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Research article

Fuzzy logic-based assessment for mapping potential infiltration areas in low-gradient watersheds

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ABSTRACT

This paper gives an account of the design a logic-based approach for identifying potential infiltration areas in low-gradient watersheds based on remote sensing data. This methodological framework is applied in a sector of the Pampa Plain, Argentina, which has high level of agricultural activities and large demands for groundwater supplies. Potential infiltration sites are assessed as a function of two primary topics: hydrologic and soil conditions. This model shows the state of each evaluated subwatershed respecting to its potential contribution to infiltration mainly based on easily measurable and commonly used parameters: drainage density, geomorphologic units, soil media, land-cover, slope and aspect (slope orientation). Mapped outputs from the logic model displayed 42% very low-low, 16% moderate, 41% high-very high contribution to potential infiltration in the whole watershed. Subwatersheds in the upper and lower section were identified as areas with high to very high potential infiltration according to the following media features: low drainage density (<1.5 km/km^2), arable land and pastures as the main land-cover categories, sandy clay loam to loam - clay loam soils and with the geomorphological units named poorly drained plain, channelized drainage plain and, dunes and beaches.

1. Introduction

Water balance can generally be viewed in terms of inputs and outputs, with the primary input, precipitation (P), balanced by processes of evaporation, transpiration, runoff, infiltration, percolation and groundwater recharge/discharge. Infiltration is an important process of the environmental system, determining water availability for evapotranspiration, groundwater recharge and surface runoff. It is the function of a large number of interactive factors related to climate, physical, and land-use elements. Infiltration and seepage transform the watershed into a dynamic reservoir of the hydrologic system, because through them an underground storage as well as a river base flow is warranted during dry periods (Soares et al., 2012).

Spatial variability is considered one of the most important aspects of the infiltration process. Many difficulties arise due to natural heterogeneities which are characteristic of most of the field studies. This characteristic complicates the development of analytical expressions in order to describe and predict the infiltration process (Achouri and Gifford, 1984). Generally, the analysis of infiltration is based on punctual tests in soil, which are sometimes, erroneously interpolated to represent the spatial variability of infiltration from too few datasets (Paige and Stone, 1996; Van Schaik, 2009; Soares et al., 2012). Field devices can supply values for parameters, but only at a very small scale (essentially a point), and thus test results are difficult to apply to larger areas, owing to the many and varied conditions which can affect infiltration and runoff that are encountered throughout a watershed (Sullivan et al., 1996). In this sense, recent studies have shown examples of using environmental parameters that can be correlated with infiltration (Kwicklis et al., 2005; Brito et al., 2006; Van Schaik, 2009; Soares et al., 2012).

With the increasing availability of spatial databases, physical

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environmental models, visualization techniques and the analytical capabilities of Geographic Information Systems (GIS), more effective Decision Support Systems (DSS) can be developed for landscape planning (Bryan, 2003). Moreover, remote sensing data provide accurate spatial information and are cost-effective compared with conventional methods of hydrogeological surveys. Digital enhancement of satellite data improves maximum extraction of information useful for groundwater studies (Solomon and Quiel, 2006). In the same sense, fuzzy systems, including fuzzy set theory and fuzzy logic, provide a rich and meaningful improvement, or extension of conventional logic (McBratney and Odeh, 1997). Compared to classical rule-based systems, knowledge representation for different problems using fuzzy logic is more precise, compact, and efficient (Waterman, 1986). The application of fuzzy logic to natural resource science and management is still relatively new, but growing rapidly. This application has been used among other things in the identification of preferred artificial recharge sites, the convertion of soil texture classes in numerical values and the prediction of daily runoff rates by using moisture and rainfall as input variables (Ghayoumian et al., 2007; Camarinha et al., 2011; Tayfur and Brocca, 2015).

Related to the objective of this study, fuzzy logic has been applied in infiltration studies analyzing only conventional tests. Two fuzzy rule base models for calculating the infiltration and movement of soil moisture in a heterogeneous soil column were developed by Bárdossy and Disse (1993). The main advantage of these models is that require fewer parameters that classical models and run much faster, nevertheless they should not be thought as a replacement of the physically based models of infiltration, rather they should be used in subsequent step for simplifying the complicated models. Moreover, a fuzzy rule-based model was implemented by Afonso et al. (2014) for simulating the displacement of water in a non-vegetated crop soil. The principle of this model establishes rules based on the moisture content of adjacent soil layers; as a result, a good adjust with data from experimental measurements was reached. However, the spatial analysis of different layers by using GIS, DDS and fuzzy system approaches offers a better understanding of features controlling the process of infiltration.

