Health risks associated with drinking water in a context of climate change in France: a review of surveillance requirements
Pascal Beaudeau, Mathilde Pascal, Damien Mouly, Catherine Galey and Olivier Thomas

ABSTRACT
It is widely recognized that climate change will impact upon human health in a variety of ways. Assessing these impacts and identifying adaptation opportunities requires appropriate monitoring. To identify the need for reinforced surveillance in metropolitan France, we defined a conceptual framework of how climate change could impact upon health risks in relation to drinking water. Three types of climate change-related impacts were identified: changes in raw water quality, changes in water treatment processes and changes in human determinants of exposure in relation to consumers' behaviour. This framework was applied to existing risks and exposure situations in France. An increase in the health burden attributable to drinking water intake is expected due to increased exposure to faecal pathogens, disinfection by-products and cyanobacteria as a result of a combination of natural, technical and human factors. Current sources of health and water data should satisfy surveillance requirements. However, we believe that the creation of a sustainable database comprising behavioural and water management data would be valuable in following and understanding emerging trends.

Key words | climate change, drinking water, France, surveillance

ACRONYMS

AGE | Acute gastroenteritis
AM | Assurance Maladie (Health branch of the French Social Security system)
CBP | Chlorination by-product
DB | Database
DBP | Disinfection by-product
FCI | Faecal contamination incident
GIS | Geographical information system
IARC | International Agency for Research on Cancer
SISE-eaux | Système d’information en santé environnement – eaux d’alimentation (Information system on environmental health – drinking water supply)
THM | Trihalomethane

INTRODUCTION
It is acknowledged that climate change will affect human health via direct and indirect mechanisms (Haines et al. 2006; McMichael et al. 2006; Parry et al. 2007). The impact of climate change on drinking water and potentially related health risks for developed countries have been discussed in detail in many reports (Hunter 2005), whereas associated surveillance requirements are poorly documented (Pascal 2010). Yet a flexible monitoring system is an asset to orientate adaptation, especially in a constantly changing situation. Surveillance data are essential: (1) to contribute to the scientific evidence of the health impact of climate change, (2) to identify and prioritize the risks, (3) to provide early warnings and (4) to help evaluating adaptation or
mitigation policies. A main challenge for achieving these objectives is to develop and maintain health and environmental surveillance systems in a sustainable way.

Bearing this in mind, we assessed the needs for reinforced health surveillance of drinking water related risks in metropolitan France, based on a conceptual framework of how climate change could impact upon those risks. We acknowledged that climate change will interact with a wide range of environmental and social changes. The links between climate change, environmental and social changes and a change in health risks are extremely complex. However, as our purpose was not to evaluate the sole impact of climate change but to promote an appropriate adaptation of the surveillance systems, we have attempted to portray a simplified overview that emphasizes the connection between the different driving forces. Our objectives are to organize the available information in order to point out gaps or opportunities in the monitoring process. The framework we used distinguishes three types of climate change-related impact: changes in raw water quality, changes in water treatment processes and changes in consumers’ behaviour.

Throughout the text, ‘France’ stands for ‘metropolitan France’. A similar approach can be applied to overseas territories, but conclusions are likely to be different given the specific environmental and social features of these territories.

THE MAIN DRIVING FORCES BEHIND CHANGES IN DRINKING WATER-RELATED RISKS

Water quality

Climate change will influence raw water quality in several ways. According to IPCC scenario A2, the worldwide average temperature rise during the 21st century, simulated by the different climate models, could vary between 1.1 and 6.4 °C. Extreme events are also likely to increase both in frequency and in intensity (Solomon et al. 2007). In metropolitan France, the average temperature could rise by 0.83 °C [0.55–1.24 °C] in 2030 compared to 1990 and by 1.37 °C [0.85–1.8 °C] in 2050. Both cold spells (Petoukhov & Semenov 2010) and heatwaves (Schär et al. 2004; Solomon et al. 2007) are expected to become more intense and frequent in Europe (Sinisi & Aertgeers 2010). Such changes in water temperature may modify the ecology of the freshwater ecosystems and degrade water quality (Delpla et al. 2009).

Rainfall projections are more difficult to assess, especially for France as it is located in a transition area characterized by extreme uncertainty in model outcomes (Solomon et al. 2007). European rainfall forecasts anticipate two opposing trends, with increased rainfall in the north and a decrease in the south. Globally, the climate in Paris may become the current climate in Marseilles with considerable uncertainty regarding rainfall whereas the climate in southern France could well become hotter and drier, especially in summer.

Extreme events such as droughts, rainfall and storms are also expected to be more frequent and intense, although this is less certain than the changes in temperatures. A key element in water quality is the amount of water available for run-off and infiltration, defined as the difference between precipitation and actual evapotranspiration. Both of these amounts vary dramatically, even on an annual scale. Future predictions are thus extremely uncertain. Average run-off currently represents 36% of the average precipitation.
in France (Ministère de l’Environnement 2010) and could fall by 30% (Boé 2007; Ducharne et al. 2009). The decrease could range from −20% to −50% during the summer and autumn months with a risk of summer drought in the Mediterranean region. Winter run-off projections are not consistent based on the models used. The expected recharge loss in the River Seine basin according to groundwater course – already overexploited – could reach the current withdrawal level (Ducharne et al. 2009). Piezometric groundwater levels could be lowered along with decreasing infiltration. Flood discharges are believed to be unpredictable based on current knowledge.

