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Temperature logging to describe the movement of sewage-polluted surface water infiltrating into a fractured rock aquifer

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Abstract

In 1992–1993, temperature logs were used to study the movement of sewage-polluted surface water infiltrating into the fractured limestone of an experimental site located in the south-eastern part of the Lez Basin (Southern France). The wells investigated were located on either side of a sewage-polluted stream and intersected water-bearing fractures characterised by large contrasts in hydraulic conductivity. From the results of temperature–depth profiles measured in four closely spaced wells of 60 m depth (W7, W8, W10 and W16) during the period February 1992–June 1993 and the findings of a previous and more extensive geothermal survey, we examined the spatial distribution and the temporal variability of ground-water temperature during periods influenced or not influenced by percolating sewage-polluted water. Results of this thermal survey, which were in good agreement with those of a physico-chemical and bacteriological survey simultaneously carried out at the site, provided a substantial amount of information on the distribution of contaminant flow pathways. Well W8, which showed high fluctuating ground-water temperature anomalies, intersected a solution-enlarged part of a bedding joint which seemed to carry much of the sewage-polluted infiltrating water. Ground water in this conductive opening also had a low physico-chemical and bacteriological 'stability' and the highest average contaminant concentrations. In contrast, Wells W10, W16 and, to a lesser extent, Well W7 displayed only low ground-water temperature anomalies during periods influenced by percolating sewage-polluted water. Ground water circulating through the thin and rather closed fissures intersected by these wells was less sensitive to pollution, as it had a greater thermal, physico-chemical and bacteriological 'stability' and the lowest average

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contaminant concentrations. Thus, we suggest that in advance of more focused monitoring programmes, temperature–depth profiles in wells could effectively be used to describe the effect of the structural features of fractured limestone aquifers on the movement of infiltrating contaminants.

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1. Introduction

As the movement of heat through an aquifer occurs by conduction and convection, the underground temperature distribution depends on the magnitude and direction of ground-water flow. Therefore, hydrogeologists who utilised sub-surface temperature measurements to describe ground-water flow were often faced with the same problems as those who conducted tracer experiments (Heath and Trainer, 1968; Andrieux, 1976; Blanchard, 1976; Lacas, 1976; Karanjac and Altug, 1980). However, thermometry is an attractive research field because available and affordable logging devices allow the rapid collection of sound and reliable temperature data.

In porous media, various field experiments have thus been carried out by several workers who have used sub-surface temperature distribution for describing flow characteristics (Cartwright, 1970; Bureau de Recherches Géologiques et Minières (BRGM), 1976; Van Dalfsen, 1981, 1982; Rojaz, 1984). In deep wells, where temperature is in equilibrium with the surrounding rocks, vertical movement of ground water causes curvature in the geothermal gradient. Several workers presented type curves, which matched well the observed temperature–depth profiles and could be used to compute vertical ground-water velocity (Stallman, 1963; Sorey, 1971; Boyle and Saleem, 1979). The limits of such an approach have been discussed by Diment and Robertson (1963), Diment (1967), Gretner (1967) and Sammel (1968), who demonstrated that because of convective transfer of heat in the column, well temperatures might differ significantly from temperatures in the surrounding rock. Temperature profiles obtained in a set of monitoring wells were used by Parsons (1970) to propose a ground-water flow model at the scale of an entire catchment area. At a smaller scale, Keys and Brown (1978) used temperature logs to trace the movement of water injected into a sandy aquifer and to locate zones of high intrinsic permeability.

In fractured media, temperature profiles in wells have been used to study the geometry of fracture networks (Trainer, 1968; Michalski, 1989), to characterise ground-water circulation (Mathey, 1974; Hosanski, 1980; Avias et al., 1980; Williams et al., 1984; Soulié et al., 1988) and to identify fracture interconnections between boreholes (Flynn et al., 1985; Silliman and Robinson, 1989; Robinson et al., 1993). Williams and Conger (1990) also suggested that temperature logging could help in defining the migration pathways of contaminants in fractured bedrock aquifers.

In this paper, we present the results of a thermal survey carried out in 1992–1993 on a fractured and karstified limestone site located in the south-eastern part of the Lez

Basin (Southern France). Our objectives were to use temperature logs to assess the impact of a sewage surface source of pollution on the ground-water quality, and to describe the movement of the infiltrating sewage-polluted water. First, the spatio-temporal distribution of ground-water temperatures during periods not influenced by percolating sewage-polluted water was described from the results of a previous study (Girona, 1978; Uil, 1978; Botton, 1984; Drogue, 1985). Second, temperature profiles measured in four closely spaced wells of 60 m depth were used to determine the spatial distribution and temporal variability of ground-water temperatures during periods influenced by percolating sewage-polluted water. Third, thermal results were compared with those of a physico-chemical and bacteriological study.

2. Materials and methods

2.1. The study site

The research site is located in the 200 km^2 catchment area of the Lez Spring, France (Fig. 1(A)). It was selected because it had previously been investigated in exceptional detail (Drogue, 1974, 1977, 1980, 1985, 1988, 1991; Drogue and Grillot, 1976; Pitard, 1976; Girona, 1978; Uil, 1978; Gottis and Drogue, 1983; Botton, 1984; Bidaux, 1987; Xu, 1990; Malard et al., 1994a,b). This is a 500 m^2 experimental area where 21 uncased wells, separated from one another by a distance of only 5 m, are located on either side of a temporary stream (Figs. 1(B) and 1(C)). The wells are of 60 m depth and 0.11 m in diameter; they all reach the ground-water table, which fluctuates at depths between 15 and 40 m below the soil surface.

2.2. Hydrogeological settings

The rock intersected by the wells is Berriasian limestone, gently dipping (15–20°) to the NW. The major subvertical fractures, which were delineated from the results of surface and airphoto surveys, are oriented N 0–40° and N 100–120° (Drogue and Grillot, 1976). The wells tap preferentially subhorizontal fractures more or less enlarged by karstification, which were previously delineated by combining temperature, fluid-resistivity and video logs (Drogue, 1977; Drogue and Uil, 1977). Although the wells are separated from one another by short distances, their yields, which are dependent upon the size of intercepted fractures, vary greatly. For example, a 72 h pumping test carried out on Well WC at a constant discharge rate of 27 m^3 h^{-1} produced drawdown of 8 m whereas Wells W7, W10 and W16 could be pumped nearly dry with a 2 m^3 h^{-1} discharge pump (Drogue and Grillot, 1976; Malard et al., 1994c).

As the site is part of the Lez Spring basin, ground-water recharge and thus fluctuations of the ground-water table depend mainly on the rainfall events which occur in the basin. Ground-water table variations from January 1992 to July 1993, which were provided by three continuous water-level recorders operating on Wells W9, W10 and W20, are shown in Fig. 2. As only sparse rainfall occurred from

January to May 1992, the ground-water level remained low. The rise of the ground-water level in March 1992 was due to rainfall which occurred in the northern part of the Lez Spring basin. Then, from May 1992 to July 1993, heavy rainfall (e.g. 672 mm from 19 May to 31 October 1992) allowed the ground-water table to maintain a high level, and intense rainfall (e.g. 99 mm on 28 May 1992) induced flash floods with stormwater runoff at the site in May and September 1992 and May 1993.

