table >3 m deep) than during the shallow water table period (water table <3 m depth deep) (mean value of 7.0 kg ha^{-1}, range = 3–35 kg ha^{-1}), specially at the lower positions of each plot, presumably as a result of increased leaching

Table 3
Components of the water balance (mm) and crop yield (Mg ha^{-1}) for each growing season and topographic position within each plot.

Year	Plot	Crop	Position	Water table depth[a] (m)	Phreatic groundwater EC[a] (dS m^{-1})	Water balance (mm)						Yield[a] (Mg ha^{-1})
						Rain[a]	Δ soil water[a]	Capillary rise[b]	Drainage[c]	Run-off[c]	ETa[d]	
01/02	Mid slope	Soybean[e]	High	2.2–2.4	na	669	−15	6	111	124	455	3.2
			Low	1.5–1.7	0.6–1.0		−38	42	111	124	514	3.8
	Toe slope	Corn	High	1.5–2.2	na	472	−38	80–88	158	65	367–375	9.8
			Low	1.0–1.7	1.5–3.1		−62	228–413	158	65	539–724	12.3
02/03	Mid slope	Soybean	High	1.6–3.2	na	579	−53	7	26	27	586	3.0
			Low	0.9–2.5	0.6–0.7		−58	75	26	27	659	3.3
	Toe slope	Soybean	High	1.6–2.9	na	575	−62	12	66	24	559	na
			Low	1.1–2.4	2.2–3.8		−18	75	66	24	578	na
03/04	Mid slope	Corn	High	2.7–4.5	na	455	−35	6	9	32	455	10.6
			Low	2.0–3.8	0.7–1.1		−26	27	9	32	467	8.1
	Toe slope	Corn	High	2.5–4.0	na	455	−49	3	17	33	457	7.3
			Low	2.0–3.5	2.0–3.3		−76	9	17	33	490	8.7

na: not available.
[a] Measured in situ.
[b] Calculated by UPFLOW.
[c] Calculated by GLEAMS.
[d] ETa = rain + capillary rise − Δ soil water − drainage − run-off.
[e] Late sown soybean (after wheat).

Table 4
Nitrogen balance (kg ha^{-1}) for corn sown at a high and low topographic position within the toe slope plot (TS) during the 2001–2002 growing season.

Year	Crop	Position	Inputs			Outputs			Difference
			Δ soil NO_3-N[a]	Fertilizer	Ground water[b]	Leaching[c]	Run-off[c]	Uptake[d]	
01–02	Corn	TS-high	76	120	15–17	12	0.4	221	−23 to −21
		TS-low	56	120	38–76	12	0.4	259	−58 to −20

[a] Difference in soil NO_3-N content (up to 1 m) between sowing and harvest.
[b] Calculated by UPFLOW.
[c] Calculated by GLEAMS.
[d] We considered that the measured aboveground plant N constituted 80% of the total uptake (Salmerón-Miranda et al., 2007).

($\chi^2 = 4.49$, $p < 0.05$, $n = 27$ and $\chi^2 = 10.41$, $p < 0.001$, $n = 35$ for the mid slope and toe slope plot, respectively).

3.3. Water and nitrogen balance

Since soil and crop sampling were performed at the highest and lowest topographic position of each plot we could complete water and N balances for each cropping season and topographic position. Water lost through drainage and run-off and water entering the rooting zone through capillary rise were estimated through modeling and crop actual evapotranspiration (ETa) was obtained as the difference between the inputs and outputs of water. Missing data at TS between December 2001 and Jan 2002 was interpolated and given that a 10 cm-difference in the estimated values (1.2–1.3 m) generated a three-fold difference in capillary upflow (from 1.5 to 4.5 mm day^{-1}) we reported water and N supply from the aquifer in that period as a range (Tables 3 and 4).

