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Shallow groundwater dynamics in the Pampas: Climate, landscape and crop choice effects

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ABSTRACT

Depending on its depth from the soil surface, shallow groundwater can represent a valuable water resource to alleviate droughts, or a stress agent that causes waterlogging and flooding in rainfed crops. Groundwater depth varies across space, following landscape topographic features; through time, accompanying climate fluctuations; and may also shift in both dimensions in response to crop choice. We evaluated the contribution of climate, topography and crop choice on the variability of groundwater depth in rainfed systems of western Pampas, throughout a five year period of extreme precipitation fluctuation (2008–2013). Sixteen permanent monitoring wells were installed in four different topographic settings along the smoothly rolling landscape, covering the three phases of a maize–soybean–wheat/soybean rotation, common in the region. Water table dynamics, measured at weekly to monthly intervals, was very similar across landscape positions, with a range of depth from the surface of −0.2 (flood) to 1.8 m and 1.8–4.4 m in the lowest and highest positions, respectively. At the inter-annual scale, water table fluctuations were predominantly dictated by climate variability with no effect due to the implanted crop. Only at the intra-annual scale, crop choice appeared as a relevant control, with wheat–soybean flattening the spring level rises and summer drops repeatedly found under maize and soybean single crops. Daily meteorological data and remote sensing estimates of live and dead crop cover were used to simulate transpiration demand and soil evaporation. As the balance between precipitation and crop evapotranspiration was positive/negative, watertables raised/dropped 0.21 cm mm^{-1} (n = 80, R^2 0.32) and 0.22 cm mm^{-1} (n = 1092, R^2 0.31) at inter and intra-annual scales, respectively. While crop choice may influence water table levels within a growing season, it has only a subtle effect on year to year fluctuation. With the explored annual crop options, farmers in the Pampas could reduce spring flooding risk when sowing double crops but cannot have a substantial effect on the longer term dynamics of the water table.

1. Introduction

The water table may offer an opportunity or a threat for dryland agriculture in flat sedimentary landscapes with widespread shallow groundwater bodies. It represents an opportunity because it can provide much of the water required by crops, ameliorating the negative effects of droughts. Yet, it can also become a threat if it increases the risk of waterlogging and flooding and reduces the productivity of crops and the possibility of farmers to cultivate the land (Aragón et al., 2011; Nosetto et al., 2009). The yield of grain crops increases exponentially as the water table approaches the root zone (Nosetto et al., 2009), enabling capillary water supply from the saturated zone (Ayars et al., 2006; Kang et al., 2001). However, when the water table creates saturated conditions within the root zone, yields fall sharply (Mueller et al., 2005; Nosetto et al., 2009). In very flat and sub-humid territories, water tables can eventually reach the surface and flood large fractions of the landscape for periods of months or even years (Aragón et al., 2011; Kuppel et al., 2015). These flooding processes reduce land availability, restrict the opportunity of field labors, and hamper transportation logistics (Viglizzo et al., 2009). In landscapes where widespread shallow water tables exist, the need to understand the drivers of

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Table 1
Ranges of sowing and harvest dates and crop yields along the five years around the 16 groundwater monitoring wells at Magdala farm.

Crop	Phenology		Yields
	Sowing dates	Harvest dates	tn ha^{-1}
Wheat	June 04–July 09	December 2–December 23	1.5–6.9
2° Soybean	December 10–January 2	April 30–June 01	1.3–3.0
Maize	September 25–October 15	March 28–May 17	7.5–12.5
Soybean	October 23–November 15	March 08–May 01	3.1–4.9

its fluctuating levels becomes critical for agricultural planning and hydrological management.

Water tables are often shallow in flat sedimentary landscapes (Fan et al., 2013), where vertical water flows prevail and horizontal surface and groundwater transport tend to be slow and local. As a result, local water excess (precipitation > evapotranspiration) often translates into raising water table levels. Rainfall variability at both seasonal and annual scales largely influences water table dynamics (Portela et al., 2009), with humid periods (precipitation > evapotranspiration) leading to waterlogging episodes and flooding over significant proportions of the landscape (Aragón et al., 2011; Kuppel et al., 2015). The subtle topographic differences within flat landscapes often explain spatial water table depth patterns (Gleeson et al., 2011). In addition to climate and topography, vegetation is an important driver of water flows and water table level in flat plains (Jobbágy and Jackson, 2007; Nosetto et al., 2013). The seasonality and magnitude of leaf area and canopy structure, together with rooting depth and waterlogging tolerance of the vegetation, influence the rate and timing of evapotranspiration. As a result, vegetation characteristics do not only shape recharge rates (deep drainage below the rooting zone) but also the intensity and depth at which groundwater is consumed. For instance, perennial pastures, which in the Pampas grow all year-round and have deeper root system than annual crops, can consume almost twice as much water than annual crops (Nosetto et al., 2012). Within annual crop agricultural systems, there are also important differences in the seasonality and magnitude of water consumption that may be taken into account in the choice of crops and rotations to regulate water table levels.

Whether water table depths from the ground can be managed and kept within the optimal range that maximizes crop access to groundwater (e.g., around 1.5 m for soybean and maize; Nosetto et al., 2009) while simultaneously reducing waterlogging/flooding is not clear. Although, land cover decisions could contribute to this purpose in flat plains (Nosetto et al., 2012), actual water table levels also depend on the less controllable and/or predictable effects of rainfall variation and topography. Consequently, a full understanding of how human land cover decisions affect water table dynamics, in interaction with these other environmental factors, is required to explore possibilities of managing levels. The goal of this work was to assess the influence of three key factors (climate, topography and crop choice) on the dynamics of water table levels in the flat plains of the Pampas. This information is crucial in order to explore the possibilities of managing groundwater levels through regular farming decisions. For this purpose we analyzed five years (2008–2013) of periodic water table level observations in an array of 16 wells specially designed to cover different topographic positions and crops within a typical farm in the Western Pampas of Argentina. Field work was complemented with water balance estimates fed by local climatic data and remote sensing information on vegetation cover.