2.3. The surface source of contamination

The temporary stream which intersects the site is a small Mediterranean

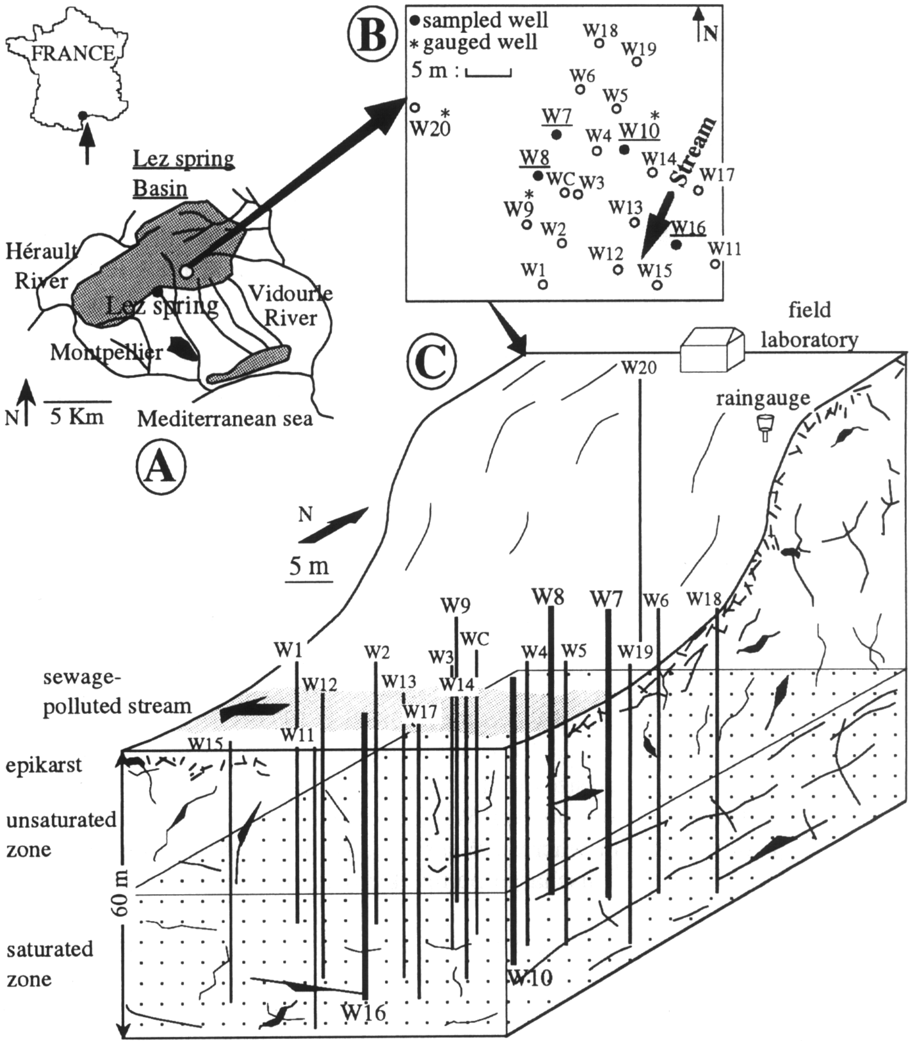
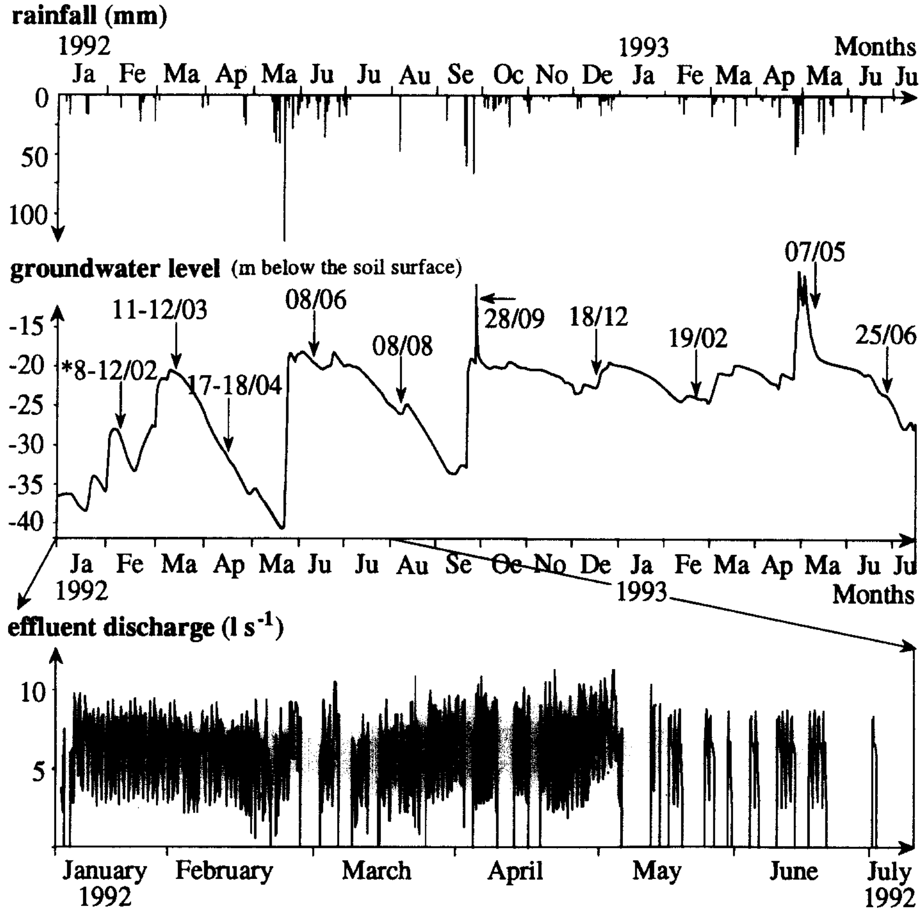


Fig. 1. Location (A), map (B) and three-dimensional drawing (C) of the limestone study site.

watercourse whose bed dips very gently to the SW. This stream is dry for most of the year and it is flushed with stormwater runoff during periods of high rainfall intensity. However, during the period January 1992–May 1992, the stream was never dry because it received the secondary effluent of a malfunctioning sewage treatment located 800 m upstream. The effluent of the plant, which served a village population of about 3000 inhabitants, ought to have been pumped to irrigate an afforestation area, but this almost never occurred. Indeed, as the plant was under-sized, the pump filter was clogged after only 3 h of pumping by sludge particles contained in the effluent, which was thus simply poured into the stream bed. From January 1992, the effluent discharge to the stream bed was recorded by a gauging station installed below the plant (Fig. 2). The effluent discharge occurred at a fairly constant average rate of 5 l s^{-1}, even though daily variations were observed in relation to water use by



*8-12/02: temperature profile in well

Fig. 2. Rainfall, ground-water table variations, and effluent discharge recorded in 1992–1993.

the inhabitants. As low rainfall did not induce any overland flow, a sludge layer developed on the stream bed and the sewage plume, which extended over a distance of 800 m in January 1992, increased gradually in length. In May 1992, all the sewage infiltrated the aquifer over a distance of 1500 m.

During the storm event of 29 May 1992, sludge particles which had previously accumulated on the stream bed were washed away. Then, from July 1992 to June 1993, the effluent discharge to the stream bed decreased markedly because some parts of the malfunctioning treatment plant were repaired. As the effluent was no longer loaded with sludge particles, it was regularly pumped to irrigate the afforestation area. Thus, the effluent discharge occurred very unevenly and was no longer recorded because the stream bed was mainly flooded during rainy periods when the plant overflowed. In this case, sewage effluent became mixed with runoff waters and sludge deposit was no longer observed on the stream bed.

2.4. Ground-water temperature measurements in selected wells

Four wells (W7, W8, W10 and W16) were selected to investigate water-bearing fractured zones with very different flow conditions. Indeed, Well W8 taps, at a depth of 43 m, an enlarged bedding joint characterised by high hydraulic conductivity of approximately 10^{-1}–10^{-3} m s^{-1}, whereas Wells W7, W10 and W16 intersect only thin subhorizontal fissures characterised by low hydraulic conductivities of approximately 10^{-7}–10^{-9} m s^{-1} (Drogue, 1974, 1985). Surface elevation measured at the top of these four wells, which are separated from one another by only a few metres, is 85.72 m, 85.78 m, 85.70 m and 84.00 m above sea-level for Wells W7, W8, W10 and W16, respectively.

Two different kinds of experiments were conducted. On 8 February, 11 March and 17 April 1992, a temperature log was recorded about every 4 h in Wells W7, W8 and W16. On 12 February, 8 June, 8 August, 28 September and 18 December 1992, and 19 February, 7 May and 25 June 1993, only one temperature profile was measured in Wells W7, W8 and W16. Temperature data for Well W10 are less numerous as only one temperature log was recorded on 17 April, 8 June, 8 August, 28 September and 18 December 1992, and 19 February, 7 May and 25 June 1993.

The instrument used to measure ground-water temperature was a WTW logger with a LF 196T sonde (Darmstadt, Germay; WTW) which contained an unoxidisable metal probe thermistor. The sonde is connected to an electrical cable of 80 m length which was used as the logging cable. This WTW logger provides temperature readings with a resolution of 0.1°C, which is an order of magnitude less than that of instruments used by most researchers (Uil, 1978; Drogue, 1985; Robinson et al., 1993). However, our logging equipment still provided some interesting data because temperature anomalies recorded in selected wells (sometimes as great as 1.5 °C) often exceeded the logger resolution by several times. The sonde was lowered to the ground-water level and maintained until the temperature reading stabilised. To avoid disturbance of the water column in the well, it was then slowly lowered, with pauses at regular 1 m intervals to take readings.

2.5. Physico-chemical and bacteriological sampling in selected wells

In 1992-1993, a physico-chemical, bacteriological and biological survey was also initiated as a part of an Interdisciplinary Research Programme in environmental studies (Ecology and Biogeochemical Dynamics of Groundwater Systems) (Malard et al., 1994a,d; Gibert et al., 1994). Sampling was carried out in Wells W7, W8, W10 and W16 on 19 March, 27 April, 9 June, 8 August, 28 September and 18 December 1992, and 21 February, 7 May and 26 June 1993. One day before physico-chemical and bacteriological sample collection, each well was pumped with an air-lift to collect ground-water invertebrates (Malard et al., 1994a). This preliminary pumping also ensured that physico-chemical and bacteriological samples would be representative of the circulating ground water. A small submerged pump was then lowered to the main fracture depth and a ground-water sample was collected after enough water had been pumped to rinse the pump and tubes. Packers were not used because most of the ground water in Wells W7, W8 and W16 originated from only one fracture depth and because fracture depths in Well W10 could not be identified precisely.

