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An evaluation of sampling methods and supporting techniques for tackling lead in drinking water in Alberta Province

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ABSTRACT

A demonstration project evaluated a range of sampling methods and supporting techniques for tackling lead in drinking water in Alberta Province, with the cities of Calgary and Edmonton as case studies. The sampling protocols specified by Health Canada in their 2009 guidance were confirmed to need further improvement and clarification; these sampling protocols produce results that are subject to variable influences and do not provide a sufficiently clear basis for identifying corrosion control needs nor for demonstrating the success or otherwise of mitigation measures. Instead, it was concluded that a risk assessment and risk management approach would be better suited to tackling the lead in drinking water problem in Canadian cities and townships. This can be applied in a more pragmatic manner that reflects the circumstances of individual water supply systems, using drinking water safety plans as the foundation.

Key words | drinking water safety plans, lead in drinking water, plumbosolvency, risk assessment, sampling

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INTRODUCTION

A collaborative project commenced in August 2013 with the aim of demonstrating a range of techniques that can be used in tackling the problems of lead in drinking water. The motivation was to investigate further the concerns that the sampling methods specified by Health Canada's (2009) guidelines did not reliably provide a basis for determining if corrective action was needed and had limited applicability to the optimisation of corrosion control; these concerns had emerged in an earlier set of case studies (Hayes *et al.* 2013, 2014) that had involved both the assessment of monitoring data and computational modelling. In Canada, many of the major cities have an issue with lead in drinking water and there is a great deal of variation across the country on how the issue is managed, including sampling protocols. This is because drinking water is not regulated at the federal level in Canada and because Health Canada's (2009) guidelines are for guidance only. The approach presented in this paper for Edmonton and Calgary is unique in Canada but has potential application elsewhere.

The main project for Alberta was completed in March 2014, with supplementary sampling exercises in mid-2014. It involved the cities of Calgary and Edmonton and the following:

- a diagnostic assessment of the relevant operational and water quality data that were available;
- laboratory testing to determine the plumbosolvency of the water supplies and their responses to orthophosphate dosing;
- sequential sampling (12 × 1 litres) at six homes in each city, after 30 minutes of stagnation and after 6 or more hours of stagnation;
- mineralogical and elemental analysis of scales on exhumed lead pipes from some of these homes;

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- computational modelling of lead emissions from the homes that were sequentially sampled, to investigate the wide range in results that were obtained;
- compliance modelling to assess the behavioural characteristics of the sampling protocols specified in Health Canada's (2009) guidelines on corrosion control, and to investigate corrosion control options;
- the prediction, by computational modelling, of the likely results from random daytime (RDT) sampling, to evaluate alternatives to stagnation-based sampling procedures;
- the prediction, by computational modelling, of daily average lead concentrations at homes with a lead service line;
- economic and environmental assessments.

DIAGNOSTIC ASSESSMENTS

For each city, the 'source to tap' relationship was examined, including:

- the type of water resources and extent of treatment;
- the population served, number of service connections and number of lead service lines;
- the current practices for controlling lead in drinking water;
- lead survey data for the past 5 years;
- general water quality assessment, including disinfection regime;
- available information on relevant investigations.

Whilst the major drivers that determine plumbosolvency are temperature, pH and alkalinity, natural organic matter (NOM) in the water can increase lead dissolution (Colling *et al.* 1992; Cardew 2009) and needed to be considered. Loose iron corrosion deposits can aggravate lead release and the extent of occurrence of 'red water' discolouration also needed to be considered (Hulsmann 1991). Deposited iron and manganese can also aggravate lead release (Schock *et al.* 2014). Whereas lead can arise from brass components and galvanic corrosion in some circumstances, the principal source was considered to be lead service lines (IWA 2010, 2012). For both cities, lead survey data were available from several sampling methods.

