



## 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 ( $<1.5 \text{ km/km}^2$ ), 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.

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## 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 conversion 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 than 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<sup>2</sup> 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<sup>2</sup>. The climate is dry sub-humid 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 Tamanguéyú. 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 Tamanguéyú 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).

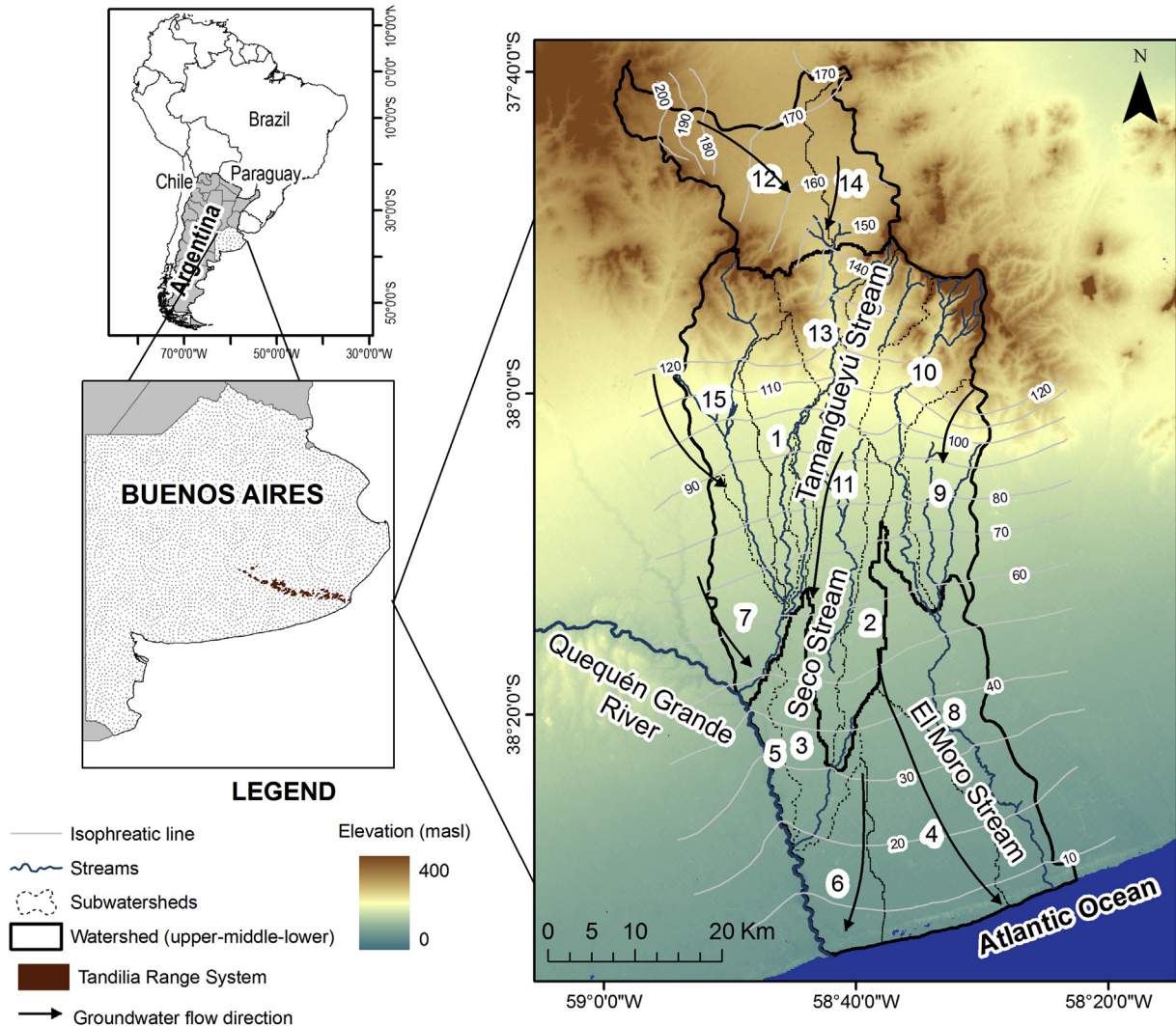


Fig. 1. Location map. Subwatersheds of El Moro, Tamangueyú and Seco stream watersheds.

### 3.1. Watershed delineation

Drainage analysis on a digital terrain model (DTM) of El Moro, Tamangueyú and El Seco stream watersheds was carried out by using the SWAT -Agricultural Research Service- (Arnold and Fohrer, 2005) model in order to obtain the surface hydrological data model. This tool is an extension of ArcGIS which was developed by the USDA-Agricultural Research Service in 1998, and was used to derive several data sets that collectively describe the drainage patterns of each watershed. Raster analysis was performed to generate data on stream definition (flow direction, which is created by filling the sinks, and flow accumulation) and watershed delineation. This process needs a raw DTM and a linear feature class (the river network) as input data. As a result, 15 subwatersheds were obtained for the study area (Fig.1).

### 3.2. Fuzzy logic-based model

The logic specification for Watershed Assessment of Potential Infiltration Areas was graphically designed with the logic-modeling system, NetWeaver Developer (Miller and Saunders, 2002). Each topic in a NetWeaver model represents an object for which a proposition is to be evaluated. For example, the potential

infiltration topic, representing the top level in the model, evaluates the proposition that Potential infiltration is high. The complete evaluation of Potential Infiltration depends on two topics, hydrologic and soil conditions, each of which incrementally contribute to the evaluation of potential infiltration, as indicated by the union operator (Fig. 2). 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. Notice that, if the potential infiltration topic is thought of as testing a conclusion, then the two topics on which it depends can be thought of as its premises. Similarly, each of the two topics under potential infiltration has its own logic specification that includes a set of subtopics or premises, in this case: drainage density and geomorphological units include hydrologic condition; and soil media, land-cover, slope and aspect (slope direction) the soil condition.

