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Transport of suspended solids from a karstic to an alluvial aquifer: the role of the karst/alluvium interface

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Abstract

This study focuses on the coupled transport of dissolved constituents and particulates, from their infiltration on a karst plateau to their discharge from a karst spring and their arrival at a well in an alluvial plain. Particulate markers were identified and the transport of solids was characterised in situ in porous and karstic media, based on particle size analyses, SEM, and traces. Transport from the sinkhole to the spring appeared to be dominated by flow through karst: particulate transport was apparently conservative between the two sites, and there was little difference in the overall character of the particle size distribution of the particulates infiltrating the sinkhole and of those discharging from the spring. Qualitatively, the mineralogy of the infiltrating and discharging material was similar, although at the spring an autochthonous contribution from the aquifer was noted (chalk particles eroded from the parent rock by weathering). In contrast, transport between the spring and the well appears to be affected by the overlying alluvium: particles in the water from the well, showed evidence of considerable size-sorting. Additionally, SEM images of the well samples showed the presence of particles originating from the overlying alluvial system; these particles were not found in samples from the sinkhole or the spring. The differences between the particulates discharging from the spring and the well indicate that the water pumped from the alluvial plain is coming from the karst aquifer via the very transmissive, complex geologic interface between the underlying chalk formation and the gravel at the base of the overlying alluvial system. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Geologic interface; Alluvium; Karst; Turbidity; Particle transport; Size distribution; Contaminant vector

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1. Introduction

Suspended sediment plays an important role in the contamination of karst aquifers and potable water because of the ability of bacteria to sorb onto particulates. Several studies have demonstrated the increased survival of microorganisms when they are associated with particulates (Pommepuy et al., 1992); particulates are thus potential vectors of microbial contamination. The transport of particulates and the associated risks to public health in areas where drinking water comes from karst aquifers has come under scrutiny over the last several years.

Suspended material can be separated into two groups: colloids (less than 1 μm in diameter) and particles (from several to tens of microns in diameter). More attention has been paid to colloids than larger particulate material, as colloids are mobile in porous media (e.g. Kretzschmar et al., 1997; Niehren and Kinzelbach, 1998; Noell et al., 1998; Van de Weerd and Leijnse, 1997) and their large specific surface area

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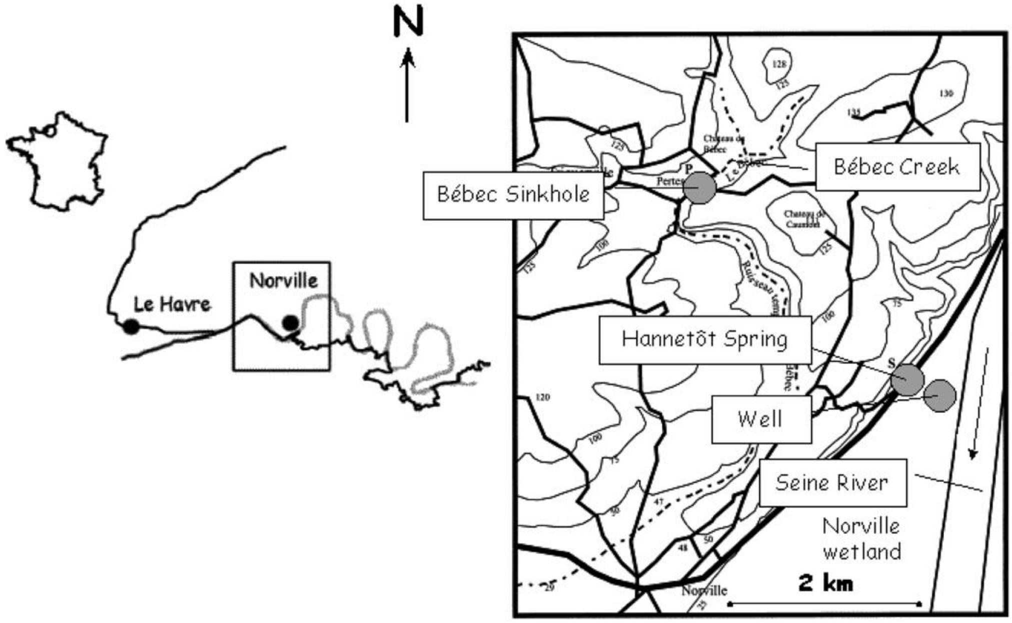


Fig. 1. Location of the study site and the three sampling points.

gives them a high capacity for adsorption of pollutants. In karst media, however, particles ranging from microns to many tens of millimetres or even larger may be mobile (e.g. Mahler and Lynch, 1999; White, 1988). Their large size enables bacteria and other microorganisms to attach to them. Atteia and Kozel (1997) demonstrated the difference between the transport characteristics of colloids and particles through the investigation of changes in particle size distributions at a karst spring: the size distribution of the colloid fraction was a function of the chemistry of the water infiltrating the karst, whereas the size distribution of the particles was a function of the hydrodynamic conditions. Colloids have a negligible settling velocity, whereas particulates are more likely to settle, and thus present the possibilities of storage and subsequent resuspension in karst media. In highly transmissive porous media, their large size may cause blockage under some hydrologic conditions and release under others. Particles may thus be involved in clogging processes in porous media whereas it is not the case with colloidal matters.

A better understanding of the risk to public health associated with suspended material requires two approaches: (1) the rigorous study of the physical transport, with physico–chemical analyses of the suspended material at the entrance and exit of the system; and (2) a better understanding of the chemistry of the fixation of microorganisms and other contaminants on the particles. The first aspect is most often investigated through the use of column experiments (Kretzschmar et al., 1997; Niehren and Kinzelbach, 1998). The tracing of tagged particles has also been undertaken, notably by Mahler et al. (1998a,b). Currently, the in situ methodologies most frequently used are based on geochemistry (Mahler and Lynch, 1999; Mahler et al., 1999; Vaute et al., 1997; Wicks and Engeln, 1997), but analysis of particle size distribution has also been shown to be useful (Lacroix et al., 1998, 2000b).

