Received: 5 February 2021 | Revised: 8 April 2021 | Accepted: 23 April 2021

DOI: 10.1002/aws2.1226

REVIEW ARTICLE

AWWA WATER SCIENCE

Lead service line identification: A review of strategies and approaches

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Funding information
U.S. Environmental Protection Agency

Associate Editor: David A. Cornwell

Abstract

Lead service lines (LSLs) represent the greatest source of lead in drinking water. Identifying the locations of LSLs can be challenging, and recent service line (SL) material surveys in Michigan, Illinois, Wisconsin, and Indiana found that on average the materials making up 16% of SLs in these states are unknown and may be lead. Given the large number of possible LSLs in the United States, new and pending regulatory requirements, LSL replacement costs, associated lead exposure risks, and the public's desire to reduce lead exposure, there is a need to rapidly and cost-effectively identify where LSLs are located, on public and private property. This review summarizes current industry LSL identification methods, including records screening, basic visual examination of indoor plumbing, water sampling, excavation, and predictive data analyses. A qualitative comparison of method cost, accuracy, disturbance, and other impacts is provided as a starting point for utilities that are developing a feasible approach for their specific needs/constraints. Lastly, an example stepwise approach to identify unknown SL materials is proposed.

KEYWORDS

drinking water, identification, lead, pipe material, service line

1 | INTRODUCTION

Lead in the dissolved and particulate forms can enter consumers' drinking water from interior and exterior house sources (Figure 1). Plumbing lead sources include lead-containing plumbing fixtures (e.g., lead brass faucets), lead pipe, galvanized pipe (Sandvig et al., 2008), and lead soldered joints (Quevauviller & Thompson, 2006). Exterior pipes, or service lines (SLs), supply a home with drinking water from the utility's water main. All or part of the SL may be the homeowner's responsibility. When present, lead service lines (LSLs) are the dominant source of lead in water (Cartier et al., 2012; Sandvig et al., 2008). On average, LSLs contribute from 50% to 86% of the total lead mass measured at the tap in sequential sampling studies (Lytle et al., 2019; Sandvig et al., 2008). The concentration of lead in a resident's drinking water tap is complicated to predict as a result of many factors, including pipe material, pipe size (i.e., length and diameter), water chemistry/quality (i.e., pH, alkalinity, disinfectant, corrosion inhibitor, water temperature), and water stagnation time (Schock, 1990; Triantafyllidou et al., 2021).

Although not health-based standards, the U.S. Environmental Protection Agency (USEPA) established a 90th percentile lead action level of 0.015 mg/L and a lead trigger level of 0.010 mg/L under the 2021 revisions to the Lead and Copper Rule (LCR); above the trigger level or action level, water utilities must initiate corrective actions such as corrosion control treatment (CCT) (USEPA Lead and Copper Rule Revisions, 2021).

Lead exposure can adversely affect human health by impairing the neurodevelopment of children and by increasing the risk of hypertension and cardiovascular disease in adults (Lanphear et al., 2018; National Toxicology Program, 2012; USEPA, 2013). Children are especially vulnerable because, compared with adults, their developing bodies absorb a greater proportion of the lead ingested. Significantly, infants who consume mostly mixed formula can receive up to 80% of their lead exposure from drinking water, with the highest exposure associated with LSLs particularly in drinking water systems with no or inadequate CCT (Stanek et al., 2020; USEPA, 2016).

LSLs were primarily installed from the late 1800s to the 1940s. However, plumbing codes of several cities allowed or required lead materials to be installed as late as the 1980s (USEPA, 1984). In 1986, amendments to the Safe Drinking Water Act (SDWA) limited the use of lead as a material in public water supplies and in residential or nonresidential facility drinking water plumbing (USEPA Safe Drinking Water Act Amendments, 1986). The most recent nationwide attempts to quantify the number of LSLs in the United States estimated between 6.1 and 10.2 million LSLs (Cornwell et al., 2016; USEPA, 2021). These LSLs serve between 15 and 22 million people or 7% of community water system (CWS) customers (Cornwell et al., 2016). Challenges with nationwide LSL surveys include the level of detail (i.e., smaller area analysis is not possible; Cornwell et al., 2016) resulting in discrepancies between the most recent national survey and individual state survey results (Perry et al., 2018); low response rates in surveys; issues with utility records (absent/incomplete/inaccurate); issues with documentation of private-side (owned by homeowner) LSL numbers (Wasserstrom et al., 2017); the fact the results may not be statistically representative; and responses that are difficult to verify (USGAO, 2018).

Given that LSLs are a major source of lead in drinking water, there is great interest in and movement by the water industry and regulatory agencies to remove LSLs. Recommendations from the National Drinking Water

Article Impact Statement

This manuscript provides water systems with a review of techniques available to identify LSLs.

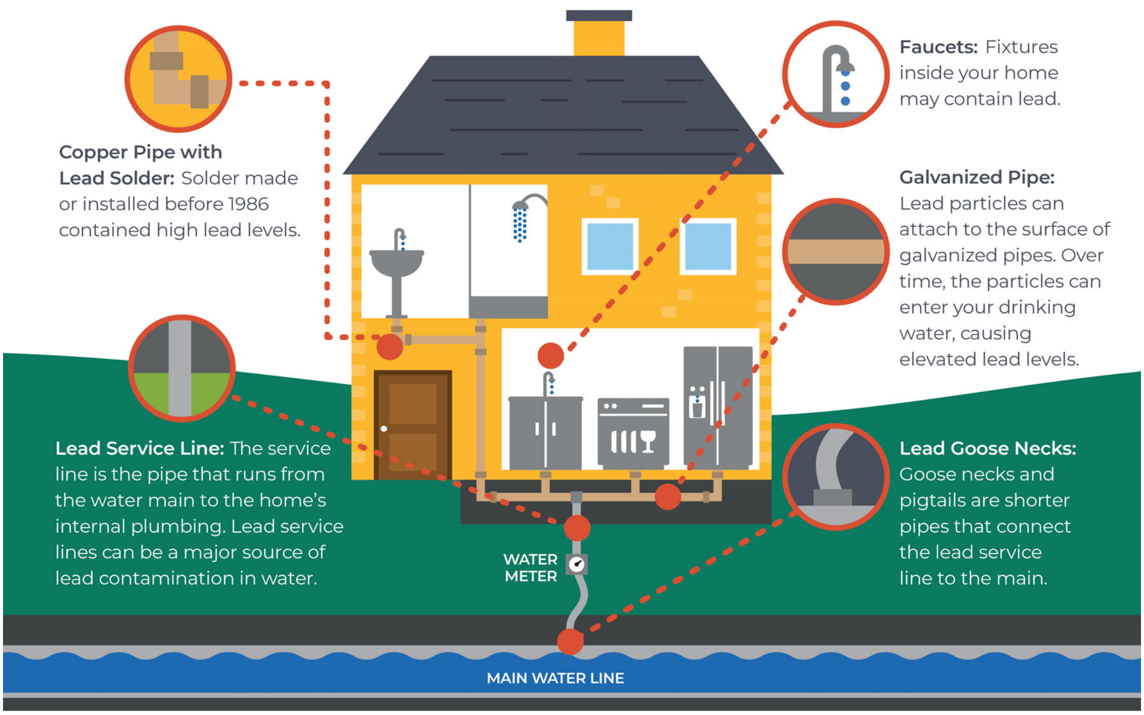

FIGURE 1 Sources of lead in drinking water (U.S. Environmental Protection Agency, 2017)

