Risk-based drinking water surveillance: a review and basis for discussion

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Sammendrag

Risikobasert tilnærming til drikkevannsovervåkning: en litteraturgjennomgang og grunnlag for diskusjon. Vannverkseiere trenger omfattende kunnskap om hele vannforsyningskjeden for å sikre at forbrukerne får levert trygt drikkevann. Risikobasert tilnærming til drikkevannsovervåking har blitt foreslått som den mest effektive tilnærmingen for å sikre trygt drikkevann hos forbruker. I denne artikkelen gjennomgår vi vanlige overvåkingsaktiviteter som et grunnlag for diskusjon om synspunkter på risikobaserte tilnærminger. De vanligste aktivitetene, som befaring og overvåking, kan kategoriseres etter hvor i vannforsyningskjeden de utøves eller er lokalisert, og en hypotetisk estimert sannsynlighet for å forhindre eller oppdage en ikke-spesifikk forurensning. Aktiviteter som er egnet for å forhindre en forurensningshendelse før den inntreffer, kan betegnes som proaktive, mens aktiviteter som oppdager forurensning etter at den kom inn i vannforsyningen kan anses som reaktive. I denne artikkelen foreslår vi et felles syn på hvordan ulike risikobaserte tilnærminger kategoriseres og betegnes. Implementering av en kombinasjon av proaktive og reaktive aktiviteter er trolig den beste strategien for å nå målet om å sikre trygt drikkevann.

Summary

Water utilities need extensive knowledge of the whole water supply chain to ensure that consumers receive safe drinking water. Risk-based approach to drinking water surveillance have been proposed as the most effective to ensure safe drinking water. In this article, we review common surveillance activities and provide a basis for discussion on views on risk-based approaches. The most common activities, such as inspections and monitoring may be categorised relative to the point of deployment in the water supply chain based on an estimated likelihood of preventing or detecting a non-specific contamination. Activities suitable for preventing a contamination event before it occurs may be designated proactive, while activities detecting contamination after it entered the water supply may be considered reactive. In this article we propose a common view on how different risk-based approaches are categorized and termed. Implementing a combination of proactive and reactive activities is probably the best strategy to achieve the goal of ensuring safe drinking water.

Background

Access to safe and clean drinking water is a fundamental human right that is crucial for maintaining public health and well-being, as reflected in Sustainable Development Goal 6 (United Nations, 2023). Routine monitoring provides information on the performance of the water supply system; however, it does not fully serve to unveil imminent health risks in the distribution system, detect outbreaks, or as disease surveillance (Rizak and Hrudey, 2007b). Unfortunately, waterborne outbreaks still occur worldwide in high-income countries with high-standard water supply systems (Kulinkina et al., 2016, Efstratiou et al., 2017), where some outbreaks have had severe impacts on human health (MacKenzie et al., 1994, O'Connor, 2002, Hrudey and Hrudey, 2014, Stirling et al., 2001). Despite statutory requirements and continuous efforts in operation and maintenance, achieving perfection in drinking water distribution is not possible; one needs to target preventive measures and early warning to minimise the potential risk factors (Rizak and Hrudey, 2007a). Several water emergencies at the turn of the millennium led to an increased focus on risk management to protect the public from contaminated drinking water (WHO, 2004), and the World Health Organization (WHO) has advocated the application of Water Safety Plans (Davison et al., 2005, WHO, 2004). Drinking water surveillance activities play a pivotal role in monitoring water quality, identifying potential risks, and implementing appropriate interventions. Within the area of drinking water surveillance, risk-based drinking water surveillance has been suggested by WHO as the best practice within the framework for safe drinking water (World Health Organization, 2011). The approach represents a shift in focus from an overreliance on the compliance testing of a predetermined list of water quality parameters to promoting a proactive approach to identifying, controlling and monitoring critical risks in the water supply (World Health Organization Regional Office for Europe). Despite the shift towards a risk-based approach within drinking water surveillance and several activities that constitutes examples of "risk-based" approaches, there exists not, to the best of our knowledge, a common perception or view on what constitutes "risk-based drinking water surveillance" and how such activities relate to each other in the drinking water supply system.