Watershed Assessment of Potential Infiltration Areas for all complete subwatersheds in the study area (15 subwatersheds) was performed with the Ecosystem Management Decision Support (EMDS) system (Reynolds et al., 2003), a decision support system that operates in ArcGis (Minami, 2000). The NetWeaver logic engine, a component of the EMDS system, was used to perform evaluations of potential infiltration and all dependent topics. Each



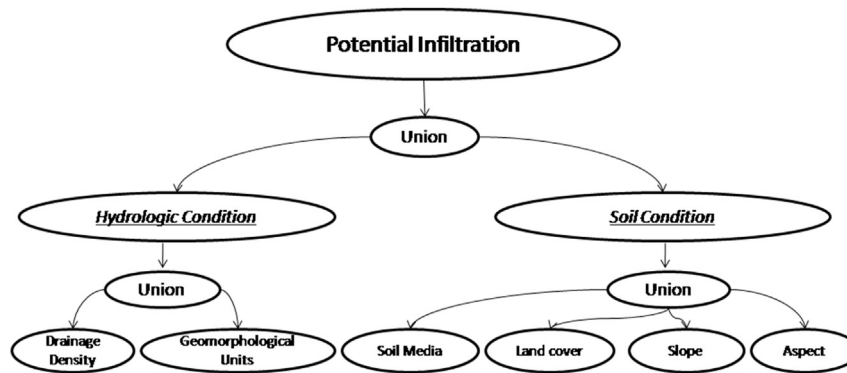


Fig. 2. Logic model for assessing potential infiltration areas.

Table 1

Logic outline for evaluation of potential infiltration sites.

Model topic	Primary topic	Secondary topic	Proposition (stated in the null form)
<b>Potential infiltration (union)</b>	<b>1. Hydrologic condition (union)</b>	1.a. Drainage density <sup>a</sup>	Potential infiltration is high Hydrologic conditions contribute to potential infiltration Expected drainage density is low
		1.b. Geomorphological unit <sup>a</sup>	Geomorphological characteristics contribute to potential infiltration
	<b>2. Soil condition (union)</b>	2.a. Soil Media <sup>a</sup>	Condition of soil contribute to potential infiltration Condition of soil media contribute to potential infiltration
		2.b. Land-cover <sup>a</sup>	Land-cover characteristics contribute to potential infiltration
		2.c. Slope <sup>a</sup>	Slope is conducive to potential infiltration
		2.d. Aspect <sup>a</sup>	Aspect is conducive to potential infiltration

<sup>a</sup> Data inputs associated with logic topics are presented in Table 2.

map product was generated by the analysis reports the strength of evidence for the proposition associated with the map topic (Table 1). The methodological framework for the proposed assessment is illustrated in Fig. 3.

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 2). Fuzzy membership values in *NetWeaver* range from −1 (totally false, or no evidence) to +1 (totally true, or full evidence). Expert judgment was used to select and rate each category of geomorphological units, soil media, land-cover and aspect parameters (Table 3) according to the infiltration capacity of each unit. In this sense, each input map was reclassified into rating values: 1, 2, 3, 4 and 5. Here, a value of 1 would indicate an area with conditions that favor the highest potential for infiltration, while a value of 5 would indicate the opposite situation.

Spatial data was originally obtained as raster maps with a spatial cell resolution of 90 m × 90 m. All raster maps were projected into the Argentine Gauss Krüger system, zone 5 (Campo Inchauspe Datum). Subwatersheds (vector format) of El Moro, Tamangueyú and El Seco stream watersheds were used as analysis units. For each raster map, zonal statistics were computed by using the spatial analysis module of ArcGIS 9.2 and results attributed to sub-watersheds. The final map in EMDS was displayed using a natural breaks algorithm to deliberately accentuate differences among scores of map features.

## 4. Results

### 4.1. Input maps to the model

The different input maps (Fig. 4) necessary for identifying potential infiltration areas were: 1a. drainage density, 2a. geomorphological units, 3a. soil media, 4a. land-cover, 5a. slope and 6a.

aspect (slope orientation). Table 2 shows a brief description of each parameter included in the overall model. A brief description of the each input maps (Figs. 4 and 5) which were necessary for the Watershed Assessment of Potential Infiltration Areas is described below:

#### 4.1.1. Drainage density

The drainage density map showed values ranging from 0 to 2.8 km/km<sup>2</sup>, with an overall average of 0.91 km/km<sup>2</sup> and a standard deviation of 0.49. This parameter displayed the highest values in the range and hilly (2.8 km/km<sup>2</sup>) areas while the lowest ones were associated with the plain zone (0.0 km/km<sup>2</sup>). Consequently, the drainage density map can indirectly indicate the suitability for potential infiltration in the less steep sector of the watershed due to its relation with surface runoff and permeability.

#### 4.1.2. Geomorphological units

Geomorphology of the area was evaluated according to six landform features based on Martínez (2007): *flat summit*, *range front and piedmont*, *aeolian hills*, *poorly drained plain*, *channelized drainage plain* and, *dunes and beaches*. The *flat summit* and *range front and piedmont* units (296–420 masl) are located in the upper sector occupying 2.6% of the watershed. The *aeolian hills*, which surround the blocks, corresponded to 12.3% of the area. The plain environment is the most extended landform, covering 82.7% of the overall area. It is divided into two units: *poorly drained plain* (38.6%) and *channelized drainage plain* (44.1%). The last category, *dunes and beaches*, is located in front of the Atlantic Ocean and correspond to 17.4%. The dunes constitute an unconfined aquifer, hydraulically connected to the Pampean aquifer (Quiroz et al., 2010).

