Groundwater Protection Using Vulnerability Maps and Wellhead Protection Area (WHPA): A Case Study in Mexico

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Abstract The need to protect groundwater resources against quality deterioration due to anthropogenic activities is unquestionable. The concept of aquifer pollution vulnerability maps and of wellhead protection areas (WHPA) as protection tools is not new; however, in spite of the elapsed time, their use has been increased as a result of the increase in economic development—and everything that this entails—and the increase in prohibitive costs of treating contaminated water or of the decontamination of aquifers. The study's objective was to establish an integrated method that defines, first of all, the areas of highest vulnerability in the aquifer, and second, within these areas, the wells that most urgently need protection. To identify these wells, additional criteria were taken, such as well constructive data, pumped volume, and the region's socioeconomic characteristics (social exclusion index). Once the wells were ranked, several of them were chosen as a pilot study to compare different methods for the delineation of WHPA based on calculated fixed radius and analytical methods and, this way, identify which method or methods best adapt to the characteristics of the study area. The Minkin analytical method proved to offer the best results since it protects well on both sides and achieves a balance in the well's upgradient distances. It is also worth mentioning that the delimitation of the WHPAs in the study area was limited in respect to hydrogeologic and technical data.

Keywords Groundwater protection · Aquifer vulnerability ·
Wellhead protection area (WHPA) · Drinking water · Mexico

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1 Introduction

The experience in the last decades has shown that groundwater is not immune to contamination and that once it is contaminated by chemical, biological or radiological agents, it is nearly always hard to clean and the possibilities of remediation involve high economic costs (UN 2006; Wang 2006).

There is no doubt that the safest way to achieve absolute protection against groundwater contamination would be to stop all type of potentially contaminating activities. Nevertheless, this would be impossible to carry out due to the technical and, most of all, economic implications that this would involve (Wang 2006).

In this sense, in stead of applying universal controls over land use on a regional level and effluent discharge to the ground, it is more cost-effective (and less prejudicial to economic development) to define the level of control required on a more local scale (De Loë et al. 2002; Fadlelmawla and Dawoud 2006). Simple and robust zones, which can be defined based on aquifer pollution vulnerability and wellhead protection areas, must be established (Hirata and Reboucas 1999), indicating which anthropogenic activities are possible and where they can be located, at an acceptable risk to groundwater (Foster et al. 2002; Sylvestre and Rodriguez 2008).

Aquifer vulnerability is defined as "an intrinsic property of a groundwater system that depends on the sensitivity of that system to human and/or natural impacts" (Vrba and Zaporec 1994). There are several methods to determine this vulnerability, which have been modified in the last years to adapt to different hydrogeological environments (Hirata and Reboucas 1999; Gogu and Dessargues 2000; Massone et al. 2010). Most of these methods are based on index and overlaying techniques. The combination of maps with a spatial distribution of data with specific attributes (soil, geology, groundwater depth, etc) leads to the assignation of a numerical index or a value for each attribute. These are combined to produce a vulnerability score. This score is reflected in a map—the vulnerability map—which produces information regarding the ease with which the groundwater can be contaminated by an external agent. The obtained map is of great use, for example, for land use planning.

Common methods are DRASTIC (Aller et al. 1985), SINTACS (Civita 1994), AVI (Van Stempvoort et al. 1992) and GOD (Foster and Hirata 1988; Foster et al. 2002). There have been studies comparing these different methods (Gogu et al. 2003); as well as research attempting to conduct a validation of the vulnerability maps obtained through the use of numerical models, for example (Neukum et al. 2008).

A wellhead protection area (WHPA) is based on the establishment of a system of zones surrounding the well, inside of which activities that are liable to modify the groundwater quality are restricted or prohibited in a gradual manner (depending on their proximity to the well; US Environmental Protection Agency 1993).

The WHPAs, as a protection tool for groundwater, are still being enforced at present, as evidenced by a recent study in South Africa by Nel et al. (2009) and there is a search to define methods which, with minimal information, guarantee the obtaining of real WHPAs (Miller et al. 2003; Paradis et al. 2007; Exposito et al. 2007; Garfias et al. 2008), likewise, there is research into new concepts such as well vulnerability (Frind et al. 2006).

According to the US Environmental Protection Agency (1993), the main assessment methods for WHPAs can be reduced to six, which can be classified in an ascending order with regard to complexity and costs, into arbitrary fixed radius,

calculated fixed radius, simplified variables shapes, analytical methods, hydrogeo-logical mapping and numerical flow and transport models.

Choosing the appropriate method requires specific procedures that consider the amount of hydrogeological data that is necessary, the hydrogeological complexity, the required accuracy of the results, time, human resources, the capabilities of the groundwater management agency, and available funding (Miller et al. 2003; Fadlelmawla and Dawoud 2006).

The study's objective was to establish an integrated method that defines, first of all, the areas of highest vulnerability in the aquifer, and second, within these areas of highest vulnerability, the wells that most urgently need protection. Once these wells are identified, an evaluation is conducted of the different methods for the delineation of protection areas, which will allow defining the method that helps obtain a delineation of the areas that are to be protected, in a sufficiently precise, simple and low-cost manner, according to the existing conditions in the study region.

