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Review of technologies for the rapid detection of chemical and biological contaminants in drinking water

ERNCIP Chemical and Biological Risks to Drinking Water Thematic Group

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Abstract

In the event of potentially intentional contamination of drinking water, the risk to public health must be minimised, which requires confirmation of contamination and, if possible, identification of the contaminant. A crucial step is to determine the type of contaminant as rapidly as possible.

This review, developed within the framework of guidance for the production of a water security plan (Teixeira et al., 2019), aims to help water utilities, laboratories and other stakeholders improve their capacities to analyse and identify unknown contaminants in drinking water. An explanation of sampling procedures in emergency situations is given, followed by a proposed approach to the use of non-targeted technologies to determine both toxicity and adenosine triphosphate (ATP) levels. A toxicity analysis quickly detects toxic chemical contaminants, while measuring the ATP gives a first indication of any contamination by microorganisms.

The non-targeted technologies for determining toxicity and ATP in water that qualify for use in emergency response – i.e. that are quick to respond, reliable and easy-to-operate are now available on the market, and could be adopted by most drinking-water utilities and/or laboratories, along with establishing appropriate sampling capabilities.

The next step – identifying the contaminant – requires the application of targeted rapid analysis technologies such as immunoassay-based, polymerase chain reaction (PCR) and sequencing technologies, and field analysis by gas chromatography (GC/MS). These targeted technologies are based on tests available on the market, with a focus on rapidness and reliability of results.

The commercially available analytical tools and methodologies for detecting and identifying a chemical or biological contaminant are reviewed through a detailed description of the equipment involved, including the technologies, equipment prices, testing costs, time needed to obtain a result, manufacturers, and the shelf life of the reagents.

Information is also provided on proficiency tests that give external quality control of the analytical process analysis of unknown contamination events in drinking water in emergencies situations.

To assist utilities and laboratories in their consideration and selection of targeted and non-targeted technologies, an approach to identifying water contaminants in emergency situations is proposed, comprising a series of analytical steps to be adapted by each water utility in line with its business goals and risk assessment.

This review of analytical technologies aims to support water utilities, laboratories, health authorities and other stakeholders in planning responses to emergency events in drinking-water quality, and in particular to enhance the rapid identification of unknown water contaminants. An assessment of these technologies, within the framework of a water security plan, along with appropriate planning and protection measures, will enable water utilities to better respond to unexpected contamination of drinking water.

1. Introduction

1.1. Background

Although EU Directive 2008/114/EC ([1]) on the protection of critical infrastructures does not designate water supply as a sector of critical European infrastructure, most national governments recognise their water supply as vital to national security. Water supply systems are vulnerable to unintentional and intentional threats, which can include physical sabotaging of equipment, cyberattacks on information or operational control systems and contamination of drinking water. More recently, EU Directive (EU) 2016/1148 ([2]) identified drinking-water production, processing, and supply as essential services, and advised consideration of sector-specific factors in determining whether a cyber-incident would have a significant disruptive effect.

With the objective of supporting water utilities in responding to emergency situations, and in particular to deliberate contamination of water supply systems, the European Reference Network for Critical Infrastructure Protection (ERNCIP) Chemical and Biological Risks to Drinking Water Thematic Group ([3]) published a technical report entitled *Guidance on the production of a water security plan for drinking water supply* (Teixeira et al., 2019) and a complementary report entitled *Practical guidelines on the requirements of a continuous online water-quality monitoring system in drinking-water-supply systems* (Carmi, 2019).

As described in Teixeira et al. (2019), water security plan scenarios consider low-probability / high-impact contamination, typically anthropogenic, characterised by a fast rise in dosage and concentration, requiring fast detection and response by the water utility operator, in as close to real time as possible (Carmi, 2019).

The first contamination alert may come from an indicator, or a combination of indicators, pointing to an abnormal change in water quality, giving an early warning of potential contamination. Subsequently, using field and laboratory tests to search for the source of the contamination, the utility should integrate all available information, such as which sensors indicated a change, and what the change was. For example, if online sensors show a decrease in residual chlorine concentration and an increase in turbidity and total organic carbon (TOC), it may indicate the presence of an organic or microbial contaminant. Thus, online sensors information should be combined with laboratory analysis when interpreting results.

Although a water security plan is mainly focused on mitigating intentional contamination of the water system, it may also cover other water contamination situations, such as:

- accidental contamination of the water supply system;
- outbreaks caused by waterborne diseases;
- natural disasters.

According to Teixeira et al. (2019), during the event detection and confirmation phases, a crucial step to determine if a credible threat exists is confirmation of the suspected contamination. The utility will need to determine the level of risk as quickly as possible, which will require evidence concerning the type of contaminant, so as to assess potential public health impacts.

Little may be known about the suspected water contaminants. For this reason, field analyses should be established and/or rapid analysis technologies in place, in order to find out quickly whether the contaminant is toxic or not, even if its precise concentration cannot be identified in the first phase. For example, if field or laboratory tests indicate that the suspicious water samples are not toxic, management actions could be taken as an immediate response to the event.

While speed of analysis and reporting are crucial, the quality of any results reported will also be of great importance, as the consequences of failing to identify or wrongly identifying a contaminant could be critical (Thompson and Gray, 2006).

The role of laboratories in the water security plan is therefore to provide water utilities with rapid detection methods as well as the analytical capabilities and capacity to support monitoring, surveillance, response and recovery in contamination events involving chemical and biological contaminants. Information from laboratories will be used to inform decision-makers, such as the utility managers and health authorities, who will establish what control/remedial action should be taken.

Usually, the search for unknown contaminants in water starts with an assessment of broad groups of chemical substances (organic, inorganic, radiological, biological, etc.), followed by a more focused examination, narrowing

([1]) Council Directive 2008/114/EC of 8 December 2008 on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection.

([2]) Directive (EU)2016/1148 of the European Parliament and of the Council of 6 July 2016 concerning measures for a high common level of security of network and information systems across the Union.

([3]) As part of the EU's counterterrorism strategy, the European Commission maintains an action plan to enhance preparedness against chemical, biological, radiological and nuclear (CBRN) security risks. The 2017 CBRN action plan details a number of measures at national and European level, including more robust preparedness for, and responses to, CBRN security incidents (European Commission, 2017). The 2017 CBRN action plan identifies **ERNCIP** as one of the specific measures for enhancing the EU's knowledge of CBRN risks (Gattinesi, 2018).

the spectrum, until the final identification. However, this approach may require both a great deal of time and highly specialised staff for the analysis, both of which may be in short supply during an emergency.

1.2. Purpose of this document

The ERNCIP Chemical and Biological Risks to Drinking Water Thematic Group has previously produced reviews of state-of-the-art technologies and methodologies, such as *Review of methods for the rapid identification of pathogens in water samples* (Tanchou, 2014), *State-of-the-art of screening methods for the rapid identification of chemicals in drinking water* (Llorca, 2013) and *Review of sensors to monitor water quality* (Raich et al., 2013).
In the present review of detection technologies, an innovative, progressive approach is proposed, starting with an initial assessment of the detection of chemical toxic compounds and/or microbial agents using simple, non-targeted technologies, followed by an assessment of the subsequent, more precise identification of the contaminant using targeted rapid analysis technologies that aim to identify the widest possible range of contaminants and minimise the response time. It should be noted that radiological contaminants are beyond the scope of this review.
Given that the water utility will require fast and reliable information about the type of contaminant in order to be able to assess potential public health impacts, a quick response will be crucial. Therefore, all the analytical technologies described share the following characteristics:

- they give a fast response (minutes/hours);
- they provide reliable results;
- they are easy-to-operate (can be used by non-specialised staff);
- they are commercially available on the market.

This review has been developed within the framework of guidance for the production of a water security plan (Teixeira et al., 2019), and is intended to support water utilities, laboratories and other stakeholders in improving their analytical capacities to search for and identify unknown contaminants in water. Depending on their specific objectives and risk management options, water utilities and laboratories can select an appropriate analytical approach using the information provided in this review.

