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Dutch drinking water sector readiness for stricter European Union lead norm

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Abstract

The revised European Union (EU) drinking water directive has imposed a stricter norm for lead in drinking water. This has necessitated a reassessment of current and future assets maintained by Dutch drinking water utilities (such as brass-containing appurtenances), primarily from the perspective of lead exposure. Should such components result in a considerable exposure, a consequent widespread rehabilitation would require a significant investment. To quantify exposure to lead from brass components in premise plumbing systems, insights from numerical modeling and laboratory experiments are combined. An important insight is that a lead leaching component present in the kitchen tap poses a much higher exposure in contrast to it being present in the service line. This underlines the need to localize lead leaching components – where is it and who needs to take action to remove it. Subsequently, the robustness and vulnerabilities of profile sampling (a lengthy flushing followed by prolonged stagnation followed by collection of a series of water samples) in localizing lead leaching components are explored. This study has led collectively to two major conclusions for the Dutch drinking water sector: (i) there is no need for accelerated rehabilitation of brass-containing appurtenances such as water meters and shutoff valves and (ii) profile sampling is to be deployed upon measuring norm exceedance.

Impact statement

In 2020, the Dutch drinking water sector faced urgent challenges due to upcoming European Union (EU) regulations lowering the permissible lead levels in drinking water. Key questions emerged: Do brass components like water meters and shutoff valves pose health risks? Should they be replaced? What materials are safe for future use? And how can utilities distinguish their contribution to lead exposure from that of private plumbing systems? The prospect of a nationwide replacement program was daunting – both logistically and financially. Complicating matters further, premise plumbing lie outside utility control. To tackle these dilemmas, the sector launched a coordinated effort combining modeling, lab tests and field studies. This proactive approach delivered clear guidance on managing existing and future assets, especially brass components, and established protocols for responding to lead exceedances. These rapid, sector-wide results were made possible by the strong collaboration and knowledge-sharing across Dutch utilities. The insights gained now offer a valuable blueprint for other European countries preparing for the full enforcement of the revised Drinking Water Directive by 2036.

Introduction

The revised European Union-drinking water directive (EU-DWD) has led to a stricter norm for lead (Pb) in drinking water. In view of long-term public health, the norm has been reduced from 10 μg/L to 5 μg/L, see Directive 2020/2184, Annex I, Part B. As a supporting measure, newly installed components that come in contact with drinking water (such as pipes and fittings) must belong to the European positive list (EUPL) of materials (Commission Implementing Decision, 2024/3672024). The EU member-states have until 2036 to enforce the new law, offering room for transition. In the Netherlands (NL), the norm has already been enforced since 2023 (see Drinkwaterbesluit, 2024, Bijlage A, Tabel II).

The 10 Dutch drinking water utilities are responsible for ensuring the compliance with the lead norm. The utilities are responsible for all materials in the drinking water supply chain until (and including) the point of delivery (water meter). Thus, the drinking water utilities are owners of articles such as shutoff valves, water meters and lead-soldered copper service lines – all of which may leach lead. Articles downstream of the water meter in the premise plumbing system are the responsibility of the premises owner. The division of responsibilities between the drinking water utility and premises owner is complicated by the fact that the utility is responsible for the satisfaction of water quality norms at the point of delivery (water meter) as well as at tap (see Drinkwaterbesluit, 2024, Artikel 13). This is typically tested through samples collected at the kitchen tap.

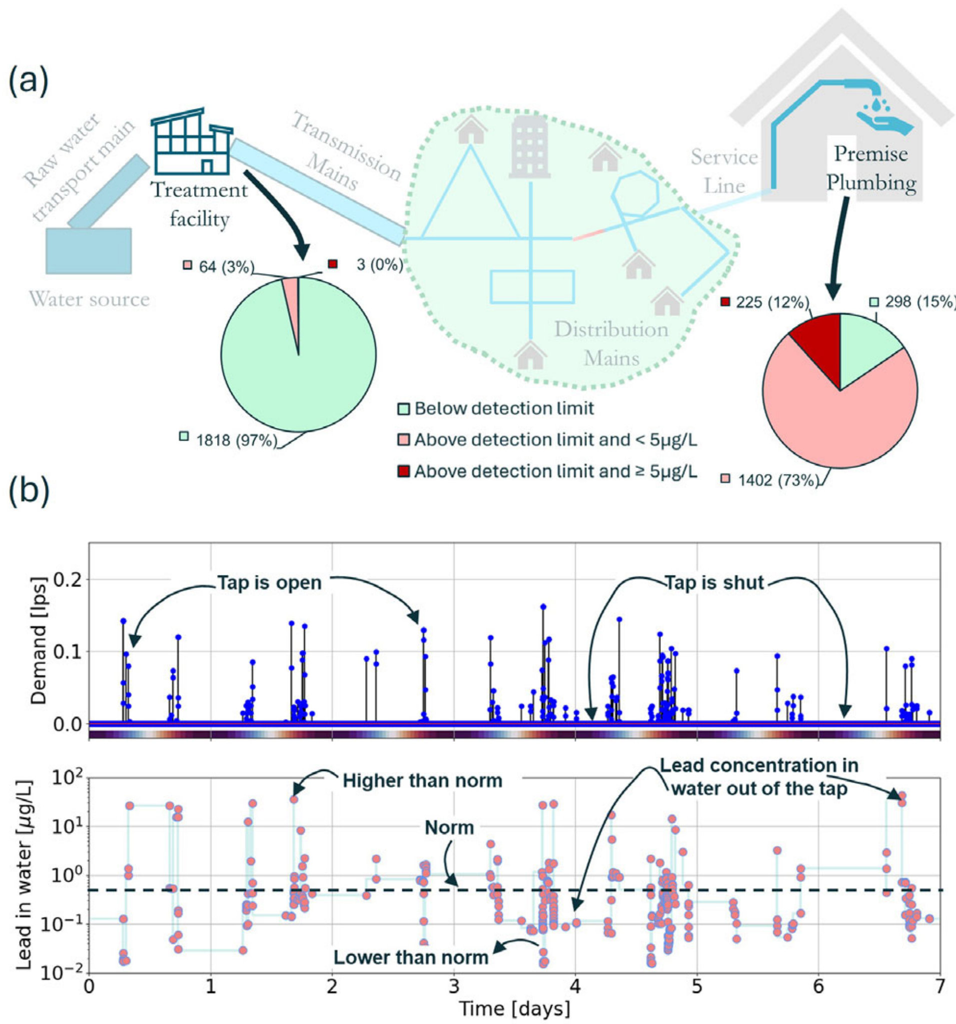

Figure 1. (a) Lead in regulatory samples in the NL above the detection limit at treatment facilities (left) and consumers' taps (right). (b) Simulations show how lead concentrations at the tap fluctuate wildly across time.