To apply these concepts, the aquifer of the Valley of Toluca, in central Mexico, was chosen as study area. There is intense exploitation of this aquifer, a growing demand for groundwater for different types of supply, constant increase in contamination risk and an intense and, in many cases, inordinate population growth (Esteller and Díaz-Delgado 2002; Esteller and Andreu 2005).

2 Study Area

The study area, the aquifer of the Valley of Toluca (Fig. 1) is located in the central area of Mexico, more specifically in the central zone of the State of Mexico, and is one of the highest in elevation in the Mexican Highlands. It borders the Atlacomulco–Ixtlahuaca Aquifer to the north, the Tenango Hill to the south, the Nevado de Toluca Volcano to the south-west and Sierra de Las Cruces and Monte Alto to the east.
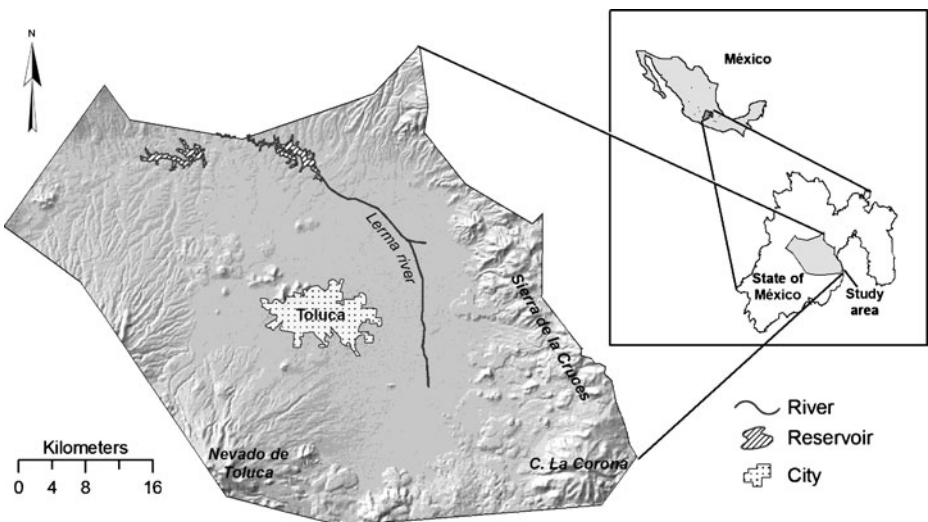

Fig. 1 Location map for the study area. Valle de Toluca (Mexico)

The climate can be considered as humid temperate with abundant rainfall in the mountain areas (1,000 mm/year) and less rainfall in the valley (700 mm/year), the rain season being from May to September. Temperatures vary considerably, with mean monthly temperatures ranging between 5°C (at altitudes of over 3,000 m.a.s.l.) and 25°C (in areas located in the valley).

The aquifer of the Valley of Toluca is formed by noticeably heterometric detrital material, predominated by gravel, sand, and conglomerates with clayey silt matrix, although it is also possible to distinguish pyroclastic intercalations with layers of tephra and tuff. Based on these characteristics, it can be pointed out that this system is formed by several superimposed aquifer layers that constitute a multilayered aquifer, but the existence of hydraulic continuity allows us to consider a single-flow system. Nevertheless, there are significant differences in the hydraulic head. This detrital material lies over a foundation comprised of consolidated volcanic matter of a variable nature, predominantly basalt and andesite (Unitecnia Company 1996). These basalts and andesites represent a continuation of the volcanic deposits that form the mountain ranges and make up the fractured aquifers whose main function is to recharge the Valley of Toluca aquifer.

The hydraulic parameters of the aquifer of the Valley of Toluca fluctuate over a wide range due to the lithologic and geometric variability of the deposits. Hydraulic conductivity values range between 0.4 and 80 m/day and effective porosity varies between 0.3% and 0.9% (CCRECRL 1993).

This valley is an important economic center in the country and has a high population density that has led to an increase in water demand which is being covered almost entirely by groundwater.

The total volume of water extracted is 425 Mm^3/year, out of which 358 Mm^3/year (84%) are destined to public–urban use both in the valley and in Mexico City. The number of wells destined for this use amounts to 404, out of which 178 extract water for Mexico City. Agricultural use demands 7% of the extracted volume, and the same percentage goes to industrial use. The rest is used for services, cattle and aquaculture. Due to this intense exploitation, the aquifer is under prohibition and the construction of new wells is not allowed (CONAGUA 2002).

3 Materials and Methods

The development of this research was defined based on three stages: the first stage was focused on the elaboration of the pollution vulnerability map; in the second stage, a series of criteria was applied to prioritize wells located in the aquifer's most vulnerable zones; and the third stage consisted of employing and comparing different methods to define the protection areas.

3.1 GOD-based Vulnerability Mapping

There are several methods for the determination of aquifer vulnerability. These methods differ regarding the parameters that are used; there are methods that use a significant number of parameters, while others are based on only a few parameters (Martínez and García 2003).