#### 4.1.3. Soil media

Moderate permeable soils (loam-clay loam textures) predominated in the area (41.0%) and are mainly located in the middle-end

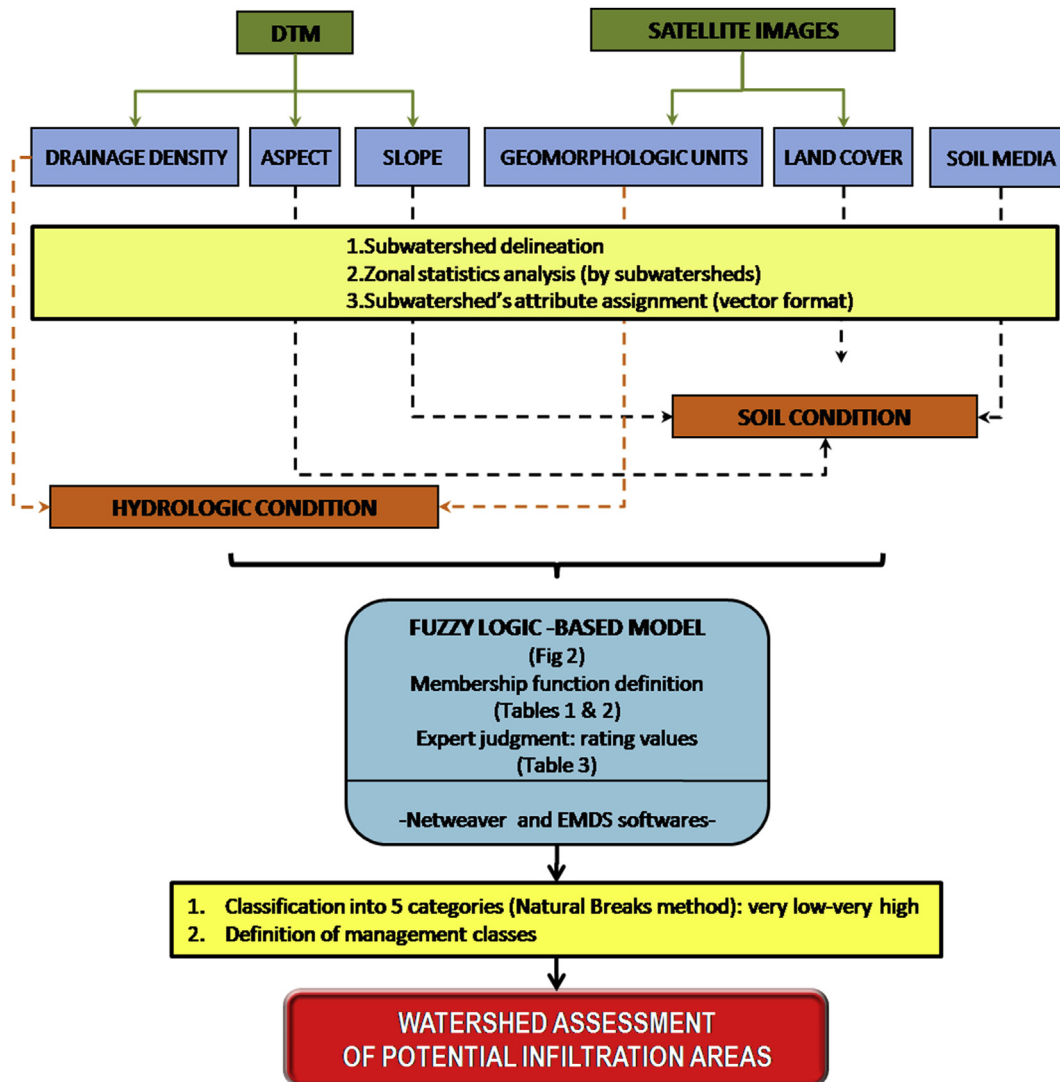


Fig. 3. Methodological framework for identifying potential infiltration areas in low-gradient watersheds based on remote sensing data.

sector. Soil media in the upper sector presented moderate to low permeability showing loam (31.3%) and clay loam-loam (25.4%) soil textures, respectively. A little portion of the watershed corresponded to sand-sandy loam soil texture (1.7%) and rock (0.7%).

#### 4.1.4. Land-cover

Land cover was classified into six distinct categories: *arable lands*, *pastures*, *water body*, *dunes and beaches*, *bare rock*, and finally, *urban fabric*. *Arable lands* and *pastures* (lands permanently used for herbaceous forage crops) occupied the largest area with 76.1% and 20.34%, respectively. Regarding the first land-cover type, the main crops are soybean, ze m ay, wheat and sunflower. Their growth in the area requires the application of fertilizers, pesticides and supplementary irrigation. Moreover, farming methods have modernized and intensified over the years directed towards increasing commercial production. Pastures are a mixture of legumes and grasses. Cattle-breeding is frequent in these lands. Artificial surface, like *urban fabric*, covered 0.58% and correspond to Necochea, Lobería and San Manuel cities. Moreover, the land-cover types *dunes and beaches* ( $\approx 2.00\%$ ), *bare rock* (2.63%) and *water body* (mainly temporary freshwater systems) (0.26%) are also present in the area.

#### 4.1.5. Slope

The steepest slope areas ( $>3^\circ$ ) are restricted to the range front and the hilly areas and occupying 4.1% of the overall area. Meanwhile, the lowest values ( $<1^\circ$ ), which are the dominant slopes, corresponded to the 88.1%. Slope in the watershed ranged from 0 to  $30.26^\circ$  with a mean value of  $0.57^\circ$ .

