Perspectives on drinking water monitoring for small scale water systems

Benoit Roig, Estelle Baures and Olivier Thomas

ABSTRACT

Drinking water (DW) is increasingly subject to environmental and human threats that alter the quality of the resource and potentially of the distributed water. These threats can be both biological and chemical in nature, and are often cumulated. The increase of technical frame of water quality monitoring following the evolution of water quality standards guarantee the regulation compliance in general but is not sufficient for the survey of small scale water system efficiency. The existing monitoring is not well suited to insure a good quality of distributed water, especially in the event of a sudden modification of quality. This article aims to propose alternative solutions, from the examination of monitoring practices, in a bid to limit the risk of deterioration of DW quality.

Key words | drinking water quality, management, monitoring, threat

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CONTEXT

A relevant regulatory frame

Water supply is becoming a matter of concern with regard to a growing population and concomitant usages for industries or agriculture. Even where water quantity does match water demand, the quality of resources may be degraded by natural (climate) or anthropogenic (discharges, runoff, etc.) pressures. The provision of improved-quality water for the entire worldwide population is now an objective mentioned on the agendas of major international organizations and national governments (Unicef & WHO 2012).

The United Nations General Assembly has recently recognized that 'safe and clean drinking-water and sanitation is a human right essential to the full enjoyment of life and all other human rights' (United Nations 2010). The recognition of this right implies the protection of water resources used for drinking water supply. Water producers are required to comply with increasingly exacting legislation on water quality. They also need to face emerging issues related to the constant appearance of new chemicals in water (pharmaceutical, endocrine disruptors, etc.) whose effects on the environment and health are still not very well known.

Even if earlier laws did exist (US Clean Water Act in 1972, French first water law in 1964), water quality regulations have been strengthened since the end of the 1990s. For example, under the amendment of the Safe Drinking Water Act in 1996, the US Environmental Protection Agency (USEPA) sets health-based quality standards of several contaminants in drinking water. The European Commission approved the Drinking-water Directive (DWD) in 1998 and the Water Framework Directive (WFD) in 2000. The latter establishes an objective of good status for all waters by 2015, a framework to ensure public health security for water intended for human consumption and an obligation

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to promote a policy for the management and protection of water resources. In 2011, the EU concluded that no legislative revision of the DWD under the ordinary procedure was required and challenged for a coordinated implementation of both (Falkenberg & Bloech 2011). However, even if knowledge of the status of water has considerably improved (three implementation reports were published), according to the commission, more efforts are needed to ensure the achievement of the directive objectives in the 2015, 2021 and 2027 planning cycles (Falkenberg & Bloech 2011)

Australian Drinking Water Guidelines (ADWG) were also published in 2004 providing a comprehensive list of potential hazardous agents in drinking water. These guidelines consider continuous, intermittent or seasonal pollution patterns, as well as extreme and infrequent events such as droughts and floods. At the same time, the World Health Organization (WHO) proposed in the revised Water Quality Guidelines the development and implementation of water safety plans (WSP) by water suppliers for a new preventive risk management approach (Bartram *et al.* 2009). This approach aims to ensure the safety of a drinking water supply through the use of a comprehensive risk assessment and risk management approach (Hulsmann 2005). These plans should address all aspects of the drinking water supply, focusing on control of abstraction, treatment and delivery of drinking water. They consist in particular of the identification of control measures in the drinking water system that will collectively control identified risks and ensure that health-based targets are met. For each control measure identified, an appropriate means of operational monitoring should be defined so as to ensure that any deviation from required performance is detected both rapidly, and in good time.

Some efforts to be pursued

Despite this regulatory framework, water quality compliance is not fulfilled in small scale water systems (SSWS) in particular for microbiological quality (Pitkänen *et al.* 2010; Risebro *et al.* 2012). It is stated that in Europe, 30 to 50% of water distributed by SSWS would often be of impaired quality (Richardson *et al.* 2009; Falkenberg & Bloech 2011).