In this sense, the first step towards conducting the groundwater pollution vulnerability mapping was choosing the method that would be employed. According to Auge (2003), the choice of method depends on factors such as knowledge of the methodology, available information, and scope of the evaluation.

Once the previous criteria was analyzed, it was concluded that the GOD method (Foster et al. 2002) will be used, because this method is widely used in Latin-America, the necessary information for its application in the study area is available, and also, the extension of the work area demands the use of a working scale higher than 1:100,000.

Both the GOD method, as well as other commonly used methods (DRASTIC; SINTACS), only offer qualitative results; however, considering the scale of the works (1:250,000) and the uncertainty of the values of some parameters such as recharge, it was considered that the GOD method would offer an acceptable estimation of the area's level of vulnerability as a first approach to a more detailed study on vulnerability.

3.2 Selection and Prioritization of Supply Wells

The great number of wells that are destined for public–urban use in the study area (404 wells) raises the need for previous planning in order to establish which wells should have priority in regard to protection; therefore, once the pollution vulnerability map was obtained, wells were chosen that needed protection in a prioritized manner within the areas of greatest vulnerability, based on priority criteria defined by Martínez and García (2003) and adapted to the conditions of the study area.

The method used was the following:

- Based on the well inventory provided by National Water Commission (CONAGUA)—the government institution in charge of the management, care and preservation of water in Mexico, wells destined for public–urban use were selected.
- Wells that supply water to Mexico City were eliminated. Exclusion of this wells was exclusively because, given the geographic proximity among these wells, the interference produced by their joint exploitation would generate excessively complex protection perimeters that are hard to estimate using analytical methods (Hirata and Reboucas 1999). These wells display, without a doubt, high protection priority, and so the delineation of a common protection area could be conducted through numerical modeling in later stages of the research.
- The rest of the exploitation wells of the database were placed in the vulnerability map, identifying those that are located in the areas of highest vulnerability.
- Populations located near wells were sited and classified according to index of social exclusion. The index of social exclusion includes a set of variables related to the population, its economic conditions and housing characteristics, and quality of life. This index is assessed for all the country's municipalities by the National Population Council (CONAPO 2001). The use of the social exclusion index in the prioritization of wells was considered as a way of evaluating the potential contaminant load that can reach the aquifer due to deficiencies in the management of solid and liquid wastes. These wastes might not represent large values, but they must be considered as sources of contamination.

In addition, this index is also useful in the evaluation of material and human resources that are available for maintaining the well in proper exploitation conditions, for locating alternative sources of water supply in the case of contamination events, or even to have proper medical attention in the face of waterborne diseases (the greater the social exclusion index, the less the availability of human and material resources; Montgomery and Elimelech 2007).

- The possible influence of land use was analyzed at the time of choosing the wells that were to be protected, using the land use map elaborated by National Institute of Statistics, Geography and Data Processing (INEGI 2003). For example, wells located in areas used for agriculture have a higher priority of protection, because these farming areas receive contaminant loads from the use of agrochemicals. By contrast, wells located in areas where land use is for forest or pasture, are not a priority because there are no pollutant loads.
- An analysis was conducted for each well, including the year in which it was constructed and the extraction volume, information obtained from the National Water Commission (CONAGUA, its Spanish acronym) inventory.

The age of the well was related to the identification of wells that have exceeded their service life (20 years) and are still operating. Higher priority was assigned to these wells, given the possibilities of structural failures that could facilitate the entry of pollutants.

The exploitation volume was considered as being more relevant than the age of the well, since the volume (considering that these wells are exclusively for urban use) reflects the number of people who could be affected by a potential contamination event (the greater the volume, the greater the population that is being supplied).

3.3 WHPA Methods Application and Comparison

The delineation of a protection area around one or several wells is the most important stage in the implementation of the WHPA program (US Environmental Protection Agency 1993). Nevertheless, in order to proceed with the selection of the method or methods to be used, it is necessary to determine if the required information is available and whether it has the required reliability (Paradis et al. 2007).

In the analyzed case, once the geological and hydrogeological works that have been conducted in the study area were revised, it was concluded that there is lack of data necessary for the application of methods based on numerical models; however, some parameters were determined so as to delineate the protection areas through other methods based on fixed radius and those of analytical nature.

Based on the available information (pumped volume, hydraulic gradient of the area, hydraulic conductivity and effective porosity of the geological materials where the aquifer is developed), it was concluded that the application of the following methods is feasible: calculated fixed radius in its volume version, and the analytical method in the versions of Wyssling (Moreno and Martínez 1991), Minkin (Oradoskaia and Lapchin 1987) and Perez and Menendez (Perez et al. 1998).

