

# Wellhead protection zones for sustainable groundwater supply

Marta del Carmen Paris<sup>1</sup> · Mónica D'Elía<sup>1</sup> · Marcela Pérez<sup>1</sup> · Josefina Pacini<sup>1</sup>

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**Abstract** Wellhead protection zones (WPZs) and groundwater supply protection areas are strategies to minimize contamination hazards and ensure a safe groundwater supply. Their implementation may require land use restrictions, industrial process changes and/or waste and effluent treatment changes, service adaptations, systematic controls of groundwater levels and groundwater quality and detailed well inspections. The aim of this paper is to present a scheme to ensure the protection of drinking water sources comprising the new pumping field supplying Esperanza and Rafaela cities in Santa Fe Province, Argentina. A 5–10-m radius was adopted for delineating the wellhead operational zones. To define the microbiological and surveillance zones, the fixed radius and Wyslingle methods were applied, taking into account the groundwater travel time of 50 and 100 days, respectively. The land activities were inventoried and categorized according to their potential for generating a subsurface contaminant load. A sanitary survey and assessment of pumping wells was made using a checklist. The results have shown that appropriate radii might be 70 m for the microbiological protection zone and 100 m for the surveillance zone. These values were obtained taking into account a pumping rate of approximately 60–70 m<sup>3</sup>/h. This abstraction rate should be regulated and maintained because it not only affects the validity of the defined zones

but also, when it is exceeded, induces an influx of water of different quality to the semi-confined aquifer.

**Keywords** Groundwater · Management · Contamination · Water security · Esperanza city · Argentina

## Introduction

One of the objectives of the new sustainable development agenda is to ensure access to water and sanitation for all human beings (Jimenez Cisneros 2015; WWAP 2017). However, the inefficient use of water resources and pollution threats often conspire against achieving water security and highlight the need to take action for the protection and control not only of pumping wells (supply sources) but also of the aquifer system (water resources).

Sanitary inspection is a good preventive action to avoid the pollution of groundwater supply sources. It is a tool for directly assessing the wellhead itself and to immediately detect the possible causes of contamination and/or failures occurring during water abstraction. These inspections should be carried out in a systematic way, including during wet and dry periods and especially considering the evolution or modification of the activities carried out in the proximity of the wells (harvesting, pastures, industries, housing, roads, drainage, etc.). In addition, these inspections should follow a standardized procedure through an inspection protocol to minimize discrepancies between different criteria and to control the implementation of the improvements suggested in previous inspections. It would also be desirable for the procedure to incorporate a quantitative indicator to define the level of pollution hazard associated with each of the pumping wells. Thus, depending on the value of the indicator, some actions to

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✉ Marta del Carmen Paris  
parismarta@gmail.com

<sup>1</sup> Facultad de Ingeniería y Ciencias Hídricas, Universidad Nacional del Litoral, Santa Fe, Santa Fe, Argentina

improve protection would be prioritized (Schmoll et al. 2006). The protocol (table or form) to be used in the field inspections should be designed and validated specifically for each case depending on the characteristics of each water supply system, its location (urban or rural zones) and environmental conditions (characteristics of the natural system and social environment).

Usually, field inspections should be conducted in an area of 200–500 m around the well. They should also be combined with other strategies designed to minimize groundwater pollution hazards and ensure safe water supply, such as perimeters, areas or zones of protection (Foster et al. 2003). There are numerous examples showing methodological developments and applications of different procedures for identifying areas to be protected: Foster et al. 2003; Rodríguez and Molano 1994; Paris et al. 1999, 2005; Hirata and Rebouças 1999; Gárfias et al. 2002, 2008; Theodossuoi et al. 2002; Jovanovic et al. 2004; Strobl and Robillard 2005; Expósito-Castillo et al. 2007, among others. However, the important progress from the academic sector is not reflected in the real and effective implementation of wellhead protection zones (WPZs). While there are a few study cases showing the practical development of WPZs in different cities in England, Canada, Spain, South Africa and United States (Morris 1994; Xu and Van Tonder 2002; NYGS 2003; Martínez Navarrete and García García 2003), it is recognized that in many other situations, political, administrative, technical and cultural factors influence the implementation of these strategies (Massone et al. 2011).

The delineation of groundwater supply protection areas in the zone of influence around the pumping wells can be undertaken using a wide variety of methods, ranging from overly simplistic to more elaborate, such as aquifer numerical modelling (Foster et al. 2003). Most methods are based on the analysis of hydrodynamic responses to the effects of pumping, mainly considering the natural ability of the strata overlying the aquifer to mitigate the possible impacts of land use activities. In all cases, the representativeness of the defined protection zone is subject to the knowledge of local hydrogeological conditions. In addition, the defined WPZs are influenced by uncontrolled flow abstraction rates, sporadic or seasonal well operation, proximity to other pumping wells, the occurrence of hydraulic connections with other water bodies (surface water or groundwater), etc. Therefore, neglecting these situations render WPZs ineffective as a strategy to ensure the quality of water supplies.