In the NL, lead is typically introduced during distribution, as illustrated in Figure 1(a), based on measurements between 2012 and 2022 (REWAB, 2025). It shows how lead concentrations in the water leaving the treatment facility rarely show norm exceedance (0.2% above 5 μg/L) in contrast to the water sampled at premises (12% above 5 μg/L). There could be many possible sources – service lines, appurtenances and plumbing articles. As of 2021, there were 1,700 lead service lines in the NL and a further 23,000 service lines where further assessment is necessary to exclude lead as the pipe material (van Steen et al., 2021). These are a considerable fraction of the about 7 million service lines present in the NL. There are hundreds of thousands of premises where the supplied water comes in contact with either lead-soldered copper service lines (lead in solder was only phased out around 1995 in the NL) and/or lead-containing brass articles. Extrapolating the results of a past study, it may be estimated that hundreds of thousands of premises might still contain lead plumbing downstream of the water meter (see Baron et al., 1995, Table 11.5). Moreover, it cannot be ruled out that premises owners might unknowingly introduce lead leaching articles in the plumbing. For mainland Europe, it is acknowledged that legacy lead plumbing is present in many countries (see Jarvis and Fawell, 2021, Figure 1).

To the best of our knowledge, there are only a few recent European studies (Döhla et al., 2021; Gartner et al., 2024) where the revisions in the EU-DWD are explicitly reflected upon. This suggests that European nations are yet to take concrete actions to safeguard the stricter norm. In contrast, there exist numerous scientific studies emanating from the United States focusing on lead, as a consequence of the Lead and Copper Rule and subsequent amendments (Environmental Protection Agency, 2025). A major difference between the United States and the NL is how lead service lines are viewed. In the United States, conditioning the water (with orthophosphates, for example) to reduce leaching of lead from lead service lines (to promote scale growth) is viewed as an acceptable mitigation strategy, especially in the presence of chlorine (Edwards and McNeill, 2002; Schock et al., 2014; DeSantis et al., 2020). Thus, a lot of attention has been paid in the United States on understanding the fundamental aspects of lead leaching from lead service lines. Unfortunately, this extensive body of lead research in the United States is not directly relevant for the non-chlorinated water supply in the NL. In the NL, the preferred mitigation strategy was and is replacement, underlined by large-scale replacement campaigns in the past.

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Given the situation in the NL and the state of current affairs brought upon by the EU-DWD, the following practical questions exist for the Dutch drinking water utilities:

1. What policy should a drinking water utility adopt with regard to existing and future assets that leach lead (with a special focus on brass)?
2. What should the drinking water utility do when an incidental norm exceedance is encountered?

While field measurements reflect reality, they also pose a challenge while interpreting the findings. In the NL, the standard way to test for lead in drinking water is by collecting a 1-L sample at the kitchen tap (without any pre-flushing) at a random day and time – the random daytime (RDT) sampling. This methodology is appropriate for assessing lead exposure at a community level (see Triantafyllidou et al., 2021, Table 3). However, it is inappropriate for assessing the situation at a household level. This is illustrated in Figure 1(b). One sees that the lead concentration at a tap fluctuates by orders of magnitude owing to the stochastic nature of water usage. The graph at the top shows moments at which a tap has been opened and the graph at the bottom shows the lead concentration in the water out of the tap when open. The lead concentration at a random moment can be much higher or lower than the average concentration over a longer period. In fact, Jarvis et al. (2018) provide an empirical example where the consumption pattern seemingly affects lead exposure among inhabitants in the same household. The impact of water use patterns is considered to be one of the most understudied contributors to lead variability (Triantafyllidou et al., 2021). Thus, the moment at which a random sample is collected can have a huge impact on the conclusion drawn about exposure or presence of lead.

As a result, the following research questions were formulated to address the aforementioned practical questions:

1. Modeling: Can a computational model that integrates plumbing system geometry, stochastic water demand, and time-dependent lead leaching accurately capture their complex interplay?
2. Validation: Can the validity of a complex lead-leaching model be established through empirical calibration and one-to-one experiments?
3. Application: Can a validated model of lead leaching in plumbing systems be effectively deployed to generate insights applicable to real-world scenarios, such as exposure risk assessment and sampling strategies?

This paper demonstrates how a composite framework, including a numerical model, laboratory experiments and field measurements, could help water utilities make informed decisions on the risk of lead in drinking water. The research presented here has been documented extensively in a Dutch report (Dash et al., 2024).

Methods

Mechanistic model LEadGO

This study relies largely on a mechanistic model schematically illustrated in Figure 2(a). The modeling framework is called LEadGO which was developed during the course of this study (Dash et al., 2025). It comprises of three key ingredients:

1. The plumbing system (lengths/diameters of pipes and location of various consumption points);
2. The water consumption time series (dependent on the number of inhabitants and their behavior); and
3. The location and characteristics of lead leaching (lead dissolution curve, as a first-order saturation growth model).

The lead concentration at the tap depends on the interplay between the three ingredients. The package WNTR (Klise et al., 2017) forms the backbone for all the hydraulic and water quality calculations. Mathematically, the lead dissolution curve is described using the equation $C = E\left(1 - e^{-t/T}\right)$, where C is the lead concentration [µg/L], t is time [s], E is the equilibrium lead concentration [µg/L] and T is the characteristic dissolution timescale [s]. The timescale is dependent on other parameters such as the dissolution rate M [µg/(m^2·s)] and pipe diameter, D [m] via the mathematical relationship: $T = \frac{DE}{4M}$.

Similar models have been used in the past to study the dissolution and propagation of lead in drinking water (Abokifa and Biswas, 2017; Burkhardt et al., 2020; Hatam et al., 2023; Hatam et al., 2025). Such a model tackles one of the most understudied contributors to lead variability – the impact of water use patterns (Triantafyllidou et al., 2021).

In the present study, a typical Dutch single-family residence is considered as the basis for the plumbing geometry. The water demand patterns are based on average water consumption behavior for a Dutch household with two adults – generated using SIMDEUM (EJM Blokker et al., 2010). The lead leaching characteristics are based on actual laboratory experiments (performed in the present study) on components found in Dutch plumbing. It is assumed that the incoming water from the distribution network is free of lead, which is reasonable for the Dutch drinking water network (Figure 1[a]).