Another phenomenon to be considered when studying particle transport through karst aquifers is the storage properties of such media (i.e. the emptying and filling of karst with sediment). This aspect was investigated by Mahler and Lynch (1999) at Barton Springs, Texas, and in Haute-Normandie by Coquerel et al. (1993), Rodet (1991, 1993, 1996) and Lacroix et al. (1998). Intra-karstic sedimentation results from a decrease in flow competence: this phenomenon usually appears as flow paths widen in the karstic network (e.g. from small conduits to zones such as large cavities or conduits). The decrease in velocity allows the larger particles to decant—the resulting size-sorting during transport is a function of the degree of complexity of the karst network. This phenomenon results in non-conservative transport from the point of view of particle size distribution. These particles may later be resuspended and transported by subsequent high competence flow events.

Mobile sediment in karst is characterised by an autochthonous (chemical alteration of the chalk/limestone aquifer) and an allochthonous portion (introduction into the aquifer of products of surface erosion). The proportions of these two contributions are variable. The approach most often used to differentiate between these two sources relies on investigation of the inorganic and organic geochemistry of the particles (Albéric, 1998; Mahler and Lynch, 1999; Mahler et al., 1999).

In Haute-Normandie, where virtually 100% of the groundwater resources are in karst, suspended particulates have a non-negligible influence on public health (Beaudeau et al., 1999). At karst springs, the problem is generally correlated with high turbidity associated with periods of heavy rainfall. Wells drilled into the karst underlying the alluvial plain of the Seine, although cased through the alluvium and screened in the karst, are much less prone to turbid episodes and bacterial contamination.

Here we present the results of a study investigating the role played by the karstified chalk–alluvium interface on water quality and evaluate the respective influences of each medium on the transport of suspended particulates. Data were collected from the limits (entrance and exit) of the karst system and from a nearby well located in the alluvial plain.

2. Study site

The study site (Fig. 1), located in Haute-Normandie (France) near the town of Norville, is characteristic of many public drinking water sources in the region that are affected by turbidity. The system is composed of a sinkhole, a spring, and a well.

The sinkhole is the point of infiltration of Bébec Creek, which flows across the Pays de Caux plateau, draining a small watershed of about 10 km^2. Land use in the watershed consists of cultivation and grazing. The elevation of the plateau averages about 100 m. Soils on the plateau, consisting of silts approximately 10 m thick, are highly susceptible to crusting, compaction, and erosion, particularly during autumn and winter sowing. Discharge in Bébec Creek is variable, from 3 l s^{-1} in summer dry periods to 15 l s^{-1} in winter, and close to 500 l s^{-1} in response to major winter storms. Water from the Creek recharges the chalk aquifer via a sinkhole. When the discharge exceeds the infiltration capacity of the sinkhole (‘saturation’), the Creek overflows its banks and floods the valley. During periods of high flow the water in Bébec Creek is very turbid, up to 2000 NTU.

Hannetôt Spring discharges from the foot of a karstified chalk cliff. After storms, the turbidity of the water discharging from the spring can exceed 600 NTU. In the past, Hannetôt Spring water supply, but drinking water is now obtained from a well drilled 130 m away in the alluvial plain. The borehole is cased through the overlying alluvium and screened where it intercepts the chalk.

2.1. Geology

The topography of Haute-Normandie is characterised by moderate relief (<300 m). North of the Seine River, the Pays de Caux plateau is incised by a hydrographic network made up of a few larger valleys with perennial streams and numerous smaller dry valleys. The karstic chalk plateaus of Haute-Normandie form part of the western edge of the Paris Basin and are composed of strata that slope gently (<10°) to the east. The overall structure is characterised by a series of lineaments oriented N135 that divide the substrata into different compartments. The geologic medium is almost exclusively chalk relatively rich in chert, dating from the Cenomanien to the Campanien. Jurassic and lower Cretaceous calcareous marls and clays outcrop along anticlines.

Thick surficial formations cover the karstified chalk plateaus. The major formation is composed of a red clayey-silty-sand (RS) composed of the residue from the alteration of the chalk, tertiary sands, and reworked ancient loess (Laignel, 1997). The thickness ranges from 5 to 10 m, and on the Pays de Caux

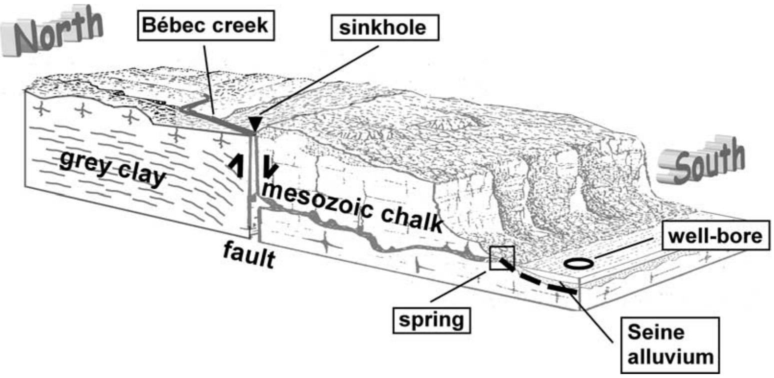


Fig. 2. 3D geomorphologic diagram of the Norville karst/alluvial system.

plateau is of plioquaternary age (Antoine et al., 1998). Quaternary quartz silts overlay this formation.

The alluvium of the lower Seine River and its tributaries is made up of periglacial bottom gravels overlain by fine Holocene deposits (Lefebvre et al., 1993). Along the axis of the Seine Valley approximately 15 m of alluvium cover the Mesozoic substratum, with the thickness increasing up to 35 m in the estuary.

