World Health Organization

Lead in drinking-water

Health risks, monitoring and corrective actions

Technical brief

About this technical brief

This technical brief provides guidance on managing lead contamination in drinking-water supplies, from hand pumps to piped supplies. The information in this brief is primarily intended for water suppliers and agencies responsible for overseeing the safety and acceptability of drinking-water in resource-limited settings. Certain sections of this brief are also useful for other stakeholders involved in drinking-water quality management.

The information in this technical brief has been structured around actions to take when elevated lead concentrations are detected in drinking-water. These actions range from further monitoring, informed by investigation of lead sources, to remedial measures to reduce lead in drinking-water. The technical brief also includes background information on the potential health risks of lead exposure and sources of lead exposure in the environment.

> As lead is a priority chemical hazard, a proactive approach to identifying, assessing and managing lead in drinking-water should be adopted. This should include understanding lead sources in drinking-water, monitoring lead in drinking-water (including in supplies known or suspected to contain lead materials), and adopting appropriate procurement and installation programmes to prevent the introduction of lead into new water systems.

Key messages

Lead is recognized as a chemical of major public health concern. There is a need to decrease human exposure to all sources of lead in the environment, including in drinking-water.

Lead should be included in national drinking-water quality standards and monitored as part of a drinking-water quality surveillance programme.

The primary source of lead in drinking-water is leaching from lead-containing materials in water systems, including plumbing in buildings (e.g. homes, childcare facilities, schools) and hand pump components. These materials can be made of lead, lead-containing metal alloys, or polyvinyl chloride (PVC) or unplasticized polyvinyl chloride (uPVC) with lead stabilizers. Other exogenous sources include pollution or leaching from lead-containing bedrock.

Prevention is the most effective action. For materials in contact with water, only low-lead or lead-free water system parts should be used when constructing new water systems or rehabilitating old ones. Programmes should be developed to support the adoption of standards, including appropriate procurement and installation of parts. Compliance with these standards should be monitored to minimize and ideally prevent the introduction of lead into new water systems.

Elevated lead levels in drinking-water should trigger a systematic investigation to understand exposure and contamination sources, and to inform remedial actions. Where elevated lead levels in drinking-water are confirmed, **remedial actions should be taken to progressively reduce lead concentrations** to levels as low as reasonably achievable and ideally to below the World Health Organization provisional guideline value of 10 μg/L.

Actions should take into consideration that lead concentrations in drinking-water can vary over time. Because of this variability, a probability-based adaptive sampling plan should be used to assess exposure. If prior knowledge exists about possible lead sources, sampling and actions can be directed towards these sources.

Cooperation and coordination are critical, including with drinking-water suppliers, agencies responsible for overseeing drinking-water safety and agencies responsible for broader public health. Cooperation and coordination are needed to communicate about issues relating to lead in drinking-water and to understand the broader public health significance of lead in drinking-water. This understanding is appropriate to inform investment decisions and communications with the public.

Remedial actions may include a combination of interim and long-term measures. Interim measures include alternative sources of safe water for vulnerable groups, certified lead removal units at points of consumption (e.g. at the customer tap), flushing at the tap or hand pump, or corrosion control. Longer-term measures include replacing materials in contact with drinking-water. Shutting down water supplies is generally considered an inappropriate response.

Actions should be prioritized to areas where exposures or risks are high. Remedial actions should ideally be implemented first in settings with the highest lead concentrations in drinking-water, particularly focusing on infants, children and pregnant individuals.

Lead in drinking-water should be considered as part of broader efforts to improve the safety of drinking-water and public health. Reducing any exposure to lead supports health protection efforts. However, reducing lead in drinking-water should also be part of an overall programme to reduce microbial and other priority chemical risks from drinking-water systems.

Introduction

Lead is recognized as a chemical of major public health concern that should be included in national drinking-water quality standards and monitored as part of a drinking-water quality surveillance programme. Lead concentrations in drinking-water should be kept as low as reasonably achievable.

Lead is a naturally occurring toxic metal. Its widespread use has caused extensive environmental contamination, human exposure and health problems in many parts of the world. It is a cumulative toxicant that can affect multiple body systems. Children are particularly vulnerable to the neurotoxic effects of lead (WHO, 2016a).

Lead exposure causes a significant burden of disease: it is estimated that lead exposure accounts for 0.9 million deaths per year (IHME, 2020) and 30% of the global burden of developmental intellectual disability of unknown origin (WHO, 2019). The World Health Organization (WHO) has identified lead as one of 10 chemicals of major public health concern needing action by Member States.

Lead as an additive in petrol was previously an important source of exposure, but from 2021 all countries have banned such use of lead (UNEP, 2021). However, other important potential sources of exposure to lead remain because of its widespread use, including in batteries, paint, aviation fuels, and ceramic glazes in food containers, as well as in pipes and fittings, and other components in contact with drinking-water. Further efforts are required to reduce the use and release of lead, and reduce environmental and occupational exposures, particularly for children and women of childbearing age (WHO, 2021a).

Given the public health significance of lead in drinking-water, WHO has assessed this contaminant regularly in the *Guidelines for drinking-water quality* (see Box 1). Lead can occur in drinking-water as a result of leaching or particulate release from lead-containing components or materials. The lead content of the water depends on the lead content of materials exposed to water, the duration of contact between the affected materials and the water, how and where in the supply system these materials are installed, and the overall water chemistry.

For piped water supplies, lead-containing components can include service connection pipes (between the water mains and buildings), solder joints, and taps and fittings in household plumbing systems. In hand pump systems, lead contamination can come from lead-containing components in pumps or well parts. In some cases, lead is present in the water source itself, originating from the bedrock or pollution. Further, regardless of source, lead can accumulate as deposits on galvanized or cast iron components, which can then be released.

BOX 1

Understanding the WHO drinking-water guideline value

Since 1993, the guideline value for lead in the WHO Guidelines for drinking-water quality has been 10 µg/L. In 2011, this health-based guideline value was changed to a provisional value to reflect treatment achievability, recognizing that it is difficult to achieve lower than 10 µg/L with central treatment. Previously, the guideline value was supported by the provisional tolerable weekly intake (PTWI) for infants and children established by the Joint Food and Agriculture Organization of the United Nations (FAO)/WHO Expert Committee on Food Additives (JECFA). In 2010, the PTWI was withdrawn because JEFCA concluded that it was no longer considered health-protective and that there is no apparent health-based threshold for lead (i.e. no safe level of lead). At this time, JECFA reaffirmed that fetuses, infants and children are the population groups most sensitive to lead, with neurodevelopment effects still considered the key end-point. However, uncertainties remain in the epidemiology of lead exposure, associated with very low blood lead levels, and end-points (e.g. neurodevelopmental effects) that are affected by many other factors. Nevertheless, every effort should be made to maintain lead levels in drinking-water as low as reasonably practical and below the guideline value when resources are available.

Although the guideline value of 10 µg/L has been in place since 1993, many authorities had standards that were higher than this until recently. For example, in the European Union (EU), the decrease in the lead limit in drinking-water from 50 to 10 µg/L in 2011 (SCHER, 2011) was approached by setting an interim limit of 25 µg/L (Postawa, 2015) for 5–15 years after the EU drinking-water directive took effect. Setting an interim limit allowed water suppliers sufficient time to implement the necessary actions, recognizing the practical difficulties and time required to achieve the stricter standard in many countries.[1]

Accordingly, exceeding the WHO provisional guideline value of 10 µg/L does not necessarily constitute an emergency unless concentrations are continuously very high (e.g. over 100 µg/L). Where concentrations are high and vulnerable groups (fetuses, infants and children) are exposed, interim remedial actions should be considered – for example, flushing if the source is suspected to be in the plumbing system or use of an alternative safe drinking-water supply if the water source is contaminated.

[1] In 2021, a new EU drinking-water directive lowered the limit further to 5 µg/L, which must be met by 12 January 2036 at the latest. This is in line with legislation in several other countries. The parametric value for lead until that date is 10 µg/L. However, caution is needed when comparing limits because interpretation should be informed by the sampling regime, which may or may not be specified in the regulation.

What to do if elevated lead levels are detected in drinking-water

Elevated lead levels in drinking-water above the WHO guideline value or national standard should trigger a systematic investigation of exposure and the contamination source. Remedial actions, informed by investigations on source contamination, should be taken if elevated lead levels in drinking-water are confirmed.

Fig. 1 describes a process to support systematic and sustainable management when elevated lead levels are found in drinking-water. First, there is a need to understand what the sample represents, including whether the elevated level is an isolated event, or typical and representative of exposure. In most cases, further sampling or investigation is needed to understand exposure (step 1 in Fig. 1).

Communication is vital throughout the investigation and management process, starting with a dialogue between the water supplier and the drinking-water regulator or other relevant authority when elevated lead in drinking-water is first detected. A wider communication process should be initiated when elevated lead levels have been confirmed, including with water users. Interim remedial actions may need to be taken if lead concentrations in water are high and vulnerable groups are exposed (step 2).

