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The dynamics of cultivation and floods in arable lands of central Argentina

E. F. Viglizzo[1,2], E. G. Jobbagy[3], L. V. Carreño[1], F. C. Frank[1], R. Aragón[3], L. De Oro[2], and V. S. Salvador[1]

[1]INTA, Centro Regional La Pampa, Area of Environmental Management, Av. Spinetto 785, P.O.Box 302, 6300 Santa Rosa, La Pampa, Argentina
[2]CONICET, Av. Spinetto 785, P.O.Box 302, 6300 Santa Rosa, La Pampa, Argentina
[3]Grupo de Estudios Ambientales IMASL, Universidad Nacional de San Luis y CONICET, Ejército de los Andes 950, 5700 San Luis, Argentina

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Correspondence to: E. F. Viglizzo (evigliz@cpenet.com.ar)

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Abstract

Although floods in watersheds have been associated with land-use change since ancient times, the dynamics of flooding is still incompletely understood. In this paper we explored the relations between rainfall, groundwater level, and cultivation to explain the dynamics of floods in the extremely flat and valuable arable lands of the Quinto river watershed, in central Argentina. The analysis involved an area of 12.4 million hectare during a 26-y period (1978–2003), which comprised two extensive flooding episodes in 1983–1988 and 1996–2003. Supported by information from surveys as well as field and remote sensing measurements, we explored the correlation among precipitation, groundwater levels, flooded area and land use. Flood extension was associated to the dynamics of groundwater level, but these two variables displayed a poor association with rainfall, being particularly decoupled from it during the rainy periods. Correlations between groundwater level and flood extension were positive in all cases, but while highly significant relations ($P<0.01$) were found in highlands, non significant relations ($P>0.05$) predominate in lowlands. Our analysis supports the existence of a cyclic mechanism driven by the reciprocal influence between cultivation and groundwater levels in highlands. This cycle would involve the following stages: (a) cultivation boosts the elevation of groundwater levels through decreased evapotranspiration; (b) as groundwater level rises, floods spread causing a decline of land cultivation; (c) flooding propitiates higher evapotranspiration favouring its own retraction; (d) cultivation expands following the retreat of floods. Thus, cultivation would trigger a destabilizing feedback self affecting future cultivation in the highlands. It is unlikely that such sequence can work in lowlands. The results suggest that rather than responding directly and solely to the same mechanism, floods in lowlands may be the combined result of various factors like local rainfall, groundwater level fluctuations, surface and subsurface lateral flow, and water-body interlinking. Although the hypothetical mechanisms proposed here require additional understanding efforts, they suggest a promising avenue of environmental management in which cultivation could be steered in the region

to smooth the undesirable impacts of floods.

1 Introduction

Since ancient times, the hydrological dynamics of watersheds were associated to land use/land cover change. Floods were frequently attributed to the conversion of woodlands and grasslands into grazing, cropping and urban lands. Various studies (Elwell and Stocking, 1976; Lee and Skogerboe, 1985; Francis and Thornes, 1990) concluded that water runoff decreases exponentially as plant cover increases, yet a review of 137 paired experiments showed that the hydrological response of vegetated and devegetated watersheds is highly variable, rather unpredictable, and poorly understood (Andréassian, 2004). However, it is generally accepted that forests have greater water storage and retention capacity than grassland, and the latter have more than arable lands.

Beyond increased runoff, the effect of cultivation on groundwater levels and its relation to land flooding was less studied and is still poorly understood. Because of the expansion of saline areas in agricultural lands of Australia, Ferdowsian and Bee (2006) reported an excessive groundwater recharge under traditional cultivation that led to the rising of the water table. They recommended the use of deep-rooted perennial pastures (such as *alfalfa*) to reduce recharge and lower water level.

As it happens in complex biotic and non biotic systems (Jeong et al., 2000), the large scale dynamics of flooding processes are also essentially unknown. Holistic approaches are necessary to improve our knowledge and forecasting ability (Clark et al., 1988). Data from long-term series have supported watershed studies, but they are frequently criticised because most research was focused on certain spatial scales (Hornbeck et al., 1993). This is a relevant issue because agronomists, ecologists, environmentalists, land managers, policy makers and development agents who make decisions at different levels (plot, farm, ecosystem, landscape, eco-region) increasingly demand scientific information about cross-scale relations and interactions in hierarchical systems (Viglizzo et al., 2005).

Some authors (Buringh and Dudal, 1987; Bailey, 1995; O'Neill et al., 1991; Wagenet, 1998) have stated that high-level environmental factors like landform, climate and land quality have strong top-down influence on lower levels. On the other hand, human-dependent factors at lower levels, such as land-use and management, may exert bottom-up influences, that are smoothed at successively higher levels (King, 1993; Viglizzo et al., 2004).

