Natural and technical factors in faecal contamination incidents of drinking water in small distribution networks, France, 2003–2004: a geographical study

Pascal Beaudeau, Danièle Valdes, Damien Mouly, Morgane Stempfelet and René Seux

ABSTRACT

This geographical study aimed to show natural or water-processing-related factors of faecal contamination incidents (FCIs) of drinking water in continental France. We defined a FCI as the occurrence of at least 20 colony-forming *Escherichia coli* or enterococci among all the 100 mL samples collected for regulatory purpose within one day from a given drinking water supply zone (SZ). We explored correlations between the standardized number of FCIs per *département* (*N_Pols)* and various indicators related to weather, land cover, topography, geology and water management for three SZ size sub-classes. In 2003–2004, 2,739 FCIs occurred in SZs supplying fewer than 2,000 people, mainly with simply disinfected groundwater. *N_Pols* correlates with four covariates: (1) precipitation; (2) the extension of the karst outcrops; (3) the extent of disinfection; and (4) catchment protection. One hundred millimetres of yearly excess in precipitation increases the pollution risk by 28–37%, depending on the sub-class. A 10% extension of the karst areas, a 10% increase of unprotected resources, or of SZs with no disinfection, could entail a higher risk of FCI by about 10%. The correlations are reproducible over the three sub-classes and corroborate expert appraisals. These results encourage the ongoing effort to generalize disinfection and catchment protection.

Key words | chlorination, faecal contamination, France, geographical study, groundwater, precipitation

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ABBREVIATIONS

AGE acute gastroenteritis
FCI faecal contamination incident
RR relative risk
SZ supply zone

INTRODUCTION

For a century, the regulatory monitoring of the microbiological quality of drinking water has relied on the identification of bacterial indicators such as coliforms, and then faecal coliforms, *Escherichia coli* and enterococci. Several epidemiological studies have shown a link between the presence of faecal indicators in drinking water and the incidence rate of acute gastroenteritis (AGE) (Zmirou *et al.* 1987, 1995), without demonstrating any quantitative relationship between the concentration of these bacteria and the probability of AGE occurrence. Several factors actually disrupt the relationship between faecal contamination of drinking water and the incidence of AGE: (1) waterborne transmission is minor compared to foodborne and faecal–oral transmission (Bennett *et al.* 1987; Payment *et al.* 1997); (2) the number and diversity of pathogens involved (Percival *et al.* 2004); (3) variability of

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the epidemiological context, i.e. the presence or absence of pathogen shedding in the catchment area; (4) final chlorination of drinking water, widely used in France at a low dose (e.g. 0.3 mg/L at the plant outlet), which inactivates bacteria without necessarily inactivating the parasites or viruses which are responsible for most waterborne gastroenteritis (Payment 1999; Linden 2004). Nevertheless, faecal bacterial indicators remain the main tool for the routine monitoring of water microbial safety, even if they are not very sensitive or specific. This approach is crucial in the case of small water supply zones (SZs), since the small size of the population at risk impedes epidemiological surveillance.

This study proposes a pragmatic indicator-based definition of faecal pollution of drinking water distributed in France, and aims to identify its causative factors, whether technical or natural, through an ecological-geographical study, using the *département* as the basic unit. In France, the monitoring of drinking water quality is organized and implemented at the level of the *département* (administrative district). The scope of correlations in terms of both causality and public health is discussed. Detailed methods and full results are shown in the study report available online (Beaudeau 2008).

MATERIALS AND METHODS

According to the European directive 98/83/EC, 'a supply zone is a geographically defined area within which water intended for human consumption comes from one or more sources and within which water quality may be considered as being approximately uniform'. A faecal contamination incident (FCI) was defined as the occurrence of a total of 20 or more colony-forming units in *Escherichia coli* and enterococci counts from all the 100 mL samples collected on the same day within the same SZ for regulatory monitoring purpose. We considered the samples taken from both the treatment plant outlet (22% of distributed water samples) and user taps (78%). The membrane filtration method was used according to the ISO 9308-1:2000 (*Escherichia coli*), and ISO 7889-1:1998 (enterococci) international standards. The FCI definition covers intermediate level contamination identified by a single sample, as well as low-level contamination identified at several points. We took 20 as the maximum threshold value that allowed a sufficient number of events to support a statistical conclusion.

The study was limited to SZs in mainland France supplying fewer than 2,000 people. This size range is consistent with the need for homogeneity in both the resource used (groundwater) and the treatment applied (simple chlorination at best). In 2004, only 4% of abstraction facilities supplying selected SZs drew on surface water, and only 17% of SZs had their water filtered. In contrast, SZs covering 2,000 to 10,000 inhabitants showed significantly greater use of surface water (21% of abstraction facilities) and clarification processes (37%), and were therefore not included in the study. We distinguished three SZ sub-classes within the size category of SZs studied: SZs supplying a fixed population of fewer than 100 inhabitants (class 1), 100 to 499 inhabitants (class 2) and 500 to 2,000 inhabitants (class 3).

N_Pols1, N_Pols2, N_Pols3 were the variables to be modelled. They represented the number of FCIs by sub-class reported during the 2003–2004 period within the *département*, and standardized according to the number of SZs in the sub-class. We tested seven covariates: (1) the percentage of SZs without disinfection within the *département* (*nDis*); (2) the percentage of catchments without any official protection within the *département* (*nCPA*); (3) the percentage of surface area in the *département*' occupied by limestone likely to have developed karstic drainage systems (*Karst*); (4) the percentage of cultivated surface areas within the *département* (*Cult*); (5) the average yearly precipitation during the study period (*Prec*); (6) the precipitation deviation compared to normal values (*dPrec*); and finally (7) the median altitude of the cities located in the *département* (*Alt*). Similar to *N_Pols*, the *nDis* and *nCPA* covariates were broken down by SZ sub-class.

According to French regulations, the passage of an official catchment protection order implies that (1) the parcel of land around the catchment has been purchased by the land management authority; and (2) regulation rules prohibit storage or spreading of polluting substances, e.g. manure or slurry, within the surface area that fits the catchment's cone of depression.

