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# METHODS OF DELINEATING WELLHEAD PROTECTION AREAS IN GRANULAR POROUS AQUIFERS. RESULTS FOR AN AQUIFER IN THE DUERO RIVER BASIN (SPAIN)

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**Abstract**. Protection of groundwater intended for human consumption has a transcendental importance in Europe. Its protection is arranged mainly by the establishment of groundwater source protection areas. In this paper, twelve methods selected as the most appropriate for granular porosity aquifers will be analysed, comparing results of their application to four catchments in a detritic aquifer located in the Duero river basin, northwestern Spain, for 1 day, 50 days, 4 years and 25 years travel time. Results obtained by other methods that do not consider travel time, will also be evaluated. Results from mathematic simulation made with VisualMODFLOW and VisualMODPATH codes will be used as reference for cartographic overlap of the protection areas.
Comparison of results obtained with the different methods shows that the error is small in zones delineated by 1 and 50 days travel time, and that it increases for the furthest zone (usually of several years travel time). This analysis will allow to establish differences between methods and to estimate their accuracy for different hydrogeological conditions, so it might guide selection of the most suitable ones in any area with similar characteristics.

**Key words**: source protection areas, groundwater pollution, analytic methods, mathematic models, travel time.

**Abstrakt**. Ochrona wód podziemnych przeznaczonych do picia ma największe znaczenie w Europie. Jest ona organizowana głównie przez ustanawianie obszarów ochrony formowania się zasobów wód podziemnych. W artykule przeanalizowano 12 wybranych metod oceny czasu przepływu wód podziemnych dla t = 1 dzień, 50 dni, 4 lata i 25 lat w porowym ośrodku skalnym, porównując wyniki obliczeń wykonanych dla 4 ujęć znajdujących się w zlewni rzeki Duero w północno-zachodniej Hiszpanii. Oceniono również wyniki uzyskane innymi metodami, które nie pozwalają na ocenę czasu przepływu wody. Wyniki matematycznej symulacji przepływu z wykorzystaniem programów VisualMODFLOW i VisualMODPATH posłużyły jako odniesienie do kartograficznego odwzorowania obszarów ochronnych.
Wyniki badań wykonanych różnymi metodami wskazują, że małe błędy występują przy ocenie zasięgu przepływu wód dla czasu od 1 do 50 dni, lecz wyraźnie zwiększają się przy dalszych zasięgach przepływu, zwykle dla czasu wynoszącego ponad kilka lat. Przeprowadzone analizy pozwalają ocenić różnice między stosowanymi metodami obliczeń i określić ich dokładność dla różnych warunków hydrogeologicznych, co umożliwia wybór najwłaściwszej metody badań dla dowolnego obszaru o podobnej charakterystyce.

**Słowa kluczowe**: tereny ochrony wód podziemnych, zanieczyszczenie wód podziemnych, metody analityczne, modele matematyczne, czas przepływu wód podziemnych.

## INTRODUCTION

Protection of the groundwater intended for human consumption has a transcendental importance in Europe because it serves as water supply for an average of 70% of total population. This percentage raises to 99% in countries such as Austria and Denmark (European Environment Agency, 1999). The protection means mainly the establishment of groundwater source protection areas. These may be defined as areas surrounding groundwater sources. In those areas activities and facilities capable of polluting groundwater are gradually restricted or prohibited (Moreno Merino *et al*., 1991).

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Relevant methods to delineate zones in which these areas are detached depend on the characteristics of the aquifer from which groundwater is extracted (with granular porosity or similar in functioning: karstic or fissured), and which characteristics have been analysed in several research works (USEPA, 1987; Environment Agency, 1998; Lallemand-Barrès, Roux, 1999; Krijgsman, Lobo Ferreira, 2001; Martínez Navarrete, García García, 2003).

## SOURCE PROTECTION AREAS IN POROUS MEDIA AQUIFERS

In porous media aquifers or in those with a similar hydrogeological functioning, relatively homogeneous media in which Darcy's law can be applied are those in which still more precise methods can be used because of possibility to use hydrogeological and analytic methods and mathematical models.