Conductivity and dissolved oxygen were measured in the field with a Merck (WTW) CM 85 T conductivity meter and a Merck (Darmstadt, Germany; WTW) LMC 85 T oxygen meter. In the laboratory, ground-water samples were analysed for bicarbonate, calcium, magnesium, sulphate, orthophosphate, ammonium, nitrate, faecal coliforms and faecal streptococci. Bicarbonates were assayed with the use of hydrochloric acid and a mixed methyl red and bromcresol green indicator (American Public Health Association (APHA), 1985). Calcium and magnesium concentrations were measured with the EDTA complexometric method (Rodier, 1984). The ascorbic acid and turbidimetric methods using a Hach-IR/DR colorimeter (Hach, Ames, IA, USA) with Hach reagents were selected for the analysis of orthophosphate and sulphate concentrations, respectively. The same apparatus was used for the determination of ammonium (Nessler method) and nitrate (low-range cadmiun reduction method). Faecal coliforms (FC) and faecal streptococci (FS) were enumerated with the membrane filtration method (Association Française de Normalisation (AFNOR), 1990) at the Pasteur Institute of Lyon, and were reported as colony-forming units (CFU) per 100 ml.

2.6. Statistical analyses and graphical displays

A between-site principal component analysis (PCA) was applied to physico-chemical and bacteriological data to describe the spatial distribution of contaminants. This between-class analysis was developed by Foucard (1978) and Dolédec and Chessel (1987, 1989, 1991, 1992) to examine the spatial effect only in a three-dimensional data table (several sampling points × several sampling dates × several variables). In our case, the stream water and the ground water of four wells (five sampling points) were sampled nine times (nine sampling dates) and analysed for 12 physico-chemical and bacteriological parameters (12 variables). Briefly summarised (see details given by Dolédec and Chessel (1987, 1989)), the between-site principal component analysis corresponds to the PCA of a new two-dimensional data table in which the initial normalised physico-chemical and bacteriological data have been averaged by a point (the stream and Wells W7, W8, W10, W16) for each variable. Centres of classes are then scattered on a factorial map, the initial data for each class being then plotted as supplementary individuals. The resulting graphical display is a

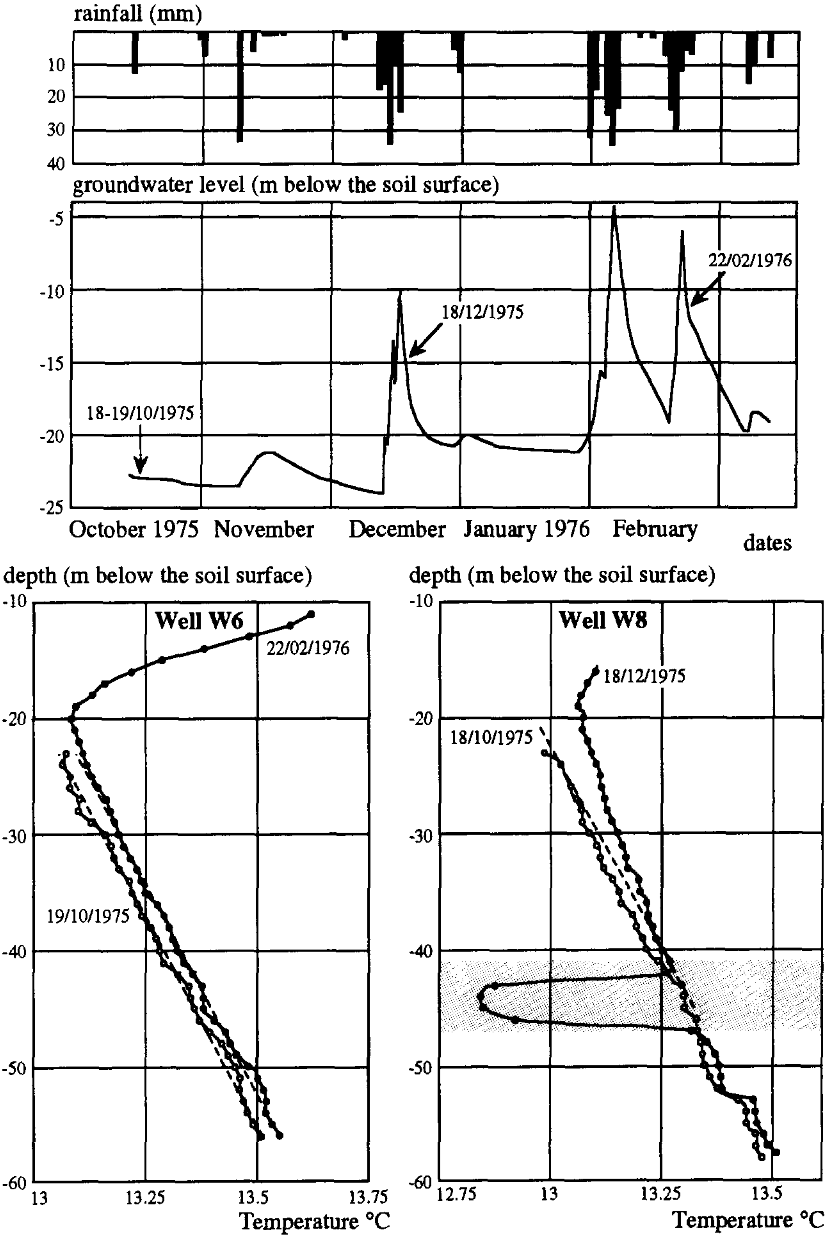


Fig. 3. Examples of low- and high-water thermal profiles measured in Wells W6 and W8 during periods not influenced by percolating sewage-polluted water (modified after Uil (1978)).

'spider' diagram which provides a typology of sampling points with respect to their physico-chemical and bacteriological characteristics as well as a view of the variability of sampling dates around the different mean points (see Fig. 11 below).

3. Results

3.1. Spatial distribution and temporal variability of ground-water temperatures during periods not influenced by percolating sewage-polluted surface water

While no effluent was discharged to the stream bed, Girona (1978), Uil (1978), Botton (1984) and Drogue (1985) measured temperature–depth profiles at the site during low- and high-water periods. During low-water periods, they showed that none of the well profiles displayed temperature anomalies at precise depths. However, the shape of temperature profiles might differ from one well to another. Some wells (e.g. Wells W1, W3, W4, W6, W9, W10, W13) displayed linear thermal gradients, whereas others (e.g. Wells W7, W8, W11, W12, W16) had profiles with concave or convex parts (Fig. 3). Despite these irregularities in some of the well profiles, Drogue (1985) calculated the mean thermal gradient for 14 wells out of 21 (Fig. 4). Considering the spatial distribution of geothermal gradients at the site, Drogue demonstrated that the gradients increased from west to east.

The spatial distribution of ground-water temperature during high-water periods was shown to be highly heterogeneous as compared with that observed during low-water periods. Only the profiles of wells intersecting thin and rather closed fissures in the saturated zone (e.g. Wells W6, W10, W13, W18, W19) had thermal profiles similar to low-water profiles (Fig. 3). In contrast, wells intersecting fractures more or less enlarged by karstification (e.g. Wells W2, W3, W5, W7, W8, W9, W11, W12, W15, W17) were deformed by warm or cold circulating ground water and exhibited at precise depths temperature anomalies of varying magnitudes (Fig. 3). Among these wells, particular attention was paid to profiles of Well W8, which showed, each time a flood occurred, the highest temperature anomalies at a depth of 43 m. Negative and positive temperature anomalies of −1.8°C and 0.11°C, −3.12°C and 0.85°C, and −2.5°C and 0.3°C were reported for this well by Girona (1978), Botton (1984) and Drogue (1985), respectively. Microflowmeter measurements taken in Well W8 at depths between 41 and 45 m indicated a downward flow with maximum water velocity ranging from 0.25 to 0.60 m s^{-1} (Girona, 1978; Botton, 1984; Drogue, 1985).

3.2. Spatial distribution of ground-water temperatures during periods influenced by percolating sewage-polluted surface water

Temperature logs that we obtained in Wells W7, W8, W10 and W16 from February 1992 to June 1993 are plotted in Fig. 5. Temperature profiles shown for Wells W7, W8 and W16 on 8 February, 11 March and 17 April 1992 correspond to the average of the profiles measured during these three sampling dates. Except on 25 June 1993, temperature measurements were conducted while the sewage-polluted stream was flowing.

