Ground and Water: Theory to Practice
Proceedings of the 55th Canadian Geotechnical and 3rd Joint IAH-CNC and CGS Groundwater Specialty Conferences, Niagara Falls, Ontario, October 20-23, 2002
Edited by D. Stolle, A.R. Piggott and J.J. Crowder and published by the Southern Ontario Section of the Canadian Geotechnical Society

ESTIMATING THE AREA OF CONTRIBUTION TO A PUMPING WELL: APPLICATIONS OF SEISMIC REFRACTION AND TRACER TESTING

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ABSTRACT
Analytical models that are used to estimate the contributing area to a pumping well consider an isotropic and homogeneous aquifer, and they generally neglect important factors such as vertical infiltration, thickness variations of the aquifer and interaction with surface water bodies. We are developing a sequential approach that considers a number of factors causing differences between the actual and an estimated contributing area to a well. This approach includes geological and geomorphological investigation, tracer testing and geophysical methods such as seismic refraction. Application of this approach to a well site at Saint-Félicien (Quebec) has provided information on the vertical extension of the aquifer, on its internal geometry, and on the influence of a surface stream. All of this information is very valuable to the estimation of the contributing area to the pumping well.

RÉSUMÉ
Les modèles analytiques qui sont utilisés pour estimer l'aire d'alimentation d'un puits de pompage ont été élaborés pour des milieux isotropes et homogènes, et ils négligent généralement d'importants facteurs tels l'infiltration verticale, les variations d'épaisseur de l'aquifère et les interactions avec les plans d'eau de surface. Nous développons une approche progressive visant à intégrer des facteurs qui contribuent à écarter de la réalité l'estimation qui est faite de l'aire d'alimentation. Cette approche inclut une investigation géologique et géomorphologique, des essais de traçage et des méthodes géophysiques tels la sismique réfraction. Une application de cette approche à un puits de pompage de Saint-Félicien, au Québec, a fourni des informations sur les dimensions verticales de l'aquifère, sur sa structure interne et sur l'influence d'un cours d'eau de surface. Toutes ces informations sont pertinentes et utiles dans l'estimation de l'aire d'alimentation du puits de pompage.

1. INTRODUCTION

The estimation of the contributing area to a pumping well can be realised using different methods such as analytical equations, hydrogeological mapping, numerical modelling, etc. (e.g. Barlow 1994; Forster 1997; Paradis 2001).

Analytical equations consider an isotropic and homogeneous medium, and they generally neglect important factors such as vertical infiltration, thickness variations of the aquifer and interaction with surface water bodies (Bear and Jacob 1965; Grubb 1993). Relations proposed by Bear and Jacob (1965) provides an estimate of the surface area contributing to a pumping well, in a vertical section normal to flow direction in a confined aquifer; this surface area simply satisfies Darcy's law in term of flow rate. By extension, the width of this vertical surface area is considered as the width of the horizontal area contributing to the well.

Banton (1998) developed an analytical approach that considers vertical recharge. In opposition to the methods mentioned above, this approach estimates a surface area at the ground surface over which the recharge rate corresponds to the flow rate extracted from the pumping well. All of these approaches consider that the well screen extends over the entire thickness of the aquifer.

Numerical modelling is frequently used to estimate the contributing area to a well. However, the validity of a numerical simulation depends greatly on the quality of the conceptual model. Determining the geometry and the boundary conditions of a model generally requires an important quantity of information.

A number of factors result in differences between the real and the estimated contributing area to a pumping well, including the presence of rock fractures or other complex internal geometry in the aquifer, an irregular aquifer thickness and the interaction between ground water and surface water bodies.

An approach that is essentially based on field investigation is proposed in order to obtain a more accurate estimation of the contributing area to a pumping well. This approach includes three categories of method: geological and geomorphological investigation, ground water tracer tests, and geophysical methods. We present applications of this approach to a municipal pumping well at Saint-Félicien, Québec (Figure 1).