## Objective

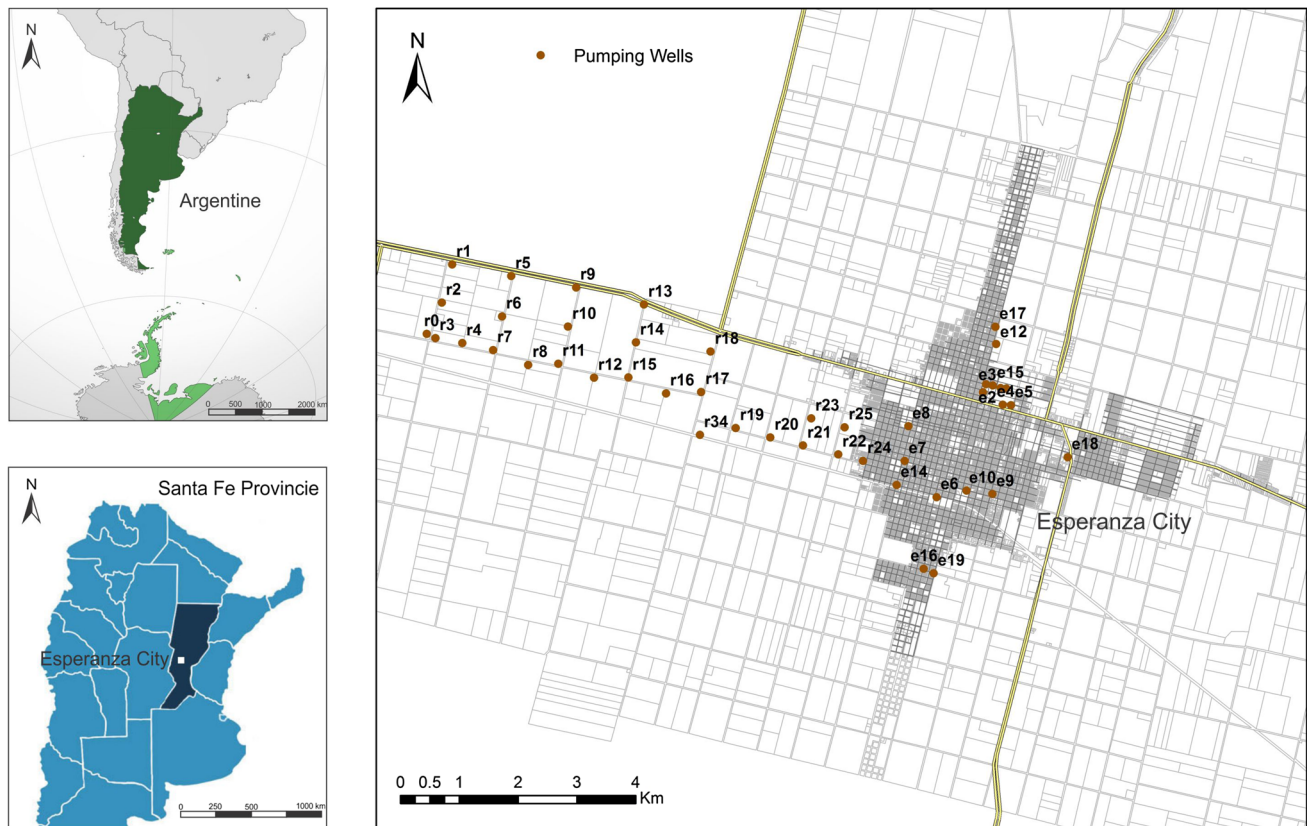
The purpose of this paper is to present a scheme to guarantee the protection of drinking water wells comprising the pumping field for Esperanza city (Santa Fe, Argentina) by

delineating WPZs with different semi-analytical methods and considering the vertical hydraulic connection that occurs in the multilayer aquifer system underlying the region. The main contribution of this study is to show that, in these kinds of aquifers, methods for defining WPZs are useful for the implementation of protection measures only when flow is strictly regulated.

## Characteristics of the study area

Esperanza city is the main city in Las Colonias Department (Santa Fe Province, Argentina) (Lat S 31°45'; Long W 60°93'). It has a total area of 276 km<sup>2</sup> (with an urban area of 13.5 km<sup>2</sup>) (Fig. 1). The city has very diverse economic activities; industries (tanneries, furniture manufacturing, metal and food), agriculture and livestock-raising activities (crops, cattle and poultry) continuously interact with the aquifer system, changing water quality and its dynamics (Paris et al. 1998). There is no irrigator registry to estimate the volume of groundwater used for irrigation. However, data from the National Agricultural Census conducted in 2002 by the National Institute of Statistics and Census (IPEC 2013) show that there are 13 pumping wells used for irrigation in Las Colonias Department. These pumping wells are located in ten rural areas to produce corn, soy beans and vegetables. Although there is no other updated information, it is estimated that, depending on agricultural production and water deficit periods registered, at this time the number of irrigators is greater and, therefore, the proportion of groundwater use is higher (D'Elia et al. 2012).

Agua Santafesinas S.A (ASSA) is the utility company that supplies water to the urban area of Esperanza city. The control and regulation of this service is carried out according to Provincial Law No. 11,220. The purpose of this law is to guarantee the maintenance of the service, to promote its improvement, to establish standards of quality and to protect user rights, public health, water resources and the environment. This law also creates a provincial control agency: Ente Regulador de Servicios Sanitarios (ENRESS). The Quality Control Regulation 0325/11 promulgated by the ENRESS establishes that sanitary inspections are obligatory and defines a sanitary inspection as “a comprehensive assessment of all components of a water system where operating conditions and suitability of the system are evaluated”. Additionally, and depending on the population served, the frequency for carrying out the sanitary inspection is also established: in a population served  $\leq 2000$  inhabitants, sanitary inspection shall be made every 6 months; in a population served  $> 2000$  inhabitants but  $\leq 5000$  every 4 months;  $> 5000$  inhabitants and  $\leq 10,000$  every 3 months; and  $> 10,000$  inhabitants every 2 months. The latter case corresponds to Esperanza city.



**Fig. 1** Location of the wells in the pumping field for Esperanza city

The water main covers 92% of the city and the water is produced from a pumping field located westward, mainly in rural areas. This pumping field is comprised of 32 wells supplying not only Esperanza city's demands but also Rafaela city (located 50 km westward). The water provided to Esperanza city comes from 11 pumping wells and is stored in an underground cistern with a capacity of 1250 m<sup>3</sup>. Each of these wells has a maximum pumping rate of 700 m<sup>3</sup> day<sup>-1</sup>. The water supplied to Rafaela city comes from 21 pumping wells with a maximum pumping rate of 1200 m<sup>3</sup> day<sup>-1</sup> each. Groundwater is carried to Rafaela by an aqueduct with three underground cisterns. For both cities, the only treatment applied prior to distribution is the chlorination with sodium hypochlorite. According to Pérez et al. (2014), the total water abstraction from the aquifer in 2013 was 13.9 Mm<sup>3</sup>. Figure 2 shows some of the wells in the pumping field.

The main aquifer layer exploited for water supply is semi-confined and it is lodged in a succession of fluvial sands, ranging from fine to coarse, covered by silts (the Ituzaingó Formation, Pliocene, known informally as “Puelches sands”). This layer is 25–35 m thick and has a very good yield and quality of water. The transmissivity ( $T$ ) obtained by a pumping test is 600 m<sup>2</sup> day<sup>-1</sup>. Overlying this layer, there are “Pampeanos sediments”, which Tujchneider (2000) calls the Pampa Group (Holocene). They are aeolian

sedimentary deposits of silt, clay, and loess, light brown, dark, red or grey, which were deposited in palustrine and lacustrine environments. This is the only geological stratum that outcrops in the zone. They have a thickness ranging from 15 to 25 m and the aquifer they contain is unconfined, with a low yield and variable quality water. At the base of this stratum, more clayey and calcium bicarbonate sediments are usually found. These sediments form an aquitard layer 2–3 m thick on average with regional discontinuities (Filí et al. 1999; Tujchneider et al. 1998; Dalla Costa et al. 2007). Underlying the semi-confined layer, at a depth of 45–53 m, there are grey sands, clayey sands and green clays of marine origin (Paraná Formation, Miocene). These contain high-salinity water of a continental origin. Figure 3a shows the regional geological–geomorphological characteristics and Fig. 3b shows these geological settings and the conceptual model of the hydrological system's behaviour in the study area.