Experiments in experimental rigs

The mechanistic model is supported by the following experiments:

1. **Tabletop stagnation experiments:** Lead-releasing components are filled with water and sealed for a fixed duration. By analyzing the water following a series of predetermined stagnation periods, the lead released as a function of stagnation duration is derived (Kuch and Wagner, 1983). The lead dissolution curve is used to extract parameters for the first-order saturation growth model. These experiments provide input values for the mechanistic model.
2. **Experimental rigs for brass:** Rigs at two locations ('Weesperkarspel' and 'Leiduin' – water treatment facilities of the utility Waternet), contain various brass components (two each of CW614, CW617, CW602, CW724R and one piece of PVC as a reference for correction), which are subject to water flow of 125 L per day (programmed flushing of rig multiple times a day for 1–2 min). An example of a brass sample is shown in Figure 2(b). Two types of experiments were performed. 'Run-time' tests involved collecting water samples following 16 h of stagnation, with sampling being performed every 4 weeks. These 'run-time' tests allow determining whether the lead leaching tendencies change following extended operation. A second test involved collecting water samples following 0.5, 1, 2, 4, 8, 16 h of stagnation. These were performed after conditioning in the rig for 3 months. The outcomes aid extracting the lead dissolution curves. These experiments provide input values for the application of the mechanistic model.
3. **Premise plumbing rig:** This rig called the HomeWaterLab (Dash et al., 2023) mimics a Dutch premise plumbing system with 11 points where water can be used. This facility is similar to the Home Plumbing Simulator in the United States

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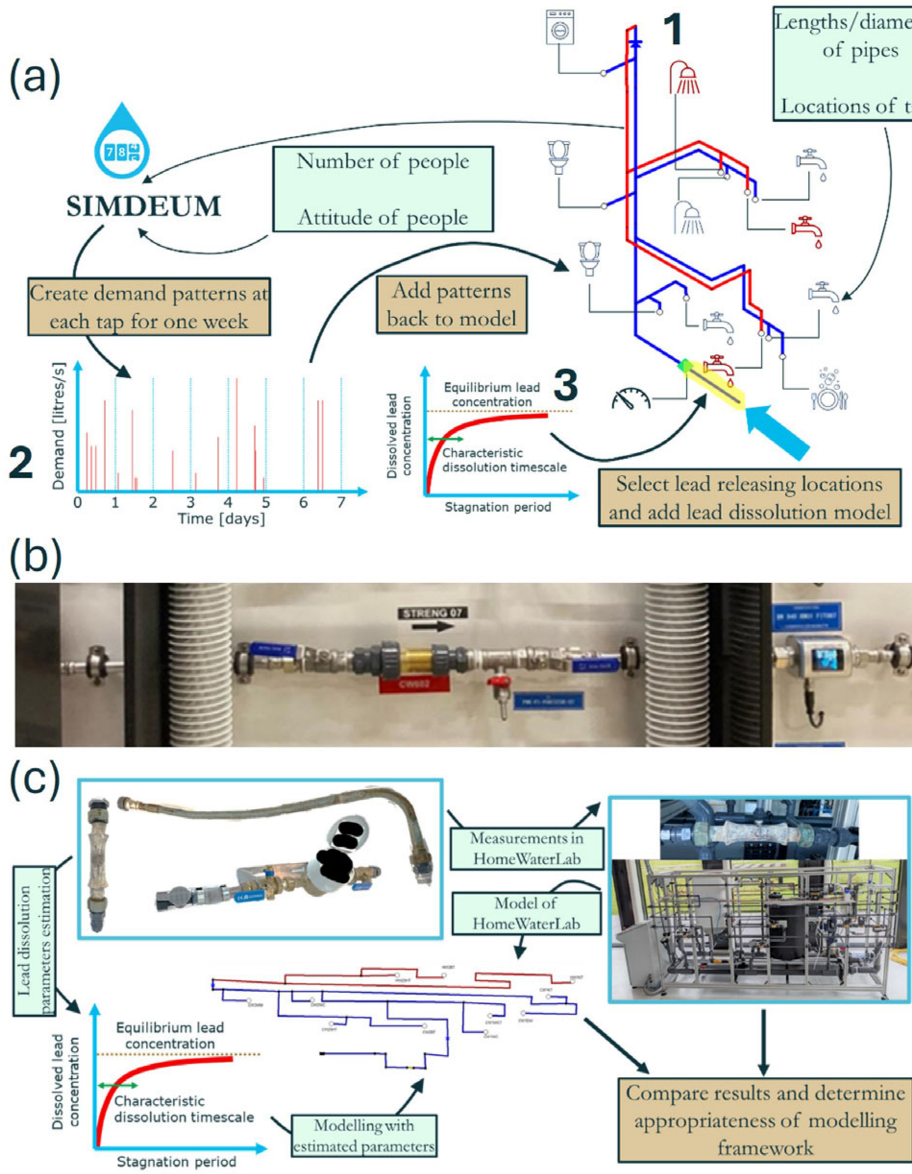

Figure 2. (a) The key ingredients of the modeling framework. (b) A brass sample in the experimental rig for brass. (c) Framework to validate the modeling approach with experiments.

(see Lytle et al., 2021, Figure 1). Water consumption in HomeWaterLab can be automatically controlled through inputs in an Excel file containing SIMDEUM-generated water demand patterns. These experiments are used for validating the mechanistic model.

The construction and operation of the experimental rigs for brass were inspired by the European norm for assessing metal release (Nederlands Normalisatie Instituut, 2008, 2010). Deviations from the norm (in design and operation) exist since the rigs were used to estimate the urgency to replace existing assets and not to assess the suitability of a material for market introduction (material certification). This research activity was a proactive step taken by the utility (in 2023) before the EUPL was published (in 2024). It helps assess existing assets (lead dissolution curves translated to exposure at the tap) and future assets (anticipating which types of brass may be purchased/installed).

There is one major difference between the tabletop experiments and the experimental rigs for brass with respect to the leaching mechanisms. In the experimental rigs, the brass articles are installed 'in-line' with a stainless steel pipe. Lead leached into stagnant water from brass can diffuse longitudinally, allowing for more lead to be leached into the system. Such a mechanism is not possible when an article is filled with water and sealed off (like in the tabletop experiments). This behavior has been emphasized previously by Triantafyllidou et al. (2012), implying that the 'in-line' measurements significantly increase lead concentrations and are more representative of reality. However, from the perspective of modeling where the diffusion is not accounted for, the tabletop experiments offer a more representative input.

In the Supplementary Material, the water compositions at Weesperkarspel and Leiduin are available (Supplementary Tables S1–S2); so are the outcomes of the 'run-time' tests (Supplementary

Figures S1–S4) and lead dissolution curves from the rig experiments (Supplementary Figures S5–S8) and tabletop experiments (Supplementary Figures S9–S10).

Validation of the mechanistic model LEadGO

These experiments collectively were used to validate the mechanistic model. The validation framework is schematically illustrated in Figure 2(c) involving the following steps.

1. Lead dissolution curves for various specimens were gathered. Tabletop stagnation experiments were performed on a lead pipe, a copper pipe with lead soldering and a water meter containing brass. The experimental rigs for brass offered information on leaching of various types of brass.
2. The lead pipe from the tabletop experiments was integrated into the HomeWaterLab facility. HomeWaterLab was operated for 5 weeks with unique weekly water demand patterns. A total of 25 composite water samples were collected across 5 weeks and five end use points.
3. A computer model of HomeWaterLab was made in LEadGO. The location of the lead pipe in the model corresponded with the location in HomeWaterLab. The lead leaching characteristics in the model were based on tabletop stagnation experiments. Five weeks of simulations were performed with the same water demand patterns used for the experiments, to facilitate a one-to-one comparison (25 composite water samples in simulations).