If these emerging conditions can reduce the raw water quality, the net impact on drinking water will certainly depend on the water treatment plants and their efficiency at removing pathogens and hazardous chemicals between the water resource and consumers’ taps. However, this paper does not set out to review potential technological advances that may reduce the negative impacts of climate change on water quality.

**INDIVIDUAL AND SOCIAL BEHAVIOUR**

One of the main factors affecting the risks is individual and social behaviour, which affects both the intake of water and the choice of drinking water resources. Significant changes in the behavioural determinants of exposure have already been observed. In 1999, 31% of the French population reported that they did not drink tap water except when heated, thus indicating a minimal average use of tap water (0.51 L/day), including tea and coffee compared to the USA (1.26 L/day) (US Environmental Protection Agency 1997). The consumption decreased by 30% with age and varied considerably between regions. After a period of regular decrease, a trend reversal was observed in the use of tap water for drinking purposes in France. The intake reached a minimum after 2001 with 36% of non-drinkers in France, before increasing again, with 29% of non-drinkers in 2009 (Centre International sur l’eau 2009).

Besides the direct effect of tap water intake, other human factors will impact upon the exposure level by modifying water contamination. A trend towards saving water is already appearing worldwide. Voluntary water-saving actions are on the increase, reflecting the progression of an environmentally friendly approach. For instance, the Paris water board recorded a 32% decrease in production between 1980 and 2008 and anticipates that the falling trend will continue at the rate of 1 to 2% per year (Eau de Paris 2009). However, the cut in consumption hits rural sectors first of all because of the increasing cost of garden watering. In 2009, 15% of French households were already provided with rainwater-harvesting facilities; this included one in two houses in rural areas (Centre International sur l’eau 2009). No national data were available on the prevalence of private wells or boreholes, nor about their use as a drinking water resource. However, a national survey suggested an ongoing fashion to drill private boreholes in connection with public water pricing evolution (Montginoul & Rinaudo 2011). An economic model showed that the mean prevalence of private boreholes could reach 20% of the detached houses in southern part of France. In the sectors where groundwater is abundant and shallow, one house in two could be soon equipped. The drop in the consumption of public sector water leads to increased residence time in the public distribution network, which is likely to affect the water quality through the production of disinfection by-products and the development of biofilms sheltering opportunistic pathogens.

In August 2003 extreme drought resulted in reduction of the water table to below drill depth. Water operators then observed unexpected peaks of public water consumption which overwhelmed the treatment capacity of the plant. Poor drilling practices may also connect different aquifer layers together and cause contamination of deep healthy aquifers by contaminated waters from upper ones. The increasing use of private resources for drinking-purposes may also directly generate main risks of infection (see section on ‘Faecal pathogens’), as well as toxic exposure, e.g. from metal dissolution due to aggressive raw waters. Furthermore cross-connections, may cause accidental contaminations of the public distribution network.

**DEMOGRAPHIC CHANGES**

Finally, from a health perspective, a significant aggravating factor is the population growth. In 2050, the population of France could reach 70 million inhabitants (+15% compared
to 2005). Elderly subjects will constitute a group that is especially vulnerable to the risks related to climate change, particularly with regard to the risk of infection and the consequences of heat waves. Forecasts from the French National Institute for Statistics and Economic Studies (INSEE) for 2050 conclude that the number of people aged 75 years or over could rise from 4.2 to 8.3 million between 2000 and 2030 and those aged 85 or over would increase from 1.2 to 2.4 million. When these projections are extended to the year 2050, they show that the number of people aged 60 years or over would double in comparison to the year 2000; those aged 75 or over would triple and those aged 85 or over would quadruple. Given their loss of immunity with advancing age, elderly people are particularly at risk of infection due to faecal pathogens. According to Gerba and colleagues, 20% of people in the USA are currently immunocompromised as a result of ageing as well as chronic disease (e.g. cancer or diabetes) or medical treatment (e.g. chemotherapy) (Gerba et al. 1996). For Cryptosporidium parvum, the doses responsible for 50% of infections is assessed at 132 oocysts in healthy adults (DuPont et al. 1995) versus 2 in severe immunodeficient adults (Yang et al. 2000). As a result of immunity loss, the mortality rate due to enteric infection among people living in nursing home is 10 to 100 times higher than in the community (Brutel & Omalek 2003).

### EXAMPLES

Our framework was applied to faecal pathogens, disinfection by-products and cyanobacteria-related risks to illustrate: (i) the increasing level of uncertainty amongst determinants, from climatic to hydrological factors, and beyond to ecological and human ones, and (ii) the complexity of interactions among them, in order to identify the most relevant surveillance strategies.

Indeed, the World Health Organization pointed out that the risk of faecal infection remains the primary concern for drinking water, even in developed countries, whereas toxic problems are mostly manifested at local or regional level (World Health Organization 2004). France does not differ from other developed countries. Disinfection by-products and cyanobacteria-related risks are also expected to evolve with climate change (Janus 2008; Pascal 2010).