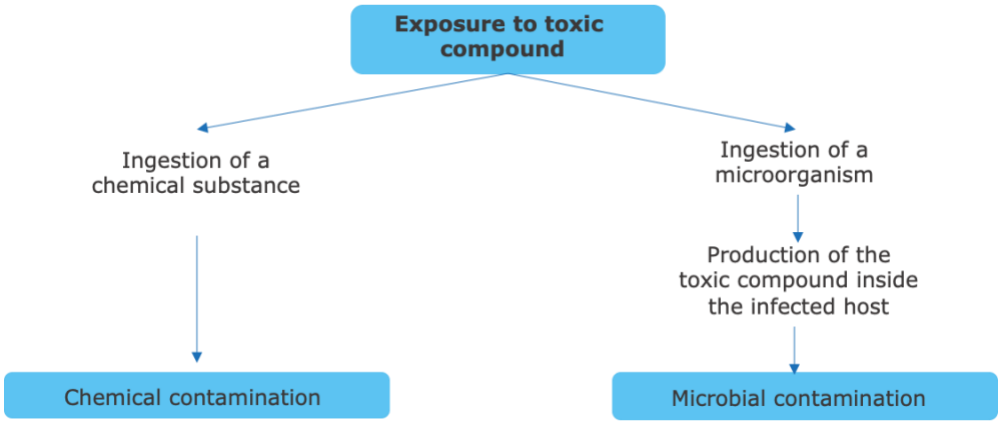
1.3. Structure of the review

The review sets out an overview of the issues associated with the rapid identification of unknown contaminants in water in emergency situations. Subsequent sections provide an insight into sampling requirements and a description of various non-targeted technologies for determining toxicity and adenosine triphosphate (ATP) levels. The use of rapid targeted methods to complement these technologies is also presented. The review of the commercially available analytical tools and methodologies that can quickly detect and identify a chemical or biological contaminant in a water supply system includes a detailed description of the equipment, covering the technological principles, price for purchasing the equipment (i.e. capital expenditure (CAPEX)), cost per test, time needed to obtain a result, manufacturers, and the shelf life of the reagents.
As laboratories will be called upon to rapidly identify contaminants, often with very little information as to the source of the contamination, the value of proficiency tests designed to test the capabilities of laboratories is discussed.
Finally, the overall approach to identifying water contaminants is reviewed, positioning the use of non-targeted technologies prior to targeted ones when identifying water contaminants in an emergency.
It should be emphasised that the information presented regarding equipment, particularly the prices, is indicative and up-to-date details will need to be obtained from local distributors, as they can vary considerably from country to country.

2. Identification of unknown compounds in emergency situations

Contamination of drinking water due to a deliberate attack may lead to consumer exposure to toxic substances, which may produce acute toxicity in those affected (in the short term), with various consequences, including harmful neurological, hepatic, gastrointestinal and renal effects. The main source of the harm will be a toxic compound, or a mixture, ingested by the consumer. Exposure may occur in different ways: through direct ingestion of a chemical substance (synthetically or biologically produced) or through the ingestion of a microorganism that, once inside the body, multiplies and produces a toxic compound (Figure 1).

Figure 1 *– Routes of human exposure to toxic compounds in drinking water*



In a classical approach, the identification of an unknown contaminant in water starts with an assessment of broad groups of chemical substances, such as organic compounds, metals, or ions. Based on this assessment, a more refined search has to be performed to narrow down the spectrum of contaminants until the final identification. This approach, however, may be time consuming and it requires highly specialised staff for the analysis; both time and specialised staff may be in short supply in an emergency.
Therefore, searching for the nature of the water contaminant in an emergency will require a reliable, quick response (within a few hours) from the laboratory and a step-by-step approach.
An efficient analytical strategy that can be adapted to the various threats resulting from deliberate water contamination will allow:

- the necessary analysis to be accomplished as fast as possible to minimise the impact on the water supply in the affected areas, and a fast response to the contamination event;
- the greatest possible number of potential contaminants to be identified;
- the possibility for the analysis to be performed on a 24h/365 days basis.

Therefore, the analytical methodologies for this first assessment need to be:

- quick (only taking a few minutes or hours);
- reliable (quality control must be ensured);
- based on easy-to-operate technologies (can be used by non-specialised technicians);
- based on commercially available technology / technology at technology readiness level (TRL) 9 ([4]).

After the first alert, an action plan must be deployed to quickly determine the nature of the contaminant. The goal of this plan is to reduce the response time as much as possible and allow for the identification of the greatest possible number of potential contaminants. Rapid testing of the contaminated water, as close as possible (in time and location) to the source of contamination, provides valuable information about the nature of the emergency and informs potential courses of action to manage the situation.
There are many different technologies available that are capable of providing a fast response. However, when facing an episode of unknown contamination, it is not possible to test for all the potential threats. This would make the process of detection a long and very expensive operation and risk failing to identify the contaminating substance or microorganism while valuable time passes.

(3) TRLs are indicators of the maturity of a given technology. This measurement system provides a common understanding of the status of a technology and covers the entire innovation process. There are nine TRLs, TRL 1 being the lowest and TRL 9 the highest (https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf).

Besides speed, it is also critical to ensure that the first assessment is based on methodologies that cover as wide a range of contaminants as possible.

In order to determine whether the contamination is chemical or microbial, tests for toxicity and ATP levels are run. If the toxicity test is positive, the contamination is caused by chemicals. In a case of microbial contamination, the ATP test will be positive. In the worst-case scenario, both results will be positive, indicating simultaneous chemical and microbial contamination.

Following a positive toxicity test, further rapid targeted analyses of the sample have to be carried out. This approach narrows down the range of potential chemical contaminants, eventually leading to the identification of the substance. In further steps, the TOC level or an absorbance of ultraviolet (UV) at 254 nm can also provide valuable further information about the content of organic compounds.

In the event of positive ATP results, rapid targeted measures such as immunoassays, polymerase chain reactions (PCRs) or the use of sequencing technologies have to be performed to identify the contaminating microorganism. Nevertheless, conventional procedures targeted at the specific microorganism may still be needed for a full identification, and may be time consuming, requiring specialised technicians.

3. Sampling in emergency situations

Drinking-water suppliers are strongly encouraged to establish appropriate and standardised sampling capabilities and procedures. Ideally, each utility should have an in-house sampling team capable of collecting samples, performing basic field analysis and responding immediately in an emergency.
Collecting representative samples is of crucial importance for a proper understanding of the contamination. Special attention must be given to this step as using the wrong sampling methodologies may compromise all the subsequent processes of identifying the source and nature of the contamination. Sampling in response to potential drinking-water contamination has to follow accepted procedures, which need to be well documented and familiar to the personnel implementing them. Staff collecting samples must be trained and/or be under the direct supervision of a trained staff member.

Planning for sample collection involves preparation, in advance, of supplies for sampling for contaminants or contaminant classes that the laboratory or water utility would analyse for in response to possible water contamination incidents (United States Environmental Protection Agency, 2015).

Furthermore, contact with contaminated water, or even with residues of the contaminant or other materials at the site of contamination, may pose serious health and safety threats to laboratory staff, emergency responders, or other water utility staff. Anyone collecting, handling or analysing samples that may contain unknown contaminants should ensure their own safety and that of their staff.

To minimise risks, the sampling team should follow common-sense safety practices, such as:

- approach the site from upwind;
- do not eat, drink or smoke at the site;
- do not smell, touch or taste the suspect water;
- use appropriate personal protective gear (e.g. splash-proof goggles, respirator, disposable gloves, disposable shoe covers and disposable lab coat);
- avoid skin contact with suspect water;
- fill sample containers slowly to avoid splashing or spraying droplets of water that could spread the contamination;
- do not spend any more time at the site than necessary to characterise it and obtain the samples.

As speed is critical in protecting public health, all sampling procedures and supplies should be planned and prepared well in advance. It is advisable for utilities to keep all sampling supplies and equipment prepared, well maintained and ready for use in an emergency response kit.

For this purpose, the laboratory (or an internal water-quality control team) should prepare and store in a dedicated location or locations the following emergency response supplies:

- flasks/containers for water samples;
- thermal containers and sample coolers;
- equipment and laboratory supplies for field analysis (of e.g. conductivity, turbidity, pH and residual chlorine, if applicable);
- reagent kits;
- personal protective equipment.

