# Land-Use as possible strategy for managing water table depth in flat basins with shallow groundwater

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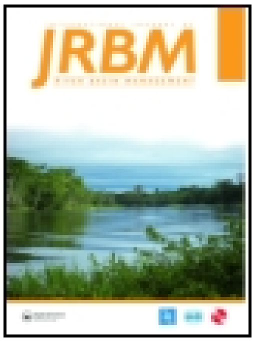

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RESEARCH PAPER

# Land use as possible strategy for managing water table depth in flat basins with shallow groundwater

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**ABSTRACT**
In flat plains groundwater affects agricultural production outcomes and risks. Agricultural land use decisions, however, may strongly impact groundwater levels available for production. This paper explores the scope for managing groundwater levels through land use decisions in a sub-basin of the Salado River in the Argentine Pampas, a very flat area that plays a key role in world agricultural production. A spatially distributed hydrological model implemented with MIKE SHE software was used to establish the impacts of different land uses on groundwater dynamics, and to assess the interdependencies among spatially close decision-makers sharing a water table (WT). Additionally, groundwater level changes in response to climate variability were quantified. We found land use has strong effects on WT levels both for oneself (e.g. pastures can lead to significant decreases (up to 4.5 m) in WT levels) and others, in the form of strong interdependencies that exist between farmers sharing a WT where land use decisions of one farmer effect groundwater level of neighbouring farms and vice versa. However, the effectiveness to control groundwater levels through land use decisions is subject to the rather unpredictable effects of rainfall variability. The results presented in this paper provide key insights in relation to physical and social aspects that should be considered for managing groundwater levels through land use decisions, in order to avoid negative and/or maximize positive effects on agricultural production.

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Land use change; groundwater dynamics; interdependencies; Argentine pampas; hydrological modelling; climate variability

## 1. Introduction

Throughout history, water and food production have been closely linked. The bulk of the world's food is supplied by rainfed agriculture that relies on soil moisture coming almost exclusively from precipitation (de Fraiture and Wichelns 2010). Water is a key driver of several ecosystem functions (including the provision of biomass and crop yields) and of supporting and regulatory services. Understanding linkages between agroecosystems, water, and food production, therefore, is important to the health of all three systems (Boelee 2011).

This paper targets agricultural systems in the Pampas of central eastern Argentina, one of the main cereal and oilseed producing areas in the world (Calviño and Monzón 2009). Most of the Pampas has an extremely flat topography with regional slopes <0.1% (Jobbágy *et al.* 2008). In such hyperplains, low topographic gradients and poorly developed drainage networks preclude the surface drainage of excess water (i.e. precipitation exceeds evapotranspiration), which in turn leads to shallow water tables[1] (Fan *et al.* 2013).

Shallow water tables (WTs) (generally less than 3–5 m deep) can affect and, reciprocally, be affected by the annual field crops and pastures that dominate land use in the Pampas. WT can have either null, positive, or negative impacts on crops depending on their depth (Nosetto *et al.* 2009, Zipper *et al.* 2015). If the WT is deep, groundwater is not accessible to roots and thus does not influence crop growth or yield. If the WT is closer to the surface (1.5–2.5 m), groundwater may reach the root zone through capillary rise and thus provide up to 50% of a crop's water requirements (Ayars *et al.* 2009). If the WT is very close to the surface, the positive effect of groundwater on yields is replaced by a 'groundwater penalty' – the negative impacts of waterlogging that limits root activity, nutrient availability, and plant establishment (Kahlown and Azam 2002, Zipper *et al.* 2015).

Reciprocally, agricultural land use may have strong effects on groundwater dynamics. Vegetation exerts a strong control on water balance and key hydrological variables, influencing both groundwater recharge and discharge (Seyfried *et al.* 2005, Santoni *et al.* 2010, Nosetto *et al.* 2015). The Pampas have experienced recent major changes in land use, shaped by the interaction of marked decadal rainfall fluctuations, technological innovations, and shifting economic contexts (Schnepf *et al.* 2001, Lamers *et al.* 2008, Barsky and Gelman 2009, Eakin and Wehbe 2009). In the last few decades, field crops have expanded throughout the Pampas, displacing grasslands and pastures (Manuel-Navarrete *et al.* 2009, Viglizzo *et al.* 2011).

The Pampas show marked climate variability on scales from years to decades. On seasonal-to-interannual scales, El Niño-Southern Oscillation (ENSO) is the major source of precipitation variability in the Pampas (Ropelewski and Halpert 1987, Grimm *et al.* 2000). The area also has shown considerable precipitation variability on multi-annual scales (Castañeda and Barros 1994, Berbery *et al.* 2006, Seager

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*et al.* 2010). Rainfall trends in the region have been among the largest observed in the twentieth century (Giorgi 2002). A steady increase in annual precipitation (particularly in spring-summer) has been observed since the 1970s (Rusticucci and Penalba 2000, Vargas *et al.* 2002, Liebmann *et al.* 2004, Haylock *et al.* 2006).

There is a strong, positive association between rainfall, water table depth (WTD) and the areal extent of free-standing water bodies (lagoons, flooded areas) determining the magnitude and impacts of flooding events (Kruse 2001, Tanco and Kruse 2001, Kruse *et al.* 2006, Forte Lay *et al.* 2007, Aragón *et al.* 2010, Venencio and García 2011). Historical WTD observations and hydrological modelling, therefore, suggest that the combination of precipitation increases and changes in land use since the 1970s have induced a progressive rise in WTD that has, in turn, increased flood risks (Viglizzo *et al.* 2009, Contreras *et al.* 2011).

Horizontal groundwater flows among fields with different WTDs induce linkages among spatially adjacent farms. When crops uptake groundwater, they lower WTD and trigger lateral flows from the surrounding environment. Similarly, shallower WTs (e.g. resulting from a long fallow) may generate groundwater flows *towards* surrounding areas. Because of these lateral flows, land use within a farm may influence WTD in surrounding areas; similarly, WTD at a farm or a field also may depend on land use in nearby areas. Consequently, the flooding or drought risks faced by a farm manager are influenced not only by her own land use decisions, but also by those of others nearby sharing the WT.

The implications of shared groundwater go beyond spatial interdependencies: when the land use strategies of one farm impact the availability of groundwater in adjacent farms, the economic outcomes of the various farms become interdependent. This situation, in which one's decisions influence the physical and financial risks faced by others and vice versa can be thought of as a commons dilemma (Hardin 1968, Ostrom 2000), characterized by the fact that an individual farmer can make a cooperative choice (e.g. select a given land use) and reduce the likelihood of negative scenarios (e.g. flooding) for everyone or, instead, choose to focus on one's individual benefit alone. Interdependence in environmental problems may require cooperation among individuals and eventually coordination among everyone's actions (when more than one option is available) before collective benefits can be fully realized.

In interviews with farmers in the Pampas, the authors have found a strong optimism that groundwater tends to manage itself by generally having similar levels at the start of every cropping cycle, independent of rainfall during the previous cycle. Consequently, farmers also tend to ignore the rise/fall in WTD associated with one's crop choices (e.g. the shift away from pastures). Our interviews showed that farmers consistently dismiss the notion of interdependencies between one's land use choices and those of one's neighbours as they relate to WTD fluctuations. The physical and socio-economic interdependence among farmers sharing groundwater increases further the challenges of flood/drought mitigation. Unfortunately, the concept of groundwater as a common resource in small regions has received limited attention, possibly because basic background from the physical sciences is needed; this paper aims to produce some of the required background.

The Pampas are a unique environment to simulate and study important links and feedbacks between hydrological and agroecosystem processes because of (i) the strong coupling between climate, surface and groundwater in very flat sedimentary landscapes, (ii) the complex reciprocal linkages between shallow groundwater and crops, and (iii) the observed land use changes that, together with strong climate variability, modulate groundwater recharge, WTD, and flood frequency. In particular, this paper addresses the associations between climate, hydrology, and land use decisions in order to provide the physical background necessary to understand the effects of spatial and socio-economic interdependence among farmers sharing groundwater. We believe understanding the spatial and temporal implications of land use strategies on groundwater is vital to fully understand the impact of human decision-making on the physical context and the creation of a sustainable agricultural system. To achieve these goals, we use a spatially distributed, time continuous, surface-groundwater hydrological model that simulates WT dynamics, streamflow in surface water courses, and the presence/extent of flooded areas.

## 2. Study area

We focus on the 'A1' sub-basin (hereafter 'SA1', Figure 1) of the Salado River in Argentina, a part of the Río de la Plata hydrographic system. The SA1 basin shows most of the characteristics (see Introduction) that make the Argentine Pampas an interesting area for studying the close linkages between climate, surface and groundwater, and land use decisions. The SA1 is located in the northwestern part of the Salado Basin and encompasses approximately 14,500 km$^2$, extending about 230 km east–west and 140 km north–south. The SA1 is a sedimentary basin where Cretaceous, Tertiary, and Quaternary sediments overlay the Precambrian crystalline basement (Santa Cruz and Silva Busso 1999). Soils have developed on loessic materials of loamy to sandy loam textures and are predominantly Hapludolls (INTA 1989). The SA1 has very flat topography, poor hydraulic conductivity, and disintegrated drainage networks that constrain both surface and groundwater horizontal flows (Aradas *et al.* 2002, Viglizzo *et al.* 2009).