2. Materials and methods

2.1. The study area

Our work is focused on the western fraction of the Argentine Pampas (Western Pampas). The Argentine Pampas is one of the main agricultural regions in the world, and the Western Pampas makes a particularly relevant contribution to its total production (Calviño and Monzón, 2009). This area offers a very interesting setting to explore the interaction between fluctuating groundwater levels and crops. First, the landscape is extremely flat presenting regional slopes <0.1% (Jobbágy et al., 2008). Second, there is a strong climate variability on inter-annual (Goddard et al., 2001) to inter-decadal scales (Boulanger et al., 2005; Rusticucci and Penalba, 2000). Third, neither groundwater pumping nor drainage infrastructure are important in the region (Menéndez et al., 2012), and floods and droughts have been alternately reported since the colonial times in the region (Moncaut, 2001; Kuppel et al., 2015). At present, annual field crops occupy most of the area in the Western Pampas and the typical rotation involves soybean, maize and double cropping of wheat followed by a short-cycle soybean. However, before the nineties pasture-crop rotations were more common and before then, native grasslands and pastures were the dominant cover. During the last three decades, livestock production systems become increasingly replaced by agriculture in the Pampas (Paruelo et al., 2005).

The study was conducted at Estancia Magdala (36.08 S, 61.70 W), a farm located in the Western Pampas (Soriano et al., 1991), near the town of Pehuajó (Buenos Aires, Argentina). The climate is

Table 2
Absolute elevation (meters above sea level) and geographic coordinates (decimal degrees) of groundwater monitoring wells, indicating their lansdcape position (H: highland, IH: intermediate highland, IL: intermediate lowland, L: lowland), crop (mz: maize, sb: soybean, ws: double crop of soybean after wheat in the first four seasons and barley in 2012), and sowing dates (Julian day, first and second when double crop) through time.

Landscape position	#	Height (masl)	Lat°	Lon°	2008	2009	2010	2011	2012
H	1	96.4	−36.0417	−61.7006	mz 274	ws 171–350	mz 277	sb 303	sb 310
H	2	95.3	−36.0400	−61.7409	mz 285	ws 173–357	mz 269	sb 298	ws 177–345
H	3	94.1	−35.9999	−61.7439	sb 302	sb 296	ws 157–353	mz 269	sb 319
H	4	93.3	−35.9854	−61.7597	ws 156–348	mz 278	sb 309	ws 177–363	mz 289
IH	5	94.4	−36.0386	−61.6953	mz 274	ws 171–350	mz 277	sb 303	sb 310
IH	6	94.1	−36.0392	−61.7415	mz 285	ws 173–357	mz 269	sb 298	ws 177–345
IH	7	93.5	−35.9991	−61.7427	sb 302	sb 296	ws 157–353	mz 269	sb 319
IH	8	92.7	−35.9839	−61.7622	ws 156–348	mz 278	sb 309	ws 177–363	mz 289
IL	9	94.4	−36.0402	−61.6980	mz 274	ws 171–350	mz 277	sb 303	sb 310
IL	10	93.8	−36.0382	−61.7424	mz 285	ws 173–357	mz 269	sb 298	ws 177–345
IL	11	93.8	−36.0200	−61.7068	mz 274	sb 296	ws 173–361	mz 272	sb 311
IL	12	91.8	−35.9813	−61.7619	ws 156–348	mz 278	sb 309	ws 177–363	mz 289
L	13	93.0	−36.0406	−61.7403	mz 285	ws 173–357	mz 269	sb 298	ws 177–345
L	14	92.4	−35.9977	−61.7433	sb 302	sb 296	ws 157–353	mz 269	sb 319
L	15	91.2	−35.9820	−61.7633	ws 156–348	mz 278	sb 309	ws 177–363	mz 289
L	16	91.0	−35.9668	−61.7655	sb 306	ws 190–357	mz 277	sb 309	sb 320

temperate subhumid (Hall et al., 1992), with a mean annual precipitation and a standard deviation of 971 ± 243 mm for the last 42 years at the farm, with two thirds of the rain occurring during the austral spring and summer months. For the same period, mean daily average temperature at Pehuajó (weather station of the National Meteorological Service situated 29 km north of the study sites) vary from 8.6 °C at the end of July to 23.0 °C at the beginning of January. Once every five years, frost was registered after October 18th and,with the same frequency, before April 17th. Annual reference evapotranspiration, calculated using FAO Penman–Monteith equation (Allen et al., 1998), averages1161 ± 107 mm, with meandaily rates ranging from 5.8 mm d^{-1} at the end of December and 0.9 mm d^{-1} at the end of June. The landscape displays a slightly rolling wind-shaped topography with local (~2 km) slopes of 0.5% and as much as two meters of ground-level differences between uplands and lowlands. Regional and local flooding frequently affect lowlands, covering as much as 30% of the landscape during the largest recorded flooding cycle between 2000 and 2002 (Aragón et al., 2011). Soils developed on loess material of loamy to sandy loam texture and are predominantly Hapludolls (INTA, 1989). Agriculture spreads all over the topographic positions, with the exception of the extreme lowlands (Haplaquolls, Natraquolls, and Natraqualfs) and the highest crests (Udipsaments), where permanent limitations such as waterlogging and/or soil salinity, or low water retention and vulnerability to erosion, respectively, prevent cultivation.

2.2. Field and remote sensing observations

For the study period, which encompassed five full growing seasons between 2008 and 2013, we performed periodic field observations of water table depth from the ground in 16 permanent monitoring wells. In addition, we used remote sensing observations to characterize water demand around each well and to quantify the flooded area around the farm. Our observations focused on soybean, maize and wheat, which are the main crops sown in the farm and in the surrounding region. Most of the farm is under continuous no-till agriculture, also following the regional trend. Typically, most management units host a three-year rotation with the sequence maize–soybean–wheat/soybean double crop, what results in one third of the whole farm being occupied by each one of these crops every year. Departures from this target may occur in response to flooding events, however, with some of the maize plots being replaced by soybean in those situations. Maize and soybean are sown in spring, one month apart, and wheat is sown in late autumn, followed by the second soybean crop immediately after wheat harvest, in early summer (Table 1). Usually, fallow periods are completely free of weeds and the crops reach full cover and high yields for what is considered typical in the region (Table 1).