More generally, water resource quality is influenced by both 'natural' and anthropogenic driving forces. The former include spatial and temporal variation in water availability (Richardson *et al.* 2009), wildlife, topography, geology, vegetation and the impact of climate change, particularly with respect to the frequency and severity of droughts or rainfalls. Anthropogenic driving forces come from each of the key sectors that use water (industry, energy production, public water supply and agriculture) and include point sources (e.g. wastewater discharges) and non-point sources (e.g. surface runoff). For example, municipal wastewater discharge can be a major source of pathogens; urban runoff and livestock can contribute substantial microbial load; body contact recreation can be a source of faecal contamination; and agricultural runoff, including agrochemicals and manure (the main sources of nitrate and pesticides) can lead to increased treatment challenges. Water contamination by pathogens is of particular interest both because of its consequences (waterborne infectious disease) and because of the difficulty of predicting it (due to failure of the use of indicator organisms (Harwood *et al.* 2005). Emerging pollutants are also increasingly under consideration (Deblonde *et al.* 2011; Boxall 2012; Tiehm *et al.* 2012), due to poor knowledge of their impact on the population at ultratrace concentrations (Touraud *et al.* 2011; Stuart *et al.* 2012). For the first time, three substances (diclofenac, 17β-estradiol, 17α-ethynylestradiol), was just included in the priority list of the WFD. Even though there are no agreed environmental quality standards at the moment, such molecules have been monitored in a number of installations as well as in many resources since several years (Deblonde *et al.* 2011; Rodil *et al.* 2012).

Climate change issues

Climate changes act as an indirect aggravating factor for the anthropogenic pressures on the environment (Cromwell *et al.* 2007; Delpla *et al.* 2009; Roig *et al.* 2012). In particular, the main determinants of climate change having a direct or indirect impact on water quality are air temperature and extreme water events (flood, drought) (Van Vliet & Zwolsman 2008; Brodie & Egodawatta 2011; Hrdinka *et al.* 2012). Resource availability is linked to these periods (Ranjan *et al.* 2006; García-ruiz *et al.* 2011; Nan *et al.* 2011), and it becomes important to consider these extreme events in assessing both evolution of water stress and efficiency of the treatment processes (Wilby *et al.* 2006; Johnson *et al.* 2009; Emelko *et al.* 2011).

Changes in water temperature may modify the ecology of freshwater ecosystems and degrade water quality

(Delpla *et al.* 2009). Most physico-chemical (solubilization, complexation, degradation, evaporation, photolysis, etc.) and biological (microorganisms catabolism, etc.) reactions are promoted by an increase in temperature and/or in solar irradiation (Malmaeus *et al.* 2006; Monteith *et al.* 2007; Soh *et al.* 2008). Droughts, for example, increase the concentration of dissolved substances in water while at the same time decreasing the concentration of dissolved oxygen (Prathumratana *et al.* 2008; Van Vliet & Zwolsman 2008). But droughts can also promote the assimilation of nutrients by plants or the adsorption/complexation of heavy metals on total suspended solids (TSS) or sediment.

Phototransformation processes occurring in the environment should also be considered because they generate transformation products (Buerge *et al.* 2006; Petrovic & Barceló 2007; Canonica *et al.* 2008), the toxicity of which remains questionable in some cases.

Heavy rainfall events produce an increase in river flow rates, the higher risk of which is an increased transport of pollutants by runoff. In temperate countries, predictions forecast an increase in mean volume of each rainfall event (Brunetti *et al.* 2001; Bates *et al.* 2008). In addition, rainfall is admitted to be one of the more climatic factors affecting the microbial quality of very small (private) water supplies (Richardson *et al.* 2009).

Climate change is not the sole factor responsible for alteration of water quality. Global changes, including soil use, urbanization and its consequences on moisture, etc., also contribute to water quality degradation (DiDonato *et al.* 2009; Carlson *et al.* 2011; Astaraie-Imani *et al.* 2012).

Specificity of SSWS

In addition to natural and anthropogenic pressure, drinking water quality degradation can be affected by treatment plant inefficiency through the process itself and the water supply size. Concerning treatment processes, some outbreaks in the recent past (Curriero *et al.* 2001; Schuster *et al.* 2005; Tickner & Gouveia-Vigeant 2005; Aryal *et al.* 2012), showed a need for regular reevaluation of techniques to ensure effective drinking water disinfection. This is particularly important to protect small (vulnerable) water supplies (Pitkänen *et al.* 2010). Indeed, such processes, in addition to effectively eliminating harmful microorganisms, are strong oxidants (chlorine, ozone, chlorine dioxide, chloramines) that oxidize the organic matter and bromide naturally present in most source waters, forming so-called disinfection by-products (DBP), the trihalomethane (THM) of which such as haloacetic acids, oxyhalides, haloacetonitriles, halonitromethanes, haloamines, iodo-acids, haloamines, nitrosamines, iodo-THM (Mouly *et al.* 2008), have been more investigated due to their potential cancerogen suspected effect (Singer 1993). In addition, many factors significantly influence the formation of DBP: temperature, pH and dissolved organic carbon (DOC), ammonia and ions bromides concentrations, as well as the types of treatment applied, the doses of chlorine and time of contact (Nikolaou *et al.* 2004; Teksoy *et al.* 2008).