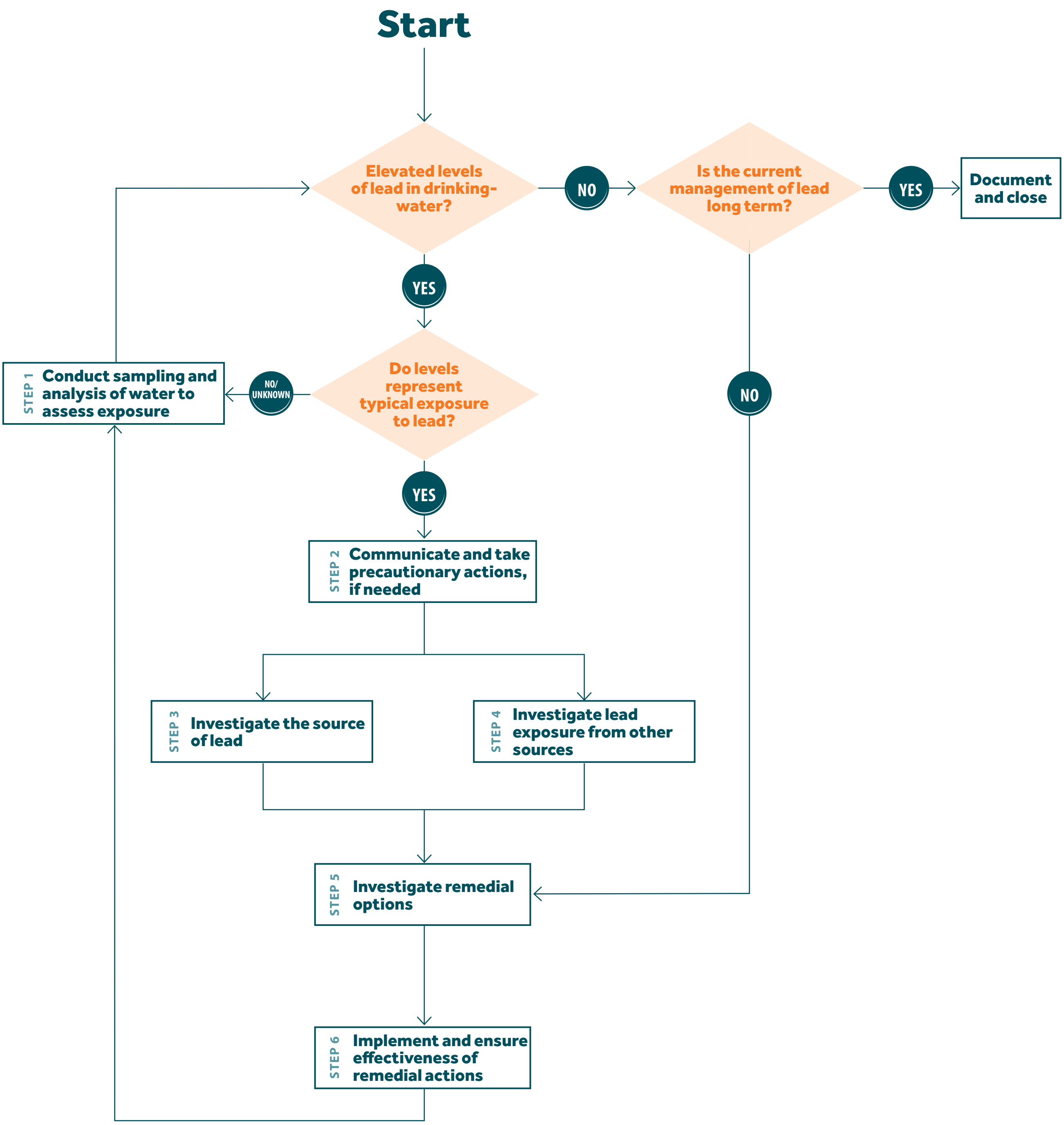
Understanding the source of lead is the next step of the process, which should inform further remedial actions, if needed (step 3). In parallel, a more comprehensive investigation can be conducted to understand the public health significance of lead in drinking-water compared with lead exposure from other sources (step 4).

The information gathered in steps 1, 2, 3 and 4 should inform prevention and remedial options. These should be assessed (step 5) and implemented (step 6) using an integrated and coordinated risk-based approach, to maximize impact considering available resources. Since investigations can take considerable time, it is essential to evaluate the need to implement interim measures in parallel with taking actions to increase understanding of lead exposure, sources of exposure and public health significance. Obtaining a comprehensive understanding of these aspects, particularly step 4, should not significantly delay implementing cost-effective interim measures. The knowledge and resources gained should inform further management actions.

To verify the effectiveness of remedial measures – that is, that the remedial actions have reduced lead concentrations to acceptable levels in drinking-water – lead in drinking-water should be analysed after implementation of the remedial actions (step 1). If subsequent sampling shows acceptable lead levels, the process described in Fig. 1 has reached an end, and lead should then be periodically monitored in drinking-water as required by national standards and when circumstances that can affect lead release occur. If lead levels remain elevated in subsequent monitoring, the actions described in Fig. 1 should be repeated.

Each of the steps in the flow chart is explained in more detail in the following sections.

FIG. 1
Work flow for investigation and management when elevated lead levels are detected in drinking-water



Note: Diamonds indicate key decisions, and boxes indicate activities.

STEP 1

Conduct sampling and analysis of water to assess exposure

Since lead concentrations in a water system can be highly variable and, therefore, highly dependent on the sampling strategy, an understanding of what the results represent is gained through further, structured sampling. Rarely should remedial actions be taken based on only a few samples.

When elevated lead concentrations in drinking-water are initially identified, subsequent sampling and analysis should aim to determine the extent to which lead is present and whether this may result in levels of exposure requiring further investigation. Laboratory and field methods for lead detection are summarized in Annex 1.

Lead concentrations can vary significantly, depending on the source of the lead, whether the lead released is dissolved or in particulate form and the time for which the water is in contact with the leaded material (stagnation time) (Pieper et al., 2015; Deshommes et al., 2016; Chan et al., 2020). Exposure must therefore be assessed using an appropriate sampling strategy, considering when, where and how to take samples, and how many samples to take. This approach is applicable to assessing drinking-water exposure to lead for a single household to wider scales, such as a city (Riblet et al., 2019; Triantafyllidou et al., 2021).

Choosing where to take samples and how many samples to take

A sampling plan describes how many samples to take and where they should be collected to understand lead exposure for a population of interest. A probability-based sampling plan is generally recommended since this approach is flexible and is suitable for producing representative statistics on an area or set of systems.

First, a decision is needed on how prior knowledge should be considered. Prior knowledge can include information from previous surveys, and knowledge of particular building types, ages of distribution systems, types of pipework (e.g. lead service pipes), types of homes or types of pumps. The disadvantage of using prior knowledge is that conclusions may be drawn too early, leaving unknown lead-contaminated sites undetected. The benefit is that the process will be faster, and limited resources will be most effectively targeted, assuming correct assumptions.

Second, more extensive areas or systems often need to be divided into subareas or subsystems (Hoekstra et al., 2009). The division may be done geographically into, for example, townships, local government authorities, blocks or buildings, or according to where water quality is expected to be uniform, based on prior knowledge, thereby serving the purpose of testing a hypothesis. Dividing into subsystems also makes it possible to prioritize areas to sample using a risk-based approach; this means that areas with high numbers of vulnerable groups, such as schools or childcare centres, can be assessed first (Health Canada, 2019).

Third, the number of samples required in each subarea for a representative description of exposure (i.e. average concentrations) depends on the assessed variability of measured concentrations and the desired certainty in the results. If the variability is too high, another round of samples will be required to increase confidence.

If resources are limited, the intensity of the sampling plan can be modest initially. It can be expanded over time – for example, starting with sampling areas with high numbers of vulnerable groups (e.g. childcare centres) or areas suspected to have the highest contamination, and subsequently expanding the area or increasing the number of samples to reduce the uncertainty of the assessment.

Even though the purpose of sampling is to assess exposure, rather than to investigate the source, the data can direct the investigation of the source. If other attributes, such as building type, plumbing system/materials or hand pump materials, are recorded for each sample, results can be interpreted for these, guiding the source investigation. Because not all sources are necessarily sampled in a given monitoring round, the resulting data may not always be useful in identifying individual issues with every system. However, they can indicate trends for problematic components or source types.

BOX 2

Example of a sampling strategy for lead contamination in China, Hong Kong Special Administrative Region (SAR)

After lead in drinking-water was initially identified in Hong Kong SAR in 2015 as a potential issue, the need to undertake sampling to cover large areas including households was identified. To increase efficiency, authorities used a combination of different protocols, taking a tiered approach.

Tier 1
The first tier consisted of a single screening sample using random daytime (RDT) sampling. A 1 L unflushed sample was randomly taken during the daytime.

Tier 2
The second-tier sample provided better representation of an individual's potential exposure to lead. A 30-minute stagnation (30MS) sampling was used. If exceedance was found in the Tier 1 sample, the Tier 2 sample was analysed to verify exposure of consumers to lead. The tap was flushed for 5 minutes and then stagnated for 30 minutes. After stagnation, a 1 L unflushed sample was taken at the tap.

Simultaneous sampling for exposure and the source of lead
While collecting the Tier 1 and Tier 2 samples, auxiliary samples were also taken simultaneously, which were only tested to provide supplementary information if exceedance was found in the Tier 1 and Tier 2 samples. A number of 1 L sequential samples (generally 2–6) were taken from taps at the premises for assessing whether the problem was confined to the premises or not. In addition, a 2-minute flushed sample was taken to confirm the applicability of flushing advice provided to consumers as a mitigation measure in case of exceedance. The approach meant that all samples from one apartment could be collected for analysis on one occasion by professional samplers.

The investigation determined that the soldered joints in the copper piping installed in a limited number of buildings were the dominant lead source in the drinking-water, with brass fixtures and fittings identified as a second potential source.

Choosing how and when to take samples

The sampling protocol describes how and when samples should be collected. In practice, the sampling protocol to be implemented depends on the objective of the analysis and regulatory requirements. Annex 2 shows examples of sampling protocols with different purposes. The key components of most sampling protocols are:

- stagnation time – the contact time between materials and water, which determines the time available for chemical equilibration between the materials and the water;
- volume – the volumes of water captured, which determine the lead-contributing plumbing parts that can influence the result (depending on where the water stagnates) and how lead levels are averaged; and
- flow rate – affects the extent to which scale and other particles are likely to be included in samples.

When seeking to understand the average exposure to lead from any source of water, the sample should ideally represent the water used for consumption, taking flow rates, flushing times, duration of storage and amounts of water into account. However, information on the range of potential exposures, including frequencies of elevated exposure and highest concentrations, is also important to better determine and understand the full range of exposures of concern.

Sampling piped supplies

For piped water supplies, sampling should generally include consumer taps, since the primary source of lead in drinking-water for these systems is often service connections or plumbing in buildings (WHO, 2022).

For assessing the average exposure of lead in water systems serving a larger population or a particular district or water supply zone, random daytime (RDT) sampling is often used, with or without prior flushing, depending on whether or not household plumbing is of concern. If the number of samples is sufficient, this strategy may give a good representation of the overall exposure of a population (Health Canada, 2019). However, results might be misleading at the household level because of the element of randomness, particularly in relation to stagnation times (Schock & Lemieux, 2010). Some studies have shown that concentrations can vary more than tenfold using RDT sampling from the same tap over an extended period (Cartier et al., 2011; Gora et al., 2020). See Box 2 for an example of a sampling approach applied in one country to assess both population and household exposure and the source of lead.

To ensure that the water sample represents the water used for consumption, a fixed proportion of water should be collected, either manually or using a sampling device. This strategy is called composite proportional sampling. However, it is not practical for extensive sampling at many households.

