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Decision support model for assessing aquifer pollution hazard and prioritizing groundwater resources management in the wet Pampa plain, Argentina

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Abstract This paper gives an account of the implementation of a decision support system for assessing aquifer pollution hazard and prioritizing subwatersheds for groundwater resources management in the southeastern Pampa plain of Argentina. The use of this system is demonstrated with an example from Dulce Stream Basin (1,000 km² encompassing 27 subwatersheds), which has high level of agricultural activities and extensive available data regarding aquifer geology. In the logic model, aquifer pollution hazard is assessed as a function of two primary topics: groundwater and soil conditions. This logic model shows the state of each evaluated landscape with respect to aquifer pollution hazard based

mainly on the parameters of the DRASTIC and GOD models. The decision model allows prioritizing subwatersheds for groundwater resources management according to three main criteria including farming activities, agrochemical application, and irrigation use. Stakeholder participation, through interviews, in combination with expert judgment was used to select and weight each criterion. The resulting subwatershed priority map, by combining the logic and decision models, allowed identifying five subwatersheds in the upper and middle basin as the main aquifer protection areas. The results reasonably fit the natural conditions of the basin, identifying those subwatersheds with shallow water depth, loam–loam silt texture soil media and pasture land cover in the middle basin, and others with intensive agricultural activity, coinciding with the natural recharge area to the aquifer system. Major difficulties and some recommendations of applying this methodology in real-world situations are discussed.

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Introduction

Contamination of groundwater with agricultural chemicals is a major concern in the environmental management of watersheds. One environmental monitoring strategy is to develop maps of groundwater pollution hazard and prioritize those areas located in potentially

highly contaminated watersheds for testing of agricultural contaminants such as animal waste components, fertilizers, and pesticides. Groundwater pollution hazard from chemicals is determined by combining groundwater sensitivity maps (intrinsic characteristics of the aquifer) with the presence of crop type, land-use practices, pesticide use, and irrigation. (Aller et al. 1987; Hamerlinck and Arneson 1998; Connell and Daele 2003; Lowe and Butler 2003).

Although it is easy to see the benefits of a map to guide environmental monitoring strategy, the generation of maps showing delineated zones of potential contamination for monitoring purposes is difficult since groundwater contamination depends upon numerous, complex interacting parameters with inherent spatial and temporal uncertainty. Therefore, there is a need to develop an affordable but reliable mapping methodology that is capable of dealing with uncertainty to generate groundwater contamination potential maps at the watershed or regional scale (Dixon 2005).

Decision support systems (DSS) facilitate the decision-making process in a qualitative manner based on the knowledge of experts (Sewilam et al. 2007). An important feature of these systems is that they allow the use and capture of specialized knowledge from a wide spectrum of natural sciences, and they can be effectively applied to a variety of environmental management and design activities (Rizzoli and Young 1997). Many researchers have been working on development of various models and decision support tools to address complexity in management of water resources, integrating models, and tools for environmental impact assessment (Salewicz and Nakayama 2004). Many sources in the literature demonstrate that considerable progress was made in recent decades in DSS. General areas of application include watershed management and planning (Lam et al. 1994; Fredericks et al. 1998; Reynolds et al. 2000), groundwater pollution risk evaluation (Uricchio et al. 2004; Chowdary et al. 2005), landscape evaluation and restoration planning (Reynolds and Hessburg 2005), integrated wetland management (Janssen et al. 2005), and analysis of the impact of water restriction policies (Recio et al. 2005).

The Ecosystem Management Decision Support (EMDS) is a system for integrated environmental analysis and planning that provides decision support for landscape-level analyses through logic and decision models. It is a framework within which developers can design logic and decision models to address many different kinds

of questions related to natural resource management and at whatever spatial scale(s) may be relevant to their questions (Reynolds et al. 2003). The logic model focuses on the question, “What is the state of the system?,” and the decision model focuses on the question, “Given the state of the system, what can be done about it?”

Although the environmental decisions are an inherently political matter, there is a growing awareness that management plans need scientific underpinning and the support of local stakeholders prior to implementation (de Kok et al. 2009). Water policy decision makers find DSS valuable when used with appropriate technical guidance (Nakayama 1997). With the increasing availability of spatial databases, physical environmental models, visualization techniques, and the analytical capabilities of Geographic Information Systems (GIS), more effective DSS can be developed for landscape planning (Brett 2003).

This work presents a DSS for assessing aquifer pollution hazard and prioritizing subwatersheds for groundwater resources management. We demonstrate the use of the system with an example from a stream basin representative of the wet Pampa plain, Dulce stream basin in Argentina. It was chosen according to criteria that included the high level of agricultural activities and the extensive available data regarding aquifer features. From a hydrological point of view, this area involves significant local extraction of groundwater resources for drinking water and irrigation. It is expected that this decision support model would improve water management in plain areas providing an important tool for siting future aquifer protection areas. In spite of the strategic importance of water planning, there are no records of local precedents.

Study area

The Dulce stream basin (1,000 km²), which is located in the southeast of the Buenos Aires Province, 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 (plains, flood plains, marshes, deltas, and barrier of dunes; Iribarne 2001).

The study basin presents ranges in elevation 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 the hydrogeological bedrock. An inter-range fringe surrounds the blocks; it is formed by 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). 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 area has a "moderate-humid" climate (Köppen's classification), or "sub humid-humid, mesothermal, without water deficiency" type (Thorntwaite's method). 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° and in winter 10° (Lima et al. 2011).