In contrast with the results of previous works, temperature anomalies at precise depths in Wells W7, W8 and W16 were observed during low-water periods (8 February, 12 February, 17 April, 8 August and 18 December 1992, and 19 February 1993). Concave and convex bulges were observed at the same depths as those mentioned by Girona (1978), Uil (1978), Botton (1984) and Drogue (1985) on the basis of the examination of high-water profiles: 45 m in Well W7, 43 m in Well W8 and 35 m in

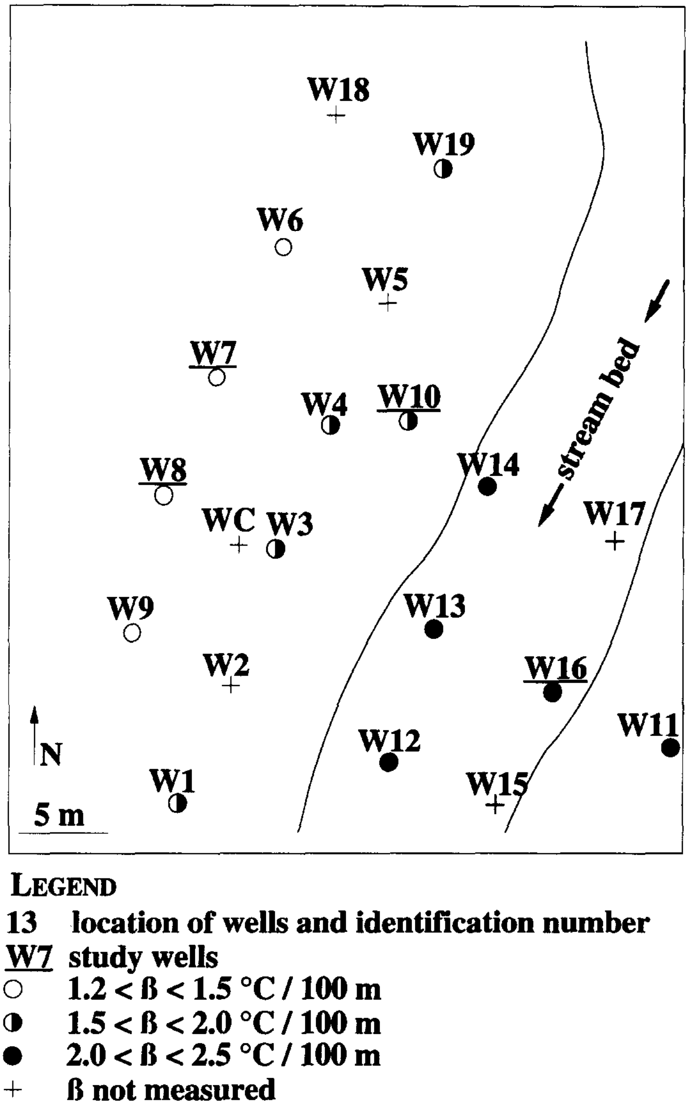


Fig. 4. Spatial distribution of mean geothermal gradients (β) at the site during low-water periods not influenced by percolating sewage-polluted water (modified after Drogue (1985)).

Well W16. Ground-water temperature anomalies at precise depths could not be detected in Well W10, but profiles did not always display linear thermal gradients as had previously been observed during low- or high-water periods. Indeed, on 17 April, 8 June and 8 August 1992, the temperature profiles showed a significant concave curvature between 35 and 50 m.

Distinct differences appeared between the magnitudes of the temperature anomalies observed in Wells W7, W8 and W16. For all the thermal surveys considered, negative and positive temperature anomalies of −1.5°C and 1.0°C were measured in Well W8, whereas inflections of only −0.5°C and 0.3°C in Well W7, and −0.2°C and 0.1°C in Well W16, were observed. For a given sampling date, temperature anomalies always decreased as we considered successively Wells W8, W7 and W16.

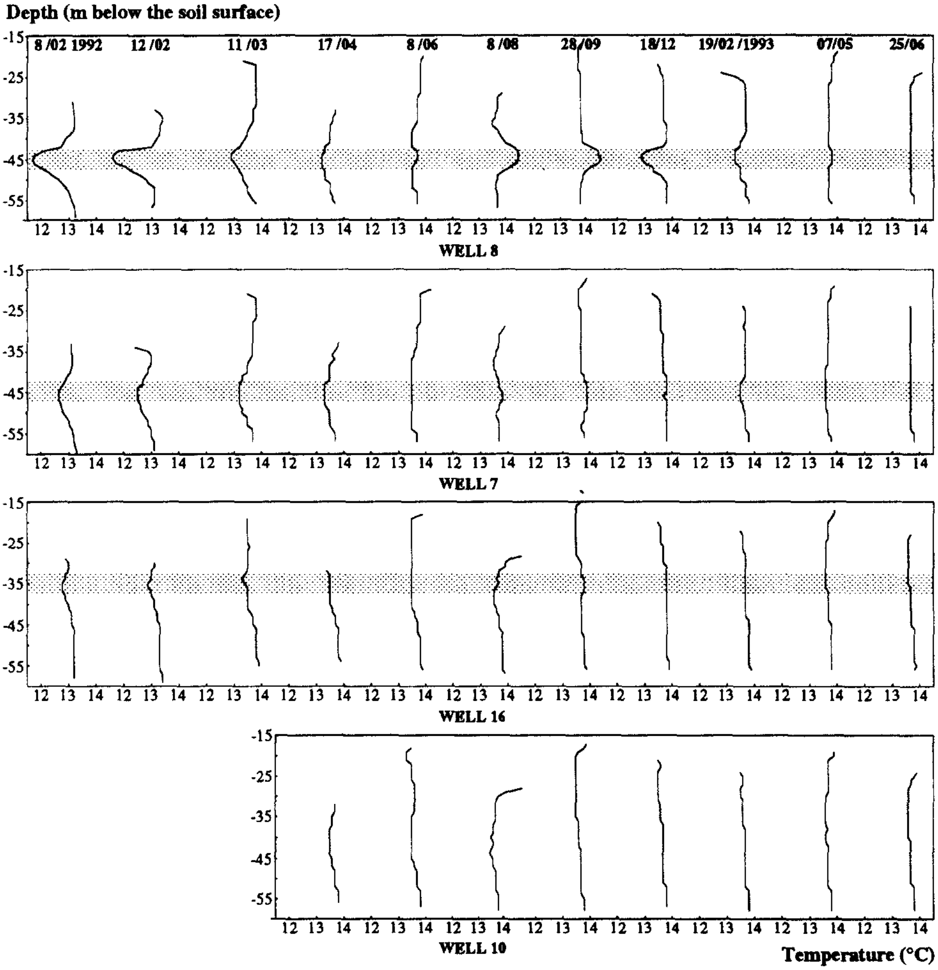


Fig. 5. Thermal profiles measured in Wells W7, W8, W10 and W16 from February 1992 to June 1993. Except on 25 June 1993, temperature measurements were conducted while the stream bed was flooded with sewage effluent.