Applying LEadGO: Lead concentrations at the tap

LEadGO was applied to various informed scenarios. Only six examples are considered for brevity. The six examples have three combinations of leaching locations (shutoff valve, water meter and kitchen tap) and two brass types (CW602 and CW617). CW602 contains 1.7–2.8% lead by weight whereas CW617 contains 1.6–2.2% lead by weight. The equilibrium lead concentrations, *E*, for CW602 and CW617 were measured and found to be 223.7 μg/L and 19.3 μg/L respectively. The leaching rates, *M*, were measured and found to be 0.014 $\mu g/(m^2 \cdot s)$ for both. The CW602 parameters were based on the experimental rigs for brass whereas the CW617 parameters were based on the tabletop experiments. Simulations were run for 20 weeks, each week with a different water demand pattern.

Using profile sampling to localize lead leaching components

One powerful method to localize lead leaching components is through profile sampling (also known as sequential sampling). Triantafyllidou et al. (2021) provide a good overview of this methodology. This sampling technique involves three key steps: (i) flushing the system long enough to rid it of existing leached lead, (ii) facilitating stagnation to allow a disturbance-free leaching and (iii) collecting multiple samples in a sequence.

In our study, we reflect on the robustness of this sampling method through several routes:

1. **Numerical modeling:** It has been previously discussed in Dash et al. (2022). Lead is assumed to leach from a lead service line. To simulate profile sampling, a stagnation period of 6 h as well as sample collection following the stagnation (20 samples of 300 mL) were built into the existing water demand patterns. The stagnation was not preceded with flushing to rid the plumbing of existing leached lead. The resulting lead concentrations in the 20 virtual samples were studied on 140 simulated days.
2. **Experiments in HomeWaterLab:** The lead pipe tested in the tabletop experiments was installed in HomeWaterLab. The system is flushed, and a stagnation period of 6 h follows. Thereafter, 20 samples of 180 mL were collected successively at one tap.
3. **Field measurements:** Profile sampling was tried out at one residence in two rounds. In the first round of sampling, five samples of 1,000 mL were collected. In the second round, 2 samples of 1,000 mL were followed by 10 samples of 100 ml (decomposition of the third liter).

Results

Long term behavior of lead leaching from brass

The long-term leaching behavior of four types of brass were investigated. Only the results of CW617 and CW724R are considered for brevity – see Figure 3. Lead concentrations leached from CW617, when it is brand new, are extremely high (>100 μg/L). After a couple of months of conditioning, the concentrations dropped to about 10 μg/L. Even after about 8–10 months of conditioning, the leached concentrations from CW617 did not fall below this plateau of about 10 μg/L. A qualitatively similar observation had been made in the past (see Latva et al., 2017, Figure 4). For CW724R, the lead leached from a brand new specimen is about 5 μg/L, significantly lower than CW617. With more conditioning, the leached concentrations reduced further to under 2.5 μg/L. Lead leaching from brass is known to be sensitive to the chloride-to-sulfate mass ratio (CSMR) in water (see Triantafyllidou, 2006, Chapter 4). The CSMR at Weesperkarspel and Leiduin were 8.8 and 1.5, respectively. Nonetheless, there do not seem to be major differences in the lead concentrations measured at the two sites.

Validation of the mechanistic model LEadGO

The validation of LEadGO was achieved through a one-to-one comparison between the measured and modeled average concentrations at five consumption points, with 5 weeks of unique water demand patterns. It is observed that the order-of-magnitude of the measured and modeled lead concentrations are the same (<5 μg/L), as displayed in Figure 4(a). In this sense, the model is found to be sufficiently reliable for the present objectives (determining exposure with respect to the norm). The experimental work herein should be seen as a first rigorous attempt at validating the mechanistic model and there is certainly room for further improvement. For example, the model does not include aspects such as particulate lead and longitudinal dispersion, which can influence outcomes (Abokifa and Biswas, 2017; Burkhardt et al., 2020). The validation also relies on one type of lead source at one location. Additional experiments with variation in the lead component and placement will certainly test the robustness of the validation framework.

Applying LEadGO: Lead concentrations at the tap

Once sufficient confidence was gained in the mechanistic modeling framework, it was applied to various informed scenarios. The case studies and outcomes are shown in Figure 4(b) and (c) respectively.

We focus in our case study on the results of lead concentrations in water coming out the cold water kitchen tap, as this is the most

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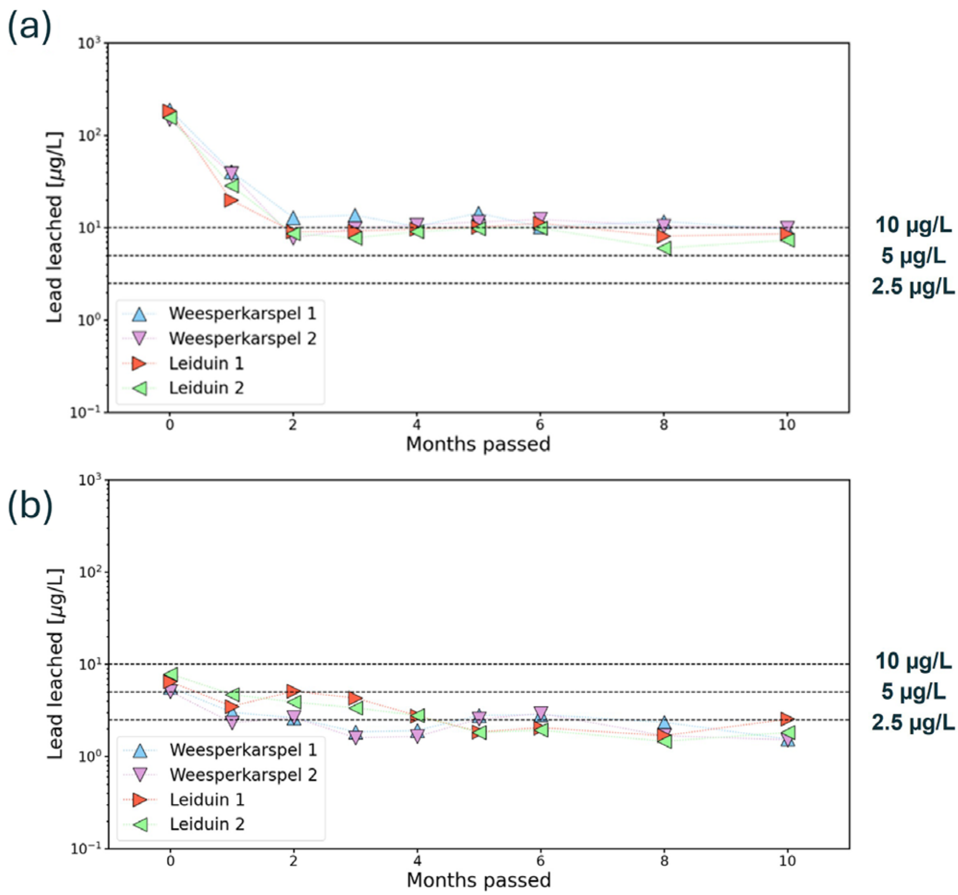
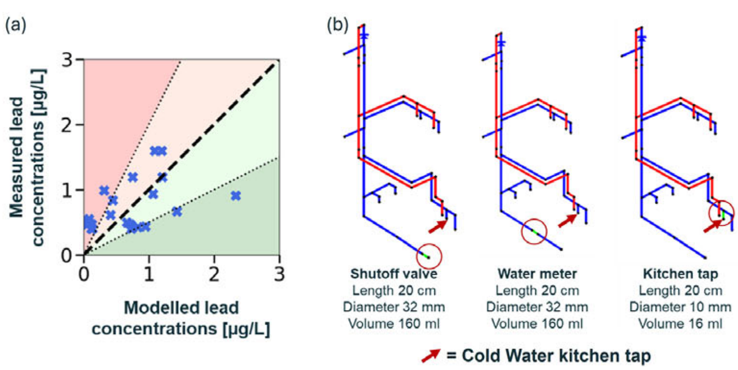


Figure 3. Lead concentration leached into water following 16 h of stagnation as a function of the number of months conditioned. (a) Results for CW617. (b) Results for CW724R.