The aquifer is formed by silts and silty-to-sandy sediments with variable amounts of calcium carbonate, which can reach a thickness of up to 100 m. This defines a multilayered unconfined aquifer with a thickness ranging from 30 to 100 m and a hydraulic conductivity of 10 m/day. The transmissivity is about 800–1,000 m²/day. The storage coefficient, estimated from pumping tests, is 0.001, and the porosity is 0.15 (Sala 1975; Massone et al. 2005; Quiroz Londoño et al. 2006). The mineral composition of the aquifer is mainly quartz, plagioclases, orthoclase with variable amounts of volcanic glass shards, with the occasional appearance of mica and opaque minerals (Teruggi 1954). Recharge to the aquifer system mainly predominates in the hilly area, and it is due to infiltration of precipitation excess, and discharge occurs towards surface streams and water bodies.

Methodology

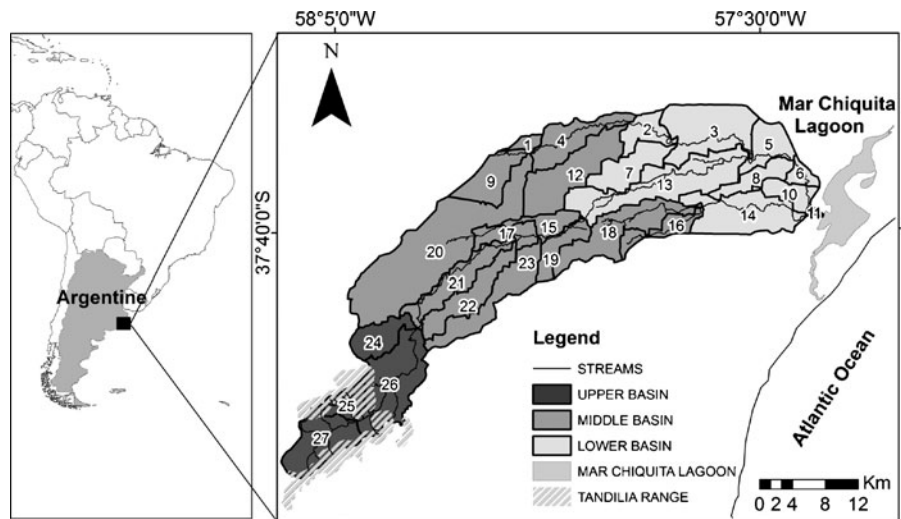
Drainage analysis on a digital terrain model (DTM) of Dulce stream basin was performed using the Arc Hydro Tools in order to obtain the surface hydrological data model. It is an extension of ArcGis developed by the Center for Research in Water Resources at the University of Texas, in 2001. The Arc Hydro Tools were used to derive several data sets that collectively describe the

drainage patterns of the basin. Raster analysis was performed to generate data on flow direction and accumulation, stream definition, stream segmentation, and watershed delineation. First, the DTM reconditioning is necessary. This process needs a raw DTM and a linear feature class (like the river network) as input data. Moreover, the function of fill sinks in the DTM is also required to continue with the following procedures. If cells with higher elevation surround a cell, the water is trapped in that cell and cannot flow; the Fill Sinks function modifies the elevation value to eliminate these problems. The utility of the Arc Hydro Tools is demonstrated by applying them to develop attributes that are useful for hydrologic modelling (Lima et al. 2012). Within this study area, the aquifer pollution hazard for 27 subwatersheds was evaluated (Fig. 1). The average size of subwatersheds was about 36.70 km², ranging from 1.34 to 146.62 km².

The current system is based on three separate software components. Aquifer pollution hazard was performed by a "rule based" knowledge, which uses the NetWeaver logic engine (Reynolds et al. 2003). Spatial evaluation and map presentation were handled in ArcMap (ESRI 2007). Multicriteria analysis was performed using the software Criterium DecisionPlus (CDP) (InfoHarvest, inc. 1997). All components except CDP were integrated in the EMDS, a decision support system that operates in ArcGis (Reynolds et al. 2003). The CDP was operated as separate program, and then it was linked to the obtained spatial analysis. The obtained maps in the EMDS were displayed using a natural breaks algorithm in ArcMap to deliberately accentuate differences among scores of map features. This algorithm identifies breakpoints between classes using a statistical formula called Jenks' optimization (Jenks and Caspall 1971; Jenks 1977). It is rather complex, but basically it minimizes the sum of the variance within each class (Slocum 1999; Murray and Shy 2000).

The different thematic maps necessary for the assessment of groundwater pollution hazard were prepared with the GIS software ArcGis 9.2 (ESRI 2007). Most spatial data used in this study came from previous studies in the region (Auge 2004; Massone et al. 2005; Lima et al. 2011) and were originally obtained as raster maps with a spatial cell resolution of 100×100 m. All raster maps were projected into the Argentine Gauss Krüger system, zone 6, (Campo Inchauspe Datum). Subwatersheds (vector format) of the Dulce stream basin were used as analysis units. For each

Fig. 1 Location map. Subwatersheds of Dulce stream basin



raster map, zonal statistics were computed using the spatial analysis module of ArcGIS, and results attributed to subwatersheds (new table, with attribute names, descriptions, and units). The zonal statistics tool calculates statistics (mean, maximum, minimum, standard deviation, etc.) on values of a raster within the zones of another dataset. In this case, the estimated statistic type was the mean value, i.e., the average of all cells in the input in value raster that belong to a same zone (subwatershed).

The DSS consists of a logic model and a decision model. The methodological framework for the proposed assessment is illustrated in Fig. 2. In the logic model, groundwater pollution hazard is assessed as a function of two primary topics: groundwater and soil conditions (Table 1). Each primary topic has secondary topics under which data are evaluated. This logic model shows the state of each evaluated subwatershed with respect to aquifer pollution hazard based mainly on the parameters of the DRASTIC (Aller et al. 1987) and GOD (Foster 1987) models. The secondary topics are the following: water depth, net recharge, and aquifer media for aquifer condition, and soil media, topography, hydraulic conductivity, and land cover for soil condition. The full logic structure was a fuzzy logic network. The complete evaluation depends on two primary topics, each of which incrementally contributes to the evaluation of aquifer 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 logic specification that includes a set of secondary topics or premises.