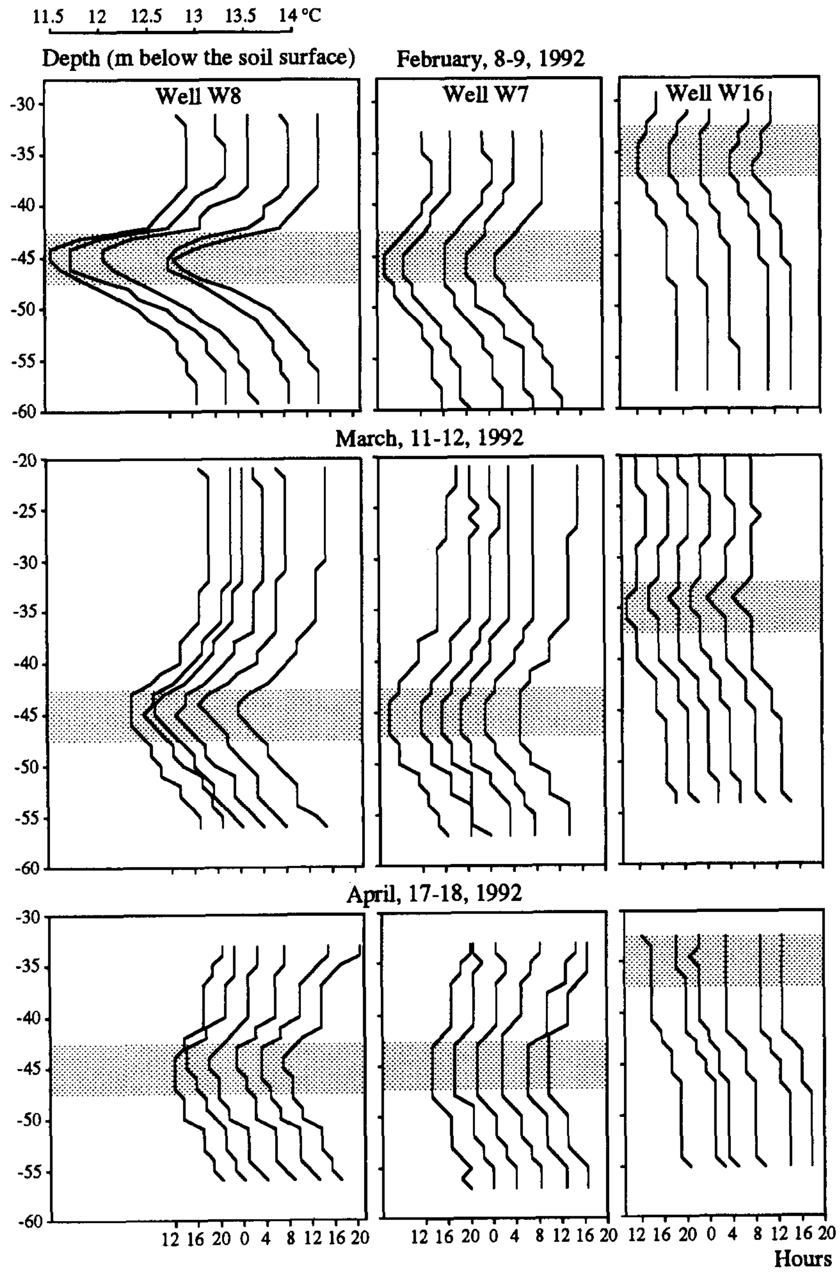


Fig. 6. Thermal profiles measured in Wells W7, W8 and W16 on 8–9 February, 11–12 March and 17–18 April 1992. Temperature scale is the same for each date and profile, but has been displaced to show time. Bottom well temperature 13.2°C on 8–9 February and approximately 13.8°C on 11–12 March and 17–18 April 1992.

3.3. Temporal variability of ground-water temperatures measured in the wells

3.3.1. Daily fluctuation of the ground-water temperature

Temperature profiles measured on 8 February, 11 March and 17 April 1992 in Wells W7, W8 and W16 are shown in Fig. 6. Five temperature logs were recorded on 8 February 1992 and six temperature logs on 11 March and 17 April 1992. The time interval between each log was about 4 h. For the three sampling dates, daily changes in effluent discharge, surface water level (measured by means of a staff gauge installed near the experimental site) and surface water temperature are shown in Fig. 7.

To determine daily ground-water temperature fluctuations, we only considered temperatures measured at depths from 42 to 48 m in Wells W7 and W8, and at depths from 32 to 38 m in Well W16. These depths were selected because they were thought to provide the best approximation of the temperature of the ground water circulating within the fractures (see Fig. 6). For each well and each sampling date, we then calculated the average of differences between temperatures measured about every 4 h at the previously defined depths. Results of calculations for each sampling date showed that with respect to the resolution of the logging instrument (0.1 °C), only three profiles measured on 8 February in Well W8 were different. These profiles, which are shown in Fig. 8, corresponded to those measured at 16:45 h and 21:50 h on 8 February and 13:55 h on 9 February. Considering the depths between 42 and 48 m, a mean decrease of 0.2°C was observed between temperatures measured at 16:45 h and 21:50 h on 8 February and then a mean increase of 0.2°C between temperatures measured at 21:50 h on 8 February and 13:55 h on 9 February.

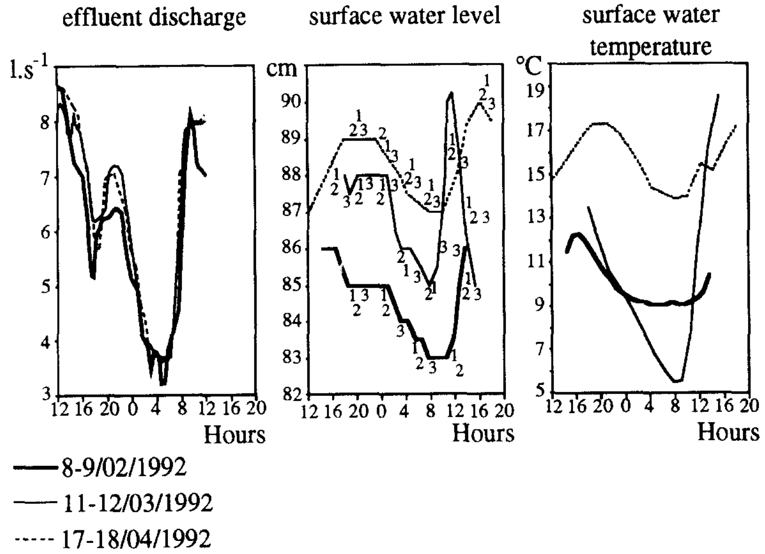


Fig. 7. Effluent discharge, surface water level and temperature recorded on 8–9 February, 11–12 March and 17–18 April 1992. 1, 2 and 3, thermal profiles measured in Wells W8, W7 and W16, respectively.

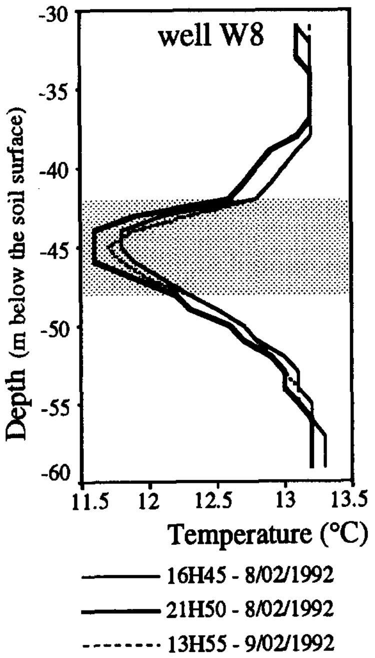


Fig. 8. Evolution of thermal profiles measured in Well W8 on 8–9 February 1992.

3.3.2. Seasonal fluctuations of ground-water temperatures

Clear differences appeared between seasonal changes in ground-water temperatures measured in Wells W7, W8, W10 and W16. Except when the stream was dry on 25 June 1993, profiles of Wells W7 and W8 were always deformed by ground-water temperature inflections at depth of 43 and 45 m (Fig. 5). Three reversals of the bulges in Well W8 and two reversals in Well W7 were observed, but they did not necessarily occur at the same dates. For example, temperature reversals in Well W8 were observed on 8 June 1992 and 7 May 1993, whereas inversion of the bulge in Well W7 only clearly appeared on 8 August 1992 and was not detected on 7 May 1993. In Well W16, whose temperature logs only displayed noticeable and significant breaks in slope or inflections on 8 February, 12 February, 11 March, 8 August and 28 September 1992, only one reversal was observed on 8 August 1992. Finally, profiles of Well W10, which did not show any clear temperature inversion, were only deformed on 17 April, 8 June and 8 August 1992 and then remained very stable with time.

Because of thermal variations with depth, visual comparison of the well profiles presented in Fig. 5 did not allow a full understanding of their respective temporal variabilities. Such a comparison was easier if each profile was reduced to a unique point whose temporal evolution could be perceived through a simple curve. Therefore, for each sampling date, we again calculated for Wells W7, W8 and W16 the average of temperatures measured at the seven previously defined depths: from 42 to 48 m in Wells W7 and W8, and from 32 to 38 m in Well W16. Results of this

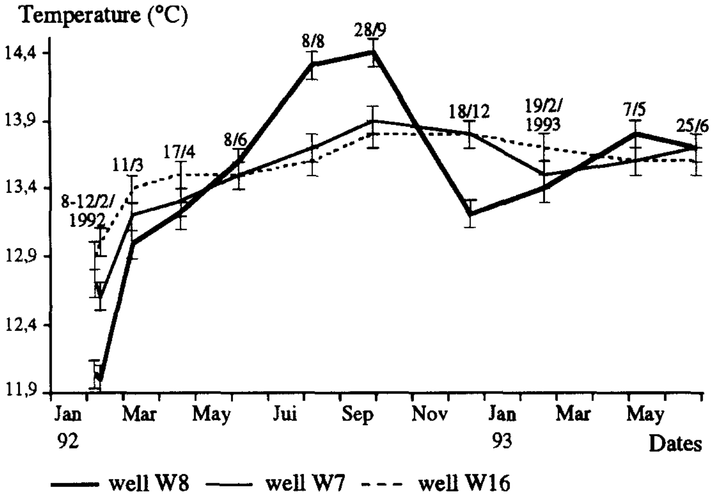


Fig. 9. Temporal changes in average temperature of 11 profiles measured in Wells W7, W8 and W16 from February 1992 to June 1993. Only the temperatures measured at depths from 42 to 48 m in Wells W7 and W8, and at depths from 32 to 38 m in Well W16 were used to calculate the average temperature for each profile.

calculation, which was not made for Well W10 as no major fracture was delineated at a precise depth, are plotted in Fig. 9. It appears clearly that ground-water temperature fluctuates much more in Well W8 than in Wells W7 and W16. In these last two wells, the ground-water temperature deviates markedly from 13.7°C, which is considered

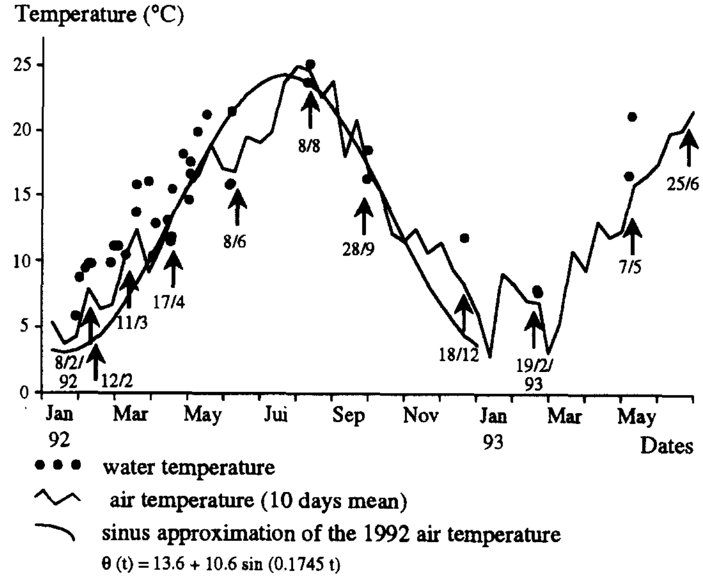


Fig. 10. Fluctuations of the air and surface water temperature recorded from January 1992 to June 1993.