The upward flow from groundwater provided an additional moisture supply in the lower positions of each plot leading to higher ETa, increased crop biomass and yield than at the higher positions of the same plot (Table 3). Grain yield tended to be higher in the lower positions of each plot in periods of shallow water table levels (<2.5 m at MS and TS) ($R^2 = 0.33$, $p < 0.05$, $n = 19$), likely as the result of timely groundwater contributions.

Corn sown in the toe slope plot during the 2001–2002 growing season accumulated 221 kg N ha^{-1} at the high zones and 259 kg N ha^{-1} at the low zones of the plot (corresponding grain yields were 9.8 and 12.3 Mg ha^{-1}). Soil N supply (nitrate content at sowing–nitrate content at harvest) and fertilizer N were insufficient to satisfy the crop's demand and N upflow from phreatic groundwater contributed with 7–8 and 15–29% of the crop's requirement at the high and low topographic positions, respectively (Table 4).

4. Discussion

Throughout a 10-year period we detected a sharp increase of nitrate concentration in phreatic groundwater at the low topographic position of an agricultural landscape of the Rolling Pampas. This change, which was absent at higher positions, was not directly associated with drainage and leaching events but linked to water table rise. Our results support the idea that higher nitrate transport rates from recharge zones to lowlands, favored by stronger hydraulic gradients, and local concentration of solutes (and nitrate) triggered by groundwater consumption by crops, were the mechanisms explaining the observed nitrate concentration spikes.

When the water table was deep, downward water transport (ecosystems to aquifer) was the predominant flux and the primary pathway of N inputs to groundwater, with crop-fallow switches influencing the timing of that exchange. Under these situations, there was a positive correlation between nitrate concentrations in percolating water and in groundwater, with increasing lags as the depth to groundwater increased. The development of a shallow water table across different landscape units following a high rainfall period, produces changes in groundwater flow direction and velocity (Legout et al., 2007; Molenat et al., 2008) and establishes a hydrological connection between upland and lowland domains that affect nitrate and chloride transport (Ocampo et al., 2006). With a rising water table, groundwater flow direction in the saturated water table fluctuation zone changes from vertical (as classically observed in unsaturated conditions) to horizontal and the hydraulic gradient between upland and lowland increases, strengthening the hydrological connection. Nitrate loss from deep soil layers in higher topographic positions could have been the result of removal and lateral transport to lowland positions, following the rise of water table levels and hydraulic gradients. Water loss through run-off is low with average rain but increases during rainy periods and could contribute to increase the lowlands N load. However, Mugni et al. (2005) found that nitrate concentration decreased in Pampasic streams in response to rain events due to dilution with N-poor run-off water.

Although highly rainy periods may stimulate recharge and dilution of phreatic groundwater (Legout et al., 2007), we found rising chloride concentrations at the lowest topographic position during the period of maximum rainfall, an indication that rising water tables promoted evaporative discharge and solute concentration. Chloride is an ideal solute to trace evaporative concentration since uptake by plants is low and local inputs from rock weathering negligible. The arrow in Fig. 2C shows that at the maximum ET-induced water upflow from groundwater at TS chloride concentration increased 3-fold (from 85 mg l^{-1} on October 01 to 284 mg l^{-1} on November 01) while NO_3-N concentration was almost maintained (from 10 to 12 mg l^{-1} in the same period). An increase in the Cl/NO_3 ratio suggests selective nitrate removal, driven by non-exclusive processes such as crop uptake and denitrification. Although our results show how corn benefited by the use of phreatic water and nitrate at TS, our data did not allow us to constrain the net effect of N uptake on groundwater nitrate concentrations. Denitrification generally occurs in fully saturated riparian floodplains and underlying shallow groundwaters with long residence times (Molenat et al., 2008). Our lowest topographic position (TS) is on an extended toe slope approximately 1500 m away from the main stream and our results show rapid water circulation in periods of high water table levels, suggesting that plant uptake may have been the predominant nitrate removal process. However, without detailed chemical and isotopic observations we can only speculate that denitrification played a minor role on groundwater composition.