The laboratory should maintain the emergency response kit, including the equipment for *in situ* field analysis as described above, and carry out regular inspections to ensure it is always ready for use.

Samples must be unequivocally identified. In all cases, an indelible label should be securely attached to the sample container. The label should display a unique identifier, allowing the date, location, and number of the sample to be traced.

According to the best practices in water sampling described in detail in the International Organization for Standardization (ISO) standard 5667 (all parts) and in ISO 19458 (ISO, 2006), the process of preservation and

handling of water samples comprises several steps. During this process, the person or people responsible for the samples might change. To ensure the integrity of the samples, all steps involving them should be documented.

Besides collecting samples for targeted and non-targeted analysis, procedures should include the collection of a significant volume of water, in both glass and plastic containers, which may be needed for further laboratory analysis.

Water samples are susceptible to changes as a result of physical, chemical or biological reactions that occur between the time of sampling and beginning the analysis. The nature and rate of these reactions are often such that, if precautions are not taken during sampling, transport and storage (for specific analytes), the concentrations determined by the analysis are different to the original concentrations at the time of sampling. The extent of these changes is dependent on the chemical and biological nature of the sample, its temperature, its exposure to light, the type of container in which it is placed, the length of time between sampling and analysis and the conditions to which it is subjected.

Where samples are to be transported, the sampling plan (as in ISO 5667-1) should take into account:

- the time between sampling and beginning transportation;
- the transport time;
- the time between the arrival of the samples at the laboratory and the beginning of the analysis.

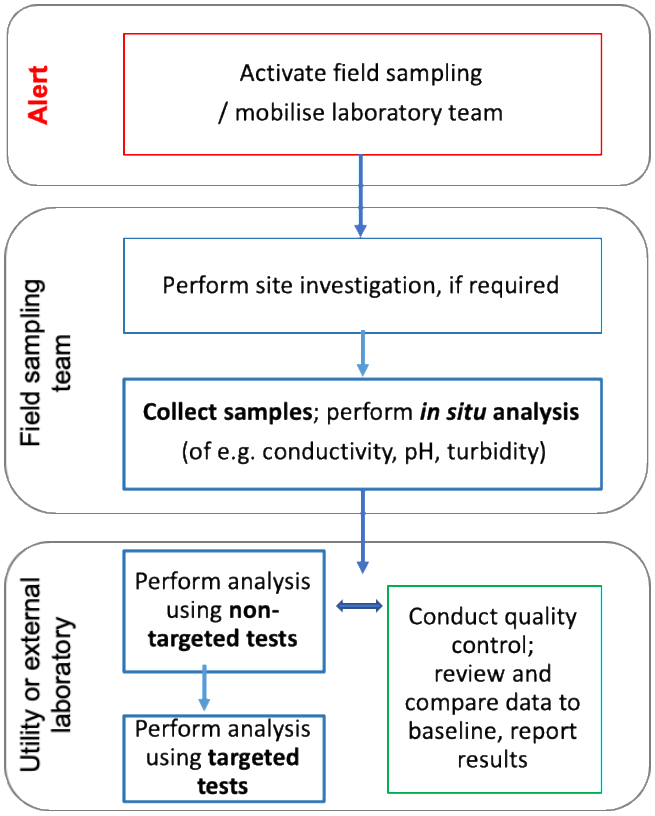
The sum of these three periods must be limited to the maximum storage times of each of the analytes to be analysed and should be known by the staff. Samples with unknown compounds should be cooled or frozen to increase the time available for transport and storage.

Containers holding samples should be cooled, protected, and sealed during transport in such a way that the samples do not deteriorate or and none of their content is lost. The procedures applied should be in line with instructions from the laboratory. Packaging for the containers should protect them from potential external contamination, particularly near the opening, and should not itself be a source of contamination (ISO 5667-3).

If analyses are planned to be carried out by external laboratories, it is strongly recommended that the above best practices be communicated to those laboratories.

The sequence of activities involved in sampling and the different steps of analysis to be followed in the event of a water-quality alert are presented in the following scheme (Figure 2).

Figure 2 *– Sequence of activities involved in sampling and analysis following a water-quality alert (based on United States Environmental Protection Agency (2015))*



4. Non-targeted technologies – identifying the nature of the contaminant

4.1. Introduction to non-targeted technologies

Once the potential-contamination alarm is triggered (by online equipment or other means), the use of non-targeted technologies can be very useful as a first step for indicating whether the contamination is chemical or microbial. Toxicity and ATP tests are considered non-targeted methods because they do not attempt to identify specific compounds or microorganisms; instead they are sensitive to wide range of compounds. These technologies aim only to identify whether the contaminant is chemical or microbial in nature, pointing the way for subsequent steps. There are a variety of technologies for determining toxicity and ATP levels in water that are appropriate for use in emergency response in that they are quick to respond, reliable, easy-to-operate and available on the market (TRL 9).

Considering the relatively low investment needed to purchase equipment to determine whether a contaminant is chemical or microbial, and the need for a fast response, this type of analysis could be carried out by most drinking-water utilities and/or laboratories. The results obtained can have varying degrees of precision and be qualitative or quantitative, but constitute a starting point for further action. For example, the absence or presence of toxicity in suspicious water samples could inform the immediate first response and any further management of the event.

In the following subsections, a description of the commercially available equipment used for analysis of toxicity and ATP will be presented.

It should be noted that measurement of both toxicity and ATP levels can be carried out by online equipment in water supply systems (Carmi, 2019).

4.2. Toxicity tests

Aquatic toxicity tests are used in a variety of applications to detect toxicity of known or unknown chemicals in drinking water, in environmental water samples and for effluent compliance, using different aquatic organisms and biological endpoints. Water toxicity tests and related statistical methods have been standardised over recent decades and are now available and accepted for routine monitoring and regulatory purposes worldwide.

There are several technologies available on the market that provide a very sensitive and rapid (within minutes) measurement of acute toxicity. Most of these technologies are based on the effect of a water sample on a specific population of organisms, in particular bacteria (one single species or a combination of different species). The most common technologies use a strain of naturally occurring luminescent bacteria (e.g. *Aliivibrio fischeri* (formerly *Vibrio fischeri*)) to provide acute toxicity detection. These bacteria emit light as a natural part of their metabolism. Exposure to a toxic substance disrupts the respiratory process of the bacteria, resulting in reduced light output. The equipment measures the light levels before and after adding the sample, and the reduction in light output is a measure of the sample's toxicity.

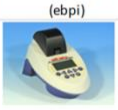
Analytical technologies include those based on colorimetric, bioluminescence and fluorescence analysis, all using bacteria as toxicity 'sensors'. Results can be read with the naked eye or, for more precise results, with equipment. To be applicable in emergency situations, it is important to have background data on normal toxicity levels so that results are based on relative changes in water quality. For this purpose, criteria for defining abnormal changes in the pattern should be established beforehand. Regular monitoring of toxicity in drinking-water systems can also add value for normal operational purposes.

Examples of commercially available equipment for toxicity testing are presented in Table 1.

For each device a detailed description of the technology is given, including the time needed to obtain a result, CAPEX, cost per test, shelf life of the reagents and the technological principle.

The CAPEX is the investment a company makes to acquire the equipment as fixed assets, while OPEX (operational expenditure) is the cost of the ongoing operation of the product. As the CAPEX depends on different factors (the commercial conditions in each country, the distributors or customer-specific requirements) instead of an exact cost, a price range is presented.