2. THE STUDY SITE

The stratigraphy of the Saint-Félicien aquifer system is principally composed of a discontinuous clay layer at the top, covering a sand and gravel layer, a fractured calcareous rock layer paleozoic in age, and finally the precambrian crystalline bedrock. The clay layer and the crystalline bedrock are considered impermeable as a first approximation. Near the Ashuapmushuan river (Figure 2), the fractured calcareous rock appears to constitute the main aquifer. In the foothills area in the south western part of the site, the clay layer is absent and the unconfined aquifer is mostly constituted of sand and gravel.

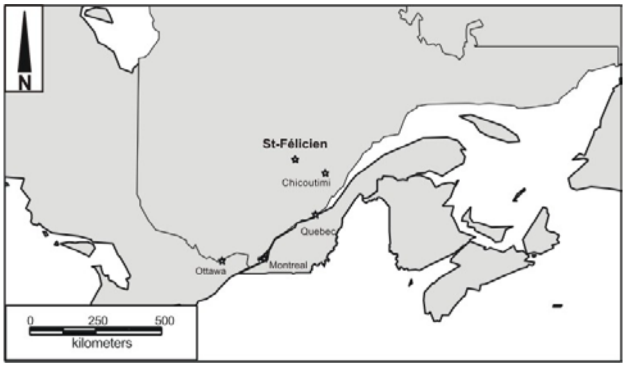

Figure 1: Localisation of Saint-Félicien, Québec, Canada.

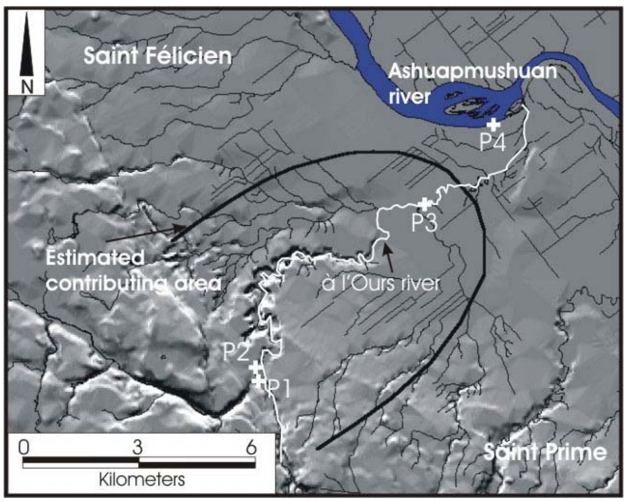

Figure 2: Topographic model of the well field located at the southern limit of the town of Saint-Félicien. This figure shows the four pumping wells (P1 to P4), and a previous estimation of the contributing area to well P3 (Hydrogéo-Sol Inc., 1997)

Two main rivers are present on the site: à l'Ours river is oriented NE and the larger Ashuapmushuan river is oriented NW (Figure 2). The general ground water flow direction is towards Ashuapmushuan river, but à l'Ours river seems to show local influence.

Four pumping wells are present on the site. Wells P1 and P2 are located in the unconfined sand and gravel aquifer, which is thicker at this foothills location. Wells P3 and P4 are screened in a thinner sand and gravel aquifer, and also in the underlying calcareous aquifer that covers the crystalline bedrock.

A first estimation of the contributing area (Figure 2; Hydrogéo-Sol Inc., 1997) was obtained using Bear-Jacob's (1965) relations, neglecting such factors as the interaction with surface water bodies and the influence of other pumping wells.

3. GEOLOGICAL AND GEOMORPHOLOGICAL INVESTIGATION

A geological and geomorphological analysis must be conducted before field investigation, in order to obtain a first estimation of the shape of the contributing area to a pumping well and to determine the approximate area of subsequent field investigation.