2.2. Hydrogeology

The two major aquifers of the region are the Seine alluvium and the Cretaceous chalk. The alluvium consists of two strata with contrasting characteristics. The basal gravel is very permeable (hydraulic conductivity of 2×10^{-3}m s^{-1} at the study site). The overlying fine material (silts, clays, and compacted peat) is semi-permeable to impermeable, so that in some places the aquifer is confined. The Seine River and its alluvial drainage are thus, in some places, disconnected (Lefebvre et al., 1993).

Groundwater moves from the uplands of the chalk aquifer toward the valleys in two ways: rapid drainage through the karstic network, and a slower drainage through the microfissured porosity. Discharge occurs both through springs at the feet of chalk cliffs and through the porous alluvial aquifer of the Seine valley. This geomorphologic situation (Fig. 2) is aptly represented at Hannetôt Spring, which is located at the interface between the Seine alluvium and the karstic chalk. In the Seine Valley, the soil is made up of fine, little-altered alluvium. A permanent unconfined alluvial aquifer drains the surrounding countryside, where grain is intensively cultivated.

The well of interest penetrates fine clayey sand and basal alluvial gravel before encountering the chalk at 18.3 m depth. Altered chalk is found from 18.3 to 23.7 m. Six tons of acid were injected during development of the well, increasing the connectivity between the upper altered part of the chalk and the alluvium.

3. Materials and sampling methods

Data from the three sites (sinkhole, spring, and well) were collected continuously and samples were collected during responses to rain events. The sinkhole and the spring were equipped with datasonds (YSI 6820) for the measurement of turbidity, conductivity, and temperature. Data was collected on a 15 min interval. The turbidity sonds were calibrated in the laboratory with a Hach turbidimeter–nephelometer as a reference. Discharge was determined in Bébec Creek at the entrance to the sinkhole and at Hannetôt Spring to allow calculation of fluxes of tracer and particulates, using ISCO 4150 Doppler flow meters to perform flow measurements every 15 min.

Samples were collected with autosamplers (ISCO 6700s at the sinkhole and the spring, and an ISCO 3700 at the well). Samples collected in response to rain events were filtered through pre-weighed Millipore filters (0.45 μm pore-size), and the resulting concentrations correlated to the measured turbidities.

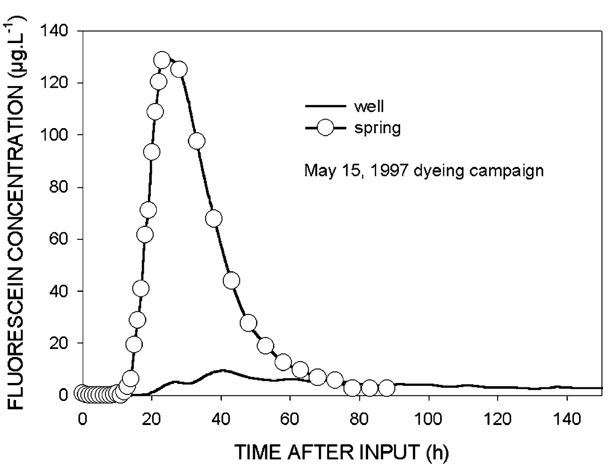


Fig. 3. Fluorescein breakthrough curves at the spring and well (May 1997 dye traces). Fluorescein was injected the 14th at 5:30 PM.

The grain-size distributions were determined with a Coulter Multisizer particle counter, using a 100 μm aperture. Filtered particulate material was identified by SEM (Au–Pd coating, secondary electrons-based method, voltage of 20 kV). The investigation thus consisted of both a quantitative and qualitative comparison of the particulate material introduced into the sinkhole and that discharging from the spring.

4. Results

4.1. In situ tracer tests

The apparent transport velocity at the study site was measured by tracer test (Lacroix et al., 2000a). The velocity from the sinkhole in Bébec Creek to Hannetôt Spring varied depending on hydrogeologic conditions from 75 to 125 m h^{-1} (total transport time 17 to 30 h), following several other dye tracings already performed on the site. This velocity is fairly low for karstic terrains, where subsurface velocities often exceed 200 m h^{-1}.

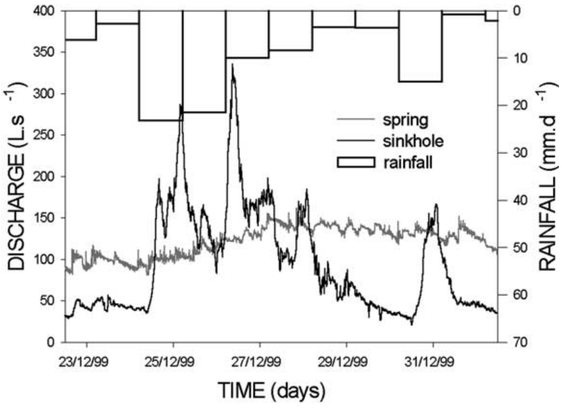


Fig. 4. Discharge measured at the sinkhole and spring and associated precipitation during the sampling period.

The recovery rates (percentage of mass recovered) of fluorescein at the spring were calculated by integrating the flux over the duration of the recovery. The recovery rate approached 90% for traces carried out during periods of low water level. The lag in arrival of the fluorescein at the well in relation to that at the spring varied from 6 to 10 h, yielding an apparent velocity between the two of 22 m h^{-1} for the tracer test carried out in May 1997 (Fig. 3). The fluorescent signal received at the well was much weaker than that at the spring. The ratio of the maximum concentrations at the well (w) and the spring (s), $C\mathrm{w}_{\max}/C\mathrm{s}_{\max}$, was 14% during low water periods and 3% in high water periods.