An evaluation score of -1 results if all parameters have the worst possible score, while an evaluation score of 1 is reached if all parameters 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 aquifer pollution hazard and the subordinate propositions under this model topic (Table 1). Recall that all propositions take the null form; for example, low strength of evidence based on the underlying evaluation implies that the proposition of low aquifer pollution hazard has poor support.

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).

A decision model was developed and implemented in order to support prioritizing subwatersheds for groundwater resources management according to decision scores (Fig. 3). Stakeholder participation, through interviews, was used to provide a better insight into the conditions and consequences of human economical activities on subwatersheds. These data in combination with expert judgment were used to select and weight each criterion. Interviews were 10–15 min in length and conducted in a semistructured format in order to be

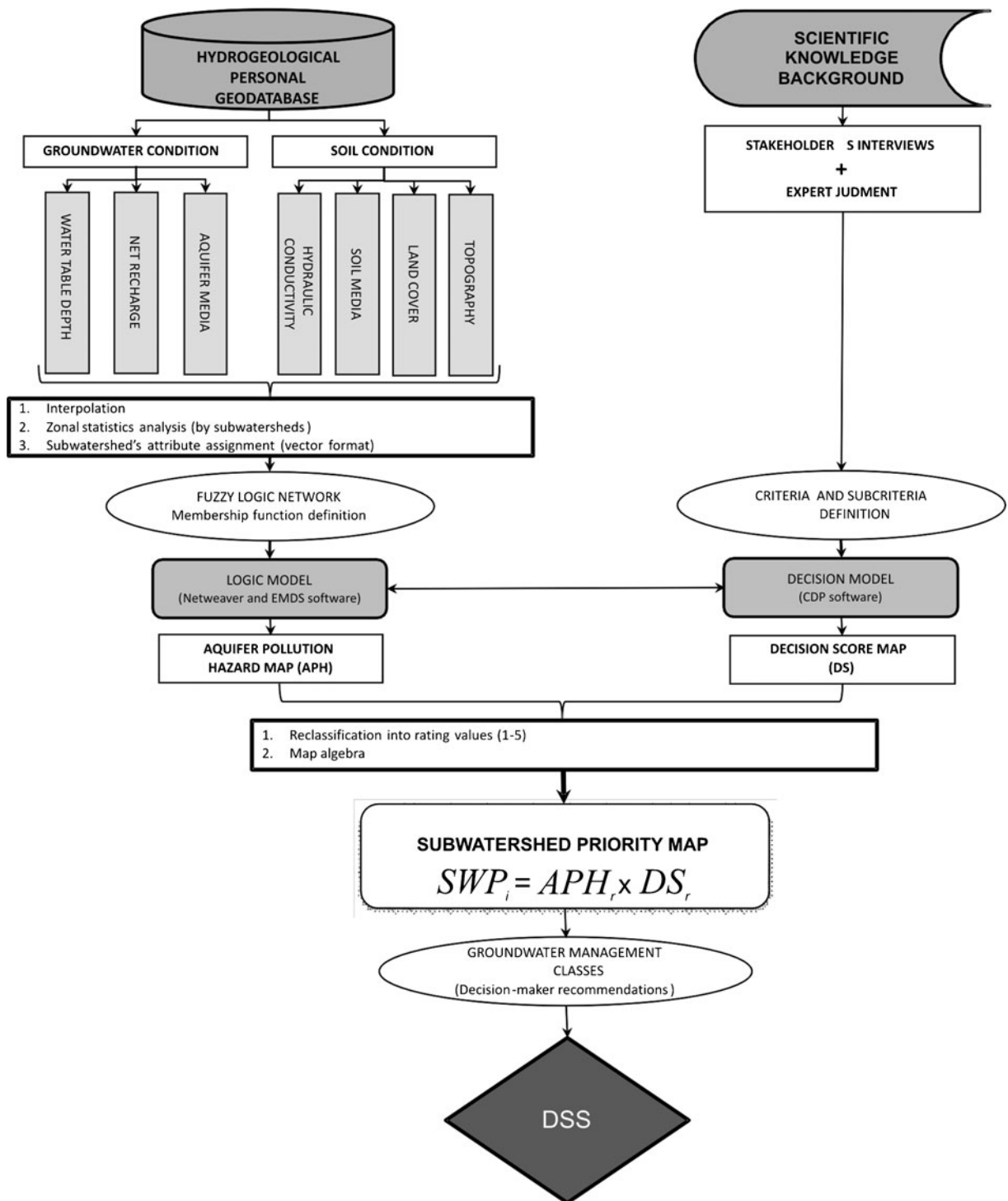


Fig. 2 Methodological framework for the proposed decision support system

“open enough for unanticipated value judgments and unorthodox world views, but structured enough to permit comparisons among respondents and obedience to

the discipline of a more detached and abstracted understanding” (MacMynowski 2007). The semistructured form was chosen because the analysis and presentation

Table 1 Logic outline for evaluation of aquifer pollution hazard

Model topic	Primary topic	Secondary topic	Proposition (stated in the null form)
Aquifer pollution hazard (union)	1. Groundwater condition (union)		Hazard of severe aquifer pollution is low
			Groundwater conditions do not contribute to aquifer pollution hazard
		1.a. Water table depth ^a	Expected water table depth is high
		1.b. Net Recharge ^a	Net recharge is low
	2. Soil condition (union)	1.c. Aquifer Media ^a	Condition of aquifer media does not contribute to aquifer pollution hazard
			Condition of soil does not contribute to aquifer pollution hazard
		2.a. Soil Media ^a	Condition of soil media does not contribute to aquifer pollution hazard
		2.b. Hydraulic Conductivity ^a	Expected hydraulic conductivity is low
		2.c. Land-cover ^a	Land-cover characteristics do not contribute to aquifer pollution hazard
		2.d. Topography ^a	Topography is not conducive to aquifer pollution hazard