Sampling hand pump systems

The sampling protocols in Annex 2 have generally been developed for piped water distribution systems. RDT sampling and composite proportional sampling are also applicable to non-piped systems such as hand pumps. As with piped supplies, the principal components – stagnation time, flow rate and volume – should be chosen to adequately represent how water is used.

STEP 2

Communicate and take precautionary actions, if needed

Communication is vital throughout the investigation and management process, starting with a dialogue between the water supplier and the drinking-water regulator or other relevant authority when elevated lead in drinking-water is first detected.

Once elevated lead levels in drinking-water have been confirmed (step 1), a wider communication process should be initiated to support an efficient and coordinated response in affected communities.

For this wider communication process, the following actions should be taken.

Form a task force

A task force should be formed with a clear mandate to make decisions and to communicate with stakeholders and users. Who to include in the group depends on the setting. Public health authorities are vital, as are local authorities and entities in charge of building codes, schools, and other locations where prevention and management may be needed. In addition to official representatives, other stakeholders such as plumbers and community leaders can be key resources to support behaviour change (Cole & Murphy, 2014; Khaliq et al., 2021). In some settings, involvement of national academic institutions may be useful to support quality control activities relating to sampling and analysis.

The five WHO risk communication principles (WHO, 2005)

1. **TRUST**
2. **TRANSPARENCY**
3. **ANNOUNCING EARLY**
4. **LISTENING**
5. **PLANNING**

Plan for risk communication

Risk communication planning should support consistent messages from different information sources, which is one of the purposes of the task force. A communication plan for the task force should include details on who will communicate different messages, to whom and when. Clear and consistent information is critical for issues such as lead in drinking-water. Inconsistent or contradictory guidance coming from different stakeholders can undermine the credibility of the information, leaving room for doubts and speculation (AWWA, 2019). The task force could help avoid rapid changes in information and prevent dissemination of conflicting information from different agencies, which has been shown to reduce trust (Sopory et al., 2017a). Both social media and traditional media should be included in the plan, together with other forms of communication, to achieve convergence of accurate information (WHO, 2017).

Decide when and what to communicate

A systematic review of studies on how trust is created during health-related events found it important to be transparent, to not be perceived as hiding negative information, to quickly disseminate information and to intervene when necessary (Sopory et al., 2017a). Communication needs to be active and provide information about initial results, ongoing work, planned work (both short and long term, related to both sampling and analysis and possible remedial actions) and uncertainties, to create trust and minimize the spread of disinformation (Sopory et al., 2017b). Regular updates should be provided as knowledge is gained from further sampling and analysis. This includes providing updates after implementing remedial actions, and addressing learnings from listening to and engaging with users.

Listen to and engage with users

Listening to and understanding public perceptions forms the basis of a risk communication strategy, which should both inform and deal with fears. Information needs to be shaped so that the public and stakeholders see it as relevant to their lives (WHO Regional Office for South-East Asia, 2019). Listening also enables early identification of rumours and misinformation, and the collection of necessary information about use of water systems, which is valuable background information for investigations.

Social media is one means of engaging with the public. It has evolved from being an information channel to a communication platform, although messages sometimes cannot be controlled. Social media can facilitate peer-to-peer communication, monitoring and response to rumours, public reactions and concerns during an emergency, and local-level responses. Another approach is to identify people the community trusts and involve them in decision-making to ensure collaborative and accepted interventions (WHO, 2017).

Provide advice on precautionary actions, if needed

Since further investigations by the water supplier and remedial actions in plumbing systems may take time to complete, implementation of interim remedial measures may be justified to reduce lead exposure in the short term.

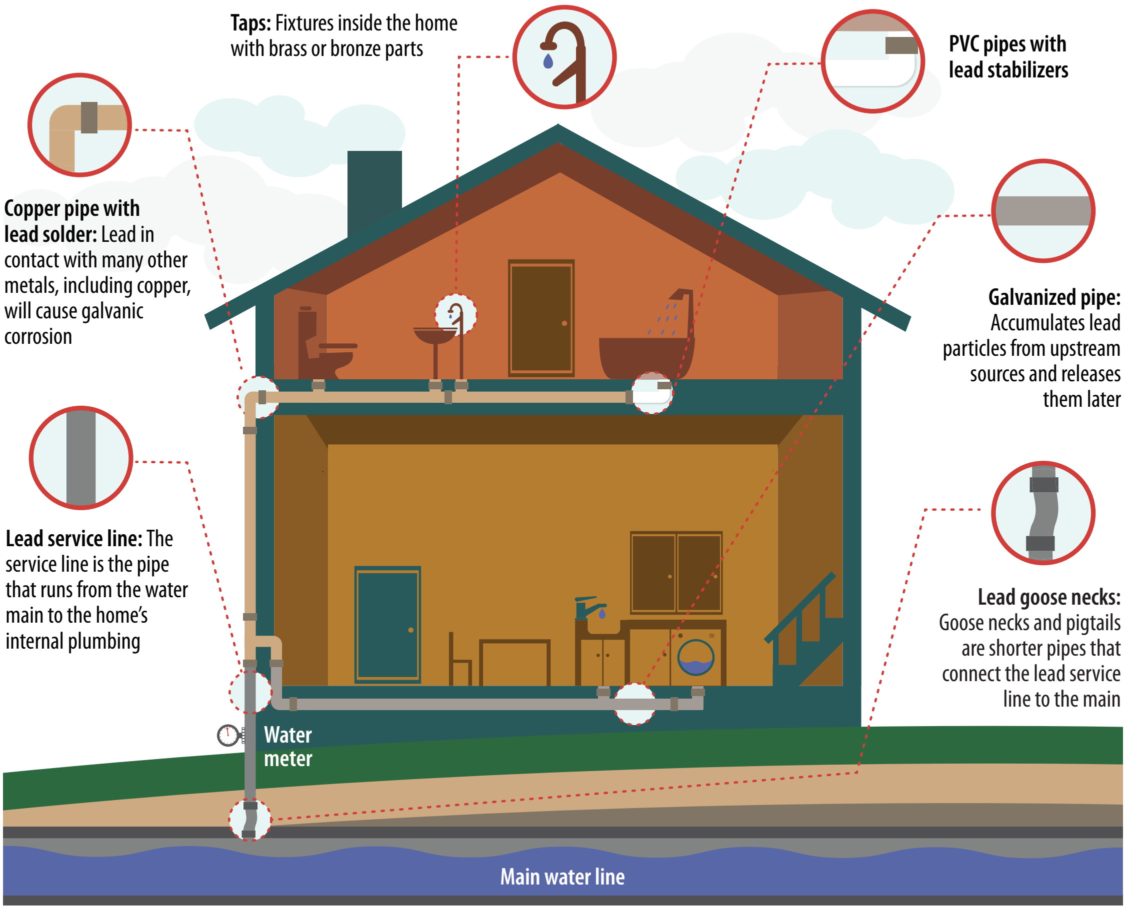
Temporary measures that can be rapidly implemented may be particularly relevant when concentrations of lead in water are high and vulnerable groups (fetuses, infants and children) are exposed. If the source is suspected to be in the hand pump or plumbing/piping system, measures include flushing, using approved filters, or providing an alternative safe water supply (e.g. bottled water certified by the responsible authorities). A contaminated water source requires approved filters or an alternative safe water supply. See step 5 for further details on temporary remedial options.

STEP 3

Investigate the source of lead

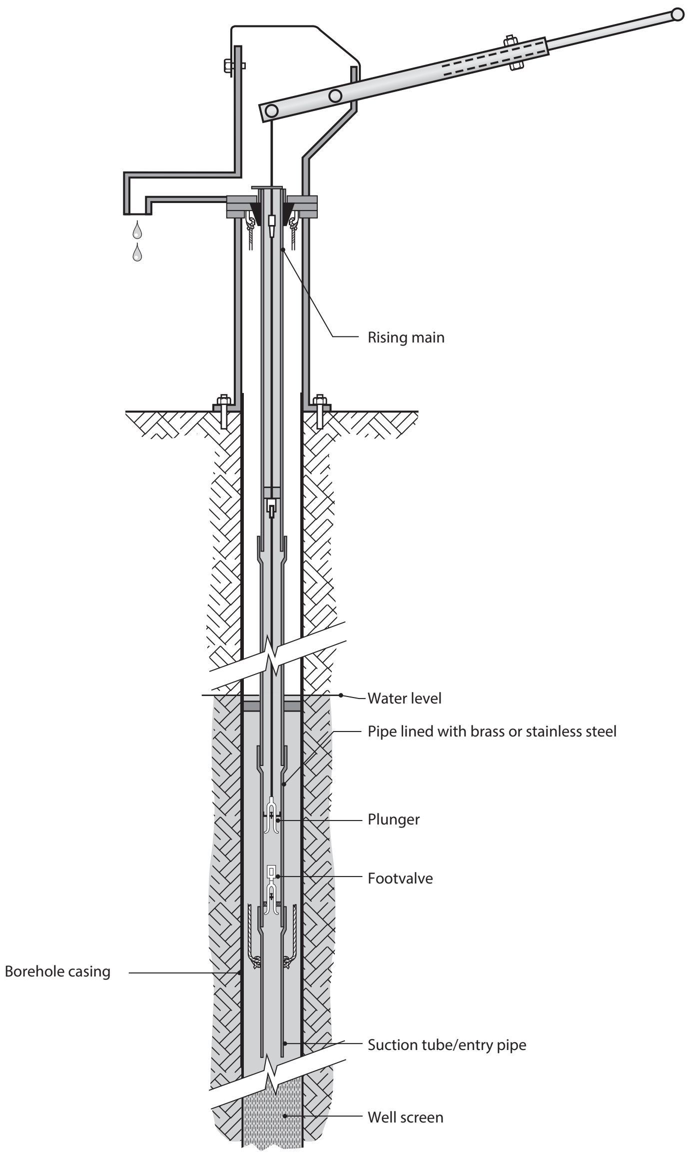
The primary source of lead in drinking-water is leaching from lead-containing materials in water systems, including service pipes, plumbing in homes (see Fig. 2) and other buildings, and components in well parts and hand pumps (see Fig. 3). These materials can be made of lead, lead-containing metal alloys, or polyvinyl chloride (PVC) or unplasticized polyvinyl chloride (uPVC) with lead stabilizers. Exogenous sources may be pollution or bedrock.