Hydrogeological methods are fundamental, always as complementary to other ones. When used alone, they have an in-

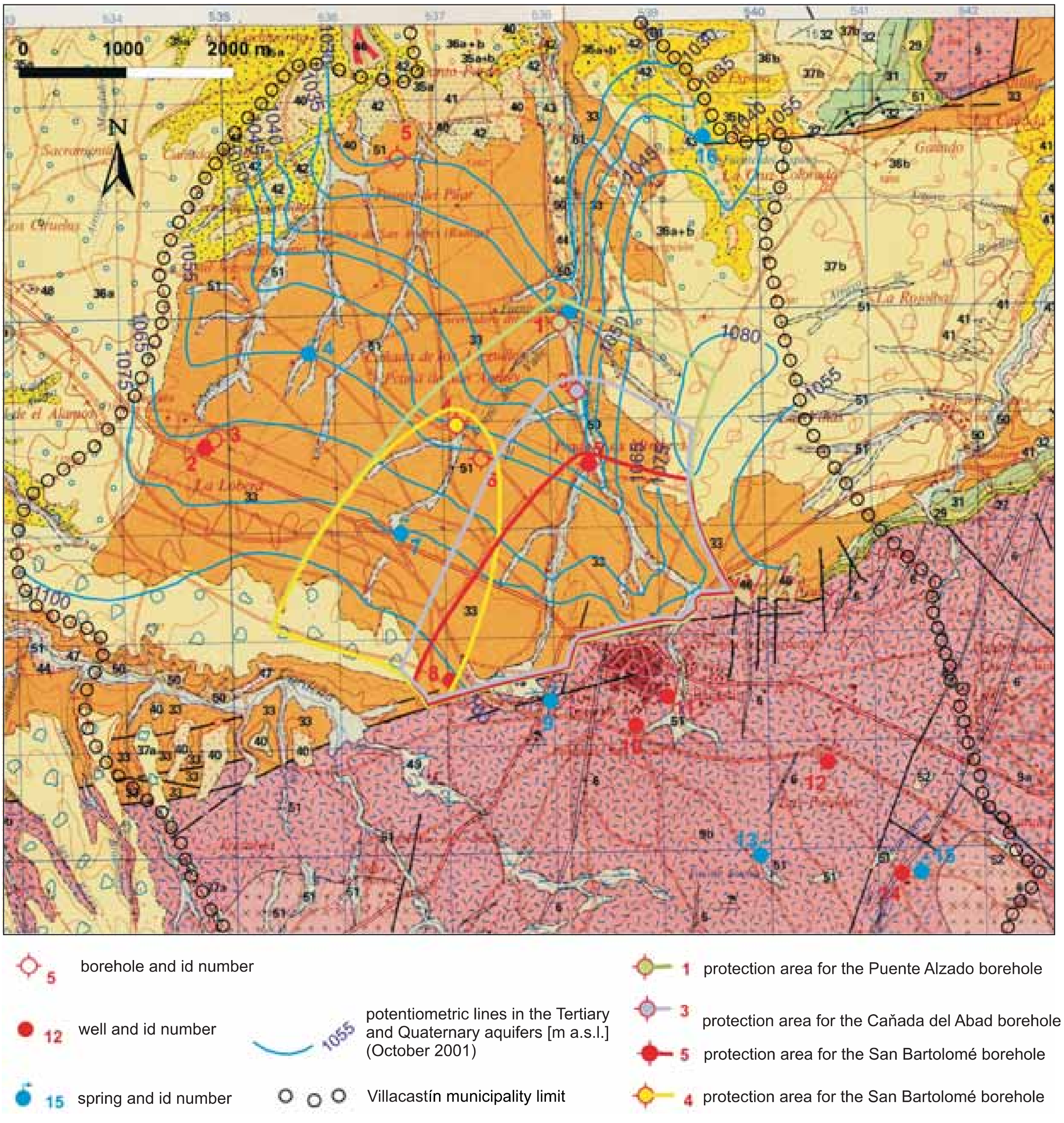

**Fig. 1. Source protection areas delineated by hydrogeological methods (from Pérez Gonzáles *et al.*, 1990 *in*: Martínez Navarrete, 2002; modified)**