All these methods agree on dividing the WHPA into different zones around the well, graded from most significant to less significant in relation to the restrictions of

Fig. 2 The WHPA concept
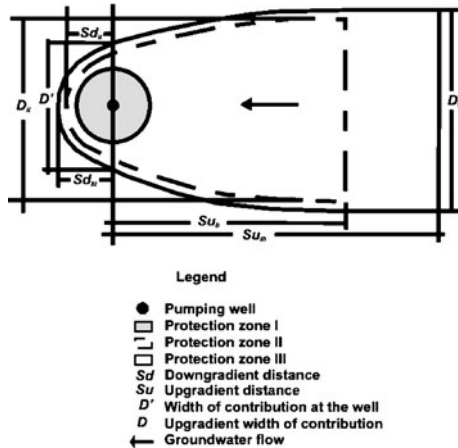
the polluting activities that are carried out within them (Fig. 2). The zones are the following (US Environmental Protection Agency 1993, 1994; Moreno and Martínez 1991; Martínez and García 2003):

- Immediate zone or absolute restriction zone (zone I). This zone is the closest to the well. Its primordial goal is to protect it and its installations against inclement weather and animal action; likewise, it prevents the direct infiltration into the well. The delineation criterion tends to be of a time of travel (time necessary for a pollutant to enter the well) of 24 h or a small area established in an arbitrary fashion.
- Proximate zone or maximum restriction zone (zone II). It represents the perimeter's main body. It includes an area that is variable but enough to protect water against microbiological pollution, either by ensuring the inactivation, elimination or dilution of the pollutant, or by allowing an alert with enough time to take the necessary measures before the foreign substance reaches the well.
- Remote zone or moderate restriction zone (zone III). This zone must protect the well against persistent pollutants, basically non-degradable or hardly degradable chemical contamination (heavy metals, hydrocarbons and organic compounds). The protection philosophy in this area is based, therefore, on dilution or alert processes, in addition to degradation or inactivation.

A brief description of methods so elected is as follows:

Calculated fixed radius method: volume version

The first of the versions corresponds to the calculated fixed radius method, which was chosen for being one of the methods that adapted to the study area due to its simplicity and low cost. Nevertheless, even though the use of this method increases precision in regards to the use of the arbitrary fixed radius, it continues to be a method that provides little accuracy, since it considers a very limited number of factors. However, when there are limitations in time, funding, or personnel, this

method is an appropriate starting point (Miller et al. 2003). The radius of protection perimeter (R) is defined as:

$$R = \sqrt{\frac{Q(t)}{n\,\pi\,b}} \tag{1}$$

were, Q is the pumped volume, t is the time of travel, n is the effective porosity and b is the saturated thickness in the well. The value of R is the upgradient distance (Su) and the downgradient distance (Sd).

Analytical method: Wyssling version

The method is based on the calculation of the zone of contribution of a given time of travel. This method is a simple procedure applicable in homogeneous aquifers, which requires a previous pumping test. The perimeter protection for a specific time of travel is calculated from the distance from the pumping well to the downgradient boundary of the zone of contribution (A), the width of contribution at the pumping well (D'), the upgradient distance (Su), the downgradient distance (Sd) and the upgradient width of contribution due to the pumping rate (D). These parameters are calculated as follows (Wyssling 1977 in Moreno and Martínez 1991):

$$A = \frac{Q}{2\pi\,Kbi} \tag{2}$$

$$D' = \frac{Q}{2Kbi} \tag{3}$$

$$Su = \frac{+d + \sqrt{d\,(d + 8A)}}{2} \tag{4}$$

$$Sd = \frac{-d + \sqrt{d\,(d + 8A)}}{2} \tag{5}$$

$$D = \frac{Q}{Kbi} \tag{6}$$

were K is the hydraulic conductivity, i the natural hydraulic gradient and $d = v^*t$, where t is the desired time of travel and v is the velocity of groundwater flow without pumping interference ($Q = 0$). The other parameters match the previous method.

The Wyssling version was chosen for being one of the well-knowing and used methods for the delineation of protection areas.

Analytical method: Minkin version

This method has been used for confined aquifers but also for unconfined aquifers on the condition that the decline of groundwater level by pumping was small relative to the aquifer thickness (Oradoskaia and Lapchin 1987). The values of the parameters to define the WHAPA is obtained by estimating the downgradient boundary of zone of contribution of the well (X_P), the indirect parameter of calculation (t^*),

the upgradient distance (Su), the downgradient distance (Sd) and the width of the perimeter (D).

$$X_p = \frac{Q}{2\pi \, Kbi} \tag{7}$$

$$t^* = \frac{Kit}{n X_p} \tag{8}$$

$$Su = R X_p \tag{9}$$

$$Sd = r X_p \tag{10}$$

$$D = 2d X_p \tag{11}$$

were n is the effective porosity. The other parameters match the previous methods. Having defined the value t*, we derive the parameters R^*, r^* and d^* from the values established by Oradoskaia and Lapchin ([1987]).

The Minkin version has been widely used in different countries in Europe (Exposito et al. [2007]).

Analytical method: Pérez and Menéndez version

Perez et al. ([1998]), introduced another option for calculating of WHPA. The equations used are:

$$Sd = \frac{Q}{2\pi \, Kbi} \tag{12}$$

$$D = \frac{Q}{Kbi} \tag{13}$$

$$Su = \sqrt{\frac{Q}{\pi b n}t + r_p} + \frac{Ki}{n}t \tag{14}$$

were r_p is the well radius. The other parameters match the previous methods.