The climate of the SA1 is temperate subhumid (Hall *et al.* 1992), with a mean annual precipitation decreasing from 1000 mm in the east of the basin to about 800 mm in the west. The colder part of the year is relatively drier, as two-thirds of annual precipitation occur during the austral spring and summer (October–March). Mean daily air temperature ranges from 8 to 10°C during winter, to 22–24°C in summer (based on data from 1961 to 1990, Argentine National Met Service) (http://www.smn.gov.ar/serviciosclimaticos/?mod=elclima&id=3#).

Floods and droughts have been reported in the larger Salado Basin since colonial times. Flooding events were very frequent during the late nineteenth and early twentieth centuries, a relatively wet period. In contrast, extensive droughts were common during the drier 1930s–1950s (Scarpati *et al.* 2002, Herzer 2003, Seager *et al.* 2010). The dynamics of floods in this region has been studied by Kuppel *et al.* (2015) and (Aragón *et al.* 2010). Severe floods have occurred in the Salado Basin in 1980, 1991–1993, and 2000–2001 (Herzer 2003). Floods in the western half of the Pampas between 1997 and 2003 left 27% of the landscape under water, halved grain production, damaged infrastructure and soil quality, and transformed the few remaining

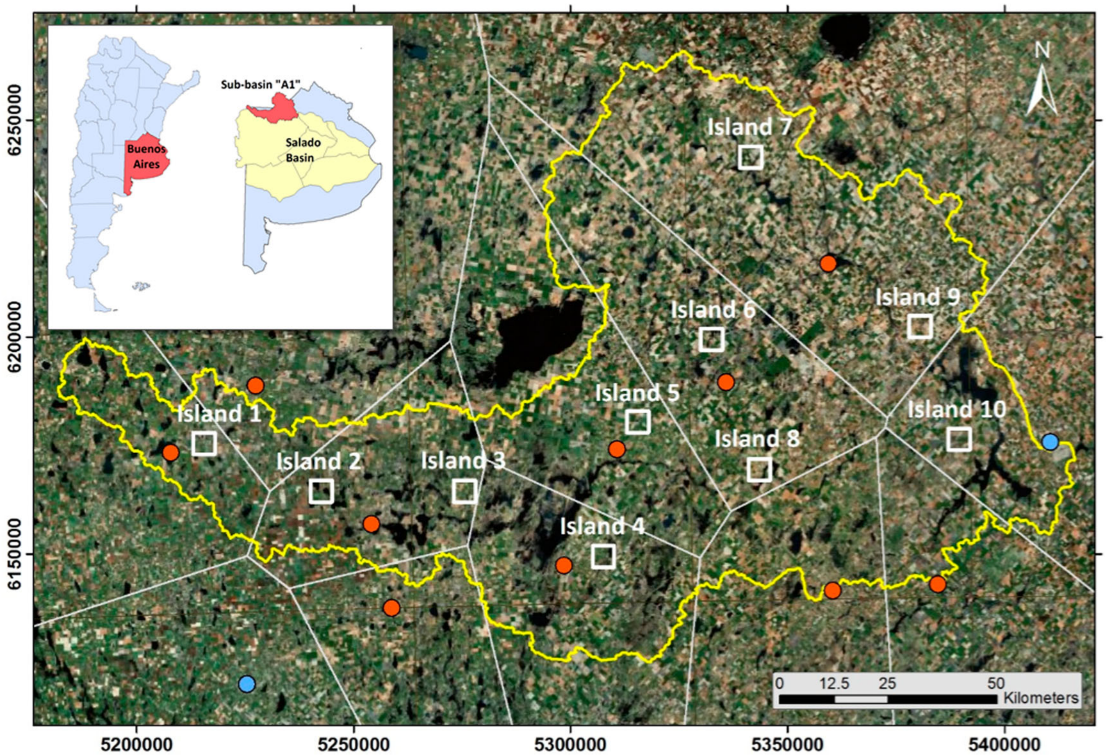

**Figure 1.** Location of study basin and Intervened areas or 'islands'. White fine lines: borders of Thiessen polygons. Points: weather stations with rainfall data. Points further south and east: weather stations with complete meteorological data.

natural areas (Viglizzo *et al.* 2009). In contrast, an almost unprecedented drought in 2008 (Skansi *et al.* 2009) decreased soybean and wheat production in the region by about 30% and 50%, respectively.

## 3. Hydrological model

We developed a hydrological model of the Salado A1 basin using MIKE SHE, a proprietary software (Refsgaard and Storm 1995, Refsgaard *et al.* 2010). MIKE SHE is a deterministic, spatially distributed, physically based numerical model that couples surface and groundwater flows. It derives from the Système Hydrologique Europèen – or SHE (Abbott *et al.* 1986a) – and was collaboratively developed by a group of European laboratories. MIKE SHE has been applied to a wide variety of basin types and sizes (Refsgaard *et al.* 1992, Vázquez *et al.* 2002, Henriksen *et al.* 2003, Liu *et al.* 2008, Stisen *et al.* 2008, Janža 2013, Wijesekara *et al.* 2014).

MIKE SHE simulates all major processes of the hydrological cycle, including evapotranspiration (ET), overland flow, unsaturated flow, and groundwater flow (Graham and Butts 2005, Sahoo *et al.* 2006, Refsgaard *et al.* 2010). For each of these processes, MIKE SHE offers multiple modelling approaches that range from simple, lumped, and conceptual, to advanced, distributed, and physically based. Further, MIKE SHE is dynamically linked to the one-dimensional surface hydrodynamic model MIKE 11 (Havno *et al.* 1996; DHI 2012a) that simulates channel flow processes in the land phase of the hydrological cycle. This linkage allows a complete representation of the drainage network within a watershed.

Evapotranspiration is simulated in MIKE SHE using the Kristensen and Jensen (1975) method. This method uses as input potential ET (PET), variables associated with land use (leaf area index (LAI) and root depth (RD)) and other empirical parameters such as the interception storage capacity of the vegetation and the root mass distribution (Janža 2013). The surface water component includes both overland and channel flows. The overland flow is represented through a two-dimensional diffusive wave approximation of the Saint Venant equations; a full description can be found in Wijesekara *et al.* (2014). Channel flow is modelled by the fully dynamic solution of Saint Venant equations, i.e. the vertically integrated equations of conservation of mass and momentum; see Wijesekara *et al.* (2014) for details. Water flow in the unsaturated zone is assumed to be vertical (Abbott *et al.* 1986b), and is modelled by the one-dimensional Richards equation (Richards 1931; DHI 2012b). Groundwater flow is represented through the 3D Boussinesq equation (Liu *et al.* 2008). This approach uses sub-surface layer information, including hydro-geologic stratification and hydro-geologic properties for each layer.

Both conceptual and practical reasons justify our choice of MIKE SHE to model the SA1 basin. Conceptually, MIKE SHE integrates all major hydrological processes into a single code and provides physically based models for these processes. From a practical point of view, MIKE SHE has been used previously in Argentina to develop a Flood Control Master Plan for the entire Salado Basin (UTN-FRA 2007). In that effort, MIKE SHE was used to assess the performance of the network of channels proposed by the Master Plan; some of this paper's authors were involved in that assessment. The availability of the MIKE SHE implementation of the Salado Basin model, therefore, reduced significantly the start-up time for the research presented here. Details about the Salado model and previous simulation results were presented by Badano (2010) and Menéndez (2012).

### 3.1. Model implementation

A regular grid with a spatial step of 1000 m (i.e. cells with an area of 1,000,000 $m^2$ = 100 hectares) was defined over the SA1 basin; about 14,000 cells encompass the basin. The grid spacing is a compromise between sufficient spatial resolution to describe the processes of interest and available computer resources: with the chosen grid size, it takes about one hour to simulate a year. In addition, the 100-hectare cell is roughly consistent with the size of a plot within farms in the study region (i.e. the size of the smallest unit for which farmers choose a land use).

A land surface Digital Elevation Model (DEM) of the basin was built based on the 90-meter Shuttle Radar Topographic Mission (SRTM) data (Farr *et al.* 2007). Altitude shifts were corrected by fitting a third order polynomial function obtained by fitting the SRTM data to the elevation data provided by Argentina's National Geographic Institute (IGN). Concentrated flow paths (permanent and ephemeral water courses) were obtained from IGN cartography. The ground elevation of the SA1 decreases from 140 m.a.s.l. in the west of the basin to about 75 m.a.s.l. in the east, with a regional slope of 0.03%.