Limestone formation aquifers provide up to 35% of the French population with drinking water, and most of the tap water of underground origin is abstracted from such aquifers. Many strata in limestone formations have developed karst features, such as sinkholes and underground drainage networks. Waters of karstic origin are dramatically vulnerable to pollution, since polluted waters may pass through the karst drainage system from the surface catchment area to the aquifer's outlet without any filtration. Two types of karst system exist (Figure 1). The karst system may outcrop; the recharge is then diffuse and the spates are not very turbid. By contrast, the karst system may be covered by impervious layers. In this case, the rainfall events induce surface runoff, active sinkholes drain large areas and the recharge is concentrated. Surface runoff pulls out particulate matter from the soil and carries it along the surface and underground course, which may result in turbid spates at the aquifer's outlet. Since runoff waters are often contaminated by faecal pathogens from manure or wastewaters, and since turbidity seriously disrupts disinfection, coping effectively with turbid spates requires the implementation of clarification facilities. Failing that, consumers are faced with a highly increased risk of infection. A mapping of French karstic formations (Figure 2; Marsaud 1997) shows a typology of karst based on tectonics and the nature of the limestone. This typology was not considered as relevant in terms of vulnerability of aquifers to microbiological pollution. Consequently, the covariate *Karst* did not distinguish several categories of karstic formations.

The cultivated surface areas encompass arable lands and permanent crops. The percentage of cultivated surface areas (*Cult*) is high in the rural plain *départements*, except in the woody Landes *département* in the southwest of France. *Cult* indicates both a risk of storage or spreading of manure and an increased risk of surface runoff and turbid spates resulting from bealing crust development along with winter rainfall accumulation. Nevertheless, the occurrence of runoffs necessitates ground slopes and soil conditions for which no relevant data was available.

Data sources are shown in Table 1. Microbiological data and data related to the health management of water were taken from the national SISE-Eaux database produced by the Ministry of Health. Geographical calculations were performed using Arc-View™, version 8.

Linear modelling of the *N_Pols* variables was performed using Stata™, version 9.2. The missing data were replaced by mean values of the variable in the SZ size sub-class. We selected the 'robust' option along with the 'regress' command in order to deal with unequal variance. We reduced the influence of *départements* for which the SZ sub-class is underrepresented, i.e. for which the estimation of FCI frequency is inaccurate, by weighting the *N_Pols* variables by the square root of the number of SZs. Assuming a random residue, this weighting evens out the contribution of *départements* to residual variance, while without it, i.e. with equally weighted observations, the *départements*' contribution would be inversely proportional to its number of SZs. We first carried out stepwise regressions in order to point out the significant covariates and then fitted sub-class

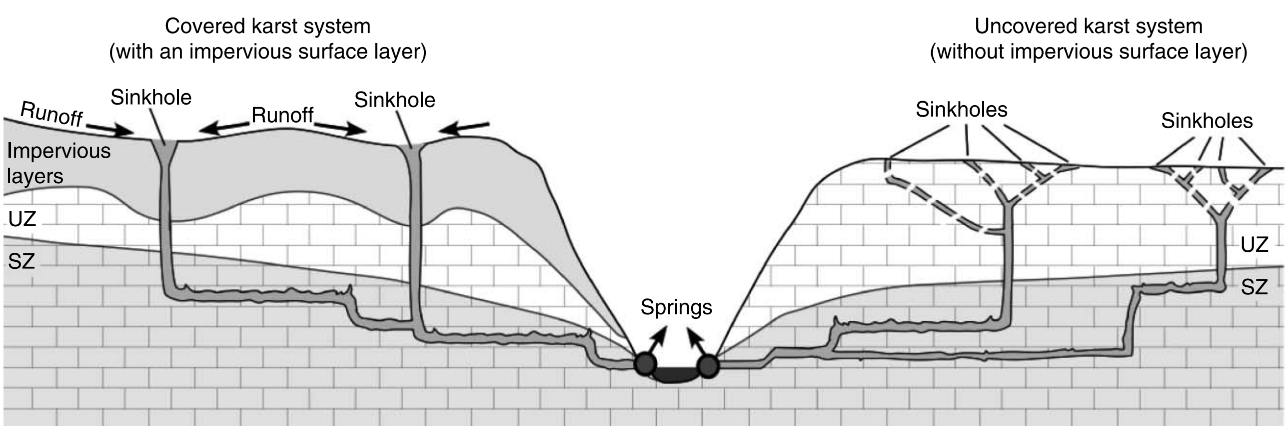

Figure 1 | Sketch of the functioning of a karst aquifer. UZ: unsaturated zone; SZ: saturated zone.

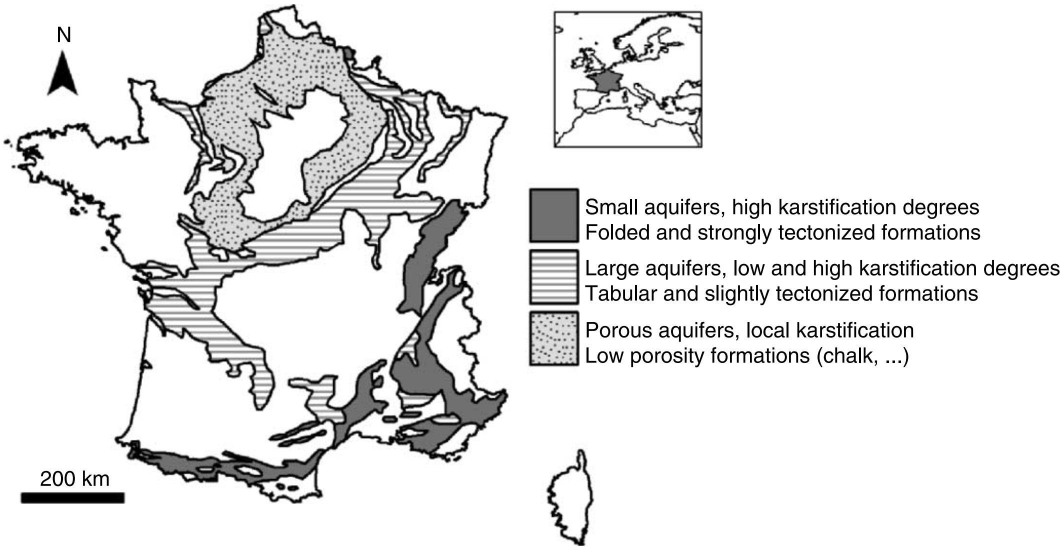

Figure 2 | Karst in France (from Marsaud 1997).

models including a common set of covariates. Three criteria were evaluated for the inclusion of a covariate into this common set: (1) the level of significance of its coefficient in the *N_Pols* model; (2) the reproducibility of this correlation over the three SZs' size sub-classes; and (3) the plausibility of the correlation. For fitting outlier *départements*, i.e. located more than three standard deviations away from the expected values, 'outlier *département*' 0/1 covariates were added to the model.

