PROTOTYPE OF DSS TO MANAGE LAND USE ACTIVITIES

1. INTRODUCTION

The carbonate aquifers provide the main drinking-water resources of central-southern Italy, supplying an average volume of about $10400*10^6$ m^3/y (Celico, 1983a and 1983b; Celico et al., 2000). Several important towns (i.e. Rome and Naples), many smaller towns and countless villages utilize this water for their public water supply. Perched springs located in high altitude are often utilized by small towns and villages as well as bottling plants. These springs are often affected by microbial pollution (Celico et al., 2004a and 2004b) and protecting measures must be applied to prevent or minimize this contamination. However, due to the strategic importance of grazing and agriculture in carbonate massifs of central-southern Italy, it is unrealistic the application of a total protection. Scientists have to work to define a protection under sustained development conditions (Biondic et al., 1998), taking into account the socio-economic needs of local inhabitants.

This approach requires a high level of knowledge of carbonate aquifers hydrogeology and a thorough analysis of the interactions between land use and groundwater contamination.

The purpose of the present study was to define the protecting criteria of groundwater in carbonate aquifers of central-southern Italy, under sustained development conditions. These criteria have been defined as a function of experimental results acquired during several years of research in different test sites. All suggestions have to be considered as an integration to the Italian Law (D.L. 152/99) and respective Addenda, which do not provide sufficient or effective solutions for problems in these hydrogeological settings. The Law states that each Region should provide appropriate indications as to the setting up of protection zones, taking into account the hydrogeological features of different areas of the Italian territory.

In the present paper, no details are given concerning the land use prohibitions. The research is in progress in different test sites, in order to define the relationships between the extent of grazing and the groundwater quality.

The criteria here proposed will allow the implementation of a “map of land use restrictions”. This map will represent the graphic core of a specific Decision Support System (sDSS), which is a computer-based system that aids the process of decision making (Finlay, 1994). The latest, in this specific case, will aid decision-makers in protecting groundwater against pollution in carbonate aquifers, with emphasis on microbial contamination.

The protecting criteria here proposed have been already accepted by four Water Authorities (Autorità di Bacino dei Fiumi Liri – Garigliano e Volturno, Autorità di Bacino del Fiume Sarno, Autorità di Bacino del Sinistra Sele, Autorità di Bacino del destra Sele), which manage water resources within a territory of about 13000 km^2. The Agenzia Regionale Per l’Ambiente of Molise Region, which manages water resources in a territory of about 4500 km^2, has granted their testing in different pilot areas. The same protection criteria have been recently applied by different Mineral Water Bottling Companies (Sangemini, Fiuggi, Fabia, Aura, Amerino).

2. HYDROGEOLOGY AND GROUNDWATER POLLUTION IN STUDY AREA

The carbonate aquifers of central-southern Italy may be divided into three groups: (a) mainly dolomitic aquifers, yielding a total of about $0.3*10^9$ m^3/y, for an average yield of about 0.023 $m^3/s/km^2$, (b) mainly limestone aquifers, yielding a total volume of approximately $10*10^9$ m^3/y, for an average yield of about 0.027 $m^3/s/km^2$ and, finally, (c) aquifers made up of alternating limestone, cherty limestone, marly limestone and, subordinate marl, yielding a total volume of about $0.1*10^9$ m^3/y, for a an average yield of about 0.015 $m^3/s/km^2$. The carbonate aquifers are generally made of rocks characterized by very low primary permeability but extensively fractured and subordinately karstified.

The main springs of the carbonate aquifers (characterized by an average annual discharge which generally ranges from a few hundreds to several thousands l/s) often occur at the contact with Miocene rocks or volcanic, marine and continental Pliocene-Quaternary deposits, which represent relative aquicludes. Some aquifers are characterized by the existence of basal groundwater and several, usually small (mean annual discharge generally <0.1 m^3/s), perched groundwater. The latest are often generated by less permeable intercalations within the carbonate succession.

The transmissivity of carbonate aquifers usually ranges from 10^{-1} to 10^{-5} m^2/s, with a most common value of 10^{-2} m^2/s (Celico et al., 2000).This wide range is a function of both a different rock fracturing and a different distribution of karst features. Due to this variability, the piezometric gradient ranges between 1‰ to 10%. Highest values have been found where intense cataclastic zones produce significant head loss.