Water supply size can also be involved in water quality degradation. Small scale water supply is of particular interest, and remains a significant challenge for many countries – partly because human, technical and financial resources are limited (Hulsmann 2005; United Nations & WHO 2011). Sadiq *et al.* (2010) have shown, with the small utility performance indicators, that a link could be established between the various technical (source and treated water quality, infrastructure) and non-technical (human and operational factors) characteristics of water supply systems and the distributed water quality of small utilities. WHO estimates that 10% of European citizens receive drinking water from these small or very small systems, including private wells. But only 60% of the small water supply zones deliver water which is fully compliant with the requirements of the Drinking Water Directive 98/83/EC.

Lastly, socioeconomic factors like demographic developments, urbanization, economic progress, and social changes, as well as lack of investment in rural and municipal water supplies, can also influence water quality.

MONITORING SYSTEMS

Parameters and proxies

With the implementation of WSP, water quality control is a key point both in ensuring the safety of a drinking water supply and in assessing hazards linked to the deterioration of water body quality, for example surface and karstic resources (Bates *et al.* 2008; Bartram *et al.* 2009). Drinking water guidelines are proposed from country to another country based on the WHO Guidelines for drinking-water quality (WHO 2011). They may be different among countries. For example, the management framework of drinking water quality in Australia (with ADWG), the UK (with BS6700) and the USA are considered stronger compared than the Canadian one, while as developing countries, India needs to improve its BIS 10500-1991 and China is still working on its premature water standards (Kusumawardaningsih 2010).

In Europe, the regulations organize water quality control from catchment to treatment plant, using a number of parameters (Table 1). In regular situations, characterized by a limited seasonal variation and a homogeneous composition in time and space, water quality monitoring based on these parameters is, on the whole, satisfactory. Quality limits have been established to allow quantified quality control.

Conventional parameters are generally recognized as relevant for health risk assessment for drinking water and easy to measure in a qualified laboratory (accredited and agreed). However, the list of parameters even completed by specific hazardous substances is actually not complete as some emerging substances showing toxic or ecotoxic effects, will likely be soon considered (e.g. estrogens). Another limitation of such parameters becomes clear when water is subjected to unexpected quality variations, in particular in case of global changes (namely climatic events with change in heavy rain pattern) or accidental or intentional contamination. These parameters can also fail to provide the right answer with regard to public health concerns. For example, the use of

Table 1 | Parameters and proxies used for quality control of surface (SW), ground (GW) and treated waters (adapted from Mons (2008))

Parameter	Resource		Treated water	Proxy
	SW	GW		
Microbiological parameters				Turbidity, NH_4^+, UV
E. coli	■	■	■	
Enterococci, *Clostridium perfringens*	■		■	
Total coliforms		■	■	
Colony count, total cell counts, cultivation-free viability analysis			■	
Giardia/Cryptosporidium, Enteric viruses, *Campylobacter*	■			
Chemical parameters				
Arsenic, fluoride, selenium, nitrate		■	■	
Benzene, benzo(a)pyrene, boron, bromate, 1,2-dichloroethane, nitrite, antimony, cadmium, copper, chromium, lead, mercury, nickel, PAHs, organic micropollutants[a], tetra- & trichloroethene, disinfection by-products, sodium, calcium, magnesium, sulphate			■	Organoleptic, UV absorption, global toxicity, genotoxicity, endocrine disruption
Cyanides	■		■	
Pesticides	■	■	■	
Ammonium	■	■		
Iron, manganese		■		
Physico-chemical parameters				UV visible absorption
DOC/TOC, turbidity	■			
Taste, odour, colour, pH, chloride, alkalinity, conductivity, T°, O_2			■	
Other parameters				
Genotoxicity, acute toxicity, algae toxins, AOC/BDOC			■	
Radioactivity		■		