(c) **Average lead concentration at the kitchen tap (cold water only)**

Brass location → Brass type ↓	Shutoff valve	Water meter	Kitchen tap
CW602	0.23 µg/L	0.28 µg/L	6.76 µg/L
CW617	0.17 µg/L	0.20 µg/L	2.02 µg/L

Percentage of time that the lead concentration at the kitchen tap (cold water) exceeds 5 µg/L

Brass location → Brass type ↓	Shutoff valve	Water meter	Kitchen tap
CW602	0.6 %	0.8 %	19 %
CW617	0.4 %	0.6 %	18 %

Figure 4. (a) Validation of LEadGO through a comparison between measured and modeled average lead concentrations. (b) Situations considered for exploring the effect of brass appurtenance location on lead concentration at the cold water kitchen tap. (c) Statistics of lead concentration at the tap.

commonly used tap for oral consumption. It is evident in Figure 4(c) that brass in the shutoff valve and water meter does not lead to an exceedance of the (new) norm of 5 µg/L, irrespective of the brass. When the brass is at the kitchen tap, the average lead concentration at the tap shoots up, despite the much lower contaminated water volume (16 mL vs. 160 mL for the shutoff valve and water meter). In this case, it does matter which brass is utilized. The use of CW602 (which leaches more) at the kitchen tap leads to an average exposure above the norm, in contrast to CW617. These examples collectively show that when it comes to exposure to lead through components in the plumbing system, location matters. In fact, the presence of a lead-releasing component in the final branch of the plumbing system toward the kitchen tap is the least desirable situation (due to longer stagnation periods and no escape routes to other branches of plumbing).

The results also offer insights relevant for RDT, especially in the context of exposure determination. The presence of brass in the water meter or shutoff valve can lead to an occasional (0.5–1%)

incidental measurement of lead concentration higher than 5 μg/L at the tap, even if the average concentration is lower than 5 μg/L. When there is brass at the kitchen tap, the percentage of time that the lead concentration in the water coming out the tap exceeds 5 μg/L is significantly higher than when the brass is in the service line, implying higher detection chances with RDT sampling. For both brass types at the kitchen tap, the amount of time the lead concentration at the tap exceeds 5 μg/L is nearly identical, in contrast to the differences in weekly average concentrations with respect to the 5 μg/L. These results suggest exercising caution while interpreting RDT measurements.

Using profile sampling to localize lead leaching components

The location of a lead-releasing component clearly affects exposure. To be able to replace such components, one needs to know the location as well as who is responsible for replacement. Thus, it is important to localize lead-leaching components. In this section, we reflect on the robustness of profile sampling by means of modeling, experiments in HomeWaterLab and field measurements. A compilation of results from all three approaches is shown in Figure 5.

The following can be observed from profile sampling in the numerical simulations:

- The first section (light blue background) comprises the first 11 samples, each of which almost always has a lead concentration <5 μg/L. These samples belong to the piping between the kitchen tap and the service line. The few outliers in these virtual samples can be avoided by flushing the pipes prior to stagnation.
- The second section (yellow background) comprises three samples that always have a lead concentration of >100 μg/L. These elevated concentrations correspond to the lead that has been released from the service line during prolonged stagnation. It can be seen that these three samples always give the same value.
- The third section (gray background) comprises the last six samples with a lead concentration of <5 μg/L. This corresponds to water from the distribution network that has been modeled as lead-free water.

The robustness was further evaluated through laboratory tests in HomeWaterLab. An example is shown in Figure 5(b), where the peak of the profile corresponds reasonably well with the location of the lead-releasing component. The lead-releasing component, a lead pipe, has a volume of 60 mL. However, one sees that the profile of lead concentrations has a much broader peak than 60 mL. This observation is similar to that of Burkhardt et al. (2020) and Lytle et al. (2021), which is attributed to the phenomenon of longitudinal dispersion. The height of the peak (20 μg/L) is significantly lower than concentrations encountered during the tabletop stagnation experiments (160 μg/L), possibly due to the dispersion. The area under the profile gives a total lead mass in the same order-of-magnitude as expected from the lead dissolution curves.

An example where the robustness of profile sampling in field measurements was demonstrated is shown in Figure 5(c). In the first round of sampling, the third sample showed increased lead concentrations. This increased lead concentration stemmed either from the water meter or shutoff valve. From the second round, it becomes evident that the released lead corresponds to the location