For Calgary, surface water is abstracted from the Bow River and the Elbow River for the provision of water supplies to 1.2 million people. The City of Calgary's waterworks system consists of the Bearspaw and Glenmore Water Treatment Plants (WTPs), treated water storage reservoirs and a water distribution system serving the city of Calgary and adjacent communities. The Bow River supplies the Bearspaw WTP and the Elbow River flows into the Glenmore Reservoir, which is the source of water for the Glenmore WTP. Physico-chemical treatment includes coagulation, settlement, filtration and chlorination. The Bearspaw plant primarily supplies water to the north sector of the city, while the Glenmore plant supplies the south. However, the water supply from the two plants is interconnected through large diameter transmission mains. In 2012, only 861 out of over 308,000 service connections were known to be lead (0.28%) on the public side. The typical water quality in the Calgary system was pH 7.7, alkalinity 120 mg/L ($CaCO_3$), chloride 4 mg/L, sulphate 50 mg/L, nitrate <1 mg/L, iron <50 μg/L and total organic carbon (TOC) 0.9 mg/L. Corrosion control has been by pH management to minimise iron problems and corrosion inhibitors are not used. The results of surveys for lead over the period 2009–2012 are summarised in Table 1. It can be seen that the survey results were highly variable. There were no changes in water treatment or general water quality over the period 2009–2012.

EPCOR operates two water treatment plants in the city of Edmonton and provides drinking water to approximately 1.2 million residents in the city and surrounding region. The source of the water is the North Saskatchewan River and both plants operate conventional treatment facilities (alum

Table 1 | Summary of lead survey results for Calgary

Year	Number of 6+HS samples[a]	% 6+HS samples > 15 μg/L	Number of 4 L 30MS samples[b]	% 4 L 30MS samples > 10 μg/L
2009	80	11.3	54	3.7
2010	84	7.1	59	15.3
2011	46	4.3	28	14.3
2012	56	12.5	45	22.2

[a]On average, about 70% of the homes sampled had a lead service line. The results are from the first draw 1 L samples taken after at least 6 hours' standing (6+HS). The 'trigger' for corrective action is if >10% samples exceed 15 μg/L.
[b]Only homes with a lead service line are included. The results are the average from 4 × 1 L samples taken sequentially after 30 minutes' stagnation (30MS). The 'trigger' for corrective action is if >10% samples exceed 10 μg/L.

coagulation, flocculation, settling, chlorine addition, dual-media filtration, UV disinfection, ammonia addition and pH adjustment) which can also be run in direct filtration mode (alum coagulation, free chlorination, dual media filtration, UV, ammonia addition for chloramine formation, NaOH for pH adjustment) when turbidity is low (winter). In 2012 there were 250,540 active service connections of which 3,833 (1.53%) were lead service lines in July 2013, on the public side. Many of these will have lead service lines on the private side. Additionally, EPCOR has identified an estimated further 600 private lead service lines where the public part is non-lead.

The typical water quality in the system was pH 7.8, alkalinity 120 mg/L ($CaCO_3$), chloride 4 mg/L, sulphate 50 mg/L, nitrate <1 mg/L, iron 60 μg/L and TOC 1.9 mg/L. Corrosion control has been by pH management to minimise iron problems and corrosion inhibitors are not used. The results of surveys for lead over the period 2008–2012 are summarised in Table 2. It can again be seen that the survey results were highly variable. There were no changes in water treatment or general water quality over the period 2008–2012.

In Edmonton, additional first draw 1 L samples were taken after overnight standing at staff houses across the city. The pipe-work was not deliberately flushed prior to the standing period. Following this sampling, the pipe-work was flushed for 5 minutes and a flushed 1 L sample was then also taken. The staff houses were sampled throughout the year (approximately 50 samples each year). None of the houses had a lead service line, except possibly one house sampled in 2008. Lead was normally observed at concentrations below or close to the limit of detection of 1 μg/l. At least in these homes, there was no evidence of significant lead contamination arising from premise plumbing, since the one occurrence of elevated lead in 2008. This is an important observation in the context of possible lead leaching from brass and galvanic corrosion effects, which can therefore be considered as insignificant in Edmonton.

Table 2 | Summary of lead survey results for Edmonton

Year	Number of 4 L 30MS samples[a]	% 4 L 30MS samples > 10 μg/L
2008	2,583	31.1
2009	1,251	29.8
2010	88	21.6
2011	27	63.0
2012	30	86.7

[a]The homes sampled were believed to have a lead service line but there were some uncertainties, particularly in 2008. In 2009 EPCOR implemented examination of the service line material in the home. The results are the average from 2 × 2 L samples taken sequentially after 30 minutes' stagnation. The 'trigger' for corrective action is if >10% samples exceed 10 μg/L.