The sixteen permanent monitoring wells were distributed across different landscape positions in six paddocks (Table 2). We defined four relative positions: highlands (H) which are the high and smoothly convex areas located just below the crests, lowlands (L) which are the lower and smoothly concave areas just above the extreme bottom of the lowlands, and intermediate-high (IH) and intermediate-low (IL) positions, with a very gentle slope, located on relatively well drained and poorly drained locations, respectively. Ground elevation differences between H and L averaged 2.0 m. Overall, farm sites covered a larger vertical gradient (91.0–96.4 meters of altitude above sea level) resulting from the overlap of local and regional level gradients. Monitoring wells were 0.1–10 km apart each other (coordinates are shown in Table 2). We assigned four wells to each landscape position, aiming to cover each year the three crop modules of the sequence. PVC pipes (10-cm outer diameter), extending 0.5–1 m below the water table and 0.3–1.2 m above the ground surface, were closely fitted inside each borehole. The upper pipe opening was covered with a PVC cap. To avoid rain water moving down through the pipe wall, the PVC pipe was covered at the ground level first with a thin polyethylene film and then with soil. Groundwater depth was manually measured at 7–77 day intervals (26 ± 12 days), with higher frequency corresponding to spring-summer periods.

We estimated green vegetation and dead biomass covers around each monitoring well as an input of our water balance model (see detail into the next section, Fig. 1), both quantified through remote sensing. The green cover fraction (GCF) was estimated using the wide dynamic range vegetation index (WDRVI, Gitelson, 2004) computed from MODIS images (Product MOD09Q1, 8 day interval, 250 m pixel size). Among the different vegetation indexes used for green vegetation cover estimation, WDRVI has proved to be one of the most accurate, particularly in the case of annual crops (Gitelson, 2013). Compared to NDVI, the most commonly used vegetation index, WRDVI showed higher sensitivity to moderate-to-high leaf area index values. We computed WRDVI for each pixel where monitoring wells were located. In some cases, because of the large pixel size, the targeted pixel included more than one management so a neighboring pixel with a full coverage of the target crop was used. An empirical linear relationship between WDRVI and GCF,similar to the one proposed by Gitelson (2013) for maize and soybean crops in Nebraska, was determined. Percentiles 1 and 99 of the WDRVI values for all the wells along the five growing seasons were considered as representative of null (WDRVI ≤ 33.8) and complete green cover fraction (WDRVI ≥ 95.8), respectively. GCF of days without remotely sensed data was obtained by linear interpolation of GCF of the two closest available dates.

Stubble and standing dead cover fraction (DCF) were estimated using the death fuel index (Cao et al., 2010) computed from MODIS images (Product MOD09A1, 8 day interval, 500 m pixel size). The dead fuel index is able to capture the cover of dead plant biomass in three-component mixtures (photosynthetic vegetation, soil and dead plant biomass) based on reflectance data from MODIS bands 1, 2, 6 and 7. Because of the pixel size, we characterized the dead biomass fraction at the paddock scale and we assigned the same value to all monitoring wells located in the same plot. Additionally, to reduce the noise generated by soil surface water at the time of satellite passage, we used the minimum computed value of dead biomass fraction of two consecutive dates.

Finally, we quantified the flooded area for the entire farm for the study period through visual classification of Landsat 7 images. For this purpose, we selected one cloud-free image per year corresponding to the spring season, between October 5th and November 12th. Flooded area classification was performed by a single-band density slicing using the mid-infrared band 5. This band has proved to have high sensitivity for the detection of water bodies (Johnston and Barson, 1993; Frazier and Page, 2000). Areas of the farm with missing data, caused by the Scan Line Corrector malfunctioning, were excluded from the calculation of flooding coverage.

2.3. Water balance estimates

We computed the water balance between precipitation inputs and evapotranspiration outputs at each monitoring well in order to analyze its relationship to water table fluctuations. It balances observations into a simple functional modeling routine (Fig. 1) using a daily time step that was integrated at the same intervals for which consecutive water table level observations were available. Precipitation (Pp: Fig. 2a) was obtained from a rain gauge located at the farm. A modified version of the FAO dual crop coefficient approach (Allen et al., 1998), adapted to apply remote sensing data (Nosetto et al., 2012), was used to estimate crop evapotranspiration. Reference potential evapotranspiration (ETo: Fig. 2a) was computed according to FAO Penman–Monteith

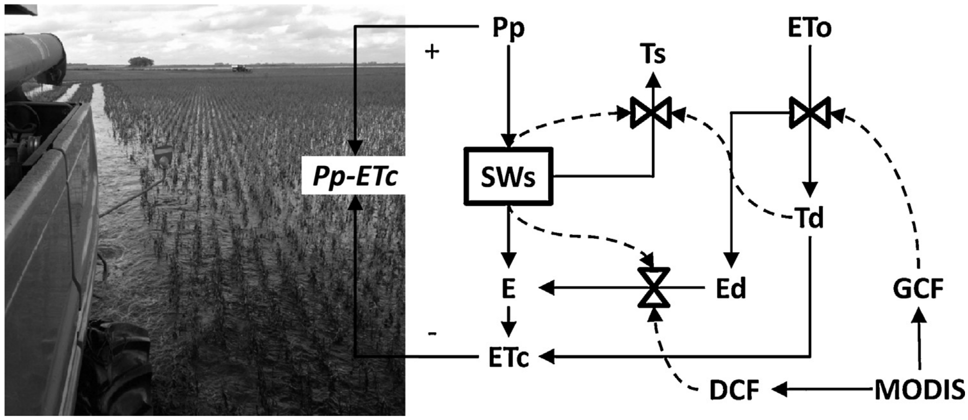

Fig. 1. Water balance (Pp-ETc) considering daily crop evapotranspiration (Etc: negative) and daily precipitation (Pp: positive). Transpiration demand (Td) was computed from reference potential ET (ETo) and green cover fraction (GCF) from MODIS images. Evaporation (E) results from scaling evaporation demand (Ed) by the dead cover fraction (DCF) and soil water content of the soil surface layer (SWs). SWs is recharged by daily precipitation and consumed by E plus the transpiration attainable in this horizon (Ts), which depends on Td and SWs. Full and dashed lines respectively represent water (mm) and information fluxes. Photo: a soybean crop being harvested during the autumn 2012 flooding close to a monitoring well in a lowland position. The photo also illustrates the flat landscape of the inland Pampas.