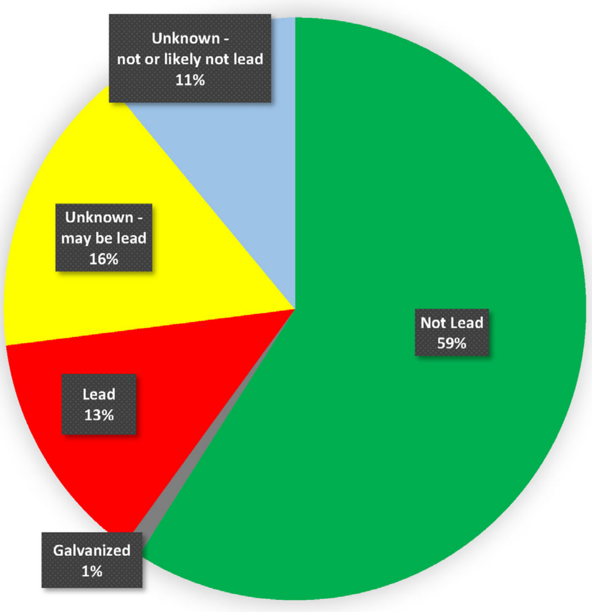

FIGURE 2 Reported average service line estimates in four states, publicly available from Michigan EGLE (March 2020), Illinois EPA (June 2020), Wisconsin PSC (July 2020), and Indiana (via EDF, July 2018). Includes a total of 9.78 million service line materials, compared with 9.83 million service connections reported to safe drinking water information system (SDWIS) for active community water systems (CWS) in these four states. See Table S1 for additional details including data sources. For Indiana, lead goosenecks were included in the lead category

Advisory Council, as part of the LCR revision process, included requiring drinking water utilities to update their distribution system materials inventory to identify the number and location of LSLs (USEPA, 2016). At least 14 states were in the process of conducting statewide LSL inventories of CWSs in 2018 (Neltner, 2018). In addition, USEPA's revised LCR requires utilities to prepare and submit LSL inventories and make information available to the public, including notices to affected residents (USEPA, 2021).

Publicly available SL information submitted by water systems in Illinois (IL), Indiana (IN), Michigan (MI), and Wisconsin (WI) provides an estimated average of 13% LSLs and 16% lines with unknown materials in these states (Figure 2). Additional details on the individual state categories and estimates demonstrate different material definitions in the individual state surveys (Table S1 and Figures S1 through S5). Publicly available estimates for California (CA) are provided separately in Figure S6 to also demonstrate unknown plumbing materials in a state with no known LSLs. Overall, these state estimates include a significant number of SLs with unknown material (i.e., may be lead), demonstrating the need for reliable and low-cost approaches to identifying lead pipes.

On the basis of Table S1, the 2016 national survey by Cornwell et al. (2016) estimated 25% more LSLs in IL, IN, MI, and WI than the most recent state-reported LSL estimates (excluding unknowns). Many uncertainties exist in these data sets. For instance, if the unknown materials are included in the LSL count as presumed lead, then the 2016 LSL estimate would be 61% lower than the four state estimates. Despite uncertainties, these statewide estimates shed light on the scope and extent of the LSL replacement challenge at the local, state, and national levels, but these estimates could not be used to identify the specific homes needing LSL replacement. Overall, the many uncertainties in current estimates and inability to extrapolate national survey results to the local scale (Cornwell et al., 2016) necessitate more accuracy at the national and local levels.

Given new and pending regulatory requirements, the number of LSLs and unknown SLs in the United States, the cost of LSL replacement, the associated lead exposure risks, and the public's desire to reduce lead exposure, there is an urgent need to identify where LSLs are located. This review summarizes current industry LSL identification methods and provides an example of a reasonable stepwise approach to identify unknown SL materials.

2 | LSL IDENTIFICATION CHALLENGES

There are many considerations when exploring potential LSL identification approaches. Resource limitations, including costs, staffing requirements, and time, must be considered. The level of property assessment needed and resources required (i.e., time, staff, funding) will vary depending on the LSL identification method. Therefore, it is important for utilities, state governments, and federal agencies to know the available techniques that can predict and confirm the presence of LSLs in drinking water systems.

2.1 | Records and resources

Many CWSs do not have a full inventory of SL materials. Moreover, particularly in older communities, any available data may be incomplete or incorrect. For example, installation records (e.g., tap cards) for LSLs and lead goosenecks/pigtails are likely 70–100 years old, and some may be lost, illegible, or incomplete (Devenyns, 2019; Goodman et al., 2017). In addition, newer SL materials at historical LSL sites may have been installed, but the repair or replacement material information may be available in separate records (e.g., service or repair tickets, construction or plumbing permits). Different authorities may have access to different records. For example, according to Massachusetts Water Resources Authority (MWRA) records, there were only 100 LSLs in Boston, MA, in 2016; however, according to Boston Water and Sewer Commission (BWSC) records, the number of LSLs was approximately 3,500 (Rocheleau, 2016). This discrepancy was presumably because the wholesaler (MWRA) and consecutive system (BWSC) had access to different data for the same geographical area, but the discrepancy has since been resolved to more closely approximate the BWSC estimate. This demonstrates the benefit of communicating information and continually improving and updating records. As part of a 2018 U.S. Government Accountability Office report on LSL communication, USEPA staff in 7 out of 10 regions identified insufficient and inaccurate records as one of the biggest challenges for conducting and publicizing LSL inventories in the United States (USGAO, 2018).

2.2 | Communication and access

Communication challenges can occur before and during an SL inspection. Some LSL identification methods require that the SL be observed inside the house where the line enters the basement. Scheduling interior SL inspections is based on a resident's (i.e., homeowner's or renter's) availability and willingness to participate (Venkatesh, 2018). If an inspection will occur on private property, advanced notice should be given for any work conducted on the property, and resident consent and participation will be critical to accessing building interiors. Other inspection methods can occur in the public right of way. Some utilities incorporate guidance for residents to reduce lead exposure (e.g., Pieper et al., 2019), particularly when LSLs may be disturbed by utility activities (Illinois Public Act, 2017; Ohio EPA, 2018) and after an LSL is confirmed to be present (Michigan DEGLE,). Utilities frequently conduct LSL inspections when repairing or replacing other water utility features such as mains and meters.

Targeted outreach and educational resources can help improve the quality and quantity of information available to residents. The most effective way to garner resident acceptance is one-on-one communication between the utility and resident (AWWA, 2005). Many water utilities have created outreach materials, such as brochures and one- or two-page fact sheets, to provide residents with information about the inspection process and the health impacts of lead in drinking water (Philadelphia Water Department, 2020). These materials can be found on a utility's website, and several utility examples have been made available on the Lead Service Line Replacement Collaborative's website (n.d.-a). AWWA (2014) has also created sample checklists, templates, and diagrams for communicating about LSL inspections and replacements.

An SL extends from the water main to a building, where it connects to premise plumbing. Typically, the length of pipe from the water main to the curb box (i.e., curb stop or shut-off valve, or property boundary) is the public side, owned by the utility, and the remaining pipe length from the curb box (or property boundary) to the building is the private side (i.e., responsibility of the property owner; Figure 3). Depending on ownership, access to all private-side sections of the SL may require owner communications, approval, and possibly involvement.