PAHs: polycyclic aromatic hydrocarbon, DOC: dissolved organic carbon, TOC: total organic carbon, UV: ultraviolet, T°: temperature, O_2: dissolved oxygen, AOC: assimilable organic carbon, BDOC: biodegradable dissolved organic carbon.
[a]General group, consisting of e.g. pharmaceuticals, industrial pollutants, endocrine disrupting chemicals (EDCs), etc.

indicator organisms (total and faecal coliforms, enterococci, Clostridium perfringens) has often proved to be powerless to predict the presence or absence of pathogens (Harwood *et al.* 2005; Field & Samadpour 2007). Simple monitoring schemes based on detection of a single indicator are not adequate for public health protection.

In this context some proxies giving a global assessment of one or several parameters may be used (as for example: turbidity for bacterial contamination, UV spectrometry for organic contamination). Generally more rapid and simple to measure than conventional parameters (proxies can be implemented on line), they are meanwhile less specific. But they can be used after comparative validation with the related parameter(s), including all analytical criteria, in particular, reproducibility and repeatability in order to estimate the measurement error. This is of high importance especially when decision making is based on these proxies.

About sampling programs relevance

Because monitoring is carried out under a discontinuous way (based on sampling and laboratory analysis) the choice of sampling frequency may be not adapted to transient water degradation. For example, in sanitary control, the frequency of monitoring a SSWS, serving less than 5,000 people is performed between once a year and once every 5 years (depending on the flow rate) for the resource and between once a month and once every 5 years for the corresponding treated water (distribution and consumption points) (Table 2).

Water sampling frequencies vary from a country to another sometimes depending on the type of quality parameters. For example the sampling frequency varies form once a month (<100 inhab.) to once a day (>100,000 inhab.) for microbiological monitoring in Australia. For chemical monitoring the frequency varies from twice per year (<5,000 inhab.) to once a month (>5,000 inhab.).

Appropriate techniques for water quality monitoring imply consideration of the entire analytical chain, from sampling strategy to transmission of results. Numerous analytical techniques are available, as reported in the WHO Guidelines for drinking water quality (WHO 2011). However, it is not unusual to find different results for an identical sample because of variability in one, or several, steps of the analytical procedure (including sampling, transport, storage, and sample preparation and analysis).

Table 2 | Example of sampling schedule and water sanitary control analysis programme for small and medium water supplies (adapted from the French Decree of 11 January 2007 (Journal Officiel 2007; Bessonneau *et al.* 2011)

Water resource Flow (m³/day)	Annual frequency GR[a]	SR[a]
<10	0.2[b]	0.5
10 to 99	0.2	1
100 to 1,999	0.5	2
2,000 to 5,999	1	3

Distribution and consumption points		Annual frequency			
Population supplied (inhabitant)	**Flow (m³/day)**	**P1[c]**	**P2**	**D1**	**D2**
0 to 49	0 to 9	1	0.1/0.2	2/4	0.1/0.2
50 to 499	10 to 99	2	0.2/0.5	3/4	0.2/0.5
500 to 1,999	100 to 399	2	1	6	1
2,000 to 4,999	400 to 999	3	1	9	1
5,000 to 14,999	1,000 to 2,999	5	2	12	2

[a]Source of raw water: groundwater resource (GR) and surface resource (SR).
[b]0.1, 0.2 and 0.5: analysis frequency every 10 years, 5 years and 2 years respectively.
[c]The P (production) and D (distribution) analyses provide information about the parameters specified in the regulations and are carried out (P2 and D2 are complementary to P1 and D1 respectively, giving only microbiological and organoleptic quality data treatment effectiveness).

Commonly-used methods are based on spot sampling. But this approach is not always representative of the overall quality of the water body. In particular it is limited where it consists of producing data that are both geographically and temporally representative of the chemical and biological quality of a water body.

Monitoring evolution

The cost of monitoring is also an influencing criterion for the implementation of water control, due to the demand that more and more substances/parameters be examined in order to ensure water quality. Alternatives to standardized methods are now on offer, such as onsite measurement (*in situ*, on line) and sampling (passive samplers). The methods are complementary to laboratory analysis, and can be used to track the dynamic of the contaminant, map the distribution of pollutants in time and space, measure evolution rather than concentration, and for water quality screening.