PLUMBOSOLVENCY ASSESSMENTS

Laboratory plumbosolvency testing

Testing was undertaken on samples from the two water treatment plants that supply Calgary and the two that supply Edmonton. In all cases the samples were taken of the final (disinfected) treated water at the treatment works just prior to entry into distribution. For Edmonton, 250 L of test water were taken from E L Smith WTP and 250 L of test water were taken from Rossdale WTP. For Calgary, 150 L of test water were taken from Glenmore WTP and 100 L of test water were taken from Bearspaw WTP. Food-grade white plastic containers were used (12.5 L volume). The sample containers were shrink-wrapped on pallets and air-freighted to the UK for testing. Samples were received within 4 days of sampling, in good condition.

The testing method has been used extensively in the UK and was based on the work of Colling *et al.* (1987). It involves pumping approximately 50 L of sample water through duplicate (in parallel) 15 cm lengths of new 12 mm internal diameter lead piping, at a flow rate (approximately 0.5 mL/min) to provide 30 minutes of contact (30MC) between the test water and the piping. Each section of lead piping, sealed with rubber bungs, is immersed in a water bath and maintained at a constant 25 °C for a test period of typically 20 days. During the test period, the flow through each section of lead piping is checked three times a week, at the same time that test water pH is checked and when a small sample of the test water leaving the lead pipe section is taken for total lead analysis. At these times, pH adjustments are made if necessary using small additions of acid or alkali. At the end of the test period, the test water was allowed to stagnate for 16 hours within the lead pipe section, prior to a further sample being obtained for lead analysis. The results are summarised in Table 3 from which it was concluded that:

- the treated waters from each water treatment plant had a moderate plumbosolvency, reflecting the general good quality of these waters;
- the orthophosphate dose responses were consistent with those often determined in the UK for waters with a moderately high alkalinity;
- an optimum orthophosphate dose of around 1 mg/L (P) was apparent, consistent with UK experience. In this context, optimum is defined as the point when higher doses achieve minimal further reductions in lead.

Sequential profile sampling

Five homes with a lead service line and one without were sampled in Calgary and six homes with a lead service line were sampled in Edmonton. Sequential samples (12×1 L) were taken after both 30 minutes of stagnation (30MS) and after 6 or more hours of stagnation (6 + HS). The aim was to investigate the extent and pattern of lead emissions associated with the pipe-work configurations of each home. The results shown in Table 4 indicated considerable variation, even when the masses of lead over the 12 L sequence were normalised by reference to the internal surface area of the lead service lines. It can also be noted that: (i) not all of the observed peaks tallied with the volumes of the non-lead and lead pipes; (ii) one home had a new water meter fitted in May 2013, yet lead emissions were intermediate in the series and any recent disturbance of lead corrosion deposits did not result in atypically high lead emissions; (iii) the masses of lead in the 12 samples, when normalised to internal surface area of lead, were generally only 1.5 times higher after 6 + HS compared to 30MS, much lower than expected. Single pipe modelling could only partly explain the wide variation in lead concentrations that was observed.

Mineralogical scale analysis

Lead service lines were exhumed after sampling at the three homes in Calgary that are asterisked (*) in Table 4 and sent to the US EPA laboratory in Cincinnati for mineralogical analysis using a combination of optical, X-ray, and elemental analysis techniques. A further lead service line sample was obtained in Edmonton, but the home was not sequentially sampled. The results of the power X-ray diffraction (XRD)

Table 3 | Summary of laboratory plumbosolvency test results[a]

Water treatment plant	Orthophosphate addition (mg/L as P)	Median 30MC Pb (μg/L) 1st	2nd	Average median 30MC Pb (μg/L)	Average 16-hour stagnation Pb (μg/L)
E L Smith	0.0	38	38	38	180
	0.5	19.5	18	18.8	24
	1.0	26	9	17.5	23.5
	1.5	5.5	6	5.8	15.5
	2.0	5.5	4	4.7	11.5
Rossdale	0.0	34.5	32.5	33.5	185
	0.5	11	9.5	10.2	25
	1.0	7.5	5	6.2	14
	1.5	4	6.5	5.2	12
	2.0	4.5	5	4.7	11.5
Glenmore	0.0	45.5	43.5	44.5	155
	1.0	7	8.5	7.7	20.5
	1.5	7	7.5	7.2	21.5
Bearspaw	0.0	69	40	54.5	232
	1.0	9	7	8	17

The median 30MC lead concentrations for each test channel (1st and 2nd) from which the reproducibility of testing was confirmed (30MC) and the average of the two test channels. pH was maintained at 7.8 (±0.2) in all test channels.