**Table 1**

**Principal characteristics of the selected methods for delineating quality protection areas in porous media aquifers (from Martínez Navarrete, 2002; modified)**

| Name of the method | Limitations | Required data | | | | | | | | | | Methodology | Delineation of the protection area |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Q | i | K | b | $m_e$ | S | N | T | $V_e$ | More data | | |
| Hydrogeological methods | Gives a unique zone for the protection area. It does not depend on travel time | | | | | | | | | | Aquifer boundaries. Hydrogeological mapping of the aquifer. Equipotential lines and flow direction. River-aquifer relationship | Hydrogeological analysis of the aquifer | Catchment area |
| Flow system analysis combined with the calculus of travel time | Bidimensional flow. Ambient flow negligible. Well with a high pumping capacity | | + | + | | + | | | | + | Equipotential line and flow direction. Hydrogeological divide | Delimits catchment areas on the basis of equipotential lines and hydrogeological divides analysis. Gives distances upstream for different travel times to be measured as radii inside the catchment area | Radius defining catchment area for different travel times |
| Calculated fixed radius. Volumetric equation | Bidimensional flow. Ambient flow negligible. Well with a high pumping capacity | + | | | + | + | | | | | | Delimits the aquifer cylindrical area needed to obtain the pumped water rate considering that it comes from the stored water, defined by means of the cylinder volume and the effective porosity, considering a negligible recharge | Radius of a cylinder inside which any particle will need a travel time to arrive to the catchment, calculated for several travel times |
| Calculated fixed radius. Recharge method | Bidimensional flow. Ambient flow negligible. Well with a high pumping capacity. Gives a unique zone. Valid only for high travel times | + | | | | | | + | | | | Delimits the area needed to obtain the pumped rate for very high time values considering water as coming solely from incomes to the aquifer due to recharge | Radius of a cylinder that defines the perimeter for high travel times |
| Calculated fixed radius. Drawdown function | Bidimensional flow. Ambient flow negligible | + | | | | | + | | + | | | Delimits the zone in which a determined drawdown of the water table is produced because of the pumped water rate, using the Theis equation for transitory regime | Distance to the catchment for which a known water table drawdown is produced for several travel times |
| Wyssling's method | Homogeneous aquifer in the surroundings of the catchment. Uniform regional gradient | + | + | + | + | + | | | | + | Equipotential lines and flow direction | It calculates the catchment area for one catchment (there is a drawdown and flow going towards the catchment) and defines the distance in the flow direction corresponding to the desired travel time | Width of the catchment area.<br>Radius of the catchment area.<br>Width of the catchment area perpendicular to the flow direction at the closest point to the catchment. Upstream and downstream distances for different travel times |

