Computational modelling techniques in the optimization of corrosion control for reducing lead in Canadian drinking water


ABSTRACT

Compliance modelling has been used to good effect in the optimization of plumbosolvency control in the UK and was evaluated in the Canadian and US contexts via three case studies. In relation to regulatory compliance, supplementary orthophosphate dosing could be justified in one water supply system but not in one other. Compliance modelling indicated that Health Canada’s Tier 1 protocol is much less stringent than its Tier 2 protocol and that optimization based on 6+ hour stagnation samples vs 15 μg/l is likely to be more stringent than that based on 30 min stagnation samples vs 10 μg/l. The modelling of sequential sampling for an individual home indicated that sample results could be markedly affected by the length of the lead service line, by the length of the copper premise pipe and by pipe diameters. The results for sequential sampling were also dependent on flow characteristics (plug vs laminar). For either regulatory compliance assessment or for the optimization of plumbosolvency control measures, routine sequential sampling from the same houses at a normalized flow will minimize these variable effects.

Key words | corrosion control, lead in drinking water, modelling, optimization, sampling

INTRODUCTION

The publication of the World Health Organization’s Booklet on Childhood Lead Poisoning (WHO 2010) has heightened concerns about lead ingestion and its potential impact on health, particularly reductions in IQ. It followed the withdrawal, earlier in 2010, of the guideline value for a tolerable lead intake by the Joint FAO/WHO Committee on Food Additives (WHO 2011) and their conclusion that there is no safe level for lead ingestion by children. More recently, the US CDC has revised its action level for lead in blood from 10 μg/dl down to 5 μg/dl (CDC 2012). These increased health concerns put renewed pressure on regulators to minimize lead in drinking water within their areas of jurisdiction and on water utilities to optimize their corrosion control systems for lead control.

However, there are a range of potential problems to be overcome in optimizing corrosion control for reducing lead in drinking water (IWA 2010, 2012):

(i) there is no simple, rapid control loop for linking corrosion control treatment to reductions in the concentrations of lead in drinking water at consumers’ faucets;
(ii) the definition of the term ‘optimization’ is vague and tends to rely too heavily on regulatory compliance (which may not be the same as treatment process control);
(iii) regulatory compliance systems are prone to distortion as a consequence of the sampling protocols used and variability due to a range of influencing factors.
These problems in optimizing corrosion control for reducing lead in drinking water have largely been overcome in the UK over the past 10 years and the experience gained should be a useful reference point for Canadian utilities and regulators, including the use of computational modelling techniques that were used to good effect by many UK water companies. This paper outlines what was achieved in the UK and summarizes the results of a recent collaborative research project that aimed to demonstrate the potential uses of computational modelling in the Canadian and US contexts; it also summarizes the results of an investigation into the behavioural characteristics of sequential sampling.

CANADIAN GUIDELINES FOR LEAD IN DRINKING WATER

The Canadian guideline (Health Canada 1992, 2010) for lead in drinking water, as a maximum acceptable concentration (MAC), has been 10 μg/l since 1992, based on flushed samples, until recently. As a consequence of flushing prior to sampling, the samples could neither determine the extent of lead in drinking water problems within a water supply system nor provide any basis for optimizing corrosion control. The guideline for lead was, in essence, revised in August 2012 (Health Canada 2012); while the MAC of 10 μg/l remains the same, reference is no longer made to flushing prior to sampling; instead, reference is made to applying the MAC as an average concentration over extended periods. Recognizing the practical limitations of the earlier guideline, Health Canada issued ‘Guidance on Controlling Corrosion in Drinking Water Distribution Systems’ (Health Canada 2009), which recommended two options for assessing lead in domestic drinking water:

(i) first draw samples after 6+ hours’ stagnation (at least 50% of the homes sampled must have a lead service line), based on the US Lead Copper Rule (US EPA 1991), with further sequential samples in some circumstances; or

(ii) if sampling after a 6+ hour stagnation time is not practical or is restricted by regulatory obligations, sequential samples after 30 min stagnation from properties with lead service lines.