In this paper we (1) describe the dynamics of flooding in the Pampas of Argentina and (2) revise their triggering mechanisms, based on the analysis of ∼30 y-long temporal series of precipitation, land cultivation, groundwater levels, and flooded area for the Quinto river watershed (124 000 km^2). Lowlands in the watershed represent a typical case of flood-prone area in the Pampas, where regular floods undermine the regional economy (Fuschini Mejía, 1994). To guide our analysis we propose two extreme and simple hypotheses that explain the onset of floods in the Quinto river watershed, acknowledging that a more complex combination of both is most likely taking place. Our climate-oriented hypothesis suggests that flooding is the result of increased precipitation inputs, which accumulated through a certain period, causes a widespread elevation of groundwater levels that eventually reach the surface and limit cultivation. Our ecosystem-oriented hypothesis, on the other hand, proposes that flooding emerges as a result of increasing cultivation, which enhances recharge and raises groundwater level when high water-consuming pastures and grasslands are replaced by low water-consuming annual crops. In this paper we explore the temporal variation and correlation of rainfall, groundwater level, flooding and cultivation, and use our extreme guiding hypotheses to explain the development of flooding, and suggest possible non-linear interactions and feedback mechanisms that might regulate the system.

2 Materials and methods

In order to understand the dynamics of floods in the study area, the associations among rainfall, groundwater and cultivation were explored. We use the term cultivation to indicate the proportion of arable land that is allocated to extensive grain crops (mainly wheat, soybean, maize and sunflower) every year, based on the fact that the rest of the land is typically occupied by perennial pastures (Hall et al., 1992).

2.1 The study region

The Argentine Pampas (33–35° S, 62–64° W) is a wide plain of around 54 million hectare of fertile lands suitable for cattle and crop production (Hall et al., 1992; Viglizzo et al., 2001). Soil quality varies (Satorre 2001) and rainfall declines from NE to SW. The climate of the western Pampas is temperate (mean annual temperature=16.2° C) with 70% of rainfalls, that average 750 mm y^{-1} (Díaz Sorita et al., 1998), occurring between October and April. Winds are more intense (around 16.8 km h^{-1}) and frequent (only 14% of calmed days) during the hot season (Hall et al., 1992), triggering wind erosion episodes. Cyclical drought and flood episodes that affect both crop and cattle production have been described by Viglizzo et al. (1997) and Moncaut (2001).

The western or "sandy" Pampas (Fig. 1) occupy approximately one third of the region and consist of a large and complex system referred as the "Sand Sea" that comprise a large regional configuration of longitudinal, mega-parabolic dunes (Iriondo, 1990). The region was shaped during the last Pleistocene glaciation and was partially reworked during later desertification episodes (Iriondo, 1999), particularly during the 1930–40's dust bowl that affected the western Pampas (Zarrilli, 1999; Fig. 1b). The linear features normally observed in satellite images correspond to a succession of elongated mounds and inter-dune depressions that constrain the natural evacuation of water (Malagnino, 1991). The Late Pleistocene-Holocene deposits provide the parent material for the modern cultivated soils (Zárate, 2003).

In hydrological terms, the region comprises an active groundwater system that is the result of the convergence of Araucana, Puelche and Pampeana formations, being the last one the top of the aquifer, which is relatively shallow (Aradas and Thorne, 2001). Very often, rainfall adds to already water saturated soils and leads to multiple ephemeral water bodies that, depending upon topographical configurations, can join and produce extensive flooding episodes (Aradas and Thorne, 2001). Losses from the system occur by runoff and vertical water fluxes that involve infiltration, evaporation and evapotranspiration from a plethora of occasional lakes and wetlands (Scarpati et al., 2002). In order to relieve vulnerable lands from flooding and water-logging problems in part of the region, and also to improve conditions for agricultural production, the political authority of Buenos Aires province commissioned in 1987 the elaboration of an Integrated Master Plan (Saravia et al., 1987) that later was only partially carried out.

2.2 The Quinto river watershed

The Quinto river watershed, where floods occur, is in part located inside the western Pampas. It extends from NW to SE following a topographic gradient that ranges between 900 m in the central hills of San Luis province (outside the Pampas), to less than 100 m a.s.l. on the flooding lowlands of NW Buenos Aires province. The Quinto river mainstream flows into the Amarga lagoon (Carignano, 1999). A broad-scale NE-SW spill-over area (of around 12.3 million hectare) raises along the river, which favours water drainage into a flooding area (Fig. 1) that comprise highly productive and valuable lands in which cultivation has increased since the 1960s (Viglizzo et al., 2001). Drainage is robust in the higher part of the watershed (hereafter highlands) because of the steep topographic gradient that cuts across the Southern districts of San Luis and Córdoba provinces. The lower part of the watershed (hereafter lowlands) is, on the other hand, a flat depression that extends over the NE districts of Buenos Aires province with elevations ranging from 130 and 50 m a.s.l. Despite flatness, episodes of weak drainage that are mediated by occasional interlinked water bodies and anthropic constructions such as channels and roads occur inside the lowlands (Kruse, 1992; Kruse et al., 2001; Kruse and Zimmermann, 2002). Despite large differences, both highlands and lowlands are prone to flooding.