In terms of access, depth to the SL can be an additional complication. Typically water lines are installed

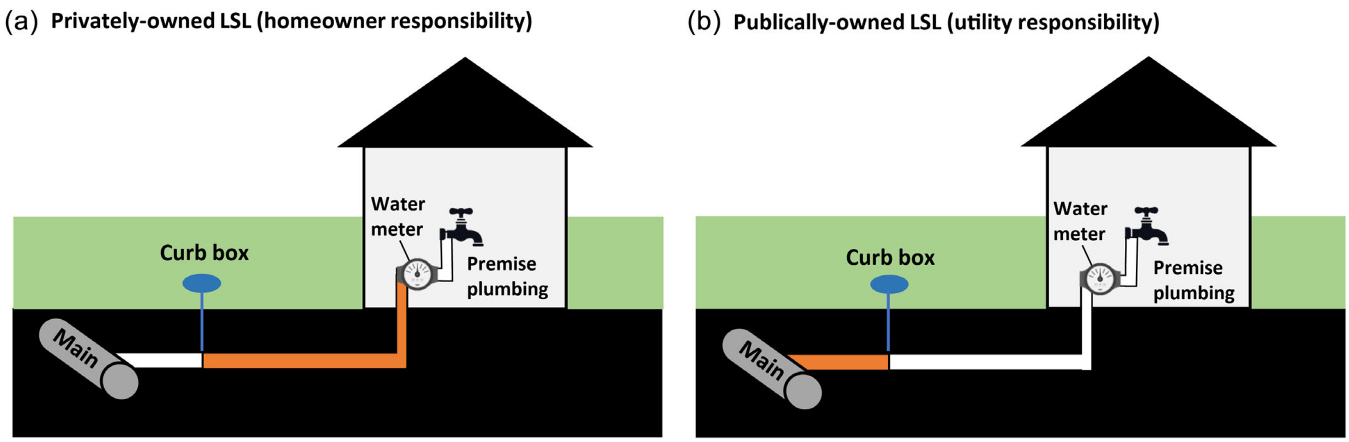

FIGURE 3 Typical example of privately owned and publicly owned lead service lines based on curb stop division (modified diagram from Deshommes et al., 2016). Water meter may be located outside or inside the building. For some materials, a gooseneck may be present, connecting the water main and the publicly owned service line

underground at approximately 12 in. below the soil frost line. In northern climates, an SL can be more than 3 ft below the soil surface, because the soil frost line occurs at a greater depth (Lead Service Line Replacement Collaborative, n.d.-b). Working deeper in the soil profile requires greater physical and/or mechanical effort to reach the SL.

2.3 | Line configuration

According to historical surveys, SL pipes average approximately 60–67 ft in length, with 33%–40% of the length being utility-owned and urban residences having shorter pipe lengths than suburban residences (Sandvig et al., 2008). Several studies have found LSL configuration, specifically pipe length, to be a major factor influencing the dissolved lead concentration at the tap (Cartier et al., 2011; Deshommes et al., 2016). Deshommes et al. (2016) found a decrease in lead concentrations at the tap as LSL pipe length decreased.

SL materials can vary depending on ownership and location along the pipe length. An SL can include different materials in segments, such as gooseneck at the main, public side, curb box, water meter, and private side (Figure 3). Because of this segmentation, the observation of a lead pipe in one location does not confirm the entire SL is composed of lead. Conversely, the absence of lead in one location does not confirm the entire SL is non-lead. Thus, each of the above segments should be inspected individually when conducting an inventory of pipe material (AWWA, 2017).

A gooseneck is a short piece of piping that may be present to connect rigid SL materials to the water main to the SL. Historically, lead was the preferred material for goosenecks because of its inherent durability and flexibility (Lead Service Line Replacement Collaborative, n.d.-a). In some cities, lead gooseneck replacements have been prioritized as a means of reducing lead sources in the distribution system. During a 16-year replacement program, the Portland Water Bureau replaced 12,562 goosenecks, equivalent to 19,000–25,000 linear ft of lead piping (Sandvig et al., 2008).

Previous studies have shown that galvanized iron pipes downstream of lead pipes (including goosenecks) can collect lead released by the leaded materials over time and periodically release particles of lead-containing scale into drinking water (Clark et al., 2015; HDR Engineering Inc., 2009; McFadden et al., 2011; Pieper et al., 2017; Wasserstrom et al., 2017). Some material identification methods in this review may be applicable to identify galvanized iron, but the focus of this review was the identification of lead pipes.

3 | IDENTIFICATION TECHNIQUES

3.1 | Preliminary records screening

Preliminary records screening can help narrow initial LSL identification and verification efforts. As awareness of lead as a public health concern grew in the late 1800s and early 1900s, many communities began restricting or prohibiting the installation of LSLs (Rabin, 2008).

Applicable municipal and plumbing codes and construction specifications can be reviewed to determine when LSLs and lead connections such as goosenecks were most recently required or allowed (Table 1). If no state or local records are available, the 1986 SDWA Lead Ban can provide an approximate end date for LSL installation (Perry et al., 2018). An additional phase-out period (e.g., 1–2 years) may be needed to allow for education about and enforcement of new requirements (Weindorf & Sweeney, 2019).

Properties that were developed before the identified end date for LSL installation and appropriate phase-out period may have lead SL materials. For example, up to 125,000 LSLs were initially estimated in Detroit (MI) on the basis of building age and the city's plumbing code, which allowed lead on the private side as recently as 1968 (Smalley & Betanzo, 2018).

Applicable municipal and plumbing codes may also indicate a maximum diameter where lead would have been used historically (Lead Industries Association, 1950), and older buildings that have smaller-diameter SLs may indicate they have LSLs.

In the 1920s, the City of Evanston (IL) stopped using lead in new construction; this time threshold was used, along with the water utility's repair and replacement records, to develop a dynamic geographic information system (GIS) map showing the potential pipe material of SLs on both the public and private sides. This mapping application has been a successful public outreach tool for the city (King, 2019). Many other utilities have reported using historical records in conjunction with time thresholds to develop similar GIS mapping applications (Bukhari et al., 2020). Starting with a screened list of potential LSL locations can efficiently target resources allocated for LSL identification.

3.2 | Community records

Historical community records maintained by water utilities and municipalities, including those listed below, can be compiled and reviewed to further refine the list of

TABLE 1 Illustrative excerpts from municipal codes, specifying that lead was allowed or required as pipe material for service lines (Miguel Del Toral, personal communication, July 2018)

Municipal code language	What the code language meant
Water Service…Sec. 23. All water pipes laid underground whether outside or inside the building and of a diameter less than 2 inch. shall be "extra strong" lead pipe	The entire service line was required to be made of lead
Pipe Material. Sec. 17. All service pipe, from the point of union with the main to the service stop inside of curb line shall be of lead, known and designated as "Extra Strong," weighing as follows per lineal foot:	Lead pipe was only required between the water main and the property line
Sec. 14. Pipe, Kind Used, Water Commissioner to Purchase.–Either lead, galvanized or enameled iron service pipes may be used at the option of the applicant. All lead and iron pipes must have sufficient strength to sustain a pressure of not less than 200 pounds to the square inch, and at the point of connection with the street main between the corporation cock and the coupling in the iron service pipe there must be at least 18 inch. of lead pipe to retain rigidity of the iron pipe	The service line could be lead pipe, galvanized iron pipe, or enameled iron pipe. However, a short lead pipe at least 18 inch. long (commonly called a 'lead gooseneck') was required at the connection with the water main
Section 995. Water Connections for Buildings: All pipes leaving the curb cock and used for connecting buildings with the City water system, shall be laid under ground, and at least 18 inch. below the established grade, and shall be of lead or galvanized wrought iron or steel	Lead was not required but was one of the types of pipes allowed
Section 660 A. Materials of Water Pipe and Fittings. All water service and distribution pipes shall be of lead, galvanized wrought iron, galvanized steel, brass, copper, or cast iron with brass, copper, galvanized iron or galvanized or malleable iron fittings	Lead was not required but was one of the types of pipes allowed

potential LSL locations (Lead Service Line Replacement Collaborative, n.d.-b; Oswald, 2019).