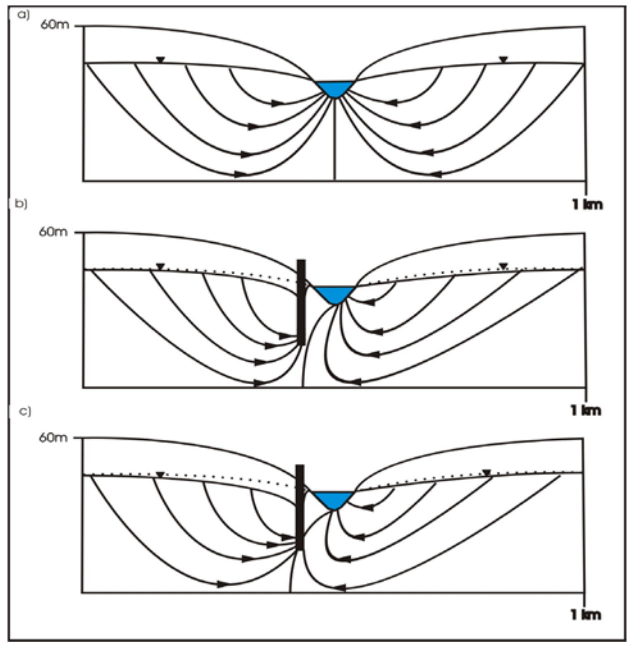

Figure 3: Schematic cross-section showing ground water flow lines towards a river, in a symmetric valley and a homogeneous aquifer: a) without pumping; b) with pumping at a small flow rate; no ground water coming to the well from the opposite side of the river; c) with pumping at a larger flow rate, and ground water coming to the well from both sides of the river.

Factors to consider at this stage include the potential interaction of ground water with surface water bodies. For instance, should it be assumed that the ground water flow lines are approximately parallel or perpendicular to a nearby surface stream (Winter et al. 1998)? In the case of ground water flow lines naturally converging to a river, it is often assumed that the river acts as a ground water flow divide (Figure 3a). The larger the pumping flowrate from a well located near the river, the greater is the perturbation from this initial flow geometry (Figure 3, b and c). For relatively high pumping rate, part of the water that is pumped at the well comes from the opposite side of the river through deep flow lines (Figure 3c). That water did infiltrate far away from the river, thus determining a relatively far located portion of the contributing area to the pumping well. On this opposite side of the river, water infiltrating nearer to the river does discharge directly to the river and does not contribute to the well. In such a case, a nearby ground surface zone is not a part of the contributing area, whereas a ground surface zone that is located farther away from the well is part of it.

4. GROUND WATER TRACER TEST

Applications of tracer tests in the determination of the contributing area to a pumping well include the estimation of ground water travel time and the determination of hydraulic connection between the pumping well and selected points in the aquifer. Three tracer tests were conducted in the ground water flowing to pumping well P3 at Saint-Félicien. Piezometers numbered 1, 2 and 3 on Figure 4 were used as injection wells for tracer tests No 1, 2 and 3 respectively.

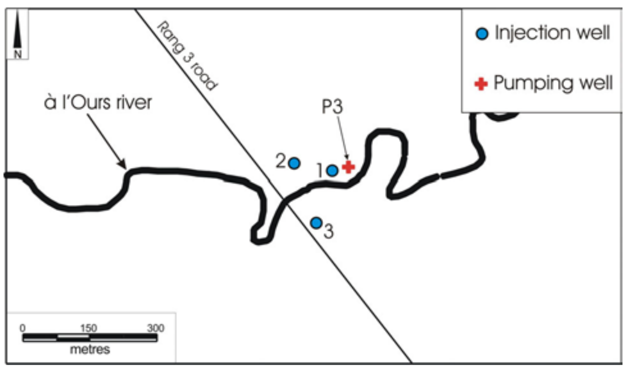

Figure 4: Localisation of injection wells and pumping well P3 at Saint-Félicien.

As well P3 is currently used for municipal water supply, it is essential that the pumped water remains drinkable during the tracer tests. Consequently, important aspects to consider in the planning of the tracer tests are the tracer selection and the determination of the quantity of tracer to be injected.