We used different sources of information to place the limit between highlands and lowlands. In first place we used a digital elevation model (DEM) that included most of the Rio Quinto watershed to identify sharp shifts in slope and elevation. Independently we worked with a Landsat scene (227–85, 32 400 km^2) that covers the transition zone within the watershed to characterize "baseline" flooding intensity based on the total area covered by ponds during the dry year of 1997. Elevation ranges between 300 and 80 m, gradually decaying towards the SE. The topography is extremely flat with 90% of the area having <1% slope. A pronounced slope shift takes place across the range of 110–120 m a.s.l. contour line. Using this contour as a limit for highlands and lowlands, the mean elevation and slope for the two regions were, respectively 183 m and 0.73% and 91 m and 0.45%. Based on the 1997 Landsat scene the area covered by water bodies was 2% for highlands and 6% for lowlands (Fig. 2).

2.3 Data sources and analysis

Data on latitude, longitude and landform were obtained from field measurements, satellite images and topographic maps. Land-use datasets were provided by the Annual Agricultural Surveys for the period 1978–2003 provided by the Secretary of Agriculture of Argentina. Public hydrological organizations (The Provincial Water Administration in La Pampa and The Plains Hydrology Institute in Buenos Aires provinces) and the National Meteorological Services provided iii) long-term precipitation data and iv) groundwater level records from a large network involving 58 phreatimetric nodes scattered among 29 locations. A subset of 11 of these data points (see Fig. 1) had continuous and homogenous data for the whole study period.

We focused our work at two spatial and temporal scales: A broad-scale analysis for the 1978–2003 period comprising highlands and lowlands as whole units in the flooding area, and a small-scale analysis for the 1996–2003 period in which information was disaggregated into eleven political districts (five located in highlands, and six in lowlands) (Fig. 1). Mean values and standard deviations were respectively used to characterize the patterns of precipitation, groundwater level and % of cultivation at the broad highland and lowland scales during 1978–2003. Simple correlation analyses using best-fitting linear models were used to evaluate relations at both scales. Correlation analysis were used at the district level during the period of 1996–2003 to estimate the degree of association between a) the groundwater level and the % of croplands affected by floods and b) the change of cultivation during the inter-flooding period of 1989–1995 and the groundwater level during the 1996–2003 flooding period. It should be noticed that cultivation increased in all districts during the inter-flooding period (Viglizzo et al., 2001).

Given that no numerical measurements of flood extension were available for the last 30-y period we estimated it based on the values of reduction of cultivated area obtained from survey data for the 1996–2003 flooding event. This estimate assumed that the cultivated area was exclusively reduced by flooding. To validate this procedure, we relied on the support of satellite images in order to estimate the extension of flooded lands along the flooded period of 1996–2003. Both, survey and satellite data sources were then correlated to check the consistency of the first approach. Considering that correlation coefficients were significant in nine out of eleven study districts, we assumed that the reduction of the cultivated area is an appropriate estimator of flood extension during the flooding periods.

3 Results and discussion

3.1 Precipitation, groundwater and land use at the broader, highland/lowland scale of analysis

Despite the similar behaviour of districts in the western Pampas regarding land-use until the middle of the 20th century, the flooded area tended to deviate from such behaviour during the rainy period that started in the 70‘s, suggesting a functional decoupling of the flooding plain during the wetter periods (Viglizzo et al., 1997, 2001).

Throughout the 25 y-long study period (1978–2003) highlands and lowlands displayed similar trends in precipitation, groundwater level and cultivated area, with correlation coefficients between regions of 0.75, 0.64 and 0.70 ($P<0.01$). Considering that both areas tend to show parallel behaviour, it can be argued that they are connected in functional terms. However, highlands were on average drier (lower precipitation and deeper groundwater) and more cultivated than lowlands, which in average show 20% more precipitation (Fig. 3a). In spite of having lower precipitation variability, lowlands displayed similar groundwater level variability than highlands, with water tables being on average 80 cm shallower throughout the study period (Fig. 3b). Highlands had on average 50% of their area cultivated with a peak of 70% of cultivation in 1995–1997 (Fig. 3c). In the lowlands, cultivation averaged and peaked 34% and 45% of the area, respectively. It should be noticed that in relation to highlands, the higher precipitation regime of lowlands agrees with a higher groundwater level and a lower cultivation percentage.