The option of sampling after 6+ hours’ stagnation involves Tier 1 and Tier 2 sampling. Tier 1 surveys relate to the first litre drawn from the faucet after the stagnation period; if the Action Level of 15 μg/l is exceeded at more than 10% of the homes sampled then corrective action is required as well as supplementary Tier 2 sequential sampling of the following second, third and fourth litres. The prompting of corrective action on the basis of Tier 1 sampling is flawed because most first litre samples will contain water that has stood in non-lead pipework adjacent to the faucet, not the lead service line, and in consequence problems with lead in drinking water will be greatly underestimated (IWA 2010). While Tier 2 samples will more likely contain water that has stood in a lead service line, this is not certain and will vary depending on the volume of non-lead pipework. Distortion of the results from Tier 1 and Tier 2 sampling will also vary due to changes in the sampling pool, due to the proportion of homes sampled that have a lead service line, if Tier 1 and Tier 2 sampling is done at different times, and as a consequence of any deviations from the sampling protocol by home-owners (IWA 2010). The use of these sampling and assessment protocols in the optimization of corrosion control must be questioned.

The second option involves taking four sequential samples (each of 1 l volume) after 5 min flushing and 30 min stagnation, from properties with lead service lines. Corrective action is required if the average result from the four samples exceeds 10 μg/l at more than 10% of the homes surveyed. This option is also prone to variable distortion from water stood in non-lead pipework as well as variation from changes in the sampling pool; further, the averaging of results is questionable. Health Canada (2009) does not recommend this option for optimizing corrosion control due to uncertainties about sensitivity and behavioural characteristics.

To complicate matters, some provinces have their own standards for lead in drinking water. For example, Ontario has a standard of 10 μg/l based on the highest lead concentration from two sequential samples (each of 1 l volume) taken after flushing then 30 to 35 min stagnation. Corrective action is required if the standard is exceeded at more than 10% of the homes surveyed. The Ontario standard is no less susceptible to variable distortion effects. Overall, it
can be concluded that there is considerable scope to develop the guidelines further, with the aim of providing a stronger basis for quantifying lead in drinking water problems and for optimizing corrosion control.

**OPTIMIZING CORROSION CONTROL FOR REDUCING LEAD IN DRINKING WATER**

A generic definition of the term ‘optimization’ as it relates to the control of lead in drinking water has been proposed in the International Water Association’s Code of Practice for the Internal Corrosion Control of Water Supply Systems (IWA 2012):

‘The application of best available techniques, not entailing excessive cost, to reduce lead concentrations in drinking water to the minimum that is practical to achieve.’

This definition implies a holistic approach that is robust scientifically, that incorporates risk assessment and that matches mitigation measures specifically to the circumstances of the water supply system. It is consistent with Health Canada’s guidance (2009) that delivered water should ‘not be aggressive’ to distribution systems, including domestic pipework. The definition in the Code of Practice is also consistent with the approach taken in the UK.

In England and Wales, optimization was defined as the ‘best practical reduction in lead concentrations’ (DWI 2000, 2001) and was taken to mean ‘maintaining an optimum orthophosphate dose throughout a water supply system, within an optimum pH range’. If pH and alkalinity control were proposed as the only treatment measures, water companies had to demonstrate that an optimum dose of orthophosphate could not achieve a further significant reduction in lead concentrations (in practice, none did so). Water companies were also expected to take into account any organic or iron discoloration interference effects. In essence, the Drinking Water Inspectorate (DWI) implemented an optimization framework, recognizing that the precise definition of an optimum orthophosphate dose was necessarily vague, at least initially. It was stated (DWI 2000, 2001) that the optimum dose of orthophosphate could be determined from laboratory tests, from full scale or pilot scale trials, by practical experience, from solubility or computational models, if an increase in orthophosphate dose produced no further worthwhile improvement or if a sufficient number of random daytime (RDT) samples had been taken and less than 2% of samples exceeded 10 μg/l. This numeric criterion was adopted by most water companies as their target for optimization.

The DWI followed up the progress being made by water companies with technical audits. Optimization schemes were subject to legally binding agreements and once concluded were reported formally. Arrangements in Northern Ireland and Scotland were broadly similar. Across the UK, 95% of public water supply systems are now dosed with orthophosphate. The concentration of orthophosphate that is dosed varies from 0.5 to 2.0 mg/l (as P), most typically between 1.0 and 1.5 mg/l (as P) and is water supply system specific, as determined by both water quality and the extent of occurrence of houses with lead pipes. For England and Wales in 2009/10, following the optimization of plumbosolvency control treatment, 99.0% of RDT samples complied with the new standard of 10 μg/l for lead in drinking water (that applies from December 2013), compared to 80.4% before orthophosphate dosing became widespread. In some regions, 99.5% compliance has already been achieved intermittently and could be considered as a national target. If optimized plumbosolvency control was reinforced by selective lead pipe replacement (DWI 2010), it might even be possible to achieve 99.8% compliance without the widespread replacement of lead pipes (Hayes & Hydes 2012).