Table 1
Means, standard deviations (SD) and ranges of 12 physico-chemical and bacteriological parameters measured in surface water (SW) and groundwater samples (Wells W7, W8, W10 and W16) collected at the site from March 1992 to June 1993 (nine sampling dates)

	Well	Mean	SD	Range		Well	Mean	SD	Range
Conductivity	SW	902	263	567–1292	NO_{β}^{-}	SW	19.9	40.2	0–128.4
	W7	719	123	527–885		W7	4.0	2.1	0.7–7.1
(μS cm^{-1})	W8	837	222	554–1246	(mg l^{-1})	W8	5.9	3.9	0–12.8
	W10	739	84	580–840		W10	6.3	4.6	2–18.6
	W16	750	115	568–895		W16	6.8	3.6	2–12.4
HCO_3^-	SW	388.7	97.6	234.9–555	SO_4^{2-}	SW	42	12	27–62
	W7	408.4	42.1	356.9–509.4		W7	23	6	14–34
(mg l^{-1})	W8	441.3	83.5	335.5–603.9	(mg l^{-1})	W8	33	11	17–50
	W10	376.5	18.4	335.5–408.7		W10	28	9	14–45
	W16	399.9	37.7	338.6–475.8		W16	31	10	18–52
Ca^{2+}	SW	114.1	9.0	97.8–128.3	PO_4^{2-}	SW	17.7	15.9	0.9–45
	W7	137.8	6.7	125.9–146.3		W7	3.4	4.2	0.7–15
(mg l^{-1})	W8	133.2	11.1	111–148.7	(mg l^{-1})	W8	12.0	11.3	1.2–35
	W10	132.7	3.6	126.3–136.3		W10	2.7	1.6	1.5–6.9
	W16	133.7	7.5	116.6–141.1		W16	4.2	3.4	2.5–13.5
Mg^{2+}	SW	10.5	3.8	5.3–18.2	Cl^-	SW	117	46	45–165
	W7	5.9	1.0	4.1–6.8		W7	60	24	30–90
(mg l^{-1})	W8	8.4	2.2	5.6–12.6	(mg l^{-1})	W8	80.5	43	32.5–132.5
	W10	6.2	0.6	5.3–7.5		W10	76.5	19.5	50–105
	W16	7.1	1.1	5.6–9.2		W16	67	26	37.5–117.5
Oxygen	SW	99	85	1–240	FC	SW	11 000	18 000	0–50 000
	W7	23	15	2–51		W7	620	905	0–2550
(% saturation)	W8	20	18	3–52	(CFU per 100 ml)	W8	6200	11 200	0–35 000
	W10	42	29	11–97		W10	70	110	0–360
	W16	29	18	2–59		W16	700	1250	0–4000
NH_4^+	SW	19.6	27.1	0.5–70.7	FS	SW	31 500	54 000	0–140 000
	W7	3.4	4.7	0.4–15.5		W7	215	175	2–500
(mg l^{-1})	W8	8.4	12.1	0.6–38.6	(CFU per 100 ml)	W8	2190	4600	6–15 000
	W10	1.2	1.2	0.4–4.5		W10	195	170	2–470
	W16	2.5	3.5	0.4–11.6		W16	360	455	6–1550

here as an average temperature for shallow ground water in the region, only on 8 February, 12 February, 11 March and 17 April 1992.

Fig. 10 shows the seasonal evolution of surface water and air temperatures. Although surface water temperature was not monitored continuously, it appears that the stream water temperature closely followed the seasonal fluctuations of air temperature. The comparison of Figs. 9 and 10 shows that the examination alone of the evolution of surface water temperature does not fully explain the changes in ground-water temperature. For example, a major inconsistency appears on 8 and 12 February 1992. Average ground-water temperatures measured on these two sampling dates in Wells W7, W8 and W16 are very low. Surprisingly, such low ground-water temperatures were not detected on 11 March 1992, whereas the surface water temperature and effluent discharge were rather similar to those measured on 8 and 12 February 1992 (see Figs. 2 and 7). Finally, although the evolution of the highly fluctuating temperatures measured in Well W8 was rather similar to that of the surface water temperature, some inconsistencies were also observed. Surface water temperature began to decrease as early as August 1992 whereas the average temperature in Well W8 continued to rise to 28 September 1992. Moreover, it clearly appeared that the amplitude of the temperature reduction in Well W8 late in 1992 and early in 1993 was substantially less than that observed in the surface water.

3.4. Spatial distribution and temporal variability of contaminant concentrations

The means, ranges and standard deviations for 12 parameters measured in the surface water (SW) and the ground water (Wells W7, W8, W10 and W16) during nine sampling surveys carried out from March 1992 to June 1993 are indicated in Table 1. High ground-water average values for parameters such as ammonium, phosphate, chloride, faecal coliforms and faecal streptococci clearly showed that all the wells were contaminated with surface sewage-polluted water.

Results of the between-site PCA performed on the 12 physico-chemical and bacteriological variables measured nine times in 1992–1993 at five sampling points (the surface water and Wells W7, W8, W10 and W16) were used to describe the spatial heterogeneity in contaminant concentrations. Fig. 11, which provides a graphical interpretation of this between-site PCA, shows for the first two components of the analysis (F1 (Factor 1) and F2(Factor 2)) the correlation diagram for the variables (Fig. 11(A)) and the factorial map of samples (Fig. 11(B)). Only the first two components of the analysis were considered because they accounted for a large percentage of the spatial variance in the data matrix (49% for F1 and 25% for F2). The correlation circle shows that there is an opposition between calcium and the other parameters (with the exception of bicarbonate) along F1. F2 is mainly related to bicarbonate. Considering the position of parameters along F1 and F2 of the correlation diagram, the distribution of sampling points on the F1–F2 factorial map shown in Fig. 11(B) can easily be interpreted. As could be expected, ground water and surface water (Wells W7, W8, W10 and W16) plot respectively in the positive and negative region of F1. Surface water is characterised by a lower mean concentration of calcium and higher mean concentrations of contaminants such as phosphate, chloride, faecal coliforms and faecal streptococci, ammonium, nitrate and sulphate (see also Table 1). More interesting is the fact that for the same reasons, Well W8 is clearly separated from Wells W7, W10 and W16 along F1. Well W8 is also separated along F2 as its mean bicarbonate concentration is higher than those measured in Wells W7, W10 and W16 and surface water.

The temporal variability (i.e. the dispersion of sampling dates around the centre of gravity of the different sampling points) of physico-chemical and bacteriological parameters measured in surface water is obviously higher than those of parameters measured in ground water (see also Table 1). Indeed, the surface flow corresponds either to sewage effluent during low-water periods or to water runoff during rainy periods. Once more, it also appears that ground water of Well W8 is different from

