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Assessing groundwater pollution hazard changes under different socio-economic and environmental scenarios in an agricultural watershed

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HIGHLIGHTS

- A DSS for assessing groundwater pollution hazard changes is implemented.
- Two different socio-economic and environmental scenarios were considered.
- Relegate Sustainability Scenario showed a 20% increase in groundwater pollution hazard.
- Sustainability Reforms Scenario displayed a 2% increase in groundwater pollution hazard.
- This tool allows identifying future protection areas and optimizing water management.

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ABSTRACT

This paper proposes a modeling approach for assessing changes in groundwater pollution hazard under two different socio-economic and environmental scenarios: The first one considers an exponential growth of agriculture land-use (Relegated Sustainability), while the other deals with regional economic growth, taking into account, the restrictions put on natural resources use (Sustainability Reforms). The recent (2011) and forecasted (2030) groundwater pollution hazard is evaluated based on hydrogeological parameters and, the impact of land-use changes in the groundwater system, coupling together a land-use change model (Dyna-CLUE) with a groundwater flow model (MODFLOW), as inputs to a decision system support (EMDS). The Dulce Stream Watershed (Pampa Plain, Argentina) was chosen to test the usefulness and utility of this proposed method. It includes a high level of agricultural activities, significant local extraction of groundwater resources for drinking water and irrigation and extensive available data regarding aquifer features. The Relegated Sustainability Scenario showed a negative change in the aquifer system, increasing (+20%; high–very high classes) the contribution to groundwater pollution hazard throughout the watershed. On the other hand, the Sustainability Reforms Scenario displayed more balanced land-use changes with a trend towards sustainability, therefore proposing a more acceptable change in the aquifer system for 2030 with a possible 2% increase (high–very high classes) in groundwater pollution hazard. Results in the recent scenario (2011) showed that 54% of Dulce Stream Watershed still shows a moderate to a very low contribution to groundwater pollution hazard (mainly in the lower area). Therefore, from the point of view of natural resource management, this is a positive aspect, offering possibilities for intervention in order to prevent deterioration and protect this aquifer system. However, since it is quite possible that this aquifer status (i.e. groundwater quality) changes in the near future, the implementation of planning measures and natural resource management is recommended.

1. Introduction

Groundwater is one of the most valuable natural resources, which supports life on earth, economic development and ecological diversity. Even though, groundwater systems can display a high degree of natural variation, generally present several inherent characteristics (e.g. consistent temperature, widespread and continuous availability, good natural quality, limited vulnerability, low extraction/exploitation costs, and drought reliability), which have lead them to become an immensely important and dependable source of water supplies within all climatic regions including both urban and rural areas of developed and developing countries (Todd and Mays, 2005). Unfortunately, the excessive use

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and continued mismanagement of water resources to supply an ever-increasing water demand to irresponsible users have led to water shortage, increasing pollution of freshwater resources and degraded ecosystems worldwide (Jha et al., 2007).

Agricultural land-use is one of the factors which most affects the quality of surface water and groundwater (William et al., 1996; Friedel, 1998; Fohrer et al., 2001). Intensive agricultural activity increases erosion and sediment load, and leaches nutrients and agricultural chemicals into groundwater, streams, and rivers (Foley et al., 2005). Nowadays, agricultural expansion in Argentina has added to the increasing pressure on natural resources (Viglizzo, 2001). This has lead to a greater threat of aquifer pollution. Many studies (Costa et al., 2002; Aparicio et al., 2008; Gonzalez et al., 2012, 2013) show evidence of high concentrations of contaminants in groundwater in the southeast of the Buenos Aires Province in Argentina, probably due to rain and irrigation leaching.

Land-use change models are useful tools for understanding the dynamics of land-use and to support national political decision on land-use management. On the one hand, they allow understanding socio-economic and biophysical factors which have an influence on the spatial parameters and in the rates of land-use changes. In addition to this, these models can help to explore future land-use changes under different scenarios and identify regions that qualify as critical areas of land-use change (FAO, 2002; Verburg et al., 2002, 2004; UNEP, 2010). UNEP (2010) defined four regional scenarios for Latin America and the Caribbean: *Relegated Sustainability*, *Sustainability Reforms*, *Unsustainability* and *Increased Conflicts*, *and Transition to Sustainability*. These scenarios are neither predictions nor projections, but rather plausible images of the future defined by using different combinations of driving forces where the economical, social and environmental costs of each of the trajectories depend to a greater extent on the speed with which the objectives of sustainability and human well-being are integrated into the decision making process (UNEP, 2010).

Frequently, changing land use is used as an input in models that calculate environmental impacts such as pollution, emissions and erosion (King et al., 1989). Analysis of the impact of land-use on the dynamics and quality of groundwater needs the integration of information about characteristics of the surface (topography, permeability, type and thickness) and geological strata, along with the configuration of different types of coverage of the land cover (Arnold and Friedel, 2000). The improvement of land-use change models combined with developments in hydrological models allows for more realistic predictions of future subsurface hydrology (Dams et al., 2007).

Even though an extensive amount of research concerning land-use impacts on groundwater exists in primary literature (Giacomelli et al., 2001; Batelaan and De Smedt, 2001; Klöcking and Haberlandt, 2002; Batelaan et al., 2003; Scanlon et al., 2005; Dams et al., 2007; Jiang et al., 2008; Singh et al., 2010; Lima et al., 2011a; Khan et al., 2011; Ouyang et al., 2014), the complex interactions between hydrologic and socio-economic factors are yet to be elucidated.

The aim of this study is to propose a modeling approach for assessing recent and forecasted changes on groundwater pollution hazard under two socio-economic and environmental scenarios. Particularly, in the Pampa Plain, agricultural expansion has become an increasing economic trend and, in this context, two possible scenarios were defined in this study for the region according to UNEP (2010). The first one takes into account an exponential growth of agriculture land-use (Relegated Sustainability, RS) and the second, includes several agricultural land-use restrictions (Sustainability Reforms, SR). Recent and forecasted groundwater pollution hazard is evaluated based on hydrogeological parameters and the impact of land-use changes on the groundwater system, coupling together a land-use change model Dyna-CLUE 2.0 (Verburg and Overmars, 2009) and a groundwater flow model (MODFLOW) (Harbaugh, 2005), as inputs to a Decision System Support (DSS) (EMDS, Reynolds et al., 2003).

2. Study area

The study area is located in the southeast of Buenos Aires Province, covering an area of 1000 km^2. Dulce Stream is originated in the Tandilia Range System and flows into the Mar Chiquita lagoon (Fig. 1). The area of the lagoon was incorporated as a MAB Reserve (Man and Biosphere Program, UNESCO) in 1996 due to the high conservational value of its biodiversity related to different ecological regions (plain, flood plain, marshes, deltas, dune barriers) (Iribarne, 2001).

The area has a “moderate-humid” climate (Köppen's classification), or “sub-humid–humid, mesotermal, without water deficiency” type (Thornthwaite's method) (Lima et al., 2011a). In the last 20 years, the average annual rainfall in the region has ranged from 960 to 1170 mm, whereas the average temperature in summer is 20 °C and in winter 10 °C.

Elevation in the watershed ranges from 2 to 357 masl with ranges of the Tandilia System in the upper basin. The Tandilia Range System in the area consists of two big geological units: a Precambrian crystalline bedrock called Complejo Buenos Aires (Marchese and Di Paola, 1975), and a set of sedimentary rocks of Precambrian–Lower Paleozoic origin, grouped under the name of Balcarce Formation (Dalla Salda and Iñiguez, 1979). They are both considered to be hydrogeological bedrock. An inter-range fringe surrounds the blocks; it is formed by hills which quickly give way to plain areas that stretch out towards the sea. Hills and plain are formed by Cenozoic loess-like sediments (especially of Pleistocene–Holocene age). Hills have Typic Argiudolls and Petrocalcic Paleudolls soils (slope and water storage limitation), while the plain area has Petrocalcic Hapludolls soils (sodium excess, drainage problems and high pH) (INTA, 1989; USDA, 1999).

The Dulce Stream Watershed can be divided into three sectors according to geomorphological and land-cover aspects (upper, middle and lower) which are composed of multiple subwatersheds. The upper sector of the watershed (hilly area) presents soils with a high agricultural productivity (soybeans, wheat, sunflowers, corn, potatoes). Furthermore, this sector is characterized by high agrochemical application and irrigation water demand. In relation to the middle sector, mixed economic activity is shown (agricultural and cattle breeding activities) with some productive soil sectors for agriculture. To the contrary, in the lower sector cattle breeding is the dominant activity. The last two sections coincide with the plain area.