Table 1 *– Selection of some devices available on the market to determine toxicity in water*

Device name (and manufacturer)	Time needed to get a result	CAPEX (*)	Cost of reagents (**)	Reagents	Shelf life of reagents	Expression of results	Technological principle
 DeltaTox II (Modern Water)	125 min (for preparation of reagents) + 5 min	Medium–high	Low	Acute reagent, Microtox diluent, osmotic adjusting solution	24 months frozen (at – 20 °C)	Quantitative (Equitox)	Bioluminescence (of *Aliivibrio fischeri*)
 NIDS ACE I (ANP Technologies®)	45 min	High	Low	ACE I Acetylcholinesterase Inhibitor Detection Test Military-Pack (Reagents for 1 Test)	12 months at room temperature	Qualitative (visual read-out)	Fluorescence-based assay; acetylcholinesterase
 LumiMARA (NCIMB Ltd)	60 min (for preparation of reagents) + 30 min	High	Medium	Microplates	18 months Freezed vials and L1 and L2 reagent chill	Quantitative (% inhibition)	Bioluminescence (of 11 species of naturally occurring bioluminescent bacteria)
 Toxi-ChromoTest (ebpi)	90 min (for preparation of reagents) + 15 min	Low	High	Rehydratation solution, Toxi-ChromoTest lyophilised bacteria, reaction mixture, MgCl2, chromogenic substrate, diluent	Months (at 2-8°C), years (frozen)	Qualitative (blue visual display), quantitative (microplate reader (615 nm))	Colorimetric (spectrometry); bacteria (inhibition of B-galactosidase) + chromogenic substrate
 BioFix® Lumi-10 (MACHEREY-NAGEL)	15 min (for preparation of reagents) + 15 min	Medium–high	Low	Lyophilised and frozen bacteria, control solution, reactivation solution, osmotic adjustment solution, pH adjustment	> 12 months	Quantitative (Equitox)	Bioluminescence (of *Aliivibrio fischeri*)

(*) Low: < EUR 1 000; medium: EUR 1 000–5 000; high: EUR 5 000–10 000.

(**) Low: < EUR 50/test; medium: EUR 50–100; high: > EUR 100.

NB: Links to the manufacturers' websites can be found in References (p. 23).

All the devices described in Table 1 provide a quick response time, varying from 30 min to approximately 2 hours. There is a wide range of purchase prices, depending on the measurement technology. Most technologies deliver quantitative results, or both qualitative and quantitative, while others (NIDS® ACE I) only allow for qualitative measurements. In the case of the Toxi-ChromoTest™, the qualitative version is based on simple visual readings and thus has a low CAPEX that could be suitable for laboratories and small utilities with limited financial capabilities. The shelf life of reagents has improved over the years and now varies from a few months to a few years, although some may require refrigeration. The price of reagents, per test, ranges from EUR 10 to EUR 150 depending on the type of test and quantity purchased.

Besides the price per test, utilities may wish to estimate the full OPEX of the equipment. In that case, the cost of labour and equipment maintenance must be added to the reagent costs.

4.3. ATP measurement

All organisms contain ATP as their main energy source and the amount of ATP in a sample is directly proportional to its biomass.

ATP provides energy for cellular operations by donating phosphate groups, resulting in the formation of either adenosine diphosphate (ADP) or adenosine monophosphate (AMP), which are subsequently recycled and regenerated back into ATP as the organism consumes food. This process typically occurs many times per second (Goodsell, 1996). Therefore, the intracellular ATP (i.e. ATP contained inside living cells) can be considered the potential energy contained within an active biomass population at any given time. ATP production is directly related to the growth rate of the cell and therefore higher ATP levels are indicative of greater mass and cell volume (Johnston et al., 2012).

ATP can be easily measured with high specificity through a firefly luciferase assay. Luciferase is a naturally occurring enzyme that is most commonly found in the tails of fireflies. ATP reacts with luciferin/luciferase to produce light. In this reaction, each molecule of ATP produces 1 photon of light and the light output of this reaction can be accurately measured, within a matter of seconds, using a luminometer.

A luminometer is a light-detecting instrument like a spectrophotometer but does not contain its own light source and is generally much more sensitive. It is the luminescent reaction that acts as the light source. The result obtained by luminometers is typically expressed as a relative light unit (RLU).

ATP measurement is thus a quantitative method to detect active cells; its main advantages are the quick acquisition of results (in minutes) and the detection of microbial activity from any type of living microorganism.

As with toxicity, for the results to be useful in emergency situations, a pattern of normal ATP levels should be obtained beforehand so that results are based on clear changes from the status quo. Furthermore, routine

measurement of ATP provides background information that can also be useful for operational monitoring of drinking-water systems.
There is a wide variety of brands on the market for these devices, with different designs depending on the intended application. For more sensitive applications, photomultiplier-tube-equipped luminometers are often used and can typically achieve several orders of magnitude of enhanced sensitivity. Luminometers are also available in both single-chamber and 96-well-plate format.
Examples of commercially available equipment for ATP measurement are presented in Table 2.
For each device, a description of the technology is given, including the manufacturer, time needed to obtain a result, CAPEX, cost and shelf life of reagents and technological principle.

Table 2 *– Selection of some devices available on the market for ATP measurement*

Device name (and manufacturer)	Time needed to get a result	CAPEX (*)	Cost of reagents (**)	Reagents	Shelf life of reagents	Expression of results	Technological principle
 GloMax® 20/20 Luminometer (Promega)	Minutes	High	Medium	Lysis reagent, buffer, detection reagent	6 months, refrigerated, after Water-Glo™ reconstitution	Quantitative (RLU)	Bioluminescence technology: firefly luciferase assay
 B-QUA™ + PhotonMaster™ (LuminUltra)	Minutes	Medium	Medium	Luminase™ enzyme and buffer vials, UltraCheck™	12 months (3–6 months after reconstitution)	Quantitative	Bioluminescence technology: firefly luciferase assay
 AquaSnap™ (Hygiena)	Seconds	Medium	Low	AquaSnap test device	15 months refrigerated	Quantitative (RLU)	Bioluminescence technology: firefly luciferase assay; liquid stable chemistry
 PROFILE® 1 (New Horizons Diagnostics)	15 min (preparation) + 5 minutes	Medium	Low	Filtravettes, somatic realising agent, bacterial cell realising agent, luciferin-luciferase	Refrigerated (6 hours after reconstitution)	Quantitative (RLU)	Bioluminescence technology: firefly luciferase assay

(*) Low: < EUR 1 000; medium: EUR 1 000–5 000; high: EUR 5 000–10 000.
(**) Low: < EUR 10/test; medium: EUR 10–50.
NB: Links to the manufacturers' websites can be found in References (p. 23).

All the devices presented provide a quick response within minutes, but AquaSnap™ is even quicker, giving results in seconds, as it does not require any preparation of reagents due to its liquid-stable chemistry. Most of the devices are portable, but GloMax® can also be purchased as a benchtop device. Bioluminescence is the analytical technology used in all the instruments displayed.

5. Targeted technologies – rapid detection and identification methodologies

5.1. Introduction to targeted technologies

As previously mentioned, positive toxicity and ATP results identify the source of the contamination as chemical or microbial, respectively, thereby determining the next phase of laboratory analysis. Subsequent tests with targeted technologies are used to identify the compound responsible for the contamination and are the focus of this section. As opposed to the analytical methodologies described in the previous section, targeted technologies aim to identify specific compounds or microorganisms in the water.

Generally speaking, targeted methods include not only rapid detection methods but also the conventional laboratory methodologies for identification of different chemical and biological contaminants, which are not described in this review.

The technologies described below comprise tests available on the market that focus on rapidness, reliability and ease of use by technicians. Wherever possible, analysis should be carried out by accredited laboratories, to ensure reliability and comparability of results.

It should be noted that rapid targeted methods available on the market are directed at detecting the most probable contaminants associated with deliberate contamination of water, but they do not cover all possibilities and it may be necessary to extend the analysis to include complementary laboratory methods.

There is a wide variety of rapid detection technologies targeted at specific contaminants on the market, with a corresponding extensive range of prices. Relevant information on these technologies is presented in Table 3. The analytical technology, manufacturer, time taken to deliver results, CAPEX range and number of targets is described.