According to Tujchneider et al. (2005), this is a multilayer aquifer system, with upward and/or downward flows through the aquitard depending on the hydraulic head relations. Groundwater withdrawal from the semi-confined aquifer may lead not only to downward flow from the overlying unconfined aquifer but also to an increase in lateral flow from the aquifer itself and may induce the rise of salty water lodged in the



**Fig. 2** Some of the wells in the pumping field. **a** Well r15, **b** well e14, **c** well r11, **d** well e17

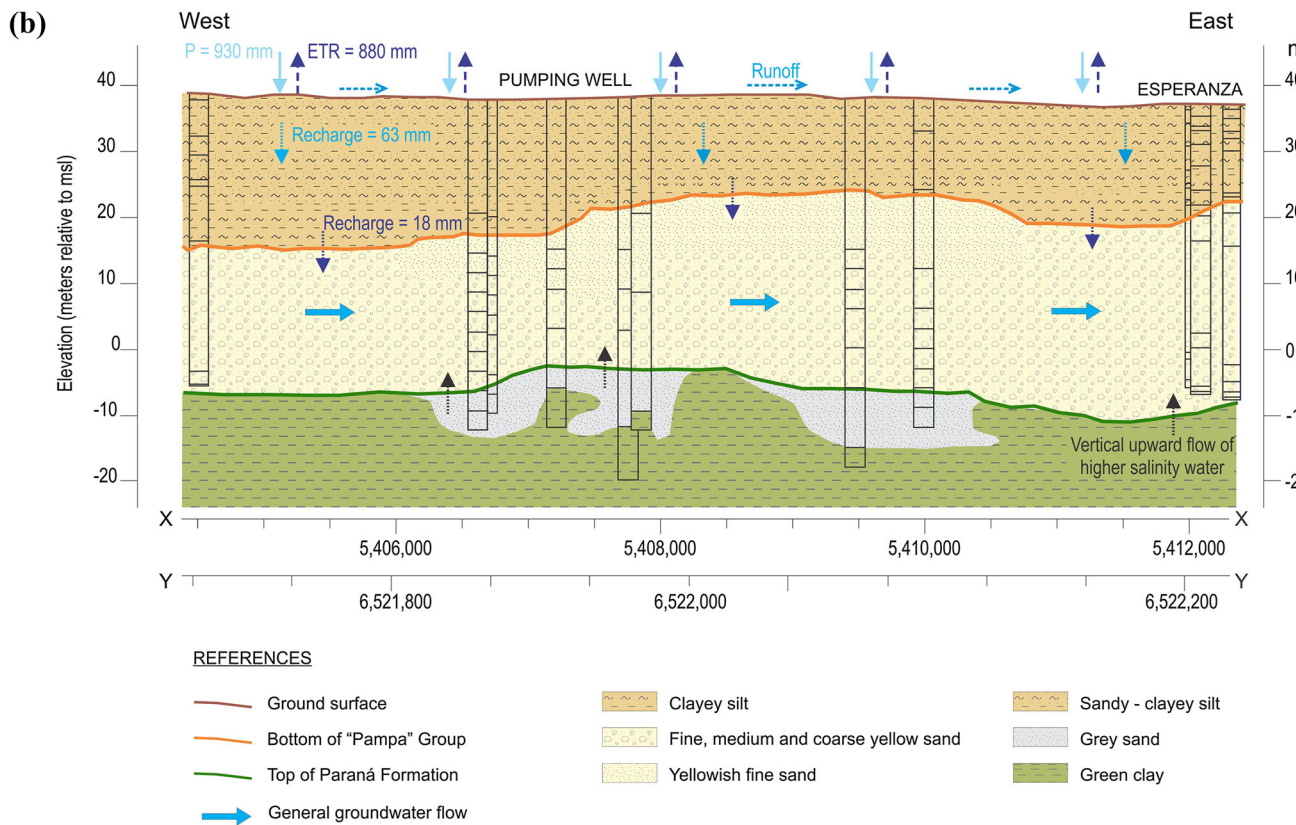
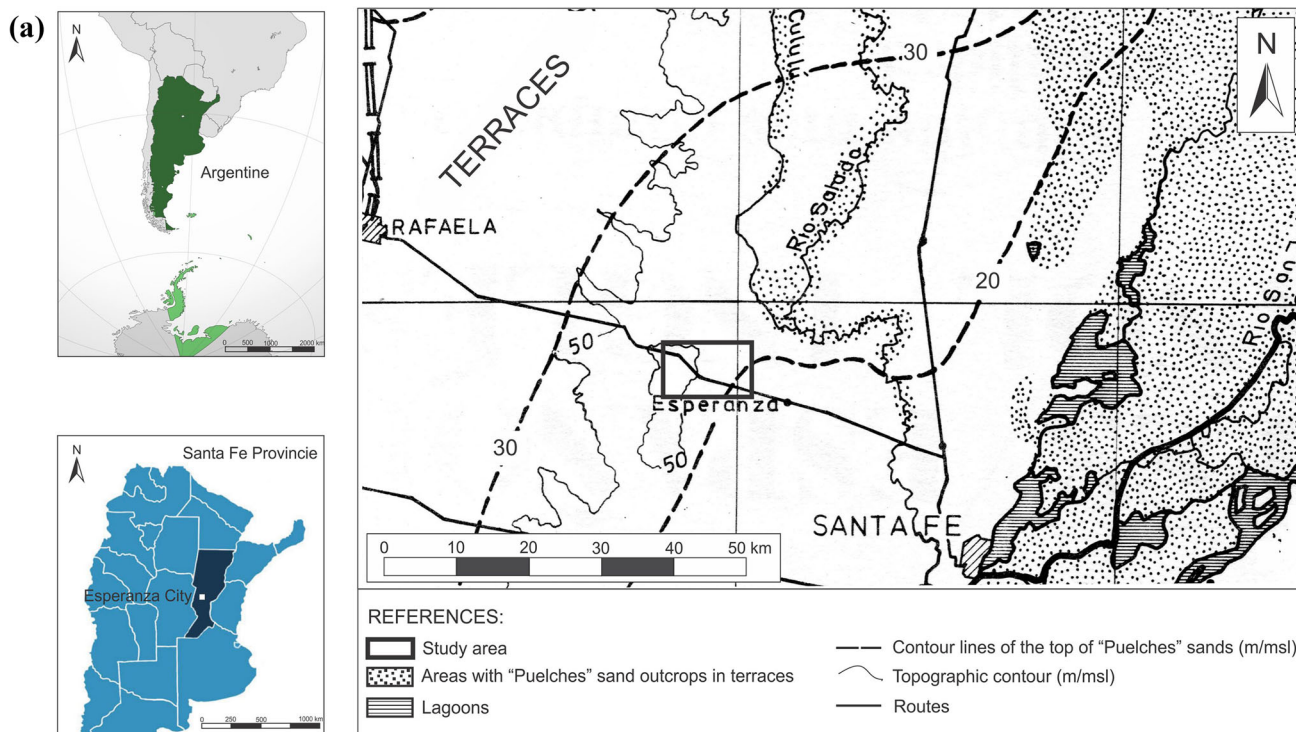
marine sediments. Local recharge to the unconfined aquifer is approximately  $63 \text{ mm year}^{-1}$  and approximately  $18 \text{ mm year}^{-1}$  to the semi-confined aquifer. The  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  records of groundwater samples from both aquifers show that the recharge comes from local rainfall, which occurs in summer and autumn, reflecting no significant evaporation processes. Likewise, the values of tritium detected in the groundwater samples from the semi-confined aquifer indicate a residence time of more than 50 years and suggest a mixture between both aquifer layers (unconfined and semi-confined) (D'Elia 2013). The presence of nitrate—related to agricultural activities—would corroborate this characteristic, and would be favoured by the discontinuity of the semi-confining layer (D'Elía et al. 2007, 2008). According to D'Elia et al. (2014b), the pumping field is located in an area of high potential for recharge.