Hypothetically, this could be explained not only by large recharge due to the higher rainfall regime of lowlands, but also by other factors like transfer of runoff water from highlands to lowlands. The cultivation pattern seems to show a cyclical behaviour with increasing and decreasing phases that probably responds to flooding events. This flooding/cultivation cycle deserves particular attention in our hypothetical interpretation.

The relations between rainfall and groundwater on the one hand, and rainfall and cultivation on the other hand, are less clear (Table 1). While rainfall and groundwater level are positively and significantly ($P<0.05$) correlated in highlands, such correlation is not significant ($P>0.05$) in the case of lowlands. The relation between rainfall and cultivation was non significant ($P>0.05$) in both areas, but the correlation coefficient R in lowlands was substantially higher than in highlands. Therefore, in terms of flooding potential, the analysis would support the argument that while groundwater might have a larger effect in highlands than in lowlands, rainfall might be more influential in lowlands. This finding seems to weaken the local belief stating that groundwater levels, and consequently floods, are only strongly related to short-term precipitations. The negative relationship between groundwater and cultivation may have practical implications in highlands: first, groundwater level can be useful to predict a cultivation reduction in response to flood expansion; second, considering the slow movement of groundwater in soils, groundwater level can be monitored to anticipate flood risk, helping to cope in advance with its potentially harmful consequences.

Whenever we use rainfall or groundwater arguments to explain flooding, both tend to support our climate-oriented hypothesis, which suggests that floods are the result of increased precipitation that directly expands water bodies, or indirectly cause a widespread elevation of groundwater that saturates land surface and limits cultivation. Nevertheless, in isolation this hypothesis seems to be unable to explain the potentially cyclical behaviour of floods and cultivation.

3.2 Groundwater and floods at the district scale

Considering the predominant and significant positive correlations between survey and satellite data to estimate the extension of floods, we proceeded on our analysis by using the first set of records from annual surveys. Figure 4 shows the temporal change of the flooded area at the district scale in highlands (Fig. 4a) and lowlands (Fig. 4b). Three aspects should be highlighted: i) Lowlands showed a more disperse and erratic behaviour than highlands, where a relatively homogeneous flooding pattern predominated ii) the flooding extension picked one year earlier in highlands than in lowlands, probably suggesting a slow transference of water from highlands to lowlands. In fact, when floods began to decrease in highlands (2002), they showed maximum expansion in lowlands (2003).

The association between groundwater and flooding is likely to be the most promising relation to explore (Table 1). Results show curious relations (Fig. 5) because highlands (Fig. 5a) and lowlands (Fig. 5b) behaved differently when groundwater level and the percentage of croplands affected by floods are related. Setting aside the fact that correlations were positive in all study districts, relations were unambiguous and highly significant ($P<0.01$) in highlands, and rather anarchic and non-significant ($P>0.05$) in lowlands. While groundwater level seems to play a dominant role to trigger floods in highlands, drivers other than groundwater seem to predominate in lowlands. Because of the flat landscape, it is likely that some other factors like local rainfall, outside and inside runoff, subsurface drainage, and even the coalescence of scattered water bodies can be enhanced in wet periods. These factors probably merge with groundwater levels to trigger anarchic and unpredictable flooding episodes in lowlands.

3.3 The potential effect of cultivation on flooding

Our ecosystem-oriented hypothesis can provide an extra insight to the study problem. Two hydrological mechanisms have been suggested to explain the potential influence of cultivation on flooding: increased runoff and decreased evapotranspiration (ET). Various authors (Fullen, 1985; Faulkner, 1990; Evans, 1993; McNeill and Winiwarter, 2004; Withers et al., 2007) have reported that cultivation is likely to increase surface runoff and flooding. On the other hand, ET rates can decline in cultivated lands (Newman et al., 2006). Changes of ET in response to land use change proved to have a powerful effect on soil water balance (Wilcox et al., 2003; Nosetto et al., 2005; Wilcox and Thurow, 2006) in turn affecting groundwater level (Scanlon et al., 2005). The timing of groundwater raise in relation to land-use/land-cover change is not still well understood, but different spatial and temporal plant-cover configurations can create different ET patterns (Gilfedder et al., 2003). While perennial vegetation tends to show long-term and rather continuous ET patterns, annual crops show short-term ET pulses that agree with periods of active growing (Doorenbos and Pruitt, 1977). Therefore, it is expected that the substitution of permanent or perennial plants by annual crops may reduce ET rates, and eventually increase groundwater level because of a shortened growing period. In Australia, Allison et al. (1990), Ward et al. (2006) and Ferdowsian and Bee (2006) reported that the broad-scale clearing of perennial vegetation and its replacement by annual crops and annual pastures has resulted in rising groundwater levels. An additional aspect that may restrain ET once the onset of floods has taken place is the fact that land with the water table close to the surface (e.g. <0.8 m deep) often ceases to be sown and is deprived from plant transpiration. This process can proceed until groundwater reaches the surface and direct surface evaporation occurs. There is an incomplete understanding about the time lag between land-use change and groundwater level change, but today this information is essential to design sound land use and land management strategies (Gilfedder et al., 2003).