#### 4.1.6. Aspect

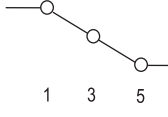
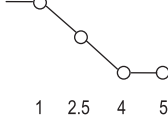
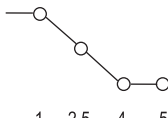
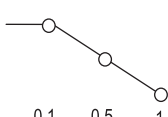
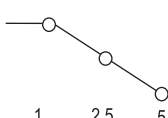
The aspect map displayed values ranging from 0 to  $360^\circ$ . In general, the N and NW slope orientation dominate in the area (50%). This direction is opposite to the regional groundwater flow system therefore it is associated with a better condition for infiltration, increasing the time of water in surface and improving infiltration. The NE, E and W, SW, and S-SE orientations correspond to 8.2%, 10.5%, 8.4%, and 22.9%, respectively.

#### 4.2. Watershed assessment of potential infiltration areas

Fig. 5 shows the partial products of the entire evaluation process; from viewing this composite, it is possible to see the various contributions to overall potential infiltration. A summarization of the results of the partial products are mentioned immediately

**Table 2**

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

Topics	Definition	Data source	Reference conditions		Fuzzy argument
			Full evidence (1)	No evidence (–1)	
Drainage density (km/km <sup>2</sup> )	This parameter is an inverse function of permeability. The less permeable a rock is, the less the infiltration of rainfall, which conversely tends to be concentrated in surface runoff (Chowdhury et al., 2010).	Digital terrain model (Shuttle Radar Topography Mission – SRTM) and stream network	<0.5	>1.25	
Geomorphological units	This parameter controls the subsurface movement of groundwater (Kumar and Kumar, 2011). Six landform features have been identified and mapped according to Martínez (2007) criteria.	Satellite images Landsat TM (December 19th 2002) and field trips	1	5	
Soil media	Soil has a significant impact on the amount of infiltration into the ground (Aller et al., 1987). Sandy loam soil has more infiltration capacity than clay loam soil, contrary, low permeable soils (silt-clay to clay soils) facilitate surface run off, therefore being the worst condition for infiltration process.	National Institute of Agricultural Technology-INTA, Geospatial database of Argentina (2008)	1	5	
Land-cover	Land-cover provides information about the soil permeability. For example, areas that are under residential, commercial and industrial use are non-feasible areas for groundwater recharge (Rahman et al., 2012). The opposite condition occurs in sites under agricultural and forest lands (Scanlon et al., 2005).	Satellite images Landsat TM (December 19th 2002) and field trips	1	5	
Slope (%)	Slope is a critical parameter with a direct control on runoff and therefore on infiltration (Shankar and Mohan, 2006). Flat areas allow high infiltration rates and are suitable for aquifer recharge; contrary, steeper slopes do not permit high infiltration rates (Rahman et al., 2012).	Digital terrain model (Shuttle Radar Topography Mission – SRTM)	<0.1	>1	
Aspect (°)	Aspect can be thought of as the slope direction. It identifies the downslope direction of the maximum rate of change in value from each cell to its neighbors. Cells with opposite direction to the surface runoff were associated with better condition for potential infiltration, as these areas would act as natural barriers increasing the time of water in surface improving infiltration conditions.	Digital terrain model (Shuttle Radar Topography Mission – SRTM)	1	5	

below.

#### 4.2.1. Hydrologic condition

Assessment of hydrologic condition in subwatersheds of the upper watershed presented high evidence for contributing to potential infiltration. Throughout the middle watershed, evaluation of hydrologic condition showed low to very low contribution to potential infiltration. In contrast, results in the lower watershed displayed five subwatersheds (3, 4, 5, 6 and 8) with a moderate to high contribution to potential infiltration.

Considering the secondary topics of hydrologic condition, in the upper watershed, evaluation of drainage density and geomorphological units showed moderate to high evidence for contributing to potential infiltration. Moderate drainage density values (<1.5 km/km<sup>2</sup>) and landform features such as aeolian hills and channelized drainage plain dominate in this sector. Subwatersheds of the middle watershed displayed conditions favoring the low potential infiltration by drainage density (>1.5 km/km<sup>2</sup>). Generally, in the subwatersheds of the lower portion of the study area, the evaluation suggested that expected drainage density values (low values, < 0.5 km/km<sup>2</sup>) and the presence of poorly drained plain and dunes and beaches units would contribute to potential infiltration.

#### 4.2.2. Soil condition

The upper subwatersheds did not show favorable soil conditions for potential infiltration. On the other hand, results in the lower portions displayed a moderate to high evidence for contributing to

potential infiltration from soil condition. The middle watershed presented a mixed condition with a considerable number of sub-watersheds showing low to moderate contribution to potential infiltration.

The soil condition was composed of the partial evaluations of soil media, land-cover, slope and aspect. The upper watershed displayed conditions which not contribute to potential infiltration due to soil media characteristics, mainly clay loam and loam texture, slope values higher than 10°, an agricultural use and aeolian hills-range system. In the middle portion, subwatersheds evidenced a moderate to low evidence contribution to potential infiltration since clay loam to loam soil textures, slope values reaching 30° and, the predominance of cattle-breeding and agricultural activities in the zone. Finally, the lower watershed displayed favorable soil conditions to potential infiltration since the cattle-breeding activities, low slope values (<1°) and loam to silt loam soil textures.

#### 4.2.3. Potential infiltration assessment

Evidence classes in the evaluation of potential infiltration areas are defined as follows: very low (–0.4145––0.4008); low (–0.4007––0.2768); moderate (–0.2767––0.1029); high (–0.1028–0.04479); very high (0.04480–0.2269).