The general direction of groundwater flow is from west to east with an average hydraulic gradient of  $2 \times 10^{-3}$ . D'Elia et al. (2014a) estimated that this aquifer system contributes to the base flow of the Salado River with an average annual discharge rate of approximately  $55 \text{ Mm}^3$ .

According to background studies, groundwater is sodium bicarbonate dominant (Filí et al. 1999; Paris et al. 1999; Tujchneider et al. 1998, 2002, 2005). However, since the mid-1990s, when some pumping wells were located in the urban area, the groundwater showed a change in chemical composition, changing from sodium bicarbonate type to sodium chloride type. Specifically, during 1994–1996, an increase in the water abstraction not only produced decreasing groundwater levels but also an increase in groundwater salinity. Then, by the end of 2003, the lower salinity that was observed was consistent with the regulation of groundwater abstraction proposed in a new groundwater management model defined by Filí et al. (1999) and (Paris 2010).

## Materials and methods

Sanitary inspections were performed 200 m around the pumping well using an adaptation of the standard method proposed by Lloyd and Helmer (in Foster et al. 2003).



**Fig. 3** Geological, geomorphological and hydrogeological settings. **a** Regional geological-geomorphological characteristics (CAAAS 1973). **b** Conceptual model of the hydrological system's behaviour in the study area (Paris 2010)

Therefore, the environmental factors and constructive characteristics of each well and its surrounding area were identified and assessed. A questionnaire based on checklist criteria was designed ad hoc. For the checklist, hydrogeological and climatic characteristics, economical activities, and infrastructure (among others) of the study area were evaluated. To describe the supply source contamination hazard, a score was defined according to the presence (=1) or absence (=0) of these factors and their importance (Table 1). Other factors were cross marked if they were found in the study area. After this information was collected, each well was classified depending on the contamination hazard resulting from the ranking system proposed according to the total accumulated score (Table 2).

To define WPZs, the following methods were used:

- WPZ 1 (wellhead operational zone)—arbitrary fixed radius. In this case, the zone will be defined by a radius of 5–10 m or a similar rectangular area.
- WPZ 2 (wellhead microbiological protection zone) and WPZ 3 (wellhead surveillance zone)—fixed calculated radius based on travel time and Wyssling methods (Wyssling 1979). Both methods were selected according to available data and after considering the different semi-analytical methods proposed in international references (Gárfias et al. 2008; Strobl and Robillard 2005; Expósito-Castillo et al. 2007; Rajkumar and Xu 2011, among others).

The fixed calculated radius is dependent on time and is determined by the following equation:

$$R = \sqrt{\frac{Q \cdot t}{m_e \cdot b \cdot \pi}} \quad (1)$$

where  $R$  is the radius of the WPZ,  $Q$  is the well discharge,  $m_e$  is the effective porosity or specific yield,  $b$  is the saturated thickness where the well is located (exploited aquifer thickness) and  $t$  is the travel time to the pumping well.

On the other hand, Wyssling's method defines the width of the capture zone ( $B_1$ ) and the width of the capture zone near the pumping well ( $B'$ ) taking into account the pumping rate ( $Q$ ), hydraulic conductivity ( $K$ ), the saturated thickness ( $b$ ) and the hydraulic gradient ( $i$ ) (Fig. 4). Then, by considering the effective flow velocity ( $V_e$ ) and the selected travel time, it is possible to define ( $S_0$ ) and ( $S_u$ ), the upward and downward distance from the well, respectively, as dimensions of the WPZ (Eqs. 4–7).

$$B_1 = \frac{Q}{K \cdot i \cdot b} \quad B' = \frac{B_1}{2} \quad (2)$$

The radius of capture,  $X_0$ , is obtained using the below equation:

$$X_0 = \frac{Q}{2 \cdot \pi \cdot K \cdot b \cdot i} \quad (3)$$

$$S_0 = \left( L + \sqrt{L * (L + 8 * X_0)} \right) / 2 \quad (4)$$

$$S_u = \left( -L + \sqrt{L * (L + 8 * X_0)} \right) / 2 \quad (5)$$

$$V_e = K * i / m_e \quad (6)$$

$$L = V_e * t \quad (7)$$

Therefore, to define WPZ2 (the Wellhead Microbiological Protection Zone), a travel time = 50 days is adopted (Foster et al. 2003). These 50 days should be interpreted as the time necessary to eliminate or reduce the amount of contamination to an acceptable level, in this case mainly due to biological decay. WPZ3 (the Wellhead Surveillance Zone) is defined considering a horizontal flow isochron of 100 days. This time is arbitrarily selected to delineate the area in which controls and field inspections must be carried out.

It is important to note that the “travel time ( $t$ )” is the time that a hypothetical contaminant needs to travel into the aquifer and reach the pumping well, considering that (a) the contaminant has actually reached the saturated zone, (b) it has the same water density and viscosity, (c) it moves at the actual groundwater flow velocity, and (d) advection is the only transport process, and no diffusive, dispersive or reactive transport processes occur. Therefore, the size of the protection zone could be smaller taking into account the fact that most contaminants are applied on the land surface. The downward vertical flow in the vadose zone delays the travel time of contaminants towards the saturated zone, and in the case of a semi-confined aquifer, the aquitard overlying the geological strata gives some protection. However, this geological protection can be affected by excavations, burials, the extraction of materials, inadequate construction, sealing or abandonment of wells (and other situations), which would serve as preferential pathways for groundwater pollution or decrease the level of protection of the unsaturated zone. In addition, in the case of non-decaying pollutants, their danger is not diminished by the presence of this vertical path. Strobl and Robillard (2005) note that groundwater protection programmes in Germany normally assume that the natural clean-up of groundwater can be generally estimated from the overlying unsaturated layers of the aquifer (or those that confine the aquifer). Depending on the depth of the groundwater level, hydrogeological type, thickness and extent of the upper layers, this attenuation capacity can be considered to delineate the protection zone. Nevertheless, to obtain security, only the cases where the depth of groundwater table exceeds 4 m are taken into account (for unconfined aquifers, this level should be the highest one).