| Name of the method | Limitations | Required data | | | | | | | | | | Methodology | Delineation of the protection area |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Q | i | K | b | $m_e$ | S | N | T | $V_e$ | More data | | |
| Flow system analysis combined with the uniform flow equation | Gives a unique zone for the protection area not depending on travel time. Bidimensional flow. It does not consider travel time | + | + | + | + | | | | | | Equipotential lines and flow direction. Hydrogeological divide | Delimits hydrogeological divide using equipotential lines and flow lines analysis. It uses the uniform flow equation to define the width of the catchment area on the hydrogeological divide and the distance downstream | Catchment area indicating its width at the hydrogeological divide and distance downstream |
| Jacobs and Bear's method | Homogeneous aquifer in the surroundings of the catchment. Uniform regional gradient | + | + | | + | + | | | + | | Equipotential lines and flow direction | A "reduced time" is calculate, seeking in the collection of travel time curves defined by the authors for the intersection points with the ordinates axis and those graphic distances are transformed into meters using equations | Distances upstream, downstream and towards both sides for each travel time |
| Simple analytical solution for the isochrones defining transport zones approach | Homogeneous aquifer in the surroundings of the catchment | + | + | + | + | + | | | | | Equipotential lines and flow direction | Equation that defines travel time needed for a particle to move in the flow direction from a point of known distance, upstream or down stream, from the catchment until it reaches the catchment | Distances upstream and downstream for travel times determined with the trial and error method using an equation |
| Krijgsman and Lobo Ferreira's method | Only for 50 days travel time with values 0<x<18 upstream -3.3<x<0 and $m_e$>0.1 (10%) downstream (1) | + | + | + | + | + | | | | | Equipotential lines and flow direction | Equations from an empirical solution that minimises differences between the Jacobs and Bear's equation and the results from the computer program VisualMODFLOW for a 50 days travel time | Distance of ellipses upstream, downstream, perpendicular and final rounded shape of the ellipse |
| Rehse´s method for calculating auto-purification power of materials | Gives a unique zone for the protection area. It does not depend on travel time | | + | + | | + | | | | + | Lithologic description and length of the pathway in different materials in both saturated and unsaturated zones | Empirical method for quantifying the purification power of materials inside the unsaturated and the saturated zones against polluting effluents (not specified), capable of passing through, taking the needed values from tables | Purification inside the non-saturated zone and minimum distance in the saturated zone to reach a total purification |
| Mathematical models: VisualMODFLOW and VisualMODPATH | They consider the advective component of solute transport, but does consider neither diffusion nor dispersion | Hydrogeological boundaries of the modelling zone. Boundary conditions (recharge, constant level cells, rivers and drains characteristics). Layers (geometry and kind of aquifer). Hydraulic head values. Hydraulic parameters values in each cell (kx, Ky, Kz, S, me). Pumping rate and pumping regime in each catchment | | | | | | | | | | Modflow is a tridimensional finite differences model that solves equations that define flow considering specific values for the aquifer properties in each cell, and gives hydraulic potential for each one in steady state and transient regime. Modpath uses the flow results from Modflow and calculates the path considering the advective component in solute transport. | Delimits precisely the area for the protection zone with different travel times in cross-section and plan |

Q — pumping rate, i h—ydraulic gradient, K — hydraulic conductivity, b — saturated thickness, $m_e$ — effective porosity, S — storage coefficient, N — recharge, T — transmisivity, $V_e$ — effective velocity;

(1) limitations to Krijgsman and Lobo Ferreira's method $x = 2 \cdot \pi \cdot i \cdot \sqrt{\frac{\pi \cdot b \cdot t}{Q \cdot m_e}}$

convenience of delineating a unique zone corresponding to the catchment area instead of dividing the protection area in a way allowed by other methods, that allow for easier establishment of gradual restrictions.

Analytic methods use simple equations that need few data. Their inconvenience is that they make a simplification of the aquifer characteristics, and the exploitation conditions that may be noticeably far from reality.

In this paper (Table 1), twelve methods selected by the authors as the most appropriate for granular porosity aquifers will be analysed, comparing results from their application to four catchments in a detritic aquifer (sands and gravels embedded in a sandy, silty, and clayey matrix) located in the Duero river basin, northwestern Spain (Martínez Navarrete, 2002).

Source protection areas delineated by hydrogeological methods are shown on Figure 1, being the effect of an analysis used also for an accurate application of all the considered methods.

Results obtained from the use of different selected methods, for one day travel time, are shown in Table 2. To carry out a comparative analysis of the different methods results, a cartographic overlapping of the protection areas delineated separately with the use of each singular method has been applied.

Results from mathematic simulation made with VisualMODFLOW and VisualMODPATH codes (Martínez Navarrete, 2002) have been used as a reference for the cartographic overlapping of the zones containing protection areas, delineated with different methods, after 50 days, 4 years and 25 years of travel time. Results obtained by other methods that do not considered travel time, such as hydrogeological methods or Rehse's method, to calculate the self-purification power of the terrain (Rehse, 1977), have also been evaluated.