4.1 Tracer Selection

Besides being conservative, tracers to be used in a water supply well must imperatively be non-toxic, odourless and also colourless in the supply water. Potential tracers that were identified include uranine, chloride and sodium. Only uranine was used in the tracer tests discussed below.

Uranine is the most frequently used ground water tracer (Kass 1998), because of it's low detection limit, strong solubility (>600 g/l), and low sorption rate. According to previous studies (USEPA 1979; Davis & al. 1985; Field & al. 1995; and Kass 1998), uranine is harmless for humans and the environment for concentration in water not exceeding 1 mg/l over 24 hours. It's low concentration in natural ground water makes uranine easy to analyse. Water pH and the presence of particular salts in solution can increase the fluorescence of uranine. The maximum fluorescence level is obtained for a water pH around 8 (Kass 1998). Therefore, standards must be prepared with ground water coming from the study site, in order to properly evaluate a number of quantitative parameters, such as the tracer recovery rate.

4.2 Determining the Quantity of Tracer to Inject

In order to evaluate the maximum tracer concentration to be expected at the pumping well, three determining factors must be considered: the effective porosity of the aquifer, the flow rate at the pumping well, and the distance between the injection point and the pumping well. Important unknowns include the tracer dispersion in the aquifer and the ground water travel time. Dispersion increases with the travel distance; also, the higher is the dispersion, the lower is the maximum concentration at the sampling point. The travel time is inversely proportional to the effective porosity, as expressed in the following relation for seepage velocity:

$$v = \frac{Ki}{n} \qquad [1]$$

where v is the seepage velocity (L/t), K is the hydraulic conductivity (L/t), i is the hydraulic gradient ( ), and n is the effective porosity ( ).

A computer program was developed by Field (2001) to determine design parameters for a tracer test, such as the quantity of tracer to inject in accordance with the previously mentioned factors. This software was used to predict the first arrival time of the tracer at pumping well P3 at Saint-Félicien, and the maximum tracer concentration in the well water. The tracer quantity to be injected was determined on the basis of an expected maximum tracer concentration of 0,1 mg/l in pumping well P3.

4.3 Field Tracer Test and Results

Three tracer tests were conducted at pumping well P3 at Saint-Félicien. For tracer tests No 1 and 2, the tracer was injected in piezometers No 1 and 2 respectively, which are located on the same side of à l'Ours river as the pumping well P3 (Figure 4). The main objective of these first two tests was to calibrate hydrogeologic parameters such as effective porosity and travel time. Tracer test No 3 was carried out by injecting the tracer in piezometer No 3 located on the opposite side of the river; it's main objective was to evaluate the hydraulic connection between pumping well P3 and the portion of the aquifer that is located on the opposite side of the river.

During all three tracer tests, the pumping flowrate at well P3 was maintained at the normal value of 114 m^3/day, and the duration of tracer injection was about one hour. The distance between pumping well P3 and the injection well is 5 m for test No 1, 42 m for test No 2, and 58 m for test No 3. Table 1 shows a summary of tracer test results.

For tracer test No 1, the mass of injected tracer in piezometer No 1 was 11,5 g. A relatively long injection duration and a short travel distance has resulted in a concentration plateau because of the low dispersion. The tracer recovery was quick: roughly all the injected mass was recovered after two hours, and the maximum concentration at the sampling point was approximately 0,2 mg/l (Figure 5). Tracer mass recovery was estimated by numerical integration using Simpson's 1/3 rule:

$$\int_{x0}^{x2} f(x)dx \approx \frac{h}{3}\left(f(x_0)+4f(x_1)+f(x_2)\right) \quad [2]$$

where h is the sampling interval and must be constant.