3. Methodology

3.1. Overview

The methodology consists of three steps. In the first part, the medium-term land-use changes in the study area are modeled, based on the Dynamic Conversion of Land-Use and its Effects model (Dyna-CLUE 2.0) (Verburg and Overmars, 2009), under two socio-economic and environmental scenarios, called Relegated Sustainability (RS) and Sustainability Reforms (SR). Annual land-use maps have been created since 2011 (the original land-use map) up to the year 2030. In the second step, the 2030 land-use maps (RS and SR scenarios) are used in a steady state MODFLOW model (Harbaugh, 2005) of the groundwater system of the area to determine the depletion of groundwater levels due to supplementary irrigation. Finally, actual (2011) and forecasted groundwater pollution hazard (2030; RS and SR scenarios) is evaluated based on both hydrogeological parameters and the impact of land-use changes on the groundwater system, integrated into a decision support system (EMDS, Reynolds et al., 2003). Most spatial data used in this study came from previous studies of the region (Massone et al., 2005; Zelaya et al., 2009; Lima et al., 2011a, 2011b). Subwatersheds of the Dulce Stream Watershed were used as analysis units. ArcGIS 9.2 (Environment System Research Institute, 2007) was used to manage spatial data of the different models. A spatial cell resolution of 100 m × 100 m was used. Information was projected

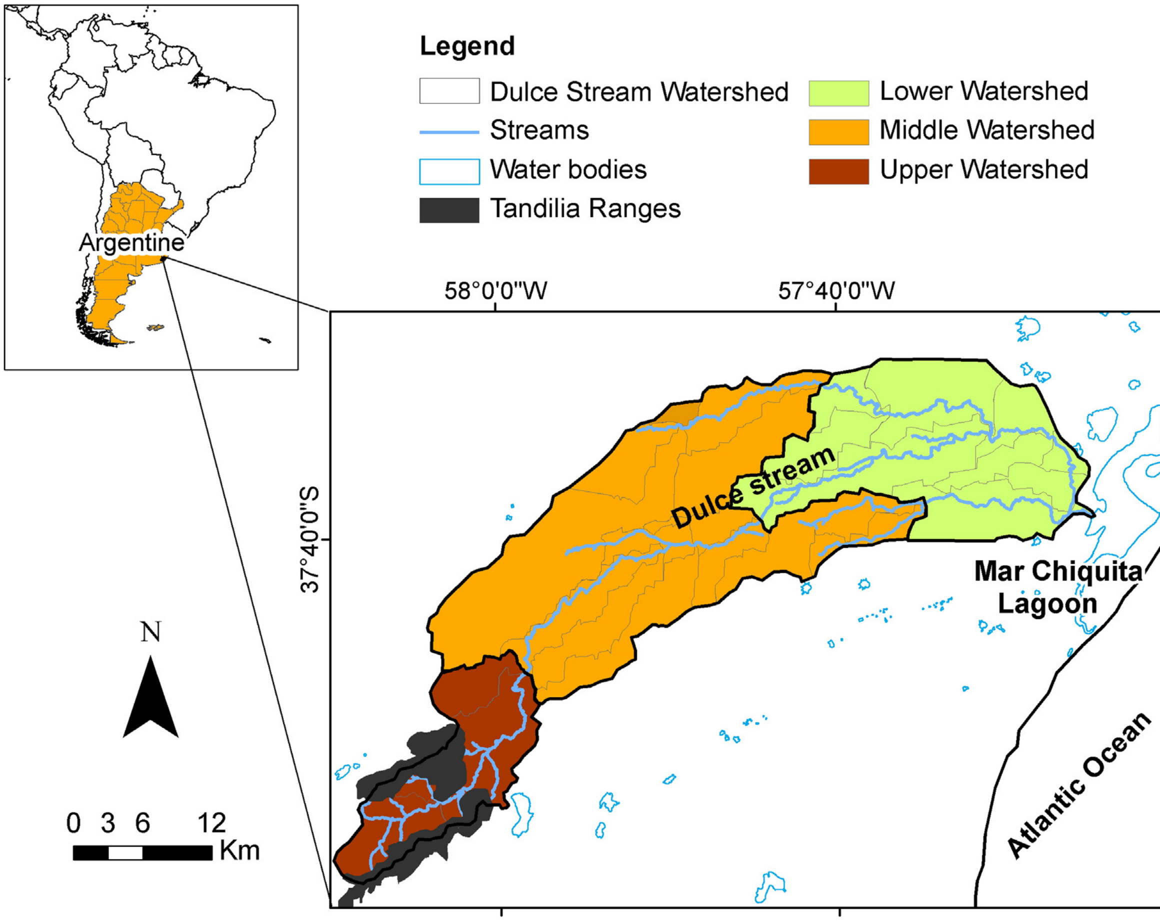


Fig. 1. Location map. Subwatersheds of the Dulce Stream Watershed.

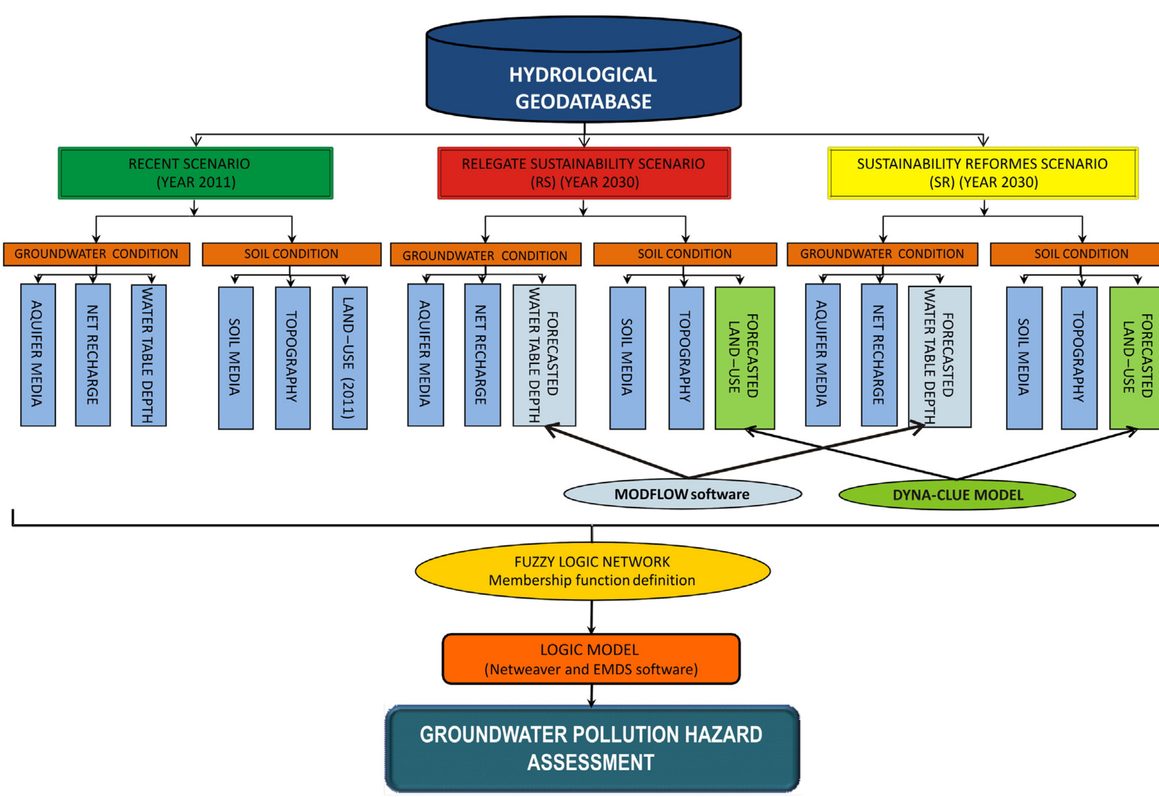


Fig. 2. Methodological framework for the proposed decision support system (DSS).

through an Argentine Gauss Krüger system, zone 6 (Campo Inchauspe Datum). The methodological framework for the proposed assessment is illustrated in Fig. 2. Different input maps necessary for the assessment of groundwater pollution hazard are shown in Fig. 3.

3.2. Step 1. Dyna-CLUE model: simulation of land-use changes under socio-economic and environmental scenarios

The empirical land-use model, Dyna-CLUE, was employed to simulate future land-use patterns in the study area. This dynamic spatial simulation model uses historical and recent land-use patterns related to socio-economic and biophysical driving factors at different scales. This Dyna-CLUE model was calibrated using remote sensing data (Zelaya et al., 2009; Lima et al., 2011b).

In order to achieve this simulation, and because land-use changes are related to a large number of biophysical and socio-economic factors, the model uses the coefficients (β) from a logit regression model, in which land use is the dependent variable and the driving factors are the explanatory or independent variables. The allocation is based upon a combination of empirical, spatial analysis and dynamic modeling. The total allocated area of the different situations of land use is compared to the land use requirements (demand) (Verburg et al., 2002).