- SL installation records (Figure 4(a))
- Inspection and maintenance records, including replacement or repairs of specific SLs and larger water main replacement projects
- Plumbing permits
- Meter installation records
- Property tax records
- Distribution system maps and drawings, including as-built drawings

Interviews with experienced people, including distribution system staff, building inspectors, and plumbers, can also help identify locations with LSLs. In some locations, property transaction disclosure records may be an additional reference (McCormick, 2017).

3.2.1 | Database development

Over the past several years, many water utilities have converted paper records into electronic records, even allowing the data to be interactively displayed using GIS. During the Flint (MI) water crisis, more than 45,000 index cards were manually converted into an electronic database. Similar labor-intensive data entry efforts have been completed by other communities (Bolenbaugh & Pickering, 2018). Compiled information has been used to prioritize resources for LSL identification and removal (Arnette, 2020). For prioritization to be effective, quality assurance and quality control must be used when establishing or adding to a database (Deb et al., 1995).

3.2.2 | Database evaluation

SL address and date of installation are important variables for predicting pipe material (Deb et al., 1995; Mistry, 2017). Studies have reported a higher probability of LSLs for older dwellings, such as those built between 1900 and 1940 (Bukhari et al., 2020; Goovaerts, 2017). Temporal patterns can be determined in the database since many utilities have records of their practices and policies over time, such as the year lead was phased out as the primary material for SLs. These patterns allow utilities to predict the occurrence of LSLs when records are incomplete or missing; the accuracy of this method depends on the amount and accuracy of collected data (Deb et al., 1995). For example, two case studies completed for an AWWA Research Foundation project looked at SL data from Chester (PA) Water Authority (CWA) and DC Water, then the Water and Sewer Utility Administration (WASUA), to test the validity of statistical predictions across utilities. Both studies used installation records as the main variable for the analysis. The statistical models were 92.2% and 73.7% accurate in classifying known LSLs for CWA and WASUA, respectively (Deb et al., 1995). However, a Northern New Jersey case study found that a utility's existing temporal information may not be reliable enough to use as an effective predictive method (Mistry, 2017). Field verification identified discrepancies in SL material records, both on the public and private side.

FIGURE 4 Lead service line identification techniques include (a) community records such as tap cards with lead listed as service line material; (b) water quality sampling from a kitchen faucet such as sequential sampling; (c) vacuum-excavation; (d) mechanical excavation for identification and concurrent removal of lead service lines

3.3 | Basic/visual observations

Lead is a dull, soft, nonmagnetic material that turns a shiny silver color when scratched. Therefore, a scratch test can be used as a simple, quick method for determining the SL material entering a building. After locating the water SL coming into the home or building (e.g., in a basement), a resident can carefully scratch the exterior of the pipe with a key or coin; it is important to not use a sharp object as this could puncture the pipe. If the scratched area turns yellow–orange, the material is likely copper. If the area scratches easily and turns a shiny silver color, this is indicative of a lead or galvanized iron pipe. To distinguish between lead and galvanized iron, a resident may place a strong magnet on the pipe. If the magnet attaches to the pipe, this is indicative of galvanized iron and not lead. This method identifies LSLs and iron pipe (AWWA, 2017) but would not be able to identify lead-lined galvanized iron pipe. Water utilities and nonprofit organizations have developed step-by-step online visual/basic LSL identification tools to increase the accessibility of outreach materials (National Public Radio, n.d.).

In many communities, residents have been enlisted in the identification of private-side SL materials; outreach and education can help improve resident participation and the quality of such community survey results (Philadelphia Water Department, 2020). Economic incentives, such as financial assistance for private-side LSL replacement or LSL property transfer disclosure, may also improve resident response rates (Hiltner et al., 2019). For example, Madison (WI) Water Utility surveyed residents at properties developed before the local lead phase-out date (1928) to locate private-side LSLs; this effort included outreach and education about basic/visual LSL identification methods as well as the utility's cost-share incentive for private-side LSL replacement (AWWA, 2005; Theising, 2019). Similar residential surveying approaches have been conducted by other water utilities (Arnette, 2020). Even with outreach and education materials, resident-reported SL materials may be inaccurate and may need to be verified, such as via photographs provided by the resident or onsite inspection by a plumber or the utility (Quirk, 2018; Schmelling, 2019).

In addition, the LCR requires water utility staff to record private-side SL materials during water meter replacements, meter readings, service requests, and any other normal operations that require access inside homes or otherwise observe SL materials (USEPA, 2021). Some utilities have accelerated LSL identification through partnerships with municipal personnel (e.g., building inspectors), non-water utilities, and plumbing professionals who may observe LSLs during their work. In addition to the basic/visual identification approach described above, lead paint test kits or portable X-ray fluorescence analyzers may also be useful methods that could easily be applied by utility field crews for the confirmation of lead materials. Visual examination of SL material encountered during utility maintenance activities such as water main replacement should also be made and, where identified as LSLs, replacements are strongly preferred at that time (USEPA, 2011).

3.4 | Water quality sampling

In general, several water sampling techniques can be used to determine the concentration of lead in drinking water, such as first-draw, flushed, random daytime, sequential, or a specific-liter sample (e.g., fifth liter). These approaches may require resident participation or access to the property to collect the water sample(s) from a tap, usually the kitchen faucet. Sampling results are influenced by factors such as house configuration, water temperature, sampling protocol, water usage patterns, plumbing materials, homeowner/resident compliance, and LSL length and location (Cartier et al., 2012; Deshommes et al., 2013). It is important to note that a single test might not be an effective indicator as a result of variability of lead occurrence in samples (AWWA, 2017). Depending on the complexity of the sampling method, water samples can be collected by water utilities as well as by residents (AWWA, 2017). Lead analysis of one water sample by a certified commercial laboratory may cost between US$20 and $100 (USEPA, n.d.), but the cost will presumably be significantly lower if performed by a large water utility's in-house, appropriately certified laboratory.

The concentration of lead from the tap may be used as a method for identifying LSLs, but an appropriate sampling protocol and lead threshold must be established to reflect local conditions. In the United Kingdom and France, 2.5 μg/L in random daytime samples and 5 μg/L in the first liter after 30 min of stagnation have been respectively used as indicative thresholds of LSL presence (Cartier et al., 2012). Low lead and nondetect levels do not ensure the absence of LSLs but may point to a low probability of their existence. More importantly, lead thresholds may vary on the basis of community-specific conditions such as effectiveness of CCT, seasonal variability, length of LSL and/or lead gooseneck, and choice of sampling protocol. This work discusses three sampling approaches that have effectively identified LSLs.

3.4.1 | Targeted SL sampling

To collect a targeted SL water sample from a sampling tap, the volume of water contained within premise plumbing (i.e., between the sampling tap and SL) must first be flushed out. Because the premise plumbing volume is variable, precise measurements of pipe diameters and lengths would be needed to ensure the sample is collected from the SL. In Montreal, Quebec, the second liter was selected on the basis of typical premise plumbing volumes in that community (median of 0.9 L), and a lead concentration threshold of 3 μg/L on the second liter after 15 min of stagnation (15MS) was indicative of an LSL (Cartier et al., 2012). Higher lead levels in 15MS second liter showed even higher probability of LSL based on field verification—for example, 99.5% probability when lead was 9 μg/L or higher. However, LSLs were found at 20 of 70 sites where 15MS second-liter lead levels were less than 3 μg/L; these "false negatives" were attributed to temperature effects, short LSLs, or larger premise plumbing volumes. These observations suggest that while the approach was suitable for identifying the presence of LSLs, it may be restrictive in its ability to confirm the absence of LSLs. Furthermore, the sensitivity of the approach is likely site-specific and dependent on factors such as water quality and effectiveness of corrosion control.