### Faecal pathogens

The driving forces are illustrated in Figure 2. France does not differ from other developed countries with respect to water-borne faecal exposure and infections. Water systems supplying over 10,000 consumers generally meet regulatory standards whereas the risk is concentrated in small rural facilities (less than 1,000 consumers supplied). Facilities supplying fewer than 2,000 people cover 13% of the French population (7.8 M people) but accounted for 60% of the faecal contamination incidents (FCI) in 2003/2004, defined as a concentration in faecal indicators (Escherichia coli and enterococci) exceeding 20 colony-forming units per 100 mL. In these areas, the daily probability of FCI is still over 1%. Public health initiatives, such as the promotion of disinfection and catchment area protection, targeting small facilities, are the most efficient in reducing the disease burden at national level (Beaudeau et al. 2008b). Data from countries with hotter climates than France (Hunter 2005) do not indicate a significant rise in water-borne risk levels in line with an increase in temperature for pathogens originating in faecal matter, except for Cyclospora sp. (Rose et al. 2001). On the contrary, hotter temperatures should enhance their predation and their die-off in surface water (Fijioka et al. 1981; Servais et al. 1985; Beaudeau et al. 2001).

Actually, the essential mechanisms that will increase the risk of contamination of water courses by faecal matter are: (i) heavy rainfall resulting in surface run-off and (ii) severely low water levels rather than variations in temperature. Heavy rainfall rapidly fills up sewerage systems leading to the discharge of raw water into rivers through waste water overflows. It may also trigger surface run-offs, which usually carry particulate matter and associated faecal matter into surface water courses (Kistemann et al. 2002; Lake et al. 2005) and poorly protected aquifers such as alluvial and karst aquifers (Dussart-Baptista et al. 2005). Water-borne acute gastroenteritis (AGE) outbreaks are also more frequent during heavy rain (Curriero et al. 2001; Nichols et al. 2009; Beaudeau et al. 2008b). The endemic risk of infection principally affects rural populations that are supplied by vulnerable underground resources influenced by surface water (karst waters and shallow alluvial aquifers), particularly for small-scale water supply systems devoid of treatment facilities (Zmirou et al. 1987) or only equipped with chlorination (Zmirou et al. 1987).
et al. 1995). However, clarification treatment of large facilities fed by surface or karstic waters might also be adversely affected by the rise in organic matter concentration in raw water following extreme climatic events (Hurst et al. 2004). Because of the wide range of treatment sophistication observed for large water systems and the possibility of other routes than drinking water for exposure, the link between rainfalls and endemic incidence of AGE (Chou et al. 2010; Drayna et al. 2010) remains poorly reproducible.

The shift in use currently observed from the public water sector to private resources (wells or rain water) could have two consequences. Firstly, it will induce a risk of voluntary or accidental intake of water from contaminated private facilities. The use of private wells for drinking water is linked with a high relative risk of infection compared to the exclusive use of public water (Hunter et al. 2010), e.g. a relative risk of 5 (Uhlmann et al. 2009). Although the harvesting of rainwater is, in theory, reserved for garden watering and toilet flushing, accidental intake can occur. This kind of risk is currently poorly documented (Water Quality Research Australia 2010). Another avenue for concern is the possible increase in the number of accidents due to the backflow of contaminated water into the urban network. This can be attributed to the installation of unprotected connections between the urban network and the domestic network dedicated to local water production, as it existed up to the 1960s when both private and public resources were jointly supplied via a shared indoor network.

In addition, the direct intrusion of surrounding contaminated groundwater into leaking pipes of the distribution networks might be more frequent along with the climate change (LeChevallier et al. 2003). A combination of leaking pipes and submersion by ground water is needed to make the risk effective. An increase in the frequency of pipe breaks is expected due to severe ground drought in summer whilst the local winter outcropping of the water table cannot be excluded in northern France because of increased precipitation.

**Disinfection by-products**

The mechanisms are illustrated in Figure 3. Several epidemiological studies have suggested a positive relationship between disinfection by-products (DBP) and bladder and colorectal
cancers in humans at a trihalomethane (THM) concentration greater than 50 μgL⁻¹ (Morris 1995; Villanueva et al. 2004, 2007; Hrudey 2009). The effects of DBPs on reproduction and development, although widely studied, have yet to be clearly demonstrated (Graves et al. 2001; Bove et al. 2002; Hwang et al. 2002). No studies on bromate, chlorite or chlorate have been published (Environment Canada Health Canada 2010). Disinfection by-products are caused by the reaction between disinfectants (in France, chlorine, chlorine dioxide and ozone) and organic matter present in water (Reckhow et al. 1990; El-Shahat et al. 2001). In France, the public health code set the quality limit in drinking water at 100 μgL⁻¹ for THMs and 10 μgL⁻¹ for bromate in 2008. At this time, about 6% (1.5 million people) of the French population were supplied with drinking water with a THM/L content exceeding 50 μgL⁻¹ and 1% (0.2 million people) with a content over 100 μgL⁻¹. More than 92% of the water treatment plants concerned were fed by surface water. One-third of finished water in France is produced from surface water (Ministère chargé de la santé 2008). In the western (especially Brittany) and southern regions, which do not have large groundwater bodies, surface water accounts for three-quarters of drinking water production. Although water data is sparse at the present time, exposure was expected to peak in the 1980s when prechlorination was largely implemented as the initial step in drinking water treatment. This practice then diminished and was banned in 2001.