These methods started to be developed 20 years ago, out of the miniaturization, automation and adaptation of laboratory techniques to make direct use in the field a possibility. There is a set of current methods (on site, *in situ*, on line) (Greenwood *et al.* 2007; Roig *et al.* 2009) which are able to provide quantitative, semi-quantitative and qualitative information by expressing conventional parameters and/or proxies in a faster way. New on line and/or *in situ* monitoring tools, based on integrated sensor technology (measurement + results interpretation) (Hassan 2005) have emerged in recent years. These consist more of evaluation of quality difference between a normal situation and a contamination event due to biochemical and physical interaction (Kroll 2009; Storey *et al.* 2010) than a quantitative assessment of a contaminant. They are mainly used to detect intentional as well as accidental contamination events in a more reliable and less expensive way (Skadsen *et al.* 2008).

Initially based on physico-chemical principle, other monitoring tools have emerged by exploiting the sensitivity of biological systems. Bioindicators, bio or immunoassay and biomarkers, based on living organisms or part of them respectively, were proposed as on-line or field methods. Their sensitivity is not only used for the detection of ultra-trace level of contaminant but to detect more early any perturbation of the water body considered. These early warning systems, able to analyze and interpret results in real time (Storey *et al.* 2010) are, in general, not specific (some are like immunoassays), but inform of the overall water quality (presence/absence or toxic/not toxic, etc.) as for example daphnia and algal toximeter that detect the whole toxicity in environmental samples (Jeon *et al.* 2008; Mons 2008). These methods permit frequent and rapid analysis and are adapted to manage sensitive locations such as SSWS. However, one of the main drawbacks of these biological based methods for drinking water monitoring could be in some cases their cross-reactivity with chlorine.

Performance assessment is a requirement for a large use of these techniques. Currently, it is based on linearity domain, repeatability, limit of detection, limit of quantification, specificity, robustness and includes (i) validation of the performances in the laboratory using reference material and calibrated solutions, followed by (ii) a verification of the analytical characteristic directly on the field by insisting on the robustness (Gonzalez *et al.* 2007; Roig *et al.* 2007). However, this methodology, well adapted for laboratory transposed chemical methods becomes limited when qualitative, semi-quantitative as well as biological methods are considered.

The next evolution in such techniques is currently underway, with the association of telecommunication and/or data transfer procedures (Figure 1). Such progress favours

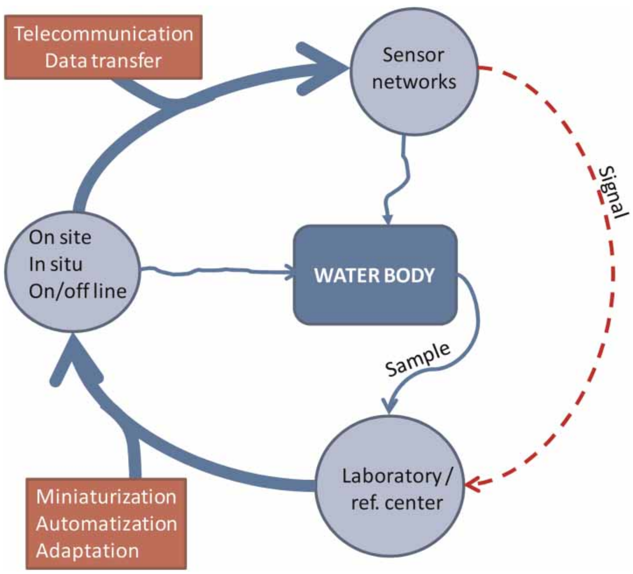

Figure 1 | Evolution of monitoring techniques.

transport of the signal (obtained by on site devices) instead of transport of the sample itself.

However the ability to collect, store and use large amounts of data from *in situ* sensor networks require new techniques and approaches for quality assurance/quality control (QAQC). Indeed, sensors can occasionally malfunction in particular in extreme environments, or are prone to fouling and drift, and communication systems can corrupt data (Wagner *et al.* 2006). QAQC need to include sensor calibration methods, and data-correction approaches, in particular correction of out of range/anomalous values, correction for instrument fouling and drift, correction of values, and correction of any known bias in the sensor data (Pellerin *et al.* 2012). In practice, quality assurance algorithms can be employed for each measured quantity within a subset of neighbouring sensors, or for averages of multiple sensors (Collins *et al.* 2006).