Surveillance serves as a core function for the continuous review of the safety and acceptability of water supply systems (WHO, 2011). The United States Environmental Protection Agency (EPA) provides a definition: "A Water Quality Surveillance and Response System (SRS) is a framework designed to support monitoring and management of distribution system water quality" (US EPA, 2015). In the continuous effort to achieve safe drinking water, risk-based surveillance has been suggested as a best practice (WHO, 2011). This approach promotes the dynamic identification and monitoring of critical control points in the water supply rather than reliance on compliance monitoring for a fixed set of contamination indicators. A core element of risk-based surveillance is a hazard assessment to map potential risks and manage them accordingly. Important components of risk-based surveillance are water quality monitoring, on-site inspections, hazard identification, and risk and trend analysis. By adopting a risk-based approach in drinking water surveillance, it is expected that countries will focus more on the most important issues for the protection of public health and maximise the benefits that they can accrue from limited resources (WHO Regional Office for Europe, 2019b).

Despite the obvious benefits of risk-based approaches in drinking water surveillance, to the best of our knowledge no formal operationalisation exists in terms of what specific activities are involved in the drinking water supply chain, and where they may be implemented to maximise a preventive effect on potential pollution and thereby protection of human health. In this article, we review measures for the surveillance of drinking water to establish a common understanding and basis for discussion, with a particular focus on risk-based approaches to drinking water surveillance.

Brief overview of surveillance activities

Information on drinking water surveillance activities was collected by peer-reviewed literature searches in Medline, PubMed, Web of science and Scopus, using key words such as "drinking water surveillance" and "risk-based drinking water surveillance and/or monitoring". In addition, information from grey literature such as international guidelines were collected and reviewed. In the literature searches, we found several approaches to drinking water surveillance at the water utility level. In the following, a non-exhaustive list of the different surveillance activities identified through the literature searches is reviewed.

Sanitary inspections

Sanitary inspection is an approach to map existing or potential sources of drinking water contamination. It is based on check lists adapted to the situation and the complexity of the drinking water supply (WHO, 2020, Bartram, 2009). The ability of sanitary inspections to predict faecal contamination is uncertain (Kelly et al., 2020). For instance, one study reported no correlation between risk score and *Escherichia coli* occurrence in the Sub-Saharan region (Kelly et al., 2021), with similar results in Asia (Ercumen et al., 2017). Another study found a negative correlation, with sanitary inspections being unable to predict *E. coli* occurrence. The researchers pointed out the importance of consistent and well-designed sanitary inspections forms, along with inspector training, to achieve reliable results (Daniel et al., 2020). A similar conclusion was reported by Kelly *et al.* (2020), who proposed that sanitary inspections are best utilised as part of a complete system leading to safe drinking water and not solely as a tool for predicting contamination.

Surveillance based on external risk factors

There are possible links between weather conditions, such as temperature, drought and precipitation, and the onset of gastrointestinal infections (Setty et al., 2018). For example, it has been reported that heavy rainfall and flooding were the most common events preceding outbreaks associated with extreme weather, and outbreaks following such events are often the result of contaminated drinking water (Cann et al., 2013, Hyllestad et al., 2020, Nygard et al., 2006). Heavy rainfall may cause a number of environmental changes, such as the resuspension and transport of pathogens to other areas, surface runoff from land to water, contamination of ground water sources, and overload of water and sanitation infrastructure (Levy et al., 2016). In light of risks such as floods or drought, strengthening communication and use of meteorological forecasting could be a measure to predict potential risks (WHO Regional Office for Europe, 2011).

Routine monitoring

Faecal indicator bacteria monitoring in drinking water is used to check the presence of potential pathogens and serves an important function to oversee the effect of implemented measures. *E. coli*, for example, indicates that drinking water may have been contaminated with faecal matter from humans or animals (Medema et al., 2003). Albeit widely recognised as a best practice for monitoring, the search for indicator organisms of faecal contamination has some limitations, the main one possibly being the uncertainty of whether pathogens are present alongside indicator organisms. Furthermore, most methods rely on traditional plating techniques in a laboratory, which is time consuming and may present challenges for cold storage during transport (Charles et al., 2020). Microbiological monitoring is an end-product testing for faecal indicator bacteria, and since the plating analysis takes 24 to 48 hours to complete, the sampled drinking water is most likely already consumed by the time the test results are available (WHO Regional Office for Europe, 2019a). Moreover, routine compliance monitoring is necessary to adhere to legislative drinking water standards. Long-term assessment of reported data from routine monitoring makes it possible to spot new or re-emerging risks (WHO, 2011).