Four land-use types were distinguished in Dulce Stream Watershed based on Landsat TM satellite images and field trips. They were

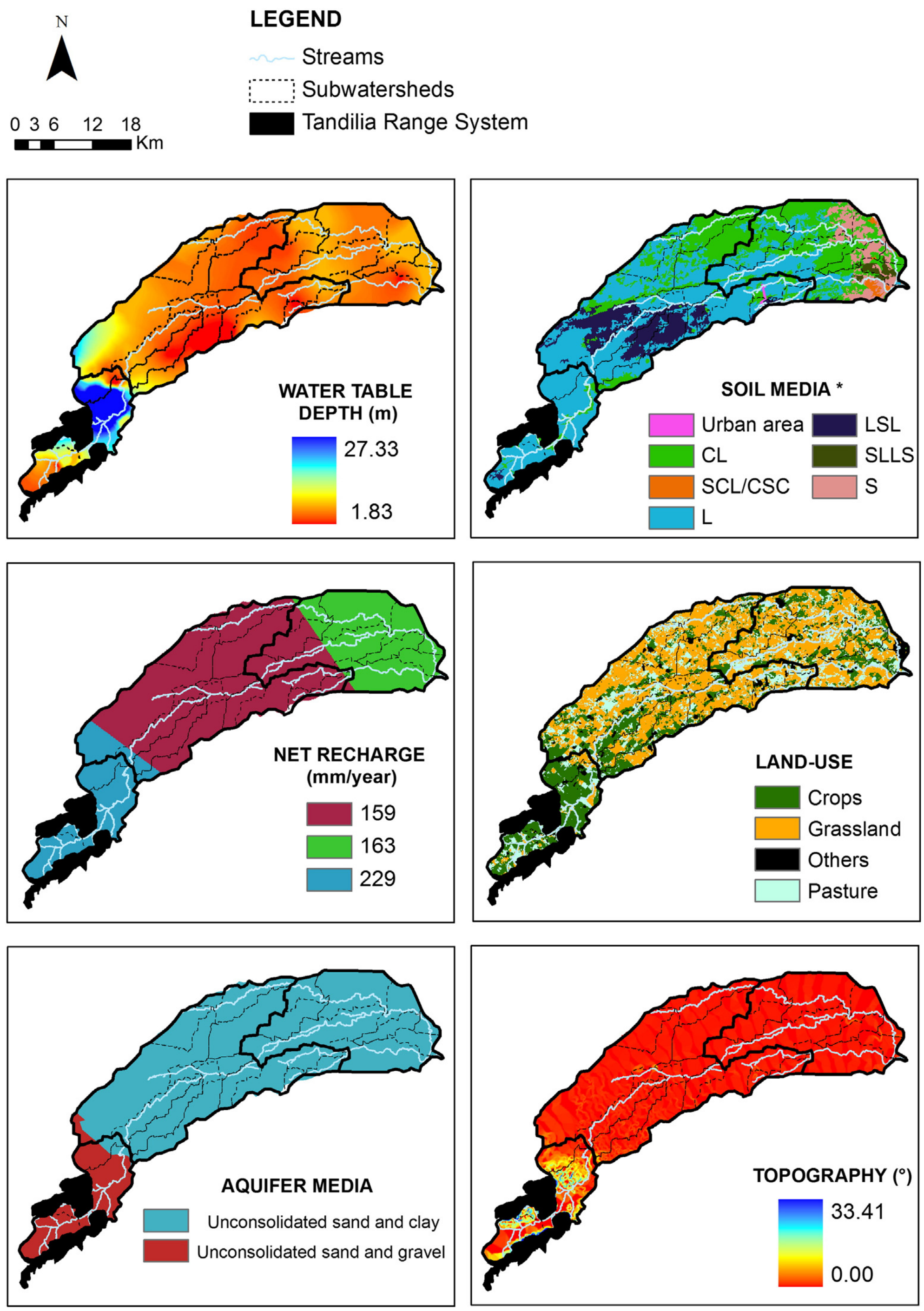


Fig. 3. Input maps for the Groundwater Pollution Hazard Assessment. *Soil media (*CL*: clay loam soil texture), (*SCL/CSC*: silty clay loam or clay to silty clay soil texture), (*L*: loam soil texture), (*LSL*: loam to sandy loam soil texture), (*SLLS*: sandy loam to loamy sand soil texture), (*S*: sandy soil texture).

Table 1
Description and data source of the driving factors which underpin the proximate causes of land-use change.

Driving factor	Description and data source
Altitude (m)	Shuttle Radar Topographic Mission Imagines (NASA), spatial resolution 90 m.
Slope (%)	Product of the altitude map.
Geomorphology (1: ranges, 2: hill, 3: plain)	Digital terrain model, satellite images and cartography from National Institute of Geography of Argentina (IGN).
Flooding areas (Boolean format)	Probability of maximum flood obtained by satellite images during a period of extreme flood event in the region (year 2002).
Annual precipitation (mm/year)	National Meteorological Service (SMN).
Land suitable for cultivation (Boolean format)	Soil Map of SAGPyA-INTA. Scale 1:50,000. Agricultural land capability classes I and II (USDA, 1989), which have few limitations for raising crops
Land suitable for pastures (Boolean format)	Soil Map of SAGPyA-INTA. Scale 1:50,000. Agricultural land capability classes III and IV (USDA, 1989), with soil limitations for cultivated crops such as poor drainage, limited root zone, climatic restriction, etc.
Land suitable for grassland (Boolean format)	Soil Map of SAGPyA-INTA. Scale 1:50,000 Agricultural land capability classes V–VII (USDA, 1989), with soils which are suited only for non-agricultural uses.
Distance to cities (m)	Distances to the central point of main cities.
Distance to roads (m)	Distance to national and province roads.
Distance to streams (m)	Distance to permanent and intermittent streams.
Distance to water bodies (m)	Distance to shallow lakes, etc.

Table 2
Hydrogeological parameters used in the groundwater flow modeling.

Parameters[a]	Units	Value (hilly area)	Value (plain area)
Hydraulic conductivity (Kx, Ky, Kz)	m/day	20	20
Storage coefficient (Ss, Sy) (Sala, 1975; Quiroz Londoño et al., 2006)	1/m	0.001	0.001
Effective porosity (Sala, 1975; Quiroz Londoño et al., 2006)	Dimensionless	0.15	0.15
Total porosity (Sala, 1975; Quiroz Londoño et al., 2006)	Dimensionless	0.15	0.15
Recharge	mm/year	185	150

[a] Parameters used in the MODFLOW model.

classified according to Zelaya et al. (2009): Crops (annual agricultural crops), Pasture (sown pasture), Grassland (natural fields which could have some human intervention) and Others (range, forest, urban area, dunes and water bodies). The exponential method was applied to calculate the growth rate of each type of land-use, using historical land-use data (1997–2005). This method, bearing a mean absolute percentage error (MAPE) of 2.10%, was selected because it is more suitable than linear or logarithmic methods (Lima et al., 2011b).

The smallest number of significant explanatory variables was selected for land-use modeling: altitude (m), slope, geomorphology, flooding areas, annual precipitation (mm), land suitable for cultivation, land suitable for pastures, land suitable for grassland, distance to cities, distance to roads, distance to streams and distance to water bodies. Table 1 shows a brief description and data sources of the driving factors which underpin the proximate causes of land-use change.

A brief description and local assumptions for each proposed scenario in the land-use model follows on:

Relegated Sustainability (*RS*) *Scenario*. On a global scale, in this scenario economic growth takes priority over social and environmental objectives so that policies and practices are fundamentally directed at developing markets (UNEP, 2010). On a regional scale,

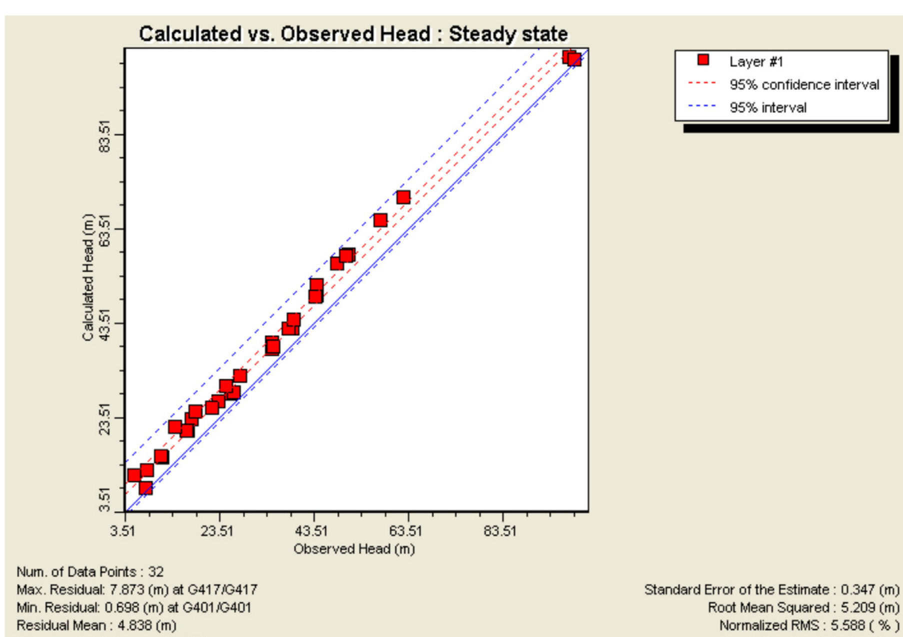


Fig. 4. Plot of the observed and groundwater levels simulated with MODFLOW.