Due to the wide distribution of cattle grazing and manure spreading in intra-mountainous planes and the fast interactions between surface and groundwater, bacterial contamination of drinking water is often detected (Celico et al., 1998, 2004a and 2004b). The time dependence of fecal contamination shows series of peaks irregularly distributed (Celico et al., 2004a and 2004b). The high variability of pollution is usually generated by the interaction of several factors, such as infiltration mechanisms, length of transport, dilution, dispersion (Matthess & Pekdeger, 1981), type of soil and its degree of saturation (Lance & Gerba, 1984), filtration (Iwasaki, 1937; Yao et al., 1971; Gannon et al., 1991), adsorption (Maier et al., 2000) and retardation factors (Matthess et al., 1985).

3. GROUNDWATER PROTECTION ZONES AND PROTECTING MEASURES UNDER SUSTAINED DEVELOPMENT CONDITIONS

Measures must be taken for the prevention of groundwater contamination or the restoration of the groundwater quality at sites where groundwater pollution has occurred. These measures include the establishment of the protection zones and the elimination of the existent pollution sources.

3.1 Zones Ia and Ib (First Protection Zones)

Zone Ia includes the area immediately adjacent to the tapping area, within a distance no less than 10 meters (D.L. 152/99). This zone comprises the capture and the facilities needed for operation, service and guarding. No other activities are allowed.

For spring protection this zone could be less large downgradient (Civita, 1988), unless the carbonate aquifer crops out or underlies high permeability deposits. In the example shown in figure 1, the groundwater flows towards the spring within a radius of about 150 meters downgradient the spring itself (Fig. 1) and 10 meters must be used as radius.

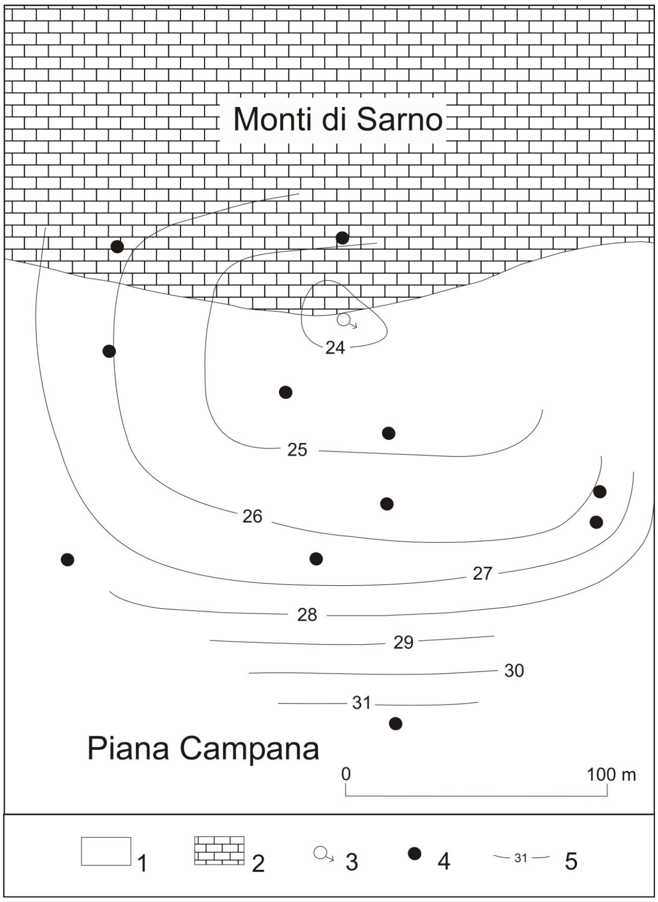

Figure 1 - Piezometric head around the Palazzo spring (1: alluvial deposits; 2: carbonate aquifer; 3: Palazzo spring; 4: wells and piezometers; 5: line of equal piezometric head in meters a.s.l.; from Nicotera & Civita, 1969, modified).

When well pumping occurs in carbonate substrata which underlie several tens or hundreds meters of low permeability rocks, the radius of 10 meters could be considerably reduced.

In other cases, pre-existing human activities could make it impossible to extend the zone within a radius of 10 meters. In these situations the tapping areas must be adequately protected with supplementary technical expedients (i.e. canalization of surface water, waterproofing, ect.).

According to other Authors (i.e. Jäckli, 1966; Avdagic & Corovic, 1990; Biondic et al., 1998; Kaçaroğlu, 1999), the same degree of protection must be applied to the swallow hole areas. Hence, it is necessary to define a Zone Ib within a radius of 10 meters from the swallow holes, in order to avoid their use for waste disposal. The remaining area of endorheic basins will be defined as Zone IIb or IIIb (see below).