**Table 1** Sanitary Inspection Form

Sanitary inspection of wells		
Well ID		
Date:	Score (Presence = 1, Absence = 0)	Observations
<b>Environmental factors external to the well</b>		
Domestic wastewater		
Cesspools		
Sewer system		
Urban solid wastes		
Domestics		
Construction wastes, hazardous wastes, others		
Urban zone		
Industrial activities, repair shops		
Rural zone		
Commercial Shops, others		
House, buildings		
Cropped areas with agrochemicals		
Outside storage of agrochemicals		
Grain storage		
Raising cattle		
Absence of livestock effluent treatment		
Windmills for water supply		
Non-coated rural canals		
Coated rural canals		
<b>Constructive factors of the well</b>		
Pumping well protection		
Absence of well cap		
Deficient state of the cap		
Absence of lock		
Absence of concrete platform/concrete platform in bad conditions		
Absence of perimeter fence		
Absence of signposting		
Uncut weeds		
Ground surface in bad conditions		
Pumping well operation		
Control panel in poor condition		
Poor condition of electrical facilities		
Power generator		
Losses in pipe or main		
Casing below ground surface		
Pumping well vulnerable to flooding		
Pump system in poor condition		
Flow meters in poor condition		
Small operational zone		
Exposed casing		
<b>Total accumulated score</b>		

**Table 2** Categories of supply source contamination hazard

Total score	Category of source contamination hazard
1–4	Moderate
5	High
6–8	Very high

Therefore, the travel time ( $t$ ) should be treated as a “chronological pattern to implement a preventive or corrective measure” against a potential or real contamination of the groundwater, while in the groundwater environment, the natural attenuation of contaminants could be produced by dilution, dispersion or other physical, chemical and/or biological processes.

For both the fixed calculated radius and Wyssling methods, the following values are employed:  $K = 24$  m/day,  $T = 600$  m<sup>2</sup>/day,  $m_e = 20\%$ ,  $i = 1 \times 10^{-3}$  and  $b = 25$  m (Filí et al. 1999).

Data on well discharge, energy consumption, hours of pump operation and, in some cases, the initial and final readings of the flowmeter were processed to obtain the monthly average yield and the monthly average of pumping hours at each of the wells belonging to the water supply system. This database has discontinuities, generally produced measuring instrument failures; the records cover the period from November 1993 to October 2001 and between 2008 and 2014. During 2014, the sanitary inspection corroborated that only 44% of the pumping wells had flow meters running properly. In addition, the water supply utility company does not perform a systematic control of the flowmeter readings. With the available data, an average flow rate value was estimated for each of the well in the supply system. This estimation was calculated taking into account the monthly well discharge from 2008 to 2011 and the corresponding energy consumption. A graphical analysis of the evolution of these discharges allowed for the determination

of their representativeness. Thus, the maximum average discharge was 78 m<sup>3</sup>/h and the minimum was 38 m<sup>3</sup>/h.

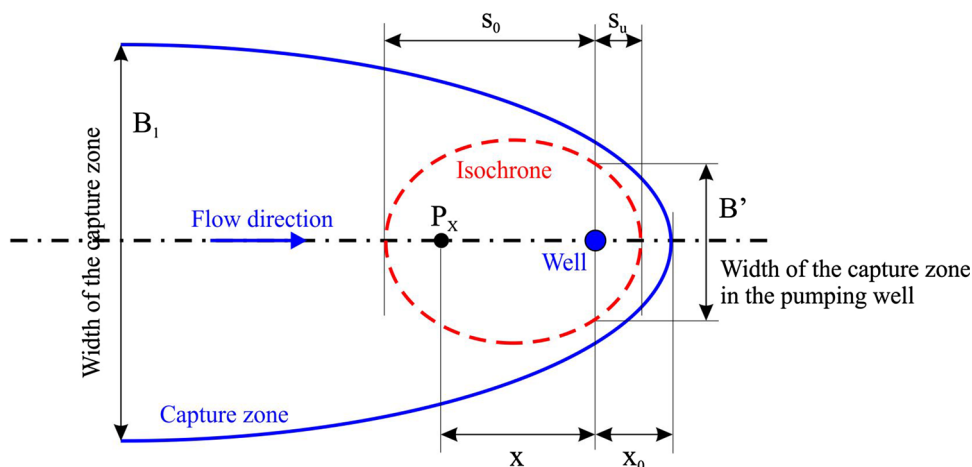
The defined WPZs were incorporated into a Geographic Information System developed in ArcGIS for joint interpretation and analysis with cadastral and land use information. The POSH method (Foster et al. 2003) was used to characterize the hazard of potential sources of contaminant load. This method is an approach used to assess potentially polluting activities based on two readily estimated characteristics: the pollutant origin (PO) and surcharge hydraulically (SH). The POSH method classifies the pollution sources (both diffuse and point source pollution) into three qualitative levels: reduced, moderate and elevated. To use this approach, a survey of the pollution sources was conducted in the pumping field.

Physical and chemical analyses from 28 exploitation wells were available. These analyses used various sources of information and correspond to groundwater samples collected at different times (between 1990 and 2014). To determine the temporal behaviour of water quality, graphs showing variations in electrical conductivity (EC), chloride, sulphate, nitrate and calcium versus time were drawn. In previous investigations, these five variables had been identified as indicators of the increase in water salinity caused by the rise of deeper groundwater levels (high-salinity water) that underlie the semi-confined aquifer and/or the inflow of groundwater from the unconfined aquifer (Paris et al. 2014). For these indicators, both alert and threshold values were considered (Table 3). Well discharge fluctuations were also taken into account. These variations regulate the hydraulic relationships in the multilayer aquifer system.

## Results

The results of the sanitary inspection show that more than 90% of the wells located in rural areas have neither perimeter fences nor electric generators to ensure service.