Online monitoring

Real-time or near real-time information on changes in drinking water quality is one approach to early contamination detection. A range of online gauges are available for various physical attributes, commonly used to monitor water treatment processes. Microbiological methods such as flow imaging and flow cytometry may provide important information on microbiological content (Koppanen et al., 2022, Cheswick et al., 2019). Flow cytometry has the potential to assess bacterial load on drinking water (Buysschaert et al., 2018). Fluorescence spectroscopy has been found to be useful for uncovering faecal contamination and the presence of *E. coli* (Ward et al., 2021, Nowicki et al., 2019, Sorensen et al., 2018). Water quality parameters are often considered to be an early warning signal for risks in water supplies, and advances in real-time monitoring suggest the potential for an earlier warning of the risk of outbreaks. However, it may be challenging to deploy the appropriate operational responses based on monitoring data (Storey et al., 2011).

Risk-based monitoring

Adapting water quality monitoring to expected risks is a more versatile approach than compliance or routine monitoring. Risk-based monitoring may be reflected in regulations, permitting derogations under given circumstances. A certain flexibility for routine monitoring has been present since the 1998 version of the Drinking water directive, the main European legislation on drinking water related issues (European Council, 1998). With the 2015 amendments to the Directive, a risk-based approach to drinking water management was expressed as a provision. The 2020 revision introduced a risk-based approach as a fully integrated part of the Directive (European Parliament, 2020), allowing for derogations from monitoring requirements if a risk assessment provides evidence that a specific substance or hazard is not present.

Consumers reacting to water quality changes or outages

Deteriorated water quality is frequently picked up by consumers. Whether deviations are detected and conveyed depends on the properties of the contamination and the quality of the system available to the consumers to alert the water service provider (Whelton et al., 2007). Fluctuations in sensory water quality, i.e., contaminations resulting in deviant odour, taste, turbulence, or colour at a level perceptible to humans, are likely to be detected by consumers (Dietrich et al., 2014). Microbiological contamination without accompanying changes to sensory parameters, on the other hand, will almost certainly go unnoticed, resulting in potential infections if not discovered by other control measures.

Perspectives and discussion on drinking water surveillance

We have identified and described different systems involved in surveillance at the water utility level. Here, we address terminology and the possibilities and limitations of the activities that may be implemented by water service providers and how they complement each other. We propose a systematisation under a hypothetical line of events from source to consumer as a basis for discussion on risk-based approaches to drinking water surveillance.

Some reflections on terminology

A unified terminology applying to the activities that may go into a water safety plan for water utilities is crucial to have a meaningful discussion about drinking water quality. Hence, we propose a clear distinction between surveillance and monitoring based on the extent, complexity, and levels of insight and knowledge of the underlying activities.

To the best of our knowledge, there is no definition of water quality monitoring that covers the entire water supply chain. Bartram and colleagues touch on the topic and have included an element of surveillance as they put forward the definition "long-term, standardized measurement and observation of the aquatic environment in order to define status and trends" (Bartram and Ballance, 1996). Monitoring of indicator organisms and chemical parameters in its simplest form may arguably be seen as a logistical operation performed by a trained technician following a procedure, or it may even be an automated process. In principle, no prior knowledge of water hygiene, statistics, and results interpretation is needed. The analysis results may be a crucial contribution to understanding water quality, but as a standalone measure monitoring is unlikely to provide enough information to assess the overall state of the water supply chain.

The WHO defines drinking water supply surveillance as "the continuous and vigilant public health assessment and review of the safety and acceptability of drinking water supplies" (WHO, 2011). Surveillance may also be described as an active and ongoing observation of a system, whereas monitoring checks whether the system is in line with a set of objectives (Christensen, 2001), i.e., comparing results to predetermined values for a set of parameters, such as *E. coli* or turbidity. For the purpose of water safety, we propose to understand surveillance as a comprehensive system to oversee all parts of the water supply chain, from catchment to faucet, encompassing all activities needed to ensure sufficient quantities of safe drinking water.

The demand for extensive knowledge of water hygiene and operational processes increases with increasing complexity and size of the water utility. Interpreting monitoring results, understanding the dynamics of the entire water supply chain, and deploying countermeasures accordingly, depend on a comprehensive overview of the water utility. In most cases, this may be achieved only through a complete surveillance programme, ideally always including monitoring. On the other hand, monitoring may be performed independently, without being part of a surveillance programme. In this case, it is important that the water utility is aware of the limitations related to monitoring activities.