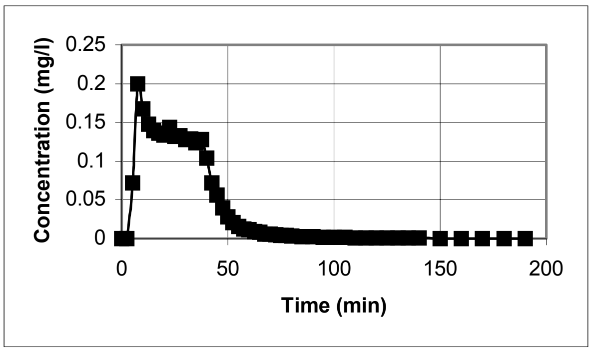

Figure 5: Breakthrough curve for tracer test No 1. The distance between the sampling point and the injection point is 5 m.

Table 1. Summary of tracer test results

Test No.	Injection - sampling distance (m)	First arrival time (hour)	Time to peak (hour)	Average TOT (hour)	Injected tracer mass (g)	Tracer recovery (%)
1	5	0.05	-----	-----	11.5	100
2	42	4	28	32	50	57
3	58	1	18	21	360	98

The first arrival time is about 3 minutes, and the small peak in the initial part of the breakthrough curve (Figure 5) corresponds to a higher injection rate at the very beginning of the test. The concentration plateau makes it impossible to obtain a meaningful value of the average time of travel, because the centre of gravity of the recovered mass is a function of the injection duration. Using the results of tracer test No 1 and the computer program developed by Field (2001), the effective porosity of the fractured calcareous formation was estimated at about 3%.

For tracer test No 2, the injected mass of tracer was 50 g. The longer travel distance (42 m) has resulted in a higher dispersion (Figure 6) than for tracer test No 1 (Figure 5). The first arrival time was 4 hours and the peak concentration was reached at about 28 hours; the peak tracer concentration was 0,008 mg/l, which is more than one order of magnitude lower than the expected maximum concentration (0.1 mg/l) at the sampling point. The average time of travel (TOT) was estimated at 32 hours and approximately 57% of the tracer injected mass was recovered after 120 hours. The effective porosity estimate obtained with the results of tracer test No 2 is 10%, which is significantly higher than with the results of tracer test No 1 (3%).

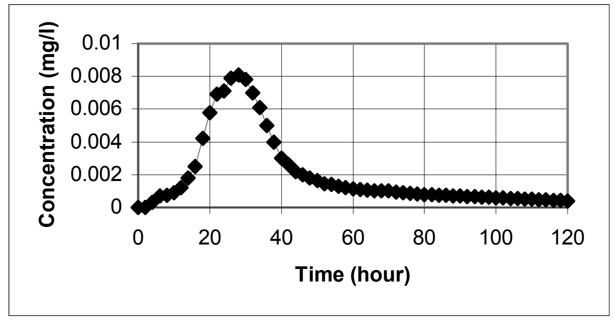

Figure 6: Breakthrough curve for tracer test No 2. The distance between sampling point and injection point is 42 m.

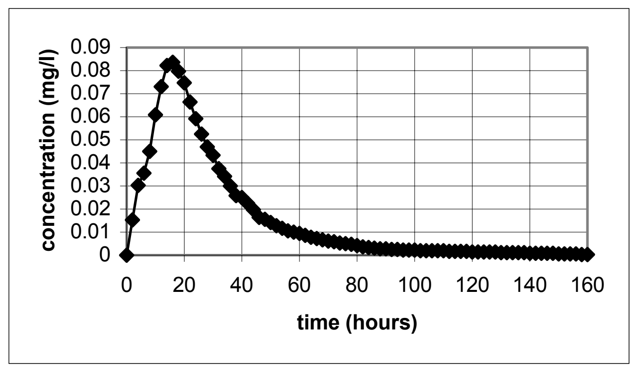

Figure 7: Breakthrough curve for tracer test No 3. The distance between the sampling point and the injection point was about is 58 m.

Because of a longer travel distance (58m), tracer test No 3 was expected to be affected by a higher dispersion; therefore, the injected mass of tracer for this test was set at 360 g of uranine. The breakthrough curve for tracer test No 3 (Figure 7) departed from the expectation and indicated a good hydraulic connection between these two points of the aquifer. The first arrival time was about one hour after the injection. The peak concentration at the pumping well was 0.085 mg/l, just 1.17 times lower than the expected value. The peak concentration took place at 18 hours, which is 10 hours earlier than the peak concentration for tracer test No 2. The tracer recovery was about 98% and the average time of travel was estimated at 21.5 hours.