4.2. Turbidity associated with two rain events

During two consecutive rain events, on December 24 and 25, 1999, (23.2 and 21.4 mm d^{-1}, respectively), the increase in discharge at the spring indicates an increase in the overall drainage of the chalk aquifer resulting from changing piezometric level. The discharge before rainfall was just over 80 l s^{-1},

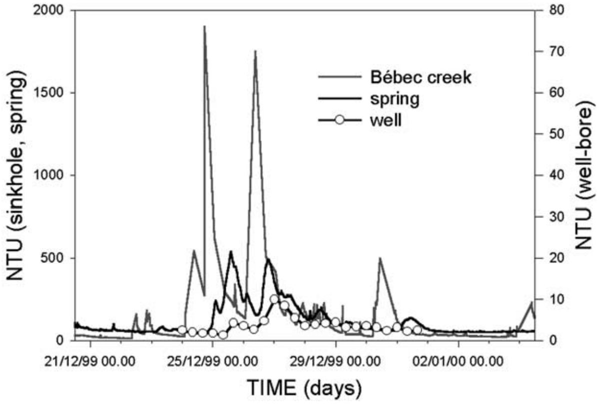
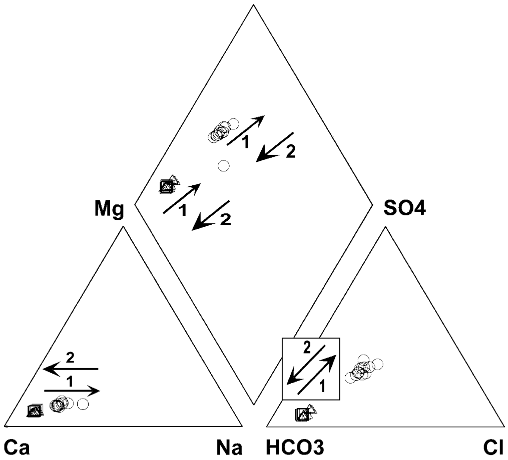


Fig. 5. Turbidity in response to rainfall at the sinkhole, spring, and well.

and increased following rainfall to almost 140 l s^{-1}. Because of the concentration of the runoff from the whole watershed, the discharge in Bébec Creek increased even more dramatically from 40 to 300 l s^{-1} (Fig. 4).

During the December 1999 storm events, the maximum turbidity at the three sites was 2000 NTU at the sinkhole, 500 NTU at the spring, and 10 NTU at the well. The baseline turbidity (i.e. when not affected by rain events) is 5–10 NTU at the spring and between 0 and 0.1 at the well. We focus our analysis on the second phase of infiltration, for which the response at the well was sharper. The turbid response at the spring was directly correlated to the turbidity of the water infiltrating via the sinkhole. The apparent dilution observed for the peak turbidity at the spring was about 65%. The lag in time of first appearance was of the same order of magnitude as those seen during the tracer tests (Fig. 5). At the well, the lag in turbidity response in relation to that at the spring was between 4.5 and 12.5 h. The uncertainty is due to an 8 h sampling interval at the well. The turbidity measured at the well was 50 times more dilute (maximum of 10 NTU) than that at the spring.



1 : shifting of water composition to max dilution
2 : back to initial water composition

Fig. 6. Piper diagram illustrating the chemical facies of infiltrating and discharging waters (Bébec creek: ○; spring: △; well bore: □).

Measurements of total suspended sediment and discharge permitted the calculation of the total mass of particulate transported in Bébec Creek and the total mass discharging from the spring for the two rain events. Computation of the mass recovered at the spring is straightforward, yielding 1.84×10^4 kg of sediment. Computation of the mass entering the sinkhole is more complicated, because during the rainfall response the maximum infiltration capacity of the sinkhole was exceeded and Bébec Creek overflowed its banks. The mass transported by the Creek was 4.48×10^4 kg of sediment, but because the entire mass did not infiltrate into the aquifer, the apparent recovery rate of 41.3% is an underestimate. Measurements of the overflow have been performed in a channel leaving the sinkhole. Thus, a correction of the infiltrated mass could be realised, and the corresponding recovery rate was 58%.

Table 1
Mean concentrations of major elements in waters for Bébec creek, spring and well bore

Mean concentration (mg/l)							
	Na^+	K^+	Mg^{2+}	Ca^{2+}	Cl^-	SO_4^{2-}	HCO_3^-
Bébec creek	7.8	5.2	2.6	27.9	17.5	25.9	54.5
Spring	9.1	4.4	3.9	75.5	19.0	11.7	198.3
Well-bore	10.6	2.8	5.5	93.3	21.1	15.1	253.7

4.3. Geochemical

Samples taken at each location (sinkhole, spring, and well) during the storm period provided data on water composition. Fig. 6 illustrates the chemical facies of the waters at the sinkhole, spring, and well. At steady state, the Bébec Creek waters are calcium bicarbonate. Within the storm period, dilution of the waters of the Creek by rainwater causes the evolution of the facies towards the sodium facies. Hydrochemical facies at spring and well are fairly the same, that is, calcium bicarbonate. The mean compositions of the waters at the three locations are summarised in Table 1. At the maximum of the flood, spring waters are diluted with surface waters, resulting in a shift towards the Bébec Creek hydrochemical facies (Fig. 6). This dilution phenomenon at the spring is also shown by the evolution of the electric conductivity during the flood (Fig. 7): the decreasing conductivity corresponds to the arrival at the spring of the less mineralised surface waters.

Suspended solids were collected at the sinkhole and at the spring tanks to sediment traps that were filled during the storm. The mass of suspended sediment at the well was not sufficient for particulate chemical analysis. Chemical analyses of major elements on particulate (Table 2) showed that suspended sediment entering the karst are of silt-type (Fig. 8a and b), as well as those discharging from the spring, although one could notice a slight enrichment in SiO_2 at the spring. Major ions analysis underlines a difference in calcium concentration between infiltrating and discharging sediment: the results provided 0.5% of CaO for the infiltrating sediment and 4% for those discharging at the spring.

4.4. SEM observations

Observation of the character of the particles by SEM suggests a marked difference between those found at the well compared to those entering the sinkhole and those discharging from the spring. In particular, particles of biologic origin are present in the well, and may act as good ‘markers’.