RESULTS

The number of small SZs varies greatly depending on the *département* (Figure 3). The smallest SZs (class 1) mainly supply isolated hamlets and villages in mountainous areas. The distribution of class 3 SZs over the territory is more homogeneous and that of class 2 SZs is intermediate. There are no SZs supplying fewer than 2,000 people in suburban Paris. Three other *départements* have no class 1 SZs and

Table 1 | Study data and variables (expressed per *département*)

Variables studied		Years	Source
*N_SZ**	Number of SZs	2003–2004	Sise-eaux database, Health Ministry
*N_Pol**	Number of faecal contamination incidents during study period	2003–2004	Sise-eaux database, Health Ministry
*N_Pols**	*N_Pol* standardized on *N_SZ*	2003–2004	Sise-eaux database, Health Ministry
*nDis**	Percentage of SZs without disinfection	2006†	Sise-eaux database, Health Ministry
*nCPA**	Percentage of abstractions without any official protection area	2003–2004	Sise-eaux database, Health Ministry
Karst	Percentage of karst formations	–	Marsaud 1997
Prec	Annual mean rainfall (mm)	2003–2004	Météo-France
dPrec	Rainfall deviation from normal (1971–2000)	2003–2004	Météo-France
Alt	Median township altitude (m)	–	Institut Géographique National
Cult	Percentage of cultivated land	2000	CORINE Land Cover, Institut Français de l'Environnement

*Detailed per SZ sub-class (number of inhabitants supplied): class 1 = [0; 100]; class 2 = [100; 500]; class 3 = [500; 2,000].
†Unarchived data.

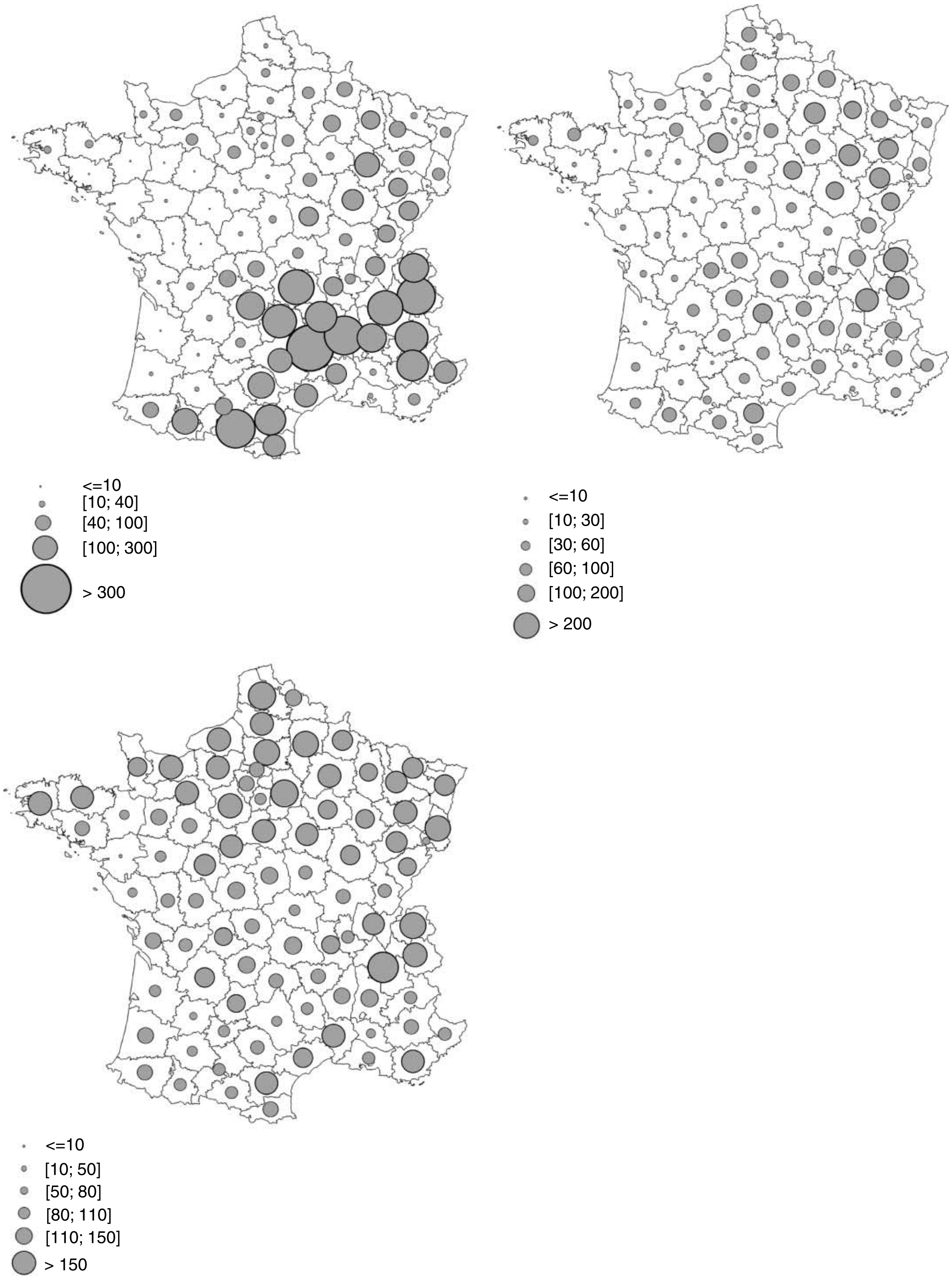

Figure 3 | Number of SZs per *département* and per SZ size sub-classes (*Source*: Sise-Eaux, Ministère chargé de la santé).

classes 1 and 2 were not represented in the Loire-Atlantique *département*.

In 2003–2004, 237,000 samples of drinking water were collected in the study area for faecal contamination assessment. The screening of the resulting data highlighted 2,607 FCIs, 88% of them were identified by an over-threshold contaminated single sample, and 12% through cumulating lower contamination in two or more samples.