The SA1 is widely covered by wind-generated depressions, where water is temporarily stored after rain events. The typical area of a depression, however, is much smaller than the model grid spacing. Therefore, depressions were considered as initial water abstractions from the corresponding cell. The volume of initial water abstraction for each cell was calculated from the DEM, through a filling-in algorithm implemented within a geographic information system; details are given in Badano (2010).

Three hydrogeological layers (Post-Pampeana, Pampeana, and Puelche) resting on a practically impermeable layer were represented (Halcrow and Partners 1999). The two uppermost layers, the Pampeana and Puelche formations, are the main source of groundwater extraction in the region (Carbó *et al.* 2008). Two main soil types with quite different properties (horizontal and vertical conductivity, saturated and residual humidity) were considered. Each soil was associated with a different geological formation: the soil on the western basin (associated with the Junín formation) included predominantly fine sand and sandy silt, whereas the soil on the east (associated with the Pampeana formation) mainly included loam. Hydraulic parameters associated with the three hydrogeological layers and the two main soil types are presented in Table 1. More details on the soil types are presented in Badano (2010). The boundary between the two main soil types is indicated by a dashed NW–SE white line in Figure 5.

In flat basins, both highways and railroads are significant obstructions to water runoff. The main highways within the basin were modelled as impermeable 1D obstructions traversed by short channel flow segments representing the integrated effect of bridges and culverts (Badano 2010).

### 3.2. Model inputs, initialization, and outputs

MIKE SHE requires daily rainfall and PET as input. Daily rainfall series for 1959–2013 were available for 12 weather stations within the study area (Figure 1). Daily PET values were calculated using the FAO Penman-Monteith (FAO PM) method (Penman 1948, Allen *et al.* 1998) that requires additional meteorological data – temperature, solar radiation, wind speed, and relative humidity. PET was estimated only at two stations where the required data were present. Both precipitation and PET were spatially discretized through 12 and 2 Thiessen polygons, respectively (Figure 1).

Other MIKE SHE inputs are daily time series of LAI (total leaf area per unit of soil area) and RD. These two variables depend on the type of crop and the crop's phenological stage, and ultimately determine water discharge through evapotranspiration (Kristensen and Jensen 1975; DHI 2012b). The input LAI and RD series were built through the following steps. First, LAI and RD series for each of the main crops in the region (maize, soybean, wheat, and sunflower) were simulated using biophysical models within the decision support system for agrotechnology transfer (DSSAT) framework (Jones *et al.* 2003). The DSSAT simulations used a single representative soil for the region and several years of observed weather. Second, the multiple annual series for each crop were averaged into single LAI and RD series. Third, we defined LAI and RD trajectories for pastures and grasslands based on field data (Nosetto, personal communication); because the LAI and RD values for pastures and grasslands were relatively similar, we used the same average trajectories for both. Figure 2(a–b) show the series of LAI and RD for crops and pasture/grassland. Finally, the average series for each crop and pasture/grassland were combined into composite daily LAI and RD trajectories for each cropping cycle. These series combined the trajectories for all land uses, weighting each use by the proportion of area they occupied – this proportion was defined for each experiment, as discussed below. When used, historical cropped areas were available only at the county level (i.e. a second-level administrative unit). The difference between cropped area and the total area of a county was assumed to correspond to pastures and grasslands; urban areas and roads represent a very small proportion of the basin and thus were ignored.

The integrated nature of the MIKE SHE model implies that very large amounts of output can be generated during a simulation. Common outputs can include actual evapotranspiration, depth of overland water, overland flow in $x$ and $y$ directions, infiltration to the unsaturated zone, unsaturated zone flow, water content in unsaturated zone, root water uptake, and groundwater flow in $x$, $y$, and $z$ directions. To limit the size of model output, here we focus only on WTD (or, as called by MIKE SHE, the depth of the phreatic surface).

### 3.3. Model calibration and validation

During the model calibration stage, a set of model parameters was estimated for the unsaturated zone that minimized the root mean square error (RMSE) of simulated and observed WTD time series. Nine observed WTD series of various lengths were available for validation; together, these series

**Table 1.** Hydraulic parameters associated with the three hydrogeological layers and the two main soil types.

| | Hydrogeological layers | | | | Soil type | |
|---|---|---|---|---|---|---|
| Parameter | Post-Pampeana | Pampeana | Puelche | Parameter | Pampeana Formation | Junín Formation |
| Horizontal Permeability [m/day] | 5 | 1 | 20 | Saturated moisture content [-] | 0.428 | 0.340 |
| Vertical Permeability [m/day] | 0.5 | 0.1 | 0.2 | Residual moisture content [-] | 0.031 | 0.052 |
| Specific Storage [1/m] | 0.0002 | 0.0002 | 0.0002 | Saturated conductivity [cm/day] | 250 | 174 |

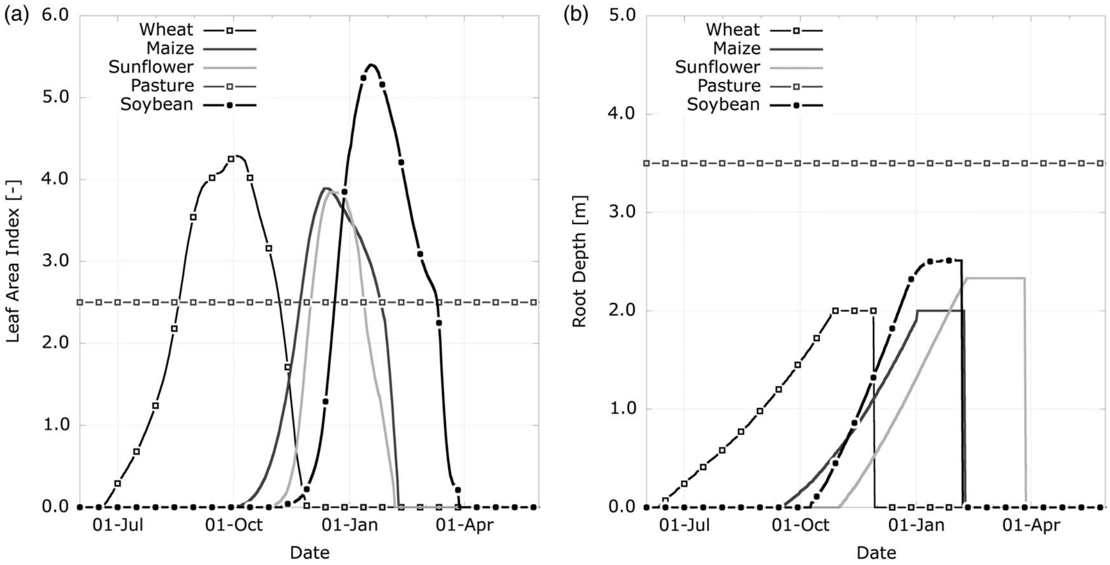

**Figure 2.** Series values of LAI and RD. (a). Leaf Area Index (unitless). (b). Root Depth (m).

included 485 WTD measurements. WTD values within the basin were measured by public agencies (e.g. INTA, Argentina's agricultural research institution) and by individual farmers. These historical WTD observations were compiled by Red MATE – a collaborative research network – and are available online (www.red-mate.com.ar). After calibration, our model reproduced very well the temporal trajectories of observed WTDs. As an example, Figure 3(a) shows historical and simulated WTD values for Junín (34°34′S–60°56′W), the location where the WTD record was longest (1963–1978, 177 records).

The model was subsequently validated by comparing simulated and observed discharge for concentrated flow, a quantity that integrates the effects of multiple simulated processes throughout the region. As discharge was not considered during the calibration stage, it provides an independent estimate of model performance. Figure 3(b) shows simulated and observed flows in Junín, the single outlet for the SA1 basin; there is good agreement between observed and simulated values. The time window used for validation encompasses both a dry and a wet period that are well captured. The model correctly simulates the increased flood frequency observed since the late 1980s. We note that the observed peak discharge in 2001 was tied to the failure of a small dike in Laguna Mar Chiquita (outside the A1 basin). Obviously, this external inflow was not reflected by the model. Details of the calibration and validation were presented by Badano (2010) and Menéndez (2012).

## 4. Numerical experiments: results and discussion

We performed various numerical experiments to simulate the response of WTD to various land use patterns and climate scenarios. Three sets of experiments were defined to address different objectives: (a) to understand the impacts of land use on WT dynamics; (b) to assess the spatial extent of WTD fluctuations among neighboring farms with different land uses; and (c) to quantify WTD changes in response to climate variability.

All simulations spanned 20 years, a period sufficiently long for the system to attain regime (i.e. stable) conditions; regime conditions were reached after 8–15 years, depending on the simulated scenario. In all simulations, a synthetic input series was built by repeating 20 times the daily weather records for a specific year ('base year'); various base years were used depending on a specific experiment's goals. For each experiment, the input land use was left unchanged throughout the simulation. Details of each set of experiments and their results are presented in the following sections.