Table 3 *– Some equipment available on the market for rapid detection and identification of contaminants*

Technology	Name	Manufacturer	Time needed to get a result (min)	CAPEX (*)	Number of targeted contaminants
PCR-based methods	FilmArray BioSurveillance	BioFire Diagnostics	60	Very high	26
	T-COR 8™ Real-time PCR Thermocycler	Tetracore	20–45	Very high	10
	RAZOR EX BioDetection System	BIOFIR Defense	30	Very high	10
	BioThreat Alert® Reader	Tetracore	20–45	Medium	10
	POCKIT™ Nucleic Acid Analyzer	GeneReach	60	Medium	15
Immunoassay-based methods	pBDi system	Bruker	20–30	High	10
	RAPTOR™	Research International	15–30	High	18
	Zephyr Pathogen Identifier	PathSensors	2–15	High	6
	SMART™-II	New Horizons Diagnostics	15–30	Very low	6
	KDTB Gold kit	NBC SYSTEM	15–30	Medium	7
	RAMP® Reader	Response Biomedical	15	Medium	5
	Defender TSR™	Alexeter technologies	18–24	—	11
	Guardian Reader™	Alexeter technologies	18–24	Medium	11
	NIDS® Biothreat Detection System	ANP Technologies®Inc.	18–24	Medium	23
	ENVI Assay System	Environics	2–15	Medium	7
	PRO STRIPS™	AdVnT Biotechnologies	3–15	Low	5
	BADD™ Biowarfare Agent Detect Devices	AdVnT Biotechnologies	3–15	Low	5
Sequencing technology	MinION	Oxford Nanopore Technologies	10	Medium	Library dependent
GC/MS	Torion T-9 Portable GC/MS	Perkin Elmer	3	Very high	Library dependent
	Griffin G510	FLIR	4–15	Very high	Library dependent

(*) Very low: < EUR 100; low: EUR 100–1 000; medium: EUR 1 000–5 000; high: 5 000–10 000; very high: > EUR 10 000.

NB: Links to the manufacturers' websites can be found in References (p. 23).

There is a wide variety of both PCR- and immunoassay-based systems on the market; this range is constantly expanding, covering anywhere from a few to a significant number of targeted contaminants. All the technologies deliver fast results (in ≤ 1 hour) and the basic models of the equipment above can be found in a wide range of prices. Each device usually comes in a variety of models, making it difficult to indicate CAPEX. For the last two technologies, particularly sequencing, the cost and range of contaminants covered will be highly dependent on the

specific libraries of targeted contaminants purchased by each client. The number of additional targets increases the price and can raise it by more than two orders of magnitude. Given all this, links to the manufacturers' websites are provided at the end of the review so that further information can be obtained.

5.2. Polymerase-chain-reaction (PCR)-based methods

For the purpose of rapid identification of pathogens in water, there are many devices based on PCR technology. This method uses the amplification of deoxyribonucleic acid (DNA) fragments and a final reading of fluorescence, providing very precise identification of microorganisms and viruses. For water samples, a pre-concentration should be carried out prior to the analysis to avoid loss of sensitivity.
Some examples of PCR-based equipment are included in Table 3.
Some devices, designed specifically for emergency events, use a preset, completely automated biothreat panel, and are rapid and easy-to-use. For example, one of the devices – the FilmArray BioSurveillance System – is able to analyse up to 26 agents, including 16 pathogens, in just 1 hour. Other portable devices can provide results in even less time.
Various different devices with an automated protocol are available on the market, such as the RAZOR® and FilmArray devices (Figure 3 and Table 3). The latter can analyse up to 26 different targets simultaneously, with easy-to-use syringe loading, using a plastic pouch with automated capabilities, including sample preparation.
Other PCR manufacturers supply two different devices: a simple, portable, cheap model and a more sophisticated, expensive one, as in the case of BioThreat Alert®, which can be used with a mobile phone, and T-COR 8™, a portable real-time PCR.
Other options include the POCKIT® Micro Series Nucleic Acid Analyzer, which is lightweight and handheld.

***Figure 3** – Examples of PCR-based equipment (see Table 3 for specifications)*

FilmArray BioSurveillance System

T-COR 8™ Real-time PCR Thermocycler

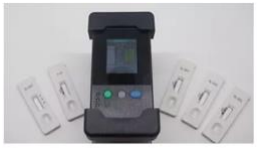
POCKIT™ Micro Series Nucleic Acid Analyzer

5.3. Immunoassay-based methods

There are many different options for equipment based on immunoassays on the market. The most common ones aim to identify known toxic agents that present high toxicity (bacteria, viruses and toxins) and are able to identify between 1 and more than 20 targeted compounds.
Information on different immunoassay-based devices is included in Table 3.
Most of the tests use immunoassay-based systems with lateral flow technology. The main advantage of the lateral flow immunoassay is the short time taken to deliver a result (15–30 min) and it can provide qualitative, semi-quantitative or quantitative results. Qualitative results are obtained from visual readings and the CAPEX of the equipment is relatively low. In contrast, quantitative tests require more expensive equipment but provide more precise and reliable results. These technologies are rapid and do not require specialised staff.
Examples of devices based on lateral flow immunoassays are shown in Figure 4 and Table 3. The more economical equipment options deliver qualitative results and are based on the use of cards (strips). A single test with one of these devices (e.g. PRO STRIPS®, BADD™, SMART II) can identify one or more compounds within a card. There are other devices also based on the use of cards, which are compatible with reading devices that perform a quantitative test (RAMP® READER, Defender TSR™, Guardian Reader™ or NIDS® Biothreat Detection System). Other options on the market include a (biothreat) panel for responding to deliberate contamination of water and can be bought as a case containing all the necessary supplies pre-prepared for an emergency (KDTB Gold kit or ENVI). This equipment delivers results in less than 1 hour and is supplied with a pre-set panel targeting the main known biological agents.

***Figure 4** – Examples of equipment based on immunoassay / lateral flow technologies (see Table 3 for specifications)*

KDTB Gold kit



NIDS® Biothreat Detection System

PRO STRIPS™

Other immunoassay-based devices, with different measurement methods, are available on the market (Figure 5 and Table 3). These provide much higher sensitivity and fall into a higher price range. They include a portable biodetector (pBDi) based on a multiplex enzyme-linked immunosorbent assay (ELISA) detection system with an electrochemical chip read-out, and a portable device based on monolayer receptor–ligand reactions taking place on the surface of injection-moulded polystyrene waveguides (RAPTOR™), or a patented system based on biosensors (genetically engineered immune cells) and light-output detection (Zephyr Pathogen Identifier – using cellular analysis and notification of antigen risks and yields (CANARY®)).

***Figure 5** – Other examples of equipment based on immunoassay technologies*

pBDi system (ELISA)

RAPTOR™

Zephyr Pathogen Identifier – CANARY®

5.4. Sequencing technology

Sequencing technology is used to sequence DNA / ribonucleic acid (RNA) chains in real time using an internal library for the identification of microorganisms.

The MinION (Figure 6) is a new portable, real-time, long-read, low-cost device from Oxford Nanopore Technologies that has revolutionised sequencing by introducing the first nanopore sequencing for qualitative analysis. Unlike traditional RNA-sequencing techniques, long-read nanopore RNA sequencing allows for a characterisation of native RNA or complementary DNA without fragmentation or amplification – streamlining analysis and removing potential sources of bias. Direct RNA sequencing also enables the identification of base modifications alongside nucleotide sequencing. Sequencing libraries can also be prepared using a MinION field sequencing kit that includes shelf-stable lyophilised reagents, incorporating real-time data analysis.

A whole-genome shotgun sequencing approach using nanopore technology results in species-level taxonomic classification, with a more complete profile starting to emerge after just 2 hours of sequencing. The final results can be available after 24 hours of sequencing, with identification of algae, archaea, bacteria and viruses. In the context of biothreat-agent identification and testing samples for unknown contaminants in the field, this classification capability can be of added value as it has the potential to identify and characterise the agents, and to support source attribution of samples through the capture of other, extraneous DNA.

Figure 6 *– MinION – equipment based on sequencing technology*

5.5. Portable gas chromatograph / mass spectrometer (GC/MS) devices

Other systems for the rapid on-site detection of toxic compounds include portable GC/MS devices. These can be used in the field for rapid screening of chemicals, especially environmental volatile and semi-volatile compounds like volatile/semi-volatile organic compounds (VOCs/SVOCs), explosives, chemical warfare agents and other hazardous substances.