Several adverse factors have been identified for the future with regard to chlorination by-products (Figure 3). Some of them will affect the level or reactivity of initial compounds (i.e. organic precursors and disinfectants), whilst others will modify the kinetic conditions of DBP formation (temperature, reaction time). Surface run-offs and low water levels that cause microbial contamination also increase organic precursors in surface water courses (Janus 2008). Climate change will probably exacerbate these pollution events by increasing extreme hydrological events. Increasing summer temperature will lead water operators to enforce chlorine doses to balance the effect of temperature on the dynamics of chlorine consumption in distribution networks. Lastly, the increased residence time in distribution pipes due to the ongoing drop in water consumption will also increase reaction time, favouring chlorine consumption and DBP formation.

Although the eutrophication of surface waters in France due to intensive agriculture and battery farming is steady, it
may result in increased DBP concentrations in drinking water. In eutrophic rivers in Brittany, high total organic carbon (TOC) concentrations (>10 mg/L) are recorded during heavy rainfall and extreme flow events (i.e. both floods and droughts). The TOC concentrations observed during these events are related to the mean nitrate concentrations observed (Delpla et al. 2010). Although the alternating nitrate and organic states of nitrogen is a common feature in surface water, the expected increase in extreme events may exacerbate the release of organic matter, which could overburden the organic matter treatment capacity of water facilities. The adaptation of water treatment to reduce organic matter and the reduction of fertilizer use in agricultural practices will be key issues for decreasing the DBP concentration at tap level (Teksoy et al. 2008; Sinisi & Aertgeers 2009).

Cyanobacteria

The mechanisms are illustrated in Figure 4. Cyanobacteria may produce a large number of toxins and cyanobacterial blooms in drinking water resources may lead to the acute poisoning of consumers (Bell & Codd 1994). Furthermore, cyanobacterial hepatotoxin water-borne intake is suspected to promote the onset of liver cancer (Yu et al. 1989; Ueno et al. 1996; Fleming et al. 2002; Svircev et al. 2009). Nevertheless, results are not consistent and the level of epidemiological evidence is currently inconclusive. Faced with the diversity of the cyanobacteria and associated hazards, and the poor capacity of bloom forecasting, the sampling strategy of the French health authorities is basically driven by visible blooming. As a result, the sampling effort largely depends on the awareness of local officers about cyanobacterial blooms and contamination data are not consistently available throughout France (Goupe de travail Afssa-Afsset 2006). Cyanobacteria and microcystin have been detected in almost 33 and 10% of drinking water samples, respectively. Levels in drinking water were mostly below the quality limit for microcystin (1 μg/L). The geographical exposure pattern is rather similar to DBP since the resource has to be a surface resource, but blooms mainly occur during the summer and early autumn (June–October) and first hit pond waters.

The ecology and the pathogenicity of toxic or ‘opportunist’ micro-organisms could be modified by changes in climatic parameters (de Toni et al. 2009). Experts agree that the frequency of cyanobacterial blooming should increase with climate change. The increase in water temperatures during the summer months will, on the one hand, encourage the growth of cyanobacteria (their optimum

![Figure 4](https://iwaponline.com/jwcc/article-pdf/2/4/230/375291/230.pdf)
temperature is around 25 °C) and, on the other hand, promote the stratification of water in the lakes or reservoirs (Jacoby et al. 2000; Jöhnk et al. 2008) which also satisfies blooming prerequisites. A study based on the effect of the summer heat wave of 2003 on the growth of cyanobacteria has shown that a high temperature was responsible for a four-fold increase in the concentration of cyanobacteria in a lake in Northern Europe (Jöhnk et al. 2008).

Toxin production, which is not constant, also seems to be determined by climatic factors but the link is not sufficiently understood to provide any forecasts. The impact of cyanobacterial blooming on the quality of water in the water supply may be reduced by adequate treatment such as flotation, decantation or filtration whereas chlorine destroys the, microcystin-A (Carrière et al. 2005) which is the most common cyanobacterial hepatotoxin. The use of an algicide is, however, prohibited since it leads to widespread lysis of algae and the release of endotoxins in water.

Since French experts encourage the creation of ponds along the river course in an attempt to offset the shortage of water (Havard et al. 2010), fertilizer control is still the best way of dealing with a cyanobacterial threat at water resource level.

**Recommendations for surveillance**

**Existing systems**

Health surveillance has been defined as ‘the continuous and systematic collection and the analysis and interpretation of data that is essential for the planning, implementation and evaluation of public health practices, closely allied with the diffusion, at the opportune moment, of such data to those that require it’ (Thacker & Stroup 1988). The World Health Organization promotes a drinking water health management programme based on the monitoring of waterborne infectious disease in addition to the regulatory follow-up of the quality of finished water (Council of the European Union 1998) and continuous risk assessment (World Health Organization 1996). As diseases originating in the water are multi-factorial (i.e. there are several causal agents and several routes of exposure), health data alone cannot indicate the extent to which they are attributable to water. In this regard, water exposure data are mandatory to implement a system which supports the allocation of the disease to water. The concept of risk surveillance was promoted to address this issue (Quénel 1995), based on the collection of both environmental and health data and the development of tools for modelling the link function between water factors and health outcomes.