3.4.2 | Flushed sampling

Sampling after a standardized time of flushing, such as running the water for 5 min, has shown sufficient difference in lead levels to distinguish LSL sites from non-lead sites in some Canadian water systems reported as not using CCT (Cartier et al., 2012; Deshommes et al., 2016).

For example, in Montreal, Quebec, 5-min flush (5MF) kitchen faucet samples, collected at approximately 3–8 L/min during warm weather and targeting freshwater from the mains, with lead less than 1 μg/L, were associated with a very low probability of LSL presence (Cartier et al., 2012). The same study showed a high probability of LSL presence if a 5MF sample was 2 μg/L or higher and the 2nd liter 15MS exceeded 3 μg/L. Deshommes et al. (2016) confirmed the LSL identification approach outlined by Cartier et al. (2012) and offered an approach for other utilities to develop their own water quality-based LSL identification process, relying on flushed samples and short-stagnation profile or targeted-volume samples. Guelph, Ontario, and Ottawa, Ontario, have also used water quality samples for identification of LSLs (Cartier et al., 2012).

In the United States, another example of using a flushed-sample approach was Denver, CO. The city (Denver Water), which uses pH/alkalinity corrosion control, selected a subset of three samples (first draw, then 30-s flush, and then another 30-s flush) to inform ongoing LSL identification (Denver Water, 2019). For Denver SLs installed in 1951 and earlier, a house with an average lead concentration of 5 μg/L in the three-bottle set is considered served by an LSL. Another example is Louisville Water (KY), which conducts additional lead source investigations by vacuum excavation or meter vault inspection if a first-draw or 3-min flush sample is greater than 5 μg/L (Aaron, 2019).

James et al. (2019) reported on the use of community-specific 5MF lead concentrations for LSL identification in two communities using orthophosphate corrosion inhibitors. A threshold, based on three times the average 5MF in a pool of representative non-LSL sites in a community, correctly predicted 63% of 16 known LSL sites sampled in the same community. Had the LSL sites been unknown SLs, the remaining 37% sites would have remained designated as unknown and would have required additional SL identification investigation. In a second community, however, a higher number of false negatives (only 11% of nine LSLs were correctly identified) were attributed to relatively low lead levels in the LSLs, and consequently in the flushed samples; the relatively low lead levels are thought to be due to good community-wide corrosion control. Considering the low cost and simplicity of this single sample approach, this method can serve as an initial screening. However, the predictability is site-specific and likely dependent on factors such as water quality, corrosion control effectiveness, and mix of plumbing materials. Although not specifically addressed by the authors, these factors and other considerations are likely important in establishing the non-LSL site pool size necessary to establish robust thresholds.

3.4.3 | Sequential sampling

Sequential sampling is well documented in the literature for identifying the plumbing sources of lead, including LSLs, at individual homes (e.g., Cartier et al., 2012; Del Toral et al., 2013; Deshommes et al., 2016; Lytle et al., 2019; Sandvig et al., 2008) and can be used to develop protocols for using flushed sampling for larger LSL identification programs. A lead profile is developed on the basis of successive water samples from the tap, collected after a defined stagnation period. The total number typically ranges from 8 to 15 samples, and the last sample generally targets water coming directly from the main (Figure 4(b)). Although sequential sampling is used to profile lead levels along an SL, it may be less feasible to use for large-scale LSL identification efforts because of the large number of samples needed per site (Ng et al., 2018; USEPA, 2011). This sampling approach also requires increased resident involvement.

Sequential sampling is often conducted using a low flow rate at the faucet to minimize mixing and longitudinal dispersion of metals, and pre-stagnation flushing is useful to clear out scale particles that could interfere with identification of lead plumbing sources (Lytle et al., 2018, 2021). Particulate lead release occurs when corrosion deposits in the pipe system are dislodged and transported to the tap because of various physical, chemical, and hydraulic factors such as changes in water chemistry, nearby ground disturbances, and fluctuating flow rates (Deshommes et al., 2017; Sandvig et al., 2008). When multiple rounds of sequential sampling are conducted, actual lead plumbing sources represented by consistent elevated lead levels in specific volumes can be differentiated from sporadic particulate lead spikes (Lytle et al., 2019). Likewise, analyzing samples for additional metals (e.g., Cu, Zn, Fe, Sn, Ni, Cd, Mn) can further differentiate materials.

DC Water, which uses orthophosphate corrosion inhibitor, enlisted residents to collect 6-h stagnation sequential samples and used a total lead mass of 5 μg in ten 1 -L sequential samples to identify the presence of LSLs (Bukhari et al., 2020; Schmelling, 2019). DC Water also looked at the shape of the stagnation profile and co-location of other metals (e.g., Sn) in the water samples to differentiate among lead plumbing sources (Schmelling, 2019). For 30 homes that later had SL work, DC Water sequential sampling correctly identified 26 as LSLs and 2 as non-lead, with 2 homes being shown to have LSLs despite low sequential sampling results. As a result of stagnation uncertainties (e.g., unknown dripping faucets, pipe leaks, or water use) or adequate corrosion control, the absence of an LSL is not necessarily confirmed by lower lead levels, and additional investigation techniques should be used in these cases.

Based on 6-h stagnation sequential sampling at nine LSL homes and seven homes with copper and lead solder, Denver Water observed that LSL homes typically had measured maximum lead at or above 5 μg/L, whereas homes with copper and lead solder had lower lead in water samples (Denver Water, 2019). However, Denver Water reported one home with very low lead (<1 μg/L) in all sequential samples, where an LSL was confirmed with separate methods. In Montreal, 30-min stagnation profiles have been determined to have very low probability of an LSL if all individual third- to sixth-liter samples were below 3 μg/L (Cartier et al., 2012).

Elevated lead concentrations in a sequential profile can be used to identify the location of lead sources, including LSLs, by comparing profile characteristics in a pool of sites that have never had an LSL with a pool of sites that are certain to have LSLs. Figure 5 shows illustrative sequential lead profiles for LSL identification in two anonymous communities. Profiles were obtained in LSL sites pre- and post-removal, as opposed to control sites that never had an LSL. Peak lead concentration in the profiles or average lead mass of all samples collected in the profiles can be compared to establish a threshold lead concentration that can be used to identify locations with LSLs among the unknown locations (James et al., 2019). James et al. (2019) reported the use of thresholds based on three times the average sequential lead peak concentration in a pool of representative non-LSL sites in two communities. Compared with the pools with known LSLs sites, 100% of 16 LSLs locations and 78% of 10 LSLs evaluated in community 1 and community 2, respectively, had peak lead levels above the threshold (i.e., the presence of the LSL was accurately predicted). The higher false-negative rate (LSLs with results below the threshold) in community 2 is thought to be due to good community-wide corrosion control. Thresholds established from three times the weighted lead sequential averages in representative non-lead sites in each CWS predicted 100% of LSLs in both communities on the basis of the individual sites' lead sequential averages. In the same communities and sites, 5MF accurately predicted only 63% and 11% of the LSL sites in community 1 and community 2, respectively. Although more time-intensive and costly, sequential sampling was a much more sensitive tool for identifying LSLs as compared with 5MF sampling.