Table 3
Logic outline for Groundwater Pollution Hazard Assessment.

Model topic[a]	Primary topic	Secondary topic	Proposition (stated in the null form)
Groundwater Pollution Hazard (*union*)			Hazard of severe groundwater pollution is low
	1. Groundwater condition (*union*)		Groundwater conditions do not support severe groundwater pollution
		1.a. Water table depth	Expected water table depth is high
		1.b. Net recharge	Net recharge is low
		1.c. Aquifer media	Condition of aquifer media is not conducive to severe groundwater pollution
	2. Soil condition (union)		Condition of soil is not conducive to severe groundwater pollution
		2.a. Soil media	Condition of soil media is not conducive to groundwater pollution
		2.b. Topography	Topography is not conducive to groundwater pollution
		2.c Land-use	Expected land-use behavior associated with groundwater pollution is relatively benign or low impact

[a] Topics and propositions specified in the NetWeaver model.

agricultural expansion is the main characteristic of this scenario due to higher international commodity prices and the introduction of new technologies. Consequently, supplementary irrigation and agrochemical compound applications also increase. Agricultural land-use grows exponentially, showing the following annual growth rate: 1.77% for Crops, 1.01% for Pasture, −3.84% for Grassland and the "Others" category remained constant. Moreover, the Dulce Stream Watershed has no protected areas and no land-use restrictions.

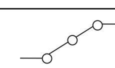
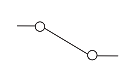
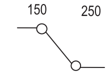
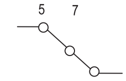
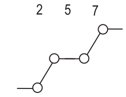
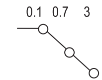
Sustainability Reforms (*SR*) *Scenario*. On a global scale, the market approach still predominates in this scenario, although advances have been made to protect the environment, natural resource management problems persist, particularly within territorial management. Specifically, at the Pampa region, agricultural land-use restrictions focusing on natural resource conservation are assumed. Annual agricultural land-use growth rate was: 1.77% for Crops, 1.01% for Pasture, −1.01% for Grassland in accordance with the following restrictions:

a. Cropland expansion should not exceed the area of high soil aptitude for agricultural use (365.41 km^2).
b. Grassland expansion must be greater or equal to the area of poor soil aptitude for agricultural use (304.60 km^2).
c. Croplands should be forbidden within 100 m of the water bodies and streams as a protection measure. Thus, a 100 m buffer area was specified in order to reduce agricultural chemical runoff into streams and water bodies.

3.3. Step 2. Groundwater modeling

The groundwater system is modeled by applying the United States Geological Survey (Department of Interior) modular three-dimensional finite difference groundwater model (MODFLOW). In

Table 4
Definition of data inputs evaluated by elementary topic, data source, reference conditions for each datum, and fuzzy argument.

Topics	Definition	Data source	Reference conditions: Full evidence (1)	Reference conditions: No evidence (−1)	Fuzzy argument
Water table depth (m)	Evaluate the thickness of the unsaturated zone, i.e. the distance that the water must infiltrate and that can be accompanied by a pollution load to the aquifer.	Hydrogeological field surveys (Lima et al., 2011a)	>30	<5	
Net recharge (mm/year)	This parameter evaluated the amount of water entering the aquifer, the main transport vehicle of the pollutants.	Thornthwaite water balance of the study area (Lima et al., 2011a)	<150	>250	
Aquifer media[a]	Represents the characteristics of the aquifer, particularly the capacity of the porous medium and/or fractured to transmit contaminants.	Previous geological information (Massone et al., 2005)	5	7	
Soil media[b]	This parameter estimates the capacity of soils to retard movement of pollutants, including the top of the vadose zone or unsaturated.	National Institute of Agricultural Technology-INTA, Map of soils. INTA (1989)	2	7	
Topography (°)	Determines the slope of the topographic surface. Is a relevant factor in the recharge of aquifer, in the drainage and in the transport of contaminants by surface runoff.	Digital terrain model and cartography from National Institute of Geography of Argentina (IGN) and Shuttle Radar Terrain Mission (SRTM)	>8	<0.1	
Land-use[c]	Determines the potential pollution load to the aquifer, through agricultural activities in the zone.	Previous land cover information (Zelaya et al., 2009; Lima et al., 2011b)	2	4	

[a] Aquifer media is a qualitative variable. It was represented as a quantitative variable being: 5 (unconsolidated sand and clay aquifers), and 7 (unconsolidated sand and gravel aquifers).
[b] Soil media is a qualitative variable. It was represented as a quantitative variable being: 1 (urban and rocks), 2 (clay loam soil texture — CL), 3 (silty clay loam or clay to silty clay soil texture — SCL/CSC), 4 (loam soil texture — L), 6 (loam to sandy loam soil texture — LSL), 8 (sandy loam to loamy sand soil texture — SLLS), 9 (sandy soil texture — S).
[c] Land-use is a qualitative variable. It was represented as a quantitative variable being: 2 (grassland), 3 (pastures) and 4 (crops).

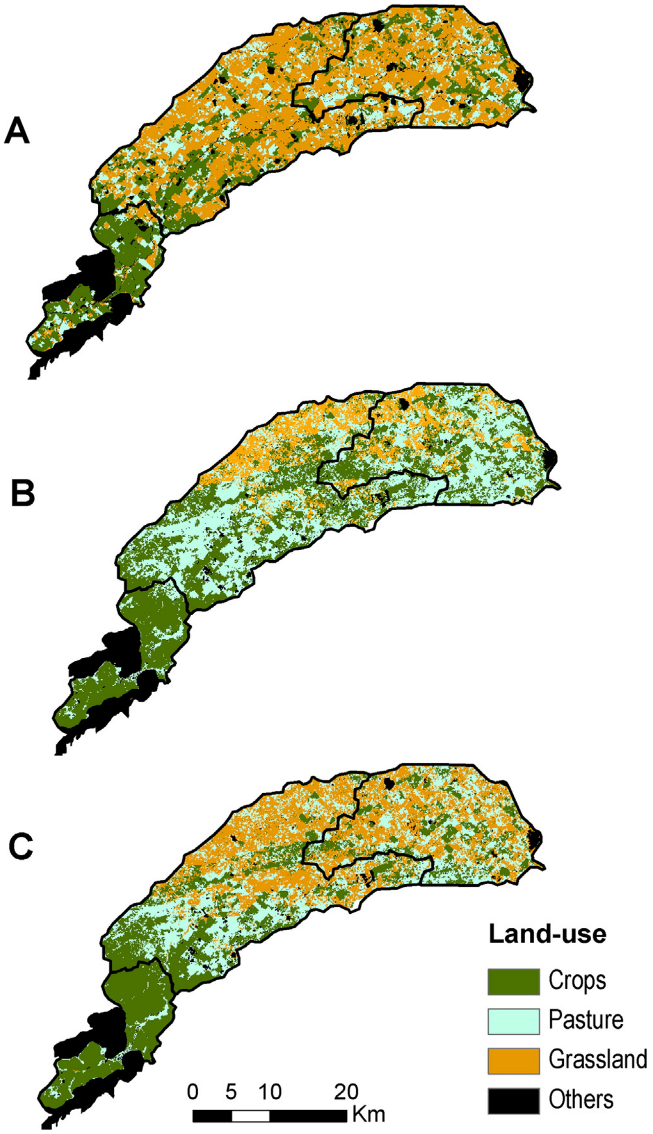


Fig. 5. A) Land-use allocation at the beginning of the simulation process (2011), B) land-use allocation simulated under Relegated Sustainability Scenario (2030) and C) land-use allocation simulated under Sustainability Reforms Scenario (2030).

order to assess the medium-term effect of land-use change on the groundwater levels, a steady state MODFLOW model of the aquifer was projected and performed for the year 2030. A 50% irrigated land increase (58.27 km^2) in the upper watershed was defined for the *Relegated Sustainability Scenario*, according to the agricultural expansion displayed in the forecasted land-use map. Also, in the case of the *Sustainability Reforms Scenario*, a 25% irrigated land increase (29.13 km^2) in the upper watershed was taken into account. An average area of 0.6 km^2 for irrigation wells is assumed; thus, a total of 97 and 48 groundwater extraction wells for irrigation were simulated in the RS and SR respectively, with an average discharge well of 210 m^3/day. This value was calculated based on the present irrigated land area, crop water requirement for the region (127.5 mm/year) and the total groundwater extraction wells for irrigation (according to the pre-established well density). Considering that 15–16.3% represents the irrigation return flow to the aquifer, this value was subtracted from the total crop water requirement (150 mm/year) (Cionchi et al., 2000; Bocanegra, 2011).