5. SEISMIC REFRACTION

Four seismic refraction survey lines were carried out in order to evaluate the aquifer thickness and geometry in a vertical section normal to the ground water flow direction. The seismic lines were located at about 1 km upstream from pumping well P3. The individual lines were located one at the extremity of the other, forming a circle arc that corresponds roughly to an equal travel time of ground water to pumping well P3.

Local stratigraphic information was obtained from the log of a nearby piezometer hole. The interpretation of seismic results was made difficult by the presence of four stratigraphic layers: a clay layer, a compacted sand and gravel layer, a calcareous rock formation, and finally the crystalline bedrock. The seismic velocity values in these layers are approximately 1000 m/s, 2000-2500 m/s, 3000 m/s and 5000 m/s respectively. The low velocity contrast between the calcareous rock formation and the compacted sand-gravel layer introduces further difficulty in the interpretation.

The crystalline bedrock is generally at a depth of about 15 m at the site. Consequently, the distance between geophones should be relatively short (e.g. a few metres) in order to distinguish the different layers. For the first two seismic lines, the inter-geophone distance was set at 10 m; with 23 inter-geophones intervals each one of these two lines was 230m long. For each one of these two lines, height dynamite shots were executed in a symmetric fashion; considering that geophone No 1 is at the distance zero, the shots were located at -70, -40, -10, 75, 155, 240, 270 and 300m. Because of the relatively large inter-geophone distance, the only inter-layer contact that was detected with these first two lines was the top of the crystalline bedrock (Figure 8).

For seismic lines No 3 and 4, the inter-geophone distance was set at 3m. For theses two lines, the covered distance was much less than for lines No 1 and 2, but a better precision was obtained on layer discrimination. Six dynamite shots were executed for each one of lines No 3 and 4. Three layers were distinguished with seismic lines No 3 and 4, by detecting two interfaces: the contact between the clay layer and the compacted sand-gravel layer, and the contact between the calcareous rock formation and the crystalline bedrock. The low velocity contrast does not permit to detect the contact between the compacted sand-gravel layer and the calcareous rock formation.

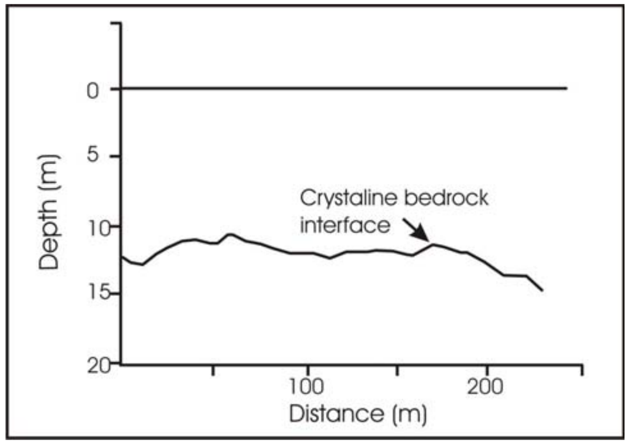

Figure 8: Stratigraphic section generated with seismic lines No 1. The only detected interface is the top of the crystalline bedrock.

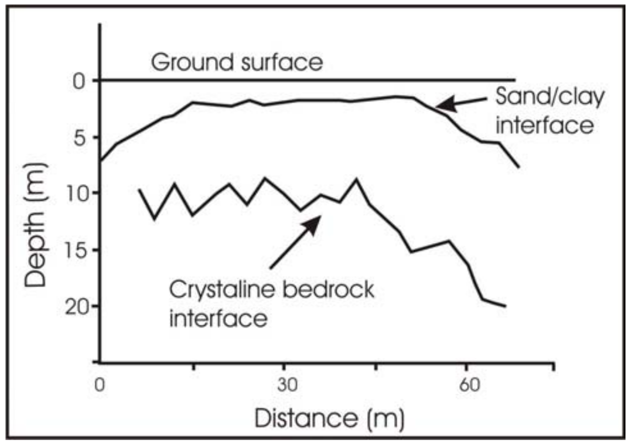

Figure 9: Stratigraphic section generated with seismic line No 3. The contact between the compacted sand-gravel layer and the calcareous rock formation is still not detected.