The Pampa Plain in Argentina is over 1.5 million km^2 in area, it is the main grain-producing region in the country and is characterized by gentle slopes (slope values <0.5%). In these flat-land landscapes watershed boundaries are diffuse or undetermined, with shallow water courses which do not integrate a well-defined surface drainage system, with groundwater levels close to the surface, and soils made up of fine-grained sediments. The infiltration proceeds at a very slow rate and the water may remain a long time ponded on the surface putting agricultural lands at a greater risk of flooding and/or salinization (Usunoff et al., 1999). Moreover, at present, agricultural expansion in this region has added to the pressure of land-use on natural resources (Viglizzo, 2001), which has lead to a greater threat of aquifer pollution.

Maximum infiltration areas present the most favorable conditions for recharge of aquifer systems and are particularly most sensitive to contamination risks (Brito et al., 2006). Considering these facts and the current increase in agricultural expansion in the Pampa Plain, the development of a qualitative approach for mapping potential infiltration areas will provide important strategic information on the location of priority protection areas regarding the susceptibility of the aquifer to potential contamination. Moreover, the implementation of water protection strategies will guarantee groundwater storage to ensure the regional productivity, as well as, the base flow for the main water courses and its tributaries, mainly during dry periods.

The objective of this study was to design a fuzzy logic-based model for identifying potential infiltration areas in low-gradient watersheds based on remote sensing data. It is expected that this model would improve water management, providing a valuable decision-making tool for optimizing the management of water resources and land-use planning.

2. Study area

The study area is located to the southeast of Buenos Aires Province, covering a total area of 2740 km^2. The climate is dry subhumid mesothermal type "B2" (Thornthwaite, 1948). Over the past 10 years, annual precipitation values have ranged from 703 to 1400 mm/year, with an average of 943 mm/year. The evapotranspiration potential values estimated for the same period by the Thornthwaite method, ranged from 750 to 833 mm/year, with an average of 786 mm/year (Quiroz et al., 2008).

The area reveals extreme flatness, 83% of the watershed present slope values <1%, with an elevation ranging from 0 to 420 m asl with ranges of the Tandilia System in the upper watershed. The Tandilia Range System in the area consists of two big geological units: a Precambrian crystalline bedrock called Buenos Aires Complex (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 the hydrogeological bedrock. An inter-range fringe surrounds the blocks; it is formed by aeolian hills which quickly give way to the plain areas that reach the sea. Hills and plains are formed by Cenozoic loess-like sediments (especially of Pleistocene-Holocene age); these sediments constitute the Pampean aquifer. It is a multi-layered unconfined aquifer, with a thin unsaturated zone ranging from 0.50 to 25 m.

Surface runoff is channeled through three streams originating in the Tandilia Range System (Fig. 1): El Moro, El Seco and Tamangueyú. El Moro Stream runs southwards and flows into the Atlantic Ocean, in the upper section it is an intermittent water course. El Seco Stream, characterized as intermittent, follows a northwestern direction and flows into the Quequén Grande River. Its flow is steady in the high and low segments of its watershed, but it fades away mid-way. Finally, the Tamangueyú Stream, of permanent regime, collects its waters from the western range sector and drains them into the Quequén Grande River.

The conceptual hydrogeological model for the area considers the existence of a regional flow originated in the north and heading towards two preferential discharge areas. The first one, located in the southwestern and towards the Quequén Grande River and the second towards the El Moro Stream mouth on the Atlantic Ocean. The aquifer recharge depends solely on rainwater infiltration. Streams have a gaining condition in relation to groundwater in most of the watershed (Quiroz et al., 2008).

This study area was chosen according to criteria that included a high level of agricultural activities, significant local extraction of groundwater resources for drinking water and irrigation (since groundwater is the only source of water supply) and extensive available data regarding aquifer features.

3. Materials and methods

Input maps for Watershed Assessment of Potential Infiltration Areas were generated by using data from the digital terrain model (DTM) of the Shuttle Radar Topography Mission (SRTM-NASA), with 90 m of spatial resolution (Rabus et al., 2003), Landsat 7 ETM satellite images (Path/Row 224/87; December 19th, 2002) and Geospatial Database of Argentina (INTA, 2008).