FIG. 2
Plumbing terminology in houses mentioned in this brief



Source: Adapted from USEPA.

FIG. 3
Components from hand pumps mentioned in this brief



Note: The exact design of components in different hand pumps might differ from this example.

Source: Adapted from Water Engineering and Development Centre (WEDC), Loughborough University, United Kingdom.

BOX 3

Source water contamination

Although the primary sources of lead in drinking-water are lead-containing components in water systems, lead may come from the water source because of its natural occurrence in the bedrock or presence in anthropogenic sources, such as industrial pollution.

Water sources can be contaminated through battery manufacturing and recycling, pottery or ceramics activities, mining (particularly sulfide mineral mining), paint manufacturing, lead smelting, municipal waste incineration and coal incineration (USEPA, 1998; Health Canada, 2019). Depending on the distribution patterns, pollution from these industries can be either diffuse or concentrated in certain areas.

In specific geological regions, concentrations of naturally occurring lead in groundwater can be high, reaching more than tenfold the WHO provisional guideline value (Dahlqqvist et al., 2016; Liao et al., 2017; Pazand et al., 2018). At these locations, lead is a natural component of the bedrock. Mining of sulfide ores containing, for example, arsenic, tin, antimony, silver, gold, copper and bismuth can often indicate that lead might be present naturally and should be considered where effluent from such operations can contaminate water sources. However, lead tends to accumulate more often in sediments and soil than in surface water or groundwater; therefore, elevated levels of naturally occurring lead in water sources are rare.

When sampling to represent source water (i.e. the "true groundwater"), boreholes should be purged, which means removing 3 times the pipe volume of water immediately before sampling (USEPA, 2013). Also, any materials that are known to contain lead should be recorded, to support interpretation of results.

Where elevated lead levels in drinking-water have been confirmed, it is essential to undertake further investigations using a combination of historical inventories, visual and mechanical methods, and chemical methods. The aim is to understand the source of contamination – for example, the water source, plumbing parts or materials, or hand pump components – and the factors that influence the release of lead into the water. This understanding is needed to inform remedial actions. Sometimes this investigation can be done in parallel with the exposure assessment (step 1).

Since the primary sources of lead in drinking-water are lead-containing materials in water systems, including household plumbing, this section focuses on determining these lead sources. See Box 3 for information on elevated lead levels in source water.

Historical inventories, and visual and mechanical identification of leaded parts

The primary concern is whether lead leaches into water or not, which means that water sampling is the ultimate method for source identification. However, water sampling is more precise if directed by a hypothesis on which parts, materials or water chemistry (i.e. corrosiveness) are responsible for lead in drinking-water. Therefore, reviewing historical records on the use of leaded materials, undertaking physical inspections and reviewing water chemistry records is beneficial before sampling. The following sections describe materials of interest and water chemistry affecting lead concentrations.

Pure lead components

In piped systems, pure lead components can be lead pipes, goose necks and lead solder. In hand pumps, lead can be found as plunger weights, valve weights or lead solder in well screens. Elemental lead that has not been painted can easily be recognized by the grey–blue colour. Since lead is very soft, it can easily be scratched with a sharp object, producing a shiny, silver mark. It also makes a dull sound when knocked. A characteristic feature of lead pipes is that they are laid with large bends (Fig. 3).

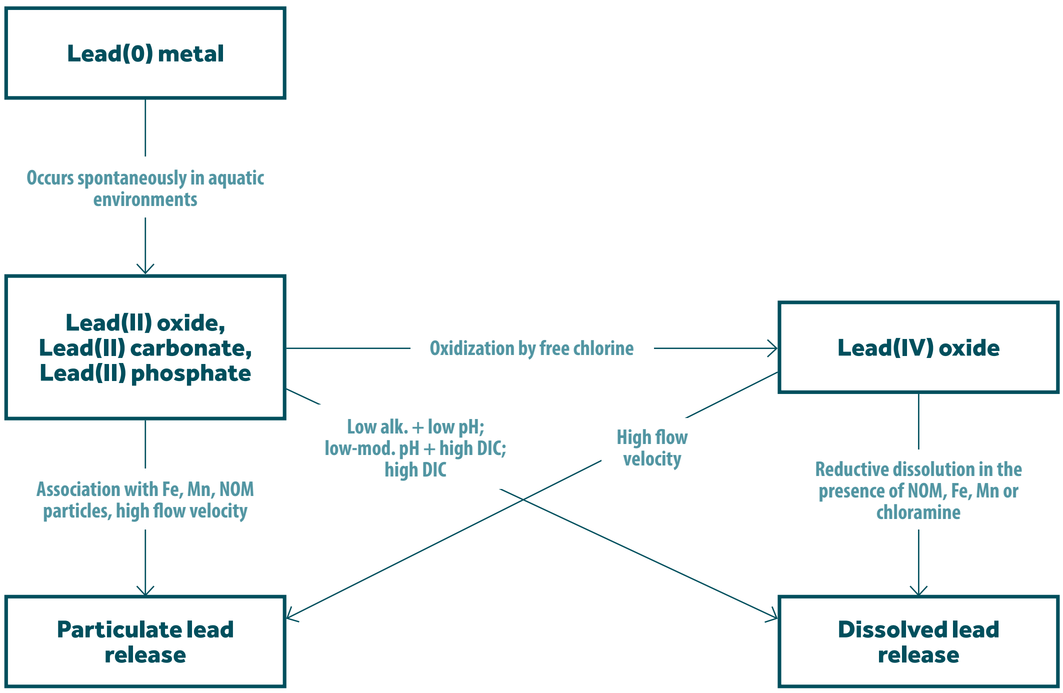
Lead oxides, lead carbonates or lead phosphates cover all lead surfaces in aquatic environments. The extent to which lead leaches into water is primarily determined by the solubility of these lead compounds, which may change with the water chemistry. Fig. 4 provides information on water quality characteristics that affect the release of lead into the water. Studies suggest that lead service lines can contribute 50–75% of the total lead at the tap after extended stagnation times (Sandvig et al., 2008).

Particulate lead or lead adsorbed to particulate iron, manganese and aluminium oxyhydroxides can make up a significant share of the total lead in many systems. This means that the total lead concentration is affected by the number of particles in the system (Deshommes et al., 2010; McFadden et al., 2011; Knowles et al., 2015; Locsin et al., 2022). If these substances are not removed sufficiently from the raw water, they may affect lead concentrations at the tap. Table 1 provides guidance on which chemical parameters can usefully be analysed to support identification of the source.

Lead components in contact with other metals

If lead components are in direct contact with copper, brass or stainless steel, galvanic corrosion can occur, resulting in release of lead into drinking-water. Galvanic corrosion is an electrochemical process in which one metal corrodes preferentially when in contact with a second metal. Lead that forms a galvanic couple with another metal generates substantially higher lead concentrations in water than components that are not in contact with these materials (Wang, 2012; St. Clair et al., 2015; Ng, Lin & Lin et al., 2020). Galvanic corrosion can result in the release into water of both particulate and dissolved lead (Wang et al., 2013). According to some studies, the release can last more than 60 years after installation of the components (St Clair et al., 2015; DeSantis et al., 2018).

FIG. 4
Chemical factors affecting release of lead to water from pure lead components
The arrows show release mechanisms, not adsorptive mechanism



Note: alk: alkalinity; DIC: dissolved inorganic carbon; Fe: iron; Mn: manganese; NOM: natural organic matter.

Brass components

In piped systems, brass is found in fittings, valves, couplings or fixtures such as refrigerated water coolers and drinking-water fountains. In hand pumps, brass can be found in parts such as well screens, cylinders, and plungers and valves (Prasad, 1979; Erpf, 2007; Akers et al., 2015). Brasses can be yellow to red, depending on the content of the principal alloying constituents: copper and zinc.

Lead is added to brass alloys, in amounts depending on the application, to improve the machinability of the alloy. Production costs of "free-machining brass" (containing up to 3% lead) are lower than costs of brass containing less lead and much lower than stainless steel because the alloy is easier to machine (Callcut, 2005). Therefore, the cost of lead-free brass fittings is typically 25–50% higher than that of regular brass fittings. Terms such as "lead-free" and "low lead" are used for products that contain less than 0.25% of lead by weight.

Brass fittings can leach lead into drinking-water (Elfland, Scardinia & Edwards, 2010; Harvey, Handley & Taylor, 2016; Fischer et al., 2021). Internal galvanic corrosion between surface lead atoms and the rest of the alloy is believed to be the driving force behind the leaching of lead from brass (Korshin, Ferguson & Lancaster, 2000). Lead-containing brass fixtures and fittings are likely to contribute significantly to the lead concentration in first-draw samples (Gardels & Sorg, 1989; Kimbrough, 2001; Asami et al., 2021). Like lead components, brass components can also release lead more rapidly when coupled with another metal (Gonzalez, Lopez-Roldan & Cortina, 2013).

Bronze components

Bronze is an alloy of copper and tin that can contain up to 8% lead. It has similar galvanic corroding properties to brass with regard to lead. Bronze is sometimes used in hand pumps and household fixtures, such as decorative taps. "Oil rubbed bronze" used in taps is essentially brass that has been treated to give an aged impression.

Other alloys

Lead–tin solder can be found on copper piping or on brass well screens (Akers et al., 2015). These metals are expected to form a galvanic couple because they are in direct contact, increasing lead corrosion.

Galvanized iron or steel pipes can also be a lead source, as lead can be part of the galvanizing process (Clark, Masters & Edwards, 2015). Once the zinc coating is detached, lead is released. Both galvanized and cast iron pipes can also accumulate lead on iron oxide scales from upstream sources and later release it, especially during periods of high flow velocity (McFadden et al., 2011; Pieper, Krometis & Edwards, 2016; Li et al., 2020). Discolouration of water can indicate iron oxides in water, which can suggest elevated lead levels (Health Canada, 2019).

Some poor-quality **stainless steel** used in riser pipes of hand pumps may contain traces of lead (levels in the range of parts per million). However, the concentrations are so low that they are not expected to cause any significant lead concentrations in the water (Danert, 2019).

PVC and uPVC

Both PVC and uPVC can contain lead, which is used as a thermal stabilizer. Lead can be released from PVC and uPVC pipes in varying concentrations and for varying durations (WHO Regional Office for Europe, 2002; Whelton & Nguyen, 2013). Water properties such as high temperature, low pH and presence of monochloramine seem to favour migration, as does the production of pipes using lower extrusion temperatures (Koh et al., 1991; Zhang & Lin, 2014).