The Perez–Menendez version has been used in Cuba as a basis for said country's regulation in regards to well protection.

Once assessment of the dimensions of the WHPAs has been conducted based on the different methods mentioned previously, a comparison among them was conducted, applying the areas of coincidence criterion (Paradis et al. [2007]) which is recommended when comparing methods of the same hierarchy (in this case, among analytical methods). This criterion consists of superimposing the results of the obtained WHPAs with the different methods and choosing the method that defines a perimeter that comprises the area that is delineated when superimposing all the WHPAs and in which all methods concur.

4 Results and Discussion

4.1 Vulnerability Map

Once the method to be used is defined, in this case GOD, an evaluation of the parameters was conducted:

(a)　*Determination of the degree of hydraulic confinement or aquifer type (G)*

The geological map prepared by UNAM (1994) was used as a basis for the analysis. The degree of the aquifer's hydraulic confinement was identified and a value was assigned to this parameter in a scale from 0.0 to 0.8 (Fig. 3a)

(b)　*Determination of the characteristics of the overlying strata or vadose zone lithology (O)*

Characteristics of the strata overlying the saturated zone were specified based on the type of lithology (indirectly considering effective porosity and infiltration coefficient), and a value was assigned to this parameter in a scale from 0.5 to 0.9 (Fig. 3b).
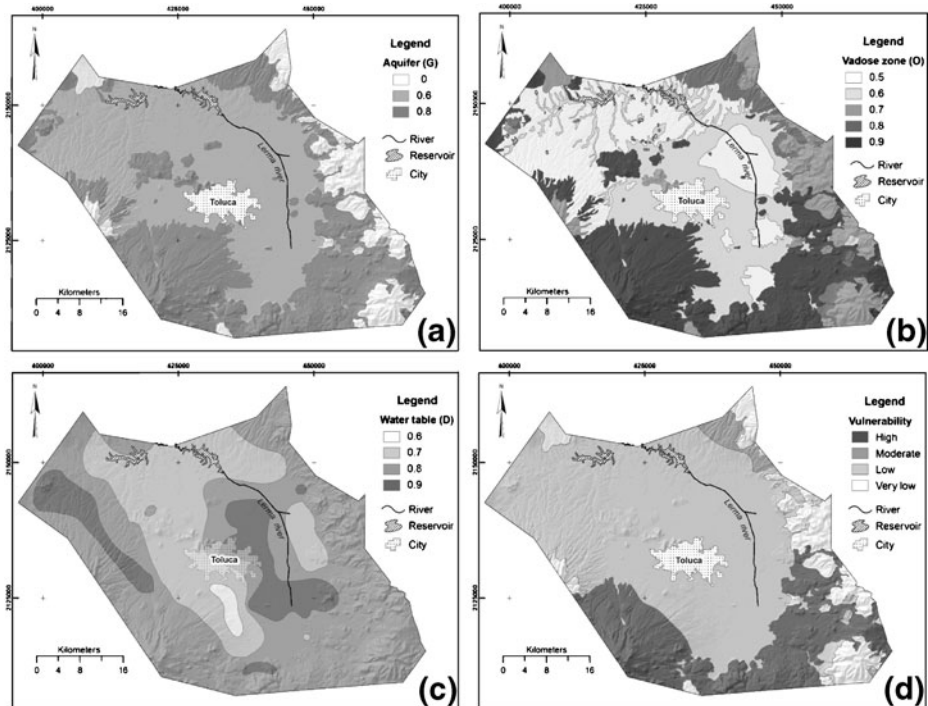

Fig. 3 **a** Groundwater occurrence map. **b** Overlying lithology characteristics map. **c** Variability of the depth to the water table map. **d** GOD map for the study area

(c)   *Depth to groundwater (D)*

Based on interpolations conducted with the water table level data, depth to ground-
water was estimated, with the assignation of different values in a scale from 0.6 to
0.9 (Fig. 3c). To determine the depth of groundwater level, data can be used which
are obtained in the piezometric monitoring networks of the aquifer. This network is
made up of 56 piezometers operated by CONAGUA.

The GOD pollution vulnerability map was conducted through a series of polygon
overlaps using ArcView software. The resulting map is shown in Fig. 3d. It is possible
to see that the most vulnerable areas are located in the recharge zones, which
correspond to the mountainous areas where fractured volcanic materials appear,
whereas in the valley the degree of vulnerability is low.

4.2 Selection and Prioritization of Supply Wells

Once the areas of highest vulnerability were delineated, public water wells located
within those areas were identified. With the data of the identified wells, which are
49 in total (Fig. 4), a database was elaborated indicating for each well the annual
pumped volume, which fluctuated between 3.9 and 0.01 Mm^3/year, and the year in
which it was constructed. Also specified in the database was land use in the area
surrounding the well, showing the predominance of agricultural use and the low
variability of this attribute, which is why this criterion was not included in the final
analysis.