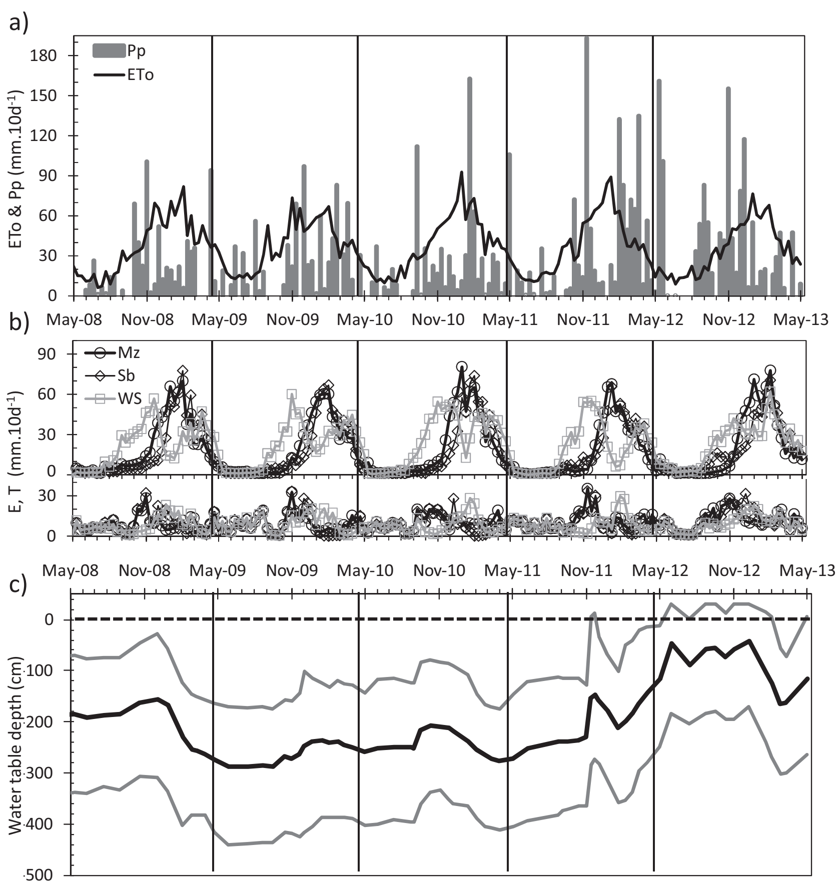

Fig. 2. (a) Potential water demand of the reference crop (ETo: mm in 10 days, line) and precipitation (Pp: mm in 10 days, bars). (b) Soil evaporation (E: lower panel) and transpiration (T: upper panel) of Maize (Mz: circles), soybean (Sb: diamonds), and wheat–soybean double crop (WS: squares). (c) Average (black line), minimum and maximum (gray lines) water table depth (cm).

equation (Allen et al., 1998), using daily total radiation (estimated by the Angström–Prescott method), maximum and minimum temperatures, average dew point temperature and wind velocity from the Pehuajó meteorological station. Daily transpiration (T: Fig. 2b) at each well was calculated as the product of ETo and the crop transpiration coefficient (Kcb). To estimate Kcb, the maximum value of 1.1 applied to all crops (Allen et al., 1998; Hsiao et al., 2009; Mercau et al., 2007) was scaled by the satellite green cover estimates (Nosetto et al., 2012) and adjusted to account for the micro-advection effect of partial cover in row crops (Steduto et al., 2009; Villalobos and Fereres, 1990). In the short term (i.e., days), our *T* values may overestimate real crop transpiration if the soil water content is not enough to satisfy crop water demand, a not simulated process in our simple model. However, this overestimation should be small at the temporal scale of weeks or one month that we used, since stresses would reduce, in those periods, green leaf area through limited expansion and/or accelerated senescence (Lizaso et al., 2003), as well as our remote sensing-based estimates of *T*.

Soil evaporation (E: Fig. 2b) was calculated using a two stage model approach,where evaporation is limited by energy in the first stage and progressively limited by water transport to the soil surface layer in the second stage (Raes et al., 2009; Ritchie, 1972). Evaporation demand (Ed) was estimated by multiplying ETo by 1.1 (Raes et al., 2009) and then subtracting the crop transpiration. Given that a fraction of the evaporative demand is intercepted by stubble and standing dead biomass and dissipated as sensible heat without reaching the soil surface layer, we assumed such a loss as proportional to the 50% of stubble and standing dead covers (Raes et al., 2009). Evaporation calculations used the first (energy limited) or second stage (water limited) rules depending on soil water content in the surface soil layer (Fig. 1). Based on the texture and organic matter content of surface soil layers in the farm, we assume 10 mm of cumulative evaporation amount in the first stage, and a water content of the surface layer in the upper and lower limit of 50 and 24 mm, respectively (Ritchie and Crum, 1989). We assumed that evaporation rate (E) was equal to Ed only when soil water content was above the threshold separating the first and second stage (40 mm), thereafter Ed was multiplied by the fourth power of the ratio of actual water content and difference between the threshold and air dry water content (50% of lower limit; i.e., 12 mm) to obtain E (Raes et al., 2009). Before computing evaporation, daily transpiration from the soil surface layer was determined as the minimum between Tp and 10% of the water content above the lower limit threshold in the horizon (Dardanelli et al., 1997). The surface horizon was replenished by daily rainfall until its upper water holding limit. Since almost all precipitation events that would have intensities or depths large enough to cause runoff would probably replenish the water content of the topsoil layer to field capacity, we ignored runoff to evaporation calculation (Allen et al., 1998; Dardanelli et al., 2010).