Table 4 | Summarised results from sequential sampling

Home ref.	30MS Peak Pb (μg/L)	6HS Peak Pb (μg/L)	Peak exhibited	Volume Pb pipe (L)	Volume non-Pb pipe (L)	30MS Mass Pb in 12 L (μg)	30MS Mass Pb in 12 L (μg/m^2)	6HS Mass Pb in 12 L (μg)	6HS Mass Pb in 12 L (μg/m^2)
Calgary									
A-122	24.7	48.2	L4-7	4.0	2.1	189	175	289	269
B-1619*	30.6	58.0	L4-6	2.6	2.9	173	253	258	377
C-420	31.8	62.7	L6-8	3.4	2.2	215	236	292	319
D-811*	14.9	19.7	L1-6	3.6	1.6	123	128	187	195
E-1218*	23.8	46.9	L3-5	3.4	0.3	119	132	153	170
F-401	1.3	3.0	L1-5	0.0	5.9	9.5	N/A	19.5	N/A
Edmonton									
A-6648	39.1	96.5	L2-6	2.8	1.4	262	321	521	638
B-17864	39.6	82.4	L2-10	6.9	1.4	364	238	618	404
C-16679	15.8	37.0	L2-9	6.9	0.9	150	97	261	169
D-9342	9.7	21.7	L2-5	8.6	2.2	107	56	143	75
E-18343	5.7	9.1	No peak	7.3	1.7	58	31	89	47
F-5990	13.9	22.4	L2-6	5.3	0.6	134	114	184	156

*Lead service lines were exhumed after sampling and sent to the US EPA laboratory in Cincinnati for mineralogical analysis using a combination of optical, X-ray, and elemental analysis techniques.

analysis of the internal pipe corrosion deposits showed that neither the Calgary nor Edmonton pipe scales were significantly composed of crystalline solid lead phases. When crystalline phases are present, XRD can differentiate between the more soluble Pb(II) compounds and the less soluble Pb(IV) compounds. No trace of Pb(IV) compounds was found by these techniques, even though the Calgary system operates with a free chlorine residual (median concentration 0.8 mg/L). Unexpectedly, the XRD analysis revealed that the thick deposits were primarily composed of amorphous material, representing more of a barrier film from deposition, than *in situ* generation from pipe corrosion. X-ray fluorescence revealed that the scale layers were unusually rich in Al, Si, Ca, and Fe (Table 5). Lead concentrations varied from about 5–10% at the water contact surfaces, to 70–80% at depth, arranged in a layered structure that did not adhere strongly to the pipe surface. Some crystalline lead phases were disseminated within the layers, and in the sample from Edmonton, the Si appeared to primarily be present as very fine quartz particles, for which their origin is unknown. The solubility of the solid material within the water interaction zone in the scale appeared to yield lead release in the profiling sampling slightly lower than would be typically expected from pure lead solids at the same background chemistry. The 6-hour stagnation lead release for Calgary followed the percentage of lead, iron and manganese in the surface layer. The scale sample from Edmonton did not have a profile associated with it, but the overall observations of lead release in the profiling indicate a slightly higher plumbosolvency potential than in Calgary. This could be related to the apparent physical difference in the scale mineralogy, which appeared to consist of more porous material that could allow more water penetration and diffusion to the stagnant and flowing water from comparatively lead-rich and carbonate-poor under-layers.