**Fig. 4** Wellhead protection zone according to Wyssling’s method. Modified from Martínez Navarrete and García García (2003)





**Table 3** Quality indicators used (alert and threshold values)

	EC <sup>a</sup> ( $\mu\text{S}/\text{cm}$ )	TDS <sup>b</sup> (mg/L)	Cl <sup>-</sup> (mg/L)	SO <sub>4</sub> <sup>2-</sup> (mg/L)	NO <sub>3</sub> <sup>-</sup> (mg/L)	Ca <sup>2+</sup> (mg/L)
Threshold	1368	2062	68	100	8	12
Alert	1541	2335	109	135	42	30
Recommended level (Provincial Law No. 11,220)		1000	250	100	25	100
Maximum permissible level (Provincial Law No. 11,220)		1500	400	200	45	250

Limiting levels fixed by Provincial Law No. 11,220

<sup>a</sup> Electrical Conductivity. Not fixed by the Provincial Law

<sup>b</sup> Total Dissolved Solids: values were estimated according to the expression  $\text{TDS} = 1.5853 \times \text{EC} - 106.97$  (based on a linear regression with available data)

**Table 4** Classification and ranking of the contamination hazard for the pumping wells

	Category of source contamination hazard		
	Very high	High	Moderate
Wells	r0, r1, r2, r17, r18, r19, r22, r24, r25, r34, e18	r3, r6, r11, r15, r16, r20, r21, r23, r30, e8	r4, r5, r7, r8, r9, r10, r12, r13, r29, e14
Total of wells	11	10	10

**Table 5** Size of the areas according to the different protection levels

Protection area (level)	Arbitrary fixed radius (m)	Calculated fixed radius $R_c$ (m)		Wyssling method (m)	
		Average	Minimum	Upward distance from the well ( $S_o$ )	Downward distance from the well ( $S_u$ )
Wellhead operational zone (WPZ1)	5–10				
Microbiological protection area (50 days) (WPZ2)		Average	69	Average	72
		Maximum	78	Maximum	82
		Minimum	55	Minimum	58
Surveillance area (100 days) (WPZ3)		Average	98	Average	105
		Maximum	111	Maximum	118
		Minimum	78	Minimum	85

There are numerous wells with reduced operation areas and no flow meters. Table 4 shows the results obtained from the cumulative checklist scores, carried out as described in the “[Materials and methods](#)” section.

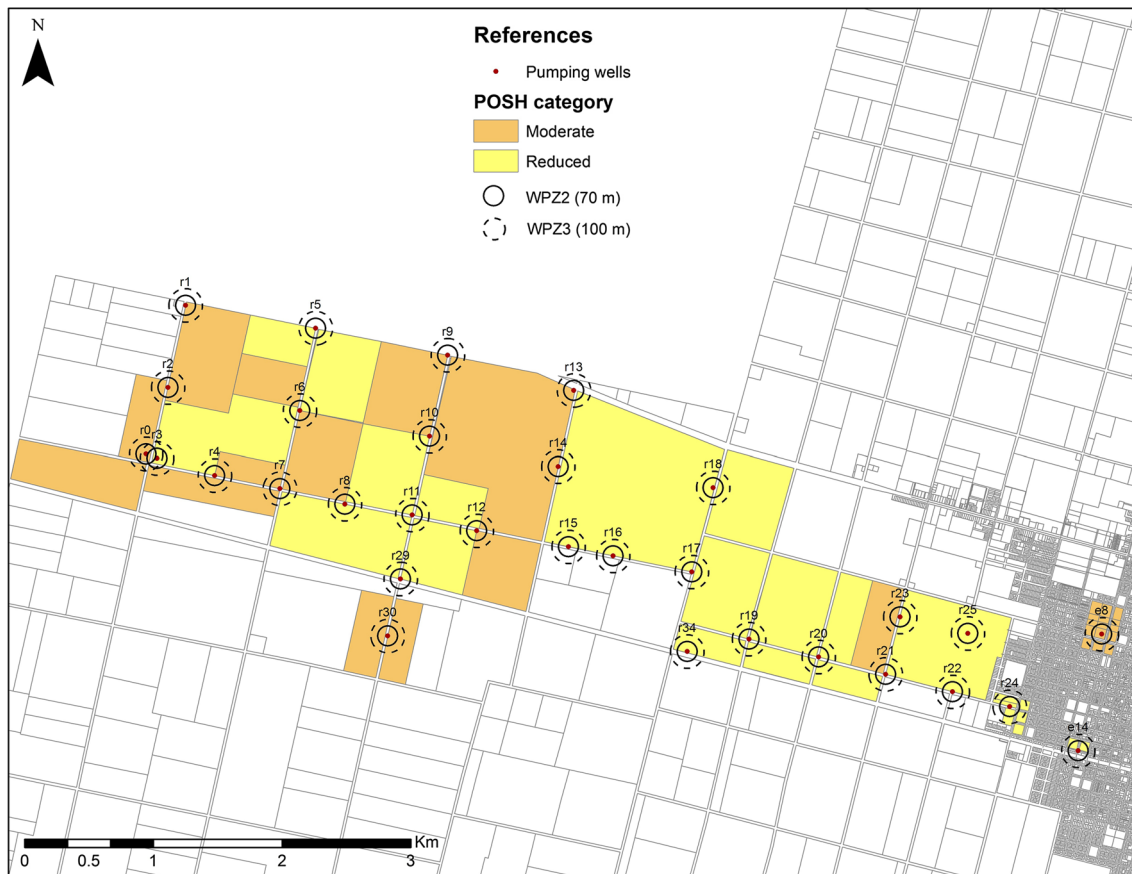
The innermost protection perimeter, or wellhead operational zone (WPZ 1), is fixed arbitrarily to maintain the minimum dimensions for control and maintenance tasks. Its radius (or side) ranges from 5 to 10 m.

Table 5 shows the average, maximum and minimum values obtained for delimiting the WPZ 2 (wellhead microbiological protection zone) and WPZ 3 (wellhead surveillance zone). As can be expected, the values obtained through the calculated fixed radius and Wyssling methods are similar. Thus, a 70 and 100 m distance from the

pumping well could be selected to define WPZ 2 and WPZ 3, respectively.

The defined zones, especially WPZ2 and WPZ3, belong to rural areas where agricultural activities take place. Therefore, it is very important to consider the potential contamination hazards that these activities represent to water supply sources. The classification and ranking of these hazards performed by the POSH method resulted in moderate to reduced rankings.

The moderate category was chosen for point source pollution taking into account that rainfall is <500 mm/year and was chosen when there were no crop rotation practices for diffuse pollution sources, while the reduced category was chosen:



**Fig. 5** Wellhead protection zones (WPZs) and POSH categories in the pumping field area

- In the case of point source pollution: when the climate of the area was sub-humid and the industries were type 1 (woodworking, food and beverage manufacturers, non-metallic material processing).
- For diffuse pollution sources: when sewer main coverage was more than 75%, the population density was less than 50 persons/ha, or the rural area has extensive pastureland.