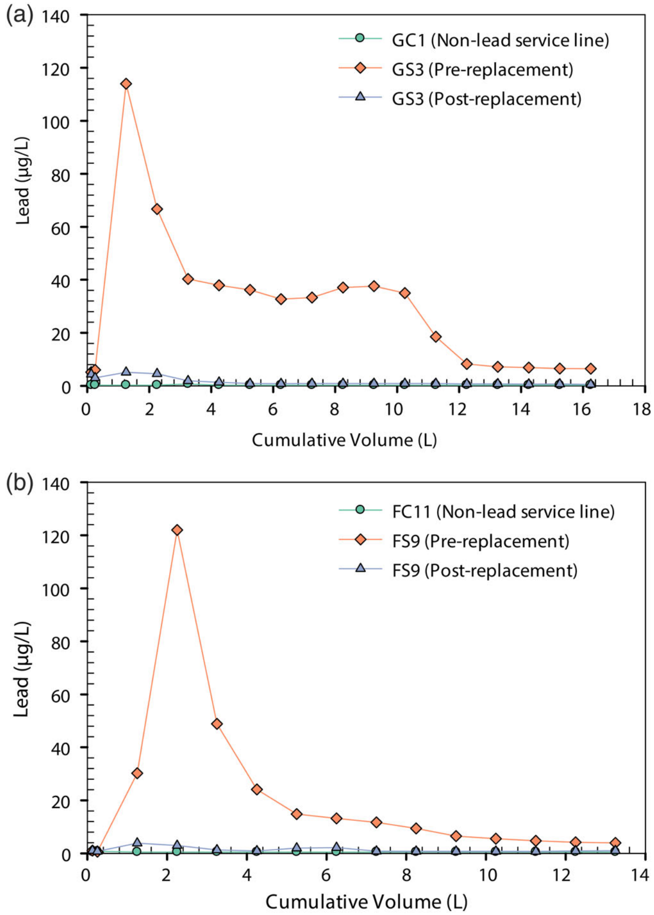

FIGURE 5 Examples of sequential sampling of lead profiles in homes of two cities (a and b). Profiles were obtained in homes before and after lead service line replacement, and in homes that never had a lead service line. The illustrative trends are meant to indicate lead service line presence or absence. The exact lead concentrations are specific to the sampled homes. They should not be generalized to reflect other homes, which may have different plumbing and/or water chemistry characteristics

3.5 | Excavation

Digging methods involve visual inspection of the underground SL. Therefore, the removal of soil, sidewalk, or other obstacles may be required to characterize the pipe material. Excavation is typically the least economical but most accurate identification method. When identified, LSLs should be removed at the time of excavation to minimize short-term elevated lead risk from pipe disturbance. Different excavation methods (Figure 4(c, d)) have different levels of disturbance, time investment, and costs.

3.5.1 | Mechanical excavation

This process involves using a backhoe or other mechanical excavator to dig a test pit down to the SL to expose the pipe and determine material composition (AWWA, 2017), typically at the curb box or shutoff valve. Mechanical "pothole" or "test pit" excavation requires the removal of topsoil, sidewalk, or other obstacles above the SL. This method can have a higher accuracy rate than other excavation methods because a longer length of SL is exposed for observation, up to 10 ft in some instances (Weaver, 2018). However, this method is labor- and time-intensive, requiring the mobilization of a skilled field crew. Staff operating the machinery should have prior experience with mechanical equipment, and a "spotter" should be present for quality control purposes, such as signaling when the SL is exposed to reduce the chance of damage (Katerndahl & Bizal, 2003). Additional health and safety precautions should be in place to reduce risks to workers and the public, such as limiting access to the worksite via traffic and sidewalk controls. Mobility and space constraints are additional limiting factors of this technique (Lead Service Line Replacement Collaborative, n.d.-b). Mechanical excavations may be more likely to disturb or damage the SL and nearby utility infrastructure (Katerndahl & Bizal, 2003; Oswald, 2018), and LSL disturbances can cause elevated lead levels in drinking water (Del Toral et al., 2013; Lewis et al., 2017). Manual excavation using a hand-held shovel can be used in combination with mechanical excavation to limit potential disturbance or damage to subsurface utilities.

At a single home, the cost of traditional backhoe excavation ranges from $1,700 to $2,500, which is approximately half the cost of replacing an LSL (Abernethy et al., 2018; Feick, 2018; Kuhl, 2018; Zahra, 2019). This identification method places a high cost burden on utilities and residents, considering that non-lead SLs do not need to be excavated and replaced. In 2018, more than 7,000 homes were checked for LSLs across Flint, and 79% of those SLs were made of copper material. As a result, the city paid approximately $19.4 million to excavate and re-bury non-lead SLs (Ahmad, 2018).

3.5.2 | Vacuum excavation

A hydro-vacuum truck consists of a high-pressure water jet and industrial vacuum. Both components are hand-held; the jet of pressurized water loosens soil around the area of interest, and the vacuum removes the material into a holding tank until the SL is exposed (Katerndahl & Bizal, 2003). Depending on soil conditions, compressed air, known as an "air knife," may be used instead of pressurized water. The crew can dig a small hole, typically between 8 and 12 in. in diameter, quickly and with minimal disturbance to the site. The hole is filled in with soil and patched with either sod or concrete. As a result, there is little disturbance to the property, and the time investment required of the homeowner is minimal (Deb et al., 1995). This method is used by electric, gas, and cable utilities to locate subsurface utilities because high-pressure air or water is unlikely to damage buried utilities.

Vacuum excavation (e.g., hydro-vacuum excavation or hydro-vac) at the curb box allows sections of both the public- and private-side portions of the SL to be inspected. Often, this method does not require homeowner approval since it can be done in the public right of way. Paved surfaces, such as driveways and sidewalks; subsurface obstacles, such as tree roots; and saturated soils can slow or limit the ability to observe some SLs (Abernethy et al., 2018; Mistry, 2017).

Hydro-vacuum excavation has become an industry standard and is cost-effective (Oswald, 2018). The cost of hydro-excavation can be as low as $77–$400 per inspection (Abernethy et al., 2018; Feick, 2018; Kuhl, 2018; Zahra, 2019). This method is efficient, with an excavation time of 20 min to an hour, allowing up to 11 sites to be inspected per day (Deb et al., 1995; Kuhl, 2018). The largest expense is the hydro-vacuum rental, at approximately $2,000/day (Mistry, 2017).

The City of Flint used hydro-excavation to identify and replace LSLs beginning in 2016 (Abernethy et al., 2018), but in summer 2018 placed a temporary moratorium on hydro-vacuum excavation because the method was not identifying buried lead pipes if portions of LSLs near the curb box were historically replaced (e.g., with copper) while leaving segments of lead pipe in service (Kuhl, 2018). This became evident when some SLs identified during hydro-excavation as having non-lead material were discovered to contain lead material after full excavation. The potential health concerns associated with these incorrect identifications cast doubt on the reliability of this method (Weaver, 2018). The hydro-vacuum excavations were exposing only 16 in. of pipe compared with the 5–10 ft of exposed pipe observed using the traditional excavation method. The state of Michigan believes hydro-excavation is a reliable method when paired with an in-home visual/basic inspection of the SL material coming into the house (Oswald, 2018). This would meet the AWWA standard, which recommends more than one screening method to confirm the absence of lead in SLs (AWWA, 2017). A single hydro-vacuum hole could be sufficient for homogeneous SL materials, but more than one hole may be needed along a heterogeneous SL, which may have lead segments that could otherwise be missed.