One example is the Torion® T-9 (Figure 7 and Table 3) a portable GC/MS. The integrated system features a low thermal mass capillary gas chromatograph with high-speed temperature programming and a miniaturized toroidal ion trap mass spectrometer (TMS). Samples are injected using a novel CUSTODION® solid phase microextraction (SPME) fibre syringe. It provides a high-resolution separation of chemical analytes and has the capability of searching mass spectra from unidentified compounds against the National Institute of Standards and Technology (NIST) library which contains 1 100 compounds or other existing libraries.

Another portable GC/MS also available on the market, with similar characteristics and an additional Scientific Working Group for the Analysis of Seized Drugs (SWGDRUG) mass spectra library, is the Griffin G510 (Figure 8 and Table 3).

These types of devices were mainly developed for military applications, in very specific situations, but can also be used for field monitoring of drinking-water supply systems.

Figure 7 *– Torion® T-9 – portable GC/MS*

Figure 8 *– Griffin G510 – portable GC/MS*

6. Proficiency tests

Water utilities and laboratories involved in emergency response need to be prepared for emergency situations related to water quality. This requires planning and ongoing training to provide a rapid and efficient response, and proficiency tests present good opportunities for training laboratories in this context.
In the event of an incident of drinking-water contamination, a laboratory will be called upon to identify any contaminants present, in the most efficient and timely manner possible, often with very little information as to the source of contamination (May, 2011).
Proficiency tests for responding to the presence of unknown contaminants in drinking water are aimed at testing the capabilities of laboratories to analyse a water sample contaminated by a completely unknown chemical on an emergency, short-term, rapid-screening basis. Thus, the primary function of these tests is to assess the ability of the laboratory to detect and identify unknown chemical contaminants in a simulated drinking-water contamination incident (May, 2011).
In Europe, besides the conventional proficiency tests, a specialised proficiency test for events of contamination of drinking water by unknown substances is commercially available from the Food Analysis Performance Assessment Scheme (FAPAS), a United Kingdom-accredited proficiency test provider since 1990: the FAPAS 'Chemical Contamination Incident in Drinking Water Proficiency Test' (https://fapas.com/shop/product/chemical-contamination-incident-in-drinking-water-proficiency-test/806).
In this proficiency test the laboratory must identify the chemical contaminants present as quickly as possible. In addition to the accuracy of the laboratory's results, the flexibility of its testing procedures and the speed of its analysis will also be assessed. All of these factors should be evaluated to ensure that the laboratory is fit for purpose and able to respond effectively to a contamination incident (May, 2011).
This particular proficiency test takes place over a 12-day period. It starts with the provider, without warning the laboratories, spiking a drinking-water sample with chemical contaminants – a combination of inorganic and organic compounds. Samples are then shipped to the participating laboratories, and included with each set of samples is a contamination scenario detailing the circumstances of the contamination.
The laboratory should then carry out the necessary analysis as quickly and accurately as possible to detect and identify any contaminants present in the samples provided. Results should be sent to the proficiency test provider as they become available, and specifically answering the following questions (May, 2011).

- Is there any significant contamination present?
- If so, what is the approximate concentration(s) present?
- What are the potential sources of contamination?
- What analytical methods have been employed to detect the contaminant?
- Were any screening tests used?
- What can the water be used for?

There is a maximum time allowed to complete the exercise and the laboratories are informed of the contaminant(s) present in the samples after the time has expired. FAPAS ensures that all information and results are secure and confidential.
For laboratories to gain maximum benefit, it is important that laboratory staff have no advance warning of the test.

7. Approach to identifying water contaminants in emergency situations

An event detection system (EDS) detects an abnormal change in the water quality based on the information coming from the online monitoring devices (Carmi, 2019). This information, together with other potential incidents identified in the water security plan (Teixeira et al., 2019), for example a breach in the utility's cyber or physical security in an integrated surveillance system or complaints from consumers or authorities, can trigger an emergency warning. Following such a warning, the procedure for the identification of the incident, as described in the water security plan, should be initiated. Each utility should have its own procedures for responding to these warnings as quickly as possible to identify the source and the type of contaminant.

Taking into account the diverse range of equipment available on the market to investigate the nature of unknown compounds in water, each water supplier should plan the course of action they intend to take to identify the contaminating compound in advance. This plan will depend on the objectives of each utility and will certainly be linked to the available budget.

With the aim of supporting utilities and laboratories in the design of their action plans, an approach is proposed in this section, comprising a series of analytical steps that can be adapted by each facility.

All the analytical technologies discussed are available on the market and were selected for their rapidness (results delivered in a few minutes to a few hours), the reliability of their results and on easy-to-operate technologies enabling their use by non-specialised technicians on a 24/7 basis. In a subsequent phase of the emergency response, the methodologies described can also be used to confirm that the situation has been remedied, supporting the safe return to normality.

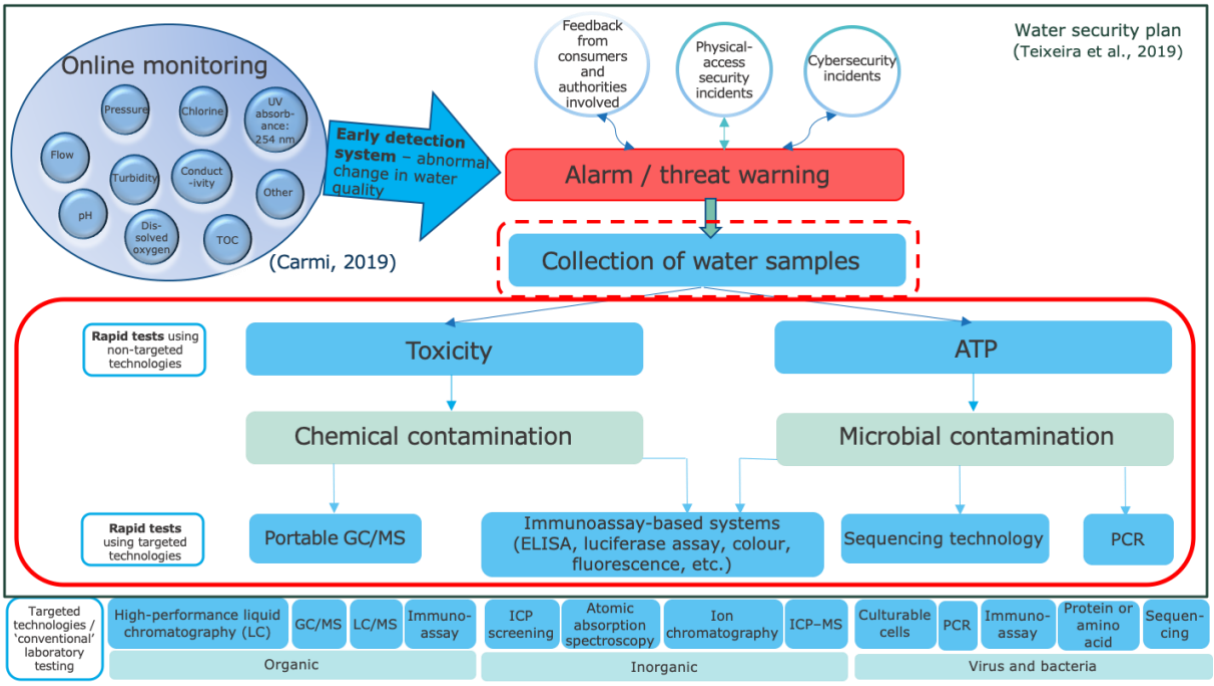
All approaches must start with the sampling procedures, which are a key element. An improper sampling process can endanger the identification of the source and nature of the contaminant. Therefore, planning and well-established procedures should be in place to ensure the proper collection of representative samples and field analysis (refer to Section 2 for details).

The step following the sample collection and transport will be the analysis with non-targeted technologies (measuring toxicity and ATP) in order to identify whether the compound responsible for the contamination is chemical or microbial in nature (refer to Section 4 for details). As already described, there are several devices available on the market to measure toxicity and ATP, with various prices and modes of measurement (qualitative and quantitative), so utilities can select devices according to their specific objectives.