The optimization of plumbosolvency control in the UK was mostly achieved in one of two ways:

(i) step changes in orthophosphate dose until optimum reductions in lead had been demonstrated by in situ lead pipes at consumers’ houses; however, in situ lead pipes can take up to 2 or 3 years to equilibrate with a new orthophosphate dose (IWA 2010) and dose responses may not have been fully established within the timescales that were available (pipe rigs using old exhumed lead pipes will be similarly affected); or

(ii) laboratory plumbosolvency testing coupled with compliance modelling to quickly determine the likely optimum dose, which was then confirmed (and adjusted if necessary) by routine monitoring of in situ lead pipes at consumers’ houses; this approach minimized the
number of iterative changes to water treatment conditions and saved both time and money.

In most water companies, RDT sampling was the principal means used for demonstrating the success of the plumbosolvency control measures, supplemented variously by fixed point monitoring (typically, 30 min stagnation sampling) at selected houses and the use of lead pipe test rigs.

The success of the second approach (Hayes et al. 2006, 2008) was the motivation for the ‘proof-of-concept’ project to demonstrate the feasibility of an amended modelling system being used in the optimization of plumbosolvency control in Canadian and US drinking water supply systems.

COMPLIANCE MODELLING TECHNIQUES

Describing plumbosolvency

The schematic diagram given in Figure 1 illustrates (top right) how the plumbosolvency of drinking water can be described by curves of the concentration of lead that increases over time when the water stands (stagnates) within a lead pipe. Curves A1 and A2 describe waters with a higher plumbosolvency than curves B and C and the shape of the curves can vary (A1, A2). These simple exponential curves are defined by the initial mass transfer rate of lead $M$ ($\mu g/m^2/s$) from the internal lead pipe surface (which determines the initial slope) and the equilibrium concentration of lead $E$ ($\mu g/l$). Such curves are an adequate representation of the lead dissolution curves generated by Kuch and Wagner’s diffusion model (1985) and offer computational advantage (much quicker computer run-times). The values of $M$ and $E$ can be determined experimentally by laboratory plumbosolvency testing using the method developed by Colling et al. (1987). This involves pumping test water continually through short sections of new lead pipe at a constant 25 °C and a constant contact time of 30 min for a period of around one month; at the end of this period the test water is allowed to stand for 16 hours before sampling. The concentration of lead after 30 min contact enables the value of $M$ to be determined from the numerical relationship determined by Hayes (2002).

Laboratory plumbosolvency testing

Figure 1 | Compliance modelling schematic.
In Figure 1 (top left) are the actual results, as median concentrations, from plumbosolvency testing for two test waters at 30 min contact. The test series in these cases both show the effect of increasing orthophosphate over a zero to 1.5 (mg/l P) range. Alternatively, a sequence of pH values could be investigated by the test procedure. Such data generate curves of different magnitude (top right) depending on the treatment condition and its associated extent of lead reduction. M and E can also be estimated from sequential sampling after 30 min and 6+ hour stagnation (respectively) at homes with a lead service line.

**Single pipe model**

The single pipe model consists of a lead pipe, non-lead pipe and an imaginary faucet that is represented by a 1 l sample volume. The pipes are broken down into elements (as illustrated in Figure 1 – middle right) and when assuming plug flow each element is treated as a stirred tank. During periods of flow, the contents of one stirred tank are passed to the next, and so on, at a time increment of 1 s. The concentrations of lead that are computed at the imaginary faucet for every second of flow are determined by: (a) the length and diameter of the lead and non-lead pipes, (b) the contact time of the water, as determined by the assumed pattern of water use, and (c) the plumbosolvency of the water. The assumption of plug flow is another simplification and describes adequately the turbulent flow that is most likely in the small-bore pipes in premise plumbing (commonly ½ and ¾ inch) at the flow rates expected in normal domestic use (around 0.1 l per second, or 1.6 US gallons per minute). Laminar flow can also be investigated but is computationally much slower. The mathematical equations used for both flow types are given in Van der Leer et al. (2002).