At the sinkhole, the particulates consist of algae, quartz grains varying in size from 8 to 30 μm, and organic-mineral flocs of about 10 μm in diameter (Fig. 9a and b). This eroded material is introduced

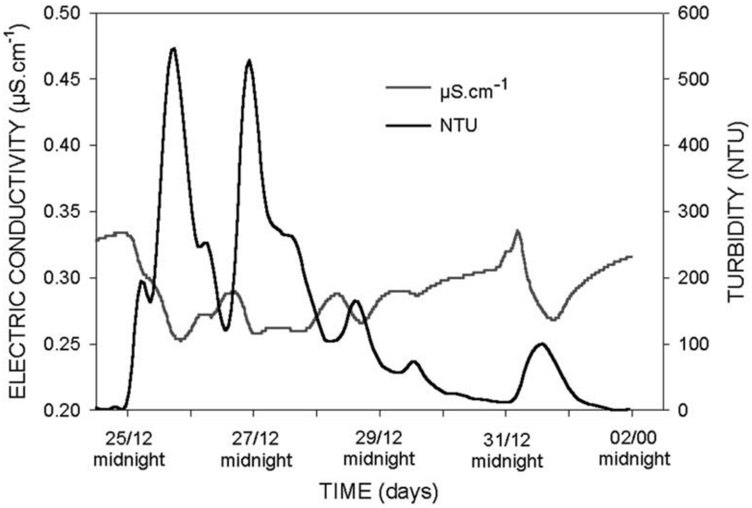


Fig. 7. Evolution of the electric conductivity (arrival of surface water) compared to turbidity breakthrough at the spring.

Table 2
Chemical analysis of the infiltrating and of the discharging sediments. Major elements are expressed in percentage of the total mass of sediment. Chalk (insoluble fraction), silts, and RS (residue from the alteration of the chalk) were sampled at various locations on the plateaus of Pays de Caux and are representative of the global sedimentary trends of the region (Laignel, 1997)

	Concentration (% mass)								
	SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	TiO_2	MgO	CaO	MnO
Infiltrating sediment (Bébec creek)	76.68	8.36	3.40	1.86	0.93	0.73	0.67	0.50	0.04
Discharging sediment (spring)	83.52	3.48	1.09	1.21	0.81	0.62	0.35	4.00	0.03
Silt (plateaus quaternary deposits)	75.10	8.22	3.04	1.64	0.89	0.60	0.74	3.03	0.05
Chalk insoluble fraction	61.75	19.26	6.18	3.56	0.78	1.03	6.91		0.55
RS matrix (chalk alteration residue)	53.02	21.78	8.34	0.87	0.10	0.62	0.59	0.72	0.03

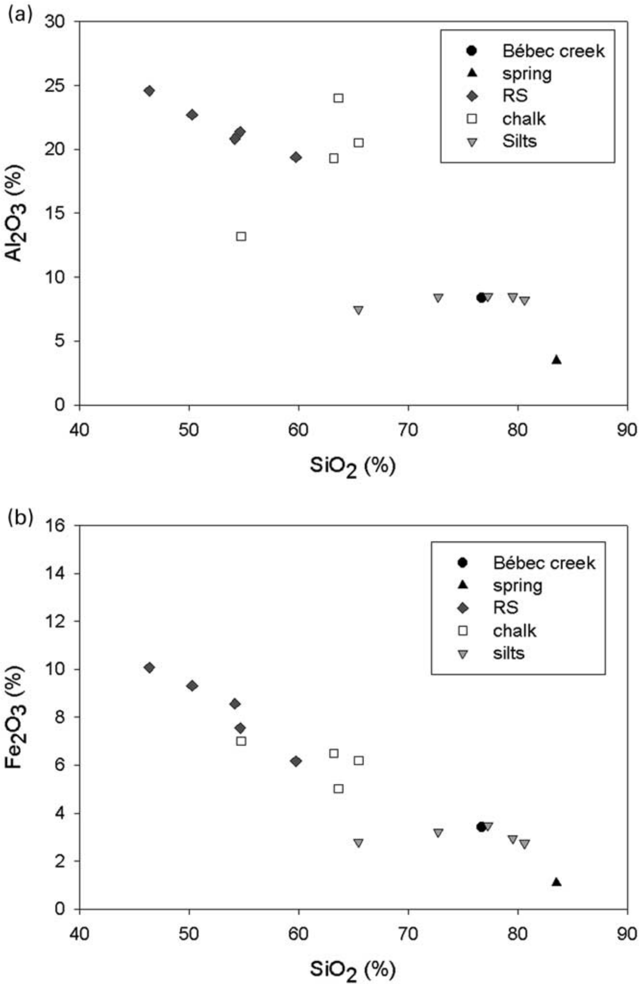


Fig. 8. Chemical analysis of infiltrating and discharging sediment. SiO_2 was plotted versus Al_2O_3 (a) and Fe_2O_3 (b), successively. This representation clearly illustrates clay versus quartz abundance in sediments of the Pays de Caux, as demonstrated by Laignel (1997).