Table 2 | Distributed water regulated monitoring: Yearly frequency of sampling and FCIs exposed population; Continental France, 2003–2004 (Source: Sise-eaux, Health Ministry)

	Class 1	Class 2	Class 3	Total
Yearly number of samples per SZ	3–5	5–6	8	3–8
Total number of SZs (a)	7,807	7,240	5,507	20,554
Yearly total number of samples (b)	31,228	43,440	44,056	118,724
Mean yearly number of reported FCIs (c)	780	394	131	1,304
Rate of FCIs ($d = c/b$)	2.50%	0.91%	0.30%	1.10%
Estimated yearly total number of FCIs ($a \times d \times 365$)	71,129	23,938	5,954	82,369
Resident population supplied (in millions)	0.32	1.80	5.73	7.86
Resident population exposed to a FCI ($1000 \times \text{day}^{-1}$)	8.08	16.32	16.98	41.39

The FCI rate, i.e. the exposure risk for a tap water drinker of a SZ supplying fewer than 2,000 inhabitants on a given day, was 1.31% on average, and increased significantly when the size of the SZ decreased. For class 1 (<100 inhabitants), it was eight times higher than for class 3 (500 to 2,000 inhabitants) (Table 2). The average standardized number of FCIs per *département* (*N_Pols)* during the two years of the study was 10.1, 6.6 and 2.9 for classes 1, 2 and 3, respectively. The statistical distributions of the 3 *N_Pols* covariates included more than 25% of null values and dramatically extended to the right, meaning that many *départements* experienced a smaller or a larger number of FCIs than expected, assuming a purely random process (Table 3; Figure 4). A threshold value of 50 instead of 20 would diminish by 53% the number of events under consideration and lead to inappropriate modelling conditions.

The covariate distributions are given in Table 3. Missing data remained under 5% in the worst case. The frequency of disinfection facilities increased with the size of the SZ; the median of *nDis* was 22% for class 1 and 6% for class 3. Similarly, the average rate of absence of regulatory

Table 3 | Distribution of the variables

Variable	N	Missing	Min	P10	P25	P50	P75	P90	Max	Mean
N_SZ1	90	0	0	1	6	36	113	262	588	86.74
N_SZ2	90	0	0	13	22	68	117	183	286	80.44
N_SZ3	90	0	2	22	32	53	94	106	138	61.19
N_Pol1	87	0	0	0	0	1	25	59	141	17.92
N_Pol2	89	0	0	0	0	3	11	29	57	8.84
N_Pol3	90	0	0	0	0	1	5	8	14	2.90
N_Pols1	87	0	0.00	0.00	0.00	4.34	18.44	29.29	53.25	10.10
N_Pols2	89	0	0.00	0.00	0.00	4.47	9.46	21.45	29.91	6.61
N_Pols3	90	0	0.00	0.00	0.00	1.53	4.37	8.83	20.62	2.91
nDis1	87	3	0.00	0.00	0.00	0.24	0.57	0.80	1.00	0.321
nDis2	89	3	0.00	0.00	0.00	0.13	0.38	0.54	0.81	0.207
nDis3	90	3	0.00	0.00	0.00	0.06	0.15	0.31	0.74	0.110
nCPA1	87	4	0.00	0.33	0.48	0.70	0.87	1.00	1.00	0.648
nCPA2	89	0	0.00	0.20	0.34	0.57	0.75	0.90	1.00	0.546
nCPA3	90	0	0.06	0.15	0.25	0.41	0.59	0.74	0.89	0.436
Karst	90	0	0.00	0.00	0.06	0.38	0.61	0.83	0.99	0.370
Prec	90	0	537	633	698	790	918	1,093	1,288	823