COMPLIANCE MODELLING

Deterministic modelling tools were developed in the UK and used successfully in the optimisation of orthophosphate dosing in numerous water supply systems (Hayes *et al.* 2006, 2008). A single pipe model can investigate lead dissolution at an individual home and was used to investigate the results of sequential sampling and to predict daily average lead concentrations as a function of pipe-work circumstances. The

Table 5 | Elemental compositions of pipe scales

		Weight (%)							
Sample ID	**Layer**	**C**	**Mg**	**Al**	**Si**	**Ca**	**Mn**	**Fe**	**Pb**
E-1218	L1	3.10	0.42	18.43	10.28	2.02	0.59	2.86	10.42
	L2	2.98	0.13	5.95	3.12	0.76	0.07	1.55	77.41
D-811	L1	3.09	0.29	18.99	9.46	1.78	0.41	2.18	8.06
	L2	2.92	0.09	4.52	2.21	0.48	0.01	0.35	80.55
B-1619	L1	3.06	0.16	11.78	5.19	1.61	2.40	7.03	51.19
	L2	2.99	–	3.77	1.50	0.42	0.18	0.60	82.57
	L3	0.37	–	0.06	0.05	–	–	0.05	74.45
Edmonton sample	L1	2.00	0.74	20.50	13.50	2.15	0.02	1.85	4.60
	L2	1.52	2.06	17.61	14.11	2.44	0.08	1.59	6.90
	L3	2.45	2.02	16.05	14.53	3.50	0.18	2.45	32.09
	L4	0.30	0.11	0.38	0.36	0.07	–	0.07	69.68

single pipe model can also be used within a probability framework that endeavours to mimic the very numerous permutations of pipe-work circumstances that occur across a city. The probability framework for each city was built up from available data or assumptions about lead pipe lengths and diameters, non-lead pipe lengths and diameters, and water consumptions. Details can be found in the Project Report that is available from the website of the Government of Alberta (WQM Associates Ltd 2014). An important input to these models is the quantification of plumbosolvency, achieved by specifying the initial mass transfer rate of lead (M μg/m^2/s) and its equilibrium concentration (E μg/l). M and E were determined from the laboratory plumbosolvency testing, for the waters sampled and for a range of orthophosphate dose conditions. A sampling model can then be used to predict the results of different sampling protocols. It is therefore possible to examine the relationship between a water's plumbosolvency and compliance with regulatory guidelines. The following sampling protocols were examined:

- Sequential 30MS sampling (4 × 1 L and average of the 4 L).
- Sequential 30MS sampling (12 × 1 L).
- Sequential 6 + HS sampling (12 × 1 L).
- First draw 1 L sampling after 6 + HS (i.e. Tier 1 from Health Canada's (2009) guidelines).
- Sequential 2nd, 3rd and 4th litre sampling after 6 + HS (i.e. Tier 2 from Health Canada's (2009) guidelines).
- RDT sampling.

Additionally, as the models calculate lead emissions from pipe-work for every second of simulated flow, it is possible to predict the daily average lead concentration for any pipe-work circumstance.

The compliance modelling results are summarised in Tables 6 and 7 for Calgary for 30MS sampling. The five simulations are compared to the average sampling results obtained by the city. Each simulation comprised 10 surveys each of 100 samples. It was concluded that: (i) the 4 L average results predicted by the model closely matched the calculated 4 L average results from the city – on this basis the calibration of the model was satisfactory; (ii) however, the predicted and observed profile for each of the 4 L differed individually; (iii) the simulations were adequately reproducible.

Table 6 | Comparing simulated to observed results: 90th percentile concentrations (μg/L) for 30MS sampling from Calgary

		L1	**L2**	**L3**	**L4**	**4L composite sample**
Observed (4 years)	Average (range)	9.2 (8.4–12.0)	9.7 (7.7–11.8)	10.5 (8.7–12.8)	13.1 (10.4–14.5)	**10.6* (8.1–13.4)**
Simulated (5 simulations)	Average (range)	1.4 (1.3–1.6)	11.9 (11.6–12.4)	15.3 (15.2–15.5)	14.9 (14.7–15.2)	**10.2 (10.0–10.3)**

*Calculated as an average of L1, L2, L3 and L4.

Table 7 | Comparing simulated to observed results: percentage exceeding 10 μg/L for 30MS sampling from Calgary

		L1	L2	L3	L4	4 L composite sample
Observed (4 years)	Average (range)	8.9 (3.7–17.8)	10.1 (3.7–17.8)	13.5 (5.6–22.2)	20.0 (11.1–25.4)	13.9* (3.7–22.2)
Simulated (5 simulations)	Average (range)	0.0 (0.0–0.0)	17.1 (15.5–17.8)	48.3 (47.2–49.1)	53.4 (52.2–54.9)	12.1 (11.1–13.0)

*Calculated as an average of L1, L2, L3 and L4.