The setting-up of data bases dedicated to health or water management led strategies for surveillance system development to focus on reusing these data for epidemiology. We thus set up a full system, i.e. encompassing exposure and health data, for the monitoring of both epidemic and sporadic AGEs risk due to the faecal contamination of drinking water. There is no such full integrated approach devoted to the monitoring of toxic risks, but only water database improvement works, whereas aetiological studies based on both water and health databases are sporadically performed. Special attention is paid to filling gaps in exposure related data, as the lack of exposure data limits the possibility to perform long-term risk assessments.

**Essential health-related data**

To date, surveillance systems have focused on monitoring health outcomes. Several information systems are available to alert the general public to health-related issues. Compulsory reporting covers collective food poisoning and some infectious diseases due to faecal pathogens (Salmonella typhi and Vibrio cholerae) that are, however, unlikely to re-emerge in France (Institut de Veille Sanitaire 2004). Reference labs also perform voluntary surveillances of Salmonella, Shigella, Campylobacter, shiga-toxin producing E. coli and non-cholera Vibrio infections. Syndromic surveillance systems, based the online detection of emergency consultation data with related diagnoses (Josseran et al. 2006), have been set up following the 2003 heat wave, in order to detect any emerging health threats right from the outset. In 2009, a poisoning and toxic substance surveillance system was launched based on monitoring calls to anti-poison centres. Both these systems are expected to provide alerts relating to rare and unforeseeable risks, such as those brought about by malicious acts or the emergence of pathogens that might strike water supplies (Simno-Tellier et al. 2009). Specific field investigations are however to be carried out to establishing a link with water whatever the
Some drugs used in the treatment of gastroenteritis have been challenged by a change in treatment or care funding. A recent study, Table 1). However, the stability of the database could be evidence in towns with a population of over 50,000 following a time series design (Tuppin et al. 2010). It has been applied to monitoring the medical treatment of AGE, which is the most common indicator for diseases that can be attributed to the intake of faecal pathogens (Table 1). Indeed it is sensitive, with an annual incidence rate in developed countries ranging from 0.2 per individual in England and Wales (Wheeler et al. 1999), 0.3 in France (Van Cauteren et al. 2011) to 0.7 in the USA (Herkstad et al. 2002), depending on the case definition and on epidemiological conditions during the study period. It also shows a convenient reactivity, with a short incubation time compared to other infections such as hepatitis A, which facilitates aetiologic research. The analysis of drug prescriptions provides AGE daily incidence rate assessments at municipality level. This AGE indicator is more specific to clinical AGE case definition than drug box counts (Bounoure et al. 2010) more often used for surveillance (Berger et al. 2006). Even restricted to cases in which medical advice was sought, the AM indicator showed adequate sensitivity and spatial and temporal awareness to address risks inherent in drinking water (Beaudeau & Bounoure 2006; Beaudeau et al. 2006). For instance, the clustering of AGE cases is expected to help detect water-borne outbreaks in villages of 1,000 inhabitants (Table 1) and risk factors of endemic AGE can be evidenced in towns with a population of over 50,000 following a time series design (‘Turbidity and AGE’ study, Table 1). However, the stability of the database could be challenged by a change in treatment or care funding. Some drugs used in the treatment of gastroenteritis have limited therapeutic efficacy. For this reason, several of them have already been partly removed from the list of reimbursed drugs and consequently deleted from the database since 2007 (Assurance Maladie 2009). Yearly field surveys involving drugstores aim at fitting the prescription-based definition of an AGE case to changes in drug-funding policy (Bounoure et al. 2010). Economic conditions and social factors, e.g. educational level (Tam et al. 2005; Beaudeau & Bounoure 2006), also impact upon the search for medical advice in relation to AGE and prescription content. Since the social and economic conditions may alter over time, the prescription-based AGE index is of limited use in detecting multiannual trends in the clinical AGE incidence rate. However, it provides adequate support for investigating short-term events and research into water-related risk factors.

The cancer registries are exhaustive epidemiological sources for supporting studies on carcinogenic effects. In France, in 2003, 17 registries covered 15% of the population (Belot et al. 2008). In the future, the ‘multi-source’ system, which will join together various databases of medical and medical-administrative activity (hospital admissions, medical insurance and anatomical pathology) will complement the cancer registries and ensure national coverage. Case anonymity, however, limits the multi-source system to ecological protocols whilst reduced diagnostic and therapeutic resources for certain cancers exclude these from potential studies, as is the case with skin cancer. Cancers to be targeted as a priority depend on (i) their current health burden, (ii) how attributable they are to drinking water and (iii) the likelihood of an increase in incidence with climate change. We suggest that relevant cancers are bladder cancer, colorectal cancer and liver cancer, even though they are not specific of an exposure to water contaminants (Table 2). Among these three types of cancers, the registries

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**Table 1 | The French monitoring system for water-borne diseases.** The light grey refers to the water-borne acute gastroenteritis (AGE) monitoring system. The statistical power needed to evidence the link with water quality depends on the level of the relative risk and the size of the exposed population, which precludes the smallest supply zones from this kind of epidemiological monitoring.