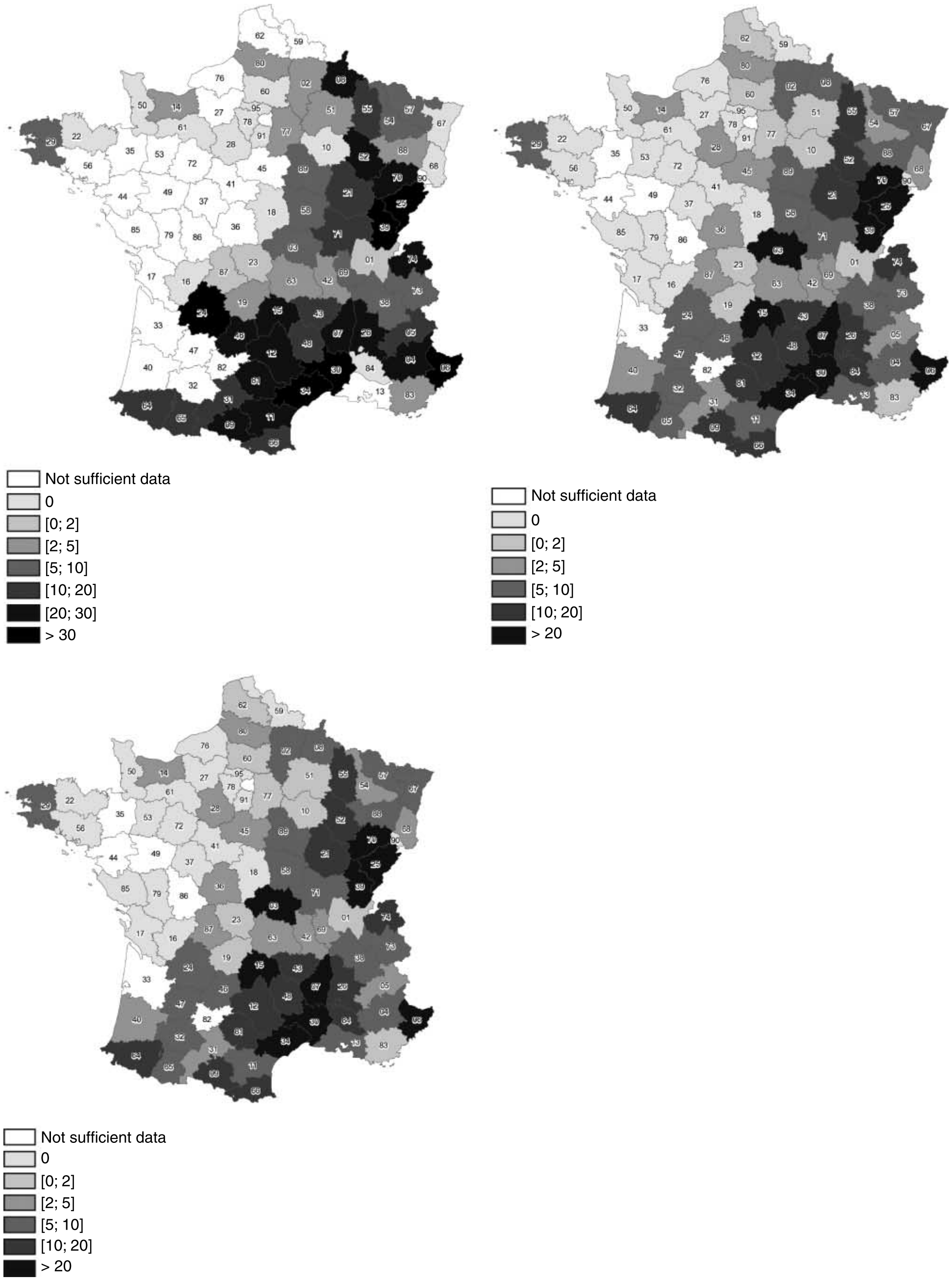

Figure 4 | Number of FCIs per *département* standardized by the number of SZs *(N_Pols)*, years 2003–2004 (*Source*: Sise-Eaux, Ministère chargé de la santé).

catchment protection areas (*nCPA*) decreased from 70% to 41% between classes 1 and 3. Average precipitation over the study period (Figure 5) was 780 mm/year, with variations ranging from 537 mm/year in the Bouches-du-Rhône County (main city Marseilles) to 1,288 mm/year in the Pyrénées-Atlantique County. Compared to the baseline period (1971–2000), precipitation during the study period showed an average shortfall of 9% which peaked in the southeastern Alps (−34%) and was greater in 2003 than in 2004 (−13% vs. −5%).

Covariates referring to the topography (average altitude of towns) and land use (percentage of cultivated land)

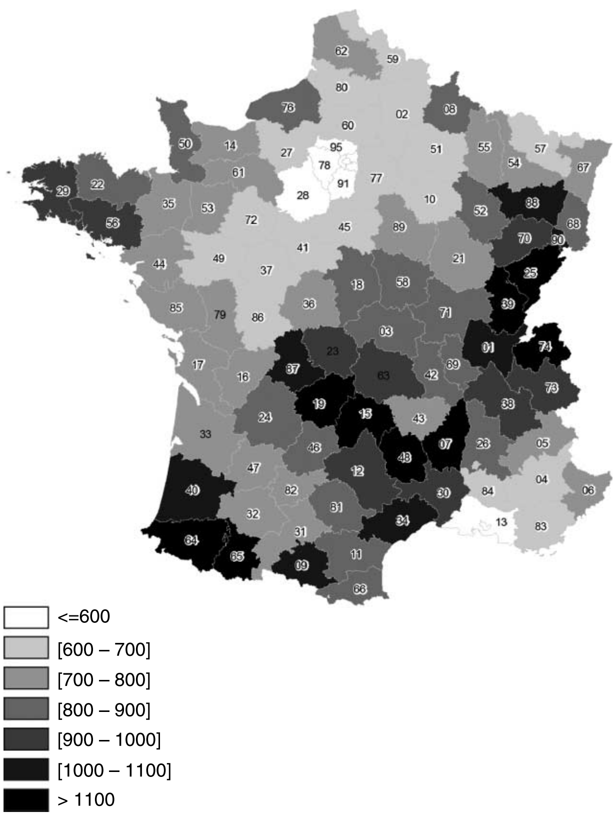

Figure 5 | Mean precipitation (*Prec*, mm year^{-1}) for 2003–2004 (*Source*: Météo-France).

did not correlate to *N_Pols* and were not included in the multivariate models presented. Four covariates met the inclusion criteria and were included: two natural FCI risk factor indicators, i.e. total precipitation (*Prec*) and the percentage of land occupied by karstic formations (*Karst*), and two indicators referring to poor technical management, i.e. prevalence of resources without catchment protection area (*nCPA*) and the prevalence of SZs without disinfection (*nDis*). The portion of the *N_Pols* variance explained by these four covariates decreased from 47% for the class 1 model to 26% for the class 3 model (Table 4). Model residues did not show significant spatial self-correlation (Figure 6). Three outlier *départements* were modelled by 0/1 covariates (Table 4).

Assuming normal residues, coefficients linked to *Prec* were very significant, those associated to *Karst* and *nCPA* were significant, and the one linked to *nDis* was borderline (Table 5). Model residues actually met normality for class 1 (Kolmogorov-Smirnov test, not significant for a α risk of 0.8), whereas class 2 and 3 model residues did not fully match normality even after the introduction of outlier *département* covariates (Kolmogorov–Smirnov test significant for a α risk of 0.01). However, the use of the distribution-free Spearman rank test showed a significant rank correlation between *N_Pols* and the selected covariates *Prec*, *nCPA*, *nDis*, and to a lesser extent *Karst* (Table 5).

Table 4 | Contribution of covariates to the variance of the standardized number of FCIs *N_Pols*

	Class 1	Class 2	Class 3
N	87	89	90
Variance of *N_Pols*	171	59	15
Part of variance explained (%) by *Prec, Karst, nCPA* and *nDis*	47%	39%	26%
Number of outlier* *départements*	0	2	1
Part of variance explained (%) by the full models†	47%	50%	42%

*Defined by a deviation from the model expectation exceeding 3 standard deviations.
†Models including *Prec, Karst, nCPA, nDis* and the outlier *département* indicators.

Relative risk estimates are shown in Figure 7. An increase of 100 mm in annual precipitation was associated with an average increase in the risk of FCI of 33%, 37% and 28% for SZ classes 1, 2 and 3, respectively. For a 10% increase in any of the other covariates *Karst*, *nDis* and *nCPA*, we observed an increase of the FCI risk of about 10%. Despite the overlap of the confidence intervals of the risk estimates, we were unable to suggest a pooled risk estimate due to the heterogeneity of *N_Pols* variances between the SZ's sub-classes (Table 4).

DISCUSSION

From ecological correlations to causality

The study presented here is an 'ecological' study, since the basic unit is not a single item, in this case a SZ, but a group of items, here the *département*. Ecological studies help formulate or reinforce hypotheses, but ecological correlations alone are insufficient to prove a causal link. However, in this case, additional criteria such as the reproducibility of correlations between three sub-classes of SZ sizes and their plausibility according to expert knowledge support the likelihood of a causal relationship.