The aquifer is formed by silts and silty-to-sandy sediments with variable amounts of calcium carbonate. The mineral composition of the aquifer is mainly quartz, plagioclases, and orthoclase with variable amounts of volcanic glass shards, with the occasional appearance of mica and opaque minerals (Teruggi, 1954). The wells near the range system reported that the thickness of the aquifer is more than 100 m (Santa Cruz et al., 1997). The depth of hydrogeological basement is assumed at 130 m for the hilly area and 150 m for the plain area, average values of the area (Sala et al., 1979–1980). Recharge to the aquifer system is due to infiltration of precipitation excess, and discharge occurs towards surface streams and water bodies. Table 2 shows the main hydrogeological parameters used in the model.

The boundary conditions considered in the numerical model were: null flux for the range area (SW sector) and watershed boundary (coinciding with the groundwater divides), prescribed flux for the irrigation wells (220 m^3/day) and a river boundary condition for the drainage system (this function simulates the influence of a surface water body on the groundwater flow based on stream water level height, depth, width and conductance). A constant value of 0.2 m/day was considered for the bed permeability, this value was obtained from the theoretical curves for fine sediments that constitute the stream bed (Quiroz Londoño, 2009). Therefore, conductance values ranging from 50 m^2/day to 2000 m^2/day (in the discharge area) were obtained. Although different hydraulic conductivity values were introduced into the model during the calibration process, a value of 20 m/day (which best represents the natural conditions) was assumed to be constant for the entire aquifer system. The calibrated groundwater model shows a mean absolute error of 4.83 m, a standard error, estimated in 0.34 m, and a model efficiency of 0.996 between 32 observed and simulated at groundwater levels (Fig. 4). Water table measurements were mainly taken from existing exploitation wells (mills or domiciliary/irrigation wells) during previous hydrogeological field studies (2007–2010).

3.4. Step 3. Decision support system for assessing aquifer pollution hazard

The current system is based on two separate software components: NetWeaver and Ecosystem Management Decision Support (EMDS) (Reynolds et al., 2003). Groundwater Pollution Hazard Assessment was carried out using "rule based" knowledge, which applies the NetWeaver logic engine for processing. The NetWeaver logic model was integrated in EMDS, a decision support system that operates in ArcGIS. The final output maps in EMDS were displayed using a natural breaks algorithm to deliberately accentuate differences among scores of map features.

It is important to highlight that groundwater pollution hazard here is considered a probability and that the aquifer will experience negative impacts from a given anthropogenic activity. In practical terms, hazard assessment implies taking into consideration the interaction between the subsurface contaminant load, as a result of human activities, and the vulnerability of the aquifer to pollution, which depends upon its natural characteristics (water table depth, permeability, degree of fracturing, etc) (Foster et al., 2002).

This logic model includes two primary topics: hydrologic and soil conditions (Table 3, Fig. 2). Each primary topic has secondary topics under which data is evaluated. This logic model shows the state of each evaluated subwatershed with respect to groundwater pollution hazard based mainly on hydrogeological parameters. The secondary topics are the following: water table depth, net recharge and aquifer

Table 5
Percentage of land-use area in the simulations of Dyna-CLUE model for the Relegated Sustainability (RS) and Sustainability Reforms (SR) scenarios.

Scenario	Crops		Pastures		Grassland	
	Area (km^2)	% area	Area (km^2)	% area	Area (km^2)	% area
2011	268.55	27.10	200.79	20.26	476.18	48.06
RS-2030	407.66	40.84	392.06	39.28	140.12	14.04
SR-2030	325.3	32.59	309.56	31.01	304.9	30.55

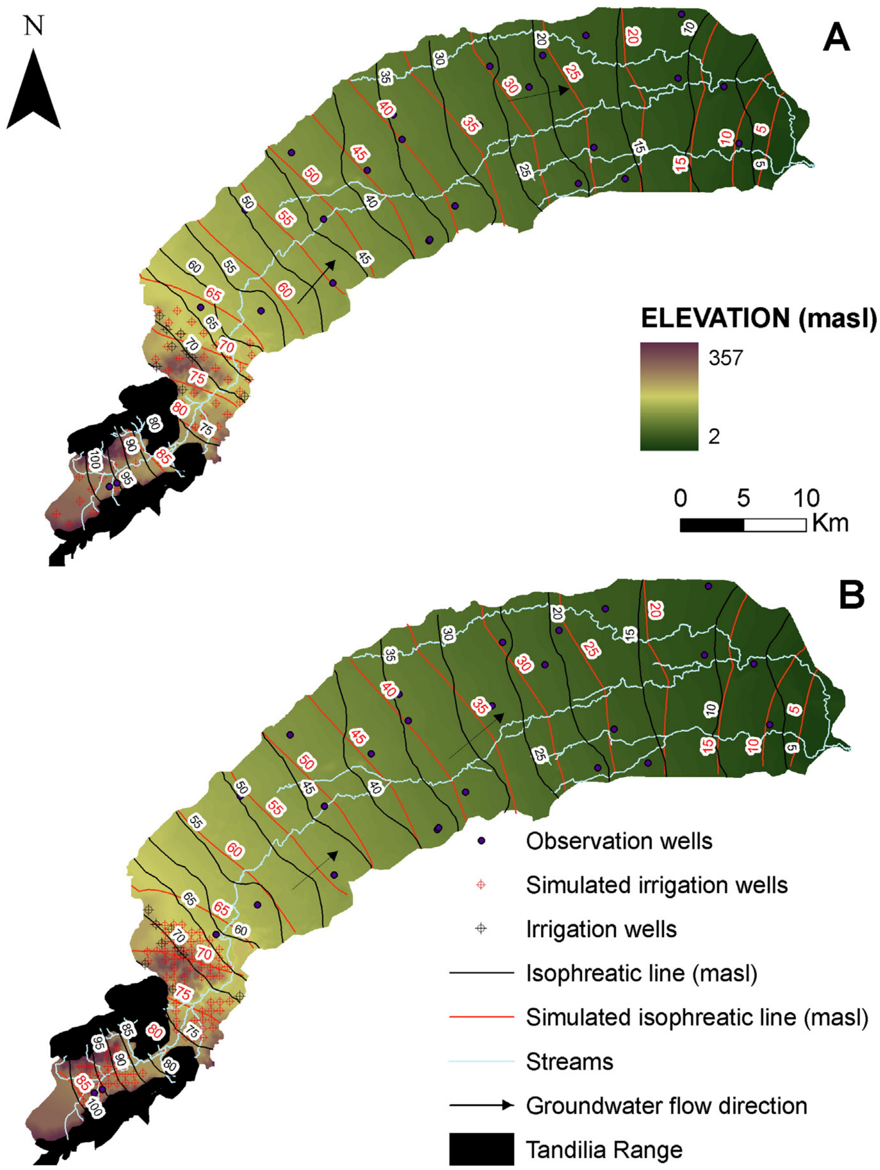


Fig. 6. Isophreatic lines in the A) Sustainability Reforms Scenario and B) Relegated Sustainability Scenario (2030) in comparison to recent isophreatic lines.

media for groundwater condition; and soil media, topography and land-use for soil condition. The full logic structure was a fuzzy logic network. The fuzzy membership function provides an explicit mathematical expression for testing an observation's degree of affinity for the concept represented by the fuzzy subset (Table 4). Fuzzy membership values in NetWeaver range from −1 (totally false, or no evidence) to +1 (totally true, or full evidence).

The complete evaluation depends on two primary topics, each of which contributes increasingly towards the evaluation of groundwater pollution hazard, as indicated by the union operator. Moreover, because the union operator specifies that premises incrementally contribute to the proposition of their parent topic, low strength of evidence for one topic can be compensated by strong evidence from others. Note that this definition of union is distinct to NetWeaver system and should not be confused with a Boolean union operator. Similarly, each of the main topics has its own logical specification that includes a set of secondary topics or premises. An evaluation score of −1 results if all data inputs have the worst possible score. An evaluation score of 1 is reached if all data inputs have the maximum possible score. Logic model results are expressed in terms of the strength of evidence in support of the overarching proposition of low groundwater pollution hazard, and the subordinate propositions under this model topic. In our model all propositions take the null form; for example a low strength of evidence based on the underlying evaluation implies that the proposition of a low groundwater pollution hazard has poor support.