Figure 2 shows an example of cartographic overlapping of protection areas delineated after 50 days travel time, using Wyssling's, and Jacobs and Bear's methods as well as a simple analytic solution method. Those are the ones that show the most similar results for this travel time with respect to the mathematic modelling taken as a reference. These three methods do also show almost identical results for the upstream

Table 2

**Comparison among quality protection zones obtained through application of different methods with a 1 day travel time or through alternative criteria**

| Employed methods | San Bartolomé Wellhead (4) distances in metres | Puente Alzado Wellhead (1) distances in metres | Cañada del Abad Wellhead (3) distances in metres | Camino del Valle Wellhead (5) distances in metres |
|---|---|---|---|---|
| Hydrogeological method (*) | it delineates a unique zone independent from time (see Figure 1) | | | |
| Flow system analysis combined with travel time calculus | d = 4 | d = 2 | d = 4 | d = 7 |
| Calculated fixed radius: volumetric equation | R = 16 | R = 16 | R = 17 | R = 17 |
| Calculated fixed radius: recharge method (*) | it does not use time; gives a unique value for long times Ex: 4 years (see Figure 4) | | | |
| Calculated fixed radius: as a function of drawdown | R = 367 | R = 367 | R = 367 | R = 367 |
| Wyssling's method | So = 23 (upstream)<br>Su = 19 (downstream) | So = 22 (upstream)<br>Su = 21 (downstream) | So= 24 (upstream)<br>Su=21 (downstream) | So = 26 (upstream)<br>Su = 19 (downstream) |
| Flow system analysis combined with the uniform flow equation (*) | it delineates a unique zone independent from time | | | |
| Jacobs and Bear's method | Xa-b = 11 (upstream)<br>Xa-c = 7 (downstream)<br>Xa-d = 8 (to the sides)<br>Xa-e = 8 (to the sides) | Xa-b = 4 (upstream)<br>Xa-c = 2 (downstream)<br>Xa-d = 3 (to the sides)<br>Xa-e = 3 (to the sides) | Xa-b = 10 (upstream)<br>Xa-c = 6 (downstream)<br>Xa-d = 7 (to the sides)<br>Xa-e = 7 (to the sides) | Xa-b = 21 (upstream)<br>Xa-c = 12 (downstream)<br>Xa-d = 15 (to the sides)<br>Xa-e = 15 (to the sides) |
| Simple analytic solution for an isochrones defining transport zones approach method | XL = 20 | XL = 20 | XL = 20 | XL = 20 |
| Krijgsman and Lobo-Ferreira's method | L = 19 | L = 18 | L = 20 | L = 22 |
| Rehse's method for the calculus of the depurative power of the materials (*) | it does not depend on time L = 107 | it does not depend on time L = 99 | it does not depend on time L = 0 | it does not depend on time L = 29 |
| Mathematic models. VisualMODFLOW and VisualMODPATH programs | simulation for 1 day has been not made because of being too small for the established grid | | | |

(*) these methods do not use travel time as a criterion; they are include as a reference of the protection area extension obtained using these criteria; they give a unique zone independent from time