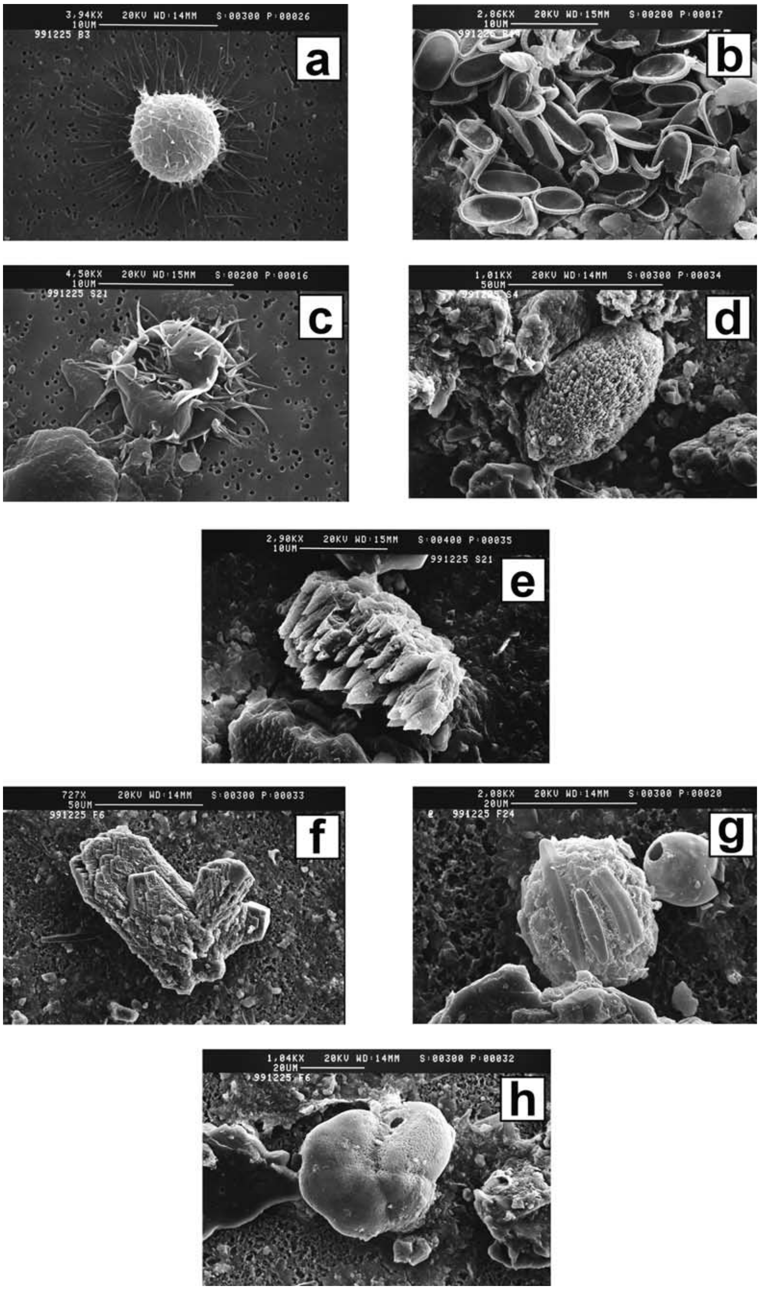


Fig. 9. Scanning electron micrographs of particulates from the sinkhole (a, b), spring (c, d, e), and well (f, g, h).

into the aquifer via the sinkhole and serves as a reference to which the material discharging from the spring and obtained from the well can be compared.

At the spring, particle size is equally variable. Rounded quartz grains of 10–15 μm originating from overlying silts are predominant. Also found is algal material, which may come from phytoplanktonic production in the surface water of Bébec Creek (Fig. 9c). Other particulates are the result of the mechanical erosion of the chalk massif (ex: nannoconus, Fig. 9d)

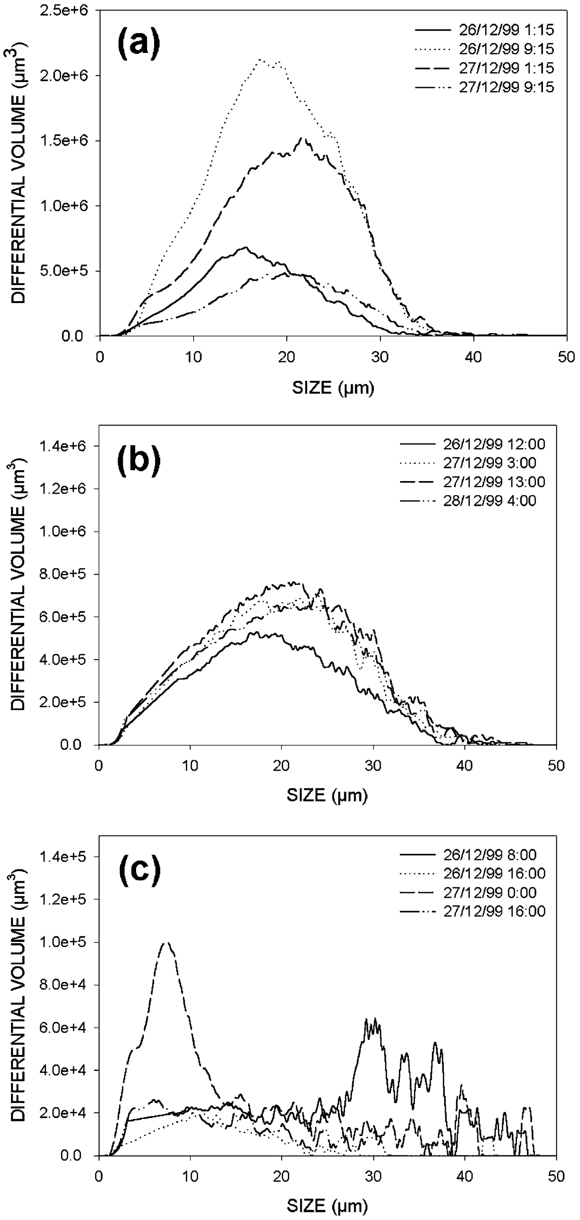


Fig. 10. Evolution of the particle size distribution over the course of the response to the December 25, 1999, rain event. The response at the spring (b) is strongly correlated to the input at the sinkhole (a) with regard to the particle size. On the other hand, the response at the well (c) shows clear evidence of size-sorting.

and dissolution structures (Fig. 9e) coming from the chemical alteration of the chalk.

At the well, the particulate material is heterogeneous without a dominant fraction. Small amounts of the same types of particles found at the spring are present as well as quartz grains with the same size (10 μm) as those found in the spring. Particulates originating from the chalk massif, however, are virtually absent. Crystalline carbonates are present (Fig. 9f), as well as other types of particles not found at either the sinkhole or the spring: diatoms of the group *Melosira* (equivalent spherical diameter of 6 μm) integrated in aggregates of 20 μm (Fig. 9g) and Foraminifera tests (20 μm) (Fig. 9h) are similar to those found in Holocene deposits.