<table>
<thead>
<tr>
<th>Size of the supply zones (# inhabitants supplied)</th>
<th>Large supplies (&gt;50,000 inhabitants)</th>
<th>50,000–1,000 inhabitants</th>
<th>Small supplies (&lt;1,000 inhabitants)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Outbreaks</strong></td>
<td>Outbreak investigations (local level)</td>
<td>Surveillance (national level)</td>
<td>Investigation tools development</td>
</tr>
<tr>
<td><strong>Background risk</strong></td>
<td>Turbidity &amp; AGE time series study</td>
<td>[Analytical individual studies]</td>
<td>Surveillance of the water microbial contamination</td>
</tr>
</tbody>
</table>
database for liver cancer remains problematic because of the high confusion rate between primary and secondary (metastatic) liver cancer (Remontet et al. 2005).

**Essential water data**

The SISE-eaux database (Health and environment information system – water supply) which brings together the results of regulatory monitoring of the quality of distributed water (The Council of the European Union 1998), is the only national resource on drinking water quality to be continuously updated since 1998. It enables the estimate of exposure to all regulated contaminants in drinking water throughout France. Some water system features dating back to 1998 are present in the SISE-eaux database: location of facilities and sampling points, annual production, connections between water facilities, treatment according to a four-class nomenclature (i.e. none, disinfection, clarification-disinfection, more sophisticated treatment), and regulatory catchment protection status. In 2010, new items and functionalities have been added to the database: structural changes in water systems are recorded from now on; annual flows transferred between interconnected water systems and a more detailed treatment nomenclature can be implemented by local environmental health officers.

More detailed treatment information largely enhances the scope of analytical data available for exposure assessment. This allows drinking water contamination to be assessed on the basis of raw water contamination values and concentration reduction values published in the literature. This is crucial for microbial risk (LeChevallier & Au 2004), because the concentration in finished water is generally below detection limits.

The introduction in the SISE-eaux database of hydraulic residence time distribution parameters (e.g. percentiles 50, 90, 100 and corresponding areas) would thus improve the knowledge of exposure to THM throughout France. Trihalomethane is indeed measured at the plant outlet but there is a two- to five-fold increase in concentration between the treatment plant and the consumer's tap. A model (Mouly et al. 2010) was necessary to assess concentrations at tap level from the items actually or potentially available in the SISE-eaux database.

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**Table 2** Water, cancer and climate change: which cancers should be monitored as a priority. Adapted from (Pascal 2010; Remontet et al. 2003)

<table>
<thead>
<tr>
<th>Location of the cancer</th>
<th>Incidence and mortality rates ((10^{-4})) Male / Female</th>
<th>Products / agents</th>
<th>Imputability of the cancer to the product</th>
<th>Specificity of the cancer to the product</th>
<th>Proportion of water involved in the exposure</th>
<th>Assumed increase in exposure by water with climate change</th>
<th>Priority ranking for monitoring in line with climate change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bladder</td>
<td>18.3 / 2.3</td>
<td>Chlorination by-products</td>
<td>Yes</td>
<td>Low</td>
<td>100%</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>Bladder</td>
<td>6.3 / 1.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kidney</td>
<td>5.7 / 2.1</td>
<td>Arsenic</td>
<td>Yes</td>
<td>Low</td>
<td>High</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Kidney</td>
<td>4.6 / 1.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rectum and colon</td>
<td>39.1 / 24.6</td>
<td>Chlorination by-products</td>
<td>Probable</td>
<td>Low</td>
<td>100%</td>
<td>Yes</td>
<td>2</td>
</tr>
<tr>
<td>Rectum and colon</td>
<td>15.8 / 8.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liver</td>
<td>52.2 / 8.6</td>
<td>Arsenic</td>
<td>Yes</td>
<td>Very low*</td>
<td>Probably high</td>
<td>Yes</td>
<td>3</td>
</tr>
<tr>
<td>Liver</td>
<td>48.9 / 7.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lung</td>
<td>7.6 / 9.5</td>
<td>Arsenic</td>
<td>Yes</td>
<td>Very low*</td>
<td>High</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Lung</td>
<td>1.6 / 1.1b</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skin</td>
<td>9.0 / 3.4</td>
<td>Helicobacter pylori</td>
<td>Yes</td>
<td>Medium</td>
<td>Probably non-negligible</td>
<td>Possible</td>
<td>No</td>
</tr>
<tr>
<td>Stomach</td>
<td>5.9 / 2.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\*Except angiosarcoma.
\bMelanoma only.

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It would also be worth recording the safety rules and mechanisms adopted by water operators: alarm devices against intrusion, pump break-down, lack of chlorine or excess turbidity, remote transmission of signals, frequency of follow-up visits and stand-by rota. They indeed condition the duration of the consumers’ exposure from the start of the water contamination event to the implementation of corrective measures. The reporting and recording of some pre-outbreak signals would also help identify adverse factors of acute water contaminations and spot the water systems subject to outbreak threat. They encompass clustered consumers’ complaints for organic pollution (‘swamp smell’) received by water operators, and ‘do not drink’ notifications issued by local health authorities.