6. DISCUSSION

The smoothness of the tracer test breakthrough curves suggest that the fracture system in the calcareous rock formation is fairly dense and well connected. Also, the average time of travel (TOT) obtained for tracer test No 2 is longer than the TOT for tracer test No 3, although the distance between the injection point and the pumping well is shorter in test No 2. This suggests that the tracer in test No 2 takes a less direct flow trajectory than for the test No 3. This longer trajectory could be due to the injection point for test No 2 being closer to the limit of the contributing area as indicated on Figure 10. This interpretation is supported by the low tracer recovery for test No 2 (57%) as compared to test No 3 (98%); a significant proportion of the tracer in test No 2 would be lost to the regional flow system. The orientation of the estimated contributing area to pumping well P3 that is based on the above interpretation (Figure 10) is significantly different from that previously obtained essentially on the basis of piezometric data (Figure 2)

Also, the result of tracer test No 3 clearly indicates that the well P3 extracts a high proportion of the pumped water from the opposite side of the à l'Ours river. This river appears to have no influence on the contributing area in the vicinity of well P3, except possibly locally where the infiltrating water along the river benches would discharge directly to the river instead of contributing to the pumping well.

Seismic refraction survey has provided an estimation of the aquifer thickness in a vertical section normal to the ground water flow direction. A more exact determination of the aquifer thickness permits a sounder estimation of the width of the contributing area, by simple application of Darcy's law expressed in term of flow rate.

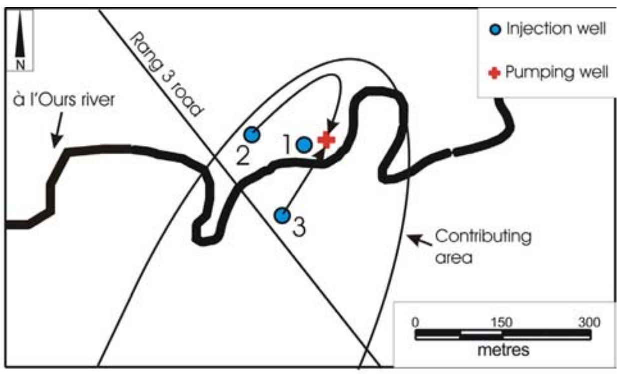

Figure 10: Orientation of contributing area of pumping well P3, based on interpretation of the results of tracer test No 3.

The combination of tracer test and seismic refraction can make significant contribution to the estimation of the contributing area to a well

7. CONCLUSION

This study has underlined the benefits of field investigation in the determination of the contributing area to a pumping well. Geological and geomorphological investigation allows a preliminary evaluation of the shape of the contributing area, including the possible interaction of ground water with surface water bodies.

Tracer tests require a more elaborate preparation, but they provide direct estimates of a number of flow parameters between the injection point and the pumping well, including the average time of travel and the tracer recovery. Seismic refraction, or other geophysical methods, provides information on the geometry and the extent of the aquifer, extrapolated between existing boreholes. All this information allows significant refinement to be made to a preliminary estimation of the contributing area.

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9. ACKNOWLEDGMENT

This work is founded by the *Programme d'aide à la recherche en environnement* (PARDE) of *Ministère de l'Environnement* of Québec, and by the *Fondation de l'Université du Québec à Chicoutimi*. The authors acknowledge the collaboration of *Ville de Saint-Félicien* and of the regional municipality of Domaine-du-Roy. Special thanks to M. Field for providing his software on tracer test design and to R. DuBerger for is support on seismic refraction.