Water sampling for investigating the source of lead

When it is suspected that lead-containing material is the source of elevated lead in drinking-water – for example, through visual and mechanical identification – water sampling is the method that ultimately determines which parts leach lead.

A suggested sampling protocol is a sequential sampling protocol. This involves sampling a series of defined volumes, revealing leaching properties through differences in concentration between the samples (Lytle & Schock, 2000). Lead concentrations can be connected to specific components depending on where the water stagnates. Sequential sampling can be deployed in both piped and non-piped systems.

Annex 2 contains sampling strategies to investigate the lead leaching source.

Analysis of co-parameters

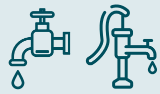
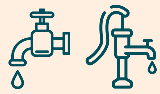
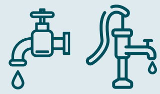
Since leaching of lead into water and the efficacy of different remedial options depend on the overall water chemistry, analysing other parameters is helpful when investigating the source of lead. Table 1 contains suggestions of chemical parameters to analyse at the same time as lead. The symbols in the table indicate whether the use is primarily for centralized/piped supplies or hand pump supplies.

Centralized/piped supplies

Hand pump supplies

TABLE 1

Suggested co-parameters to analyse when sampling water to investigate the source of lead in drinking-water

Parameter	Rationale	Relevancy
Alkalinity, pH and dissolved inorganic carbon (DIC)	Combinations of low alkalinity and low pH, or low–moderate pH and high DIC favour the release of lead into water from solids. High pH and low DIC, respectively and in combination, reduce the release of lead into water from solids.	
Cadmium, iron, zinc, aluminium, copper, nickel	Lead, cadmium and iron are correlated with zinc when galvanized iron is the source of lead (Clark, Masters & Edwards, 2015). Aluminium and iron coagulant residuals can mobilise lead from premise plumbing (Knowles et al, 2015) Zinc, and in some cases copper and nickel, is associated with brass corrosion (Korshin, Ferguson & Lancaster, 2000; Asami et al., 2021). Some studies have shown a gradual decrease in zinc leaching over time, which affects its value as an indicator of brass corrosion (Langenegger, 1994; Chao et al., 2021).	
Chlorine and chloramine	Concentration changes of chlorine and chloramine (used as disinfectants) can affect lead concentrations. The presence of free chlorine decreases dissolved lead by oxidizing it into a highly insoluble Pb(IV) oxide (PbO_2) (Triantafyllidou et al., 2015). Monochloramine is not a strong enough oxidant to form PbO_2, and thus a switch to this oxidant destabilizes any PbO_2 scales present and results in lead release into drinking-water.	
Chloride:sulfate ratio	Galvanic corrosion is favoured by a chloride:sulfate ratio higher than 0.58 (Nguyen et al., 2011; Triantafyllidou & Edwards, 2011). The chloride and sulfate content in water can change if coagulants are changed from sulfate-based coagulants to chloride-based coagulants, or vice versa. The chloride concentration might change in source water, or finished water, from road salt intruding into finished water reservoirs.	
Iron, manganese and natural organic matter (NOM)	As a result of adsorption of dissolved lead onto surfaces, iron and manganese are correlated with particulate lead (Trueman et al., 2019). NOM contains diverse functional groups that can form strong chelate complexes with lead, which may increase lead leaching. NOM can also affect the colloidal mobilization of lead (lead-containing particles) (Locsin et al., 2022). NOM, iron and manganese can act as reductants that can accelerate the dissolution of PbO_2 scales in piped supplies with excess chlorine.	

Note: When analysing water for the purpose of corrosion control, additional parameters such as corrosion inhibitors, aluminium, hardness, buffer capacity and redox potential might also be useful.

STEP 4 Investigate lead exposure from other sources

It is appropriate to broaden the investigation to include cooperation with public health and environmental authorities to understand the public health significance of lead in drinking-water.

In parallel with the source investigation, a broader investigation should be initiated in cooperation with public health and environmental authorities. Lead in drinking-water may not be the main source of exposure, and all potential sources should therefore be identified and quantified. This information, along with measurements of blood lead levels (WHO, 2020, 2021b) in affected areas, can inform assessments of the public health significance of possible remedial actions to reduce lead in drinking-water.

The broader perspective is useful to consider in implementing a progressive approach to remediating lead in drinking-water. Substantial resources are often required to mitigate lead concentrations in existing systems. Not all water systems can be feasibly remediated immediately, especially in light of multiple sources of lead exposure and other public health and environmental issues that require resources and effort.

STEP 5

Investigate remedial options

An investigation of remedial options should include both immediate interim measures and longer-term measures. Shutting down water supplies would generally be considered an inappropriate response.

When lead sources have been identified (step 3), and it has been found that drinking-water as a source of lead is of public health significance (steps 2 and 4), available remedial options need to be investigated. However, obtaining a full understanding of these aspects, particularly step 4 (investigating lead exposure from other sources), should not significantly delay the investigation and implementation of remedial actions (e.g. low-cost measures that can be implemented quickly).

In addition to costs and timescales for implementation, other factors to be considered in selecting remedial actions include expected lead reduction and ease of implementation. Both capital investment and operational and maintenance costs need to be considered.

In most cases, the main remedy to reduce lead concentrations in drinking-water below the WHO provisional guideline value is to replace the lead-containing components. However, this can require large amounts of time and money. It often requires longer-term plans for progressive replacement.

Therefore, practical measures to reduce total exposure to lead in drinking-water should be implemented in the interim. These can include using corrosion inhibitors in public supplies and actions at the household level to reduce exposure, which requires communicating with the public. New installations should comply with modern plumbing standards, including low-lead or no-lead components and solders, to prevent future contamination.

Remedial actions are categorized according to their applicability. The symbols below indicate whether the use is primarily for centralized and piped supplies or hand pump supplies.

Centralized/piped supplies

Hand pump supplies

Interim solutions

Corrosion inhibitors

If elevated lead is attributable to lead in distribution systems and the water is corrosive, it is often appropriate to adjust pH, increase the alkalinity or hardness, or introduce corrosion inhibitors as part of central treatment (USEPA, 2016, WHO, 2022).

Orthophosphate and sodium silicate are examples of chemicals used as corrosion inhibitors, added at the water treatment plant to reduce formation of lead oxides on lead surfaces (Mishrra et al., 2020). However, the dose of chemicals required can be influenced by other non-targeted and often ill-defined reactions. Therefore, the dose and impact on reducing lead in drinking-water should be evaluated through a comprehensive monitoring programme (USEPA, 2016; Wasserstrom et al., 2017) as part of water safety planning (WHO, 2009).

It should also be noted that studies have observed limited reduction of lead concentrations by orthophosphate in the event of galvanic corrosion (e.g. Cartier et al., 2013). This underscores the importance of implementing a monitoring programme to verify the effectiveness of the application of corrosion inhibitors in reducing lead in drinking-water. Also, orthophosphate can contribute to eutrophication in many surface waters if subsequently released from wastewater treatment plants without phosphorus removal (Conley et al., 2009). However, this does not mean that corrosion inhibitors should not be used to control lead (and other contaminants) in drinking-water.

Separating galvanic couples

Making sure that metals that form a galvanic couple with lead are disconnected to minimize galvanic corrosion has been shown to reduce lead concentrations by up to 20 times (Wang et al., 2013). A non-conducting material should separate metals such as copper, brass, bronze and galvanized iron to avoid galvanic corrosion. Depending on the system, this might be a more accessible but still effective remedial option.

Flushing

For systems where corrosion occurs in brass fittings or lead-soldered joints in the premises plumbing or a hand pump, flushing for 30 seconds to 2 minutes may often temporarily reduce exposure, although lead levels might be re-established in as little as 30 minutes after flushing (Murphy, 1993; Doré et al., 2018).

If the lead is in service lines, larger flushing volumes are required (i.e. more than 5 minutes using a high-volume tap) (Pieper et al., 2019). The size of the plumbing system is one determinant of how well flushing works, which is why flushing in larger buildings such as schools or multi-dwelling residences is sometimes insufficient. As a reference, flushing of at least three "plumbing volumes" – that is, 3 times the volume of the pipes from the connection point to the tap – is considered a fully flushed water sample (Hoekstra et al., 2009). In contrast, extensive flushing can, counterproductively, mobilize leaded sediments and scales, resulting in higher concentrations (Pieper et al., 2015).

In summary, flushing can be an inexpensive management strategy for residents, although it is not always effective in lowering concentrations. It might, however, result in increased operating costs and waste a significant amount of water, which is unsustainable, particularly for a limited groundwater source or in other water-scarce settings. However, flushed water can be used for non-consumptive uses such as washing or bathing, since inorganic lead in water is not absorbed through the skin (Health Canada, 2019). Flushing should be considered only as an interim measure, and its effect must be verified after it is introduced.

Temporary alternative source of water

Infant feeding formula reconstituted with tap water with elevated lead concentrations can represent a major source of exposure to lead in infants. Alternative safe sources could therefore be provided if the tap water contains elevated lead. Advice should be provided by the competent health authority, considering other sources of lead exposure in the household.

Household water treatment

Where the source is local (i.e. plumbing or hand pump components), point-of-use (POU) and point-of-entry (POE) treatment devices can reduce the total lead concentration in drinking-water. The extent of removal depends on the water chemistry and the state in which lead is found (Deshommes et al., 2012; Bosscher et al., 2019; Health Canada, 2019). Treatment can be applied on a consumer scale for both piped systems and hand pumps. If the primary source of lead is household or building plumbing systems, POU systems are preferred. However, all devices will need proper maintenance and safe disposal of waste to avoid secondary pollution. Several systems for approval and certification exist, such as NSF Standard No. 53 in the United States of America.

Longer-term solutions

Replacement of lead-containing parts

Identifying and removing lead-containing materials and materials such as cast iron where lead has accumulated over time, and replacing them with low-lead or lead-free alternatives, is often the most effective and permanent solution. It can, however, be both costly and time-consuming if the lead-containing components are pipes or other inaccessible parts. Lead-free alternatives are also more expensive than materials with a higher lead content. New plumbing installations should use suitable materials intended for drinking-water use, with as little lead as economically feasible. The use of corrosion-resistant material and low-lead plumbing parts is crucial in areas where the water has high natural corrosiveness.