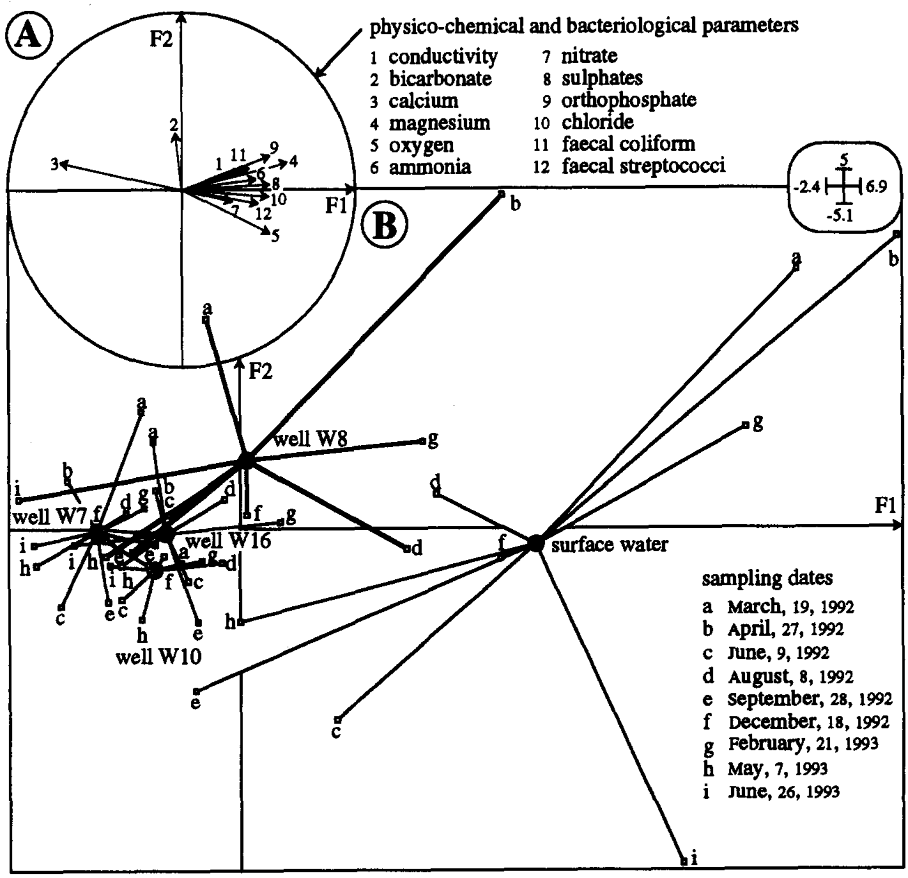


Fig. 11. Graphical interpretation of the first two factors of the between-sites PCA of the table '5 sampling points × 9 sampling dates × 12 physico-chemical and bacteriological parameters'. (A) Correlation diagram for the parameters. (B) F1 × F2 factorial map. Shaded circles identify the centres of classes (surface water and four wells) and letters identify the sampling dates (nine sampling dates from March 1992 to June 1993) plotted as supplementary individuals.

those of Wells W7, W10 and W16, because its physico-chemical and bacteriological characteristics fluctuate more through time.

4. Discussion

4.1. Influence of sewage-polluted surface water on thermal, physico-chemical and bacteriological characteristics of ground water

Girona (1978), Uil (1978), Botton (1984) and Drogue (1985) demonstrated that ground-water flow at the site during low-water periods and without surface water flow at the land surface, was not great enough to induce temperature anomalies at precise depth in the wells. However, two relevant observations were made during these studies which showed the influence of the ground-water flow on the distribution of ground-water temperatures. First, non-linear geothermal gradients observed in some of the wells were thought to be caused by downward or upward flow occurring between intercepted fractured zones under different hydraulic head (Uil, 1978). Second, differences in geothermal gradients of the wells were said to reflect spatial heterogeneity in ground-water flow. Indeed, Drogue (1985) suggested that in the western and more permeable part of the site, where geothermal gradients as low as 1.2°C per 100 m were recorded, a significant part of the heat flux was removed by water circulation.

The same workers reported that negative and positive temperature anomalies observed during high-water periods in some wells of the site were due to the rapid circulation through conductive fractures of cold infiltrating water in winter and warm infiltrating water in summer. However, the origin of the infiltrating water varied from one researcher to another. According to Uil (1978) and Girona (1978), the temperature anomalies might be due in part to the infiltration of the stream water. The same observation was made by Botton (1984), who calculated a correlation coefficient of 0.81 ($n = 9$) between ground-water temperature measured in Well W8 at the water-transmitting fracture depth and the stream water temperature. Botton also showed that downward water flow measured by means of a microflowmeter at depths between 41 and 45 m in Well W8 ceased when the surface stream dried up. In contrast, Drogue (1985) did not mention the presence of the temporary stream at the land surface and considered that temperature anomalies in the wells were exclusively caused by the rapid infiltration and circulation of rain-water.

In the present study, temperature anomalies in Wells W7, W8 and W16 and concave profiles in Well W10 were observed during low-water periods. As there was no other surface water body in the vicinity of the study site, these thermal disturbances were thus entirely due to the infiltration of the sewage-polluted surface water. This observation was corroborated by the fact that high contaminant concentrations were measured in the four study wells. During high-water periods, we also observed thermal disturbances in the four study wells. These thermal disturbances might arise from the infiltration of the sewage-polluted stream water and/or from the rapid circulation of infiltrating rain-water. Indeed, in that particular case, we were not able to differentiate the thermal effect of the rain-water from that of the stream water. However, our results did not show any relevant difference between the magnitudes of temperature anomalies measured during low- and high-water periods (e.g. between 12 February and 11 March 1992) which might indicate a significant thermal effect of the infiltrating rain-water. Finally, although the contribution of the surface stream water to ground-water fluxes in the fractures of the site has so far not been precisely determined, thermal, physico-chemical and bacteriological data collected at least during low-water periods clearly indicated that it could not be neglected.

4.2. Effect of the fracture network properties on the spatial distribution and temporal variability of ground-water temperatures and contaminant concentrations

Spatial heterogeneity of the ground-water temperature observed in 1992–1993 was consistent with the findings of previous studies. For example, Drogue (1985) used thermal data collected in Well W10 to provide a typical example of a temperature profile which had a high geothermal gradient during low-water periods and was not deformed by infiltrating water during high-water periods. In our case, we showed that Well W10 displayed the lowest temperature anomalies when effluent was discharged at the land surface. In the same way, the profile of Well W8 had a low geothermal gradient during low-water periods and displayed high temperature anomalies during high-water periods, which were also highly deformed by the infiltration of sewage-polluted water.

As temperature anomalies in the wells were shown to be caused, at least during low-water periods, by the infiltration of the sewage-polluted stream water, differences in their magnitude and temporal variability between the wells might be used to describe the spatial heterogeneity in the movement of sewage-polluted water through the aquifer. The higher and more fluctuating temperature anomalies recorded in Well W8, as compared with those observed in Wells W7, W10 and W16, effectively showed that the solution-enlarged bedding joint delineated at a depth of 43 m intersected subvertical fractures that are well connected to the surface source of pollution. These interconnected subvertical and subhorizontal conductive fractures, through which cold or warm surface water circulated rapidly enough to be in thermal disequilibrium with the surrounding rock, might thus provide preferential pathways for contaminant transport. In contrast, lower and less fluctuating thermal disturbances recorded in Wells W7, W10 and W16 might indicate lower infiltration rate through a network of small-aperture subvertical fractures. In such a case, the convection has a smaller modifying effect on the temperature distribution because low flow velocity allowed longer contact time between the infiltrating water and the surrounding rock.

Physico-chemical and bacteriological results effectively showed that much of the sewage-polluted water circulated through the conductive fractures of the site. Indeed, ground-water samples collected in Well W8 had by far the highest contaminant concentrations. For example, conductivity of 1246 μS cm^{-1}, and concentrations as high as 35 mg l^{-1} for phosphate and 3.5×10^{-4} CFU per 100 ml for faecal coliforms were measured on 27 April 1992. Ground water in these conductive fractures was also characterised by a high physico-chemical and bacteriological variability. This temporal variability was due to the channelised flow of sewage-polluted water, which induced high contaminant concentrations during low-water periods, and to the flushing effect of the ground water, which induced low contaminant concentrations during the floods. In contrast, ground water circulating through the thin fissures intersected by Wells W7, W10 and W16 had much lower average contaminant concentrations and displayed a greater physico-chemical and bacteriological stability. This might be due to lower infiltration rates and/or to self-purification processes which could occur as a result of low ground-water flow velocities.

4.3. Influence of the unsaturated zone on the temperature of ground water

Changes in ground-water temperature of monitoring wells in response to artificial recharge have been used by many researchers to describe ground-water flow characteristics of porous and fractured aquifers. Keys and Brown (1978) utilised temperature measurements in five auger holes intersecting a sandy aquifer to analyse changes in amplitude and transit time of the diurnal temperature fluctuations of water injected in a well. In a fractured granite site, Flynn et al. (1985) carried out a three-hole recirculation test in which heated water used as a tracer allowed the delineation of water-transmitting fractures zones between boreholes. At two fractured rock sites, Silliman and Robinson (1989) and Robinson et al. (1993) also analysed the thermal response through time of observation boreholes to injection carried out in nearby wells. Their thermal monitoring technique was successful, as it provided direct evidence of fracture flow and interconnectivity between boreholes. In all these short-term experiments, the temperature and the recharge rate of the injected water were perfectly known, as injection was made directly in the saturated zone. In our case, the thermal signature of the surface water could be modified by heat exchange in the heterothermic zone, and clogging of the fissures in the unsaturated zone by sludge particles might also modify the recharge rate.