2.4. Data analysis

We performed analyses of variance (ANOVA) with a factorial design (Montgomery, 2008) in order to quantify the relative weight of the influence of the particular year condition, season of the year, landscape position, and crop choice on water table level shifts. The main purpose of these analyses was to explore the relative contribution of these factors and their interactions and not to assess the statistical significance of their effects. It is important to note that complete randomization and temporal and spatial independence among level measurements were not warranted by our study, limiting statistical inference. Firstly, we evaluated inter-annual water-table depth shifts (positive values representing groundwater levels getting deeper) between two consecutive years (starting in May 1st and ending in April 30th of the following year, the time period normally spanned by the agricultural cycle), in response to the effects of "year" (5 levels: 2008–2013), "landscape position" (4 levels: highland, intermediate-high, intermediate-low, lowland), and "crop" choice (3 levels: maize, soybean, wheat–soybean double crop). For this purpose, water table level shifts at the inter-annual scale were computed for each well as the difference between the depth in the first day of the current year (May 1st) and the depth on the same date of the previous year. Additionally, to evaluate groundwater level shifts with an intra-annual resolution we performed the same analysis but considering fixed periods within the year (8 "period" levels, with boundaries within the following date ranges: June 7–July 23, August 20–September 1, October 10–November 2, November 30–December 5, December 20–January 11, February 01–February 05, March 8–March 10 and April 24–May 02). *F* and *P* values were used to assess the consistency of each sources of variation, whereas the contribution to the total treatment sum of squares (i.e., excluding residuals; de la Vega et al., 2001) of each factor and their interaction was used to estimate their relative weight as drivers. These analyses of variance described how water table level shifts, regardless of the absolute initial position of the water table, responded to stochastic vs. predictable controls. Stochastic variation was captured by "year" effects and their interactions with the rest of the variables. Predictable variation stemmed from the effects of all the other variables and their interactions except those with "year". Predictable time and space effects were represented by "period" (representing fixed seasonality) and "landscape position" (different fixed environments). The predictable effects of crop choice influencing water table level shifts directly, or in interaction with the other predictable variables, was captured by the "crop" effect and its interaction with "landscape position" and "period", whereas the modulation of stochastic "year" effects by crop choice was captured by the interaction of "crop" with "year".

We used linear regression analysis (Stell et al., 1980) to evaluate the relationship between groundwater level changes and rainfall and evapotranspiration at intra- and inter-annual scales. Depth change in each period was related to accumulated rainfall, evapotranspiration and the difference between them (water balance). Additionally, we analyzed the relationship between regression models residuals and the initial groundwater depth of each period.

3. Results

Water table levels had important inter and intra-annual fluctuations. The dynamics of water table fluctuations was very similar among landscape positions but with significant differences in the absolute depth (Fig. 2c). Water-table depth in the highest landscape positions (soil surface at 93.3–96.4 m above sea level, Table 2) ranged from 1.8–4.4 m, while at the lowest positions (91.0–93.0 masl, Table 2) it fluctuated between −0.2 (flooding) and 1.8 m. There was also a remarkable year to year shift in water table depth, with the highest inter-annual drop and raise in any given well reaching 1.1 and 1.8 m, respectively. Together with the strong water table rise that occurred during 2011–2012, there was an increase in the flooded area of the farm. Flooding covered 4% of the total farm area in spring of 2008, at the beginning of our study, and fluctuated thereafter between 0 and 0.3% between 2009 and 2011. During September 2012, the flooded area reached 24% of the farm, as a consequence of the high rainfall inputs of August–September but, more importantly, due to the wet conditions at the end of the previous season (summer–autumn 2012) that caused a systematic water table rise and earlier waterlogging conditions during the previous winter.

The strong temporal shifts in water table levels were mostly tied to rainfall variability rather than to variations in potential evapotranspiration (Fig. 2a). While the 2008–2009 growing season received 683 mm rainfall, being one of the two driest seasons in the last 41 years, the 2011–2012 and 2012–2013 periods approximately duplicated this figure (1153 and 1244 mm, respectively), achieving the upper quintile of historic records. Our study also encompassed shorter periods with unusual low and high rainfall. November 2008–January 2009 had the driest record for that trimester while the following period, January–March 2009, had the third driest record for that period, with 149 and 154 mm vs. mean values of 291 and 375 mm, respectively. On the other hand, the wettest March–May trimester was registered in 2012, reaching 542 mm and almost doubling the average of 279 mm. Reference potential evapotranspiration ranged from 1256 to 1394 mm year^{-1}, both extremes coinciding with the wettest and

Table 3
Analyses of variance of inter and intra-annual changes in water table level (cm) of the 3 crops (C) and 4 landscape positions (L) along the 5 years (Y) divided into 8 periods per year (P). *F*, *p*, and contribution of each factor to the total sum of square of all factors (%SS). Standard errors are shown at the bottom.

	Inter-annual			Intra-annual		
Factor	*F*	*P*	%SS	*F*	*P*	%SS
Year	292.1	**0.00**	95	73.0	**0.00**	**9**
Landscape	0.1	0.95	0	0.0	0.99	0
L Y	0.9	0.56	1	0.2	1.00	0
Crop	2.9	**0.08**	0	0.8	0.45	0
C Y	3.1	**0.02**	2	0.8	0.59	0
C L	0.4	0.87	0	0.1	1.00	0
Period				115.5	**0.00**	**26**
PY				37.0	**0.00**	**33**
P L				1.6	**0.05**	1
P C				23.7	**0.00**	**11**
Y L C	0.5	0.92	1	0.1	1.00	0
Y L P				1.5	**0.02**	4
Y C P				4.5	**0.00**	**8**
P L C				1.0	0.45	1
Y L C P				1.0	0.52	5
S.E. (cm)	**20**			**14**		

driest year respectively, showing that evapotranspiration slightly exacerbates wet/dry year contrasts.