Finally, modelling can also be envisaged.

HOW CAN THESE NEW THREATS BE MANAGED?

It is possible to propose different mitigation options for ensuring the quality of distributed water. The first approach could be to consider the use of long-term and short-term health effect monitoring. Several information systems (compulsory or voluntary reporting, syndromic or toxic surveillance) are available to alert the general public to health-related issues, but specific field investigation are however to be carried out to establish a link with water whatever the system (Beaudeau *et al.* 2011). New data sources can also be used. For example, data relating to the reimbursement of medication collected by the Health Service (in France) may facilitate the daily monitoring of health-related events at local level (Tuppin *et al.* 2010); or multi-source system which will join together various databases of medical and medical-administrative activity (hospital admissions, medical insurance and anatomical pathology) (Tuppin *et al.* 2010; Beaudeau *et al.* 2011). However, this approach remains limited for a study of the dynamic of the water quality evolution.

Effective catchment management has many benefits. Decreasing water source contamination means that less treatment is required. This may, in turn, reduce production of treatment by-products and minimize operational costs. Understanding the reasons for variations in raw water quality is important, because this will influence treatment requirements, efficiency and the resulting health risk associated with the finished drinking water.

The end-of-pipe approach can also be of benefit, particularly in adapting the treatment process to the water quality and the dynamic of its evolution. This is of particular interest when rapid environmental modifications occur.

In practice, remediation actions of stakeholders (people, organisms water authorities, etc.) implemented with respect to regulation compliance or local initiatives must be considered for the reduction of point source discharge and non-point source (diffuse) pollution. As an example, the impact of intensive agriculture on surface water quality coupled to climate change effects with modification of rain patterns can be limited both by animal farming and fertilization control and redesign of protection area of catchment including wetlands and long residence time reservoirs acting as passive pretreatment steps. In this context, remediation actions must be coherently implemented at local or regional scale depending on the size of the catchment.

Regardless of whether the approach is from the source or end-of-pipe, flexible monitoring tools (devices, practices, and methodologies) are assets in orientating adaptation toward new threats, particularly in the event of sudden disruption to normal functioning. In such situations, reactivity and decision making in management of local and global changes need to be improved in order to anticipate the impact downstream of the source of contamination. This is even more challenging for shared water bodies at national or international level. It is estimated that two out of three of the great rivers and aquifers in the world are shared between several countries, and that two out of five people depend on these shared waters. Although this partition is often the source of significant regional tensions, few international agreements on water management exist.

Environmental sensor networks (ESN) is a trend which is currently developing as a result of technological advances in the miniaturization of electronics and wireless communication technology. Several systems have been already developed, but they include only specific generic environmental parameters such as meteorological, global positioning system (GPS), water, air and soil temperature, conductivity, pressure, humidity, and soil moisture, pH, dissolved oxygen and chlorophyll, and are dedicated to monitoring ocean conditions, volcanic processes, and so on (Hart & Martinez 2006). They are well suited to large-scale environmental processes, but need to be adapted to suit specific actions such as water production, and the protection of water bodies and sensitive areas. ESN perspectives need to include sensor modules producing data on chemical and biological parameters. The possibility of being constantly connected to the data source allows water managers to be in close contact with the environment they depend upon (in terms of water resource, natural and anthropogenic pressure).

Until we have an intelligent system capable of autonomous decision making, ESN, combined with a network of laboratory-based experts, offer the possibility of collection and analysis of data at all levels (as appropriate), from local to global.

In addition occurrence data are not enough to assess the population's exposure and make links between water quality failure and environmental or public health outcomes. Water quality management can therefore be improved through consideration of issues such as the following:

- Structural changes in water systems, annual flows transferred between interconnected water systems, and hydraulic residence time distribution parameters (e.g. percentiles 50, 90, 100 and corresponding areas). In France, the SISE-eaux database (Health and Environment information system – water supply) introduces these new items and functionalities to improve knowledge of exposure throughout the country.
- Water operators' safety rules: anti-intrusion alarms, pump breakdowns, excess turbidity, lack of chlorine, and frequency of follow-up visits. The reporting and recording of such signals would also help identify adverse acute water contamination factors and spot any water systems subject to a sudden threat.
- Worldwide consequences of water contamination, in particular for transboundary water bodies or catchment. International and regional exchanges about both risk and mitigation measures are crucial in anticipating, and efficiently allocating, national resources (Pascal 2010). For example, 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.
- Risk surveillance, based on the collection of both environmental and health data (medical treatment, drug prescription, epidemiological studies, etc.) and the development of tools for modelling the link function between water factors and health outcomes (Quenel 1995).