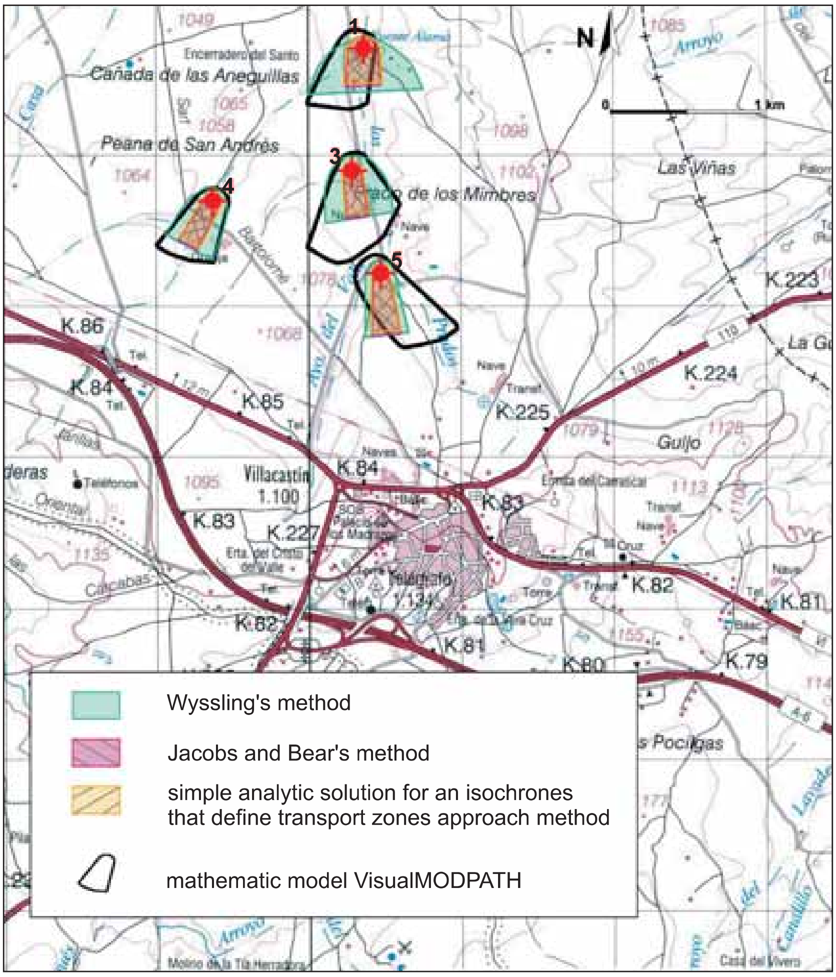

Fig. 2. Cartographic overlapping of the source protection areas delineated using different methods and a 50 days travel time (from Martínez Navarrete, 2002; modified)

and downstream length of the protection area in this zone and do usually indicate a smaller area to protect than that shown by the modelling, even though Wyssling's method delineates wider protection zones.

In each one, there is a degree of subjectivity as they have to define a unique main flow direction by means of the potentiometric values. In those values, error may be induced for the protection zone orientation in groundwater catchments with convergent flows, as illustrated by the case of wellhead number 5 in Figure 2.

In figure 3, the cartographic overlapping for a 4 years travel time protection zones is shown, obtained with the Wyssling's, and Jacobs and Bear's methods as well as with a simple analytic solution method. The last one provides much larger zones upstream than that of the mathematical simulation taken as reference, and about 1 km larger to that corresponding with the Jacobs and Bear's method.

With regard to other methods considered (Martínez Navarrete, 2002), their analysis shows that Krijgsman and Lobo-Ferreira's method gives results similar to those obtained with the Jacobs and Bear's methods. Their fixed calculated radius as a function of the drawdown gives a circle with a disproportionate radius even greater than the others; the fixed calculated radius volumetric equation and recharge methods show practically equal results and give zones defined by a circle that comprises about a half of the length upstream of the model value taken as reference and twice the length downstream; and the results from the flow system analysis combined with the travel time calculus method are very close to the hydrogeological method (Fig. 1).

And finally, Figure 4 shows the cartographic overlapping for 25 years travel time. This shows how Jacobs and Bear's, Wyssling's, simple analytic solution, Krijgsman and Lobo-Ferreira's methods delineate protection zones with very high lengths which are obviously not viable and very narrow and the fixed calculated radius as a function of the drawdown gives enormously sized areas. On the contrary, the fixed calculated radius recharge method gives very small areas, and the volumetric method, even though it reduces significantly the differences with the reference simulation, protects wide zones downstream probably in an unnecessary way.

Last of all, the flow system analysis combined with the travel time calculus method shows identical results to those of the hydrogeological method, which is the most similar to the reference area for such a high considered time.