The compliance model was then run for 6HS sampling. The predicted 90th percentile concentration of 14.7 μg/L compared well to the 14.3 μg/L average (range 11.2–17.4 μg/L) observed by the city of Calgary, thereby validating the calibration of the model.

For Edmonton, the predicted percentage of the average of 4 L 30MS samples exceeding 10 μg/L was 30.8 compared to the averaged observed percentage of 31.1. The calibration was similar to Calgary except for different values of M and E and a minor adjustment was made for assumed secondary lead contributions from premise plumbing.

For both Calgary and Edmonton (Table 8), Health Canada's Tier 1 compliance criteria (relating to first draw 1-L sampling after 6+ hours of standing) were found to be much less stringent than their Tier 2 compliance criteria (relating to second, third and fourth draw 1-L samples after 6+ hours of standing), consistent with an earlier case study (Hayes *et al.* 2014) and more stringent than compliance criteria based on 30MS. The compliance model also predicted the following:

- Compliance with 10 μg/L at homes with a lead service line based on predicted daily average lead concentrations: for Calgary, 14.6% homes were predicted to exceed 10 μg/L for the summer condition with 7.8% for the annual average condition; for Edmonton, 17.6% homes were predicted to exceed 10 μg/L for the summer condition with 5.6% for the annual average condition.
- Compliance with 10 μg/L at homes with a lead service line based on RDT samples: for Calgary, 26.6% homes were predicted to exceed 10 μg/L for the summer condition with 18.7% for the annual average condition; for Edmonton, 26.7% homes were predicted to exceed 10 μg/L for the summer condition with 17.6% for the annual average condition.
- Compliance with 10 μg/L at homes with or without a lead service line based on RDT samples: for Calgary, 0.2% homes were predicted to exceed 10 μg/L for the summer condition; for Edmonton, 0.5% homes were predicted to exceed 10 μg/L for the summer condition. This much lower non-compliance is explained by the very low percentage of homes with a lead service line in both cities.

The compliance model was also used to predict 70 and 80% reductions in plumbosolvency with reference to summer conditions to investigate orthophosphate dosing. This range in plumbosolvency reduction could be expected

Table 8 | Predicted average results of orthophosphate dosing

	Tier 1 6 + HS 50% LSLs % >15 μg/L	Tier 2* 6 + HS 50% LSLs % >15 μg/L	4-L average 30MS 100% LSLs % >10 μg/L	RDT samples 100% LSLs % >10 μg/L	DAC 100% LSLs % >10 μg/L
Calgary					
Summer	11.8	57.8/67.6/61.2	12.1	26.6	14.6
70% reduction	0.3	37.0/38.2/16.1	0.0	1.6	0.9
80% reduction	0.0	13.8/14.2/4.2	0.0	0.2	0.2
Edmonton					
Summer	15.5	43.2/48.5/48.5	30.8	26.7	17.4
70% reduction	4.6	27.1/38.4/29.0	3.8	1.1	0.0
80% reduction	0.0	14.1/23.1/13.4	0.0	0.3	0.0

*Percentages shown for 2nd, 3rd and 4th litre samples.

from an orthophosphate dose of 1 mg/L (as P), based on UK experience (Hayes *et al.* 2006, 2008). The results are shown in Table 8 for different compliance protocols, which are broadly comparable except for the Tier 2 compliance protocol. The predicted average results were derived from 10 simulated surveys, each with 100 simulated samples.

EVALUATION OF RDT SAMPLING

During the summer of 2014, RDT sampling was evaluated in both Calgary and Edmonton. The results are compared to modelling predictions in Table 9 and were broadly comparable, providing some further limited validation of the modelling.

Figures 1 and 2 show how the individual RDT results compared to 4 L average 30MS results in Calgary and Edmonton, respectively. The strong correlations obtained suggest that RDT sampling could be used as an alternative to the more laborious 30MS sampling technique.