Upward water flow from shallow water tables can be a significant component in the root zone water balance of cropping systems that lowers the risk of nutrient losses (Hurst et al., 2004). According to our estimates, in periods of maximum groundwater consumption, a corn crop in the low topographic position obtained approximately half of its water needs and one fourth of its N requirement from groundwater. The magnitude of the upflow depends on the water table depth, soil hydraulic properties, plant characteristics such as root length and net water demand (Thorburn, 1997). Other deep-rooted crops like lucerne and sugarcane have also been reported to uptake a large proportion of their water requirements from shallow, fresh water tables (Hurst et al., 2004; Zhang et al., 1999). Groundwater can move into the root zone through capillary upflow or be directly extracted by the roots. The occurrence of one process or the other depends on the proximity of roots to the water table and generates important differences in the magnitude of the upflow. The broad range of our upflow estimation resides in the uncertainty of water table depths interpolated between some measurements and the fact that small fluctuations around the maximum rooting depth determine the prevalent upflow mechanism. According to the N balance completed for corn in the toe slope plot during 2001–2002, when the upward flows were maximum, N contributions from soil, fertilizer and groundwater were insufficient to satisfy N requirements. This analysis assumed passive N uptake from groundwater and attributes the missing N source to net mineralization of soil organic N. The difference may be explained by higher than expected mineralization rates at the lower position of the plot promoted by higher soil moisture with a fluctuating water table level, and/or active N uptake from groundwater by the crop.

Precipitation patterns are becoming more variable, with more occurrences of extreme rainy periods and drought in recent decades, and model projections indicate that this trend will continue (Easterling et al., 2000). Increases in water flow through agricultural watersheds due to changes in precipitation may flush more nitrate and other nutrients through groundwater flow into streams reducing N retention in terrestrial ecosystems (Kane et al., 2008; Molenat et al., 2008). Groundwater use by crops should therefore be viewed as potential "second opportunity" to use water and nitrogen that could otherwise contribute to water resources degradation.

5. Conclusion

This study supports the idea that higher nitrate transport rates from uplands to lowlands, favored by stronger hydraulic gradients, and local concentration of solutes triggered by crop groundwater consumption, were the mechanisms explaining the nitrate concentration spikes in shallow phreatic groundwater at a low topographic position of an agricultural landscape of the Rolling Pampas. Hydrological shifts associated with water table level fluctuations affected the role of groundwater as a N transport agent in the landscape, altering the vertical direction of N exchange in the crop-soil-groundwater continuum, as well as the horizontal arrangement of recharge and discharge zones. Crop ecosystems in lower landscape positions behaved transiently as water and nutrient sinks or sources during periods of high and low water table levels, respectively. During dry to normal periods most of the Rolling Pampas landscapes function as typical uplands where water flows vertically to deep water tables and discharges only into streams. Wet periods, however, raise water table levels engaging lower areas into evaporative discharge and promoting N redistribution processes within the landscape. Agricultural ecosystems in low topographic positions could benefit from this additional resource, controlling at the same time groundwater quality. Awareness and understanding of this mechanism could help improve agricultural productivity and water resources through sound management responses to water table rises.

Acknowledgements

We wish to thank Juliana Torti, Jimena Dalpiaz and Leticia García for laboratory assistance; Marcela Bilos, Adolfo Sosa, Alberto Rondán and Fernando Rimatori for assistance with field work and Lidia Reynoso for her valuable review of the manuscript. Farm owners and manager Luis Aguirre provided access to the plots and helpful information. We gratefully acknowledge the Agencia Nacional de Promoción Científica y Tecnológica (PICT 00-01 08-08054) and the Inter American Institute for Global Change Research (CRN 2031) for providing funding for this research.

References

Abrol, I.P., Yadav, J.S.P., Massoud, P.I., 1988. Salt-affected soils and their management. FAO Bulletin No. 39. Rome, Italy, 131 pp.