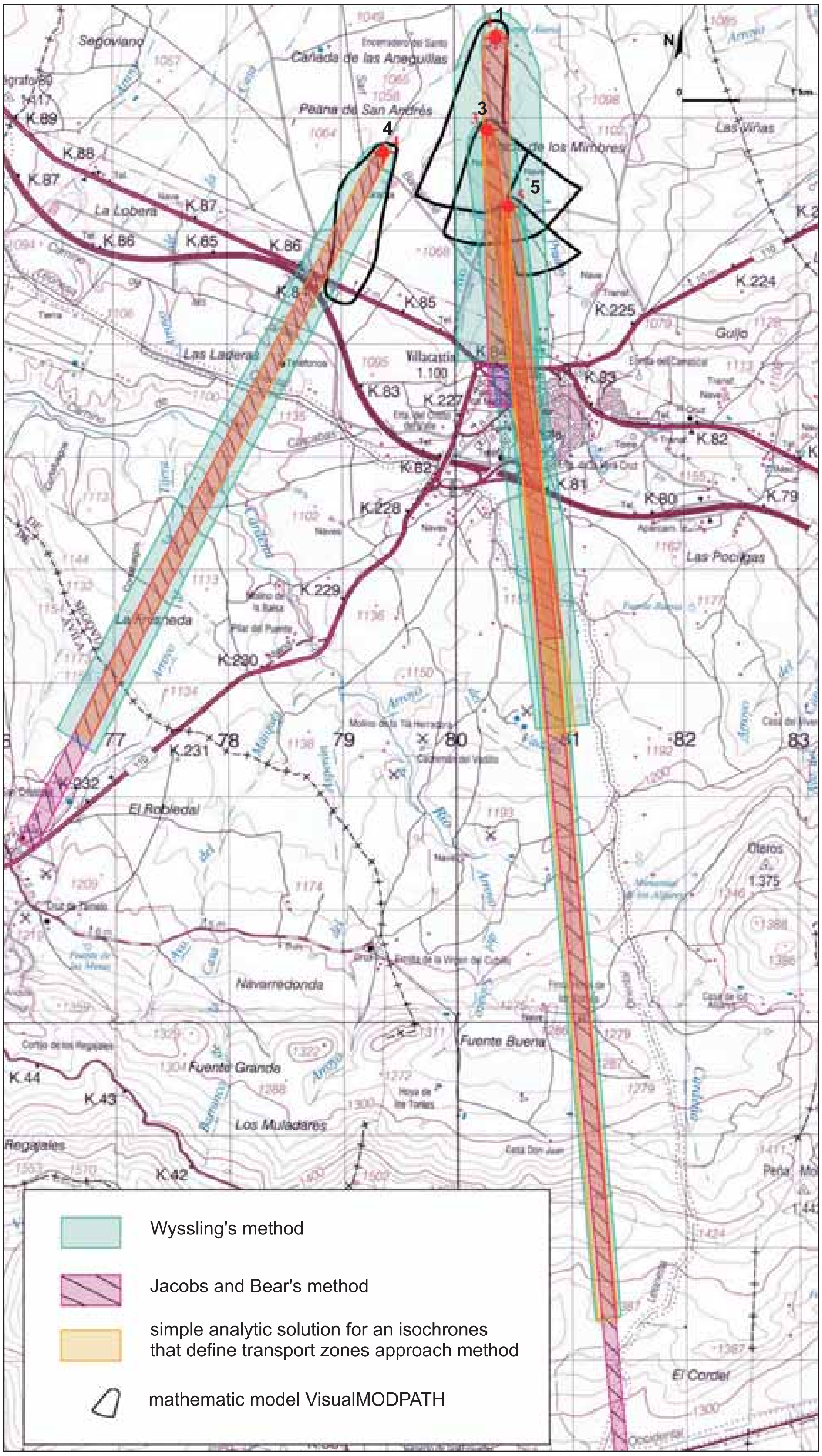

**Fig. 3. Cartographic overlapping of the source protection areas delineated using different methods and a 4 years travel time (from Martínez Navarrete, 2002; modified)**