4. Results

4.1. Land-use change with the Dyna-CLUE model

Simulation results showed in the Relegated Sustainability (RS) Scenario that crops are expanding (+14%) in the uplands and in the middle watershed, while pasture expands (+19%) in the middle watershed and throughout the lowland. On the contrary to this, grassland decreases (−34%) in the latter sector. Instead, the Sustainability Reforms (SR) Scenario showed a crop (+5.5%) and pasture (+10%) expansion mainly in the uplands and in the lower-middle watershed, respectively. Grassland decreases (−17.5%) in the middle watershed and in the lowland (Fig. 5 and Table 5). Percentages indicate changes from 2011 to 2030.

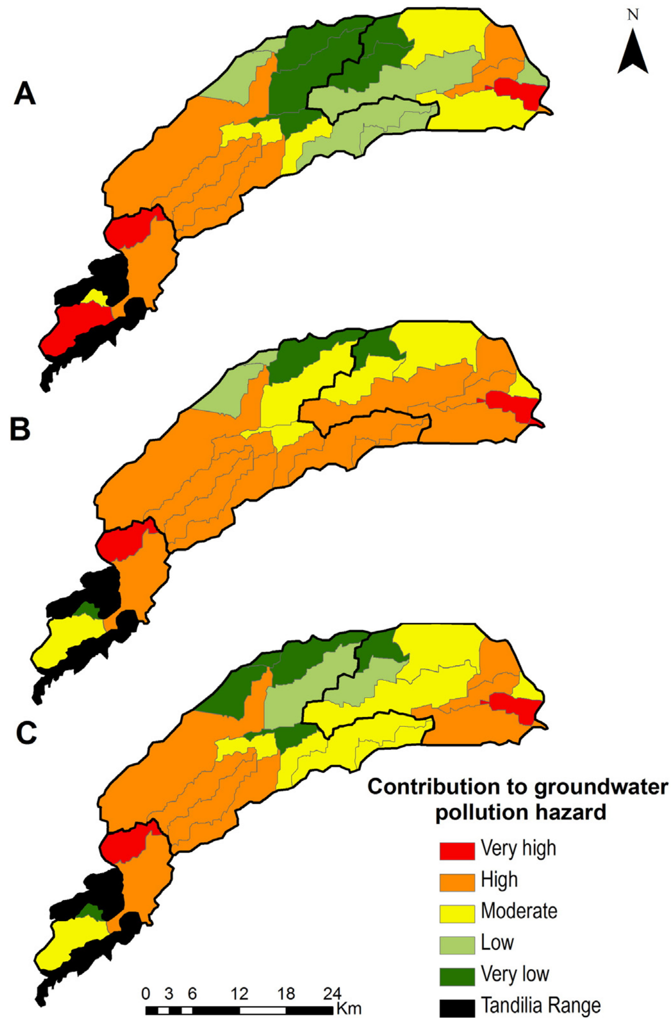


Fig. 7. Groundwater Pollution Hazard Assessment under A) recent scenario (2011), B) Relegated Sustainability Scenario (2030) and C) Sustainability Reforms Scenario (2030).

4.2. Groundwater modeling with the MODFLOW model

A monolayer model with 80 rows and 80 columns, with 620 and 830 m cell sizes, was built. Results obtained in the groundwater modeling permitted the development of the isophreatic maps for the SR and RS (2030). These simulated maps show the same similar trend of the isophreatic map for the study area. A SW to NE regional flow direction is evident in the upper sector, and W to E direction in the discharge area, similar to the drainage network. The stream presents a gaining condition in most of the watershed. Isophreatic lines range from 5 to 100 m.

In relation to the different scenarios, a 5 meter water table depth decline was detected in the plain area, corresponding to the middle-lower watershed in both maps, whereas, in the hilly area the isophreatic lines had decreased 5 and 10 m approximately for the SR and RS respectively, due to intensive irrigation extraction in the upper watershed (Fig. 6).

4.3. Decision support system for assessing groundwater pollution hazard

In order to simplify interpretation of this assessment, the labels in each partial and final map have been reversed; e.g. very low support for the null statement = very high pollution hazard, while very high support for the null statement = very low pollution hazard. This translation from the null form basically inverts the logic, and is completely legitimate because of the way the lowest level logic topics get evaluated in NetWeaver. Contribution classes in the evaluation of groundwater pollution hazard are defined as follows: very high < -0.118; high -0.118–0.020; moderate 0.020–0.100; low 0.100–0.159; and very low > 0.159. Fig. 7 shows the final maps of the Groundwater Pollution Hazard Assessment under a) recent scenario (2011), b) Relegated Sustainability Scenario (2030) and c) Sustainability Reforms Scenario (2030).

4.3.1. Recent scenario

There were pronounced differences in groundwater pollution hazard between subwatersheds of Dulce Stream Watershed in the recent scenario (2011) (Fig. 8). High to very high contribution to groundwater pollution hazard was detected in the upper and middle watershed. To the contrary, the lower sector mainly presents moderate to very low contribution to groundwater pollution hazard. Generally speaking, unfavorable conditions were due to inadequate water table depth (90% of the watershed with values < 6 m), high net recharge (>200 mm) and low slope values (83% of the watershed with values < 1%). In relation to land-use, the upper basin presented a high contribution to groundwater pollution hazard because agricultural activities dominate the area. However, one subwatershed shows very low evidence that contributes to groundwater pollution hazard considering that it coincides with the range system. The assessment in the other portions of the watershed suggested that land-use characteristics would not contribute to a groundwater pollution hazard due to the predominance of cattle-breeding activities. Appropriate soil media characteristics in the upper-middle watershed, mainly clay loam texture, showed a low groundwater pollution hazard. However, the presence of flooded lowlands and loam to clay loam soil textures in a sector of the watershed could be the reason for moderate pollution hazard exceptional behavior. Finally, the lower portion displayed a moderate to very high contribution to groundwater pollution hazard because of its sandy texture soils. Fig. 8 shows the partial products of the entire evaluation process; from viewing this figure, it is possible to see the various contributions to overall groundwater pollution hazard.

4.3.2. Relegated Sustainability (RS) Scenario

In reference to the RS, high to very high contribution to groundwater pollution hazard increased (+20%) throughout the watershed, compared to the recent scenario (2011) (Fig. 9). On the contrary, low to very low classes decreased (−25.2%) in the middle-lower watershed. Forecasted land-use and water table depth maps are the main secondary topics which conduct to changes in groundwater pollution hazard. Significant changes on the simulated land-use map increase groundwater pollution hazard contribution (+64.3%; high class) along the whole watershed. To the contrary, water table depth in the upper sector generates a lesser contribution to groundwater pollution hazard (−10%).

4.3.3. Sustainability Reforms (SR) Scenario

Regarding the SR, high to very high contribution to groundwater pollution hazard increased (+2%) in the lower watershed in comparison to the year 2011 (Fig. 10). Moreover, the moderate class increased (+13.4%) in the middle-lower watershed, while low to very low contribution to groundwater pollution hazard decreased (−15.2%) in the same sector. Forecasted land-use and water table depth maps led to changes in groundwater pollution hazard. Significant changes on the simulated land-use map increase groundwater pollution hazard contribution (+11.6%) in the higher class; more so, a moderate class rise was also detected (+30.7%). Regarding water table depth in the upper sector, it generates a lesser contribution to groundwater pollution hazard because low to very low categories increase (+6.17%).