Although the total evapotranspiration of the different covers was quite similar,there were significant differences in its seasonality and the partition between transpiration and evaporation (Fig. 2b). Transpiration was 25% greater in double-crop than in soybean (817 ± 71, 695 ± 64, 655 ± 33 mm, for double crop, maize and soybean, respectively); however, soil evaporation partially compensated these differences (314 ± 26 mm, 361 ± 40 mm and 351 ± 46 mm, for double crop, maize and soybean, respectively), reducing the overall evapotranspiration contrast to 12% (1131 ± 68, 1056 ± 72 and 1006 ± 77 mm, for double crop, maize and soybean, respectively). While under double crop the high transpiration demand of the winter cereal in spring contrasted sharply with the low one of the summer crops in their initial stages, this situation reversed in December and January, when the transition from wheat to soybean sharply reduced transpiration (Fig. 2b). Green cover fraction, as quantified by satellite, from October 1st to November 15th averaged 92 ± 14 and 13 ± 9% in wheat and summer crops, respectively. On the contrary from December 15th to February 1st these values reached 23 ± 12 and 70 ± 18%, for double and summer crops, respectively. Transpiration rates for wheat were four times higher than those for summer crops in the first period (4.1 ± 1.6, 0.9 ± 0.7 and 0.9 ± 0.7 mm day^{-1}, for double crop, maize and soybean) but less than a half in the second one (2.2 ± 1.2, 5.8 ± 1.5 and 5.0 ± 1.8 mm day^{-1}, for double crop, maize and soybean). There were high evaporation water losses when green cover was low in both periods (0.6 ± 0.5, 1.9 ± 1.2 and 1.9 ± 1.3 mm day^{-1} in the first, and 1.6 ± 1.2, 0.7 ± 0.5 and 1.1 ± 1.1 mm day^{-1} in the second period, for double crop, maize and soybean, respectively). From February 1st to May 1st, both soybean crops had in average higher green cover (64 ± 20, 42 ± 22 and 62 ± 28%, for double crop, maize and soybean) and transpiration rates (Fig. 2b) than maize. In May, just after maize and soybean harvest, high dead cover fraction (60 ± 09, 68 ± 14 and 54 ± 10%, after double crop, maize and soybean) reduced evaporation losses (Fig. 2b).

The stochastic year effect was the overriding control of the inter-annual shifts of water table levels, mainly attributable to climate variability. The "year" factor accounted for 95% of the total sum of squares (SS) (Table 3, inter-annual ANOVA). Water table levels in the 16 monitoring wells descended sharply during the dry growing season of 2008–2009 (0.9 m) and ascended even more during the wet season of 2011–2012 (1.6 m), showing relatively smaller annual shifts (<0.1 m) in the rest of the study period (Fig. 2c). The "crop" effects on annual water table level shifts were of much smaller magnitude and had no consistent pattern from year to year as shown by the significant effect of the crop × year interaction (p = 0.02). The contribution of "landscape position" to water table level shifts was almost null, highlighting that this factor in the study area influences the absolute position of groundwater but not its relative inter-annual changes (i.e., absolute levels show highly parallel fluctuations; Fig. 2c).

At the inter-annual scale, water table depth shifts were related to the annual balance between rainfall and crop evapotranspiration estimates (Fig. 3a, r = −0.73, p < 0.001, n 80). Rainfall and evapotranspiration considered independently had lower association with water table depth shifts (respectively r = −0.61, p < 0.001 and r = 0.24, p 0.03). The residuals of water table depth shifts that were not explained by the annual water balance where correlated to the initial absolute water table levels of the growing season (Fig. 3b, r = −0.59, p < 0.001), indicating that shallower water table initial conditions favored annual losses and deeper initial conditions favored annual gains. For example, being similarly rainy, 2012 had much a shallower initial water table depth than 2011 (116 vs. 271 cm) and enhanced water losses through direct pond evaporation in the large fraction of the territory that was flooded (24% vs. 0.3%) combined with overland flow along the flooded surface (Aragón et al., 2011); could have prevented further level rises in 2012.

At the intra-annual scale, land cover had a higher but still secondary effect in controlling water table levels. Stochastic effects prevailed as shown by the large fraction of the sum of error squares (42%) explained by the year in itself and by its interaction with the specific period of the year (Table 3, intra-annual ANOVA). The appreciable contribution of the period of the year (26% of SS) is associated to a predictable seasonal component that is independent of the individual year condition and the crop. The effect of crop emerged first through its interaction with the period of the year explaining 11% of the SS, revealing a consistent seasonal effect. The next effect of crops was associated to its triple interaction with year and period, explaining 8% of the SS. Landscape position effects were also nil at this temporal scale. Overall, the intra-annual analysis of variance indicates that water table level shifts have a high stochastic component which is modulated by the year and accounts for 50% of the SS (year + year × period + year × period × crop effects), whereas the predictable effects are tied to the seasonality and crop and with 37% of the SS (period + period × crop effect).

Intra-annual changes in water table depth, like the inter-annual ones, were explained by the water balance (Fig. 3c, r = −0.57, p < 0.001, n 1092). Both, rainfall and crop water demand in isolation were poorly related to water table depth shifts (r = −0.38 and 0.30, respectively, p < 0.001). Although, the linear fit between water table depth change and the water balance displayed a slightly negative intercept (−2.7 cm, p < 0.001), forcing the model through the origin produced a similar fit and roughly the same slope of 0.21 vs. 0.22 cm mm^{-1} (r^2 = 0.32 vs. 0.31, p < 0.001). An analysis of covariance of the regression between the water balance and water table depth change showed no slope differences for any landscape positions (F = 0.03, p > 0.9) or crops (F = 0.20, p > 0.8). As usual textures of soils in the farm are sandy loam, saturated horizons have ca. 2 mm cm^{-1} of water over field capacity (Ritchie and Crum, 1989; Saxton and Rawls, 2006), then the 0.22 cm mm^{-1} of water table change provide or store 0.44 mm. Likely, the remaining balance, roughly 50%, was buffered by the water storage below field capacity into the soil over the water table. At the intra-annual scale the effect of initial water table level was very low (Fig. 3d).

The high stochasticity of water table level shifts showed by the analysis of variance is illustrated by the diversity of water table level trajectories within each year (Fig. 4a–e). Yet, a predictable seasonal pattern can be isolated from these trajectories as well. Fig. 4f