^aData inputs associated with logic topics are presented in Table 2

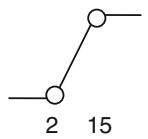

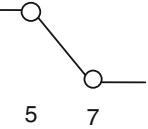
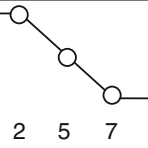
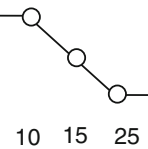
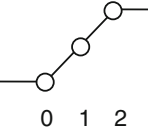
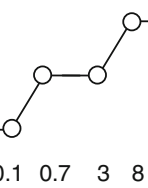
of results was easier than applying open questions (Marttunen and Vehanen 2004). Interview guides included issues concerning four main themes: (1) issues related to main land uses, (2) issues related to stakeholders' perceptions in the area, (3) issues pertaining to the sustainable use of water resources, and (4) use of agrochemicals and irrigation in their agroecosystems. The proposed questionnaire was an inexpensive and efficient way of gathering data from a potentially large number of respondents. A total of 25 interviews were carried out in order to obtain a deeper insight into opinions and knowledge of the different landscape conditions according to human activity influence.

Weights for each primary and secondary criteria of the decision model were derived from the standard pairwise comparison procedure of the Analytic Hierarchy Process (AHP) (Saaty 1992) and the Simple Multiattribute Rating Technique (SMART, Kamenetzky 1982), respectively, in which a decision maker/scientist is asked to judge the relative importance of one criterion versus each of the other criteria. We provided the judgments on relative importance for our example application. The selected primary criteria included farming activities, agrochemical application, and irrigation use. Moreover, each of these primary criteria has secondary criteria: agricultural use, agricultural–cattle breeding use, and cattle breeding use for the farming activities

criterion; high, moderate, and low for agrochemical application; and high, moderate, and low for irrigation use. Evaluations of data were performed with SMART functions (Kamenetzky 1982), which map observed values into a measure of utility for each attribute (secondary criterion) of an alternative. The utility function for each attribute was specified by two pairs of x , y parameters that defined a simple ramp, with one pair specifying the condition for complete utility ($y=1$), and the other the condition for no utility ($y=0$). The critical values were separately specified as 1 and -1 to compute its utility score corresponding to full and no utility, respectively, and represent the presence and absence of the observed data subcriterion for each alternative. In the decision model analysis, the Dulce stream basin was divided into three units (alternatives) according to geomorphological, hydrogeological, and land-cover aspects: upper, medium, and lower basin.

Spatial evaluation techniques together with multicriteria methods were used in the proposed decision support model for prioritizing, planning, and implementing groundwater resource management. In order to obtain the final subwatershed priority (SWP) map a multiplication of the reclassified aquifer pollution hazard (APH) and decision score (DS) maps were performed, by the application of map algebra. The APH and DS maps were obtained from the logic and the decision models,

Table 2 Definition of data inputs evaluated by elementary topic, data source, reference conditions for each datum, and fuzzy argument

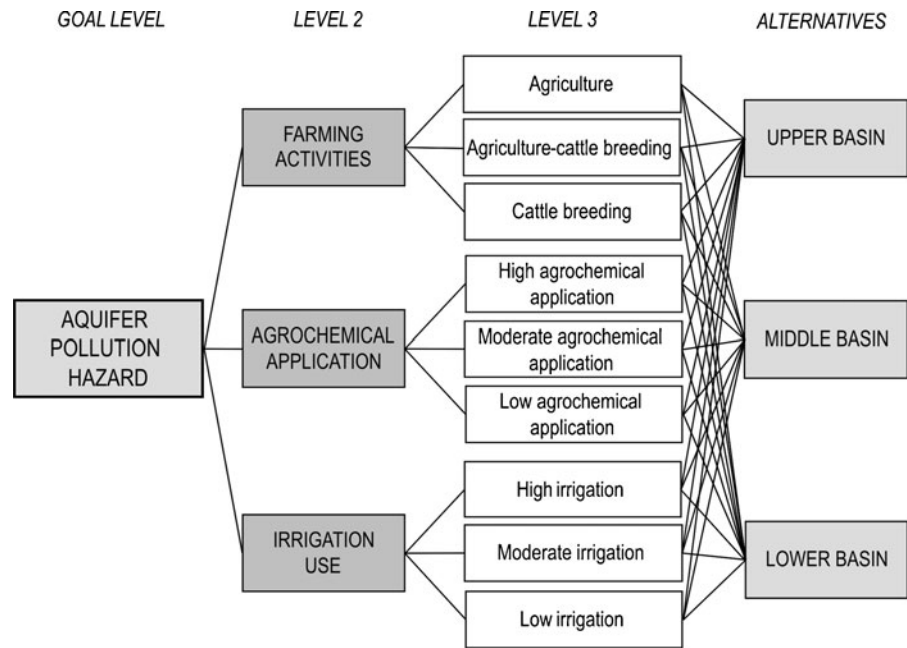
Topics	Definition	Data source	Reference conditions		Fuzzy Argument
			Full evidence (1)	No evidence (-1)	
Water table depth (m)	Evaluate the thickness of the unsaturated zone, i.e. the distance that the water must infiltrate and that can be accompanied by a pollution load to the aquifer.	Hydrogeological field work (Lima et al., 2011)	> 15	< 2	
Net recharge (mm)	This parameter evaluated the amount of water entering the aquifer, the main transport vehicle of the pollutants.	Hydric Balance of the study area.	< 200	> 300	
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, 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	
Hydraulic conductivity	Determines the amount of water flowing through the aquifer per unit time and per unit section.	Previous studies on hydraulic parameters in Pampean sediments (Auge, 2004)	< 10	> 25	
Land-cover ^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. 2011)	2	0	
Topography ^(e)	Determines the slope of the topographic surface. Is a relevant factor in the recharge of aquifer, in the drainage and in the transport o 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	