**Using a probabilistic framework for zonal modelling**

To investigate lead emissions across an entire water supply system, a probabilistic framework is established by creating a large number (normally 10,000) of simulated homes that make up the simulated system, as defined by lead and non-lead pipe and water use characteristics. The variables that define each simulated home derive from a series of statistical distributions, applied randomly, as illustrated in Figure 1 (bottom left). These distributions can be based on generally applied assumptions or on survey data provided by the water utility. Normally, the plumbosolvency characteristics are applied as a constant, but it is possible to apply a range if water quality (e.g., pH) was known to vary significantly. The single pipe model then generates the lead emission profile at each simulated home for a 24-hour period. The daily average lead concentration at each simulated home can be readily calculated.

**Sampling models**

A sampling model can then be used to investigate lead emissions across the water supply system, in terms of probability, based on a range of sampling protocols. These include: (a) random daytime samples, (b) 30 min stagnation samples (first litre drawn and sequential), and (c) 6 hour stagnation samples (first litre drawn and sequential). In the case of stagnation sampling methods, the lead concentration in the simulated pipes is assumed to be zero immediately prior to the stagnation period.

It is therefore possible to investigate the link between the plumbosolvency of the water in the system and probable compliance with regulatory sampling protocols. Simulated samples are taken randomly from the probabilistic framework, typically 100 samples in a simulated survey, repeated 1,000 times so as to gain an appreciation of variance. Mapping on to regulatory sampling protocols also involves setting the percentage of the homes that must have a lead pipe in the sampling simulations (e.g., 50% for the US Lead Copper Rule (LCR), 100% for the Canadian 30 min stagnation (30MS) sampling protocol).

**Limitations, simplifications and validation**

The deterministic models described above relate only to the dissolution of lead from lead pipes and no allowance is made for lead leaching from brass or for galvanic corrosion or particulate lead effects, although it is possible to include a correction factor for lead from premise plumbing if data are available to characterize this. Simplifications are made in the way that plumbosolvency and flow are defined and the calibration matrix can be limited to the application of generalized assumptions (such as non-lead pipe lengths) when detailed survey data are not available.
Despite these limitations and simplifications, excellent validation of predicted RDT sampling results was obtained in numerous case studies in the UK (Hayes et al. 2006, 2008) by comparison with the results of actual RDT sampling by the water companies. As a case example, data are shown in Figure 2 for pre- and post-orthophosphate dosing conditions in Cambridge (UK); systems before orthophosphate dosing commenced are numbered 1 to 6; the system numbered 7 was after orthophosphate dosing in the aggregate of the city’s four major systems. In this case example, comprehensive pipe surveys, knowledge of water use and plumbosolvency testing enabled the compliance model to be calibrated without using generalized assumptions.

In Wales (Hayes et al. 2008), orthophosphate dosing was optimized by a combination of laboratory plumbosolvency testing and compliance modelling for 29 systems that were subject to a Regulatory Programme of Work (as agreed with the Drinking Water Inspectorate). Of these 29, plumbosolvency testing data were not available for six schemes and the compliance model had to be fitted to the observed data that were available, although the benefit of orthophosphate dosing could still be predicted. Generalized assumptions had to made for pipe lengths and water use for all systems. Despite these limitations, the predicted RDT sampling results, for the pre-orthophosphate condition, were closely matched by the water company’s sampling for the 23 systems in which primary validation was possible.

The optimum orthophosphate doses that were determined were subsequently applied on a system-specific basis. The results of this optimized orthophosphate dosing were confirmed over a 2 year period by a combination of RDT sampling and the 30 min stagnation sampling of lead pipe test rigs. This approach successfully delivered 99% compliance with the future UK lead standard of 10 μg/l.

It can be concluded from the successful validation achieved in these two major case studies that the simplifications inherent in the modelling procedure do not hinder its use in operational terms. The main difference between the UK and US/CA case studies are the sampling protocols used for assessing regulatory compliance.

CANADIAN AND US CASE STUDIES

Three case studies (two US, one Canada) involved the use of modelling techniques in various ways and the results are presented below in a Canadian context. Further details of this modelling are available from the project report (Hayes & Croft 2012).

Case study 1 (US)

The water supply system serves a population of around 300,000 people and 35% of the customer connections are lead service lines, including the privately owned side. In order to control plumbosolvency, it has been long-standing practice to elevate pH in order to suppress lead solubility. The pH within the system at the present time is typically between 9.5 and 10.0. Corrosion inhibitors such as orthophosphate are not used. The system was marginally non-compliant with the criteria for lead set by the US LCR in seven out of nine surveys over the period 2007 to 2011.