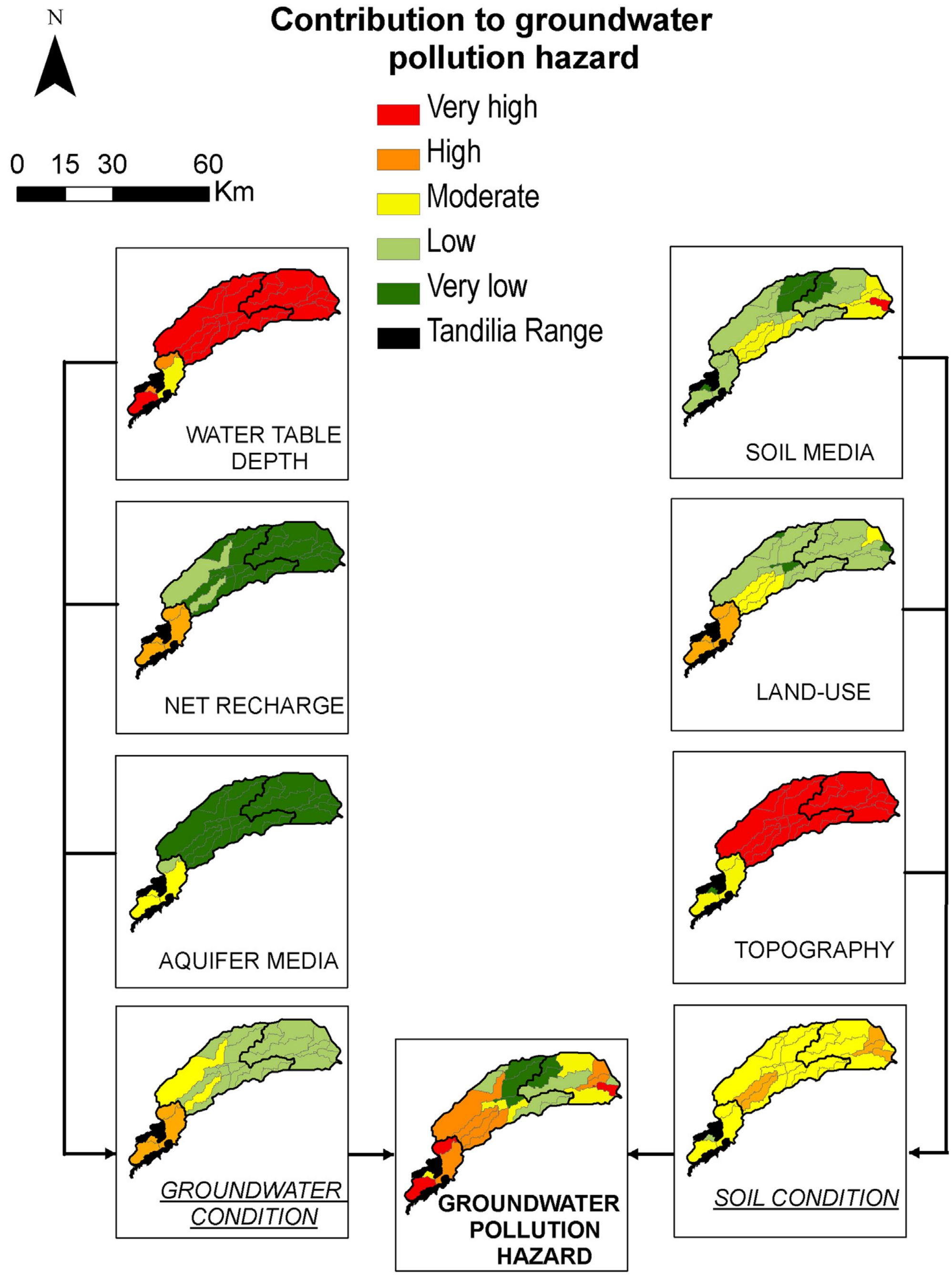


Fig. 8. Composite of all partial product evaluations leading to the full Groundwater Pollution Hazard Assessment under the recent scenario (2011).

5. Discussion

Anthropic activities cause changes in land-use and/or water extraction scenarios, modifying the dynamics of the aquifer system and its pollution hazard. Consequently, this changes with time need to be evaluated, so input maps representing the dynamics of the groundwater and land-use changes (simulated with specific software) under different scenarios should be incorporated as topics in a logic model. In this sense, a land-use change model (Dyna-CLUE) with a groundwater flow model (MODFLOW) was coupled together in our decision support system for assessing changes on groundwater pollution hazard in the Dulce Stream Watershed.

An increasing foreign demand for food and fiber promotes land for agricultural purposes, becoming an inevitable process in the current economic market. However, despite its probable economic benefit, social and environmental consequences arise, emphasizing an important need for land planning and the regulation of agricultural expansion (Paruelo et al., 2006). In the RS scenario, the Dyna-CLUE model results showed the expansion of agriculture, even when it approximates the limit of marginal agricultural soils. This leads to an expansion of agricultural land in the middle-lower watershed (soils with low agricultural potential), replacing natural grassland by sown pastures and crops. To the contrary, in the SR scenario, simulated results displayed a more balanced land-use distribution, respecting the areas with soil aptitude for agricultural use. This fact provides evidence for a future sustainable trend allowing for regional economic growth with natural resource use restrictions.

It is important to highlight that external economic, social and climatological factors act as driving forces in land-use changes, e.g. if China, the largest importer of Argentine soybean, reduces its demands

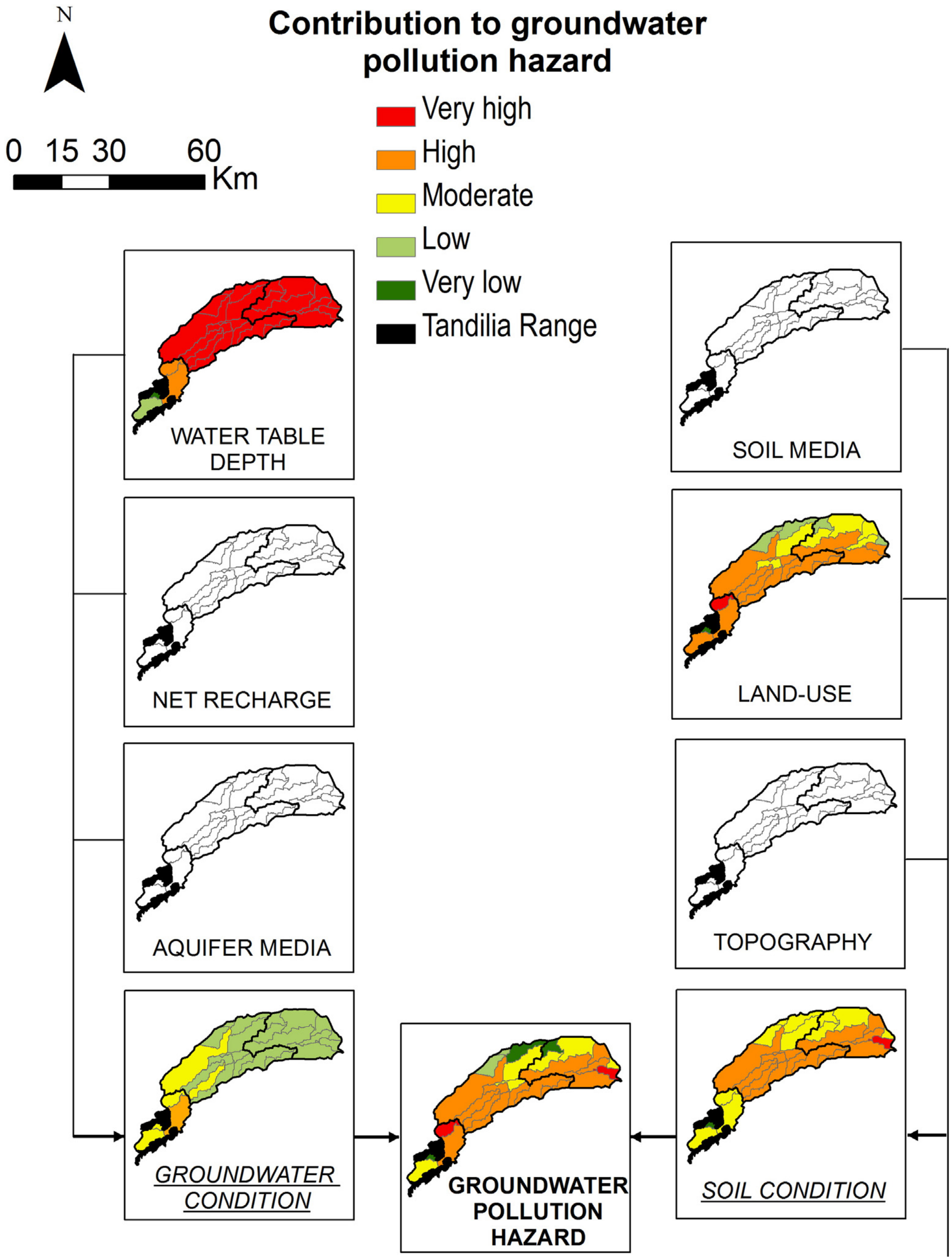


Fig. 9. Composite of all partial product evaluations leading to the full Groundwater Pollution Hazard Assessment under the Relegated Sustainability Scenario (2030). Empty maps do not change through time, so they are identical to maps of the recent scenario.

or soybean prices dropped, soil pressure would change. These variables affect the total land-use demand, for this reason there are different models for calculating the area change for all land-use types, ranging from simple trend extrapolations to complex economic models. The extrapolation of trends in land-use change in the recent past and the near future is a common technique used to calculate land use requirements. In this study, the defined regional scenarios were estimated by simple trend extrapolation (exponential method), and when necessary, these trends can be corrected for changes in population growth and/or diminishing land resources due to changes in the driving forces.