BOX 4

Example of a major lead line replacement programme

In 1986, the city of Frankfurt identified that around 8000 properties, or 10% of the citizens, still had lead drinking-water installations. An ambitious programme was launched in 1997 to make Frankfurt lead-free within 10 years. The goal was reached in 2010. The property owners covered the costs of pipe replacement. The administrative cost of running the programme for the city was €400 000 (Hentschel, Karius & Heudorf, 1999).

If only parts of the service line are replaced, the remaining lead lines should not be in contact with other metals. If they are, galvanic corrosion can cause an increase in overall corrosion (Sandvig et al., 2008; Wang et al., 2013).

For brass, lower-lead alternatives containing lead below 0.25% by weight are safe even when using corrosive water, with respect to avoiding extensive leaching (Triantafyllidou & Edwards, 2010; Turkovic, Werner & Klinger, 2014; Pieper, Krometis & Edwards, 2016).

Establishment of material approval processes

National authorities should establish and enforce approval processes to ensure the appropriate use of materials and solder in contact with drinking-water. Several international and national standardization organizations provide standards to assess the compatibility of materials in contact with drinking-water, including consideration of lead. However, as noted, lead-free and lower-lead materials are somewhat more costly. In some cases, especially where water is less corrosive, authorities may therefore take a risk–benefit approach, allowing materials with slightly higher lead content.

Trained plumbing personnel

Plumbers should be appropriately qualified, and certified or accredited; these approval processes are usually overseen by national authorities. Plumbers should have adequate knowledge to ensure that plumbing installations comply with relevant regulations to avoid installations, products and materials that may adversely affect water safety. They should check that the installed product is compatible with the local drinking-water. Further, the design of plumbing systems of new buildings should generally be approved before construction, and inspected by the appropriate regulatory authority as part of the commissioning and construction of the buildings.

Prevention and remediation of source contamination

In cases where the primary source of lead in drinking-water is anthropogenic inputs into the water source itself, mitigating source contamination is critical. The most effective mitigation strategy is enacting and enforcing regulations to control pollutants from industries or other polluting activities. Guidance on managing risks in surface water or groundwater catchment areas can be found in WHO publications (WHO, 2006, 2009, 2016b). Remediation of lead-contaminated areas is possible but costly and time-consuming, and needs a thorough investigation before it is undertaken.

In the case of elevated lead levels in the source water of centralized systems, conventional water treatment – including aluminium sulfate or ferric sulfate coagulation and filtration – is reasonably effective (Health Canada, 2019).

Source substitution

In rural settings with no or minimal water treatment, the water source can be changed from one with elevated lead to a less contaminated one. Care would need to be taken to ensure that other water quality issues, including other high-priority contaminants (e.g. microbiological contaminants), are not introduced.

STEP 6 Implement and ensure effectiveness of remedial actions

Remedial actions should be prioritized using an integrated risk–benefit approach to maximize impact, considering available resources. The aim is to reduce disparities by progressively addressing elevated lead in drinking-water in all settings. Remedial actions should ideally be implemented first in settings with the highest lead concentrations in drinking-water, particularly focusing on infants, children and pregnant individuals.

When remedial options have been mapped and compared (step 5), and considering information gathered through earlier steps, an informed decision can be made on which actions to take. As the previous section emphasized, remedial actions often require simultaneously developing and implementing both immediate interim and longer-term measures. As knowledge and resources are gained, these should inform further management actions.

The costs and public health benefits of reducing lead exposure from drinking-water should be considered in the decision (see information in step 4). Although reducing any exposure to lead in drinking-water supports health protection efforts, using a progressive realization strategy to undertake remedial actions at a feasible pace may need to be considered. When seeking to prevent and manage lead exposure, microbiological and other priority contaminants need to be adequately managed. The risk of not having a drinking-water supply must also be considered; shutting down water supplies is generally considered an inappropriate response.

Other relevant stakeholders, such as public health authorities, plumbing authorities and consumer groups, should be consulted in selecting remedial actions to ensure that the options being considered are appropriate and acceptable. These other stakeholders may also play an essential role in communicating information about remedial measures, including actions to be taken by the public.

Ensuring effectiveness

The effectiveness of remedial actions put in place should be assessed by monitoring lead concentrations in the drinking-water supply. It is advised that sampling is conducted at the affected sites using the same protocol used to detect the lead initially (step 1), until at least two monitoring events demonstrate that the actions are effective (Health Canada, 2009).

As part of water safety planning (WHO, 2009), control measures to manage lead in drinking-water (e.g. remedial actions) should be monitored routinely to confirm that they continue to work as intended and to enable timely corrective action. Lead in drinking-water should also be monitored following requirements in national standards as a final verification activity. Monitoring should also be conducted when circumstances that can affect lead release occur, such as when changes are made to the water supply system, when there are seasonal changes in the quality of raw water sources or when water-use patterns change.

For new water supplies or when rehabilitating existing systems, the focus should be on ensuring appropriate procurement and installation of parts. Regulators should ensure that standards for using and installing appropriate low-lead materials are followed. Spot checks of supplier records, random testing of parts before and after installation, and training of key personnel can be conducted.

Photo © WHO/Yoshi Shimizu

How to take action

The issue of lead in drinking-water requires action from multiple stakeholders. Below are some recommended actions that key stakeholders can take to reduce exposure to lead from drinking-water. Depending on the institutional framework, responsibilities might be divided differently between stakeholders, and other stakeholders might also need to be involved.

Regulatory agencies[2]

- Include lead in drinking-water quality standards and expand surveillance and investigation of lead-contaminated sources/ water points as resources allow.
- Adopt or support the development of standards for lead-free or low-lead materials in water systems and ensure enforcement.
- When elevated levels of lead in drinking-water have been confirmed:
  - inform users about the issue and recommend reducing lead exposure (both short- and long-term solutions);
  - sensitize and engage other authorities (e.g. education, public health), as appropriate; and
  - form a task force and develop a communication plan on lead issues in drinking-water.
- Establish or facilitate approval processes for certifying or accrediting plumbers.

Operators and installers of hand pump supplies

- Monitor lead in the water, particularly where lead-containing materials are in use, following national requirements and also when circumstances that can affect lead release occur.
- If lead levels are too high, investigate remedial options such as flushing, installing a point-of-use filter or providing an alternative source. Inform water users.
- Replace lead-containing parts, if possible, and separate different metals using non-conductive materials.
- For new water supplies, procure and use appropriately certified lead-free or low-lead parts, following national requirements.
- Use borehole drillers with good local knowledge about groundwater quality to avoid corrosive water.

Water supplies

- Identify and document where lead-containing materials are used in existing water systems as part of water safety planning.
- Monitor lead in drinking-water, particularly where lead-containing materials are in use, following national requirements and also when circumstances that can affect lead release occur.
- Progressively remove lead-containing components in contact with drinking-water from water supply systems.
- For new water systems, use appropriately certified lead-free or low-lead parts, following national requirements.
- Manage the corrosivity of the water in distribution systems.
- Inform and cooperate with authorities in informing users about exposure to lead.

Plumbers

- Use certified materials from trusted suppliers, following national requirements.
- Always separate different metals or alloys from each other to avoid galvanic corrosion.
- Be aware of the corrosiveness of the water where new parts are installed and use higher-quality materials where needed.

Property owners and consumers

- If lead levels are too high, flush the tap (following recommendations from authorities), install a validated point-of-use or point-of-entry filter, or use an alternative safe source for consumption, depending on the situation.
- If the lead source is your responsibility, have lead-containing components replaced or corroding metals separated.
- Always hire properly trained plumbers for installations in the drinking-water system.

[2] Including agencies for both drinking-water and plumbing.

References

Akers DB, MacCarthy MF, Cunningham JA, Annis J, Mihelcic JR (2015). Lead (Pb) contamination of self-supply groundwater systems in coastal Madagascar and predictions of blood lead levels in exposed children. Environ Sci Technol. 49(22):2685–93.

Asami M, Furuhashi Y, Nakamura Y, Sasaki Y, Adachi Y, Maeda N, et al. (2021). A field survey on elution of lead and nickel from taps used in homes and analysis of product test results. Sci Total Environ. 771:144979.

AWWA (American Water Works Association) (2019). Lead and drinking water: talking with your community [website]. Denver, Colorado: AWWA (https://www.awwa.org/Resources-Tools/Resource-Topics/Inorganic-Contaminants/Lead/Lead-Communications, accessed 21 January 2021).

Bosscher V, Lytle DA, Schock MR, Porter A, Del Toral M (2019). POU water filters effectively reduce lead in drinking water: a demonstration field study in Flint, Michigan. J Environ Sci Health A Tox Hazard Subst Environ Eng. 54(5):484–93.

Callcut V (2005). The brasses: properties and applications. Hertfordshire, United Kingdom: Copper Development Association (Publication No. 117).

Cartier C, Laroche L, Deshommes E, Nour S, Richard G, Edwards M, et al. (2011). Investigating dissolved lead at the tap using various sampling protocols. J Am Water Works Assoc. 103:55–67.

Cartier C, Doré E, Laroche L, Nour S, Edwards M, Prèvost M (2013). Impact of treatment on Pb release from full and partially replaced harvested lead service lines (LSLs). Water Res. 47(2):661–71.

Chan SN, Chang L, Choi KW, Lee JHW, Fawell JK, Kwok KYT (2020). Unraveling the causes of excess lead in drinking water supply systems of densely populated high-rise buildings in Hong Kong. Environ Sci Technol. 54(22):14322–33.

Chao S-J, Tsai M-H, Yu R-P, Hua L-C, Hu C-C, Huang C (2021). Dezincification of brass water meters in a long-term study: effects of anions, alkalinity, and residual chlorine. Environ Sci (Camb). 7(9):1666–76.

Clark BN, Masters SV, Edwards MA (2015). Lead release to drinking water from galvanized steel pipe coatings. Environ Engin Sci. 32(8):713–21.

Cole JM, Murphy BL (2014). Rural hazard risk communication and public education: strategic and tactical best practices. Int J Disaster Risk Reduct. 10(A):292–304.

Conley DJ, Paerl HW, Howarth RW, Boesch DF, Seitzinger SP, Havens KE, et al. (2009). Controlling eutrophication: nitrogen and phosphorus. Science. 232: 1014–15.

