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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