Our modeling framework allowed for assessing changes on groundwater pollution hazard under two different socio-economic and environmental scenarios. Mapped outputs identified 46.42%, 48.25% and 66.74% of the watershed with a high contribution to groundwater pollution hazard in the recent scenario, SR and RS, respectively. This fact is a consequence of crop expansion and to a lesser extent cattle-breeding activities. On the other hand, in the forecasted scenarios water table depth in the upper sector generates a lower contribution to groundwater pollution hazard due to a wider thickness of the vadose zone increased by an intensive irrigation extraction. Regarding the significance of these water level reductions, it is widely known that potential consequences involving changes within the hydrological regime, the drying out of wetlands, supply problems in pumps and mills and operational difficulties in the same irrigation equipment could arise.

An average difference of 2.4 m in water table levels between forecasted scenarios (25% and 50% of irrigated land; SR and RS, respectively) is in evidence, as a consequence of water extraction by irrigation wells. Water table levels in the RS varied from 12.38 to 28.23 m and in the SR ranged from 10.58 to 25.14 m. These differences are displayed in the logic model, however the final results of EMDS did not show

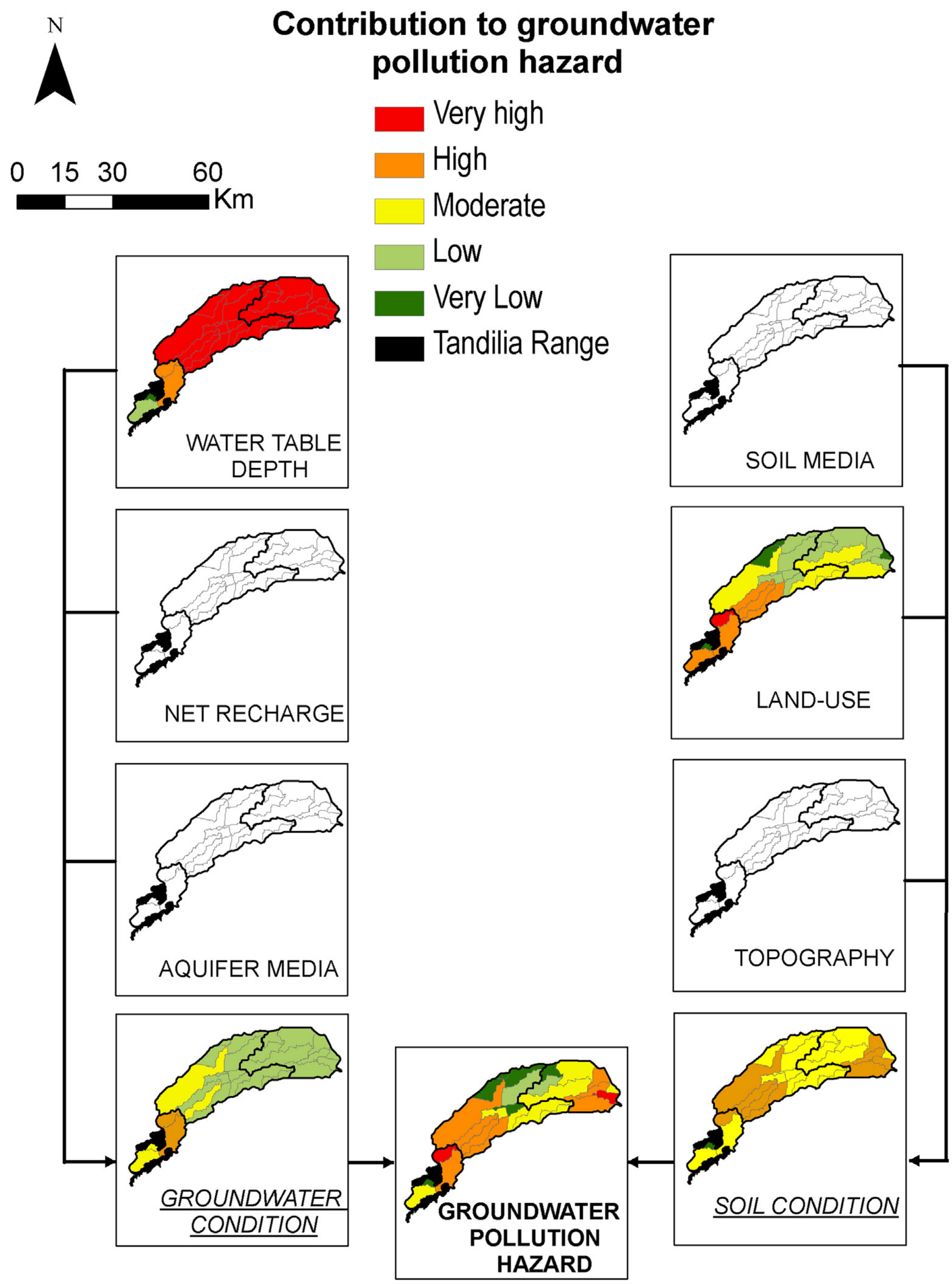


Fig. 10. Composite of all partial product evaluations leading to the full Groundwater Pollution Hazard Assessment under the Sustainability Reforms Scenario (2030). Empty maps do not change through time, so they are identical to maps of the recent scenario.

discrimination among them. This fact can be explained when considering that the different categories (very low to very high) in this software are defined by default values. In order to display these differences in the water table partial map, a new data classification method (e.g. natural breaks and equal intervals) should be used. To simplify result interpretation just the final groundwater pollution hazard maps were reclassified in this work by using natural breaks.

The main advantages of the Dyna-CLUE and MODFLOW model integration in a DSS are the generation of a dynamic methodology over time, in contrast with static methods, the discrimination in the groundwater pollution hazard map, the easy application to a wide range of study areas and other environmental sub-fields (aquifer overexploitation, climate change, aquifer recharge, among others), and the possibility to simulate different socio-economic and environmental scenarios. This integrated methodology clearly shows that agricultural land use increases groundwater pollution hazard in the study area. This model will be useful for the application or design of aquifer protection strategies in the area under study and could be applied to others of similar features. It should be mentioned that the main limitations of applying these models are their incapacity to simulate land-use dynamics in areas without a land-use change history and the necessity of having extensive available data regarding aquifer geology of the study area.

6. Conclusion

The proposed modeling approach proved to be a valuable tool for coupling together distinct models to forecast groundwater pollution hazards under contrasting land-use scenarios (*Relegated Sustainability* *and Sustainability Reforms*). This methodology allowed us to establish a ranking of subwatersheds with transitional conditions (very high to very low groundwater pollution hazard) under different land-use and restrictions.

The possibility to simulate scenarios makes this DSS a powerful instrument for natural resource management since it enables the simulation, evaluation and extrapolation of land-use changes and its effect on the groundwater pollution hazard. The integrated methodology using a land-use change model and a groundwater flow model in the DSS showed the areas where the groundwater pollution hazard increases mainly due to agricultural activities. Therefore, an effective use of this methodology can assist in land-use planning guidelines taking into account hydrogeological realities and risks.

Results in the recent scenario (2011) showed that 54% of Dulce Stream Watershed still presents a moderate to very low contribution to groundwater pollution hazard (mainly in the lower portion). Therefore, from the point of view of natural resource management, this is a positive aspect, offering possibilities for intervention in order to prevent deterioration and to protect this aquifer system. However, since it is quite possible that this aquifer status (i.e. groundwater quality) changes in the near future, the implementation of planning measures and natural resource management is recommended.

Selected scenarios enabled the prediction of possible future changes of groundwater pollution hazard in the Dulce Stream Watershed. The Relegated Sustainability Scenario showed a rather negative change in the aquifer system, increasing (+20%; high–very high classes) the contribution to groundwater pollution hazard throughout of the watershed. On the contrary, the Sustainability Reforms Scenario, displayed more balanced land-use changes with a trend towards sustainability, representing a more acceptable change in the aquifer system for the year 2030 with a 2% increase (high–very high classes) in groundwater pollution hazard.

The resulting Groundwater Pollution Hazard Assessment under the different scenarios allowed the identification of the subwatersheds in the upper and middle watershed as the main aquifer protection areas. The results reasonably fit the natural conditions of the watershed, identifying those subwatersheds with shallow water depth, loam–loam silt texture soil media and pasture land cover in the middle watershed, and others with intensive agricultural activity, coinciding with the natural recharge area to the aquifer system.

Conflict of interest

There is no conflict of interest amount authors.

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