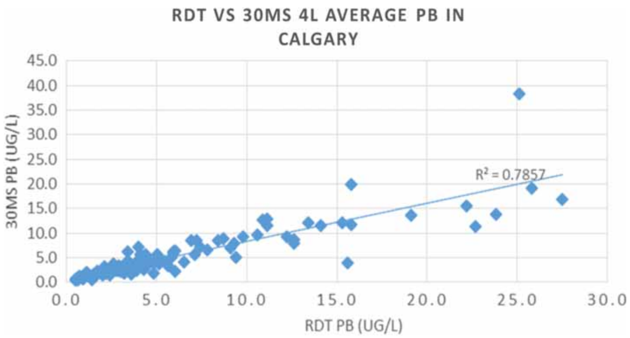

Figure 1 | A comparison of RDT samples with 30MS 4 L averages in Calgary from homes with a lead service line.

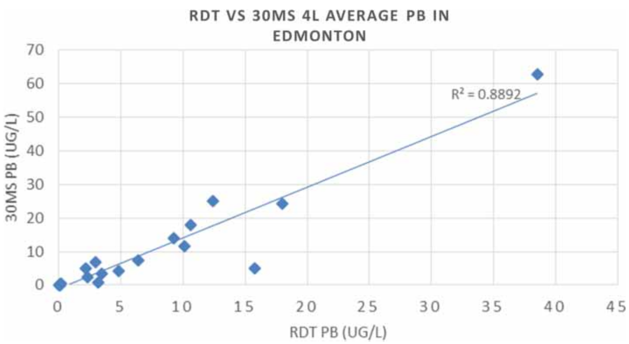

Figure 2 | A comparison of RDT samples with 30MS 4 L averages in Edmonton from homes with a lead service line.

ECONOMIC AND ENVIRONMENTAL ASSESSMENTS

Total lead service line replacement, based on $15,000 per home (data from EPCOR), would cost about $10 million in Calgary. As an alternative, orthophosphate dosing plants would cost at least $1 million and $0.3 million per year in operating costs, assuming 160 MLD (average consumption) and 0.5 c/m^3. Treating full plant capacity of 550 MLD would cost about $1.7 million per year. It was concluded that the current policy of service line replacement was the most cost effective strategy. Environmental impact was considered negligible and only to relate to short-term localised disturbance.

Total lead service line replacement would cost about $70 million in Edmonton, whereas orthophosphate dosing would cost just over $0.2 million per annum, based on the average consumption of 129 MLD. It was concluded that orthophosphate dosing was cost-competitive as well as conferring broader corrosion control benefits. An assessment of the nutrient removal capacity of the city's waste water treatment plant indicated that the small additional phosphorus loading (just over 10%) would have little impact on final effluent quality, and therefore minimal environmental impact.

Table 9 | RDT sampling from homes with a lead service line

City	% RDT > 10 µg/l predicted	% RDT > 10 µg/L observed
Calgary	26.6	15.3
Edmonton	26.7	35.7

DISCUSSION

This and an earlier project (Hayes *et al.* 2013, 2014) have clearly demonstrated that the sampling protocols specified by Health Canada, in their 2009 guidance, do not reliably determine if corrosion control treatment for lead is warranted. Nor do they provide any reliable means for optimising lead corrosion control treatment. The fundamental problem is the variability of the sampling results, as demonstrated in this study by inspection of monitoring data and by computational modelling. Surveys based on these protocols are variably distorted by premise plumbing and variably influenced in several other ways. Related problems have been identified (IWA 2010, 2012; Hayes *et al.* 2013) in the behavioural characteristics of the sampling protocol specified by the US Lead and Copper Rule, which is under revision. The World Health Organization acknowledged the limitations of 'end-of-pipe' sampling in the assurance of safe drinking water as long ago as 2004 and proposed a supplementary and complementary approach based on risk assessment and risk management, referred to as drinking water safety plans (DWSPs). There is very strong justification for tackling lead in drinking water problems within a DWSP framework, which now exists in