Once the nature of the compound is determined, the next step is to quickly identify the specific compound causing the contamination by performing rapid tests using targeted technologies (refer to Section 5 for details). The CAPEX ranges from inexpensive immunoassay-based systems to very expensive portable GC/MS devices for rapid detection of volatile compounds in water.

Depending on the outcomes of these tests and the objectives of the utility, further analysis may be needed; a full diagnosis may need to be performed using conventional laboratory tests (Figure 9). Wherever possible, analysis should be carried out by accredited laboratories, to ensure reliability and comparability of results.

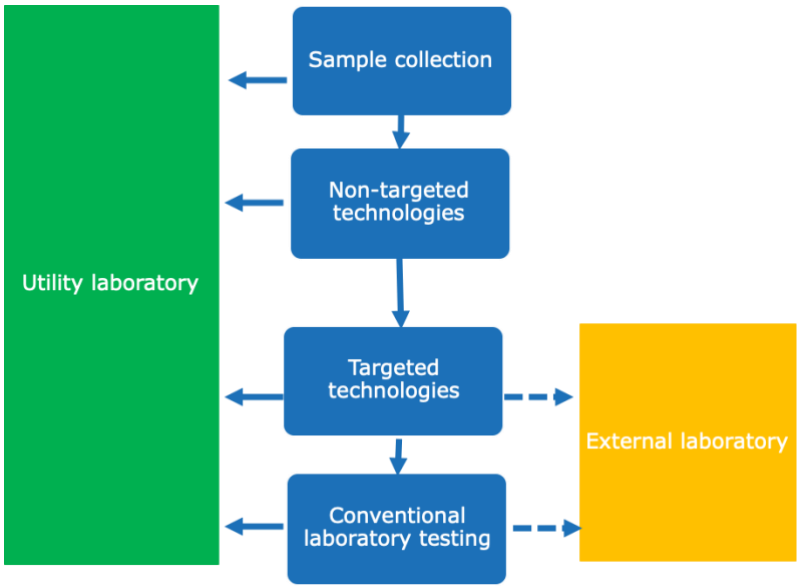
Figure 9 *– Diagram of possible analytical procedures in the event of unknown contaminants in the water supply*



The information outlined in this document serves as a guide to water utilities for performing their own procedures with a primary focus on obtaining results as quickly as possible, ensuring reliability of data and providing technicians with easy-to-use equipment. There are many options that meet these criteria, and they need to be adapted to each utility's capabilities and goals.

It is recommended that water utilities be capable of collecting water samples and performing basic field analysis, internally, on the shortest possible notice. The subsequent step towards the identification of unknown compounds includes the use of non-targeted technologies, which should preferably be carried out internally. Subsequent rapid targeted tests could be carried out internally or contracted out to external laboratories (Figure 10). If external laboratories are contracted, specific requirements for emergency situations should be included in the contracts.

Figure 10 *– Flowchart of different potential procedures for the identification of unknown compounds*

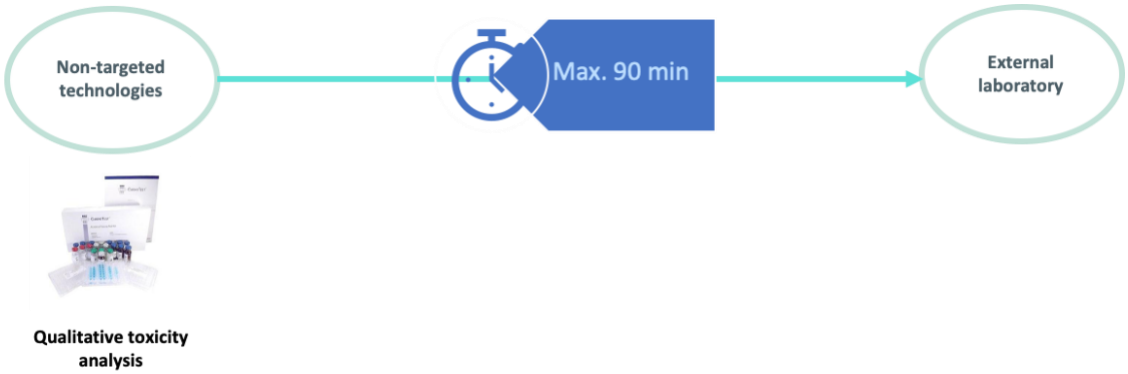


A utility's own laboratory may not be able to perform analyses for all contaminants in all emergency scenarios. Thus, as far as possible, utilities should identify in advance any contaminants or scenarios for which they will require analytical support and identify external laboratories, if needed, and emergency response partners.

7.1. Examples of analytical plans for identifying unknown compounds

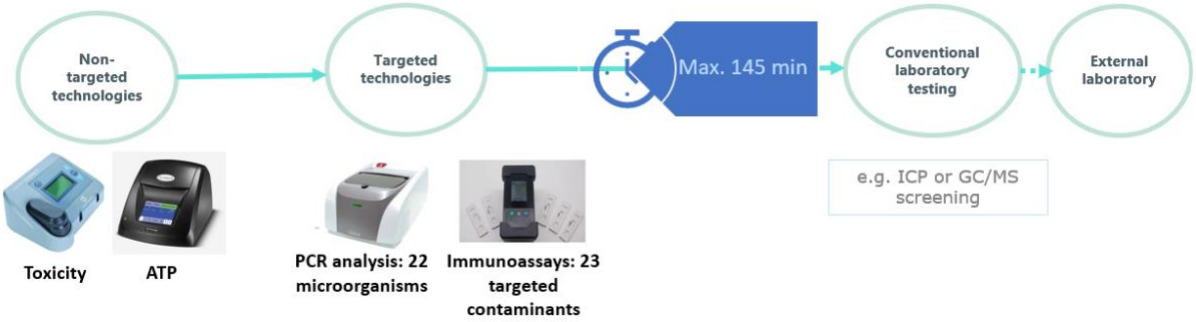
Considering the diversity of the available equipment and the objectives of different utilities, two different examples of analytical plans are described below: a simple, inexpensive solution and a more sophisticated, costly approach. The first example comprises a simple qualitative toxicity test (Toxi-ChromoTest™) estimated to take 90 minutes to deliver results. It can be performed in parallel to sending the samples to an external laboratory, thus optimising the response time (Figure 11).

Figure 11 *– Example of a quick, simple, inexpensive solution for analysing the nature of unknown compounds*



The second example comprises initial tests using non-targeted technologies, with separate devices for measuring toxicity (Section 4.1) and ATP (Section 4.2) or the use of the DeltaTox equipment for measuring both. Subsequently, the use of FilmArray analysis (PCR-based technology) will allow for the identification of at least 22 microorganisms and, in parallel, the NIDS® Biothreat Detection System will identify up to 23 targeted chemical contaminants. The identification takes a maximum of approximately 2 ½ hours (145 min). At this stage the contaminant should have been identified and triggered the next steps in the water security plan. If a full identification is not achieved, further analysis may be done using conventional laboratory methods, either internally or in an external laboratory (for example using inductively coupled plasma (ICP) screening and GC/MS) (Figure 12).

Figure 12 *– Example of a comprehensive solution for analysing and identifying unknown compounds in water*



These are just two examples from the diverse range of solutions that a water utility may consider in order to rapidly identify possible threats to drinking-water quality. The implementation of any of these procedures presents new challenges as it entails the need to act promptly along with a change of approach from routine monitoring to a new analytical strategy. Furthermore, the need to implement a series of measures – such as detailed planning, the availability of "Emergency Response Set" , staff training and plans for the restocking of reagents and consumables – or the need to perform simulations should be considered.