^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: 2 (clay soil texture), 5 (loam soil texture), and 7 (sandy soil texture)

^c Land cover is a qualitative variable. It was represented as a quantitative variable being: 2 (grassland), 1 (pasture) and 0 (crops)

Fig. 3 Decision model for the assessment of groundwater resources management priority



respectively. After the preparation of these maps, they were transformed into raster format (with the spatial analysis module of ArcGIS). The classification of the APH and DS maps involved subdividing the information into several categories. In this sense, each map was reclassified into rating values according to the range of each category: 1, very low; 2, low; 3, moderate; 4, high; and 5, very high (Table 3). Finally, the prioritization of subwatersheds for groundwater resources management can be obtained from the equation below:

$$SWP_i = APH_r \times DS_r$$

where SWP is the subwatershed priority for i mapping unit and r is the rating for each parameter, APH is the aquifer pollution hazard, and DS decision score.

Results

Aquifer pollution hazard assessment

In order to clarify the interpretation of the aquifer pollution hazard assessment, the labels in each partial and final map need to be reversed, e.g., very low support for low pollution hazard=very high pollution hazard, while very high support for low pollution hazard=very low pollution hazard. This translation from the null form basically inverts

the logic and is fully legitimate because of the way the lowest level logic topics get evaluated in NetWeaver.

Raw scores in the obtained map have been symbolized with a natural breaks algorithm that accentuates differences in scores among subwatersheds. Evidence classes in the evaluation of aquifer pollution hazard are defined as follows: very high, <-0.18 ; high, -0.16 to -0.10 ; moderate, -0.10 to -0.06 ; low, -0.06 to -0.002 ; very low, -0.002 to 0.28 .

Model topic: aquifer pollution hazard

There were pronounced differences in aquifer pollution hazard between subwatersheds in the different portions of the study area (Fig. 4). Generally, moderate

Table 3 Rating values for each parameter necessary to estimate subwatershed priorities (SWP)

Parameter (map)	Category	Rating
Aquifer pollution hazard (APH)	Very low level of support	5
	Low level of support	4
	Moderate level of support	3
	High level of support	2
	Very high level of support	1
Decision score (DS)	Upper basin	5
	Middle basin	3
	Lower basin	1

to very high contribution to aquifer pollution hazard was detected in the middle and lower basin, which also contained small pockets of low evidence. On the contrary, the upper basin presents moderate to very low contribution to aquifer pollution hazard. Dangerous aquifer pollution conditions in the middle and lower basins were largely driven by properties conducive to inadequate soil condition. Figure 5 shows the partial products of the entire evaluation process; from viewing this composite, it is possible to see the various contributions to overall aquifer pollution hazard. A summary of the results of the partial products are mentioned immediately below.

Groundwater condition

Throughout the upper basin, evaluation of groundwater condition showed high to very high contribution to aquifer pollution hazard. Evaluation of groundwater condition in subwatersheds of the middle basin presented moderate to low evidence for contributing to aquifer pollution hazard. In contrast, results in the lower basin were mixed with a considerable number of subwatersheds showing a low to very low contribution to aquifer pollution hazard from groundwater condition.

Considering the secondary topics of groundwater condition, in much of the upper basin, evaluation of

net recharge and aquifer media showed high to very high evidence for contributing to aquifer pollution hazard. Water table depth in this sector had very low to low contribution to aquifer pollution hazard due to a high thickness of the vadose zone. Subwatersheds of the middle and lower basin displayed conditions favoring the low aquifer pollution hazard by aquifer media and net recharge contributions. Outstanding exception for the former topic was a sector of the middle portion, where several subwatersheds showed high pollution hazard. Generally, in the subwatersheds of the middle and lower portion of the study area, the evaluation suggested that expected water table depth would contribute to aquifer pollution hazard since the vadose zone thickness is poor.

Soil condition

The upper subwatersheds showed conditions favorable for the proposition that the condition of soil does not contribute to aquifer pollution hazard. On the other hand, results in the middle and lower portions were mixed with a considerable number of subwatersheds showing moderate to very high evidence for contributing to aquifer pollution hazard from soil condition.

The soil condition was composed of the partial evaluations of soil media, hydraulic conductivity, land cover,