3.2 Zone IIa (Second Protection Zone)

Zone IIa comprises the immediate hinterland of the tapping area (around the zone Ia), but D.L. 152/99 does not provide operative criteria in order to delimit this zone, nor does it offer any standard dimension. The Law also requires the identification of an "inner" zone IIa as well as an "outer" zone IIa, but it does not define how to differentiate between them. The D.L. 152/99 just provides that within the outer zone it is allowed a proper storage of manure and animal slurry, while within the inner zone no storage is possible. Some other prohibitions are provided by Law (i.e. storage of potentially polluting liquids, landfill sites, infiltration of polluted waste water).

The residence time criterion may be utilized in order to define the boundaries of spring protection zone IIa (Skinner, 1985), in agreement with the Addenda 12/02/2002 to the D.L. 152/99. Because the widest problem in carbonate aquifers of central-southern Italy is the cattle grazing, which produces microbial pollution of groundwater, these boundaries should be defined as a function of the survival (60 days) of the most representative bacteria into groundwater (Pekdeger & Matthess, 1982). The residence time must be calculated by determining both the migration of microorganisms through the unsaturated medium and their transport into the saturated aquifer, taking into account the main processes which influence the behaviour of bacteria into the subsurface (water chemistry, dilution, dispersion, adsorption, filtration, ect.). Due to the difficulties involved in the experimental calculation of the residence time (no injection of microorganisms is allowed by Italian Law), the travel time of water resources must be utilized.

The calculation of the travel time also requires a careful choice of the most reliable experiments in media which are heterogeneous, anisotropic and discontinuous (the latest, at a small scale). The main approaches that may theoretically be utilized are: (a) tracer tests, and (b) calculation of the average flow rate of effective infiltration water, through the experimental determination of time lags between rainfall and groundwater level (or spring discharge) rising.

The tracer tests should represent the most reliable method. Nevertheless, significant information can be acquired in heterogeneous aquifers just in case of point source pollution (Matthess et al., 1985). It is not the case of carbonate aquifers of central-southern Italy where the main cause of contamination is the cattle grazing, which represents a non-point source pollution. Moreover, the low permeability, which often characterizes the carbonate rocks at small scale, could not allow the injection of tracers on the top of the unsaturated medium. In other cases, the injection rate could be inappropriate related to the dilution into the groundwater. More reliable could be the results obtained through tracer tests in the saturated aquifer, even if they are generally acquired in a few monitoring points (a few wells or piezometers are drilled within the Italian carbonate massifs). Hence, the flow rate into the unsaturated medium should be calculated by analyzing the time lags between rainfall and groundwater level (or spring discharge) rising.

As per the boundaries of the zone, the Addenda 12/02/2002 to the DL. 152/99 recommends to use the travel times of 60 days and 180 (or 365) days for the inner and outer zones IIa, respectively. Nevertheless, due to the high flow velocities in the carbonate aquifers of study area, these travel times are unlikely applicable to obtain a total protection. For example, the infiltration velocity of about 30 m/d (Celico, 1997) and the flow rate of about 65 m/d (Bartolomei et al., 1980) calculated in the Monti Lepini aquifer, require the application of restricting measures within a radius of several kilometres. The problem is more complicated in case of wellhead protection zones, due to the higher flow velocities induced by pumping. In the case mentioned above, it was found a flow velocity of 205 m/d (Bartolomei et al., 1980).

The solution comprises two steps. First, the inner and the outer zones IIa should be delimited by using a travel time of a few tens of days (i.e. 10 or 20) and 60 days, respectively. Monitoring wells must be drilled along the boundary of the inner zone, where possible. The choice of the number of days should depend on the time required to bring into operation an alternative water source in case of pollution too much high to be treated, if the treatment is allowed. If the local morphology does not allow to drill wells, frequent analysis are proper at the capture before pouring water into the pipeline. In these cases 24 or 48 hours are indispensable to detect fecal coliforms and fecal enterococci, respectively.