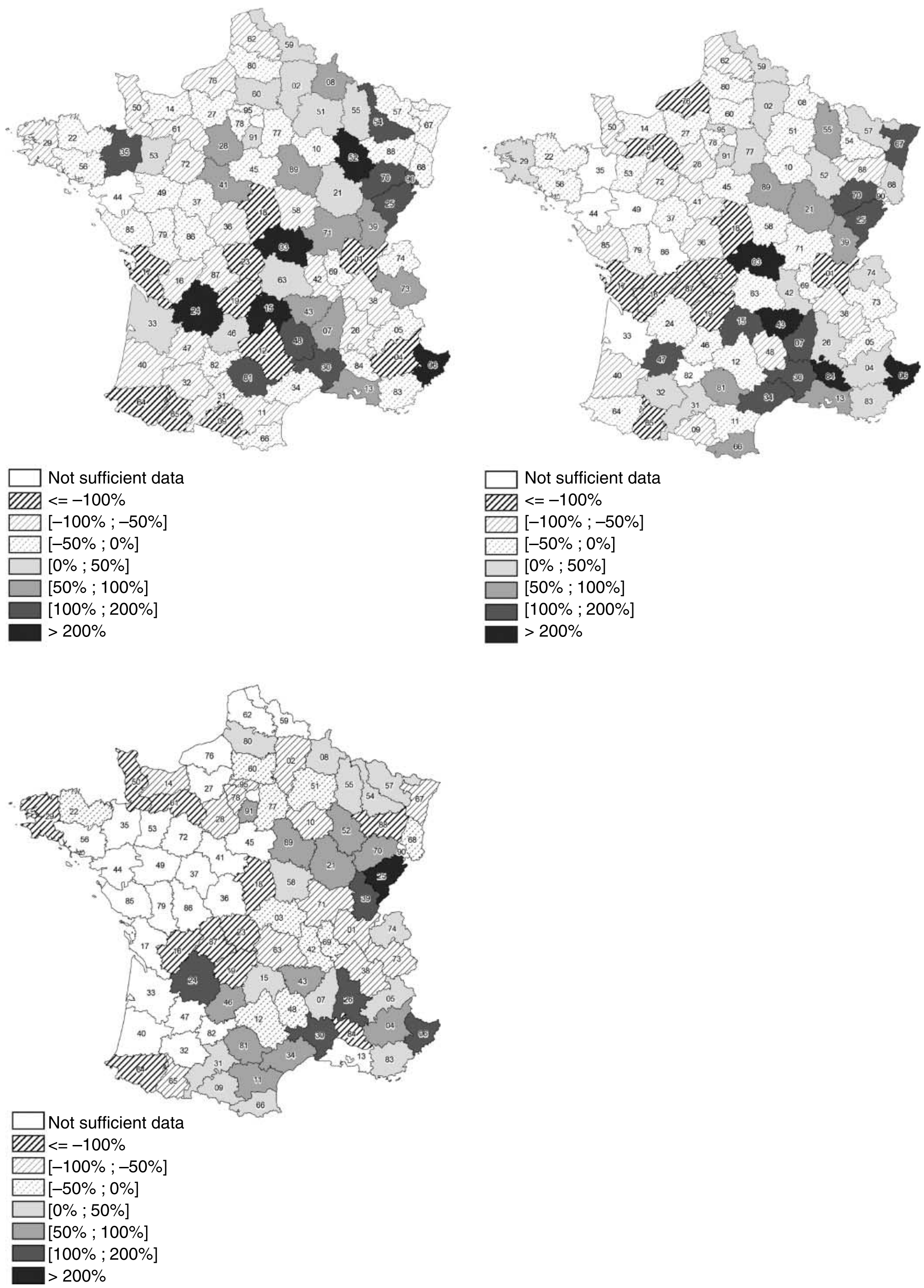

Figure 6 | Residue (%) of the *N_Pols* models, years 2003–2004. The models used do not include the outlier *département* indicators.

Correlations between *N_Pols* on the one hand, and *Prec*, *Karst*, *nCP* and *nDis* on the other hand, appeared despite the poor specificity of the variables, which would tend to reduce actual correlations. For instance, the available covariates addressed resource pollution events but not pollution introduced downstream from the pumping station into the storage tank or the distribution network. A previous study showed that the latter, mainly due to

Table 5 | Model fitting: probabilities associated to selected covariates' coefficients

	Linear model*			Spearman ranks†		
Dependent variable:	*N_Pols1*	*N_Pols2*	*N_Pols3*	*N_Pols1*	*N_Pols2*	*N_Pols3*
Covariates:						
NCPA	$<10^{-3}$	0.006	0.017	0.036	0.005	0.079
NDis	0.065	0.089	0.014	0.015	$<10^{-3}$	0.034
Prec	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$
Karst	$<10^{-3}$	0.012	0.067	0.145	0.256	0.160

*In addition to the 4 indicated covariates, the models associated with classes 1, 2 and 3 include 0, 2 and 1 outlier *département*'s indicators, respectively.
†After controlling the other 3 covariates.

backflow of contaminated water, accounted for up to 24% of the total accidental pollution of drinking water reported in France reported between 1991 and 1994 (Nedellec *et al.* 1996). In the same way, the clarification processes implemented in more than 20% of the class 3 SZs blurred the relationship between raw water quality and that of distributed water, thus decreasing the correlation between *N_Pols3* and its covariates. This effect could explain the decrease observed in the part of the variance explained by the model between classes 1 and 2 on the one hand, and class 3 on the other (Table 4). Finally, *nDis* indicates whether or not there is a treatment system, but does not take into account failures of existing systems. The duration of any failures in the disinfection system depends on the frequency of facility routine visits, as far as adequate remote alert systems remain infrequent in small water utilities. According to the operators themselves, the ongoing monitoring effort and the attention devoted to treatment malfunction decrease severely when the size of the SZs decreases. As a result, disinfection failure prevalence also strongly decreases from class 1 to class 3. This trend could explain the weakly significant correlations observed between *N_Pols* and *nDis* in classes 1 and 2 (Table 5).