Dahlqqvist P, Ladenberger A, Maxe L, Jönsson C (2016). Kartläggning och tolkning av ursprung till höga halter av kadmium och bly i grundvattnet i Maglasäte–Lillasäte, Höörs kommun, Skåne. Uppsala, Sweden: Swedish Geological Survey.

Danert K (2019). Concerns about corrosion and the quality of handpump components in Burkina Faso and beyond. St Gallen, Switzerland: Skat Foundation.

DeSantis MK, Triantafyllidou S, Schock MR, Lytle DA (2018). Mineralogical evidence of galvanic corrosion in drinking water lead pipe joints. Environ Sci Technol. 52(6):3365–74.

Deshommes E, Laroche L, Nour S, Cartier C (2010). Source and occurrence of particulate lead in tap water. Water Res. 44(12):3734–44.

Deshommes E, Nour S, Richer B, Cartier C (2012). POU devices in large buildings: lead removal and water quality. J Am Water Works Assoc. 104(4):E282–97.

Deshommes E, Bannier A, Laroche L, Nour S (2016). Monitoring-based framework to detect and manage lead water service lines. J Am Water Works Assoc. 108(11):555–70.

Doré E, Deshommes E, Andrews RC, Nour S, Prévost M (2018). Sampling in schools and large institutional buildings: implications for regulations, exposure and management of lead and copper. Water Res. 140(1):110–22.

Doré E, Lytle DA, Wasserstrom L, Swertfeger J, Triantafyllidou S (2020). Field analyzers for lead quantification in drinking water samples. Crit Rev Environ Sci Technol. 50(24):1–32.

Elfland C, Scardinia P, Edwards M (2010). Lead-contaminated water from brass plumbing devices in new buildings. J Am Water Works Assoc. 102(11):66–76.

Erpf K (2007). India Mark Handpump specifications. v.2. St Gallen, Switzerland: Rural Water Supply Network, Skat Consulting.

Fisher MB, Guo AZ, Tracy JW, Prasad SK, Cronk RD, Browning EG, et al. (2021). Occurrence of lead and other toxic metals derived from drinking-water systems in three west African countries. Environ Health Perspect. 129(4):47012.

Gardels MC, Sorg TJ (1989). A laboratory study of the leaching of lead from water faucets. J Am Water Works Assoc. 81(7):101–13.

Gonzalez S, Lopez-Roldan R, Cortina JL (2013). Presence of metals in drinking water distribution networks due to pipe material leaching: a review. Toxicol Environ Chem. 95(6):870–89.

Gora SL, Trueman BF, Anaviapik-Soucie T, Gavin MK, Ontiveros CC, Campbell J, et al. (2020). Source water characteristics and building-specific factors influence corrosion and point of use water quality in a decentralized Arctic drinking water system. Environ Sci Technol. 54(4):2192–201.

Harvey PJ, Handley HK, Taylor MP (2016). Widespread copper and lead contamination of household drinking water, New South Wales, Australia. Environ Res. 151:275–85.

Health Canada (2009). Guidance on controlling corrosion in drinking water distribution systems. Ottawa: Health Canada.

Health Canada (2019). Guidelines for Canadian drinking water quality. Guideline technical document: lead. Ottawa: Health Canada.

Hentschel W, Karius A, Heudorf U (1999). Das Frankfurter Bleiprojekt – Maßnahmen zur Einhaltung des Grenzwertes für Blei im Trinkwasser. Bundesgesundheitsblatt Gesundheitsforschung Gesundheitsschutz. 42:902–10.

Hoekstra EJ, Hayes C, Aertgeerts R, Becker A, Jung M, Postawa A, et al. (2009). Guidance on sampling and monitoring for lead in drinking water. Luxembourg: Office for Official Publications of the European Communities (EUR 23812 EN).

IHME (Institute for Health Metrics and Evaluation) (2020). Global Health Data Exchange [website]. Seattle: IHME (https://ghdx.healthdata.org/, accessed 8 March 2022).

ISO (International Organization for Standardization) (1986). Standard ISO 8288:1986 Water quality — Determination of cobalt, nickel, copper, zinc, cadmium and lead — Flame atomic absorption spectrometric methods. Geneva: ISO.

ISO (International Organization for Standardization) (2003). Standard ISO 15586:2003 Water quality — Determination of trace elements using atomic absorption spectrometry with graphite furnace. Geneva: ISO.

ISO (International Organization for Standardization) (2004). Standard ISO 17294-1:2004 Water quality — Application of inductively coupled plasma mass spectrometry (ICP-MS) — Part 1: General guidelines. Geneva: ISO.

ISO (International Organization for Standardization) (2004) Standard ISO 17294-2:2004 Water quality — Application of inductively coupled plasma mass spectrometry (ICP-MS) — Part 2: Determination of selected elements including uranium isotopes. Geneva: ISO.

ISO (International Organization for Standardization) (2007) Standard ISO 11885:2007 Water quality — Determination of selected elements by inductively coupled plasma optical emission spectrometry (ICP-OES). Geneva: ISO.

Khaliq M, Sommariva S, Buerck AM, Rakotondrazaka R, Rakotoarisoa L, Barrett LJP, et al. (2021). Midstream players determine population-level behavior change: social marketing research to increase demand for lead-free components in pitcher pumps in Madagascar. Int J Environ Res Public Health. 18(14):7297.

Kimbrough DE (2001). Brass corrosion and the LCR monitoring program. J Am Water Works Assoc. 93(2):81–91.

Koh LL, Wong MK, Gan LM, Yap CT (1991). Factors affecting the leaching of lead from uPVC pipes. Environ Monit Asess. 19(1–3):203–13.

Korshin GV, Ferguson JF, Lancaster AN (2000). Influence of natural organic matter on the corrosion of leaded brass in potable water. Corros Sci. 42(1):53–66.

Kriss R, Pieper KJ, Parks J, Edwards MA (2021). Challenges of detecting lead in drinking-water using at-home test kits. Environ Science Technol. 55(3):1964–72.

Langenegger O (1994). Goundwater quality and handpump corrosion in West Africa. Washington, DC: UNDP–World Bank Water and Sanitation Program.

Li M, Wang Y, Liu Z, Sha Y, Korshin GV, Chen Y (2020). Metal-release potential from iron corrosion scales under stagnant and active flow, and varying water quality conditions. Water Res. 175:115675.

Liao F, Wang G, Shi Z, Huang X, Xu F, Xu Q, et al. (2017). Distributions, sources, and species of heavy metals/trace elements in shallow groundwater around the Poyang Lake, east China. Expo Health. 10:211–27.

Locsin JA, Hood KM, Doré E, Trueman BF, Gagnon GA (2022). Colloidal lead in drinking water: formation, occurrence, and characterization. Crit Rev Environ Sci Technol. 52(14):1–27.

Lytle DA, Schock MR (2000). Impact of stagnation time on metal dissolution from plumbing materials in drinking water. Aqua (Lond). 49(5):243–57.

McFadden M, Giani R, Kwan P, Reiber SH (2011). Contributions to drinking water lead from galvanized iron corrosion scales. J Am Water Works Assoc. 103(4):76–89.

Mishrra A, Wang Z, Sidorkiewicz V, Giammar DE (2020). Effect of sodium silicate on lead release from lead service lines. Water Res. 188(2):116485.

Murphy EA (1993). Effectiveness of flushing on reducing lead and copper levels in school drinking water. Environ Health Perspect. 101(3):240–1.

Ng D-Q, Lin J-K, Lin Y-P (2020). Lead release in drinking water resulting from galvanic corrosion in three metal systems consisting of lead, copper and stainless steel. J Hazard Mater. 398:122936.

Nguyen CK, Clark BN, Stone KR, Edwards MA (2011). Role of chloride, sulfate, and alkalinity on galvanic lead corrosion. Corrosion. 67(6):065005-1-065005-9.

Pazand K, Khosravi D, Ghaderi MR, Rezvanianzadeh MR (2018). Hydrogeochemistry and lead contamination of groundwater in the north part of Esfahan province, Iran. J Water Health. 16(4):622–34.

Pieper KJ, Krometis LA, Edwards M (2016). Quantifying lead-leaching potential from plumbing exposed to aggressive waters. J Am Water Works Assoc. 108(9):E458–66.

Pieper KJ, Krometis LH, Gallagher DL, Benhamn BL, Edwards M (2015). Incidence of waterborne lead in private drinking water systems in Virginia. J Water Health. 13(3):897–908.

Pieper KJ, Katner A, Kriss R, Tang M, Edwards MA (2019). Understanding lead in water and avoidance strategies: a United States perspective for informed decision-making. J Water Health. 17(4):540–55.

Postawa A (2015). Problems with meeting new (10 µg/L) standard for lead in drinking water: Polish perspectives. Aqua (Lond). 64(1):85–94.

Prasad R (1979). Handpumps: problems and the search for remedies. Proc Indian Acad Sci. C2:473–505.

Riblet C, Deshommes E, Laroche L, Prevost M (2019). True exposure to lead at the tap: insights from proportional sampling, regulated sampling and water use monitoring. Water Res. 156:327–36.

Sandvig AM, Kwan P, Kirmeyer G, Maynard B, Mast D, Rhodes Trussell R, et al. (2008). Contribution of service line and plumbing fixtures to lead and copper rule compliance issues. Denver, Colorado: Water Environment Research Foundation.

SCHER (Scientific Committee on Health and Environmental Risks) (2011). Lead standard in drinking water. European Commission.

Schock M, Lemieux FG (2010). Challenges in addressing variability of lead in domestic plumbing. Water Sci Technol Water Supply. 10(5):792–8.

Sopory P, Day A, Novak J, Eckert K, Wilkins L, Padgett D, et al. (2017a). Evidence syntheses to support the guideline on emergency risk communication: Q5. Geneva: World Health Organization.

Sopory P, Day A, Novak J, Eckert K, Wilkins L, Padgett D, et al. (2017b). Evidence syntheses to support the guideline on emergency risk communication: Q11. Geneva: World Health Organization.

St Clair J, Cartier C, Triantafyllidou S, Clark B, Edwards M (2015). Long-term behavior of simulated partial lead service line replacements. Environ Eng Sci. 33(1):53–64.

Triantafyllidou S, Edwards M (2010). Contribution of galvanic corrosion to lead in water after partial lead service line replacements. Denver, Colorado: Water Research Foundation.

Triantafyllidou S, Edwards M (2011). Galvanic corrosion after simulated smallscale partial lead service line replacements. J Am Water Works Assoc. 103(9):85–99.