### 4.1. Impact of land use on WT dynamics

The rise of WTs in the study region has been partly tied to a shift from pastures to annual field crops (Viglizzo *et al.* 2011). For this reason, the first set of experiments sought to quantify variations in WTD resulting from different land uses. Three contrasting scenarios were simulated: (A) a realistic land use pattern, based on 2004 data: 25% soybean, 6% maize, 6% wheat, 1% sunflower and 62% of pastures or natural grassland (urban areas are considered as negligible); (B) the entire basin is planted with soybean; and (C) the entire basin is covered with pasture. Scenarios B and C are unrealistic, but are intended to bracket the possible range of WTD variations. The climate base year was 2004, as it had a spatially averaged annual precipitation (970 mm) very similar to the mean annual rainfall for the period 1959–2013 (980 mm).

Land use had strong effects on simulated WTD throughout the basin. Figure 4 shows time series of basin-wide average WTD for scenarios A, B, and C. Once regime conditions were reached, the spatially averaged WT was deepest (≈7 m) for Scenario C (all pasture) and shallowest (≈2.5 m) for Scenario B (all soybean); as expected, WTD for the mixed land use Scenario A (≈4.6 m) lied between those for scenarios B and C. This pattern is associated with the higher annual water consumption of pastures, arising from the combination of their deeper root system and year-round evapotranspiration. In contrast, annual crops consume soil water only during the limited time in which they occupy the land (Nosetto *et al.* 2015). Scenario B shows lower intra-annual WTD variability due to the presence of pasture throughout the year. In contrast, WTD for Scenario C is shallower during fallow months (May to October, when PET is also low) and deeper during months of maximum soybean development (November to May).

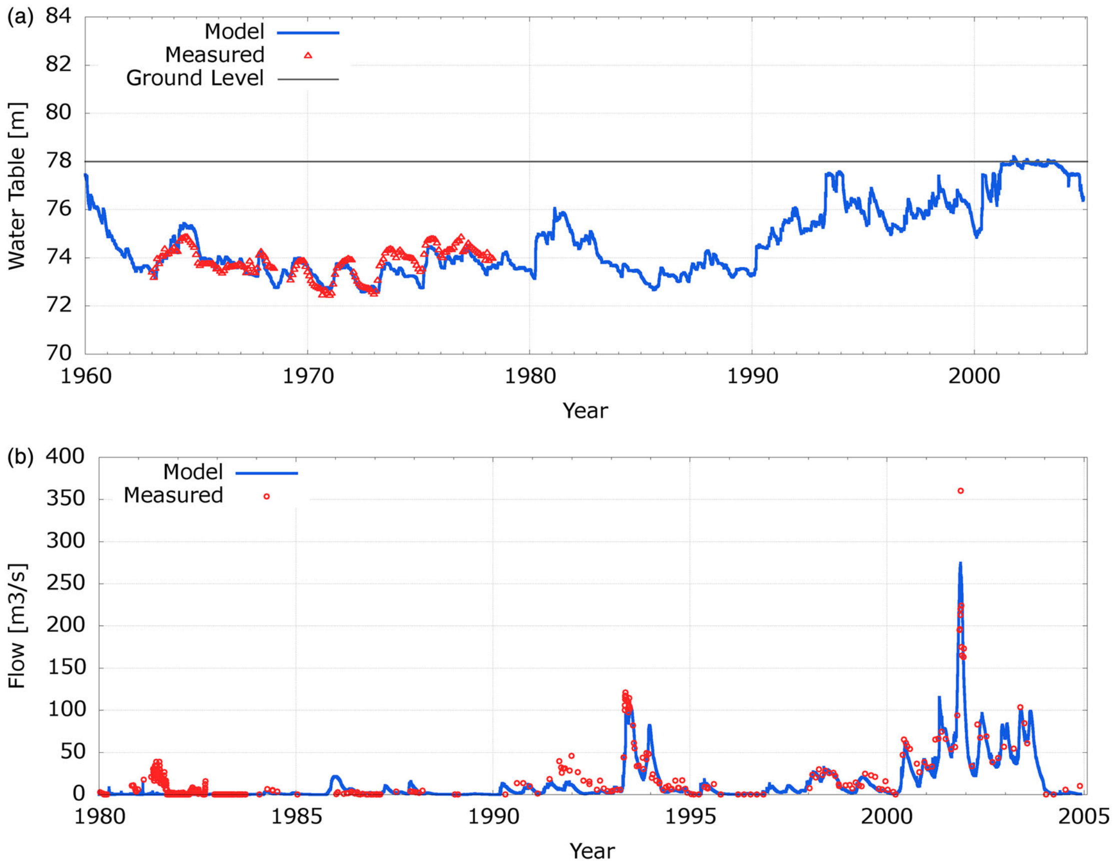

**Figure 3.** Model Validation in Junín (the single outlet for the SA1 basin). (a) Historical measurements (triangles) and simulated (continuous line) WT. (b). Simulated (continuous line) and observed (circles) flows.

The average WTD difference of ≈4.5 m between extreme land use scenarios B and C implies significant differences in flood or drought risks: for typical soils in the SA1 basin, a 4.5 m WTD change is equivalent to 800–900 mm of water, or about the same as the average annual precipitation. These results support claims that the recent expansion of field crops and the corresponding displacement of pastures and grasslands has led to a widespread increase in WT levels and flood risks.

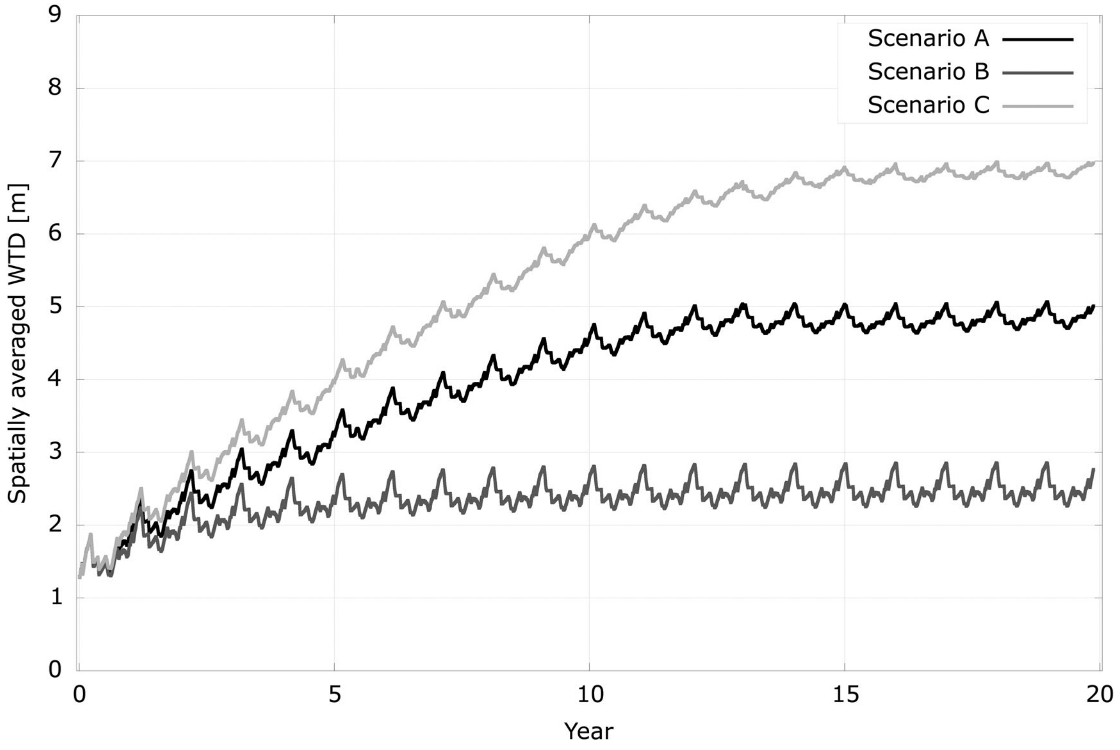

**Figure 4.** Spatially averaged WTD as a function of time for scenarios with different land uses: scenario A (realistic land use pattern), scenario B (all soybean) and scenario C (all pasture).

For the three land use scenarios, there were spatial differences in simulated WTD throughout the SA1 basin. Figure 5 shows the mean annual WTD for Scenario B once regime conditions are reached. WTD is shallowest (<1 m) in the western basin, whereas it can reach deep values (≈6 m) on the northeastern side; elsewhere in the basin, WTD lies within the 2–3 m range. The spatial WTD pattern is closely linked to variations in both precipitation and soil properties throughout the basin. The impacts of such heterogeneities are magnified because simulations are based on a weather series that repeats the same climatic conditions (the base year) 20 times. White lines in Figure 5 indicate the borders of the Thiessen polygons corresponding to available weather stations; a dashed NW-SE white line approximately separates the two soil types in the model. Based on this information, three different regions were identified (Figure 5): (i) an eastern region, where both annual precipitation and soil permeability are relatively low; (ii) a western region, where annual precipitation and soil permeability are high; and (iii) a central region, where annual precipitation is intermediate and soil permeability is high.