In calibrating the zonal compliance model, very comprehensive data were available on the length and diameter of service lines but very little on premise plumbing. The plumbosolvency factors $M$ (0.047) and $E$ (70) were estimated by inspection of the results from LCR surveys and from nine sequential sampling exercises, as data from laboratory plumbosolvency testing were not available. The assumptions about non-lead premise plumbing were initially based on those used in UK case studies, with subsequent amendment. Additionally, a correction factor was used for
lead emissions from non-lead premise plumbing; the need for this was identified from the detailed inspection of LCR survey results from premises with copper service lines. The simulated and observed LCR survey results are shown in Table 1 and indicate a good match based on the first litre sampled after stagnation, equivalent to Tier 1 sampling in Canada.

The potential benefits of orthophosphate dosing were then investigated, using the compliance model, by reducing the values of $M$ and $E$ that define plumbosolvency. As these values were reduced, an equivalent reduction factor was applied to the premise plumbing correction. The results for three orthophosphate dosing scenarios are shown in Table 2 for four sequential litre samples and are compared to the present non-orthophosphate dosed condition. Only data for the first litre were available from the LCR compliance monitoring, in order to calibrate the model (Table 1); the predictions for the second, third and fourth litres are more speculative, but do show a significant difference between the first litre and the litres that follow. If the utility had sampled beyond the first litre, it is possible that the calibration of the compliance model may have been adjusted.

The orthophosphate dosing scenario (A) defined by $M = 0.02$ and $E = 30$ is typical of many optimized systems in the UK and should be achievable with a relatively low orthophosphate dose. It was predicted that LCR compliance would be achieved, based on the first litre drawn after stagnation (Tier 1), but not if compliance was based on further sequential samples (Tier 2). This is also the case when $M = 0.015$ and $E = 22.5$. To achieve Tier 2 compliance would require $M = 0.01$ and $E = 15$, likely to be at the extreme range of orthophosphate’s ability to suppress lead solvency. These predicted results indicate that optimization based on Tier 1 sampling would be different to that based on Tier 2 sampling, if judged by the same action level of 15 μg/l. Laboratory plumbosolvency testing would be necessary to confirm the orthophosphate dosing response of the water and to determine the orthophosphate doses associated with each scenario.

**Case study 2 (CA)**

The water supply system serves a population of around 800,000 and 14% of customer connections are believed to have lead service lines. In order to control the plumbosolvency of the water supplies to consumers, it has been the utility’s long-standing practice to elevate pH in order to suppress lead solubility. The treated water has a pH of 9.2 to 9.4 and this has been successful in meeting regulatory compliance with Provincial standards, which are based on sequential sampling after 30MS. Corrosion inhibitors, such as orthophosphate, have not been used.

Detailed information on the lengths of lead service lines was not available. Instead, reference was made to information from another Canadian city (Cartier et al. 2011) with minor adjustments to help fit predicted 30MS survey results to those observed. For lead service line diameters, a consensus view from supply network engineers was used. No data were available for premise plumbing other than estimates of the pipe materials involved: >90% copper, 2% galvanized iron, 8% plastic. Again, reference was made to information from the other Canadian city with minor adjustments. Estimates of $E$ (31) and $M$ (0.026) were made in a similar manner to the first case study and fine-tuned by

### Table 1 | Matching the model to observed LCR results^a^

<table>
<thead>
<tr>
<th>Average 90th percentile concentration and range (μg/l)</th>
<th>Average percentage of samples exceeding 15 μg/l and range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted: 20.5 (6.3–37.8)</td>
<td>Predicted: 14.6 (4.0–27.0)</td>
</tr>
<tr>
<td>Observed: 20.1 (13.6–30.0)</td>
<td>Observed: 16.2 (8.0–29.4)</td>
</tr>
</tbody>
</table>

^aPredicted results based on simulated first litre samples after 6 hours’ stagnation, equivalent to Tier 1 sampling in Canada; 56.3% of the simulated houses had a lead service line, consistent with the utility’s LCR surveys.