Triantafyllidou S, Schock MR, DeSantis MK, White C (2015). Low contribution of PbO2-coated lead service lines to water lead contamination at the tap. Environ Sci Technol. 49(6):3746–54.

Triantafyllidou S, Burkhardt J, Tully J, Cahalan K, DeSantis M, Lytle D, et al. (2021). Variability and sampling of lead (Pb) in drinking water: assessing potential human exposure depends on the sampling protocol. Environ Int. 146:106259.

Trueman BF, Gregory BS, McCormick NE, Gao Y, Gora S, Anaviapik-Soucie T, et al. (2019). Manganese increases lead release to drinking water. Environ Sci Technol. 53(9):4803–12.

Turkovic R, Werner W, Klinger J (2014). The performance of nonleaded brass materials. Denver, Colorado: Water Research Foundation.

UNEP (United Nations Environment Programme) (2021). Leaded petrol phase-out globally [website]. (https://www.unenvironment.org/explore-topics/transport/what-we-do/partnership-clean-fuels-and-vehicles/lead-campaign, accessed 27 December 2021).

USEPA (United States Environmental Protection Agency) (1998). Sources of lead in soil: a literature review. Washington, DC: USEPA.

USEPA (United States Environmental Protection Agency) (2013). SESD operating procedure for groundwater sampling. Athens, Georgia: USEPA.

USEPA (United States Environmental Protection Agency) (2016). Optimal corrosion control treatment evaluation technical recommendations for primacy agencies and public water systems. Washington, DC: USEPA (4606M).

Wang Y (2012). Redox reactions influencing lead concentrations in drinking water: formation and dissolution of lead(IV) oxide and impact of galvanic corrosion. Washington University Open Scholarship.

Wang Y, Mehta V, Welter GJ, Giammar DE (2013). Effect of connection methods on lead release from galvanic corrosion. J Am Water Works Assoc. 105(7):E337–51.

Wasserstrom LW, Miller SA, Triantafyllidou S, DeSantis MK, Schock MR (2017). Scale formation under blended phosphate treatment for a utility with lead pipes. J Am Water Works Assoc. 109(11):464–78.

Whelton AJ, Nguyen T (2013). Contaminant migration from polymeric pipes used in buried potable water distribution systems: a review. Crit Rev Environ Sci Technol. 43(7):679–751.

WHO (World Health Organization) (2005). Outbreak communication guidelines. Geneva: WHO.

WHO (World Health Organization) (2006). Protecting groundwater for health: managing the quality of drinking-water sources. Geneva: WHO.

WHO (World Health Organization) (2009). Water safety plan manual: step-by-step risk management for drinking-water suppliers. Geneva: WHO.

WHO (World Health Organization) (2016a). Lead in drinking-water: background document for development of WHO guidelines for drinking-water quality. Geneva: WHO.

WHO (World Health Organization) (2016b). Protecting surface water for health: identifying, assessing and managing drinking-water quality risks in surface water catchments. Geneva: WHO.

WHO (World Health Organization) (2017). Communicating risk in public health emergencies: a WHO guideline for emergency risk communication (ERC) policy and practice. Geneva: WHO.

WHO (World Health Organization) (2019). The public health impact of chemicals: knowns and unknowns: data addendum for 2019. Geneva: WHO.

WHO (World Health Organization) (2020). Brief guide to analytical methods for measuring lead in blood, second edition. Geneva: WHO.

WHO (World Health Organization) (2021a). Exposure to lead: a major public health concern, second edition. Geneva: WHO.

WHO (World Health Organization) (2021b). Guideline for clinical management of exposure to lead. Geneva: WHO.

WHO (World Health Organization) (2022). Guidelines for drinking water quality, fourth edition incorporating the 1st and 2nd addenda. Geneva: WHO.

WHO Regional Office for Europe (2002). Water and health in Europe. Bonn: World Health Organization (WHO Regional Publications European Series No. 93).

WHO Regional Office for South-East Asia (2019). Risk communication strategy for public health emergencies in the WHO South-East Asia Region: 2019–2023. New Dehli: World Health Organization.

Zhang Y, Lin Y-P (2014). Leaching of lead from new unplasticized polyvinyl chloride (uPVC) pipes into drinking water. Environ Sci Pollut Res Int. 22(11):8405–11.

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Annex 1
Analysing water samples for lead

Since the provisional guideline value for lead of 10 µg/L is not a health-based value, the limit of detection (LOD) or limit of quantification (LOQ) should be the lowest achievable. Several laboratory- and field-based methods have detection limits lower than 1 µg/L. Double or triplicate samples should always be taken to quantify uncertainty, regardless of the chosen method. However, it should be kept in mind that lead distributes unevenly in water, resulting in large differences in concentrations between samples (Deshommes et al., 2010; Chan et al., 2020). Since a significant proportion of lead can be adsorbed to colloids, filtration using a 0.45 µm filter to target dissolved lead will not be effective because colloids can pass through (Locsin et al., 2022).

In addition to approved methods using laboratory instruments in certified laboratories by skilled technicians, portable field analysers with adequately low detection limits are becoming increasingly available commercially (Table 2). Field analysers should be validated against reference methods. As well, they only measure dissolved lead; particulate lead is excluded.

TABLE 2
Overview of portable devices for measuring lead in water

Method	LOD	Strengths	Limitations
Anodic stripping voltammetry (also exists as a laboratory method)	0.2–2 µg/L	Several brands are available, ranging in price and quality. Complexity of the procedure and cost per sample depend on the brand.	Some electrodes generate mercury waste; require acidification of the sample and maintenance of the device. Higher upfront cost. Susceptible to interference from copper, silver and gold. Higher degree of operator skill and experience is required.
Colourimetry (professional kits)	3–5 µg/L	Cheaper than other field analysers.	Larger sample volumes are required than for other field analysers (50–100 mL).
Colourimetry (home kits): • binary colour • binary strip • colourimetric vial • colour strip	Typically mg/L	Cheap, easy to use, quick, consumer product.	Visual interpretation of results is needed. High LOD for drinking-water testing. Inconsistency between commercial brands.
Fluorescence	2 µg/L	Good ratio between sensitivity and capital cost.	Only a limited number of brands are available. Higher upfront cost.

Sources: Doré et al. (2020); Kriss et al. (2021).

Analysis in a laboratory (Table 3) generally means less uncertainty than use of field analysers because it is easier to keep surfaces and equipment clean in the laboratory, avoiding contamination of samples. The increased precision often comes at a cost because trained laboratory staff and costly equipment are required.

TABLE 3
Overview of International Organization for Standardization (ISO) standards for analysis of lead in water

Method	LOQ	Strengths	Limitations
Flame atomic absorption spectrometry (FAAS) (ISO 8288:1986)	1 µg/L	Short analysis time (seconds). Relatively easy to use. Relatively few interferences. Relatively low capital and running costs.	Not a state-of-the-art method. Cannot be left unattended (flammable gas).
Atomic absorption spectroscopy-graphite furnace (GF-AAS) (ISO 15586:2003)	1 µg/L	Small sample size. Moderate price. Very compact instrument. Few spectral interferences.	Slower analysis time than ICP. Chemical interferences. Element limitations: 1–6 elements per determination. No screening ability. Limited dynamic range.
Inductively coupled plasma optical emission spectrometry (ICP-OES) (ISO 1185:2007)	2–5 µg/L	Multi-element. Economical for many samples and elements. Few chemical interferences. High total dissolved solids.	Moderate to low detection limits (but often much better than FAAS). Spectral interferences possible. Some element limitations.
Inductively coupled plasma mass spectrometry (ICP-MS) (ISO 17294-1:2004, ISO 17294-2:2004)	0.1–0.2 µg/L	Can analyse small samples (50–100 µL). Swift analysis time (<1 minute). Multi-element capabilities . Economical if used for large sample runs.	High purchase and running costs. Requires highly skilled laboratory staff. Analysis of a large number of samples is cheaper than electrothermal atomic absorption spectrometry. Limited to <0.2% dissolved solids.

Note: The LOQs shown are for a typical ISO 17025–certified laboratory.

Annex 2
Sampling protocols

TABLE 4
Examples of sampling protocols to assess lead exposure from drinking-water

	Sample type	Protocol summary	Comment
Investigation of source	Profile (or sequential) sampling	A defined stagnation time. 10–20 sequential samples of a defined volume (125 mL, 250 mL, 1 L, etc.). Differentiated volumes can be used to pinpoint the source better.	Captures the lead contribution from defined parts in a system.
	Profile sampling for particle release	Traditional profile sampling at an increasing water flow rate (low, medium and high).	Captures particle contribution of total lead concentration.
	Fully flushed sampling	Flush three "plumbing volumes" before sampling (i.e. 3 times the volume of the plumbing system until the connection point). For hand pumps, purge the borehole by flushing 3 times the pipe volume.	Identifies the source of lead as the lead service line, hand pump component or water source. It gives the "best case" scenario for the lowest lead level achievable in a particular residence, dwelling or hand pump using flushing as a remedial action. If this sample shows high concentrations, alternative water should be provided immediately.
Exposure assessment	Composite proportional	A device collects a fixed share of every draw from the tap for consumption during, for example, 1 week. It can be collected manually in the same manner, during shorter or longer periods.	Captures actual water use (and variability) at a household level. The best representativity of exposure, although time-consuming on a larger scale.
	Random daytime (RDT) sampling	Random sample collection with or without prior flushing. Collect 1 L.	Captures variable stagnation in case of no prior flushing, giving the most variable levels. Therefore, more samples are needed to determine mean exposure levels. Zonal sampling is done to characterize exposure based on water quality in a given supply zone.
Regulatory compliance	First draw (United States Environmental Protection Agency)	6+ hr – overnight stagnation. Collect 1 L.	Intended use is the assessment of corrosion control effectiveness. Relies on customer cooperation.
	RDT sampling (United Kingdom/ European Union)	Random sample collection without prior flushing. Collect 1 L.	Samples collected in supply zones with similar water qualities.
	30 minutes stagnation (30MS) (Ontario, Canada)	2–5 minute flush, 30 minute stagnation. Collect the first 2 L (two 1 L samples).	Of the two samples taken on the same day from the same plumbing location, the sample with the highest lead concentration is used. Does not consider particulate lead release generated mostly after longer stagnation.

Sources: Hoekstra et al. (2009); WHO (2016b); Health Canada (2019); Triantafyllidou et al. (2021).

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