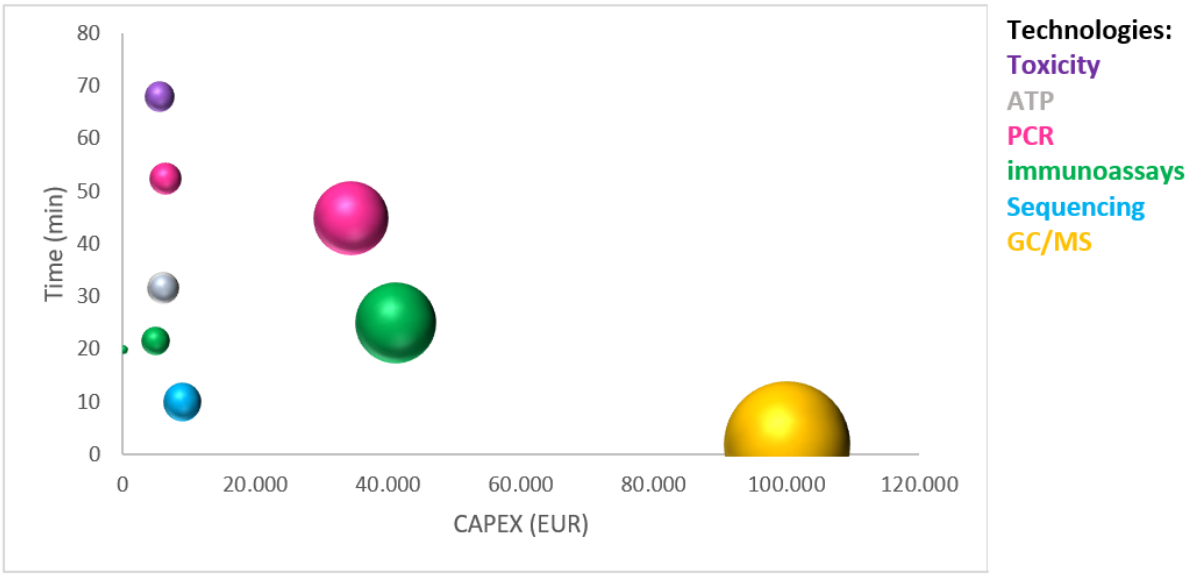
8. Conclusions

According to the United Nations' sustainable development goals, by 2030 the entire human population must have access to safe drinking water and sanitation. While water safety requires the water sector to be concerned with the quality of drinking water and its impact on human health, the sector must also now consider the security of drinking-water systems to avoid or minimise the impact of intentional contamination of the drinking-water supply systems.

This review has identified the analytical technologies capable of providing a fast and reliable response in the event of unexpected contamination of drinking-water supply systems, comprising a series of analytical steps that can be adapted to suit each utility and laboratory. The choice of measures available to water suppliers will depend on their risk assessment process and their management of emergency situations. It will therefore be useful to understand, for each type of technology, the relationship between the CAPEX of the equipment and the time it takes to deliver results.

The relationship between the average CAPEX of the technologies described in this review and their respective average times taken to deliver results is shown in Figure 13. An additional indication of the CAPEX is given by the size of the globes. The cost differences within the same family of technologies (represented by globes of the same colour) are due to a diverse range of technological options: some only provide qualitative, visual analysis, while other options require a greater investment but deliver more precise, quantitative measurements.

Figure 13 *– Relationship between average CAPEX and average time needed to obtain results, for different groups of technologies*



By considering the CAPEX, price per test, number of targets and time needed to obtain results for different technologies, together with their own needs and capabilities, utilities can acquire the necessary equipment to enhance their response to deliberate contamination of drinking water. Alternatively, utilities could purchase equipment for basic field and laboratory analysis and collaborate with partner laboratories to create networks dealing specifically with the issue of emergency response.

It should be noted that this is not an exhaustive assessment of all the devices available in the market. This review has used information available online from different manufacturers to provide utilities and laboratories with an overview of the options available on the market. Prospective purchasers are advised to obtain more detailed information directly from local manufacturers or distributors concerning different devices, depending on their specific needs and objectives.

This review of analytical technologies aims to support water utilities, laboratories, health authorities and other stakeholders in planning responses to emergencies in drinking-water quality, and in particular to enhance the rapid identification of unknown water contaminants. Careful consideration of these technologies, within the framework of a water security plan, along with appropriate planning and protection measures, will enable water utilities to better respond to unexpected contamination of drinking water.

9. Recommendations

The pace of change in the analytical technologies described in this review is such that improvements in capabilities will continue to appear. It is also likely that the costs of the technologies will change in the future.
It is therefore recommended that ERNCIP schedule periodical updates to this review, for example every 24 months. These updates should identify any new types of technologies that would be relevant, and review the information provided, such as the costs.
As this document aims to provide guidance to water utilities, feedback from users on how useful the review has proved, along with suggestions for potential improvements, would be very useful to ERNCIP. Therefore, a process whereby readers can easily give feedback should be implemented.

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Links to manufacturers' websites, by technology

Toxicity tests

https://www.modernwater.com/assets/downloads/120412/DeltaTox_II_Emergency_Response.pdf
https://www.anptinc.com/chemical-detection-system
https://www.ncimb.com/service-by-industry/environmental-services/toxicity-testing/
http://biotoxicity.com/index.php/ebpi-toxicity-tests/acute-toxicity/toxi-chromotest-kit
http://www.aadee.com/00pdf/industria_investigacion/lb962_centroliapc_72dpi_brochure.pdf
https://www.mn-net.com/StartpageWaterAnalysisTesting/Microbiologicaltests/BioFixLuminometerLumi10/tabid/5000/language/en-US/Default.aspx

Adenosine triphosphate detection (ATP)

https://www.promega.es/products/microplate-readers-fluorometers-luminometers/microplate-luminometers/glomax-20_20-luminometer/?catNum=E5321&accordion0=0
https://www.luminultra.com/wp-content/uploads/LuminUltra-PhotonMaster-Luminometer-PBM-Product-Instructions_2017.pdf
https://www.hygiena.com/other-products/aquasnap-other.html#video-demo
https://www.nhdiag.com/profile_one.shtml

Polymerase chain reaction (PCR)

https://www.biofiredefense.com/products/filmarray/
https://www.tetracore.com/t-cor8/index.html
https://www.biofiredefense.com/products/razorex/
https://www.tetracore.com/bio-warfare/index.html
https://www.genereach.com/index.php?func=product&action=view&product_no=2
https://www.cepheid.com/uk/cepheid-solutions/systems/genexpert-systems

Immunoassay-based systems

https://www.bruker.com/news-records/single-view/article/bruker-announces-acquisition-of-field-portable-platform-for-fast-and-universal-immunoassay-detection.html

https://www.resrchintl.com/RAPTOR_Bioassay_System.html
https://pathsensors.com/applications/biodefense/
https://www.nhdiag.com/anthrax.shtml
https://www.nbcsystem.it/prodotto/ktdb-difesa-biologica/
http://responsebio.com/products/ramp-reader
http://www.alexeter.com/biow/products/products/defender.asp
http://www.alexeter.com/biow/products/products/guardian.asp
https://www.anptinc.com/biothreat-readers
https://www.environics.fi/product/envi-assay-system/
https://advntbiotechnologies.com/pro-strips-bio-threat-detection-kit
https://advntbiotechnologies.com/badd

Sequencing technologies

https://nanoporetech.com/products/minion

Gas chromatography / mass spectrometry (GC/MS)

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http://www.perkinelmer.com/es/product/torion-t-9-portable-gc-ms-instrument-ntsst090500
https://www.flir.com/products/griffin-g510/

FAPAS proficiency test

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https://fapas.com/shop/product/chemical-contamination-incident-in-drinking-water-proficiency-test/806

List of abbreviations, acronyms, initialisms and definitions

ATP	Adenosine triphosphate
CBRN	Chemical, biological, radiological and nuclear
CANARY	Cellular analysis and notification of antigen risks and yields
CAPEX	Capital expenditure
DNA	Deoxyribonucleic acid
ELISA	Enzyme-linked immunosorbent assay
ERNCIP	European Reference Network for Critical Infrastructure Protection
FAPAS	Food analysis performance assessment scheme
GC/MS	Gas chromatography / mass spectrometry
ICP	Inductively coupled plasma
ISO	International Organization for Standardization
LC	Liquid chromatography
pBDi	Portable biodetector
PCR	Polymerase chain reaction
RLU	Relative light unit
RNA	Ribonucleic acid
TOC	Total organic carbon
TRL	Technology readiness levels
UV	Ultraviolet

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