The index of social inclusion of the population located near wells was also
consulted. Once this index was consulted, special attention was paid to populations
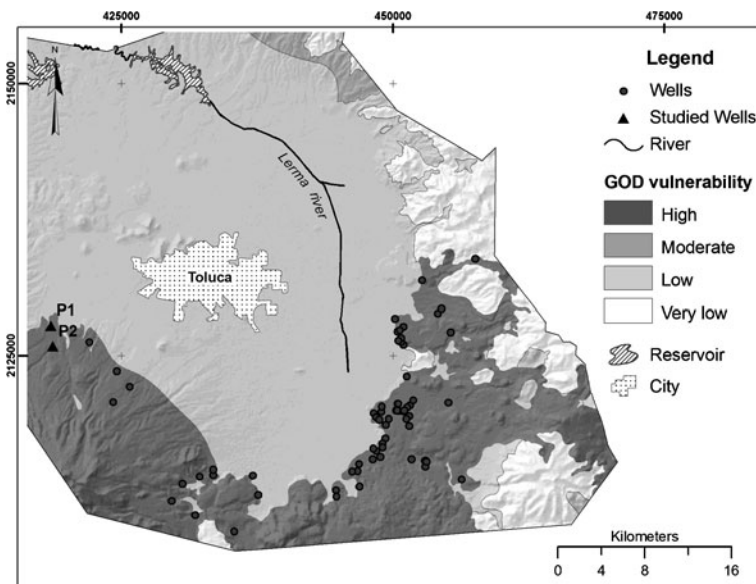with a high value of this index, considering that these populations are the ones that

Fig. 4   GOD vulnerability map and public drinking wells location

have the lowest percentage of sewerage coverage and therefore could be a focus of contamination.

The social exclusion index in the prioritization of wells was not only considered as a way of evaluating the potential contaminant load that could reach the aquifer, but it also useful in the evaluation of material and human resources that are available for maintaining the well in proper exploitation conditions, for locating alternative sources of water supply in the case of contamination events, or even to have proper medical attention in the face of waterborne diseases.

Once all the information is obtained, wells with highest pumped volumes, the oldest ones, and those located downgradient of populations with high index of social exclusion were identified as the ones that would have priority protection-wise since these are the wells that show the highest risk of contamination.

4.3 WHPA Methods Application and Comparison

Once the priority wells were identified, two of them were chosen (San Isidro Well-P1 and Santa Juanita Well-P2) to conduct a pilot study (Fig. 4). The different chosen methods were applied to these wells.

For the definition of zone I of the protection area, it was considered that, since this zone is generally defined in an arbitrary fashion, then its determination would not be necessary and in the study cases, it corresponded to the fenced area surrounding the well.

The calculations were directed towards establishing the dimensions of zones II and III of the perimeter, assessing the following parameters: Su and Sd are the upgradient and downgradient distance, respectively, from the pumping well to a point on the flow axis with the desired time of travel, D is the upgradient width of contribution in meters due to the pumping rate and D' is the width of contribution at the pumping well in meters (Fig. 2); for this, the input values shown in Table 1 were used.

Table 1 Hydrogeological parameters used with WHPA delineation methods

Well	Parameters	Symbol		Values	Source of information
San Isidro P1	Pumped volume	Q	m³/day	3,110	Survey
	Saturated thickness	b	M	210	Survey
	Effective porosity	n	Adimensional	0.18	Custodio and Llamas (1983)
	Hydraulic gradient	i	Adimensional	0.034	Survey
	Hydraulic conductivity	K	m/day	1.7	Survey
	Time of travel (zone II)	t	Days	60	Moreno and Martínez (1991);
	Time of travel (zone III)	t	Days	3,650	Martínez and García (2003)
Santa Juanita P2	Pumped volume	Q	m³/day	3,024	Survey
	Saturated thickness	b	m	200	Survey
	Effective porosity	n	Adimensional	0.18	Custodio and Llamas (1983)
	Hydraulic gradient	i	Adimensional	0.034	Survey
	Hydraulic conductivity	K	m/day	1.7	Survey
	Time of travel (zone II)	t	Days	60	Moreno and Martínez (1991);
	Time of travel (zone III)	t	Days	3,650	Martínez and García (2003)

The times of travel (time necessary for water or contaminant to reach the well from the location) that were chosen were 60 days in zone II (maximum restriction) and 3,650 days in zone III (moderate restriction), these times being considered enough to protect the well from bacteriological contamination in zone II and from persistent contamination in zone III (Moreno and Martínez 1991; Martínez and García 2003).

It must be taken into account that any uncertainty in the data reliability means that the well is not being completely protected; therefore, it is a common practice to multiply the results obtained by factors of safety or to insert such factors into the formulas of the calculations (NC 93-01-209 1990; WDEQ 2003; Exposito et al. 2007). In the analyzed case, the results were multiplied by 1.3, so that, once the factor of security is applied, the results obtained with the original formulas define WHPAs of larger dimensions.

The dimensions obtained of the WHPAs are shown in Table 2, once the factor of security was applied. It is necessary to emphasize that the differences that were obtained for the different protection areas of each well in the study, when using the same method, were minimal. This is because the only parameter that is different in the input data is pumped volume, whereas the hydrogeological characteristics of the areas in which the wells are located, based on data obtained from the geological map as well as from the well's stratigraphic column, indicate that the wells are built in the same geological environment.

