Science of the Total Environment 530–531 (2015) 333–346

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

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

M. Lourdes Lima [a,b,*], Asunción Romanelli [a,c], Héctor E. Massone [a]

[a] Instituto de Geología de Costas y del Cuaternario, FCEyN, Universidad Nacional de Mar del Plata, Funes 3350, Nivel 1, 7600 Mar del Plata, Argentina
[b] Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina
[c] Instituto de Investigaciones Marinas y Costeras (IIMyC), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina

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.

ARTICLE INFO

Article history:
Received 16 March 2015
Received in revised form 7 May 2015
Accepted 7 May 2015
Available online xxxx

Editor: D. Barcelo

Keywords:
Groundwater pollution hazard
Land use change
Simulated scenarios
Decision support system
Pampa Plain, Argentina

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

* Corresponding author.
E-mail addresses: mlima@mdp.edu.ar (M.L. Lima), aromanel@mdp.edu.ar (A. Romanelli), hmassone@mdp.edu.ar (H.E. Massone).

http://dx.doi.org/10.1016/j.scitotenv.2015.05.026

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