### Table 2 | Predicted LCR compliance for orthophosphate dosing scenarios: average 90th percentile concentrations from Tier 1 and Tier 2 sampling^a^

<table>
<thead>
<tr>
<th>Modelling scenario</th>
<th>Average 90th percentile concentrations (μg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st Litre Tier 1</td>
</tr>
<tr>
<td>--------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>M</td>
<td>0.047</td>
</tr>
<tr>
<td>E</td>
<td>70.0</td>
</tr>
<tr>
<td>Without o-PO₄</td>
<td></td>
</tr>
<tr>
<td>o-PO₄ – (A)</td>
<td>0.015</td>
</tr>
<tr>
<td>o-PO₄ – (B)</td>
<td>0.015</td>
</tr>
<tr>
<td>o-PO₄ – (C)</td>
<td>0.010</td>
</tr>
</tbody>
</table>

^aPredicted average 90th percentiles from 1,000 simulated samples, each of 100 simulated samples after 6 hours’ stagnation, using the plug flow model; $M$ – initial mass transfer rate (μg/m²/s); $E$ – equilibrium concentration (μg/l); 56.3% of the simulated houses had a lead service line.
A correction for lead release from premise plumbing was not considered necessary as the utility had indicated that in their experience, lead was very rarely detected at homes that did not have a lead service line. The match between simulated and observed 30MS survey results is shown in Table 3, based on the first four litres sampled after flushing and stagnation.

The slight reductions in $M$ to 0.020 and $E$ to 30, the conditions typical for optimized orthophosphate dosing in the UK, resulted in a very substantial change in compliance (Table 3). This is because 30MS values of 10 $\mu$g/l cannot be exceeded by the lead dissolution curve generated by the model using these values for $M$ and $E$. It can be concluded that the case for supplementary orthophosphate dosing is weak, assuming that the estimates of $M$ (0.026) and $E$ (31) are correct (or close) for this water supply system.

Simulated results for sequential sampling after 6 hours’ stagnation are shown in Table 4 (US LCR basis) and Table 5 (Canadian Tier 1 and 2 basis) for surveys in which 50% of simulated houses had a lead service line, in order to investigate the protocol specified by Health Canada (2009) guidelines. With $M = 0.026$ and $E = 31$, compliance was predicted to be achieved with Health Canada’s guidelines for Tier 1 sampling but not for Tier 2 sampling, the difference being the effect of water stood in non-lead pipework. Similar results were obtained for $M = 0.020$ and $E = 50$. A reduction to $M = 0.010$ and $E$ of 15 would be required for Tier 2 compliance, likely to be at the limit of what plumbosolvency control treatment can achieve.

It appears that compliance with Health Canada’s guidelines (2009) is less stringent if based on 30 min stagnation samples than for 6 hours’ stagnation, much closer than expected. For any given sequential sampling, the ratio between lead concentrations after 30 min stagnation, much closer than the lead concentrations after 6 hours’ stagnation, are expected to be fairly similar.

Further work will be required to reconcile the model with the utility’s limited survey results.

### Case study 3 (US) and the modelling of sequential sampling

The emphasis of this case study was the sequential sampling of homes after 6 + hours’ water stagnation to investigate the behavioural characteristics of the sampling protocol used by the US LCR. It is also relevant to Tier 1 and 2 assessments in Health Canada’s guidelines. Sequential sampling survey data were provided from two surveys by the US Environmental Protection Agency. After flushing for 5 min and at least 6 hours’ stagnation, 12 or more 1 l samples were taken in sequence from each site. The lead concentrations that were observed varied from 2 to 37 $\mu$g/l and all first litre

<table>
<thead>
<tr>
<th>Predicted with $M = 0.026$ and $E = 31$ (range in brackets)</th>
<th>1st Litre</th>
<th>2nd Litre</th>
<th>3rd Litre</th>
<th>4th Litre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed over 8 surveys from 2008 to 2011 (range in brackets)</td>
<td>0.21 (0.00–3.00)</td>
<td>1.92 (0.00–7.00)</td>
<td>7.79 (1.00–18.00)</td>
<td>15.23 (4.00–25.00)</td>
</tr>
<tr>
<td>Predicted with $M = 0.020$ and $E = 30$ (range in brackets)</td>
<td>1.33 (0.00–2.56)</td>
<td>2.36 (0.00–5.98)</td>
<td>8.55 (2.42–16.24)</td>
<td>11.95 (1.92–26.50)</td>
</tr>
</tbody>
</table>

*Predicted average percentages from 1,000 simulated surveys, each of 100 simulated samples; in the modelling, 95% of simulated houses were assumed to have a lead service line, reflecting the utility’s 100% objective and their indication that a few of the earlier survey samples were taken from homes without a lead service line.*