Given that both the percentage of annual crops and the flooded croplands were estimations obtained from the same data source, any correlation between them would inevitably connote circular calculation and spurious results. To manipulate independent data periods, we alternatively explored the correlation between cultivation during the inter-flooding period (1989–1995) and groundwater level during the flooding period (1996–2003). Our hypothesis was that cultivation increase leads to groundwater elevation. Correlation results are presented in Fig. 6. Provided that positive correlations were obtained for all highland districts (Fig. 6a), this response gives room to speculate that the increase of cultivation during the inter-flooding period can trigger groundwater elevation that later saturates the soil and expands floods. Thus, with a variable time lag, increased cultivation in one period would reduce the chance of cultivation in the following period. This interpretation is consistent with our ecosystem-oriented hypothesis, which proposes that flooding possibly responds to increasing cultivation, which enhances recharge and raises groundwater level when high water-consuming pastures and grasslands are replaced by low water-consuming annual crops. However, in principle this interpretation is not strictly applicable to lowland districts (Fig. 6b), which again showed a random behaviour that deviates from that showed by highlands. Probably, the same multiple drivers of flood mentioned above generated noisy responses.

3.4 Cyclical behaviour and the ecosystem-oriented hypothesis

A complete and useful compilation of drought and flooding episodes that occurred in the Argentina Pampas between 1576 and 2001, reconstructed through historical chronicles and numerical data by Moncaut (2001), indicates that flooding was a natural episode that repeated cyclically in the history of the study region. Given the qualitative nature of such information, quantification was not possible. Considering that colonization of lands in the study area started between the end of the 19th and the beginning of the 20th century, it is likely that cultivation affected the intensity and frequency of flooding episodes. The rapid cultivation wave that began at the end of 1970's and still persists probably untied a force that destabilized the hydrology of the flooding lands. The abrupt transition from cultivation to flooding, and again to cultivation, especially in highlands, suggests that both hydrology and cultivation are probably subjected to a cyclical behaviour.

One hypothetical interpretation to this cycle is that the competition between amplifying (positive) and controlling (negative) feedbacks is probably modulating the hydrological response of flooding lands. The inversion of phases within each cycle probably occurs when one feedback dominates over the opposite one. By triggering a positive feedback, cultivation could destabilize the hydrological balance of the area. On the other hand, floods could trigger a negative feedback that forces the ecosystem to a lower cultivation level that would stabilize the regional hydrology. While positive and negative feedbacks may be mutually neutralizing in a sequential order, we can presume that the flooding process moves between two (upper and lower) critical thresholds that, in theory, were not still irreversibly surpassed (Scheffer et al., 2001; Rial et al., 2004). The consequences of positive feedbacks prevailing over the negative ones in the long term are pure speculative at this point, yet the possibility of irreversibly surpassing threshold as stated by Peters et al. (2004) and Briske et al. (2006), should be considered.

Beyond the competing-feedback interpretation to explain cycles, one answered question in our ecosystem-oriented hypothesis is what can explain water withdrawal once flooding extension peaks. Flooding can favour vertical water-loss pathways through pan-evaporation from water bodies, hypothetically surpassing the ET rates observed under any herbaceous vegetation cover. Another vertical pathway can be the slow infiltration process that later causes lateral subsurface drainage to lower lands. Flooding water can also overflow beyond the watershed boundaries and connect large chains of water bodies, favouring surface flows towards the Atlantic Ocean. This situation was observed under the extreme flooding conditions of 2001 when the Quinto river watershed get a surface connection with the Eastern Salado river watershed (Scarpati et al., 2002). Certainly, a nested-scale configuration seems to be necessary to interpret the agro-eco-hydrological dynamics of the study region.

4 Conclusions

Our findings are useful to interpret the complex and dynamic relations between rainfall, groundwater level and cultivation in flooding lands of the Quinto river watershed. Results indicate that a purely climate-oriented perspective that sets aside essential biological aspects like those related to land-use and land-cover change may be insufficient to explain the potential cyclical behaviour of floods and cultivation, and a complementary, ecosystem-oriented view, may be required. Cultivation may have a strong influence on the dynamics of groundwater and floods in the highlands of the study region. In practice, cropping would cause a negative self-impact that could deplete cultivation in the near future. Besides, because of its location in an upper transitional drainage area, the hydrological effect of cultivation in highlands could indirectly contribute to alter the dynamics of floods in lowlands. So, on broad-scale basis both the climate- and the ecosystem-oriented hypothesis should not be considered mutually excluding but complementary hypothesis.