There were pronounced differences in the potential infiltration between subwatersheds in the different portions of the study area (Fig. 6). Mapped outputs from the logic model displayed 15.10% very low, 26.93% low, 16.03% moderate, 14.09% high, 27.85% very

**Table 3**

Brief description and rating values of each geomorphological, land cover, soil media and aspect classes included in the logic model.

Geomorphological units	Description	Rating
Range front and piedmont (RfP)	It is the main body of the block-range system; vertical and subvertical walls bounding the flat summits and accumulation of quartzitic debris mixed with fine sediments.	1
Dunes and beaches (DB)	Fine to medium silica sand deposits located in front of the Atlantic Ocean.	1
Aeolian hills (AH)	It is formed by silt and silty-sand sediments with frequent beds of caliche. Slopes in this unit range from 1° to 2.5°. Well developed soils with excellent agricultural aptitude exist in it.	2
Poorly drained plain (PDP)	Flat to gently sloping topographic features, subparallel drainage with scarce development and high presence of flooding areas.	3
Channelized drainage plain (CDP)	Water table depth in this unit is deeper than in the poorly drained plain diminishing the flooding areas; slope values <0.2% and presence of small size temporary water courses.	4
Flat summit (FS)	It corresponds to the plain top of the ranges, with a table mountain aspect due to the horizontal position of the quartzitic strata.	5
<b>Land-cover</b>		
Water body	It includes several temporary freshwater shallow lakes (less than 1.5 m depth) located in the upper basin (NE). Highly dependent on <i>in situ</i> rainfall events.	1
Dunes and beaches	They are located in front of the Atlantic Ocean and constitute an unconfined aquifer, hydraulically connected with the Pampean aquifer. They are semi-natural areas with commercial and tourist uses which generate high anthropic impact during the summer season.	1
Pastures	Land permanently used for herbaceous forage crops. Pastures are a mixture of legumes and grasses. Fertilizers could be used in some periods of the year. They are mainly associated with cattle production.	2
Arable land	The main crops are soybean, zea may, wheat and sunflower. Their growth in the area requires the application of fertilizers and pesticides. Farming methods have modernized and intensified over the years directed towards increasing commercial production.	3
Bare rock	It corresponds to ranges from the Tandilia System. Generally, in hydrogeological studies they are considered as the impermeable bedrock of the aquifer. No commercial and tourist uses are evident.	4
Urban fabric	It includes three important cities Necochea, Lobería and San Manuel, located in the lower, middle and upper watershed, respectively. Poor septic system is found close to the cities (peri-urban areas).	5
<b>Soil media</b>		
Sand; Sandy loam	Textures related to very high permeable soils	1
Loam; Silty loam	Textures related to high permeable soils	2
Loam - Clay loam; Sandy clay loam	Textures related to moderate permeable soils	3
Clay loam - Loam	Textures related to low permeable soils	4
Rock	Textures related to very low permeable soils	5
<b>Aspect (slope direction)</b>		
N; NW	Slope direction highly favors surface runoff	1
NE	Slope direction favors surface runoff	2
E; W	Slope direction moderately favors surface runoff	3
SW	Slope direction poorly favors surface runoff	4
S; SE	Slope direction does not favor surface runoff	5

high contribution to potential infiltration in the whole watershed. Results showed that the middle section of the watershed has the lowest potential infiltration. Appropriate infiltration conditions in the upper and lower watershed were largely driven by properties conducive to adequate hydrologic conditions. The landscape integrated evaluation allowed identifying seven subwatershed (2, 3, 4, 5, 6, 8 and 14) as the main areas for potential infiltration with high to very high contribution in the lower and upper watershed.

A map of homologous infiltration areas was obtained, which represents the spatial arrangement of potential infiltration areas varying from very low to very high. The description of each class in the evaluation of potential infiltration and some associated management recommendations are the following:

- (1) This area has a VERY LOW potential for infiltration. Critical condition for infiltration capacity is associated to clay loam and loam - clay loam soils. Natural conditions favor surface runoff. A lower groundwater risk pollution is expected.
- (2) This site has a LOW potential for infiltration. Natural conditions have little influence in the process of infiltration for the watershed. These sites are characterized by loam and loam-clay loam soils and high drainage density values. Most of the ranges presented in the watershed are located in this class. The probability of an adverse impact to water resources would be low.
- (3) This site has a MODERATE potential for infiltration. Regular infiltration potential is associated to aeolian hills and range front and piedmont units with loam to clay loam soils. Moreover, slope values higher than 15° are presented in most

of these sites. The probability of an adverse impact to water resources is greater than that from a low rated site.

- (4) This site has a HIGH potential for infiltration. Good hydrological and soil conditions for water recharge. Areas with high infiltration potential are mainly found in channelized and poorly drained plain units, associated to loam-clay loam and sandy clay loam soils. There is a high probability of an adverse impact to water resources unless remedial action is taken.
- (5) This site has a VERY HIGH potential for infiltration. Very good hydrological and soil conditions for water recharge. Under-ground storage as well as the base flow for streams and their tributaries might be warranted during dry periods. The most favorable condition for infiltration is mainly found in channelized drainage plain (loam-clay loam and sandy clay loam soils) and, in a less extent, in poorly drained plain (loam-clay loam soils) and dunes-beaches (sandy soils) units. The probability of an adverse impact to groundwater resources is very high due to the presence of sources with high potential of pollution and a very high potential for infiltration. A routine monitoring strategy for testing the presence of agricultural contaminants in groundwater such as animal waste components, fertilizers, and pesticides should be developed. This is a priority area which requires the implementation of recommended management practices, e.g. guidelines on agrochemical management and utilization, better regulation and control of the area by provincial and district authorities, some remedial actions if necessary, among others.