Fig. 4 Evaluation of aquifer pollution hazard for the Dulce stream basin

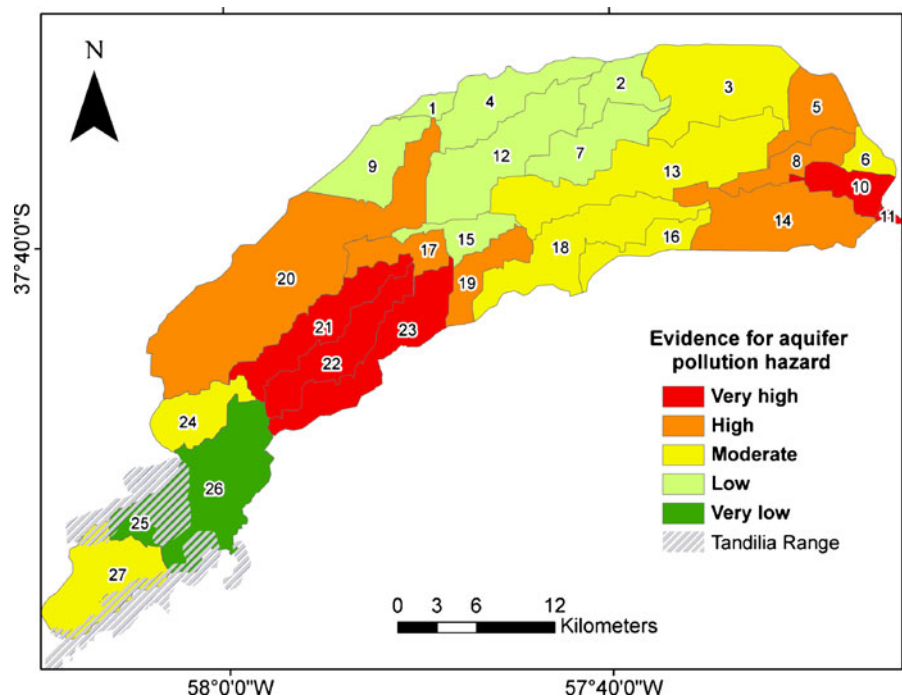
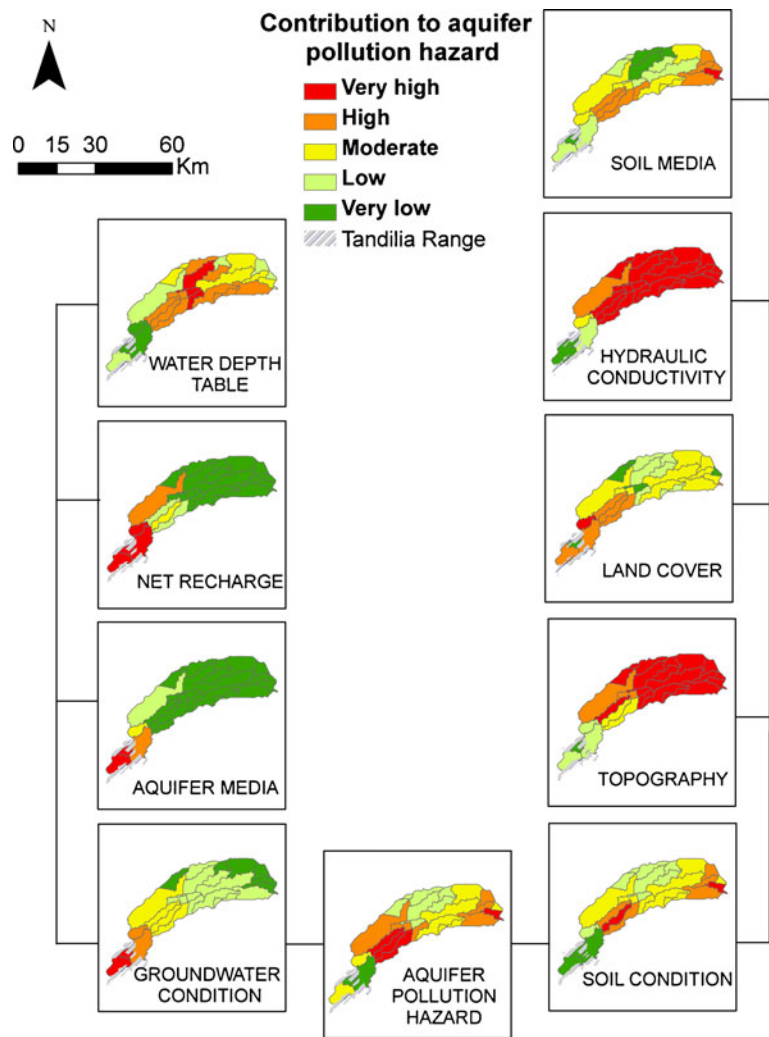


Fig. 5 Composite of all partial product evaluations leading to the full assessment of aquifer pollution hazard for the Dulce stream basin



and topography. Generally, the topography and hydraulic conductivity showed subwatersheds of the upper basin displaying conditions favorable for the proposition that the condition of soil does not contribute to aquifer pollution hazard. Most subwatersheds in both middle and lower basin evidenced high and very high contribution to aquifer pollution hazard. Related to land cover, the upper basin presented high contribution to aquifer pollution hazard since agricultural activities dominate the area. However, one subwatershed has very low evidence for contributing to aquifer pollution hazard considering that it coincides with the range system. The evaluation in the other portions of the basin suggested that land-cover characteristics would not contribute to aquifer pollution hazard due to the predominance of cattle-breeding activities. Appropriate soil media characteristics in the upper basin, mainly clay loam texture, showed low aquifer

pollution hazard. The middle portion had especially moderate to high evidence for contributing to aquifer pollution hazard. Loam to sandy loam soil texture dominated in this area. It also contained small pockets of low to very low evidence for contributing to aquifer pollution hazard. The presence of flooded lowlands and loam to clay loam soil textures is the explanation for this exceptional behavior. Finally, the lower basin displayed high contribution to aquifer pollution hazard since the soil in the area has a sandy texture.

Priorities for groundwater resources management

According to the interview results, different landscape conditions related to the influence of human activity in the Dulce Stream Basin were detected. As a consequence, the basin was divided into three specific areas

for the decision model design: upper, middle, and lower basin. A decision on which management alternatives (Fig. 3) to choose depends on the weights assigned to the individual criteria (Table 4).

The decision scores (DS) produced by the CDP model indicate a clear priority ordering, from upper (highest priority) to lower basin (lowest). Moreover, Fig. 6 provides a partial explanation of the derivation of priority scores, in terms of the relative contributions of primary criteria to each priority score. The upper basin receives the highest priority (0.742) because there is mainly extensive agricultural use, with both high agrochemical application and irrigation water demand. Soils in this sector of the basin are the most productive. In relation to the middle basin (0.193), mixed economic activity is shown (agricultural and cattle breeding activities) with productive soil sectors for agriculture. Moreover, it is characterized by moderate agrochemical application and irrigation water demand. Consequently, it has moderate priority for groundwater resources management. Finally, the lower basin received the lowest priority (0.057) since cattle breeding is the main land use, and it is characterized by low agrochemical application and irrigation water demand. Poorly drained soils dominate in this area. It is evident that land use and agrochemical application were not only the largest contributing criteria but also the generally account for the greatest differentiation among the three areas of Dulce stream basin.