The WT tends to be shallower where both precipitation and soil hydraulic conductivity are high (e.g. the western region), as this combination of factors enhances groundwater recharge; conversely, the WT is generally deeper where precipitation and conductivity are low (i.e. the eastern region). Note, however, that this unusual pattern of higher (lower) rains at the western (eastern) ends of the basin was particular to the base year (2004) selected: the normal pattern in the Pampas is the opposite, i.e. a decrease in precipitation from East to West. Nevertheless, the previous discussion about rain and soil properties is valid. These results confirm that, due to the extreme flatness of the basin, the water balance is dominated by vertical fluxes. The intermediate WTDs in the central region suggest that WTD is more sensitive to precipitation than to soil permeability. This hypothesis was confirmed through a numerical experiment (results not shown) in which the same precipitation amount was imposed to the entire basin.

### *4.2. Spatial effects of land use on WT fluctuations*

Previous simulations showed that land use at a specific location (e.g. within a single farm) clearly can modify WT levels. If a landscape includes a mosaic of land uses – each with different impacts on WTD – WT levels may vary between adjacent areas with different land use. However, the spatial extent of the impacts of a given land use on WTD in adjacent areas needs to be quantified, as this effect has received little attention in the literature. The quantification of this impact is critical to assess the importance of an interdependent situation in which the decisions of one person (the owner of one farm) may influence the outcomes of others. In this section, we conduct simulations to assess the extent of WT fluctuations associated with different land uses in adjacent areas.

The all-soybean land cover in Scenario B was intervened with 10 square ‘islands’ covered with pasture; the islands were irregularly distributed throughout the basin (Figure 1). Three different island sizes were tested: 3 × 3 km (900 hectares, Scenario D), 5 × 5 km (2500 hectares, Scenario E), and 9 × 9 km (8100 hectares, Scenario F). The opposite situation was also tested: the entire basin was covered with pasture, except for 10 soybean islands of size 3 × 3 km (Scenario G), 5 × 5 km (Scenario H), and 9 × 9 km (Scenario I). Finally, to represent a more realistic land use pattern, a variant of Scenario F was also considered: each of the 9 × 9 km all-pasture islands was replaced by a chessboard pattern (81 squares

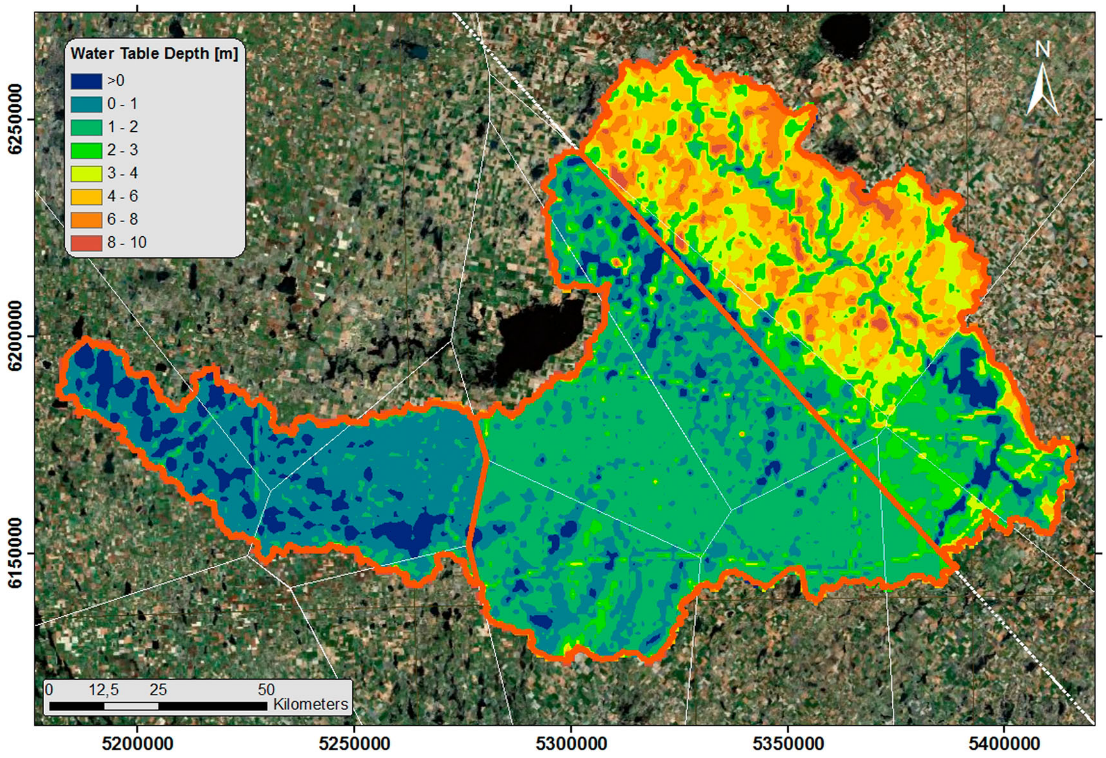

**Figure 5.** Annual average WTD for scenario B. The white lines mark the borders of Thiessen polygons based on available meteorological stations. The white dashed line marks the separation between soil type zones. The thick lines mark the zoning of the basin based on total annual precipitation and permeability: (i) East region, where the total annual precipitation and soil permeability are (relatively) low; (ii) West region, where the total annual precipitation and soil permeability are high; and (iii) Central region, where the total annual precipitation is intermediate and the soil permeability is high.

of 1 km$^2$, alternating soybean and pasture, Scenario J). The perimeter of each chessboard was the same as in Scenario F, but the soybean area was approximately half.

Heterogeneous land use within a landscape generated differences in WTD between adjacent areas. The absolute magnitude of WTD changes decreased with distance from the centre of an island with different land use. For example, Figure 6 shows WTD differences (once regime conditions are reached) between scenarios F (pasture islands) and I (soybean islands), and their respective reference scenarios (B and C) for island 9 (see Figure 1). WTD differences are plotted as a function of distance from the island's centre. The boundary of a 9 × 9 km island lies between 4.5 and 6.4 km from the centre (due to the square form of the island); this range is indicated by two vertical dashed lines in Figure 6.

For Scenario F, the year-round water consumption of pasture induces a deepening of the WT (i.e. a positive difference with respect to the reference scenario) around the centre of the island. For Scenario I, the opposite occurs: the soybean island has a shallower WT than the surrounding pasture, thus the difference with the corresponding reference scenario is negative. For both scenarios, absolute WTD differences decrease rapidly with distance from the island's centre. The rapid decrease of the spatial influence of land use on WTD seems to confirm the limited role of lateral transport in the water balance of very flat basins. The maximum WTD variations (at the centre of the island) were (i) a deepening of 5 m when the pasture island was placed on an all-soybean cover (Scenario F), and (ii) a WT rise of about 4.3 m for a soybean island in a pasture landscape (Scenario I). At the edge of the island, absolute WTD differences were in the 0.5–4.0 m range for Scenario F; the corresponding range for Scenario I was 1.0–3.0 m. For both scenarios, the WTD variation decreased below 0.1 m (i.e. it is practically undetectable) at about 13 km from the island's centre. Note that there is a higher dispersion of WTD differences within the dashed lines: this is because this range includes cells inside and outside the island. In general, absolute WTD variations are slightly larger for Scenario F than for Scenario I, suggesting a higher impact of interventions with pasture on a soybean landscape than for the opposite case.

Figure 7(a–b) show the differences in annual mean WTD (for regime conditions) between Scenarios D (3 × 3 km pasture cells) and F (9 × 9 km pasture cells) and the reference whole-basin soybean scenario (B). In both cases, WTs deepen in soybean areas around the pasture islands (cf. positive WTD changes in Figure 7(a–b)). Nevertheless, the spatial extent of 'island effects' on WTD seems to vary across the basin. Only little WTD differences were observed both within and outside islands in the western basin (islands 1 and 2). Conversely, significant WTD differences appeared in the eastern basin (islands 7, 9, 10). In the central basin, WTD differences are intermediate.