The results obtained with the use of the different methods for the delineation of WHPAs for both the San Isidro Well-P1 and the Santa Juanita Well-P2 show significant variability (Table 2 and Fig. 5a, b), which is especially marked in zone III (Fig. 5b). For example, in the case of the Santa Juanita Well-P2, the downgradient distance that was obtained for zone III is 405 m. with the calculated fixed radius, which is four times the distance obtained with Wyssling's method of 102 m. On the other hand, the upgradient dimensions determined with the fixed radius method are smaller than those obtained with the analytical methods. This means that the

Table 2 Calculated parameters with WHPA delineation methods

| Method	Zone II			Zone III		
	Upgradient Su(m)	Downgradient Sd(m)	Width D(m)	Upgradient Su(m)	Downgradient Sp(m)	Width D(m)
San Isidro—P1						
Calculated fixed radius	51	51	102	402	402	804
Wyssling	65	40	$D' = 166$ $D = 333$	1,617	98	$D' = 166$ $D = 333$
Perez–Menendez	76	53	333	1,924	53	333
Minking	70	36	101	1,706	53	319
Santa Juanita—P2						
Calculated fixed radius	52	52	104	405	405	810
Wyssling	66	41	$D' = 170$ $D = 340$	1,620	102	$D' = 170$ $D = 340$
Perez–Menendez	77	54	340	1,928	54	340
Minking	71	37	102	1,715	54	326
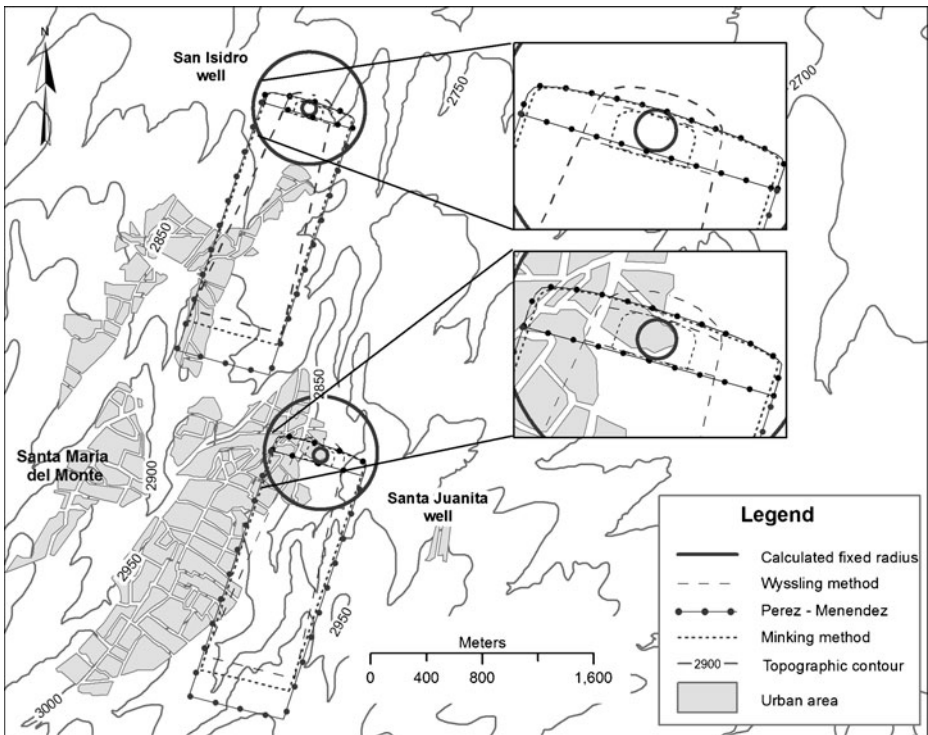
Fig. 5 Comparison of the WHPAs at the San Isidro P1 and Santa Juanita P2 wells

calculated fixed radius method overprotects the well's downgradient area and does not protect correctly the well's upgradient. This is because it does not consider the aquifer hydraulic gradient in its calculations.

On the other hand, when comparing the results obtained for both wells with the analytical methods, it is observed that the most apparent differences occur because the Wyssling method considers a smaller perimeter width at the height of the well than the other methods, a situation which could put the well at risk due to the uncertainty that could exist in the assessment data.

Considering these elements, it is concluded that the most adequate method to be used in the area is the Minkin method, since it properly protects the well at its sides and achieves a balance in the upgradient distances, positioning itself between the value obtained by the Wyssling method and that obtained by the Perez–Menendez method. In addition, making a comparison with the areas of coincidence criterion, it is possible to show that the WHPA defined with the Minkin method has a coincidence with the rest of the calculated WHPAs of 98.96% for the case of the San Isidro Well-P1 and 99.07% for the case of the Santa Juanita Well-P2.

The previously mentioned elements are common for both wells given the similarities of the area's hydrogeological characteristics and of their respective constructions.