A sensitivity analysis to provide diagnostics concerning the robustness of a decision model was performed. In CDP, the sensitivity analysis reports, for each goal–criterion and criterion–subcriterion pair, the percent change in weight required to produce a reordering of priority scores such that the highest ranked alternative is superseded by another alternative. A long-standing heuristic for AHP-related sensitivity analyses

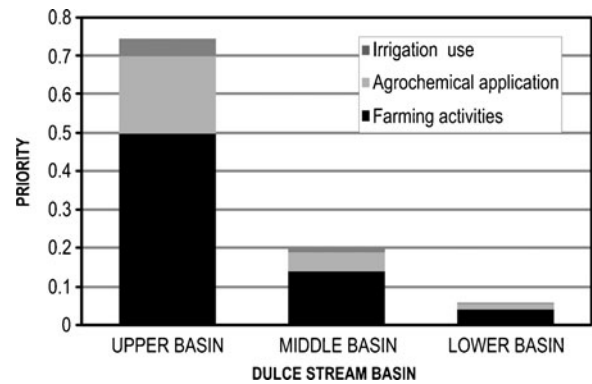


Fig. 6 Contributions of primary criteria to overall priority of sub-basins for groundwater resources management. Total bar height represents the overall priority score for each basin zone

is that a model can be considered adequately robust (in the sense that priority score ordering does not readily change) if the most sensitive weight in the model must be changed by at least 10 % (Saaty 1992). The model developed in this study for Dulce stream basin satisfied this basic sensitivity test.

The proposed DSS allowed integrating both the environmental analysis and the groundwater resources planning through the logic and decision models. The resulting SWP map illustrates groundwater resources management priorities (Fig. 7). The map identifies three priority classes which are discussed below:

1. High priority (SWP \geq 12): The probability for an adverse impact to water resources is very high. Remedial action is recommended to reduce the risk of aquifer pollution problems, water quality degradation and soil structure loss. Soil and water conservation practices plus a management plan might be adopted to reduce the potential of water quality degradation. A study of detail is essential (1:10,000 or greater).

Table 4 Weights for sets of subcriteria under each criterion in the decision model

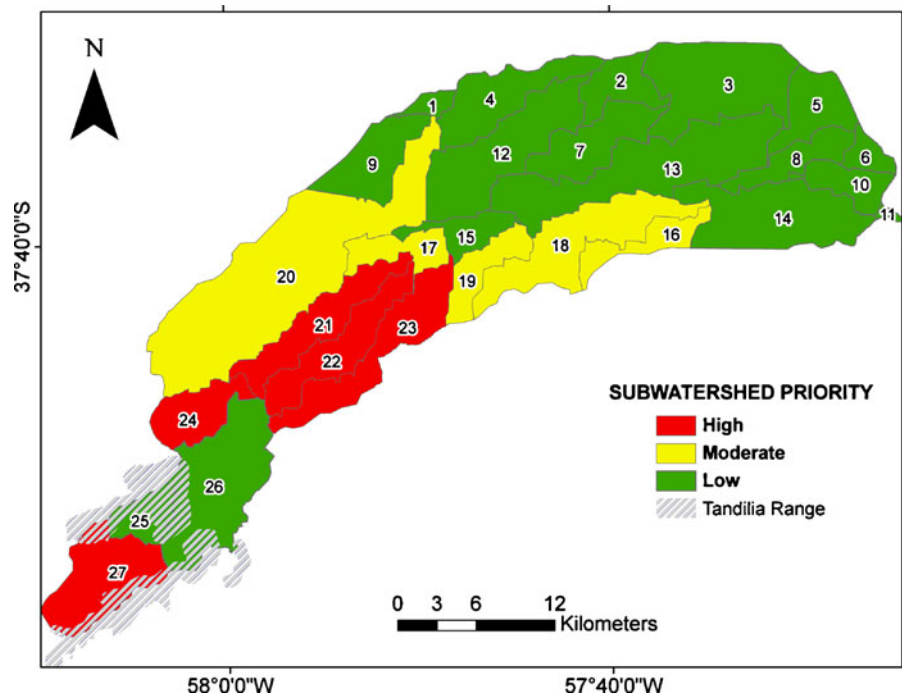
Goal level	Primary criteria	Secondary criteria ^c
Groundwater pollution hazard	Farming activities (0.673 ^a)	Agriculture (0.494 ^b)
		Agriculture- Cattle breeding (0.139 ^b)
		Cattle breeding (0.039 ^b)
	Agrochemical application (0.267 ^a)	High agrochemical application (0.202 ^b)
		Moderate agrochemical application (0.050 ^b)
		Low agrochemical application (0.015 ^b)
	Irrigation use (0.061 ^a)	High irrigation (0.046 ^b)
		Moderate irrigation (0.011 ^b)
		Low irrigation (0.003 ^b)

^aWeights of primary criteria sum to 1

^bWeights of secondary criteria sum to the weight of their respective primary criterion

^cThe scale unit is expressed as presence/absence of the observed subcriterion for each alternative

Fig. 7 Subwatershed priority map for groundwater resources management in Dulce stream basin



Routine monitoring of soil solution chemistry and groundwater quality is recommended. Moreover, guidelines on agrochemical management and utilization and the promotion of environmental education and awareness in order to involve stakeholders in the planning process should be considered.

2. Moderate priority ($6 < SWP < 12$): The probability for an adverse impact to water resources and soil is greater than that from a high rated priority. Remedial action is recommended to lessen the probability of aquifer pollution problems. An evaluation of detail (1:25,000–1:10,000) is suggested using data that permit establishing a hydrogeological and hydrochemical baseline. Special care in the case of persistent and/or mobile pollutants is also recommended.
3. Low priority ($SWP \leq 6$): If farming practices are maintained at current level, the probability of an adverse impact to water resources and soil would be low. A hydrogeological evaluation in a regional scale (1:50,000 or minor) is suggested.