A basis for discussion on risk-based approaches

Surveillance activities are separated spatially and temporally throughout the water supply chain, serving the purpose of preventing or detecting contamination events. Following the water flow, we labelled the reviewed surveillance and monitoring activities proactive and reactive (Figure 1). As the figure shows, the surveillance and monitoring activities are structured in relation to each other based on a theoretical flow of water from source to tap, separated by a contamination of non-specific origin or composition.

Proactive surveillance activities happen before a hypothetical contamination event and are of low specificity, thus having the potential to detect a variety of risks for contamination. Inspections of the catchment area and raw water source during heavy precipitation is one example. Reactive activities happen after contaminations events and may detect contamination in the distribution system only after it occurs. A typical activity is monitoring indicator organisms in drinking water. Reactive monitoring also provides information on naturally occurring water quality fluctuations, which is essential knowledge that makes supervisors able to distinguish abnormal occurrences from normal events.

Surveillance activities have a varying likelihood of preventing and detecting contamination. In Figure 1, we propose a theoretical hierarchy based on the assumed ability of the activities to prevent contamination before an event on the left, and on the right the ability to detect the contamination after it entered the system. Proactive approaches are generally precautionary, such as identifying agricultural runoff or high turbulence during drought. Surveillance of meteorological data could serve as an early warning for potential risks, and if applied properly may have a fair chance of preventing contamination. Reactive activities, i.e., monitoring drinking water quality in the distribution system may be seen as random activities with a limited likelihood of detecting contamination. Risk-based monitoring, and indeed online monitoring, are possibly better suited to

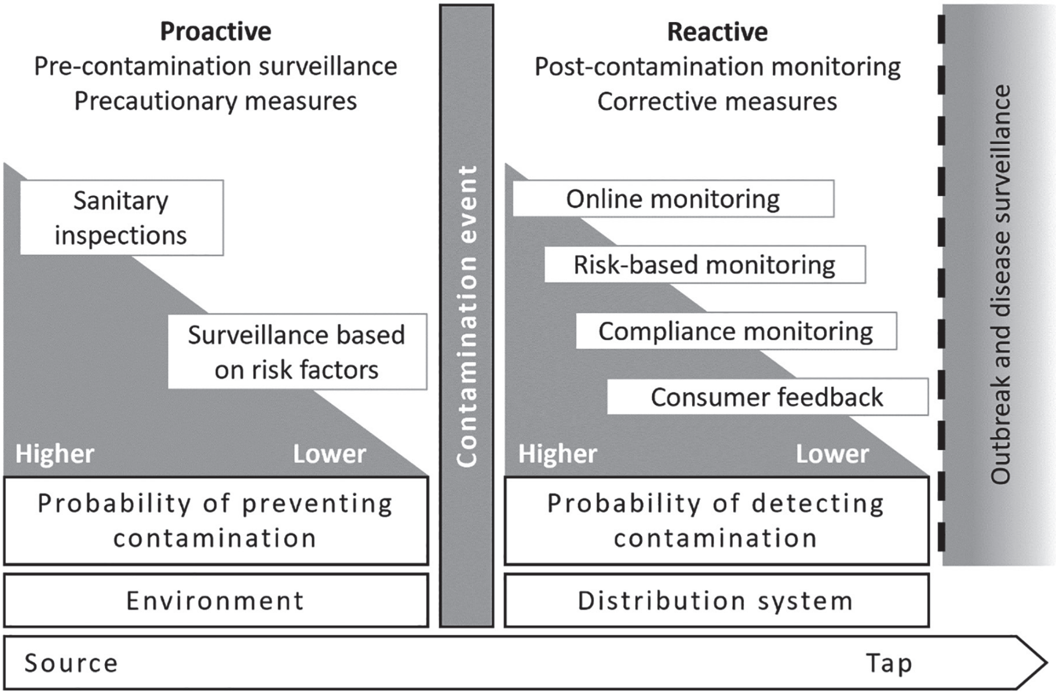

Figure 1: Schematic presentation of water flow through a water supply chain, from source to consumer, with proactive and reactive surveillance activities organised based on their theoretical probability to prevent or detect a non-specific contamination.

detect contamination in the system, as depicted in the figure. As microbiological contamination is unlikely to be picked up by consumers, it could develop into an outbreak, and surveillance will be replaced by outbreak detection and disease surveillance, which is outside the scope of our discussion.