The effect of the heterothermic zone on the temperature of the infiltrating water was clearly observed when several temperature profiles were measured on 8 February, 11 March and 17 April 1992 (Figs. 5 and 6). These experiments were conducted because we expected to observe, at least in Well W8, some variations of the ground-water temperature which could be then related to the daily fluctuation of the surface water temperature. Indeed, tracer tests carried out in 1988 and 1991 (Critt Verseau, 1988; Gombert and Villeneuve, 1991) showed that the transit time of fluorescein between the stream and Well WC, which intersects the same bedding joint than that delineated in Well W8, was only about 2 h (transit time of 90 min in 1988 and 120 min in 1991). Despite this rapid transit of surface water, our results showed that daily fluctuations for stream water temperature of 3.2°C on 8 February, 13.1°C on 11 March, and 3.4°C on 17 April 1992 were not sufficient to induce significant daily fluctuations of the ground-water temperature.

Even more surprising were the low ground-water temperatures recorded on 17 April 1992 at a depth of 43 m in Well W8 (13.2°C) and at a depth of 45 m in Well W7 (13.3°C). These ground-water temperatures could not be explained on the basis of the surface water temperature, which was found to vary between 13.9 and 17.3°C (average 15.75°C). In that case, we had to admit that temperature of the infiltrating water was modified by heat transfer which occurred in the heterothermic zone. To illustrate this assumption, we calculated the theoretical temperature of the rock vs. depth in the heterothermic zone. The temperature at any depth z at time t in the heterothermic zone, which is influenced by the geothermal flux (1) and the solar flux (2), is given by the equation (Girona, 1978; Uil, 1978; Botton, 1985; Recordon, 1987)

$$\theta(z,t) = \underbrace{(\mathrm{grad}Tz)}_{1} + \underbrace{\theta_o + A_o \exp\left[-z\left(\frac{\pi}{TD}\right)^{1/2}\right] \sin\left[\frac{2\pi}{T}t - z\left(\frac{\pi}{TD}\right)^{1/2}\right]}_{2}$$

where grad$T$ is the geothermal gradient of the well; θ_o is mean temperature at the soil surface found by extending the geothermal gradient to the surface; T is a period equal to 36, as the year was divided into 36 units of 10.16 days; $A_o = (\theta_{p\max} - \theta_{p\min})/2$ is the annual amplitude of the air temperature, where θ_p is the mean temperature for the 10.16 days unit; $D = \frac{K}{\mu C}$, where K is the thermal conductivity of the rock, μ is the density and C is the specific heat.

The calculation was made for 17 April 1992, using the following values: grad$T = 0.0185°\mathrm{C}\mathrm{m}^{-1}$; $\theta_o = 12.65°\mathrm{C}$; $A_o = 10.6°\mathrm{C}$, where $\theta_{p\max}$ (24.9°C) was the mean temperature of the second period of 10.16 days of January 1992 and $\theta_{p\min}$ (3.7°C) the mean temperature of the third period of 10.16 days of July 1992; $K = 6.13 \times 10^{-4}$ kcalm^{-1}s^{-1}°C^{-1} is the mean of the thermal conductivities of four

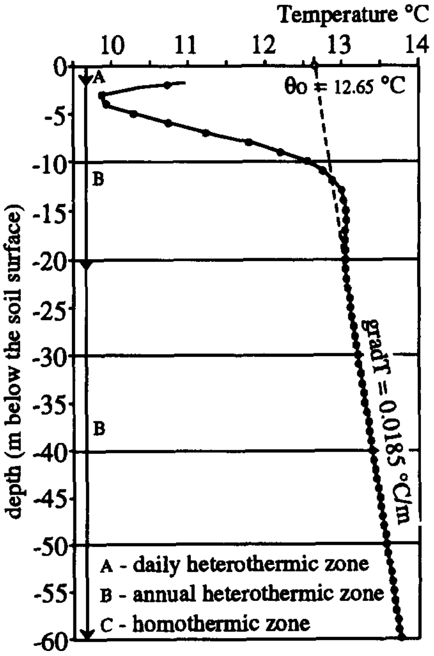


Fig. 12. Theoretical temperature–depth profile in the heterothermic and homothermic zones of the study site. Calculations were made for 17 April 1992.

Berriasian rock samples (two samples were taken at depths of 26 and 37 m in Well WC and two samples were taken at the surface) measured at the Physical Institute of the Earth (IPG) in Paris (Uil, 1978); $\mu = 2300\ \mathrm{kgm}^{-3}$; $C = 0.217\ \mathrm{kcalkg}^{-1}{}^{\circ}\mathrm{C}^{-1}$.

Results are shown in Fig. 12. Calculated temperatures cannot be compared with observed temperatures because no profile was measured while the ground-water level in the wells was high (e.g. in September 1992 and May 1993). However, Girona (1978), Uil (1978) and Botton (1984), who carried out temperature logs during periods of high ground-water level, had already demonstrated that the above equation provided temperatures which matched well those of profiles measured in the heterothermic zone. Moreover, the theoretical profile shown in Fig. 12 explains the low ground-water temperature measured in Wells W7 and W8 on 17 April 1992. In the heterothermic zone, the infiltrating water could effectively cool down by exchanging heat with the rock. This example also shows that the temperature of the infiltrating water might depend mainly on the temperature of the rock in the heterothermic zone rather than on the temperature of the surface water. Although supplementary data are required to confirm this assumption, it would partly explain the absence of daily fluctuations of the ground-water temperature as well as the major inconsistencies between the seasonal evolution of the surface water and ground-water temperatures.

The influence of the unsaturated zone on the infiltration rates of sewage-polluted surface water was suggested from the results of the simultaneous examination of the effluent discharge and surface water level on 8 February, 11 March and 17 April 1992 (see Fig. 7). Although the sewage discharge at the outflow of the treatment plant was rather similar on the three sampling dates, the surface water level rose from 8 February to 17 April 1992. This rise in water level was due to the continuous accumulation of sludge particles on the stream bottom, which also caused the increase in length of the sewage plume from about 800 m in January 1992 to 1500 m in May 1992. Sludge deposits could thus reduce the infiltration rate by clogging the fissures in the superficial layer of the unsaturated zone (epikarstic zone). This clogging process has already been discussed in a previous paper (Malard et al., 1994d), in which we showed that filling of the thin fissures of the unsaturated zone by percolating sludge particles could slow down the vertical movement of faecal bacteria which were then eluted by subsequent rainwater percolation. Differences in the magnitudes of ground-water temperature anomalies measured during periods with similar effluent discharges and stream water temperatures (e.g. 8 February and 11 March 1992) might thus also be due to variations in the quantity of infiltrating water.

5. Conclusions

Michalski (1989) and Keys and Brown (1978), who conducted thermal studies in porous media, have already demonstrated that temperature logging could be a powerful tool for identifying preferential migration pathways of contaminants. More recently, Williams and Conger (1990) presented the results of two case studies, in which temperature, fluid-resistivity, gamma, single-point resistance, caliper and acoustic-televiewer logs were combined to delineate contaminated water-bearing fractures in sandstone and gneiss aquifers.

In a hydrogeological setting as complex as that of a fractured and karstified limestone site, the ground-water flow medium was shown to be characterised by large contrasts in hydraulic conductivity ranging over six orders of magnitude. A clear understanding of the hydraulic features controlling flow and contaminant transport in such a setting often requires the use of sophisticated techniques (pumping tests, tracing experiments). However, we have demonstrated that simple temperature data could be interpreted and related to the ground-water and sewage flow pattern. We considered the spatial distribution and temporal variability of ground-water temperature during periods not influenced and influenced by percolating sewage-polluted water. Disturbances of the temperature profiles, which were caused at least during low-water periods by the infiltration of the stream water, indicated that subvertical fractures intercepted by the wells in the saturated zone were hydraulically connected to the surface stream. Ground-water physico-chemical and bacteriological sampling effectively showed that all the wells were contaminated with sewage-polluted surface water. Differences in the magnitude and temporal variability of temperature anomalies between the wells were then related to the heterogeneous movement of the sewage-polluted water within the aquifer. High and fluctuating temperature anomalies recorded in Well W8 versus low and relatively balanced thermal disturbances recorded in Wells W7, W10 and W16 suggested that the sewage-polluted water flow in the saturated zone occurred preferentially through the solution-enlarged parts of a bedding joint. Ground water in this conductive opening also had the highest average contaminant concentrations and a low physico-chemical and bacteriological stability. Limitations of the thermal approach were: (1) the low resolution of the logging equipment; (2) the modification of the thermal signature of the surface water by heat exchange in the heterothermic zone; (3) changes through time of the infiltration rate of surface water caused by clogging of the fissures in the superficial layer of the unsaturated zone. It was thus very difficult to find a clear relationship between the evolution of surface water and ground-water temperatures. Despite these major limitations, and although each site is unique, we believe that the method used in this study is applicable to other sites and may provide an effective basis for further surveys, by helping to delineate the preferential ground-water and associated contaminant flow pathways. In our case, temperature logging was even a more efficient investigation tool than fluid-conductivity logging, which could not be used without prior pumping because of sewage accumulation in the wells.

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