4.5. Particle size distribution of suspended solids

Fig. 10a–c show the grain-size distributions of the samples collected during the second episode of turbidity. Grain-size distributions at the sinkhole and the source evolve similarly, with the larger particles becoming increasingly prevalent during the recovery, evidence of a strong connection between these two locations. The grain-size distributions seen at the well are very different. The sample collected at the beginning of the recovery (December 26, 8:00) contains a relatively large portion of large particles, but by the time that turbidity reaches a maximum (December 27, 0:00) the population of small-size particles (2–12 μm) dominates.

5. Discussion

Discharge from the well in the Norville alluvial plain may reach values as high as 180 $m^3 h^{-1}$ without showing any evidence of turbidity or bacterial contamination. The difference between the bacterial water quality at the spring and the well is largely a factor of their different hydrogeological settings. Despite the fact that the screened interval of the well is in the same chalk aquifer from which the spring emerges, turbidity at the well in response to rain events is much lower than that at the spring. The difference in size distribution of the particles discharging from the spring and the well suggests that the mode of transport from the sinkhole to the spring and from the sinkhole to the well is different. SEM photomicrographs of the particulates were consistent with this hypothesis. The lack of turbidity implies that the water must not be moving through a karst conduit, but rather that the water is being drawn

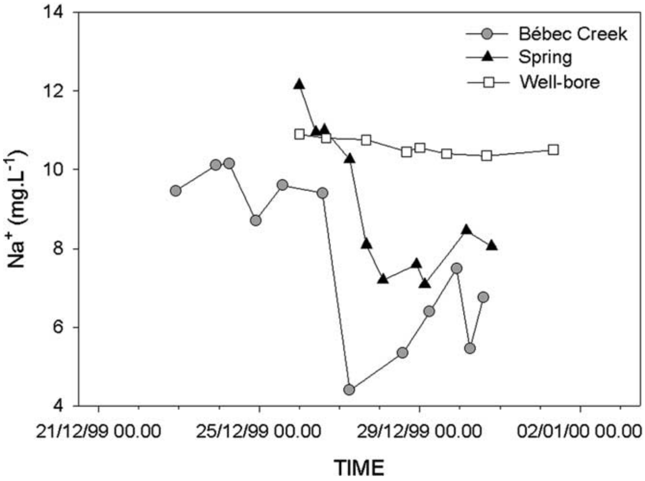


Fig. 11. Evolution of sodium concentration (as dissolved conservative tracer) with time at Bébec creek, spring and well.

from a highly transmissive layer, based on the limited drawdown induced by pumping (<3 m). Transport from the spring to the well would occur along the interface between the fissured chalk and the basal gravels of the overlying alluvium.

The several tracer tests carried out at the site clearly indicate continuity of the hydrologic system from the sinkhole to the spring to the well. Moreover, although the peak turbidity observed at the well is extremely low compared to that observed at the spring, it still demonstrates continuity in the transport of particles from the sinkhole. The similarity between the lag times for arrival of the peak of both the tracer and turbidity at the spring and at the well suggests that the particulates are following the same pathway as the tracer, which in turn implies that their source is the same: the Bébec sinkhole. The substantial difference in the peak concentrations of turbidity between the spring and the well indicates that either there is a large amount of dilution or dispersion, or that particles are trapped in the aquifer between the well and the sinkhole.

Hydrochemistry demonstrates that the waters of the spring are really close to those of the well bore, that is, typical calcium bicarbonate facies. Yet, at the peak discharge spring water facies shifts towards the Bébec Creek water facies due to increasing dilution. The PHREEQC mixing function provided by the AquaChem software (Waterloo Hydrogeologic) was used for dilution rate estimation. The geochemical inverse modelling was realised regarding to conservative dissolved species such as sodium and chloride. As an example, one can notice in Fig. 11 the similar trends in the evolution of sodium during the sampling period at each location. The inverse modelling consists in computing the dilution rate between two pre-determined solutions in order to obtain a third optimised solution that matches best a previously known sample. We attempted to estimate the contribution of the waters of Bébec Creek to the waters of the spring at the peak discharge. For the calculation, the two initial solutions were (i) a sample taken at the spring before the flood (steady state, i.e. karst water), (ii) a sample corresponding to the peak discharge at Bébec Creek. These two samples were mixed so as to provide an optimised solution that matched the water chemistry at the spring at the peak turbidity (maximum dilution in Fig. 11). The result was 60% of karst water at the peak turbidity, that is, close to the apparent dilution based on turbidity (65%). This would suggest similar transport behaviour for both suspended sediment and dissolved species. Following these results, it would appear that nearly 40% of the infiltrated mass (calculated recovery rate of 58%) does not reach the spring. At the well, application of the same process gave an 8% contribution of Bébec Creek waters. Apparent dilution calculated based on tracer tests was of the same order of magnitude (3–14%). The apparent dilution obtained from turbidity is 99.5%, that is, only 0.5% of the infiltrated mass of suspended solids would be recovered at the well. Assuming that virtually 10% of the waters of the Creek reach the well, one could expect a lower apparent dilution ratio (i.e. higher suspended solids concentration) for particles than the calculated one (0.5%). Suspended particles would consequently have been trapped into the aquifer.

Chemical analyses of the suspended sediments demonstrate that material discharging at the spring as well as Bébec Creek suspended matters are of silt-type, which is characteristic of the plateaus erosion. The observed SiO_2 slight enrichment at the spring may correspond to intra-karstic (autochtonous) resuspended sediment. Actually, quartz minerals are more expected to settle in head-loss zones of the aquifer, and may be resuspended owing to high water flow. Yet, this last phenomenon should not be so marked in this case, as electrical conductivity evolution shows that arrival of surface waters coincide with turbidity occurrence. The CaO enrichment for sediments sampled at the spring is related to the occurrence in the samples of carbonated dissolution structures (Fig. 9e). Nevertheless, chemical analyses demonstrate that the contribution of Ca-rich particles originating from the chalk to the total mass of sediment is fairly low (4%).