Mediated by groundwater variability, the recurrent occurrence of cultivation-flooding cycles appears to be an outstanding feature of highlands that is not so evident in lowlands. Floods in lowlands appear to be the combined result of various factors that may include not only groundwater variations, but also local rainfall inputs, runoff from upper lands, subsurface drainage and interlinking of water bodies. Considering the flat configuration of lowlands, such factors can converge to mask a foreseeable relation between groundwater and flooding.

Taking into account the relative importance of groundwater in highlands as a driver of flood, land planners and decision makers can take advantage of this condition to prevent catastrophic situations: the slow pace of groundwater processes is suitable to implement an early-warning monitoring system to facilitate adaptation before the flooding outbreak. Likewise, a knowledge-based land-use policy for highland should not discard the potential effect of cultivation on flooding. To deal with this, we suggest the following hypothetical mechanism to explain the cultivation-flood relation: first, cultivation boosts the elevation of groundwater level through decreased evapotranspiration; second, as groundwater level rises, floods spread causing a decrease of land cultivation; third, flooding propitiates higher evaporation favouring its own retraction. Despite nowadays most drivers of the hydrological dynamics escape to human control, cultivation emerges a promising human-controlling factor that could be managed to smooth the undesirable impact of floods. This view would become more relevant under a wetter climate scenario like that the IPCC (2007) report predicts for the Argentine Pampas.

Given that drainage from highlands appears to be a strong factor affecting the lowlands hydrology, a sensible land-use policy should treat the flooding area a whole hydrological unit. In practical terms, the combination of an engineered channel-infrastructure plus a designed plant-cover structure in highlands seems to be necessary to smooth the impact of drainage water on lowlands.

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HESSD
5, 2319–2345, 2008

Table 1. Correlation analysis between rainfall, groundwater level and percentage of cultivation.

Correlation between			*a*	*b*	*R*	*SE*
High-lands	Rainfall	Groundwater level	−4.48	0.002	0.46	141.17
		% annual crops	62.15	−0.006	−0.09	158.52
	Groundwater level	% annual crops	37.04	−6.79	−0.41	0.56
Low-lands	Rainfall	Groundwater level	−2.37	−0.000	−0.06	130.37
		% annual crops	51.67	−0.015	−0.28	125.50
	Groundwater level	% annual crops	28.85	−2.52	−0.23	0.64

References: Regression coefficients: *a* (linear) and *b* (independent); *R*: determination coefficient and *SE*: standard error.

HESSD

5, 2319–2345, 2008

The dynamics of cultivation and floods

E. F. Viglizzo et al.

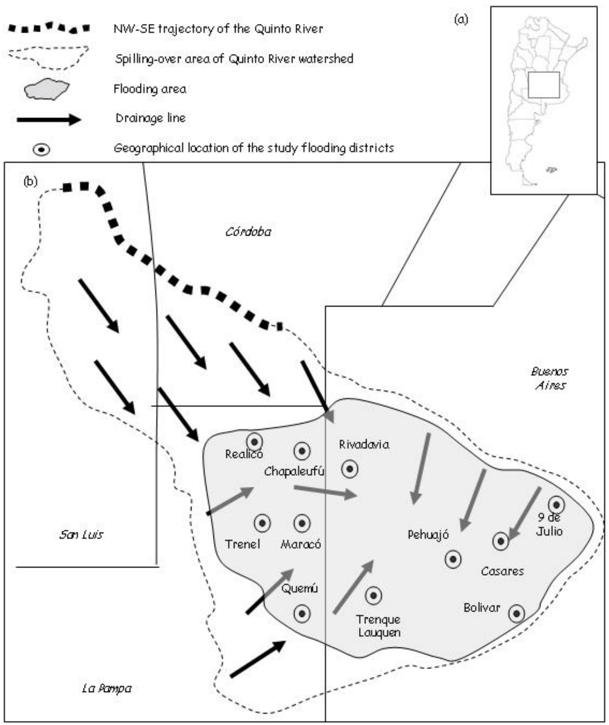

Fig. 1. Location of the Quinto river watershed shared by San Luis, La Pampa, Córdoba and Buenos Aires provinces; **(a)** location of the western Pampas and the watershed in the Argentine territory, **(b)** detail of the watershed showing the Quinto river trajectory, the spill-over area, the flooding area, the drainage lines and the geographical location of the study districts.