Austin, A.T., Piñeiro, G., Gonzalez-Polo, M., 2006. More is less: agricultural impacts on the N cycle in Argentina. Biogeochemistry 79, 45–60.

Easterling, D.R., Meehl, G.A., Parmesan, C., Changnon, S.A., Karl, T.R., Mearns, L.O., 2000. Climate extremes: observations, modeling, and impacts. Science 289, 2068–2074.

Freeze, R.A., Cherry, J.A., 1979. Groundwater. Prentice Hall, Englewood Cliffs, NJ.

Galloway, J.N., Aber, J.D., Erisman, J.W., Seitzinger, S.P., Howarth, R.W., Cowling, E.B., Cosby, B.J., 2003. The nitrogen cascade. BioScience 53, 341–356.

Hall, A.J., Rebella, C.M., Ghersa, C.M., Culot, J.Ph., 1992. Field-crop systems of the pampas. In: Pearson, C.J. (Ed.), Field Crop Ecosystems. Ecosystems of the World. Elsevier, Amsterdam, pp. 413–450.

Högberg, P., 2001. Interactions between hillslope hydrochemistry, nitrogen dynamics, and plants in Fennoscandian boreal forest. In: Schulze, E.-D., Heimann, M., Harrison, S., Holland, E., Lloyd, J., Prentice, I.C., Schimel, D. (Eds.), Global Biogeochemical Cycles in the Climate System. Elsevier, pp. 227–233.

Hurst, C.A., Thornburn, P.J., Lockington, D., Bristow, K.L., 2004. Sugarcane water use from shallow water tables: implications for improving irrigation water use efficiency. Agric. Water Manage. 65, 1–19.

Jobbágy, E.G., Jackson, R.B., 2004. Groundwater use and salinization with grassland afforestation. Global Change Biol. 10, 1299–1312.

Jobbágy, E.G., Jackson, R.B., 2007. Groundwater and soil chemical changes under phreatophytic tree plantations. J. Geophys. Res. 112, G02013, doi:10.1029/2006JG000246.

Kane, E.S., Betts, E.F., Burgin, A.J., Clilverd, H.M., Crenshow, C.L., Fellman, J.B., Myers-Smith, I.H., O'Donnell, J.A., Sobota, D.J., Van Verseveld, W.J., Jones, J.B., 2008. Precipitation control over inorganic nitrogen import–export budgets across watersheds: a synthesis of long-term ecological research. Ecohydrology 1, 105–117.

Keeney, D.R., Nelson, D.W., 1982. Nitrogen-inorganic forms. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties. 2nd edition. Soil Science Society of America and American Society of Agronomy, Madison, WI, pp. 643–698.

Legout, C., Molenat, J., Aquilina, L., Gascuel-Odoux, C., Faucheux, M., Fauvel, Y., Bariac, T., 2007. Solute transfer in the unsaturated zone-groundwater continuum of a headwater catchment. J. Hydrol. 332, 427–441.

Leonard, R.A., Knisel, W.G., Still, D.A., 1987. GLEAMS: Groundwater Loading Effects of Agricultural Management Systems. ASAE 30, 1403–1418.

Michelena, R.O., Irurtia, C.B., Pittaluga, A., Vavruska, F., Sardi, M.E., 1988. Degradación de suelos en el sector norte de la Pampa Ondulada. Ciencia del Suelo 6, 60–66.

Molenat, J., Gascuel-Odoux, C., Ruiz, L., Gruau, G., 2008. Role of water table dynamics on stream nitrate export and concentration in agricultural headwater catchment (France). J. Hydrol. 348, 363–378.

Mugni, H., Jergentz, S., Schultz, R., Maine, A., Bonetto, C., 2005. Phosphate and nitrogen compounds in streams of Pampean Plain areas under intensive cultivation (Buenos Aires, Argentina). In: Serrano, L., Golterman, H.L. (Eds.), Proc. 4th Intl. Symposium Phosphates in Sediments. Backhuys Publishers, The Netherlands, pp. 163–170.