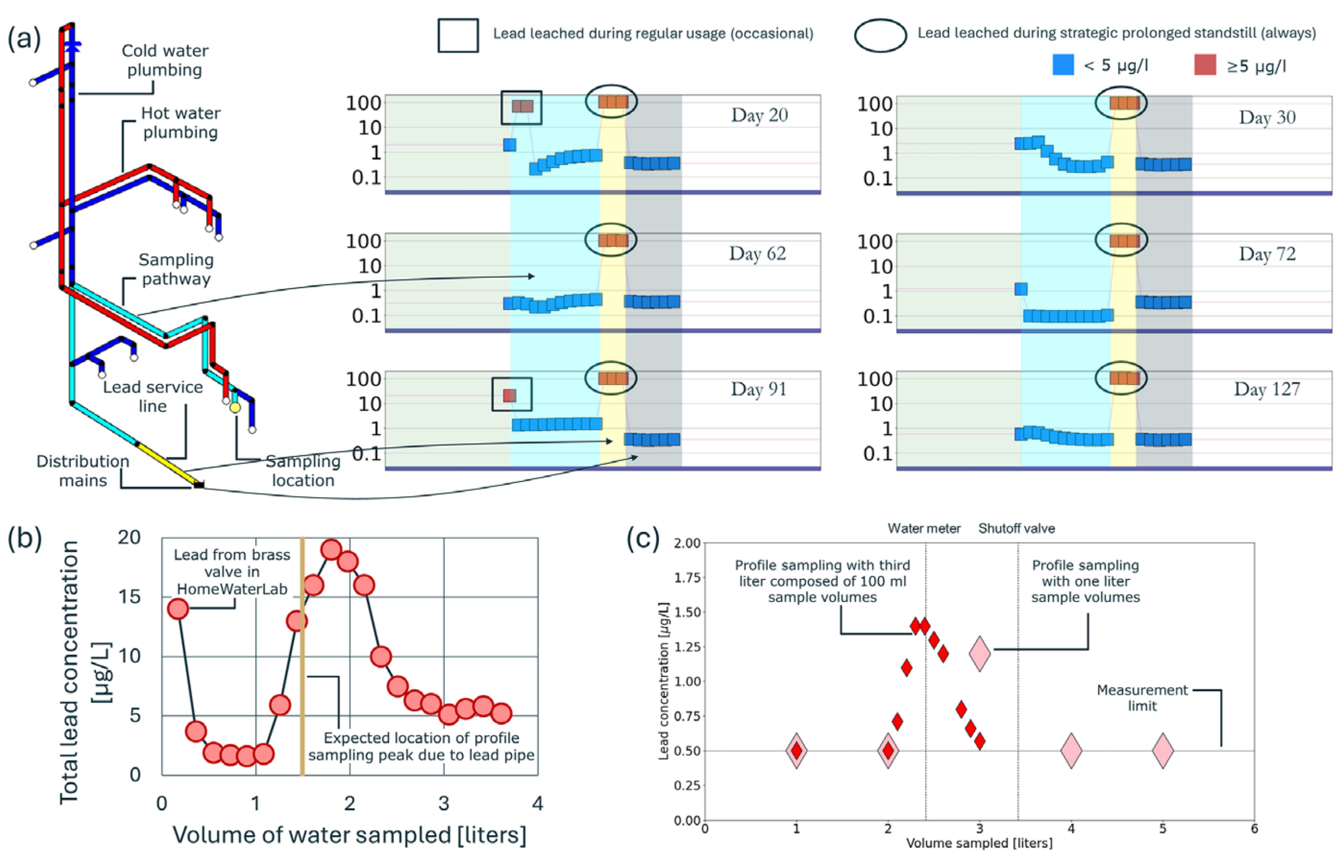


Figure 5. Robustness of profile sampling. (a) Numerical modeling. (b) Laboratory experiments. (c) field measurements.

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of the water meter. The two iterations have nearly identical areas under the profiles.

Discussion

Long-term behavior of lead leaching from brass

The lead concentrations from the 'run-time' tests are in agreement with the choices for materials made in the EUPL. The EUPL shall succeed the 4MS common approach (a consortium initiated by four EU nations including the NL). A full historical overview of norm development falls outside the scope of our work. For the interested reader, the work of Estelle (2016) offers a historical overview of the 4MS approach, including references to the norms EN 15664 and DIN 50930. The work in the European Commission and Directorate-General for Environment and Umweltbundesamt GmbH (2017) offers an overview of recommendations surrounding the update to the Drinking Water Directive in the context of materials in contact with drinking water. In the 4MS approach, both CW617 and CW724R were deemed acceptable for contact with drinking water (4MSI Common Approach, 2025). This has changed in the EUPL, where CW617 is not allowed. For metallic materials that come in contact with drinking water and leached lead, there is an additional allocation factor of 50% (see Commission Implementing Decision, 2024/3672024, Table 1, Annex V). This means that such metallic materials may not leach more than 50% of the normative lead concentration (50% of 5 μg/L = 2.5 μg/L), as illustrated in Figure 3.

A couple of consequential outcomes for drinking water utilities based on the observations are as follows:

- Increased lead leaching from brass components in the first months of usage is expected, a phenomenon that is known (Wuijts et al., 2008; Versteegh and Boshuis-Hilverdink, 2010). This requires good communication toward consumers.
- While it is commercially referred to as 'lead-free', it is known that CW724R may contain up to about 0.05% Pb by weight (see Zoghipour et al., 2024, Table 1), possibly due to recycling of brass. This suggests exercising caution while placing purchase orders.

Applying LEadGO: Lead concentrations at the tap

The simulations provide significant insights into lead exposure caused by brass components. There are two types of observations from our results: (a) absolute value of average lead concentration at the kitchen tap with respect to the norm of 5 μg/L and (b) role of location of the lead-leaching component.

The simulations presented herein are limited in range, which may raise questions on the robustness of our findings. Below, we discuss different parameters that affect observation (a).

- **Drinking water consumption:** It has been shown that reduced water consumption can lead to increased average lead concentrations, up to a factor of 3 (see Hatam et al., 2023, Figure 6). Given the lead concentration due to brass components in the service line is about 0.2 μg/L, we anticipate that variations in water consumption behavior will not lead to an exceedance of 5 μg/L.
- **Drinking water composition:** Water composition at the plumbing of the consumer may differ from that at treatment sites. For example, higher concentrations of copper in the water can affect the leaching mechanisms in brass (Maynard et al., 2008). Uncertainty in drinking water composition was modeled by increasing the equilibrium lead concentration by a factor of 11.6 (while holding the same lead dissolution timescale). This leads to an increase in average lead concentration at the tap by the same factor. Even under such an exaggerated lead dissolution behavior, the average lead concentration at the kitchen tap due to brass components in the service line remains below 5 μg/L.
- **Particulate lead:** The tabletop experiments for brass water meter suggest that particulate lead is less prevalent in brass. See Figure S.9 in the Supplementary Material. In that sense, we expect our conclusions not to be affected severely by particulate lead.
- **Temperature:** While not relevant for the service line, it is known that lead leaching from brass is exacerbated at higher water temperatures (see Sarver and Edwards, 2011, Figure 6), suggesting increased exposure via brass in hot water plumbing. While relevant from a human health perspective, the hot water plumbing falls outside the jurisdiction of a drinking water utility. This suggests that our conclusions for rehabilitation is robust for this parameter too.

The observation (b) regarding the role of lead leaching component location will stay robust to the parameters stated above. As a consequence of the simulated lead concentrations and the expected robustness of our findings, the urgency of immediate replacement of brass appurtenances in service lines is reduced. RDT measurements during regular monitoring campaigns can serve as an indicator for further investigation.

Using profile sampling to localize lead-leaching components

When RDT measurements show norm exceedance, profile sampling can serve as a useful tool. The height, breadth and location of the peak in the profile give information on the equilibrium lead concentration, volume of the lead-releasing component and location of the lead-releasing component respectively. This can additionally help identify who is responsible for replacing it while also offering an indication on the priority of urgency in which the replacement needs are to be approached. Of course, practitioners need to be aware that precise interpretation of the results in practice will be hindered (e.g., height and breadth of the peak affected due to dispersion). In 2023–2024, profile sampling was attempted by a few drinking water utilities in the NL, and several practical challenges in implementation were encountered (such as residents disturbing the stagnation or the sampler letting water flush away between two samples or not all samples being analyzed to save costs or collecting large sample volumes leading to dilution), which undermine the strength of profile sampling. To help Dutch practitioners make the most of profile sampling, a simple list of 'good practices' has been formulated (Dash et al., 2024).