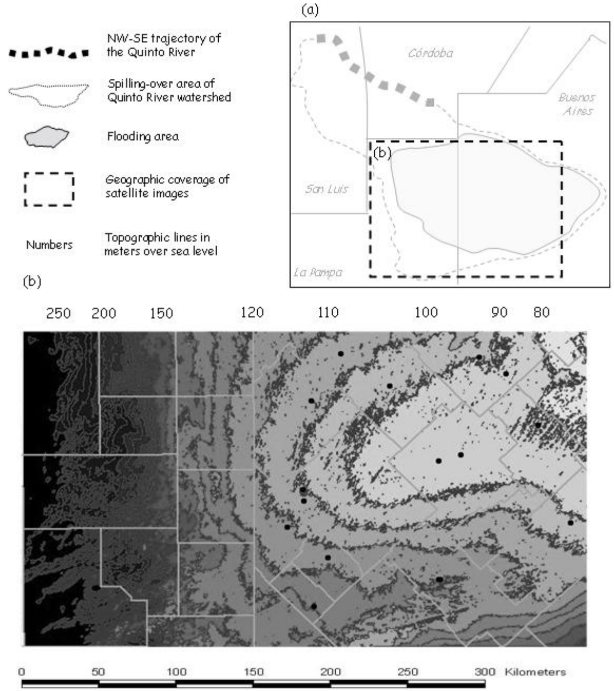

Fig. 2. **(a)** graphic of Fig. 1 showing the area of the Quinto river watershed, **(b)** Topographic features of the flooding area from Landsat images showing the strip that separates highlands from lowlands on 110–120 m on sea level.

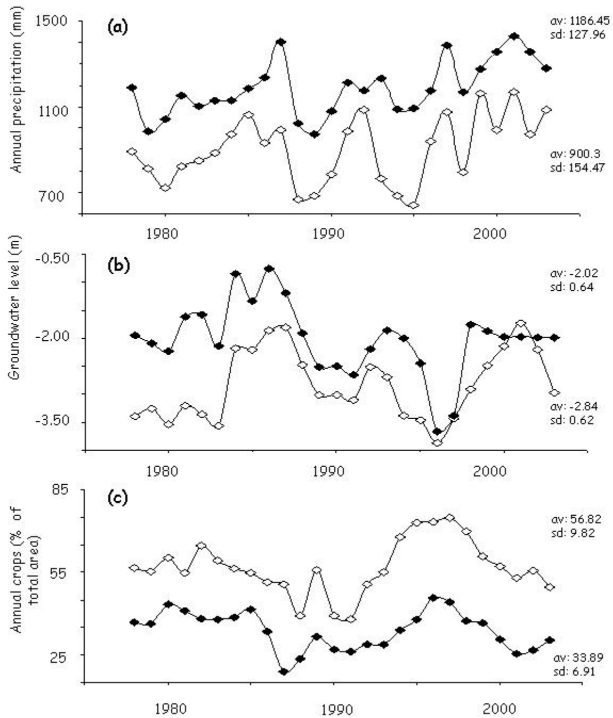

Fig. 3. Temporal variability in patterns of precipitations **(a)**, groundwater level **(b)** and annual cultivation **(c)** in highlands (white symbols) and lowlands (black symbols) within the spill-over area of the Quinto River watershed during the period 1978–2003. Av: average value, sd: standard deviation. Analyzed period: 1978–2003.

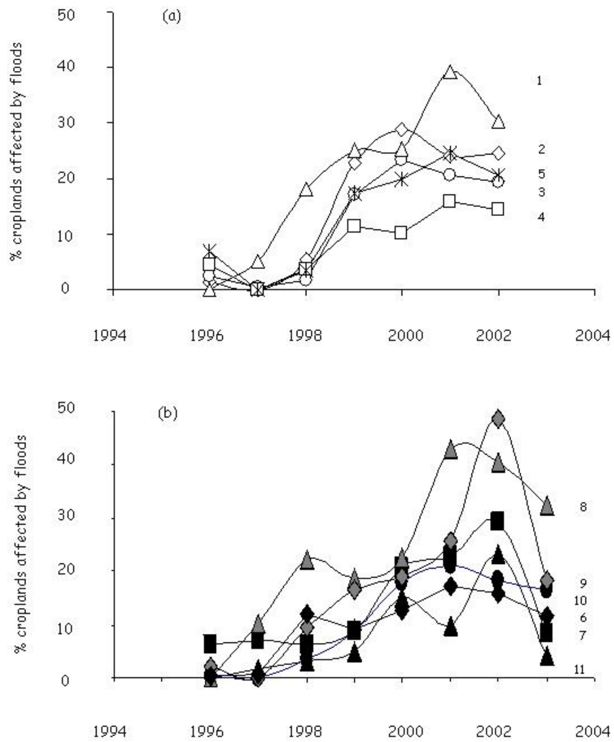

Fig. 4. Percentage of cropland affected by floods during the period 1996–2003 in the flooding area of the Quinto River basin. Highland districts **(a)** comprise 1. Chapaleufú, 2. Realicó, 3. Trenel, 4. Quemú , 5. Maracó. 1996–2002 was the period covered by floods in highlands. Lowlands **(b)** comprise 6. Bolivar, 7. Rivadavia, 8. 9 de Julio, 9. Casares, 10. Pehuajó, 11. Trenque Lauquen. 1996–2003 was the period covered by floods in highlands.