3.6 | Predictive data analysis

3.6.1 | Geospatial modeling

Water utility records and verified field data from SL inspections can be used to develop geospatial models. By considering spatial patterns and proximity to known LSLs, predictions can be made for unsampled sites. Goovaerts (2017) used kriging, a spatial interpolation method, to predict the likelihood of finding LSLs in Flint on the basis of building age, digitized records, private-side visual/basic inspections, and proximity to known LSLs. The resulting probability maps may assist with prioritizing inspection and SL replacement.

3.6.2 | Machine learning model

The application of geospatial models can be expanded by incorporating a predictive self-learning algorithm. Abernethy et al. (2018) used available data along with a statistical and machine learning model in Flint. Existing data on SL material and the age of housing stock were used in conjunction with environmental vulnerability indicators such as the presence of high lead levels in drinking water and vulnerable populations (i.e., pregnant women, the elderly, and children under 6 years old). These variables were used as inputs to a machine learning algorithm, which produced a probabilistic output regarding likelihood of finding lead or galvanized SLs at each home with an unknown material type in the database. Information on vulnerable populations (i.e., pregnant women, the elderly, and children under 6 years old) was also incorporated into the model for prioritization purposes. The model developers estimated significant cost savings by decreasing the chance of excavating pipes of non-lead material (Abernethy et al., 2018), but others have raised questions regarding the approach (Fussell, 2021). Data analysis approaches to LSL identification have been reported in other communities as well (Gurewitsch, 2019; Hajiseyedjavadi et al., 2020; Muylwyk, 2020; Oswald, 2020; Schwartz, 2020; Walker, 2020). This is a relatively new approach and as more information, data, and examples become available, we will be better able to assess its feasibility (i.e., pros and cons).

3.6.3 | Video at curb box

Cameras have been used to observe SL materials from inside the curb box (Conway, 2017; Deb et al., 1995). Pittsburgh (PA) found that lead could be positively identified in some cases, but SL materials could not be observed in many cases (Bolenbaugh & Pickering, 2018; Gurewitsch, 2019; Hajiseyedjavadi et al., 2020). Because the absence of lead at the curb box is not conclusive that lead is absent in other section(s) of the SL, Pittsburgh also used historical records, service records, and excavation to further investigate locations where no lead was observed at the curb box.

Utilities such as Tucson Water (AZ) and Green Bay (WI) have used a high-resolution camera equipped with a flexible fiber-optic scope and a light source to observe pipe materials from inside the pipe (City of Tucson, n.d.; Bukhari et al., 2020). At potential LSL locations where lead is not confirmed by previous steps (e.g., records review or curb box inspection), Tucson Water has inspected public-side and private-side pipe interiors, using cameras after shutting off water service and disconnecting the water meter located outside at the curb box. However, pipe scale and corrosion deposits can interfere with observing pipe material from inside the pipe, and the technique itself may cause physical disturbance to the pipe. Before inspecting SL pipe interiors, measures should be taken to reduce scale disturbance and minimize the potential impact of lead release and resultant lead exposure to drinking water consumers.

3.7 | Alternative approaches

Other approaches to pipe material identification have technical basis but limited research or field implementation to demonstrate their effectiveness (Bukhari et al., 2020; Deb et al., 1995; Venkatesh, 2018).

3.7.1 | Cumulative lead sampling device

Filtration of tap water through point-of-use (POU; i.e., pitcher) water treatment devices has gained popularity due in part to concerns regarding lead contamination from plumbing materials in homes. Appropriately certified POU filters under NSF/ANSI-53 for total lead and NSF/ANSI-42 for fine particulates are challenged with water containing 150 μg/L (only NSF/ANSI-53) and must reduce lead to ≤5 μg/L to receive certification. Because these POU filters act as a "trap" for all lead (Cantor et al., 2013), the concept has been proposed, with some modification, as the basis for a sampling device to identify the presence of LSLs and assess lead exposure (Lytle & Schock, 2019). POU devices are placed on taps commonly used for cooking and drinking, and after a specified time, the filter cartridge is removed and replaced. The internal filter material is removed, trapped lead is extracted, and the average lead concentration is calculated using the total volume of water that passed through the filter (Triantafyllidou et al., 2021). Average lead concentrations for a pool of homes that never had an LSL are compared with a pool of homes that have LSLs to establish a trigger lead level above which the presence of an LSL is highly certain and could be used to identify the makeup of unknown SLs.

3.7.2 | Acoustic wave technology

Several companies use acoustic wave technology to assess pipe wall thickness and locate pipe leaks in underground water distribution systems. In these cases, the diameter and materials must be known (Bukhari et al., 2020). Theoretically, this same technology could be used to identify SL material on the basis of a spectral signature, but a library of known return frequencies and associated material types would need to be established (Welter, 2009).

3.7.3 | Electrical conductivity and eddy current technology

Eddy current technology measures the localized conductivity of an object, which requires a sensor probe's physical contact with a pipe. Field demonstration of eddy current technology to identify SL material was reported in an AWWA Research Foundation study (Deb et al., 1995). In conjunction with vacuum excavation, pipe material could be identified externally at the curb box in 15–20 min and 30–40 min if the ground was soil and pavement, respectively. Pipe material was also identified by accessing the inside of the pipe through a meter connection, but maneuvering the probe was difficult when the pipe had multiple bends. At least one case was noted in which different materials were observed in different locations along the SL when partially replaced (Deb et al., 1995). Another evaluation of "no-dig" methods that do not require visual pipe inspection concluded that eddy current technology was the most promising (Welter, 2009). The eddy current probe could accurately identify pipe material, but minor excavation was still required (Welter, 2009).

3.7.4 | Electrical resistance

Ballinger et al. (2020) measured electrical resistance by digital low resistance ohmmeter (DLRO) to distinguish between lead and copper pipe. Initial laboratory work used extracted pipe and plumbing components, and field demonstrations evaluated SL materials by measuring between the curb box and the interior water meter. This method did not require water service disruption but did require access inside the home. In the field, excavation was needed to access the curb box; similarly, excavation would be required at the water main to evaluate the public-side SL materials. Additional challenges were observed at some test sites, including the need for smaller-diameter DLRO leads for some curb boxes and the need to abrasively clean some pipes to remove debris interfering with the DLRO's electrical connection. The authors also noted interpretation complications from higher electrical resistance due to the coupling of pipes; the presence of brass, galvanized, or plastic plumbing components; ground loops; differences in pipe dimensions over the length; poor electrical connection; and interactions with surrounding soil or structures.

3.7.5 | Other alternatives

Bukhari et al. (2020) reported on very-low-frequency technology for identifying ferrous (iron) pipes and terahertz technology for identifying ferrous metals, nonferrous metals, and plastics. Research would be needed to identify unique characteristics to discriminate lead from other materials. In addition, material identification by metal detector is reportedly limited to pipe depths up to 12–15 in. (Bukhari et al., 2020; Deb et al., 1995). Ground penetrating radar (GPR) has been used to locate and determine dimensions of buried objects. As described in Bukhari et al. (2020), utilities may be able to indirectly identify LSLs on the basis of pipe diameter measured via GPR. In addition, GPR backscatter may be able to be used to differentiate pipe materials. Stress wave propagation has been reported as a potential LSL identification method from initial laboratory and field tests (Bukhari et al., 2020; Sjoblom et al., 2018).

4 | DISCUSSION

LSL inventories are needed for accurate budgeting and cost-effective LSL replacement; in some cases, inventories are required by states (CA, IL, MI, OH, WI), and inventories are being required by the revised LCR (ASDWA, 2019; USEPA, 2021). In addition, sharing LSL location information with the public can help residents and homeowners take additional precautions at known or possible LSL locations, such as water filters (Purchase et al., n.d.; Bosscher et al., 2019); property selection and transactions (Lu et al., 2019); and engagement in LSL replacement.