Second, the unacceptable human activities have to be removed within the inner zone. On the contrary, they can be temporary preserved within the outer zone, if they produce a sustainable contamination, related to the possible water treatments. Nevertheless, in each case, the definition of this kind of measures needs a high level of knowledge concerning the impact of existent land use on the groundwater quality, to avoid a limited effectiveness of protection zones. Within these zones it is necessary to work towards a gradual introduction and extension of non-polluting or low-pollution technologies (Orloci et al., 1985), even though the protection has to be immediately effective. In some cases, the immediate effectiveness can be obtained by integrating these “developing protection zones” with technical measures which minimizes the capture of polluted groundwater. These integrative techniques may be defined as “dynamic measures” because they correspond to groundwater management solutions and / or catchment criteria. This is the case of several springs which are fed by both surface and groundwater. These sources are often contaminated by the rapid and episodic arrival of polluted surface water which infiltrates into swallow holes directly interconnected with springs. If no measures can rapidly remove the source of pollution, the problem can be solved by drilling an horizontal hole through the fracture network and, then, by capturing just the non contaminated groundwater. The effectiveness of this kind of capture is limited to those cases in which there is no significant percolation of surface water from karst conduits through the fracture pattern. When there is a significant and wide interaction between surface and groundwater the microbial pollution is detected at springs and into wells drilled into the fracture network. This is the case, for example, of the pumping wells drilled nearby the Capo di Fiume spring, which generally show from a few to a few tens of CFU/100 ml of fecal bacteria coming from an endorheic area located 2 km upgradient (unpublished data).

The impact of existent land use on the groundwater quality has to be thoroughly analyzed. The monitoring must be developed through a water year, at least, by utilizing a weekly collection. A daily monitoring must be used in case of fast arrival of contaminant at springs (i.e., where karst conduits directly interconnect swallow holes and springs or huge quantities of manure are spread within a radius of a few hundreds of meters from the springs; Celico et al., 2004a). In these cases the breakthrough curve is often detectable for a few days at most (Celico et al., 2004b). Moreover, due to the higher reliability of fecal enterococci, these bacteria must be analyzed as well as fecal coliforms where the land use causes a low contamination (Celico et al., 2004a and 2004b) and / or in high mountains, where freeze-thaw treatments are highly lethal for fecal coliforms (Allocca et al., 2006).

The zones IIa can be strongly reduced where well pumping occurs into carbonate rocks which underlie a thick sequence of low permeability deposits.

3.3 Zone IIb

Zone IIb is often located far from the springs and comprises some endorheic basins and catchment areas of streams which feed a carbonate aquifer. Zones IIb comprise those areas where the surface runoff infiltrates in the subsurface into a swallow hole and / or through a high permeability medium, as well as areas where there is not a significant dilution of surface water into groundwater. This restrictive measure has been defined as a function of results obtained in different test sites, where microbial monitoring showed that a significant increase in contamination is caused by the interaction between surface runoff and springs (Celico et al., 2004a). A significant example is represented by the Mt Capraro carbonate aquifer, where a discontinuous bacterial contamination is partially produced by the interaction between S. Mauro spring and an endorheic area located some hundreds of meters from the spring itself (Celico et al., 1998).

These zones are not included into the D.L. 152/99 and then no rules provide the elimination of specific contamination sources. The solution could be the application of protecting measures depending on the vulnerability to pollution (Skinner, 1985). Within these areas, an aquifer is differently vulnerable from diffuse infiltration of rainfall and concentrated infiltration of surface runoff in topographically low areas (Celico & Naclerio, 2005). Hence, it is necessary to take into account both the type and the degree of vulnerability. As per the vulnerability related to the infiltration of surface water, it must condition the prohibition of land use activities which cause the spreading of pollutants over the field.

3.4 Zone IIIa (wider protection zone)

Zone IIIa comprises all the catchment area which keeps filling the groundwater source (in the case study it generally ranges from a few tens to several hundreds of km^2), except the endorheic basins, if existent (see zones IIb and IIIb).

Within this zone the D.L. 152/99 does not include the elimination of specific sources pollution. Hence, it is possible to regulate the land use as a function of the vulnerability degrees.