Conclusions

Concise answers to the research questions are as follows:

1. **Modeling:** Using a mechanistic model which relies on integration of the underlying physicochemical processes, the interplay among these various processes are captured. While the model in the present study can certainly benefit from refinements, the current version captures enough detail to answer the questions at hand.
2. **Validation:** Carefully formulated laboratory experiments helped with the validation of the mechanistic model, LEadGO.

Lead dissolution experiments provide empirical inputs for the mechanistic model whereas composite sampling in a plumbing rig facilitate one-to-one comparison with modeling outcomes.
3. **Application:** A prudent selection of case studies allows the model to provide valuable insights on practically relevant scenarios. By being able to statistically study lead concentrations at the tap, a statement can be made on the risk posed by a certain component. Additionally, such a model serves as a test bed for sampling protocols, as shown for profile sampling.

The outcomes of the research activities have then been used to provide answers to questions relevant for the Dutch drinking water sector:

1. What policy should a drinking water utility adopt with regard to existing and future assets that may leach lead (with special focus on brass)?
   - The present research shows that it is mainly lead leached closer to the end use points (e.g., a kitchen tap) that poses a higher risk for exposure. Lead leached from brass appurtenances in service lines leads to much lower lead concentrations at the tap.
   - Thus, several utilities have decided not to pursue an accelerated rehabilitation strategy and to replace existing brass components at end of lifetime. Due to the presence of moving components, a water meter has a shorter lifetime than a shutoff valve, necessitating separate strategies.
   - For future assets, a few utilities will select brass types that appear in the EUPL. However, a few utilities have also taken the decision to step away from brass entirely and are installing composite-based water meters (as a mitigating measure for future reductions in lead norms).
   - For newly installed brass appurtenances, heightened lead leaching is expected in the first few months. Corresponding consumers are advised to flush water before consumption.
   - A drinking water utility can also communicate to consumers to be mindful with choices of plumbing materials, since these have a higher influence on exposure. Specific advice could include recommendations to flush water at brass taps especially for stagnation periods exceeding a couple of hours.
2. What should the drinking water utility do when an incidental norm exceedance is encountered?
   - As of now, the Dutch drinking water sector will continue relying on RDT measurements as the standard way of monitoring when it comes to detecting norm exceedance.
   - If RDT measurements return a lead concentration above the legal threshold (leading to an incidental norm exceedance), the profile sampling technique will be deployed.
   - Profile sampling (when deployed correctly) can help localize the lead-leaching components, as well as reveal whether the drinking water utility or the premises owner is responsible for replacing it.

Outlook

In closing, this study reflects the research-based efforts undertaken by the Dutch drinking water sector to support decision making in response to the EU-DWD. The sector has a clearer view on the way forward with respect to rehabilitation of existing assets as well as choices for future assets. Moreover, the sector is prepared for incidental norm exceedance with the help of profile sampling, a method which can help identify whether the utility or the premise owner is responsible for follow-up actions. The present study was possible thanks to the tightly knit nature of the sector. The findings and conclusions of this study can be used as a starting point by drinking water utilities of other nations, where the stricter norm for lead in drinking water is yet to be enshrined into the law.

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References

4MSI Common Approach (2025) Acceptance of metallic materials used for products in contact with drinking water; Part B – Positive list of compositions for metallic materials (23rd Version, 05 December 2025). Available at https://www.umweltbundesamt.de/system/files/medien/5620/dokumente/ca_mm_part_b_-_positive_list_of_compositions_5_dec_25_rev23.pdf.

Abokifa AA and Biswas P (2017) Modeling soluble and particulate lead release into drinking water from full and partially replaced lead service lines. *Environmental Science & Technology* **51**(6), 3318–3326. https://doi.org/10.1021/acs.est.6b04994.

Baron J, Leroy P, Wagner I, van den Hoven TJJ, Brink H, Miller S, Crosbie RA and Jackson PJ (1995) tech. rep. EC3818: The financial and economic implications of a change of the MAC for lead: Final report to the European COmmission Directorate General for Environment. CRECEP et al.

Blokker EJM, Vreeburg JHG and van Dijk JC (2010) Simulating residential water demand with a stochastic end-use model. *Journal of Water Resources Planning and Management* **136**(1), 19–26. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000002.

Burkhardt JB, Woo H, Mason J, Shang F, Triantafyllidou S, Schock MR, Lytle D and Murray R (2020) Framework for modeling lead in premise plumbing systems using EPANET. *Journal of Water Resources Planning and Management* **146**(12), 04020094. https://doi.org/10.1061/(ASCE)WR.1943-5452.0001304.

Commission Implementing Decision (2024) Commission Implementing Decision (EU) 2024/367 of 23 January 2024 laying down rules for the application of Directive (EU) 2020/2184 of the European Parliament and of the Council by establishing the European positive lists of starting substances, compositions and constituents authorised for use in the manufacture of materials or products that come into contact with water intended for human consumption. Official Journal of the European Union L. Available at https://data.europa.eu/eli/dec_impl/2024/367/oj.

Dash A, **Blokker M**, **Dignum M**, **ten Kate N and Gardien D** (2024) Profielbemonstering voor het lokaliseren van loodafgevende onderdelen: Good practices. *H2O*. Available at https://www.h2owaternetwerk.nl/vakartikelen/profielbemonstering-voor-het-lokaliseren-van-loodafgevende-onderdelengood-practices.

Dash A, **Galama-Tirtamarina A**, **Dignum M**, **ten Kate N and van der Leer R** (2024) Lood uit messing onderdelen en loodsoldeer. KWRWater Research Institute.tech. rep. BTO 2024.058

Dash A, **Hillebrand B**, **Mitrovic D and Blokker M** (2025) LEadGO - Mechanistic model for dissolution and propagation of substances through a premise plumbing system. https://doi.org/10.5281/zenodo.17434115.

Dash A, **Steen van J and Blokker M** (2022) Robustness of profile sampling in detecting dissolved lead in houshold drinking water. In *2nd International Joint Conference on Water Distribution Systems Analysis & Computing and Control in the Water Industry*. https://doi.org/10.4995/WDSA-CCWI2022.2022.14741.

Dash A, **Summeren van J and Blokker E** (2023) Beter begrip van de laatste loodjes met het HomeWaterLab. *TVVL Magazine* **5**, 5–12.

DeSantis MK, **Schock MR**, **Tully J and Bennett-Stamper C** (2020) Orthophosphate interactions with destabilized PbO2Scales. *Environmental Science & Technology* **54**(22), 14302–14311. https://doi.org/10.1021/acs.est.0c03027.

Directive 2020/2184 (2020) Directive (EU) 2020/2184 of the European Parliament and of the council of 16 December 2020 on the quality of water intended for human consumption (recast) (text with EEA relevance). *Official Journal of the European Union* **L435**(1), 1–62. Available at https://data.europa.eu/eli/dir/2020/2184/oj.