Although devoted to water regulatory monitoring, the SISE-eaux database has acquired an increasing potential for exposure assessment and could also help identify those installations and populations that are most vulnerable to climate change and target these categories for adaptation. Connecting health, water, geological and socio-demographic geo-referenced data through a geographical information system (GIS) is a prerequisite to efficiently achieve this objective. It would also enable recognition of waterborne outbreaks by testing how distribution zones fit the municipalities’ areas where AGE case clusters may be pointed out through AM data periodic screening. Tests are in progress in the Haute-Loire pilot département.

Regulatory water testing does not cover household water systems. Home owners are, in theory, obliged by law to declare both their abstraction facilities. In the case of alimentary use of water, they are also expected to carry out a basic analytical follow-up of water quality. Compliance with these regulations is, however, believed to be poor since no acceptable control procedures can be implemented. Specific surveys and economic models applied to southern regions (Montginoul & Rinaudo 2011) are thus to be carried out throughout France to address this issue.

Some studies carried out over time (Schwartz et al. 1997; Beaudeau et al. 1999; Aramini et al. 2000; Schwartz et al. 2000; Egorov et al. 2003; Tinker et al. 2010) have highlighted the opportunity of using on-line water operation data (e.g. turbidity, free chlorine residues) as indicators for faecal water contamination. This non-microbial approach to exposure offers specific advantages such as the possibility to catch transient risky events (e.g. treatment commutation, filter washing, local lack of chlorine) that cannot be recorded through occasional manual point sampling. Since the risk is described as a function of data drawn from routine operations, its interpretation and consequent technical recommendations have to be strengthened through dialogue with water operators in order to progress towards improved field management. Eligible sites for a time-based approach must, however, meet size conditions for statistical power (Table 1) and a simple distribution scheme (e.g. a single resource) to avoid misclassification for exposure. The InVS is investigating the option to appraise this approach as part of a multi-centre study known as the ‘Turbidity and AGE’ study (Beaudeau et al. 2010a). The most challenging aspect of this approach is the inter-site heterogeneity of the link between turbidity and the pathogen load, depending on the raw water grade (e.g. pathogen shedding on the watershed, vulnerability of the water course) and the treatment (e.g. presence/absence of clarification process). The use of additional probes, such as UV absorbance for surface water and electrical conductivity for groundwater, is currently being investigated in order to improve the specificity of water data with regard to pathogens load.

**Essential human factor data**

The monitoring of water-borne exposure-related behaviour will be crucial in order to achieve a greater understanding of the risks inherent in change. It is a question of moving away from considering exposure in proportion to water contamination, assuming the water drinking behaviour constant over time and thus overlooking the collection of water intake data or exposure-related behavioural components that may develop faster than water contamination in the climate change prospect.

Human exposure factors are rarely considered when working on the impacts of climate change. However, they could become a high-priority focus in terms of understanding, assessing and monitoring the exposure of the population. To this end, repeated large-scale transverse surveys could be carried out that look at water-related behaviour patterns, but also on water operators’ strategies to cope with the water resource scarcity and changes in
the socio-economic context. Table 3 lists some valuable information, which is either already collected or which should be collected in the future. The effects on tap water intake of outbreaks, ‘do not drink’ reports, chronic or temporary chemical or microbiological discrepancies in distributed water systems are not documented in the present batch of surveys. The water drinking behaviour of French and foreign tourists in rural areas should also be examined considering the appeal of France as a tourist destination.

The ongoing drilling and rainwater harvesting fever has to be monitored through specific approach in order to understand and anticipate the shift of water related risks towards household provision (see section on ‘Essential water data’).

**DISCUSSION**

The current state of the French surveillance system devoted to infectious risk should achieve the objectives of surveillance (Thacker & Stroup 1988) to different extents:

- **Attributability of health events to water exposure.** Since AGE like other waterborne diseases is not specific to drinking water route of exposure, the attributability of health events to water exposure is a prerequisite of other objectives. The availability of both adequate water and health data conditions the achievement of this objective. Specific methodological developments are carried out to establish the link between the health and exposure data to model the waterborne microbial risk: adaptation of time series modelling tools to deal with the endemic risk (AGE and turbidity study) and AGE cluster testing to find out possible water zone involved in outbreaks (Table 1).

- **Early warning.** At the current stage, outbreak surveillance remains retrospective since health outcome data are delivered every six months. First results (Rambaud et al. 2011) advocate for a real-time use. However, at best five days will run between the onset of the outbreak and the epidemiological signal. Acknowledging that the harmful exposure lasts less than one week in most of the outbreaks thanks to local management, only a part of cases associated with long lasting unreported outbreaks could be avoided by the daily provision of AM data. Thus, the system targets the risk factors identification to avoid subsequent outbreaks and promote relevant preventive action, more than the early management of the outbreaks, as already stated elsewhere (Berger et al. 2006).