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**Table 3** | Simulated and observed 30MS survey results

Average % 30MS samples $>10 \mu$g/l

<table>
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<tr>
<th>Predicted with $M = 0.026$ and $E = 31$ (range in brackets)</th>
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*Predicted average percentages from 1,000 simulated surveys, each of 100 simulated samples; in the modelling, 95% of simulated houses were assumed to have a lead service line, reflecting the utility’s 100% objective and their indication that a few of the earlier survey samples were taken from homes without a lead service line.*
samples had a lead concentration below the Action Level of 15 µg/l. Significantly, over 90% of houses had a premise plumbing volume greater than 1 l, helping to explain the observed compliance with LCR criteria. However, in the June 2011 survey, 13 out of the 28 sites exceeded 15 µg/l in at least one sequential sample and in the September to October 2011 survey, 16 out of the 29 sites exceeded 15 µg/l in at least one sequential sample. At some sites, elevated lead concentrations were observed for greater parts of the 12-sample sequence (up to twice) than could be explained by the volume of the lead service line, implying laminar flow influences during sampling. Similar observations have been made in Rhode Island (RIH 2011).

The single pipe model was used (after validation) to investigate the lead emission characteristics of different pipework circumstances at a single home, comprising a simulated lead pipe (service line) and a simulated copper pipe (premise plumbing) of various lengths and diameters, for both plug and laminar flow conditions. The detailed results are reported in Hayes & Croft (2012) and are summarized below.

(i) Length of lead pipe:
- for plug flow: the longer the lead pipe, the greater were the number of sequential samples with an elevated lead concentration;
- for laminar flow: lead concentrations were lower generally than for plug flow, the elevation of lead was spread over a greater number of samples, and the longer the lead pipe, the higher was the peak lead concentration in the sample sequence.

(ii) Length of copper pipe:
- for plug flow: the longer the copper pipe, the later was the elevated lead in the sample sequence;
- for laminar flow: lead concentrations were lower generally than for plug flow, the elevation of lead was spread over a greater number of samples, and the longer the copper pipe, the lower was the peak lead concentration in the sample sequence.

(iii) Pipe diameter:
- for plug flow: the larger the diameters, the more extensive was the sequence of lead concentrations associated with the lead pipe and the lower was the concentration of peak lead in the sample sequence;
- for laminar flow: lead concentrations were lower generally than for plug flow, the elevation of lead was spread over a greater number of samples, and the larger the diameter of the lead pipe, the lower was the peak lead concentration in the sample sequence.

### Table 4 | Predicted LCR compliance

<table>
<thead>
<tr>
<th>Plombosolvency</th>
<th>Average 90th percentile concentrations (µg/l) after 6 hours’ stagnation</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>1st Litre</td>
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<td>M</td>
<td>E</td>
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<td>15</td>
</tr>
</tbody>
</table>

*a*In Canada, corrective action is required if more than 10% of sites exceed 15 µg/l; the modelling assumed that 50% of simulated houses had a lead service line.

### Table 5 | Predicted Tier 1 and 2 compliance

<table>
<thead>
<tr>
<th>Plombosolvency</th>
<th>Average percentage samples &gt; 15 µg/l after 6 hours’ stagnation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st Litre</td>
</tr>
<tr>
<td>M</td>
<td>E</td>
</tr>
<tr>
<td>0.026</td>
<td>31</td>
</tr>
<tr>
<td>0.020</td>
<td>30</td>
</tr>
<tr>
<td>0.010</td>
<td>15</td>
</tr>
</tbody>
</table>

*a*In Canada, corrective action is required if more than 10% of sites exceed 15 µg/l; the modelling assumed that 50% of simulated houses had a lead service line.
This modelling suggests that sequential sampling results can be markedly affected by the length of lead service pipe, by the length of copper premise pipe and by pipe diameters. In consequence, it appears that sequential sampling may be too subject to variable influences to be used in definitive terms, for either regulatory compliance assessment or for the optimization of plumbosolvency control measures, if sampling is undertaken from different sets of houses from within a changing sampling pool.

Sequential sampling can be used for diagnostic purposes, but differentiating specific sources of lead within the premise plumbing may be affected by skewing and lowering effects. While sequential sampling appears to have limitations, it will provide a much better insight into lead emission characteristics than the sampling protocols that only utilize the first litre drawn after the stagnation period.