Discussion

The applied methodological framework allows decision makers to rank the state of each evaluated subwatershed with respect to aquifer pollution hazard and support

planning activities such as priority setting, alternative selection, and resource allocation. The resulting subwatershed priority map (Fig. 7), by combining the logic and decision models, allowed identifying five subwatersheds in the upper and middle basin as the main aquifer protection areas. These subwatersheds were selected from the predicted outcomes obtained in the logic model and the CDP results. Although the selected subwatersheds from the upper basin (24 and 27) had moderate evidence for aquifer pollution hazard they are located in an intensive agricultural area and coincide with the natural recharge area to the aquifer system. The remaining subwatersheds (21, 22, and 23) presented very high contribution to aquifer pollution hazard due to the shallow water depth (2.86–3.14 m), the loam–loam silt texture of the soil media, and the pasture land cover, which dominates the area, while the decision model evidenced a moderate priority category for them. As a consequence, these subwatersheds were considered areas with high priority requiring a careful groundwater resources planning. The main advantage of the EMDS is that resulting applications are not at all black-box solutions. The knowledge base component (NetWeaver) provides a graphic interface that lets users easily trace and understand the derivation of conclusions. Similarly, the decision component (CDP) graphically displays the derivation of decision scores. This analysis process

allows the assessment of aquifer pollution hazard over time. This ability is intrinsic to the EMDS analysis and planning process, which can be clearly demonstrated over time as the base resource data that drive the analysis of aquifer potential pollution are updated. Moreover, the incorporation of new data in the decision support model could improve and adjust the landscape evaluation according to the main goal under study.

The main limitation of applying these models in the assessment of groundwater pollution hazard is their inability to perform integrated evaluation and planning in areas without extensive available data regarding aquifer geology and soil characteristics of the study area. The only possible way around these limitations is the use of empirical relations derived from an area with very similar characteristics. Another drawback of applying the logic model is its incapability to perform the evaluation for each subwatershed (by a zonal statistics analysis) without an average value for each input in the model. This procedure generates a mean value for each subwatershed, which can lead to underestimating or overestimating contributions of the evaluated topics.

We note that this logic model represents one of many possible logical configurations, and the current configuration may be readily adapted. Any of the primary and secondary topics may be modified, and topics may be added or removed with relative ease. Likewise, thresholds of elementary topics can be modified to fit customized or evolving evaluations as a function of adaptation and learning.

After priorities have been derived by the decision model concerning what to do about the existing aquifer pollution hazard conditions, the decision maker can review at the decision model outcomes and see the relative contributions of the criteria and their social context(s) to the overall decision. This transparent model design and structure aids in decision explanation, and it allows decision makers to consider, in the sense of scenario planning, the effects of alternative weightings of important decision criteria.

Thus, as with any model intended to support significant management decisions, our model of aquifer pollution hazard requires both verification and validation. The present model has, in fact, been substantially verified in the sense that it adequately represents the natural conditions of the basin based on our own field analysis. Moreover, it has been compared with the study of Lima et al. (2011) (where the aquifer

pollution hazard assessment was performed using the DRASTIC model in combination with the land-use variable), obtaining similar quantitative and spatial results. The Dulce stream basin has 38.58 % of high to very high evidence for aquifer pollution hazard and 41.25 % of very high category of aquifer vulnerability according to the latter authors.

In contrast to verification, validation is a more rigorous process in which model accuracy is objectively evaluated by comparing predicted and actual outcomes, ideally with statistical procedures. Model validation was not feasible within the temporal scope of our study. If the model for the assessment of aquifer pollution hazard was to be adopted as a tool by decision makers, we certainly recommend that explicit provisions for validation be an integral part of any ongoing assessment process designed to support it (e.g., the collection of groundwater samples for pesticides determination could be performed).

Conclusions

Given the agricultural expansion in Argentina during the last 10 years, the pressure of land use on natural resources has led to a greater threat of aquifer pollution since this activity increases erosion and sediment load, and leaches nutrients and agricultural chemicals into groundwater, streams, and rivers. Decision support systems such as EMDS can play a role in assisting with restoration to improve or maintain natural resource sustainability. Issues surrounding decisions about water management are complex and often require abstraction, but logic and decision models are well suited to representing the inherent complexities and abstractness of the problem, thus rendering the analytical problem more manageable. This particular application of EMDS also is an example of how decision support systems can not only be used as tools for technical specialists and decision makers but also as tools for communicating clearly and effectively with the general public who understandably have a strong interest in the topic of aquifer pollution hazard and want to understand, and be involved in, any proposed solution.

The successful application of this decision support system to real-world situations requires the interdependency between science, policy, and decision support systems. The practical application depends on a

close collaboration between the scientists, which bring the interpretation of environmental issues and the policy makers that need to reach decisions based on that information and additional social and economic considerations. Decision support systems provide a conspicuous advantage in this context by providing documentation of a decision-making process. With ongoing monitoring and evaluation of water resources in the region, new knowledge can be readily incorporated into decision models providing increasing effectiveness to decision making and an explicit vehicle for adapting water management.

Although virtually all logic and decision model interpretation embeds some degree of subjectivity, the applied methodology allowed prioritizing groundwater resources management areas. In this sense, the landscape integrated evaluation by combining the logic and decision models allowed identifying five subwatersheds in the upper and middle basins as the main aquifer protection areas. The obtained results reasonably fit to the natural conditions of the basin identifying those subwatersheds with shallow water depth, loam–loam silt texture soil media and pasture land cover in the middle basin, and others with an intensive agricultural activity, coinciding with the natural recharge area to the aquifer system.

The integration of the logic and decision model, results in a more complete and realistic picture of aquifer pollution hazard in the region. This study shows that decision support systems, such as the EMDS, are valuable tools for the prediction of agricultural activity impacts on groundwater resources. The purpose of the designed DSS 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 are a prerequisite for achieving socio-economic and biophysical sustainability in an increasingly agricultural region.

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