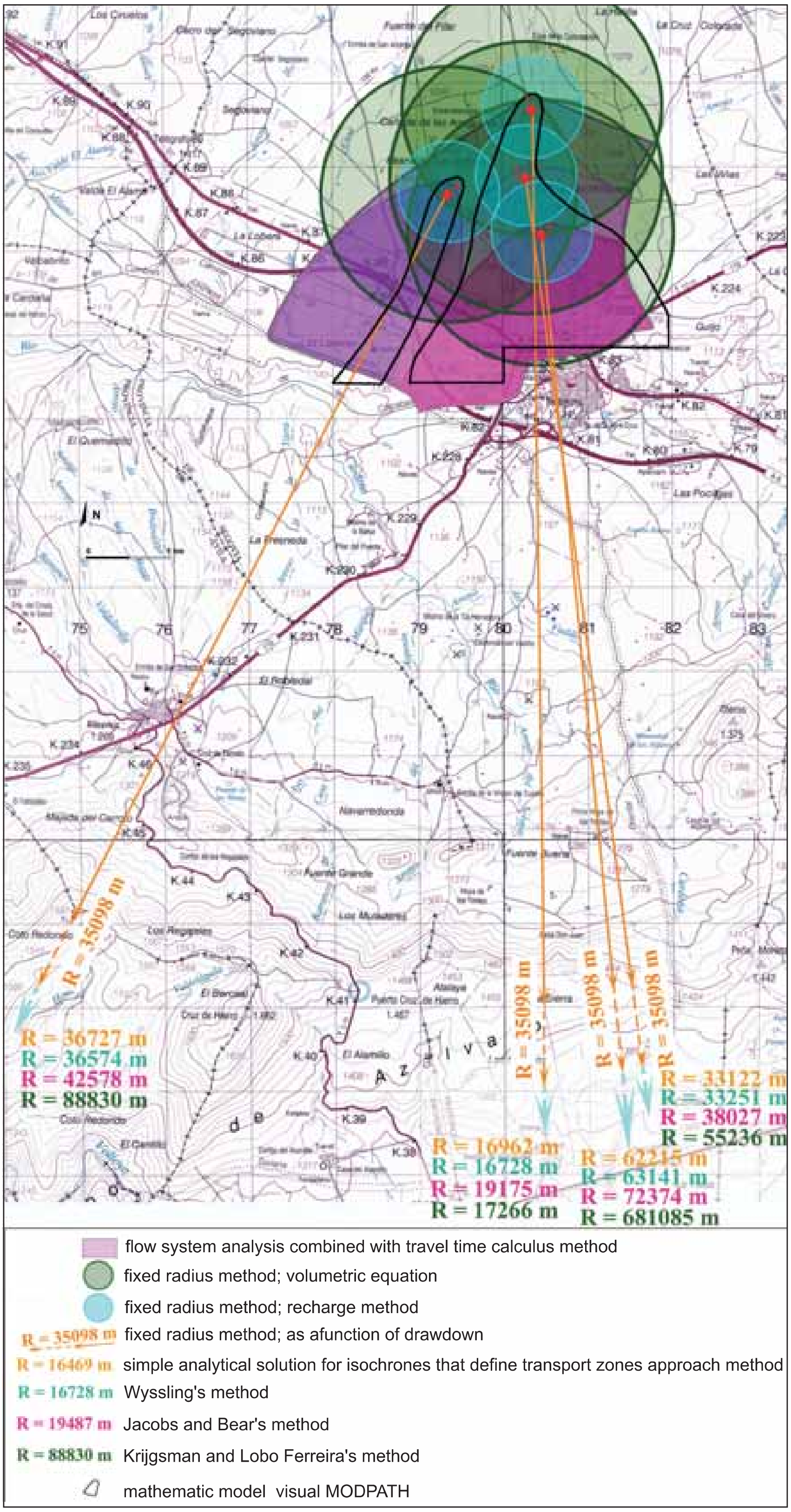

**Fig. 4. Cartographic overlapping of the source protection areas delineated using different methods and a 25 years travel time (from Martínez Navarrete, 2002; modified)**

## SUMMARY AND CONCLUSIONS

Comparison of results obtained with different methods selected for delineation of protection areas shows that the error is small in zones delineated by means of 1 and 50 days travel time, and that it increases for the furthest zone (usually delineated by means of several years travel time).

Mathematical models, when enough data is available for their calibration and performance, allow considering variations of the main hydraulic parameters, aquifer heterogenesis, pumping influences and others, so they give more precise results, especially for delineating the moderate restrictions zone, and even more when the travel time used is extended from 1 to 25 years in this zone.

This analysis allows to establish differences between methods and to estimate their accuracy for the different hydrogeological conditions of each of the four analysed catchments, so it may guide selection of the most suitable ones at the beginning of any project delineating wellhead protection area in similar conditions.

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