The categorisation above is hypothetical. In practice a contamination may enter the supply system at any time and at any point. For instance, heavy rainfall may occur at any time or location, and cause contamination that is hard to predict and detect even with sanitary inspections. However, such a categorisation may help to emphasize how inspections before the water treatment plant and monitoring of the distribution system may complement each other.

Monitoring chemical constituents and indicator organisms in the water source is useful to assess the water treatment efficiency, but it serves a very limited purpose in regard to contamination prevention, as water treatment should be designed to remove any contamination before the distribution of water. Likewise, surveillance should not be limited to precautionary actions in the catchment, as it will not discover contamination entering the distribution system. Although risk-based monitoring may increase the likelihood of timely detection of contamination in the distribution system, such contamination is still at risk of going undetected.

Online monitoring instruments are developing, yet online monitoring is no guarantee for safe drinking water. Online detection is also highly dependent on where the instruments are located. A common trait of most online monitoring methods for microbiological contaminants is that they resemble traditional laboratory analysis, in the sense that they detect contamination indirectly by cell count or fluctuations in organic matter. Correlation with indicators and potentially pathogenic faecal contamination is uncertain. A notable advantage of online monitoring over laboratory analysis is a generally shorter analysis time, and a reduced demand for trained personnel to withdraw water samples. Despite extensive research within this field challenges prevail, mainly due to sensitivity, portability, and high cost (Kumar et al., 2019). Moreover, culture techniques are more powerful for microbiological species identification. On the other hand, cytometric and similar online monitoring techniques are more likely to detect viable but nonculturable (VBNC) bacteria (Zhang et al., 2018). E. coli and Campylobacter, among others, have the ability to enter a VBNC state, UV treatment being a known inducer (Pienaar et al., 2016). Deviations, by online or laboratory monitoring, should always be followed by appropriate measures, such as sanitary inspections, extended monitoring, and boil water advisory, but it is also likely that the contaminated water has already been consumed. Instigating mitigating measures when detecting a microbiological deviation might already be too late to avoid disease.

Single measures will most likely not be sufficient to uncover all short- and long-term challenges in a water supply chain. There is no evident solution to what monitoring regime to choose, as every method has its strengths and weaknesses. Furthermore, it takes a complete overview of all parts of the water utility and an understanding of how, when, and where to apply the different measures. Combining several different techniques in a comprehensive surveillance programme seems to be the best approach.

Most studies on the correlation between sanitary inspections and microbial load on drinking water have focused on small to medium scale drinking water supplies in rural areas of the Sub-Saharan and Asian regions, often with high expected risk scores. The applicability to larger scale utilities remains unclear. An overreliance on risk scores to predict contamination is probably problematic, no matter the size of the water supply, as it places high demands for knowledge on the executor. More importantly, faults and deviations must be met with immediate actions to reduce risks, rather than waiting for microbiological analyses.

The literature within the field of drinking water surveillance is limited. An increase in research and published papers addressing the application of surveillance activities to a broader selection of water utilities would be advantageous to increase knowledge and as a basis for future discussions.

Concluding remarks

In this article we reviewed and systematised different activities in drinking water surveillance in a risk-based approach as a basis for discussion. Surveillance should be understood as a system that demands a high level of knowledge of risk situation analysis and may be used as a collective term for all activities involved in water safety. Monitoring should refer to activities following a routine procedure, including automated procedures. Furthermore, the term monitoring should not be limited to environmental sampling but should also include drinking water sampling. As this by no means concludes on the use of the terms surveillance and monitoring, we see it as a valuable contribution to the all-important understanding and differentiation of the two.

A suggested approach for water utilities to achieve their goal of distributing enough and safe drinking water is to incorporate a comprehensive and adaptable water surveillance system, including all activities discussed in this paper. We suggest that a common understanding of drinking water surveillance in a risk-based approach is established to improve drinking water safety and to achieve the UN Sustainable Development Goal 6 of supplying the world with safe water.

Declarations

Authors' contributions:

AB drafted the first article text, designed the figure, and completed the final text.

EA provided critical comments throughout the article's development.

SH initiated the article, drafted the primary outline, and provided critical reading of the final draft.

All co-authors revised the manuscript and have approved the final version.

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