- **Evidence for impact and trends.** The re-use of data generated by medical activity leads to an AGE indicator, the level of which depends on both socio-economic and epidemiological factors. Impact assessments are thus possibly biased by socio-economic factors. At the national level, specific surveys on health-care seeking enable

<table>
<thead>
<tr>
<th>Practice</th>
<th>Indicators and level of collection</th>
<th>Data resource and availability starting year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change of public water resources</td>
<td>Abandoned abstraction facilities (WS)</td>
<td>SISE-eaux, 2000</td>
</tr>
<tr>
<td>Protection of catchment area</td>
<td>Official orders (WS)</td>
<td>SISE-eaux, 2000</td>
</tr>
<tr>
<td>Private resources</td>
<td>Number of private wells/drills (D)</td>
<td>Regulatory census (2010)</td>
</tr>
<tr>
<td></td>
<td>Use as drinking resource (N)</td>
<td>Survey, potential</td>
</tr>
<tr>
<td></td>
<td>Sale of rain-harvesting facilities (N)</td>
<td>Survey, potential</td>
</tr>
<tr>
<td>Water treatment</td>
<td>Treatment standard definition (WS)</td>
<td>SISE-eaux, 2000 (detailed from 2010)</td>
</tr>
<tr>
<td>Water safety</td>
<td>Description of alarms (WS)</td>
<td>SISE-eaux, potential</td>
</tr>
<tr>
<td></td>
<td>Stand-by rota (WS)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Frequency of the check visits (WS)</td>
<td></td>
</tr>
<tr>
<td>Public water consumption</td>
<td>Daily volume (N)</td>
<td>Water operators, annually</td>
</tr>
<tr>
<td>Backflows in public distribution networks</td>
<td>Rate of backflow preventers (WS)</td>
<td>Water operators, potential</td>
</tr>
<tr>
<td>Contamination accidents</td>
<td>Boiling advices (WS)</td>
<td>SISE-eaux, 2010</td>
</tr>
</tbody>
</table>

*aWS: water system; D: district; N: national (surveys).*
limited inference from medicalized AGE case counts to clinical case estimates (Van Cauteren et al. 2011). At the local level, socio-economic heterogeneity impaired spatial comparison of incidence rate in endemic conditions, but it does not prevent outbreak detection, since the incidence rate is then much higher than in endemic contexts (Beaudeau & Bounoure 2006).

- Evidence for risk factors and their evolution. The main purpose of the microbial risk surveillance remains the search for risk factors rather than the impact estimation. Since risk factor identification basically relies on relative risk examination and not on considerations about health burden, the surveillance system should resist to changes in the drug prescription based AGE case definition.

- Support public health decision and public health action appraisal. The surveillance of the microbial risk is tightly bound to health and water management. Concerning the outbreak surveillance, the local stakeholders are both the providers of the field signals and the final receivers of public health recommendations. This continuous feedback favours the issue of realistic recommendations at local and national level. Similarly, the extensive use of water operation data for exposure assessment for endemic risk surveillance also guarantees the consistency of the risk expression with water operation daily practice.

- Support research and international exchange. Once validated, data are available to researchers for specific works. Besides statistical risk modelling, the development of specific concept-driven models, e.g. ‘Susceptible, Exposed, Infectious and Recovered’ (SEIR) models (Eisenberg et al. 1996) could help establish the link with microbiological approach and support simulations on the role of behavioural components in infectious waterborne disease monitoring. Concerns about climate change consequences spread worldwide. Southern France shares the threat of drought with Mediterranean countries whereas Northern France could experience wetter winters like North European countries. International and regional exchanges about both risks and mitigation measures are crucial for anticipation and efficient allocation of national means (Pascal 2010).

Collaboration is especially needed in the field of toxic risks because no routine epidemiological exploitation is planned by the surveillance team, but only methodical improvement of exposure and health data collection. As stated in the section ‘Examples’, the lack of French epidemiological data, the national specificity of water processing and the probable adverse evolution of the risks should warrant incentive measures to stimulate the interest of researchers in DBP and cyanobacteria issues.

As water-related risks are more sensitive to environmental and social changes than climate change, the relevance of factors such as land use, water process adaptation or consumer behaviour can be dismissed (Pascal 2010). The ongoing use of alternative water resources (e.g. private wells) deserves attention since consequent exposure to pathogens could locally exceed the exposure attributable to public water. Furthermore, since hazardous behavioural changes precede health outcomes, the follow-up of related human factors could provide earlier warnings than health-related signals, which would be useful for prompt public health intervention.

The public health aspect of the monitoring system should, however, adjust in line with the main risk factors, shifting from public drinking water supplies to a private resources. Public health intervention would thus be increasingly complicated by data anonymity, which precludes direct use of the information for notification purposes and at a personal level. Other preventive measures, such as education, should be considered.

Some requirements for knowledge improvement can be highlighted. Downscaling of climate models to local and decennial scope is necessary in order to refine consequent health projections. In the field of toxic risks, a better understanding of the chemistry of organic matter and DBP toxicity could help assess the exposure to DBP, more relevant dose-risk functions and guide water operators to healthier water management.

CONCLUSION

The surveillance of water-borne faecal risk has warranted the development of some specific tools such as the AGE syndromic database from existing resources on the one hand. On the other hand, toxic water-borne risks are
addressed by studies based on pre-existing health databases such as cancer registries. In both fields, exposure is drawn from the database for the regulatory monitoring of water quality. Besides, water operation data are being assessed as a promising resource to highlight the dynamic feature of risks.

The expected impact of climate change on drinking water-related health problems does not justify the development of new health surveillance mechanisms. Existing systems should be strengthened and enriched by behavioural data to ensure their sustainability.

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REFERENCES


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