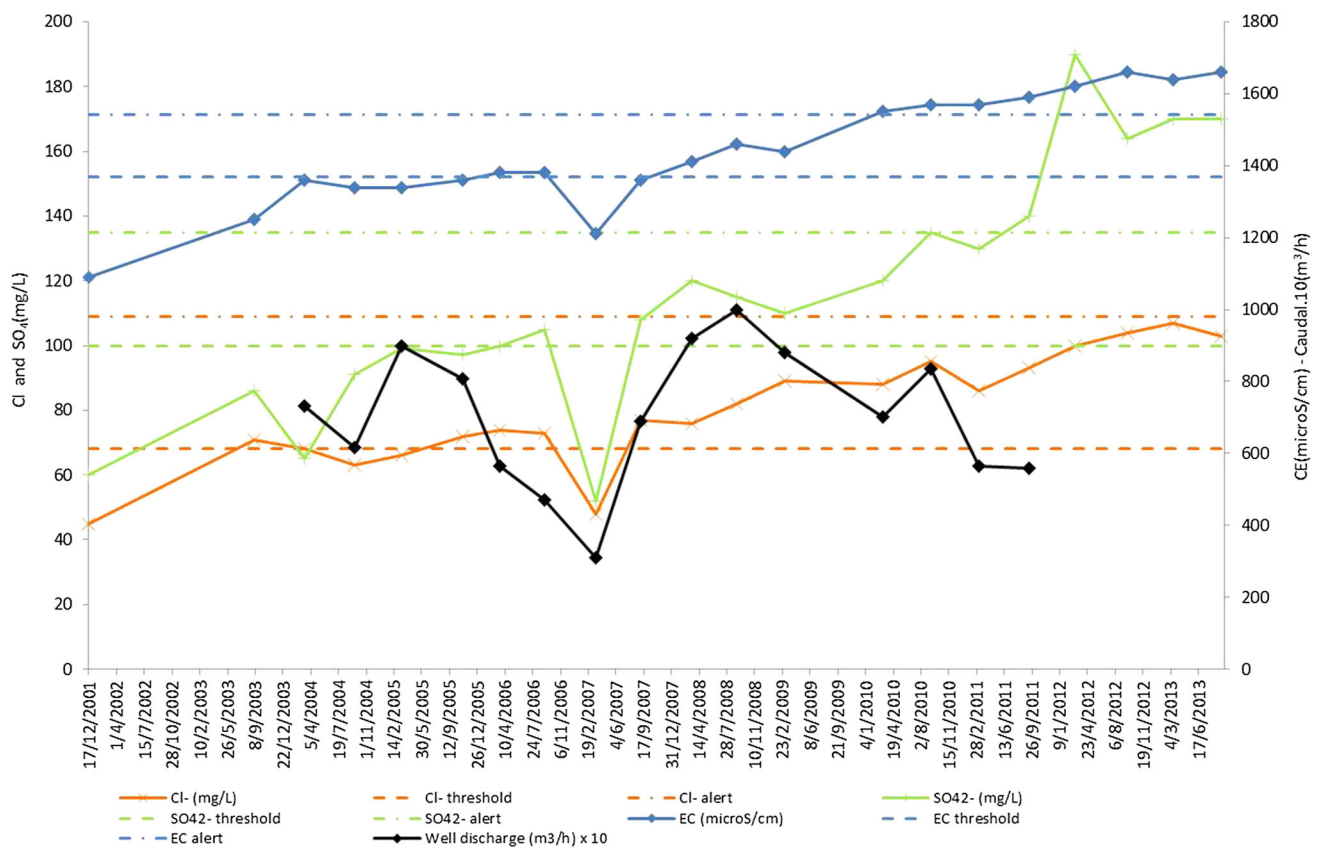
Figure 5 shows the relationship between the WPZs and POSH categories.

According to Rodríguez et al. (2013), local administrations (municipalities) can protect water supply sources (pumping wells) and their WPZs through land use regulation. This regulation should combine the use of geographical space with activities consistent with the aquifer vulnerability conditions, establishing areas with urban, industrial, agricultural and livestock restrictions (based on Article 9, National Law No. 25,675 *General Environmental Law*). In Santa Fe Province, Law No. 11,220 may be applicable, as it regulates the provision, concession, regulation and control of drinking water, sewerage and sanitation services. Articles

60, 61, 63 and 70 of this Provincial Law enable, broadly, the necessary legal instruments for the implementation of WPZs. Such legislation establishes a general guideline for the application of regulated institutions. As such, the general guidelines need to be adapted to the specific needs in every case, either by the simple identification of the property necessary for the pumping well location or by establishing limit levels to ensure the proper operation of the well. However, despite the existence of this legal instrument, only limited use of this rule was employed to achieve the implementation of the WPZs in Santa Fe Province.

Nevertheless, all these measures aimed to mitigate the potential effects of land use and may not be sufficient to achieve water security considering the hydrogeological complexity of the study area. This complexity is owed to the hydraulic relationships that occur between the groundwater layers composing the multilayer aquifer system and their impacts on water quality:

- downward flows of lower quality water (and/or contaminated water) from the unconfined aquifer overlying the exploiting semi-confined aquifer and



**Fig. 6** Well discharge variations, electrical conductivity (EC), chloride ( $\text{Cl}^-$ ) and sulphate ( $\text{SO}_4^{2-}$ ) contents in well r24

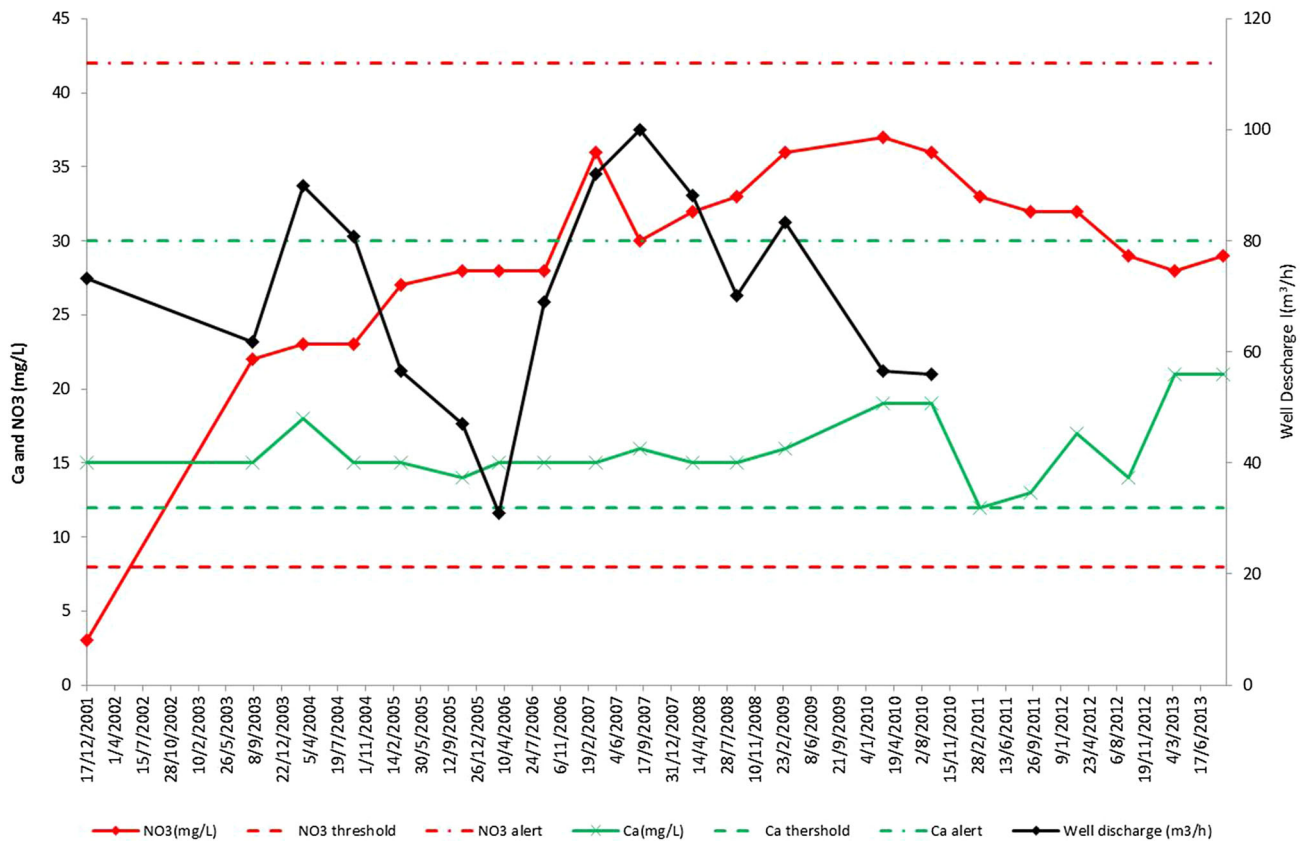
- upward flows of high-salinity water from the aquifer underlying the semi-confined aquifer.