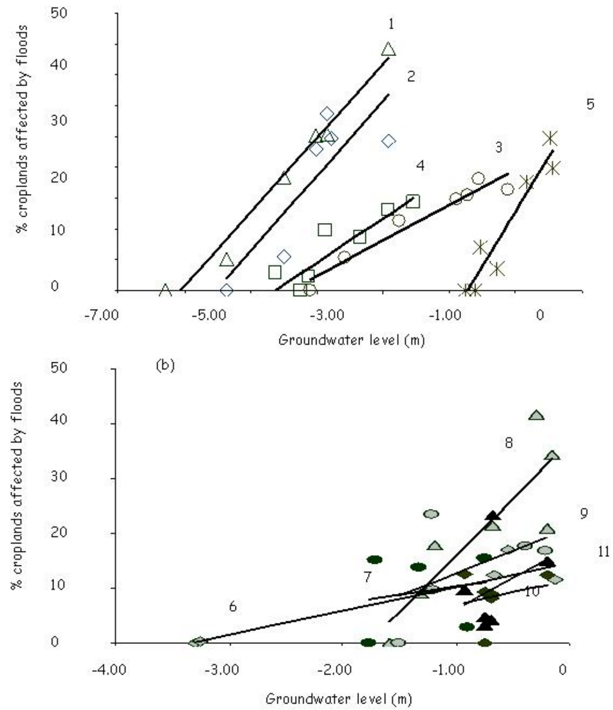

Fig. 5. Relationships between groundwater levels and % of cropland affected by floods in the flooding area of the Quinto River basin during the period 1996–2003. Highland districts **(a)** comprise 1. Chapaleufú (R=0,99, P<0.01), 2. Realicó (R=0.84, P<0.01), 3. Trenel (R=0,97, P<0.01), 4. Quemú (R=0.91, P<0.01), 5. Maracó (R=0.95, P<0.01). Lowlands district **(b)** comprise 6. Bolivar (R=0.92, P<0.01), 7. Rivadavia (R=0.18, P>0.05), 8. 9 de Julio (R=0.86, P<0.05), 9. Casares (R=0.26, P>0.05), 10. Pehuajó (R=0.23, P>0.05), 11. Trenque Lauquen (R=0,35, P>0.05). 1996–2003 was the period covered by floods in highlands.

HESSD

5, 2319–2345, 2008

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀◀ | ▶▶
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

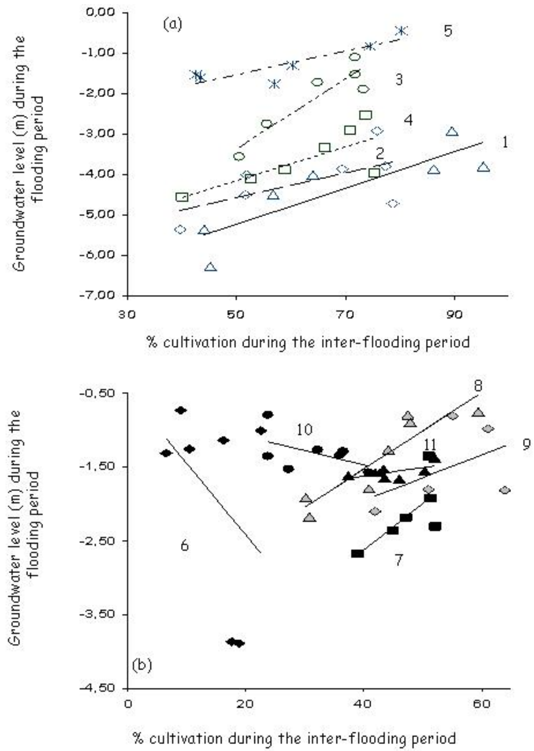

Fig. 6. Relationships between % cultivation during the inter-flooding period (1989–1995) and groundwater levels during the flooding period 1996–2003. Highland districts **(a)** comprise 1. Chapaleufú (R=0,86, P<0.01), 2. Realicó (R=0.61, P>0.05), 3. Trenel (R=0,92, P<0.01), 4. Quemú (R=0.75, P<0.05), 5. Maracó (R=0.88, P<0.01). Lowlands districts **(b)** comprise 6. Bolivar (R=−0.42, P>0.05), 7. Rivadavia (R=0.70, P>0.05), 8. 9 de Julio (R=0.91, P<0.01), 9. Casares (R=0.48, P>0.05), 10. Pehuajó (R=−0.51, P>0.05). 1996–2003 was the period covered by floods in highlands.