Döhla M, **Jaensch A**, **Döhla C**, **Voigt A**, **Exner M and Färber H** (2021) Blei im Trinkwasser – Ein altes problem, eine neue EU-Richtlinie. *Bundesgesundheitsblatt, Gesundheitsforschung, Gesundheitsschutz* **64**(4), 501–508. https://doi.org/10.1007/s00103-021-03292-2.

Drinkwaterbesluit (2024) Drinkwaterbesluit, Valid from 01/01/2024. Available at https://wetten.overheid.nl/BWBR0030111/2024-01-01 (accessed 30 July 2025).

Edwards M and McNeill LS (2002) Effect of phosphate inhibitors on lead release from pipes. *Journal-American Water Works Association* **94**(1), 79–90. https://doi.org/10.1002/j.1551-8833.2002.tb09383.x.

Environmental Protection Agency (2025) 40 CFR Part 141 Subpart I. Available at https://www.ecfr.gov/current/title-40/part-141/subpart-I (accessed 10 October 2025).

Estelle AA (2016) Drinking water lead regulations: Impact on the brass value chain. *Materials Science and Technology* **32**(17), 1763–1770. https://doi.org/10.1080/02670836.2016.1220906.

European Commission and Directorate-General for Environment and Umweltbundesamt GmbH (2017) Support to the implementation of the DWDirective – Study on materials in contact with drinking water – Final report. *Publications Office of the European Union*. https://doi.org/10.2779/888439.

Gartner N, **Leban MB and Kosec T** (2024) Materials matter: A case study on Slovenian internal plumbing installations and their impact on lead content in drinking water. In *CEOCOR*, Leuven, Belgium.

Hatam F, **Blokker M**, **Doré E and Prévost M** (2023) Reduction in water consumption in premise plumbing systems: Impacts on lead concentration under different water qualities. *Science of the Total Environment* **879**, 162975. https://doi.org/10.1016/j.scitotenv.2023.162975.

Hatam F, **Blokker M and Prevost M** (2025) Integrated Flushing and corrosion control measures to reduce Lead exposure in households with Lead service lines. *Water* **17**(15), 2297. https://doi.org/10.3390/w17152297.

Jarvis P and Fawell J (2021) Lead in drinking water–an ongoing public health concern? *Current Opinion in Environmental Science & Health* **20**, 100239. https://doi.org/10.1016/j.coesh.2021.100239.

Jarvis P, **Quy K**, **Macadam J**, **Edwards M and Smith M** (2018) Intake of lead (pb) from tap water of homes with leaded and low lead plumbing systems. *Science of the Total Environment* **644**, 1346–1356. https://doi.org/10.1016/j.scitotenv.2018.07.064.

Klise KA, **Hart D**, **Moriarty DM**, **Bynum ML**, **Murray R**, **Burkhardt J and Haxton T** (2017) Water network tool for resilience (WNTR) user manual.

Kuch A and Wagner I (1983) A mass transfer model to describe lead concentrations in drinking water. *Water Research* **17**(10), 1303–1307. https://doi.org/10.1016/0043-1354(83)90256-7.

Latva M, **Kaunisto T and Pelto-Huikko A** (2017) Durability of the non-dezincification resistant CuZn40Pb2 brass in Scandinavian waters. *Engineering Failure Analysis* **74**, 133–141. https://doi.org/10.1016/j.engfailanal.2017.01.011.

Lytle DA, **Formal C**, **Cahalan K**, **Muhlen C and Triantafyllidou S** (2021) The impact of sampling approach and daily water usage on lead levels measured at the tap. *Water Research* **197**, 117071. https://doi.org/10.1016/j.watres.2021.117071.

Maynard B, **Mast D and Boyd G** (2008) Kinetics of lead release from brass water meters and faucets. In *WQTC Conference Proceedings*.

Nederlands Normalisatie Instituut (2008) *NEN-EN 15664–1 Influence of Metallic Materials on Water Intended for Human Consumption - Dynamic Rig Test for Assessment of Metal Release - Part 1: Design and Operation*. Delft, The Netherlands: Nederlands Normalisatie Instituut.

Nederlands Normalisatie Instituut (2010) *NEN-EN 15664–2 Influence of Metallic Materials on Water Intended for Human Consumption - Dynamic Rig Test for Assessment of Metal Release - Part 2: Test Waters*. Delft, The Netherlands: Nederlands Normalisatie Instituut.

REWAB (2025) Registratie Waterkwaliteitsgegevens Bedrijven. Available at https://www.kwrwater.nl/tools-producten/rewab/ (accessed 5 August 2025).

Sarver E and Edwards M (2011) Effects of flow, brass location, tube materials and temperature on corrosion of brass plumbing devices. *Corrosion Science* **53**(5), 1813–1824. https://doi.org/10.1016/j.corsci.2011.01.060.

Schock MR, **Cantor AF**, **Triantafyllidou S**, **Desantis MK and Scheckel KG** (2014) Importance of pipe deposits to Lead and copper rule compliance. *Journal-American Water Works Association* **106**(7), E336–E349. https://doi.org/10.5942/jawwa.2014.106.0064.

Triantafyllidou S (2006) *Addressing and Assessing Lead Threats in Drinking Water: Non-leaded Brass, Product Testing, Particulate Lead Occurrence and Effects of the Chloride to Sulfate Mass Ratio on Corrosion*. PhD dissertation, Virginia Tech. Available at http://hdl.handle.net/10919/35097.

Triantafyllidou S, **Burkhardt J**, **Tully J**, **Cahalan K**, **DeSantis M**, **Lytle D and Schock M** (2021) Variability and sampling of lead (pb) in drinking water: Assessing potential human exposure depends on the sampling protocol. *Environment International* **146**, 106259. https://doi.org/10.1016/j.envint.2020.106259.

Triantafyllidou S, **Raetz M**, **Parks J and Edwards M** (2012) Understanding how brass ball valves passing certification testing can cause elevated lead in water when installed. *Water Research* **46**(10), 3240–3250. https://doi.org/10.1016/j.watres.2012.03.022.

van Steen J, **Vertommen I and Slaats N** (2021) Monitoren loden leidingbestand Nederland: voortgangsresultaten verwijderen loden leidingen door de Nederlandse drinkwaterbedrijven. KWR Water Research Institute.tech. rep. KWR 2021.025

Versteegh JFM and Boshuis-Hilverdink ME (2010) Communicatie over drinkwaterkwaliteit in nieuwbouwwoningen: de rol van dr drinkwaterbedrijven. Rijksinstituut voor Volksgezondheid en Milieu (RIVM). tech. rep.

Wuijts S, **Slaats PGG**, **Versteegh JFM and Meerkerk MA** (2008) Drinkwaterkwaliteit in nieuwbouwwoningen. Rijksinstituut voor Volksgezondheid en Milieu (RIVM). tech. rep.

Zoghipour N, **Tascioglu E and Kaynak Y** (2024) Machinability of extruded and multi-directionally hot forged eco-friendly brass alloys. *Canadian Metallurgical Quarterly* **63**(2), 414–425. https://doi.org/10.1080/00084433.2023.2214980.