Once the protection areas of each well were delineated, we proceeded with the identification of the sources of contamination by going through the field (Table 3). The potential sources of contamination that were possible to identify and

Table 3 Summary of activities potentially generating a contaminant load

Pollution focus	San Isidro—P1		Santa Juanita—P2	
	Zone II	Zone III	Zone II	Zone III
Animal waste storage	–	2 focus	1 focus	–
Sewage discharge	–	2 focus	2 focus	3 focus
Septic tank	–	3 focus	–	3 focus
Landfill	–	1 focus	–	3 focus
Agricultural fertilizer use	–	$0.42 \ km^2$	–	$0.72 \ km^2$

were located within the WHPA, in the case of the San Isidro Well-P1, were several, including urban and agricultural sources of contamination. In the zone II (60 days) of the area, no contamination source was identified, whereas in the zone III, several sources of contamination were detected, among them the population's sewer system, since the perimeter's dimensions included 60% of the urban stain, and other sources of contamination such as latrines, uncontrolled municipal solid waste landfills, and agricultural–cattle activities (Fig. 6).

Unlike the San Isidro Well-P1, where sources of contamination were only found in Zone III, in the case of the Santa Juanita Well-P2 (Fig. 6), several types of contaminating activities were detected in both zones II and III. The registered
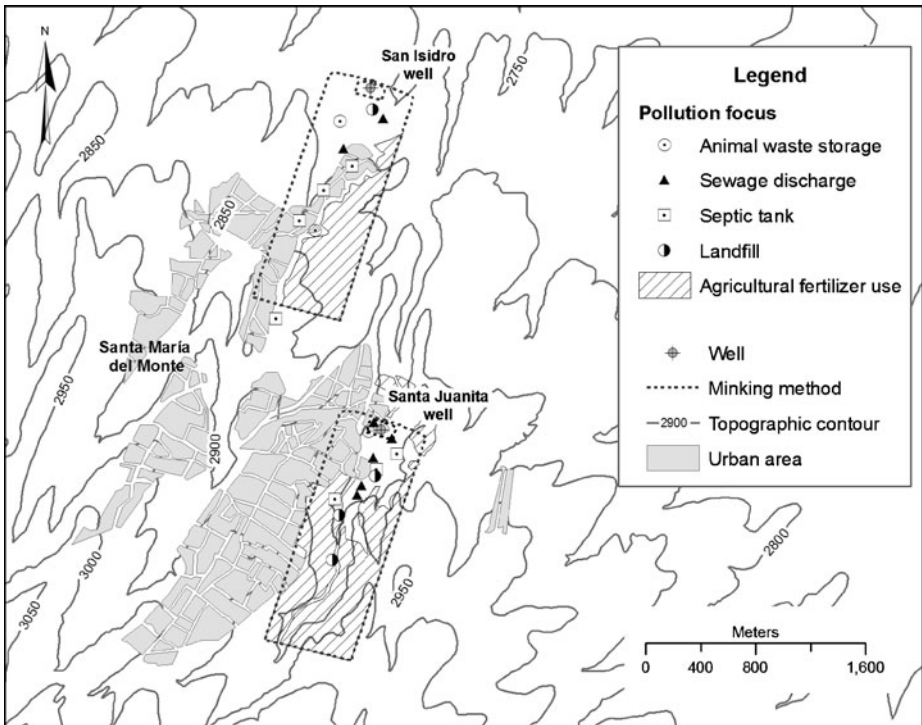
Fig. 6 Pollution sources in the WHPA at de San Isidro P1 and Santa Juanita P2 wells

sources of contamination were wastewater discharge directly into the soil, latrines, uncontrolled municipal solid waste landfills and rivers with wastewater discharge.

In the face of this situation, the appropriate authorities should propose a series of guidelines within the framework of land-use planning, that stress the restriction or cancellation of contaminating activities within the territorial sphere of the defined WHPAs or remove the wells, especially in the case of the Santa Juanita Well-P2 where sources of contamination were identified inside zone II (maximum restriction zone).

5 Conclusions

The aquifer vulnerability map shows that the areas of highest vulnerability are located in the aquifer's main recharge areas. This situation shows the need to protect the wells that are located within these areas.

The criteria used to prioritize the public water wells located in this highest vulnerability areas were mainly focused on the wells' constructive characteristics and on the existence of populations with high value of index of social exclusion. The land use criterion did not have much influence since it exhibited scarce variability.

Wells with highest pumped volumes, the oldest ones, and those located down-gradient of populations with high index of social exclusion were identified as the ones that would have priority protection-wise since these are the wells that show the highest risk of contamination.

Making a comparison the results obtained with the use of the different methods for the delineation of WHPAs (calculated fixed radius method and the analytical methods in the versions of Wyssling, Minkin, and Perez and Menendez), it is concluded that the most adequate method to be used in the study area is the Minkin method. On the other hand, contaminating activities within the WHPAs were also identified, and so, concrete measures can be taken to either restrict or prohibit these activities or remove the wells. Likewise, pinpointing the sources of contamination that exist within the WHPAs, allows defining which physical, chemical and/or biological parameters must be monitored in the well water in order to easily detect their effect on the water quality.

The dimensions of the perimeters obtained in this work can be used to define the perimeters of wells that have already been constructed or that are to be constructed within the study area.

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