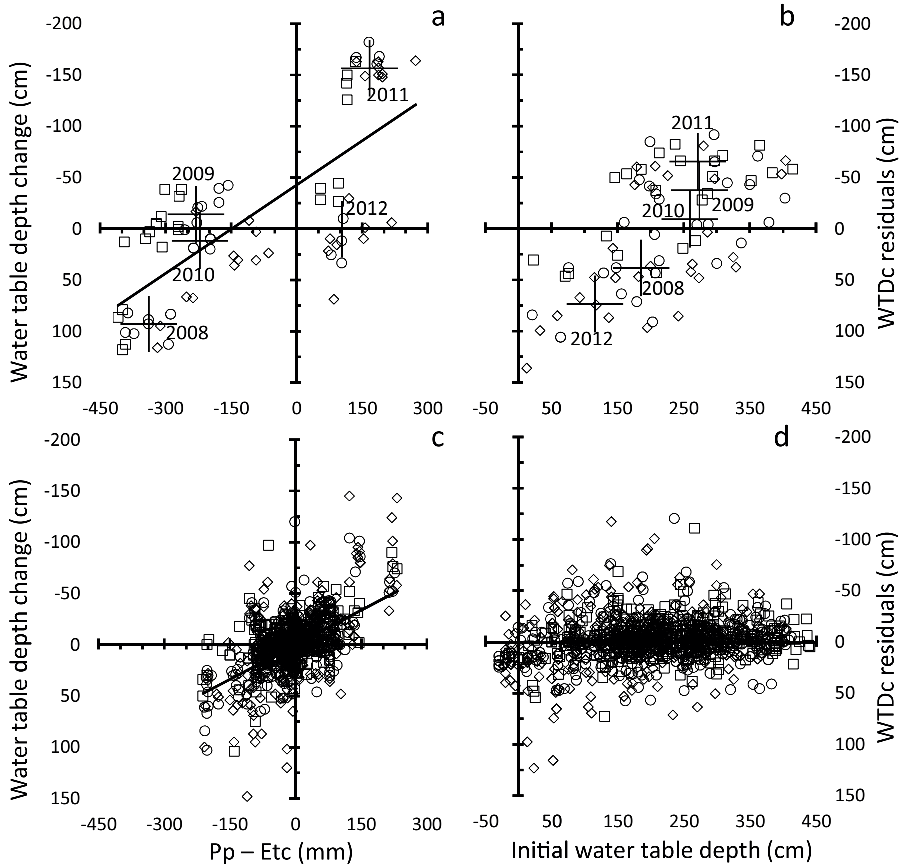

Fig. 3. (a) and (c) Relationship between water table depth change (WTDc) and water balance (Pp-Etc) along the five growing season at inter (a: WTDc = −43–0.29*(Pp-Etc), R^2 53%, $p < 0.001$, $n = 80$) and intra (c: WTDc = −0.22*(Pp-Etc), R^2 31%, $p < 0.001$, $n = 1092$) annual scales. (b) and (d) Relationship between initial water table depth and residuals of the WTDc vs Pp-Etc linear model at inter (b: WTDc residuals = 76–0.34 × WTD initial, R^2 34%, $p < 0.001$, $n = 80$) and intra (d: WTDc residuals = 5–0.04 × WTD initial, R^2 3%, $p < 0.001$, $n = 1092$) annual scales. Symbols identify maize (circle), soybean (diamond) and wheat soybean double crops (squares).

shows the mean water table levels shifts for each crop overall the 5 years. The mean values showed slight level raises (0.15–0.25 m) from May to September for all crops and then a divergence for single summer crops which showed a stronger level raise until November vs. a steady condition for the double crop in the same period. Water table levels converged for all crops again in January and afterwards single summer crops showed a steeper water table level drop than the double crop, with a new convergence situation in late April (Fig. 4f). In brief, the average seasonal trend of summer crops involved a strong spring level raise followed by a strong summer level drop and gentle recovery towards the initial levels during fall. This pronounced average seasonal cycle was not observed in the double crop (Fig. 4f). In 2012, winter crops were severally affected by flooding and waterlogging, as evidenced by grain yields dropping approximately to a third of the decade-long farm records (data not shown), a mid-spring green cover that was lower than in previous seasons (85 ± 3 vs. 96 ± 10%), and an earlier harvest date with some areas with water tables raising over the soil surface (as communicated by farm managers). Additionally, while the second soybean crop was sown 10 days earlier than in previous seasons, maize and single soybean sowing dates were delayed by 10–15 days because of large rainfalls (Table 1). Both effects contributed to reduce intra-annual differences between simple and double crop water use in this last year of our study (Fig. 2e).

Although, our study was not designed to explore lateral groundwater transport effects, observations in well 11 (Table 1), located 70 m apart from another management unit located in the same wide intermediate low landscape position, deserves a special comment. This was the only well located at such a short distance from another management unit, which in three growing seasons had a contrasting crop type. While in 2008 and 2011 well 11 was under maize and the neighboring plot was under wheat-soybean double crop, the opposite occurred in 2010. As result, well 11 displayed water table level shifts that were intermediate between those observed in wells located in pure double crop and summer crop zones (Fig. 4a, c, and d, dashed lines). These observations suggest that horizontal transport, driven by hydraulic gradients generated by contrasting water consumption of the different crops, may influence seasonal water-table fluctuations and average-out the long-term contrasts that may emerge between adjacent paddocks with different evapotranspiration rates.

4. Discussion

Rainfall variability was the overriding driver of inter and intra-annual groundwater dynamics in the agricultural landscape of the Western Pampas that was studied here. The agricultural crop choices used in the farm had a secondary effect, only evident at specific periods of the cropping cycle, and reasonably well explained by the balance between precipitation and crop demand. Landscape position was the least important factor, being determinant of the absolute water table depth but irrelevant shaping its temporal dynamics.

We found that the possibilities to regulate or manage water table fluctuations through crop choice are very limited. While previous works in the region showed an optimum water table depth range in which crops receive maximum benefits from groundwater precluding drought and waterlogging (Florio et al., 2014; Nosetto et al.,