In the early 20th century, engineers (Hazen 1914) and epidemiologists (Whipple 1921) identified water chlorination as the main means of fighting typhoid. The importance of protecting catchment areas was also acknowledged earlier (Sanarens 1921), and was covered by French health regulations as early as 1902. In France, as in other developed countries, outbreaks of bacterial (Craun *et al.*

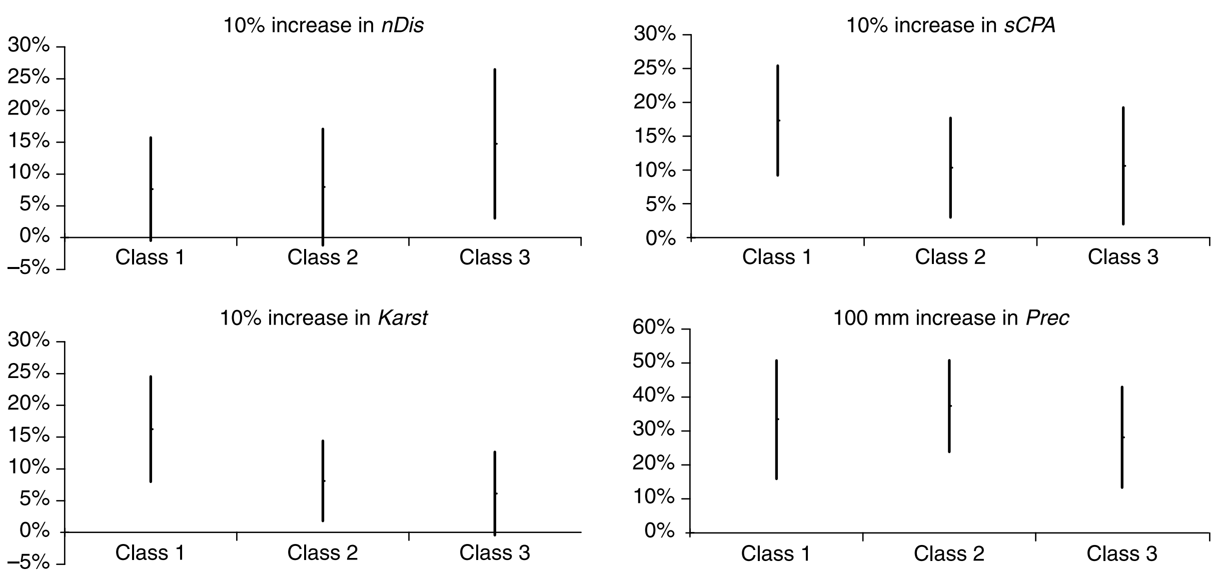

Figure 7 | Model simulations: relative increase in the number of FCIs for different scenarios (assessments and confidence intervals at 95%).

2006; Smith *et al.* 2006; Beaudeau *et al.* 2008) and even viral aetiology (Risebro *et al.* 2007), remain associated with the absence, or failure, of disinfection. The lack of disinfection also leads to the occurrence of sporadic AGE cases (Zmirou *et al.* 1987). The analysis of 61 European outbreaks (Risebro *et al.* 2007) shows the crucial role played by design or barrier failure in groundwater abstraction in the onset of waterborne outbreaks due to groundwater pollution. In 2004, the French government implemented a plan aimed at generalizing the protection of catchment areas by 2010. Since 2003, the government has also been promoting widespread disinfection in order to prevent the untoward effects of malicious actions. Our results support promotion of policies to implement both catchment protection and disinfection. Repeating the study at regular intervals would not only contribute to testing the reproducibility of ecological correlations over time, but also to quantitatively assessing the effect of ongoing actions on the frequency of FCIs.

The adverse effect of precipitation on the microbial quality of karstic waters is well known in Eastern-Normandy (Dussart-Baptista *et al.* 2003); such effects were also demonstrated with respect to the onset of waterborne infectious outbreaks (Curriero *et al.* 2001). This study confirms the importance of the effect of rainfall on the onset of FCIs. By selecting the cumulated precipitation over a 2-year period as a covariate, the protocol tends to conceal the dynamic link between rainy episodes and the onset of FCIs, which tends to weaken any correlations. Presumably, a large proportion of FCIs is conditioned by rainy episodes. This relationship should be particularly strong in the case of small SZs, due to the lack of adequate facilities to treat turbidity.

Some outbreaks have been linked to the karstic origin of drinking water (D'Antonio *et al.* 1985; Stevanovic 1988; Beaudeau *et al.* 2008). However, the absence of 'karst' as a keyword in Medline's thesaurus does not enable a systematic review of the health impact of the use of drinking water of karstic origin. Water and public health local stakeholders having acknowledged the vulnerability of karstic water to faecal contamination for a long time (Sanarens 1921), scientists addressed this concern at local level (Tranter *et al.* 1997; Mahler *et al.* 2000; Dussart-Baptista *et al.* 2003; Stambuk-Giljanovic 2003), but, as far as we know, did not conduct any systematic reviews. Even if discharges from wastewater treatment plants into the karst underground drainage network already cause pollution of karstic water in dry weather conditions in France, most of the pollution events result from rainy episodes. In rainy weather, overflows from sewerage systems and surface runoffs may enter the many pits tapping the catchment area, and spread unfiltered to the aquifer's outlets. Winter runoffs on fields free of vegetation cover are particularly dangerous as they start abruptly, bring high turbidity and faecal contaminants, and cannot be easily foreseen (Beaudeau *et al.* 2001).

Nevertheless, we did not detect any *Karst* and *Prec* interaction with respect to FCI frequency, perhaps due to an ecological bias. Unlike *nDis* and *nCPA* covariates, for which the breakdown into *départements* is fully justified by the organization of water management, *Karst* and *Prec* are exposed to an ecological bias due to their infra-*département* heterogeneity. This study does not distinguish spatially homogeneous *départements*, for which the mean estimates are relevant, from mixed situations including both dry and rainy areas, karstic and non-karstic sectors. On the whole, ecological bias may conceal a synergistic effect of high precipitation and the presence of karstic aquifers on the FCI frequency. A more accurate specification of the covariates seems possible:

- Effective precipitation instead of total precipitation (*Prec*): Most of the pathogen flows penetrating karstic aquifers come from surface runoffs. Assessment of surface runoffs is, however, particularly complex and can only be performed at a local scale. Efficient rainfall data achieve a compromise between the inaccuracy of total precipitation data, and unavailability of surface runoff data.
- Index of aquifer's vulnerability to microbial pollution based on turbidity and conductivity data instead of the geological covariate *Karst*: Turbid episodes combined with changes in conductivity may indicate the breakthrough of surface runoff water at the abstraction point. This pattern is linked to covered karsts, and locally documented. Its relevance at the national level is yet to be established.
- Altitude variability indicators instead of the average indicator *Alt* since slopes promote surface runoffs.