From the above considerations, an enlargement of the DW quality monitoring purpose could be proposed with the integration of water system breakdowns and accidental or intentional contamination, leading both to water of impaired quality with likely health consequences. In this frame, Figure 2 displays the necessary adaptation of monitoring schemes between classical monitoring for the survey of water quality and the operational monitoring for a rapid diagnosis in case of accidental or intentional contamination of water. On one hand the implementation of classical monitoring based on sampling and laboratory analysis is well fitted for long-term survey and regulation compliance. On the other hand the use of rapid measurement devices giving suited information (on time, easily understandable, and available) constitutes an adapted monitoring for early warning. In between, the monitoring must be designed if needed for measuring transient water quality variations following hydroclimatic conditions (heavy rain for example) or more simply to detect water treatment breakdowns.

Finally, Table 3 summarizes the main information used, and required, for a better water quality management.

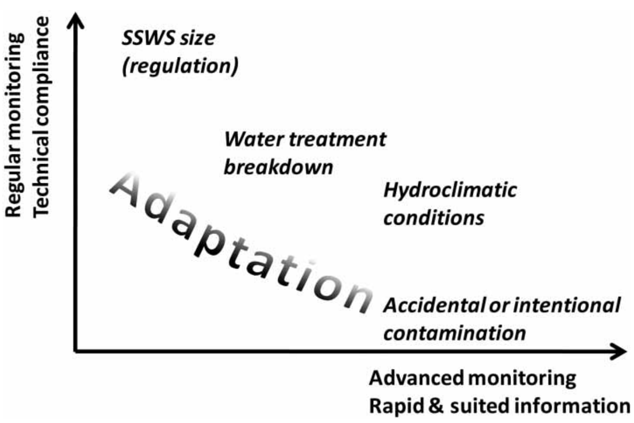

Figure 2 | Evolution of water quality monitoring form.

Table 3 | Data for water quality management and prediction

Type of information		Relevance	Availability
Water quality	Laboratory measurement	Linked to monitoring design Regulation	Sampling delay Analysis delay
	On line/on site measurement	Transient variations Remote assistance	Parameters limitation EWS[a]
	Sensors network	Process control Decision making	Very partial EWS
Complementary	Treatment plant and networks supervision	Material breakdown	EWS
	Public health data	Waterborne Epidemics Selectivity	Delay in data collection Authorization needed
	Hydro meteorological data	Climate event Anticipation	External data validation and storage
	Historical quality data	Characterization of normal conditions	Data collection

[a]Early warning systems.

CONCLUSION

Drinking water quality (from resource to tap) must be monitored thoroughly in order to preserve the population from the consequences of contamination (natural, anthropogenic, accidental or intentional). In the face of increased threats due to environmental or human pressure, monitoring should be flexible and able to be adapted to any variation, in order to drive water managers in their decision making. In particular, during exceptional events leading to a high variation in water quality (raw or treated water), they should be very responsive and able to adapt the general procedure to comply with quality standards and ensure the safety of the population.

In recent years, many emerging technologies have been developed to complement the existing laboratory-based methods (based on the expression of a parameter or proxy) which are too slow to develop operational response and do not provide an adequate level of public health protection in real time. While these techniques are promising, particularly in terms of reactivity and response time, they remain insufficient when prediction or anticipation are required – in the event, for example, of global-scale water management.

With a view to further improvement in operational drinking water monitoring, a network of sensors with remote piloting will allow a sample signal (rather than an actual sample) to be sent to the laboratory (expert network). Yet this evolution still needs years of development before it will, on the one hand, be available for numerous pollutants, and on the other, be accepted by the authorities and operators.

The integration of secondary data in addition to real-time interpretation and analysis of quality data now seems essential to ensuring reliable drinking water management. These type of data should be considered as a preliminary alert to potential causes of water quality failure (which may be more or less long term), and consequently, could be useful in mitigating the effect of such crises.

Such evolutions in drinking water monitoring are required in particular for small water supplies, serving 50 to 5,000 citizens, which appear to be the most vulnerable drinking water systems regarding sanitary outbreaks.

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