The spatial extent of WTD differences seemed to depend on the size of the island: the overall size of off-island areas influenced by land use appeared larger in Figure 7(b) (larger islands) than in Figure 7(a). To investigate the effect of island size, we estimated WTD differences between Scenarios D, E, and F (pasture islands of different sizes) and reference Scenario B (all soybean). Similarly, we calculated WTD differences between Scenarios G, H, and I (soybean islands of different sizes) and reference Scenario C (all pasture). Figure 8 displays WTD fluctuations for all scenarios listed above as a function of distance from the centre of island 9. This figure is similar to Figure 6, but both axes were rescaled. Distance from the centre of an island (the $x$-axis) was rescaled dividing it by the length of an island's side (3, 5, or 9 km depending on the scenario). The $y$-axis was also rescaled: the WTD

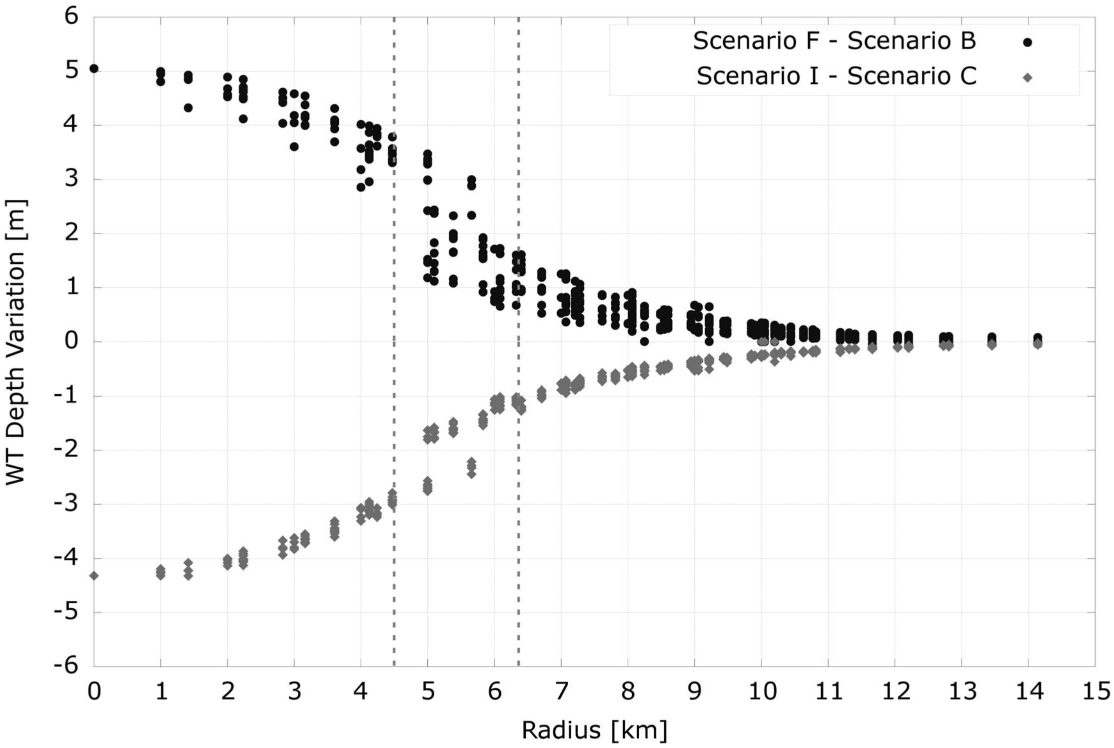

**Figure 6.** Radial distribution of annual average WTD variation for Island 9 with a size of 9 km between scenarios F (pasture islands) and I (soybean islands), and their respective reference scenarios (B and C). The border of the island lies within the transition zone delimited by vertical dashed lines. They are two edges because the island is squared.

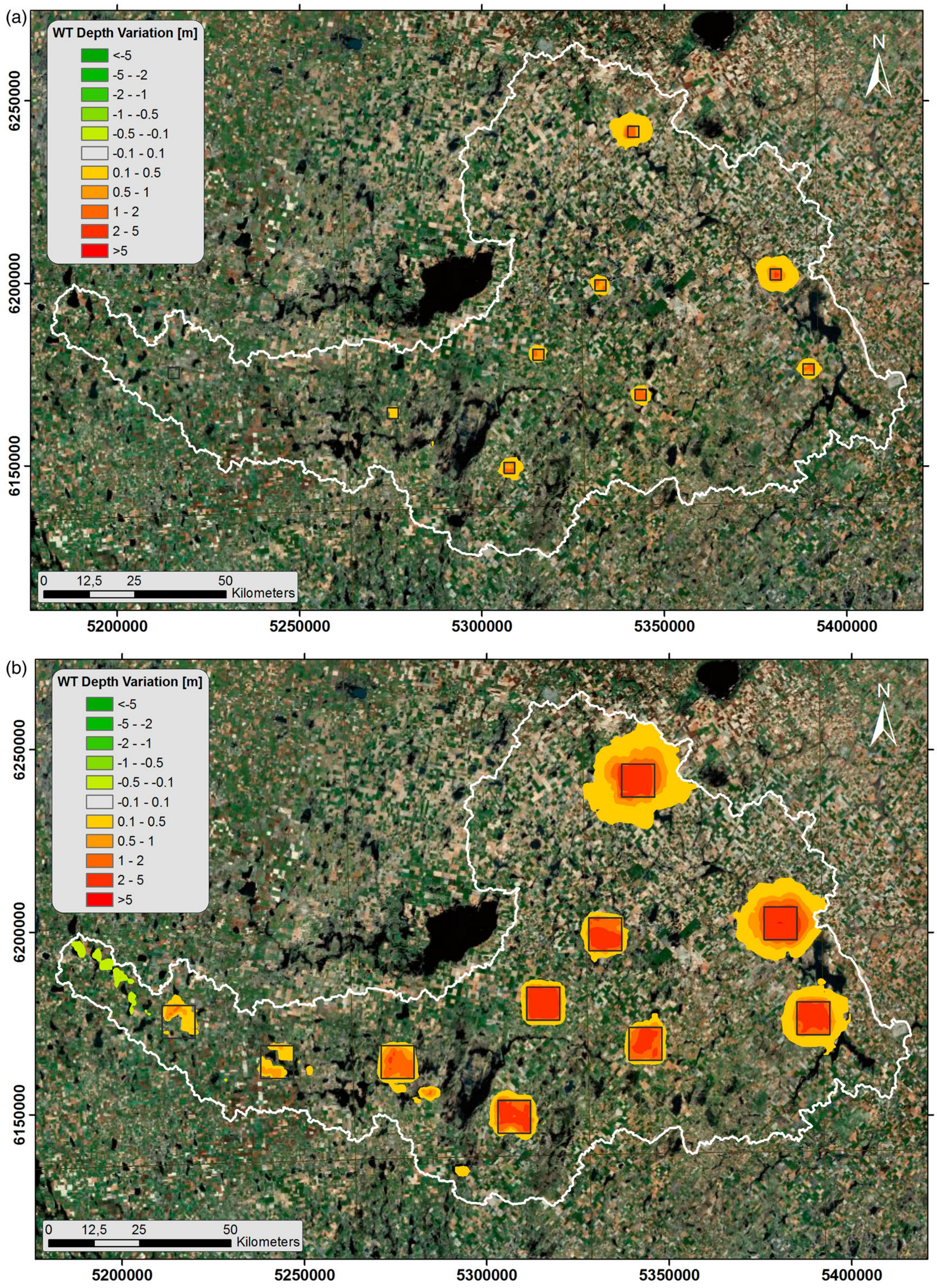

**Figure 7.** Annual average WTD variation for regime conditions. (a). Scenario D (all soybean with pasture islands of 3 km) – Scenario B (all soybean). (b). Scenario F (all soybean with pasture islands of 9 km) – Scenario B (all soybean).

differences were expressed as a percentage of the maximum WTD difference for each scenario (usually observed at the island's centre, or distance 0). Note that the WTD difference curves for the two major types of intervention were very similar. Moreover, the relative WTD variations outside the island (relative distances >0.50–0.71) were always below 50%.