From the joint analysis of well discharge fluctuations and the temporal behaviour of chemical indicator variables, a direct relationship is shown between the pumping rates and the quality of the extracted groundwater. It was found that 20 of the 28 wells examined have shown deterioration in their groundwater quality during at least one year over the study period. Specifically, 12 of these 20 wells suffered a sustained increase in salinity in recent years. Figure 6 shows the increase in electrical conductivity, chloride and sulphate, possibly caused by rising water from the lower layer. Figure 7 shows the deterioration of water quality expressed as the increase of calcium and nitrate contents, very likely due to the intrusion of contaminated water from the unconfined aquifer. These data provide clear indications of the hydraulic relationship between the different aquifer levels and, therefore, the urgent need to control withdrawals rates and the hours of pumping in all wells. Therefore, when the well discharge exceeds 60–70  $\text{m}^3/\text{h}$ , the validity of WPZ 2 and WPZ 3 is conditioned not only by the variation of the size of the defined area (which depends on the well discharge) but also mainly by the

inflow of different quality water to the semi-confined aquifer.

## Conclusions and recommendations

The methodology developed for assessing the sanitary condition of the pumping wells is considered to be adequate. The form that was designed was validated during the inspection surveys. Furthermore, the POSH method enabled the assessment of the hazards of pollution in the vicinity of the wells. These measures have led to an assessment that guides not only the protection strategies to follow but would also establish a priority order for such actions. In this case, it is clear that the greatest attention should be on the well operational area (WPZ 1) instead of its surrounding area and, particularly, on the 11 wells classified with a very high hazard of contamination. The remaining inspected wells have high and moderate contamination hazards. Thus, it is necessary to take immediate action to control and reverse this situation and to guarantee the sustainability of the water supply, both in qualitative and quantitative terms.



**Fig. 7** Well discharge variations, calcium ( $\text{Ca}^{2+}$ ) and nitrate ( $\text{NO}_3^-$ ) contents in well r24

- Restrict and control the activities carried out in the well operational zone to prevent the surface contaminant load from coming into contact with groundwater in the pumping area.
- Properly identify all the pumping wells. This simple measure is essential for people to know and appreciate that the water supply depends on these wells.
- Adjust all the well operational zones (WPZ 1) to give the operator better working conditions. The minimum dimensions should be 10 m in radius or per side. They must have concrete floors, provide lighting and have received proper maintenance (cleaning and weeding).
- Install a perimeter fence around all operating wells for proper protection against vandalism and accidents.
- Place electric generators at all wells to ensure continuity of the water supply.
- Install flow meters in all the pumping wells and implement a rigorous reading protocol (or remote control/register) to measure and control the extracted volume of water. It is necessary to have actual measurements of the well discharge to avoid estimations and averages. If the abstraction is not controlled, the validity of the WPZ 2 and WPZ 3 is mainly conditioned by the inflow of different quality water to the semi-confined aquifer.
- Perform maintenance and periodic cleaning of the exploitation wells (control of pump state, pipes, flow meters, etc.).
- For those wells located on roadsides, coat the channels in the vicinity of the pumping well at least 20 m each side from the pumping well.
- Design a monitoring network for systematically controlling the state of the aquifer (its groundwater level and water quality). It is necessary to have systematic measurements of the depth of the groundwater level to quantify the hydraulic relationships of the various groundwater layers resulting from the exploitation schema. This will provide additional evidence for the interpretation of hydrochemical information.

The methods used to calculate WPZ 2 (wellhead microbiological protection zone) and WPZ 3 (wellhead surveillance zone) yielded similar values: a 70-m buffer around the pumping well to guarantee microbiological protection and an additional 30 m for a surveillance zone. Thus, the total WPZ would have a radius of 100 m.

The methods used are very simple and require little information. The hydraulic gradient can be the most difficult to determine since its assessment involves knowing the piezometric surface. However, the calculated fixed radius

method does not have this requirement and, as presented here, the value obtained is similar to that obtained by the Wyssling method. Thus, water utility companies or municipalities could define the three protection levels presented here and implement them to protect their water sources. The water utility and the local authority (Municipal Government) and the regulatory authority (ENRESS) should jointly determine the restrictions on land use (expropriations, administrative easements or other property restrictions) and determine the control measures for the discharge rates and monitoring programme that should be applied in each case.

In the study case, 45% of the wells are located on land owned by the company, and the remaining 55% are on public areas. Since the categorization of the pollution hazard by the POSH method is moderate to low, it is essential to make institutional agreements and/or implement the most appropriate management tools with the corresponding governments to avoid increasing the threat of pollution. Some of these management tools could be legal controls, such as restrictions on new water well drilling and/or groundwater abstraction rights; economical controls, such as fines or entitlement to compensation; or educational, information and awareness tools. A change in land use (for example, from agricultural land use to industrial activity) or agricultural practices (complementary irrigation, crop rotation, intensive use of agrochemical products, etc.) or a change in the industrial activity (from type 1 to type 2) would cause an increase in the hazard of contamination in the pumping field area.

To validate the results presented, in the next research stages, we expect to assess the zones defined by the use of groundwater mathematical modelling (by particle tracking).

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