DISCUSSION

The extent of calibration data in these Canadian and US case studies was limited. The plumbosolvency of the water could only be estimated as test data were not available and data on premise plumbing were mostly absent. It would, however, be relatively easy to strengthen the calibration of the compliance model by laboratory plumbosolvency testing (quick and affordable) and by fuller pipework inspections when homes are sampled for compliance assessment purposes. For the modelling approach to gain broader acceptance, it would be beneficial to conduct case studies in cities which are already using orthophosphate or are contemplating its use. That said, there is no reason why the modelling approach cannot be applied to systems that control internal corrosion through pH elevation alone or to systems that use other corrosion inhibitors.

The compliance modelling was undertaken assuming plug flow, similar to earlier UK studies, and is considered reasonable on the basis that most premise plumbing is \( \frac{1}{2} \) or \( \frac{3}{4} \) inch diameter and the flow rates are likely be around 0.1 l per second (1.6 US gallons per minute) in home use. However, the results of actual sequential sampling in the city relating to case study 3 (and elsewhere) have often been found to be skewed, whereby the lead concentrations in these sequential samples can only be explained by laminar flow effects (Rhode Island Department of Health 2011; Hayes & Croft 2012). These results prompted a modelling investigation using the single pipe model and both plug flow and laminar flow for a range of pipework characteristics. The results have been summarized in case study 3 (above) and reported in detail by Hayes & Croft (2012) and show significant differences between the two flow regimes. Presently, it is difficult to know to what extent laminar flow occurs under normal home use and under what flow and pipework conditions; further research is planned that will endeavour to describe the behaviour of transitional flow regimes in the context of sequential sampling for lead in drinking water.

The new interpretation of the Canadian guideline for lead in drinking water, that the MAC of 10 \( \mu \text{g/l} \) should be applied as an average over extended periods (Health Canada 2012) creates new and interesting challenges, namely how to determine the average concentration of lead at a home. The most accurate sampling method will be split-flow composite sampling (Van den Hoven et al. 1999) but this has logistic limitations. Although outside the scope of the case studies reported here, the single pipe model can readily predict daily average lead concentrations and the compliance model can predict RDT sample results in support of zonal risk assessment.

CONCLUSIONS

1. Compliance modelling has been demonstrated to have a potential role in the optimization of plumbosolvency control, in the Canadian and US contexts, and to provide a deeper appreciation of the behavioural characteristics of related sampling protocols.
2. A rapid, low cost approach to optimization could comprise laboratory plumbosolvency testing, the gathering of basic information about the water supply system and compliance modelling, prior to confirmatory monitoring. Such an approach has already been used widely in the UK to good effect and can be accommodated for use in Canada and the USA by an amended compliance model that is able to simulate the relevant sampling protocols.
3. In this context, compliance modelling can help to quantify what is meant by ‘best practical reductions in lead in drinking water’ for a water supply system, by exploring
more deeply the relationship between corrosion control treatment and regulatory compliance.

4. The case studies indicated that Health Canada’s Tier 1 protocol is much less stringent than its Tier 2 protocol (if benchmarked against the same action level) and that optimization based on 6+ hour stagnation samples vs 15 μg/l is likely to be more stringent than that based on 30 min stagnation samples vs 10 μg/l.

5. In relation to regulatory compliance, the case studies indicated that supplementary orthophosphate dosing might be justified in one water supply system but not in one other.

6. Compliance modelling can assist the evaluation of sampling and assessment protocols in the further development of regulatory criteria, by examining far more scenarios than it is feasible to do experimentally.

7. The modelling of sequential sampling for an individual home indicated that sample results could be markedly affected by the length of the lead service line, by the length of the copper premise pipe and by pipe diameters. The results for sequential sampling were also dependent on flow characteristics (plug vs laminar).

8. In consequence, it appears that sequential sampling may be too subject to variable influences to be used in definitive terms, for either regulatory compliance assessment or for the optimization of plumbosolvency control measures, if sampling is undertaken from different sets of houses from within a changing sampling pool.

9. While sequential sampling appears to have limitations, it will provide a much better insight into lead emission characteristics than the sampling protocols that only utilize the first litre drawn after the stagnation period.

10. Sequential sampling under a normalized flow condition could be used in the routine benchmarking of lead concentrations at selected properties, as part of an optimization procedure for plumbosolvency control measures.

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