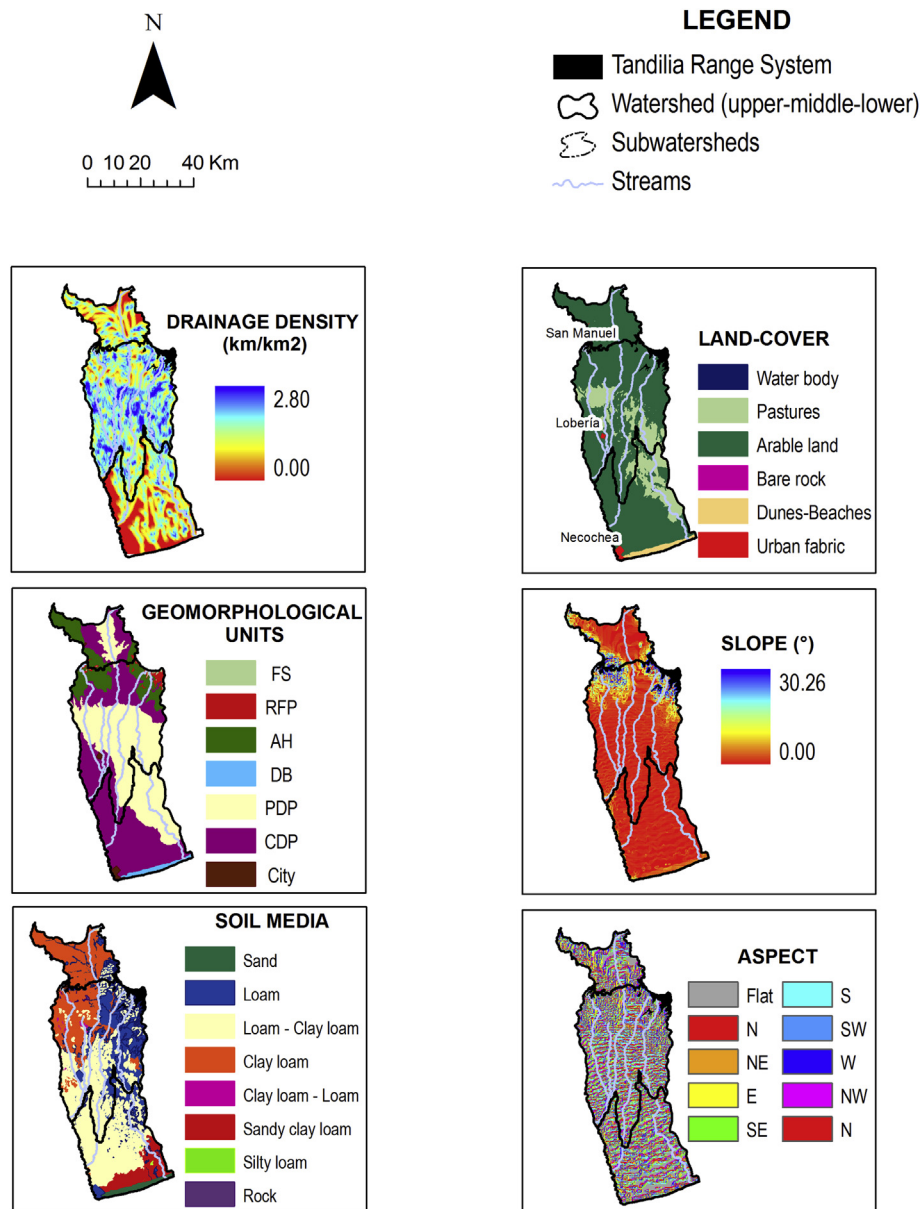


Fig. 4. Input maps to the fuzzy logic-based model.