As previously shown, a farmer's land use choice may affect WTD in adjacent farms, but the impact gets progressively smaller as the distance from that farmer's own land increases. We estimated the area influenced by a specific land use choice given four different thresholds of absolute WTD variation (the thresholds considered range from 0.25 to 2.00 m, with a step of 0.25 m). Figure 9(a) shows the 'area influenced' for two islands located in different ends of the basin; as a result of their location, the islands differ in initial WTD. Obviously, the area influenced decreases if higher thresholds are considered. For Island 9, the area influenced was larger than the island area (i.e. a farmer's land use affects WTDs over an area larger than his own land) when the threshold is ≤0.5 m for Scenario D, ≤1.25 m for Scenario E, and ≤2 m for Scenario F; the influenced area reached values between 3.5 and 4 times the intervened area if the threshold

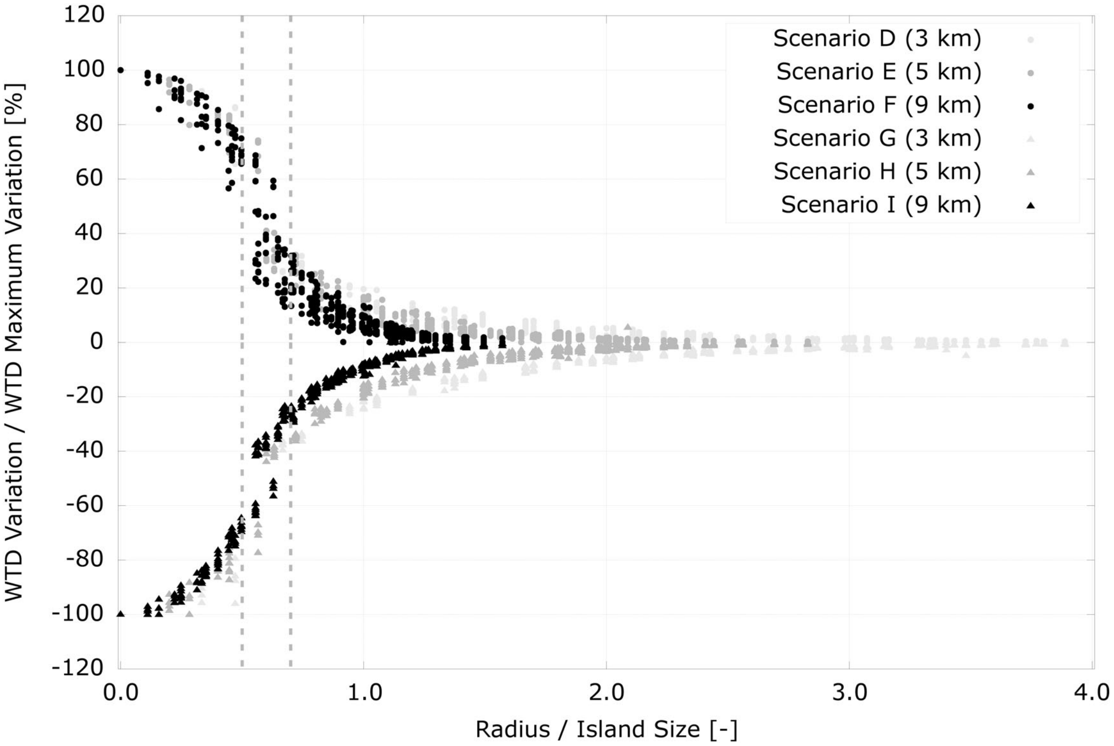

**Figure 8.** Radial distribution of annual average relative WTD variation for Island 9 for different pasture (scenarios D, E, and F) and soybean (scenarios G, H, and I) island sizes, and their respective reference scenarios (B and C).

is 0.25 m. In the case of Island 1, the influenced area was always lower than the intervened area; for a threshold value of 0.25 m, it attained a maximum of 45% of the intervened area for scenario F.

The chessboard pattern reduced the effective area subject to intervention. Figure 9(b) is similar to Figure 9(a), but compares the size of the influenced area for Scenarios F and J. Note that the spatial effects on WTD were not necessarily proportional to the reduction of the intervened area: in relative terms, the chessboard pattern showed higher spatial effects than the regular pattern. This result suggests that a chessboard strategy should be more efficient from a practical point of view. For instance, if a pasture were implanted with the goal of lowering WTD and thus reducing flood risks, the same area of pasture would influence a larger extent if it were arranged as a chessboard, rather than as a contiguous block of land.

### 4.3. Impacts of climate variability on WT dynamics

In a flat landscape such as the SA1 basin, WTD is mainly controlled by two opposing processes: evapotranspiration and precipitation. The former is mostly a function of land use and time of year; for that reason, in Section 3.1 we explored the effects of land use on WTs. At the same time, however, the SA1 basin has shown considerable rainfall variability on both interannual and decadal scales (Berbery and Barros 2002). Because rainfall fluctuations can play an important

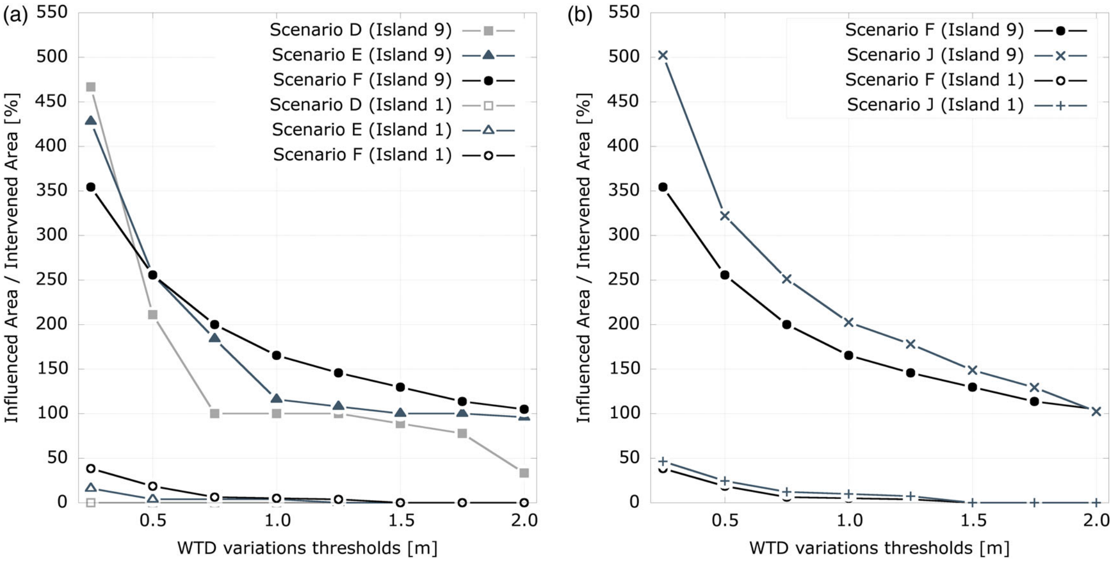

**Figure 9.** Area influenced as a function of the threshold for WT depth variation. (a). Comparison between scenarios D, E and F for different islands (1 and 9). (b). Comparison between scenarios F and J for different islands (1 and 9).

role in WT dynamics, this section explores WTD responses to variability in precipitation.

Two variants of scenario F were considered in these simulations. These two variants involved changing the base year in order to impose both drier (Scenario K) and wetter (Scenario L) rainfall conditions. The alternative base years chosen had annual precipitation closer to the 20-percentile (860 mm, year 1994) and 80-percentile (1280 mm, year 2002), respectively, of historical spatially averaged annual precipitation. Alternative scenarios I and J had total precipitations 15% lower and 30% higher than Scenario F, respectively.

Figure 10(a) shows the time series of spatially averaged WTD for scenarios F, K, and L. WTD for regime conditions was higher for the dry scenario (K) and lower for the wet scenario (L), as expected. WTD variations relative to Scenario F were about +0.5 m and −1.5 m, respectively. These results suggest a non-linear impact of rainfall on WTD: although the precipitation increase in the wet scenario (30%) was twice as large as the corresponding decrease (15%) for the dry scenario, the corresponding WTD rise was 3 times the respective WTD fall for the drier scenario.

Figure 10(b) compares the area, relative to the intervened area, as a function of the WTD variation threshold for the three scenarios. The spatial extent of the effects of land use decreased as precipitation increased. Conversely, the area impacted increased in a scenario with low precipitation. In summary, the same intervened area may have totally different effects on neighbouring WTDs, depending on weather conditions.

## 5. Discussion

In extremely flat plains, there are complex two-way interactions between agricultural production and groundwater: the latter affects agricultural production outcomes and risks, whereas agricultural production decisions – especially land use – influence groundwater dynamics.

The commons dilemma posed by groundwater may be naturally constrained in the Argentine Pampas due to the limited spatial impact of land use suggested by our results (Figure 7). Therefore, management of WTD at the landscape level requires actions that ensure maintenance of the water level in the 'goldilocks range', where it is neither too deep for the roots nor too shallow and thus likely to cause flooding, and has the greatest utility for all. Such outcomes warrant cooperative action (Niou and Ordeshook 1994) where everyone is willing to undertake actions which are best for reaching the ideal WTD in the long run, but are frequently in conflict with individual rational decision-making in the short-run, wherein each farmer seeks to maximize profit in a given cropping cycle. Land use choices leading to profit maximization can and do influence available groundwater for both the decision-maker and others connected spatially, as is illustrated in this paper. For instance, farmers could coordinate to increase pasture area in order to lower groundwater levels and minimize risks of flooding. The chessboard scenarios presented in this paper illustrate that when considered collectively over a larger area than just a farm, a combination of land uses allows farmers to affect WT levels significantly enough to assist in WTD management.

Maintaining a combination of land uses however, would require collective cooperative action and a long-term focus as the groundwater implications of land use are frequently realized only with a delay due to slower movement of groundwater below the surface: Although land use decisions are made anew for each cropping cycle (Bert *et al.* 2011), their impact on groundwater both in the decision-maker's farm and adjoining farms, may take multiple cropping cycles to be fully realized. As a result, those who make the land use decisions may or may not be the same as those who face the consequences of those decisions in terms of WTD (Arora *et al.* 2015). Thus the dilemma posed by groundwater in the Argentine Pampas embodies two levels of interdependencies – first, the traditional conflict between a rational decision for individual gain and a pro-social decision for collective management of WTD, and second, an inter-temporal conflict of maximizing economic gain today vs. managing WTD for minimizing flooding risks in the future.