3.5 Zone IIIb

As well as zone IIb, zone IIIb is often located far from the springs and comprises some endorheic basins and catchment areas of streams which feed a carbonate aquifer. Zones IIIb comprise those areas where the surface runoff infiltrates in the subsurface through a low permeability medium as well as areas where there is a significant dilution of surface water into groundwater. If no experimental data are available about dilution, these areas must be identified as zones IIb. As well as for zone IIb, a significant example of zone IIIb can be identified within the Mt Capraro carbonate aquifer, where a low but continuous microbial pollution of S. Mauro spring is caused by the infiltration of surface water along the Trigno river, at a distance of about 2.5 km (Celico et al., 1998)

These zones are not included into the D.L. 152/99 and then no rules provide the elimination of specific sources of pollution. Hence, as well as for the zone IIb, it is necessary to regulate the land use as a function of both the type and the degree of vulnerability. Concerning the vulnerability related to the infiltration of surface water, it must condition the prohibition of land use activities which cause the spreading of pollutants over the field. In general, decision makers can apply minor restrictions than those applied within the zones IIb. This is due to the existence of a higher dilution of polluted water and / or a significant interaction between fine sediments and polluted surface water during their infiltration in topographically low areas. In fact, column tests developed by using intact soil blocks collected in karst planes showed the existence of a significant retention of fecal bacteria. Less than 1% of inoculated microorganisms outflowed from the more permeable blocks analyzed, after simulating a significant infiltration event (Celico et al., 2004b). These blocks are mainly made of sands (about 50%) and silts (about 40%) and subordinately of clays (about 10%).

4. THE MAP OF LAND USE RESTRICTIONS

Once the protection measures have been defined, they can be used to implement the “Map of land use restrictions”, schematically shown in figure 2. The main goal of this map is to show what human activities are not allowed in each protection zone. Because the Law does not provide a list of specific prohibitions, except the case of zones Ia and IIa, the land use restrictions should be chosen depending on both the type (Celico & Naclerio, 2005) and the degree of vulnerability to pollution (Skinner, 1985). Hence, it is possible to define different lists of restrictions in a same protection zone. This approach is different from others (i.e. Doerfliger et al., 1999) that delineate the groundwater protection zones based on vulnerability mapping.

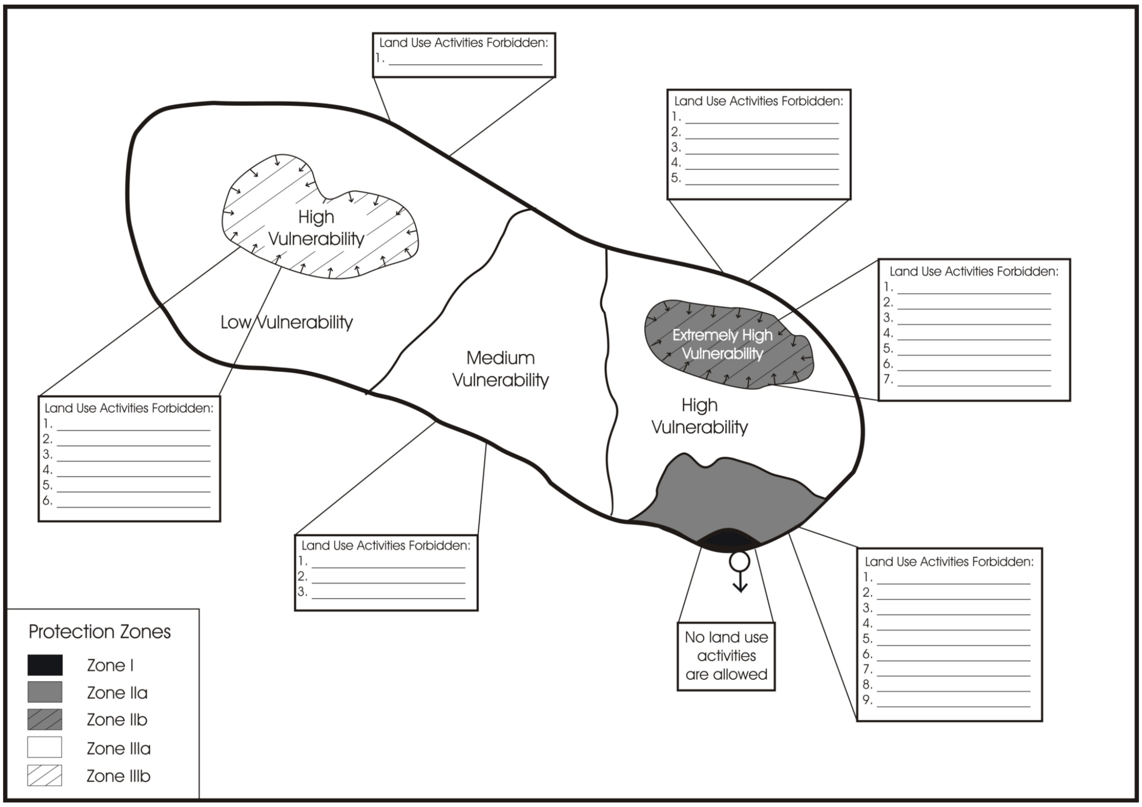

Figure 2 – Schematic example of a “Map of land use restrictions”. The list of prohibitions is a function of the type of protection zone, and both the type and the degree of vulnerability.