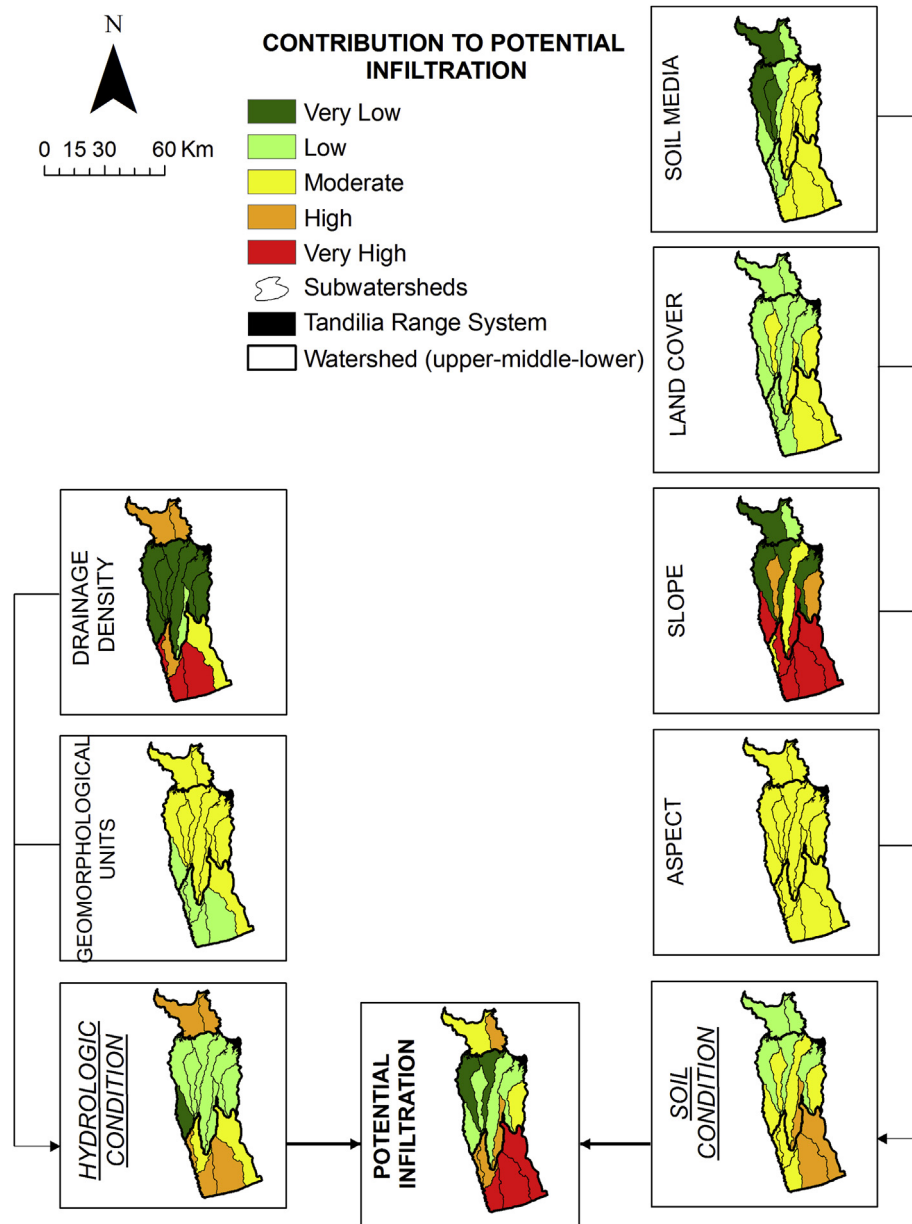
## 5. Discussion

The applied methodological framework allows decision makers to rank the state of each evaluated subwatershed with respect to its potential for infiltration. Mapped outputs from the fuzzy logic-based model identified seven subwatersheds in the upper and lower watershed with the most favorable condition for infiltration (high to very high contribution). Results of the model in the lower section of the catchment are corroborated by Quiroz et al. (2008), which identified the action of several combined local processes such as selective infiltration and surface water contribution in the middle-end section of the catchments of Seco Stream and El Moro Stream, explaining this hydrological behavior by using a combination of hydrological, hydrochemical and isotopic techniques.

It is important to highlight that subwatersheds from the upper watershed (12 and 14) had moderate and high evidence for potential infiltration, coinciding with the aquifer recharge area according to the regional groundwater flow system (Quiroz et al.,

2008). As a consequence, these subwatersheds must be considered as areas with high management priority requiring a careful water resources planning. In regional flow systems it is assumed that topographically high areas are groundwater recharge areas and topographically low areas are groundwater discharge areas (Winter 1999). However, many factors affect the occurrence of natural infiltration in a region. In this sense, the proposed methodology establishes sites with different degrees of potential infiltration capacity, providing a first approximation to the spatial variability of this parameter. Obtained results can improve the implementation of monitoring networks and/or facilitates the search for data and information focused on infiltration quantification. Authors as Brito et al. (2006) and Soares et al. (2012) have used conventional GIS methodology to define areas with similar infiltration capabilities by using Boolean logic methodology combining different layer (four and five respectively), giving to each layer the same weight in the final map. The methodology used in this contribution allowed the integration of six different layers,





**Fig. 5.** Composite of all partial product evaluations leading to the full Watershed Assessment of Potential Infiltration Areas in El Moro, Tamangueyú and Seco stream watersheds.

evaluating the degree of fuzzy membership for each of the variables included in the analysis.

Natural environmental conditions indicate a high potential for infiltration in the lower watershed, being a discharge area according to the regional groundwater flow system based on the conceptual hydrogeological model of the area. Management recommendations referred to the category of high priority should be more flexible in this case due to its location in the discharge zone, since it is areally little affected given the short distance before discharging into the sea.

In the Pampa Plain is noticed the dependence between agriculture, water availability and its quality. This region is a very sensitive environment due to weather changes and low slopes. The drought-flood period alternation in this area is a well-known problem, quoted initially by Ameghino (1896). Moreover, subwatersheds located in the lower watershed with high infiltration potential, present a 60 cm thick vadose zone (Quiroz et al., 2008).

Therefore these facts increase both the flood risk and the groundwater susceptibility to pollution in the zone. Quiroz et al. (2013) and Massone et al. (2010) established this zone as the areas with the highest flood potential and moderate to high vulnerability.

The main advantage of the application of EMDS is that it is not an all black-box model. The knowledge base component (Net-Weaver) provides a graphic interface that facilitates tracing the derivation of conclusions the derivation of conclusions. The proposed methodological framework includes easily measurable and common used parameters (obtained from remote sensing) which can be spatially and temporarily analyzed. Updating of information and the addition of several available maps with relative ease (e.g. runoff, erosion, irrigation water use) to improve landscape evaluations is a relative simple process.