TABLE 2 Relative pros and cons of lead service line (LSL) identification methods using a ranking system of H: high, M: medium, and L: low

LSL ID method	Utility cost			Disturbance		Impact on resident			Utility skills required		Overall	
	Financial	Onsite time	Pre-/post-time	Service line	Traffic flow	Water service disruption	Property damage	Resident involvement (includes pre-/post-time)	Technical interpretation	Labor	Time	Accuracy
Community records review	L or M (if digitized)	NA	M to H (L if digitized)	None	None	None	None	None	L to M	None	M	L to H
Basic/visual observations (on private side)	L	L	L to M	None	None	None	None	L	L	L	L	M to H
Water quality sampling—flushed	L	L	M to H	None	None	None	None	L	M	L	M	L to M
Water quality sampling—sequential	M	L	M to H	None	None	M	None	M to H	M	L to M	M	L to H
Water quality sampling—targeted	L	L	M to H	None	None	M	None	M to H	M	L to M	M	M
Excavation—mechanical	H	H	M to H	H	M to H	H	H	L	L to M	H	H	H
Excavation—vacuum	M to H	L to M	M to H	M	L to M	M to H	M to H	L	M	M to H	M	M to H

There are many approaches available to water utilities for identifying unknown SLs, each having pros and cons (Table 2). Specifically, the identification methods are differentiated in terms of costs (i.e., time and money) and disturbance, both associated with their degree of complexity and overall accuracy. A relative qualitative comparison of LSL identification methods can offer a starting point for utilities, as they develop a customized approach for their specific needs and constraints. Table 2 was developed with feedback from three anonymous water utilities; however, other individual utility experiences may somewhat differ. The table summarizes each LSL identification method by overall time and cost. Utility costs are qualitatively measured using financial cost (e.g., capital investment and/or operating cost), onsite time (e.g., amount of time for utility to conduct LSL identification), and premobilization and post-inspection time (e.g., time investment offsite, such as scheduling, documentation/paperwork, and sample analysis). Physical impacts are measured by SL disturbance (e.g., physical contact with SL or activity that could disturb SL pipe scale from which residents may need protection—e.g., by use of water filters) and traffic flow disturbance (e.g., blocking of roadways or pedestrian walkways). Homeowner/resident impacts are measured by water service disruption (e.g., shutting off household water supply); property damage (e.g., lawn or sidewalk removal); and resident involvement (i.e., resident must be present for access to internal plumbing/fixtures or to conduct an LSL identification method). Alternative methods and predictive data analysis are omitted from Table 2. Alternative methods are limited by research and field implementation, whereas predictive data analysis may incorporate multiple methods, making the cost, time, and accuracy too variable for qualitative comparison.

Overall, the goal of the water utility is to conclusively identify all unknown SL material, on both public and private property, while considering costs, disruptions, method reliability, and other factors. A stepwise SL identification approach that begins with the simplest, least invasive, and least expensive SL identification method and evolves toward more complicated, costly but more certain methods can help utilities effectively reach this goal (Figure 6). Such an approach would aim to identify and thus remove some LSLs from the unknown SL pool in each step, while forwarding the remaining unknown SLs to the next method or step until all the unknown SLs are ultimately identified. An SL would be removed from the unknown pool (classified as lead) only if a method strongly indicated it to be an LSL. However, if a method's results are compelling enough and all decision makers agree, SLs could be removed from the pool (classified as

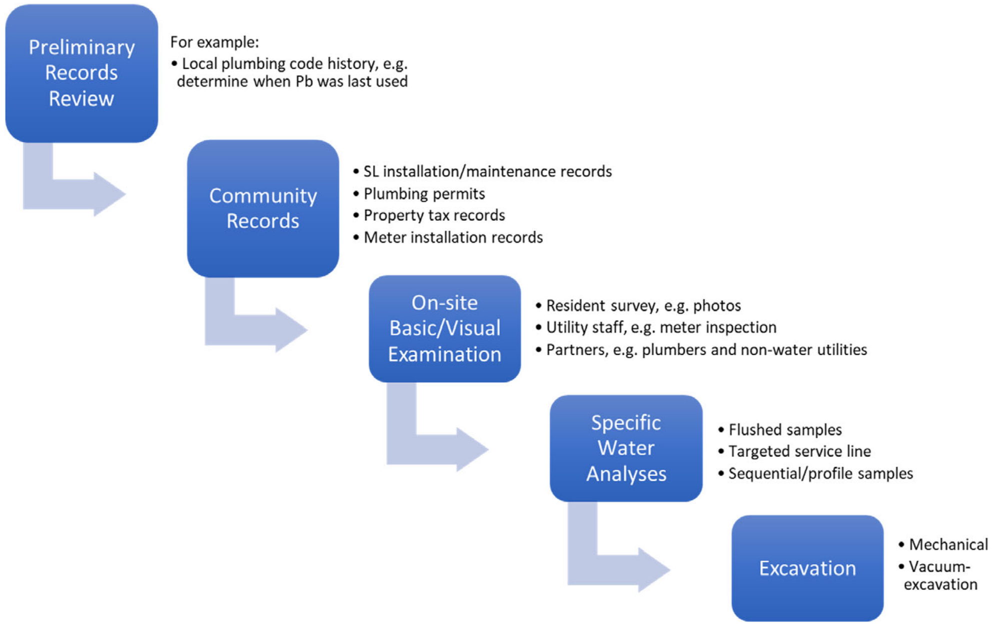

FIGURE 6 Suggested stepwise service line identification approach. Adopting the approach in its entirety assumes availability of resources

non-lead) if results strongly indicate that the SL is not made of lead.

The SL identification sequence of steps should begin with determination of a date threshold for LSL installation, community records, and visual/basic examination. Depending on the quality of historical records, an additional data source may be necessary to enhance confidence during this first step. These records may be used to create statistical or geospatial models to assist in prioritizing additional identification methods. Utilities may then consider an appropriate water sampling approach (e.g., flushed or sequential samples associated with system-specific lead concentration thresholds) as the next step toward identifying unknown SLs, followed by excavation as a final step, if needed. Considering the pros and cons of each step (Table 2), this suggested stepwise approach could be modified to account for the variable needs and constraints of different utilities. Overall, as additional LSL identification methods are developed and used, and as utilities gain and share more experiences with existing tools, better practical understanding will be achieved.

ACKNOWLEDGMENT

The authors would like to acknowledge the anonymous utilities that provided feedback to Table 2, photos of tap cards/SL excavations, as well as Miguel Del Toral (retired, previously with USEPA Region 5) who provided community code excerpts. The information in this article has been reviewed in accordance with USEPA's policy and has been approved for publication. The views expressed in this article are those of the authors and do not necessarily represent the views or the policies of USEPA. Any mention of trade names, manufacturers, or products does not imply an endorsement by the U.S. government or USEPA; USEPA and its employees do not endorse any commercial products, services, or enterprises.

CONFLICT OF INTEREST

The authors report no conflicts of interest.

AUTHOR CONTRIBUTIONS

Kelsey Hensley: Conceptualization; writing-original draft. **Valerie Bosscher:** Writing-original draft. **Simoni Triantafyllidou:** Writing-original draft. **Darren A. Lytle:** Conceptualization; writing-original draft.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

How to cite this article: Hensley K, Bosscher V, Triantafyllidou S, Lytle DA. Lead service line identification: A review of strategies and approaches. *AWWA Wat Sci*. 2021;e1226. https://doi.org/10.1002/aws2.1226