Nosetto, M.D., Jobbágy, E.G., Jackson, R.B., Sznaider, G.A., 2009. Reciprocal influence of crops and shallow ground water in sandy landscapes of the Inland Pampas. Field Crops Res. 113, 138–148.

Ocampo, C.J., Sivapalan, M., Oldham, C., 2006. Hydrological connectivity of upland-riparian zones in agricultural catchments: implications for runoff generation and nitrate transport. J. Hydrol. 331, 643–658.

Paoli, C., Giacosi, R., 2003. Características hidrológicas de la llanura pampeana central oeste. In: Maiola, O.C., Gabellone, N.A., Hernández, M.A. (Eds.), Inundaciones de la Región Pampeana. Editorial de la Universidad Nacional de La Plata, La Plata, Argentina, pp. 73–86.

Portela, S.I., Andriulo, A.E., Sasal, M.C., Mary, B., Jobbágy, E.G., 2006. Fertilizer vs. organic matter contributions to nitrogen leaching in cropping systems of the Pampas: ^{15}N application in field lysimeters. Plant Soil 289, 265–277.

Raes, D., Deproost, P., 2003. Model to assess water movement from a shallow water table to the root zone. Agric. Water Manage. 62, 79–91.

Raes, D., 2004. UPFLOW—water movement in a soil profile from a shallow water table to the topsoil, Reference Manual. K.U. Leuven University, Leuven, Belgium. , http://www.biw.kuleuven.be/lbh/lsw/iupware/downloads/elearning/software/upflow_manual.pdf.

Sainato, C., Galindo, G., Pomposiello, C., Malleville, H., de Abelleyra, D., Losinno, B., 2003. Electrical conductivity and depth of groundwater at the Pergamino zone (Buenos Aires Province, Argentina) through vertical electrical soundings and geostatistical analysis. J. S. Am. Earth Sci. 16, 177–186.

Salama, R.B., Otto, C.J., Fitzpatrick, R.W., 1999. Contributions of groundwater conditions to soil and water salinization. Hydrogeol. J. 7, 46–64.

Salmerón-Miranda, F., Båth, B., Eckersten, H., Forkman, J., Wivstad, M., 2007. Aboveground nitrogen in relation to estimated total plant uptake in maize and bean. Nutr. Cycl. Agroecosyst. 79, 125–139.

Tanco, R., Kruse, E., 2001. Prediction of seasonal water-table fluctuations in La Pampa and Buenos Aires, Argentina. Hydrogeol. J. 9, 327–415.

Thorburn, P.J., 1997. Land management impacts on evaporation from shallow saline water tables. In: Taniguchi, M. (Ed.), Subsurface Hydrological Responses to Land Cover and Land Use Changes. Kluwer Academic Publishers, Boston, pp. 6–71.

Tóth, J., 1999. Groundwater as a geologic agent: an overview of the causes, processes, and manifestations. Hydrogeol. J. 7, 1–14.

Viglizzo, E.F., Joggágy, E.G., Carreño, L., Frank, F.C., Aragón, R., De Oro, L., Salvador, V., 2009. The dynamics of cultivation and floods in arable lands of Central Argentina. Hydrol. Earth Syst. Sci. 13, 491–502.

Weiler, M., McDonnell, J.J., 2006. Testing nutrient flushing hypotheses at the hillslope scale: a virtual experiment approach. J. Hydrol. 319, 339–356.

Zhang, L., Dawes, W.R., Slavich, P.G., Meyer, W.S., Thorburn, P.J., Smith, D.J., Walker, G.R., 1999. Growth and ground water uptake responses of lucerne to changes in groundwater level and salinity: lysimeter, isotope and modelling studies. Agric. Water Manage. 39, 265–282.