- Variables referring to interactions between precipitation, karst, topography, nature of the ground and the vegetation cover: Pollution of karstic resources is the result of complex interactions between precipitation, sources of pollution and the physical shape of the catchment area and of the drainage system. Calculating interactions at the local level before integration at the *département* scale would reduce the ecological bias. The sources of pollution within the catchment areas, e.g. the distance from the abstraction point to discharge of upstream wastewater treatment plant, suffered from a lack of data at national level.

Public health scope

In every developed country, the microbiological quality of water in small SZs is problematic (Coulibay & Rodriguez 2003; Ministère de la Santé et des Solidarités 2006), and at the origin of most waterborne outbreaks (Lee *et al.* 2002; Schuster *et al.* 2005; Smith *et al.* 2006). Due to the lack of financial, technical and human resources, the presence of a vulnerable resource mechanically leads to faecal contamination of tap water. In continental France in 2003–2004, the individual exposure risk to a FCI on a given day is eight times higher in class 1 than in class 3 (Table 2), and nearly 100 times higher in class 1 than among SZs supplying more than 50,000 inhabitants ($p = 3.1 \times 10^{-4}$/year). The fraction of the population supplied by SZs of less than 2,000 inhabitants (Table 2) represented 13% of the population, but cumulated 60% of the exposure to FCIs.

The operator and health authorities can resort to few means for protecting such populations from the risk of waterborne infections. The regulatory monitoring of distributed water helps to identify regularly non-compliant facilities but rarely contributes in warning and protecting inhabitants with respect to possible waterborne infectious threats, due to the scarcity of sampling (Table 2) and the time delay required for analysis. Real time warning systems, which are not provided for in existing regulations, should also be mentioned, since their usefulness has been demonstrated in large water utilities. These combine technological devices (turbidity and chlorine probes, remote alarm transmission devices), procedures covering alarm threshold definition and intervention plans, and skilled staff on stand-by duty. This organization enables operators to react to a sudden degradation of the water quality before it is distributed. It is crucial for the management of karstic waters, knowing that their quality is subject to important variations on an hourly scale. In that case, the capability to maintain the safety of distributed water also requires appropriate treatment facilities to deal with turbidity episodes. The financial, technical and human constraints most often prevent the implementation of such systems in small SZs.

As a last resort, people supplied frequently by contaminated water may abstain from drinking tap water. This choice is mainly offered to residents receiving a yearly regulatory information letter about the quality of drinking water. Nevertheless, the tourist population may be particularly at risk because of an accumulation of risk factors: (1) lack of information regarding the quality of the water distributed on the site of their stay; (2) possible paradoxical consumption behaviour, since the good reputation of mountain water may promote tap water drinking in mountain areas (Beaudeau *et al.* 2003); and (3) low acquired immunity against faecal pathogens compared to resident populations more regularly exposed (Isaac-Renton *et al.* 1999; Payment *et al.* 2000; McDonald *et al.* 2001). This topic is of particular relevance for France as the country is an important tourist destination: 1.3×10^9 overnight stays in 2006, 51% of which were in rural or mountainous areas, and 38% of which were foreigners (Ministère de l'Économie, des Finances et de l'Emploi 2007).

In such a context, public action must prioritize general prevention interventions, such as the protection of catchment areas and disinfection. Given the sanitary and economic stakes, it seems also important to further specify the infectious risk linked to small SZs. Three topics of interest can be put forward:

- Collection of data on the consumption of tap water linked to critical circumstances and populations: Whereas data per gender, age and main region are available in many European countries (Mons *et al.* 2007), the effects of outbreaks, 'boiling advice' notifications, chronic or temporary chemical or microbiological discrepancies in the drinking water, attitudes and practices in the resident population are not documented yet. The drinking behaviour of French and foreign tourists should be also investigated.

- Epidemiology: Using prescribed drug refund data drawn from the French health insurance database would enable routine assessment of the incidence rates of AGE requiring medical attention, per day and per town, among resident and transient populations residing elsewhere in France (Beaudeau *et al.* 2006). Even if these surveillance modalities are more sensitive than the current system based on reports from general practitioners or institutional managers, the drug refund-related surveillance system would not point out AGE clusters due to the contamination of the smallest SZs. The relative risk (RR) having been defined as the ratio of the weekly incidence rates between the affected town and a control town, simulations actually showed that outbreaks are undetectable in SZs of less than 500 or 2,000 inhabitants when the RR is under 10 or 4, respectively (Beaudeau *et al.* 2006).
- Monitoring microbiological quality of drinking water and its determinants: Since there are on average 1,500 to 2,000 FCIs reported per year in France compared to only one documented outbreak, monitoring determinants of faecal pollution in the distributed water supply appears to be a relevant alternative to the monitoring of outbreaks in order to highlight common risk factors. The existence of specific factors of water contamination by parasites and viruses (Barrell *et al.* 2000; Dechesne & Soyeux 2007) tends to bias any inference towards the waterborne outbreak risk within its various aetiologies. Nevertheless, the gain in sensitivity should offset the statistical limitation of the bacterial approach, especially for the smallest SZs (<500 inhabitants) for which the syndromic surveillance is ineffective.

CONCLUSION

Tap water faecal contamination incidents are much more frequent in small, rural SZs than in large urban SZs. No available data seem to indicate that the exposure of the population to tap-waterborne pathogens might be different. Furthermore, one might fear that tourist populations, especially large in France, may be particularly exposed. Since epidemiological surveillance is confronted with a lack of statistical power due to the small size of SZs, the monitoring of incidents of faecal pollution of tap water and pollution determinants remains, in practice, an effective approach to indirectly address epidemiological risk factors in very small SZs.

This study confirmed the adverse impact of precipitation on faecal pollution of drinking water and suggested an adverse effect of karst. It also put forward the possibly favourable effect of catchment protection measures and disinfection. The public health challenge that this represents, and the absence of realistic alternative preventive measures, seem to justify the French effort to widely apply both measures. Repeating the study over time should make it possible to validate this approach.

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