The effectiveness of the proposed solutions is a function of the reliability of assessing methods. In the case study, the vulnerability must be assessed by using the DAC (Celico, 1996), which was experimentally verified as predictor of microbial contamination in carbonate aquifers (Celico & Naclerio, 2005; Celico et al., 2006a; Celico et al., 2006b).

The map of land use restrictions will represent the graphic core of a GIS-based specific Decision Support System whose goal will be, in part, the protection of water resources against pollution, taking into account the socio-economic needs of the territory. The sDSS will be addressed to Public and Private Corporations who distributes and/or utilizes water resources, such as waterworks, bottling plants and thermal resorts. They typically require to consider a multitude of social, legal, economic, and hydrogeological factors, and the sDSS have great potential for improving the management of water resources. However, only a few applications have demonstrated this potential in the past years. For example, Andreu et al. (1991) presented a computer-assisted support system for water resources management. Stansbury et al. (1991) linked a simulation model, an impact analysis module, and a multiobjective decision module in a DSS for water transfer planning. Frysinger et al. (1993) described a DSS for the design of a monitoring well network which would meet the U.S. Resource Conservation and Recovery Act groundwater monitoring regulations.

5. CONCLUSIONS

Several years of research that was carried out in different test sites of central-southern Italy allowed the identification of protecting criteria that must be integrated to those introduced by Italian Law (D.L. 152/99), in order to prevent groundwater pollution in carbonate aquifers. Since grazing and manure spreading represent the main land use activities, the research has been focused on the microbial contamination of water resources.

The integrative measures can be synthesized as follows: (a) introduction of new protection zones, (b) identification of criteria for delimiting zones IIa, (c) introduction of the concept of “developing protection zones”, and (d) use of “dynamic” protecting measures, when polluting human activities are already existent within the protection zones.

New protection zones have to be introduced in the swallow hole areas (zones Ib) and within endorheic basins and catchment areas of streams which feed a carbonate aquifer (zones IIb and IIIb), in order to correctly evaluate the role of surface – groundwater interaction on the transport of contaminants into the aquifer. Zones IIb (characterized by more restrictions) comprise those areas where the surface runoff infiltrates in the subsurface (a) into a swallow hole and / or (b) through a high permeability medium as well as areas where there is not a significant dilution of surface water into groundwater. On the contrary, zones IIIb (characterized by less restrictions) comprise those areas where the surface runoff infiltrates in the subsurface through a low permeability medium as well as areas where there is a significant dilution of surface water into groundwater.

Since no technical solutions are given by the Law, it was chosen the travel time criterion for delimiting zones IIa, taking into account the persistence of bacteria into aquatic environments. Nevertheless, due to the high flow and transport velocities within the studied aquifers, the choice of the travel time that must be used for delimiting the boundaries of zones

IIa should be diversified as a function of water destination. That to avoid the delimitation of overextended protection zones, which negatively influence the socio-economic needs of an area. The lower the water treatment allowed, the wider the zones IIa have to become. Given an aquifer, the widest extension must be used for bottling mineral water, because no treatments are allowed. On the other hand, when there are polluting human activities in the hinterland of the groundwater capture, the immediate effectiveness of protecting measures can be obtained by using “developing protection zones”. These zones must be integrated with technical measures which minimize the capture of polluted groundwater. Within these zones it is necessary to work towards a gradual introduction and extension of non-polluting or low-pollution technologies. These integrative technical measures will minimize the capture of polluted groundwater. They have been defined as “dynamic measures” because they correspond to groundwater management solutions and / or capturing criteria.

The protection criteria here synthesized can be easily adapted to other kinds of aquifers, with emphasis on those characterized by a significant interaction between surface and groundwater.

Taking into consideration the vulnerability to pollution of an aquifer, in each protection zone it will be possible to define the land use prohibitions. Decision makers will find this information in a “map of land use restrictions”, which will represent the graphic core of a GIS-based sDSS.

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