Following these results, it appears that both suspended sediments entering the aquifer and discharging at the spring are of silt-type, that is, originating from the erosion of the Bébec Creek watershed.

The absence of any change in the particle size distribution between the sinkhole and the spring indicates conservative transport with respect to the particle size distribution as far as the texture of the material is concerned, without any size-sorting imposed by the karstic network. Deposition is usually associated with size-sorting by settling, which was not observed in the comparison of the particle size distributions. This suggests that transport is via a principal conduit leading directly from sinkhole to spring, rather than via complex system. These results are consistent with those of the tracer tests and turbidity data. It is likely that only part of the material introduced into the aquifer via the sinkhole discharges from the spring, because of the continuity of the chalk aquifer underneath the Seine alluvium.

The modification in particle size distribution undergone between the sinkhole and the well indicates deposition or trapping: recovery at the well is not conservative with regard to particle transport. The evolution in particle size of the particles discharging from the well over the breakthrough curve indicates size-sorting, which is not observed between the sinkhole and the spring. This suggests that the transport of the particles to the well is fairly different than the transport between the sinkhole and the spring.

The material observed in the Bébec Creek samples is characteristic of surficial erosion of the Bébec Creek watershed (quaternary quartz silts, organic-mineral flocs, phytoplanktonic material). At the spring the quality of the conservation of fragile structures such as surface water algal material is evidence of relatively brief transport through the subsurface.

Qualitative observations suggest that most of the suspended sediment discharging from the spring originates from Bébec Creek. Diffuse infiltration and flow through the microfissured matrix of the karst are unlikely to contribute any significant amount of particulates to spring discharge. Hannetôt spring is not known to be fed by any sinkholes other than that in the bed of Bébec Creek—no other significant active recharge feature has been located since study of the Norville–Villequier karst region began in the 1960s.

At the well, crystalline carbonates not found at the spring indicate that the saturation rate is reached for the calcite in the borehole. Moreover, particles such as *Melosira* and the Foraminifera tests present at the well are often found in the Holocene alluvial formations of the Seine Valley. The presence of these particulates of biologic origin may be a good indication of contribution from the alluvium.

The connection between the sinkhole and the spring has been verified, but the difference in characteristics of the material discharging from the spring and the well raises the question of the mode of transport through the chalk towards this artificial discharge point. There are three possibilities:

1. Transport to the well may be completely of a karst type. This hypothesis is incompatible with the velocities measured at the well (for the tracer test of May 1997, apparent velocity between the sinkhole and the well: 22 m h^{-1}), and with the extremely low turbidities measured at the well. Moreover, the strong efficiency of the particle sorting, with a high truncated size distribution

beyond >20 μm sizes, would imply that the layer accounting for particulate transport rather behaves as a porous medium.

2. Transport to the well may be through the fissured matrix porosity of the chalk. In this case, we would not have found material originating from the overlying alluvium.
3. Transport to the well is retarded along the interface between the chalk and the alluvium. The resulting intermediate velocities would be compatible with those observed. This medium, consisting of 1–2 m basal gravel and of 4 m of altered chalk mixed with sand and gravels of 4 m thickness, acts as a porous medium, exerting a marked size-sorting on the particles originating from the sinkhole and from the chalk massif. This interface is more transmissive than either the fine alluvium above or the unaltered finely-fissured chalk below.

This last possibility is the most compatible with the data collected. The acidification carried out during the development of the well has evidently resulted in a connection between the screened portion of the borehole and the alluvium. If one assumes that little storage is occurring in the karst between the sinkhole and the spring, it would seem that the interface between the chalk and the alluvium is the preferential zone for trapping. The storage thus must be taking place between the sinkhole and the well in the chalk/alluvium interface, posing the question of eventual blocking or clogging of this zone. The interface zone acts as a horizontal filter draining part of the chalk aquifer, the latter being semi-confined underneath the fine semi-permeable alluvium.

6. Conclusion

The results of this investigation give insight into the transport processes taking place as water flows from the chalk aquifer into the alluvial plain of the Seine, and identify the importance of the role played by the interface between the chalk and the alluvium in the quality of water obtained from a well located in the alluvial plain.

The qualitative analysis of the particulate material transported demonstrates: (1) the transport of particles from the top of the plateau to the spring at the base; (2) the transport of material originating from the dissolution and mechanical erosion of the interior of the chalk aquifer to the spring; and (3) the marked difference between the character of the particulate material found at the spring and that found at the well, including a difference in the amount of particulates originating from within the chalk and from the alluvial prism.

The low turbidity and the size-sorting observed in the samples collected at the well indicate trapping of particles as they are transported toward the well. This behaviour is consistent with transport through a porous medium between the spring and the well. The difference between the particles observed at the spring, a natural karst discharge point, and the well clearly shows that the transport to the well does not occur through a karstic medium.

Transport between the spring and the well occurs through a preferential zone of a few metres thickness, consisting of the basal gravels of the alluvium and several metres of altered chalk mixed with alluvium. The hydrodynamic properties of this zone contrast greatly with those of the overlying and underlying formations. This zone, draining the waters of the underlying chalk, acts as the connection between the karst and the alluvial plain. It carries the majority of the groundwater flow and overall behaves as a highly transmissive porous medium. Over time, however, it could become blocked.

This investigation underlines the importance of studying the co-behavior of dissolved and particulate material to better understand dissolved and particulate transport in complex geologic media. It highlights (i) the interest in using of this type of medium as a source of potable water because of the lower health risks associated with low concentrations of particulates, (ii) the potential risk of clogging of such an aquifer. Locations of this type present an attractive alternative to purely karst sources which may have a much higher associated health risk from microbial pollution.

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