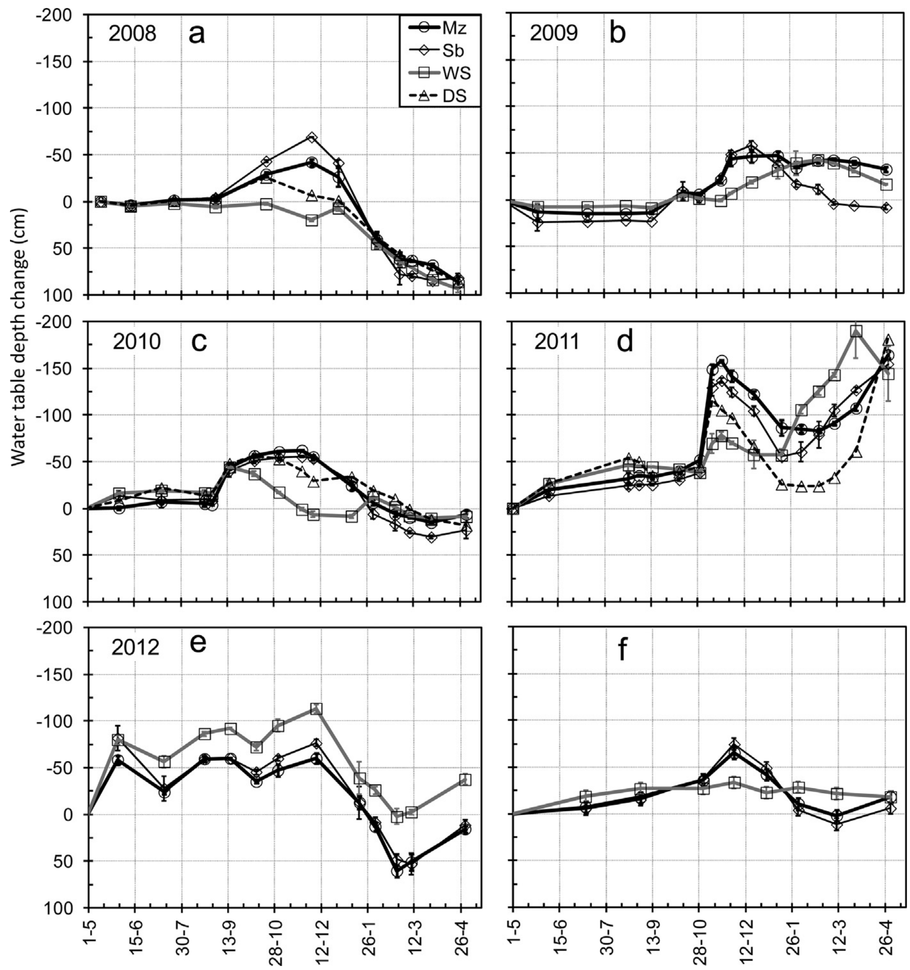

Fig. 4. Cumulative water table depth change under maize (Mz: circles and thick black lines), soybean (Sb: diamond and thin black lines) and wheat-soybean double crop (WS: squares and gray lines) along 2008 (a), 2009 (b), 2010 (c) 2011 (d) and 2012 (e) growing seasons, and the average year and fixed season effect (f). Each point represents the average value of the different wells with the corresponding crop. Bars indicate the standard errors. In 2008 and 2011 well 11 (see Table 1) was under maize, but the neighboring plot (70 m apart) was underdouble crop; in 2010 the opposite occurred (DS: triangles and dashed line).

2009), our results suggest that there are limited chances to manage water table in this useful range, since a great proportion (Table 3) of its fluctuation depends on rainfall variability at different time scales. An additional complexity for steering levels towards this optimum range comes from the spatial variation introduced by topography, which is highly consistent through time. Although the agricultural crop choices applied currently by farmers in the study area may have some effect on water table levels, they are subtle within the time and spatial scales that we covered. Alternative land uses and practices need to be considered for this purpose.

An increase in water use of agricultural systems has been proposed as a way to prevent water table rise or favor its decline when it is too close to the ground (Keating et al., 2002; Pannell and Ewing, 2006). This can be met through longer-season and more deeply rooted annual crops (Merrill et al., 2007), or by using more intensive crop systems, such as relay intercropping or double-crop systems (Caviglia and Andrade, 2010; Caviglia et al., 2004). However, it does not seem likely with the typical crop choices currently available for farmers in the Western pampas. Double crop in our study clearly smoothed seasonal water table fluctuations, reducing spring rises, but had limited utility to control inter-annual fluctuations due to the counterbalancing effect of the reduced water use during the wheat-to-soybean transition in early summer. The design of novel multiple crops, such as the intercropping of two summer species (Monzon et al., 2014) that maintain high transpiration rates from spring to early autumn, represent a potential avenue to reduce drainage and achieve greater control on inter-annual water table fluctuations.

The limited capacity of annual crops to buffer the inter-annual stochasticity of water table fluctuations leads to consider other crop alternatives. Experience from Australia and the North American Great Plains, where most of the research on the ecological control or regulation of groundwater levels under dryland conditions was performed, indicates that perennial crops (pastures or tree plantations) are more effective than annual crops in reducing recharge and lowering water table levels (Black et al., 1981; Keating et al., 2002; Pannell and Ewing, 2006). Comparing different crop alternatives, Black et al. (1981) found that perennial alfalfa had the highest water use, capable of depleting soil water to a depth of 6 m in 5 years; biennial sweet clover ranked second in water use. Within the annual crops, deep rooted safflower and sunflower were the most water-consuming. However, the effectiveness of higher water consumption land uses for depleting water table levels will depend also on time scales. Our observations do not allow us to assess the cumulative effects over time of the crops with higher consumption, as the farm analyzed followed a rotation scheme. Nevertheless, maintaining over the time crops with higher capacity for reducing recharge should magnify the effects of land use on the dynamics of water table.

While managing water table levels to preclude flooding represents a major challenge in the flat plains of Argentine Pampas, a shallow fresh groundwater body can be also a valuable resource in the region, particularly during drought periods. This is different from the Australian and North American situations, where saline groundwater represents a permanent hazard and management is aimed to lower water tables as deep as possible (George et al., 1997; Miller et al., 1981). Ultimately, the desirable water table depth and its admissible range of fluctuation would depend on the type of crop cultivated and stakeholders perceptions and attitudes towards drought and flooding risks (Mercau et al., 2013).

Finally, a last issue to consider when managing the trade-offs between flooding and drought risk is lateral groundwater transport. As suggested by our observations at well 11, groundwater flow between adjacent areas with different land uses may be significant at the seasonal scale. Recent modeling efforts in the region with spatially distributed hydrological models show that the intensification of water consumption at a given area can lead water table level decreases more than 1 km away (García et al., 2014). No matter what type of cropping alternatives are envisioned, frequent on-farm monitoring of water table level could aid the design of opportunistic cropping strategies (Sadras and Roget, 2004), that switch water consumption targets, crop rooting depths and their distribution in the landscape in response to water table fluctuations, maximizing yields and reducing waterlogging, flood as well as drought risk.

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