Past research illustrates that interdependent decisions, such as the one described above have two basic sources of uncertainty: social (i.e. the choices of other decision-makers and their impact) and environmental (i.e. the level of resource

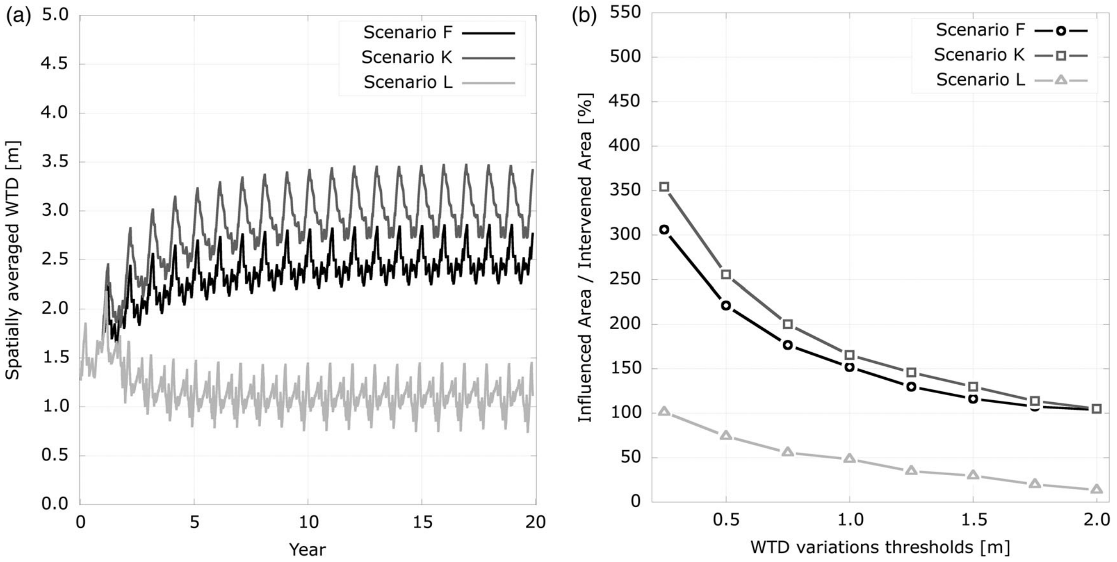

**Figure 10.** Impacts of climate variability for normal (Scenario F), drier (Scenario K) and wetter (Scenario L) rainfall conditions. (a). WTD variation to reach steady state conditions. (b). Area influenced as a function of the threshold for WT depth variation.

and its rate of replenishment). Many factors influence social uncertainty, but two that are critical and have been widely studied are group size (Brewer and Kramer 1986) and identification or affiliation with other decision-makers whose outcomes are impacted (Arora *et al.* 2015). Increasing group size results in greater likelihood of diffusion of responsibility (Darley and Latané 1968), such that the interdependency is essentially ignored (Budescu *et al.* 1992). Greater identification with others in an interdependent situation, on the other hand, leads to greater focus on group goals and this a greater willingness to make an individual economic sacrifice for the benefit of the collective (Brewer and Kramer 1986, Arora *et al.* 2012). We find anecdotal evidence of the role of group affiliation in our interviews with farmers where those who have ongoing social relationships with neighbours have been known to coordinate on temporary solutions, such as the construction and maintenance of channels to move surface water collectively from multiple spatially connected flooded farms, while others, lacking such relationships, act to manage the surface water only on their own farms. There is no evidence of coordination on land use for collective management of WTD, but the existing social relationships may allow for such a dialogue in the future.

Environmental uncertainty arises because resource size and regeneration rates are unknowns. It is difficult to predict the exact level of available groundwater, total rainfall, and the precise amount of groundwater absorbed by crops planted. Hence resource size and regeneration rates and are usually anecdotally or experientially estimated by decision-makers, who then base their choices on the past experience. In interviews with farmers, we found a strong optimism that groundwater tends to manage itself by generally achieving similar levels at the start of each cropping cycle, independent of the rainfall during the previous cropping cycle. This belief is in keeping with the trend for optimism seen in previous research regarding environmental uncertainty (Budescu *et al.* 1992), and as expected, resulted in the underestimating of the amount of increase in the WT due to land use choices, as well as an assumption of independence between one's choices and those of one's neighbours. Over the past 20 years, the average level of groundwater in the Argentine Pampas has risen by over 2 m. It bears pointing out that the typical decision-maker interviewed by the authors in the Argentine Pampas is highly educated (university education), sophisticated in his understanding of the consequences of actions along a triple bottom line – economic, environmental, and social outcomes (Arora *et al.* Under Review), and willing to consider coordination on mutually beneficial options (Arora In Preparation). A logical next step, therefore, would be to share the groundwater implications with decision-makers, perhaps in the form of an experiment, to better understand the psychological motivations that underlie the assumption of independence and environmental optimism.

## 6. Conclusions

This paper assessed the temporal and spatial dynamics of WTD in a portion of the Salado Basin in the Argentine Pampas, a major agricultural area with very flat relief. Different scenarios were simulated using the MIKE SHE hydrological model to quantify the temporal and spatial effects of climate and land use on WTD.

A novel aspect of this work is the relatively large spatial scale of the study. While previous work has examined linkages between land use and WT in flat plains, these studies often have relied on point or transect measurements collected at field or plot levels. In contrast, this paper relies on simulation to assess the effects of land use and climate variability throughout a fairly large basin (14,500 km$^2$). Our approach included detailed parameterization of land use, including the temporal evolution of root systems and leaf area of the modelled crops and pastures.

We find marked effects of land use on groundwater levels and dynamics in flat landscapes, confirming prior experimental results. Our simulations show that land uses that consume more water (e.g. pastures) lead to decreases in WT levels. Conversely, annual crops preceded by a fallow period generally increase WT levels. These results support previous evidence that the expansion of field crops and displacement of pastures and grasslands has led to increased groundwater recharge and shallower WT levels in parts of the Pampas.

Results from this paper are relevant to explore the scope for actively managing WTD through land use decisions to avoid the negative effects of groundwater on agricultural production while, simultaneously, attempting to maximize positive impacts (e.g. groundwater 'subsidies'). A key contribution of this paper is the assessment of interdependencies among spatially close decision-makers sharing a WT. These interdependencies may have different human and physical implications in agricultural systems of flat plains. For example, interdependencies between groundwater and land use may shape farmers' social relationships: a farmer's land use decisions may influence either positively or negatively the yields and flooding risks of neighbouring farmers. As this paper shows, the intensity of this influence depends on WT levels and precipitation levels during the cropping cycle (Figures 8 and 9). For instance, interdependencies may be almost nonexistent under shallow WT and in rainy years, as water is plentiful for all. However, should high levels of rainfall combined with a shallow WT result in a flood, the interdependency swiftly becomes significant and negative, as surface water flows are much faster than the underground horizontal movement of groundwater.

The present results also provide some preliminary evidence on the limitations for managing WTD through land use decisions. The first issue is the spreading of land use effects on WTD from the farm ('island') to the sub-basin level. In this respect, a negligible influence is observed if land use is changed in only a few small areas. This result indicates that landscape-wide land use changes would be necessary to effectively modify the frequency of flooding and drought at the basin level. A second issue is the cumulative effects of land use on WTD: under constant climate drivers, regime conditions in WTD are reached after 10–15 years, depending on the crop. This suggests that land use change, aimed to manage groundwater at basin level, should be not only landscape-wide, but also persistent over time.

In summary, this paper assessed the two-way non-linear interactions between land use, climate, and groundwater in flat plains. The present results suggest that although the farmers could seek to control groundwater levels through land use decisions, the effectiveness would be subject to uncontrollable and even unpredictable factors such as climate. In addition to the complexity of the physical system, the management of WT would require the willingness of farmers to adapt land use decisions, and eventually coordinate actions. Although the relatively stylized simulations of this work show clear effects of land use on groundwater and interdependencies among spatially close farmers, preliminary results from field interviews suggest that, at present, farmers in the Pampas are not completely aware of the impacts of their land use decisions on WT, and even less about the interdependencies among them. As a continuation of this work, two lines of research have been defined. In the first place, the hydrological model will be coupled to an agent-based land use change model to explore, in a more realistic way, the scope for managing groundwater levels in agricultural systems of flat plains. In the second place, the temporal dynamics of the WTD will be investigated, in order to determine the time scales required to achieve desired goals through land use management.

## Note

1. The water table is defined as the top of the water-saturated zone (or phreatic zone) in the soil profile.

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