Due to insufficient data coverage, groundwater studies often require interpolation or extrapolation from a few observation points into large areas. In areas with limited previous investigations

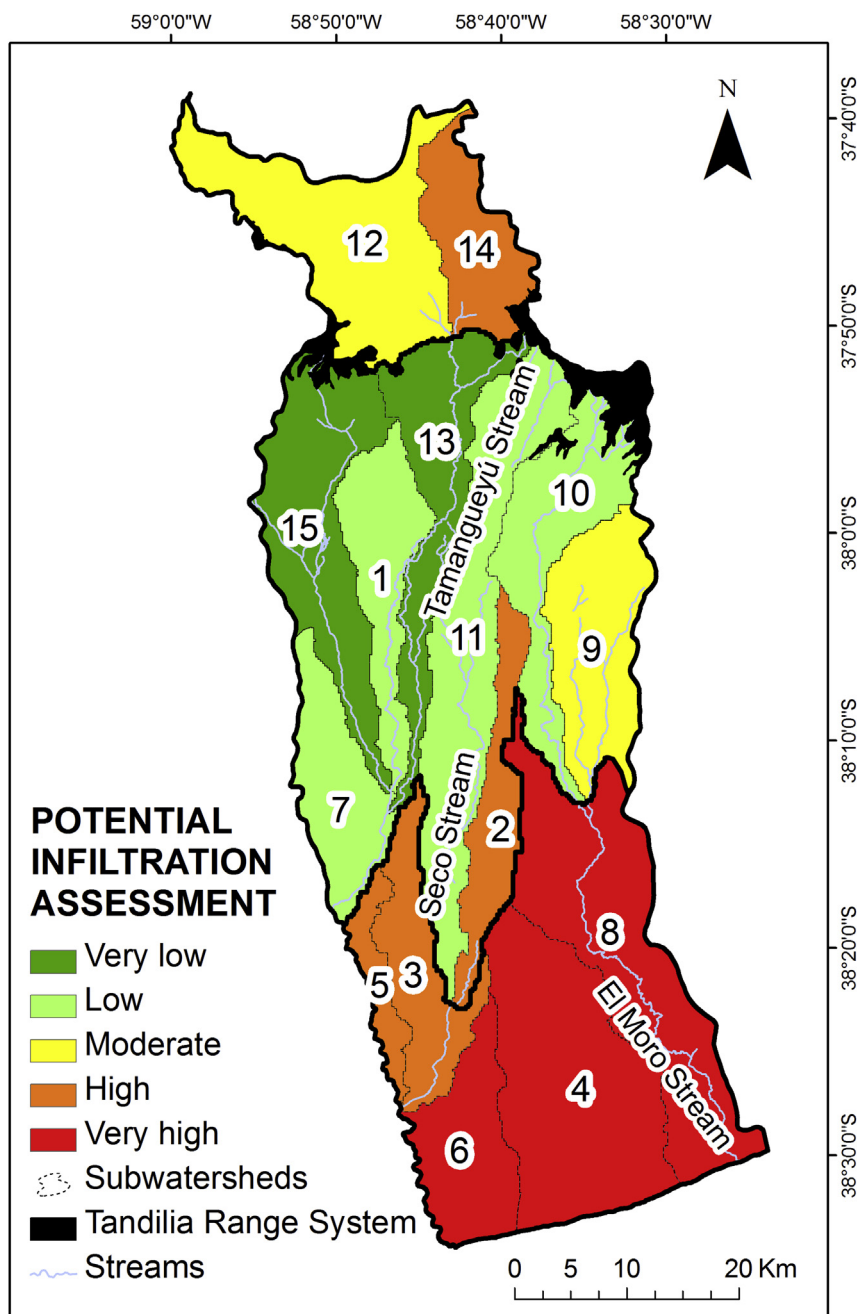


Fig. 6. Resulting map of Watershed Assessment of Potential Infiltration Areas.

and few hydrogeological data, remote sensing and GIS methods provide support in groundwater studies. Remote sensing data cover large areas with direct observations, allow the interpretation of geomorphological features, geology, land cover, drainage systems, catchments, and slope conditions, etc. and thus minimize the need for interpolation from point observations of these features.

In this model there are no considerations about time dependence of the results, showing a steady state condition. However, anthropogenic impact could cause changes on land-use and/or water extraction scenarios, modifying the dynamics of the groundwater system. In this sense, output map values could be modified, increased or decreased, *i. e.* if a land-cover category change (*e. g.* from forestland to residential), the identification of potential sites for infiltration could be assessed by considering this

change. If parameter variation with time needs to be evaluated, other input maps representing the land-use changes, simulated under different scenarios with specific software such as Dyna-CLUE (Overmars and Verburg, 2007), SLEUTH model (Dietzel and Clarke, 2007) and Fore-SCE (Sohl et al., 2007) among others, could be incorporated as topics in the logic model.

Logic and decision models in EMDS are intended to complement one another. The decision models are optional components of EMDS applications. Although a decision model has yet to be designed for the current application, a decision model is recommended since it can strengthen the management context, considering, for example, social and economic considerations or practical issues of the feasibility and efficacy of management choices associated with selecting specific subwatersheds for water and soil

protection. Criterium DecisionPlus® software (Infoharvest, 2011) could be used as a decision engine to evaluate outcomes from the logic model.

## 6. Conclusions

Logic model results can be used to investigate correlation of hydrogeologic properties obtained as point information. This knowledge can then be used to establish a model of the hydrogeological conditions, to apply this model to estimate groundwater yield and to determine suitable strategies for groundwater exploration. The resulting map of potential infiltration areas summarizes the results of this model and allows establishing a ranking of sites with different conditions for potential infiltration (very high to very low).

This approach has enabled the assessment of potential infiltration at a catchment level, taking into account six different layers by using fuzzy logic-based model. The final map can be considered as an indicative map which can improve the design of monitoring networks focused on infiltration test. The subwatersheds of the upper and lower section of the analyzed area were identified as areas with high to very high potential of infiltration. Consequently, these subwatersheds require intervention in order to prevent deterioration and protect the aquifer.

The purpose of the designed model is to allow land-use planning, minimize conflict and protect the integrity of aquifer systems which are an important resource to human life. Planning and environmental management on a scientific basis is a prerequisite for achieving socio-economic and biophysical sustainability in a region dependent on groundwater.

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