Table 10 | Risk assessment and mitigation strategies for minimising lead

Category 1: No lead service lines	Category 2: Few lead service lines	Category 3: Many lead service lines	Category 4: Elevated blood lead >5 μg/dL
Diagnostic assessment: 1. General water quality 2. Inventory of service lines	**Diagnostic assessment:** 1. General water quality 2. Inventory of service lines	**Diagnostic assessment:** 1. General water quality 2. Inventory of service lines	**Diagnostic assessment:** 1. General water quality 2. Inventory of service line and plumbing
Plumbosolvency assessment: Not necessary	**Plumbosolvency assessment:** 1. Sequential sampling after 30MS – 6 homes with a LSL 2. Laboratory testing to quantify plumbosolvency	**Plumbosolvency assessment:** 1. Sequential sampling after 30MS – 6 homes with a LSL 2. Laboratory testing to quantify plumbosolvency and to determine orthophosphate dose responses under different pH conditions 3. Computational modelling to investigate relationship between corrosion control treatment and compliance with lead standards	**Plumbosolvency assessment:** Split-flow composite sampling over 1 week to determine average Pb concentration at the home
Background metals check: RDT sampling survey over 1–3 years	**Background metals check:** RDT sampling survey over 1–3 years	**Background metals check:** RDT sampling survey over 1 year	**Background metals check:** Test for range of metals
Optimise corrosion control: Only if necessary	**Optimise corrosion control:** Only if necessary	**Optimise corrosion control:** 1. Dose orthophosphate at optimum dose at appropriate pH 2. Optimise NOM removal 3. Minimise iron discolouration	**Optimise corrosion control:** If corrosion control is practised, review its optimisation
Review: Every 1–3 yrs	**Review:** Every 1–3 yrs	**Review:** Annually	**Review:** Check adequacy of risk assessment
Mitigation: Only if necessary	**Mitigation:** Accelerate total LSL removal	**Mitigation:** 1. Maintain optimised corrosion control treatment 2. Promote total LSL removal in the longer term	**Mitigation:** Total LSL removal if present
Performance monitoring: Only if necessary	**Performance monitoring:** Sequential sampling after 30MS – 6 homes above after LSL removed	**Performance monitoring:** Monthly or quarterly sequential sampling after 30MS at selected homes before and after treatment changes	**Performance monitoring:** Repeat split-flow composite sampling after mitigation

Alberta Province for the 630 water supply utilities that are regulated by either approval or code of practice.

There is further uncertainty concerning the interpretation of Health Canada's guideline for lead in drinking water. A maximum acceptable concentration (MAC) of 10 μg/l was specified from 1992 and qualified as relating to samples after extensive flushing. This qualification rendered the MAC meaningless. In August 2012, the Federal-Provincial-Territorial Committee re-issued Guidelines for Canadian Drinking Water Quality – Summary Table. In Table 2 'Chemical and Physical Parameters' the MAC for lead is shown as 10 μg/l with the following comment: 'Because the MAC is based on chronic effects, it is intended to apply to average concentrations in water consumed for extended periods.' This comment implies an intention to implement the guideline in a similar manner to the current European Drinking Water Directive (European Union 1998) which qualified the numeric value of 10 μg/L as applying to the weekly average concentration ingested. This qualification was incorporated into European standards for lead in drinking water (25 μg/L from 2003 and 10 μg/L from 2013) and caused considerable problems because the Member States failed to agree how samples should be taken to assess compliance. In consequence, these European standards have either not been implemented or implemented wrongly in many countries (Hayes & Skubala 2009). With these problems in mind, it can be strongly recommended that Health Canada's guideline for lead in drinking water of 10 μg/L should be implemented as a MAC *without qualification*. The significant advantages would be as follows: (i) a guideline for lead in drinking water of 10 μg/L *without qualification* would set an unequivocal limit as a MAC; (b) it would put in place a level of health protection that all stake-holders could relate to and work towards; (c) it would provide a clearer and more practicable basis for corrective action by water utilities; (d) it would provide a clearer basis for risk assessment as part of the utilities' DWSPs; and (e) it would provide a clearer basis for policy development.

A pragmatic strategy for approaches that tackle lead in drinking water problems within a framework of risk assessment and risk management is outlined in Table 10, based on four scenarios. Selection of Category 2 as opposed to Category 3 should be based on an economic assessment. In a water supply system with very few lead service lines, the logical solution will be the removal of the lead service lines as opposed to corrosion control treatment (Category 2). In a water supply system with a larger number of lead service lines, the most logical solution will be to install corrosion control treatment, at least in the short term (Category 3). This categorisation (2 or 3) will depend on local circumstances. Category 4 for elevated blood lead relates to children. In each scenario, sampling is fit-for-purpose because it relates to specific circumstances; these span background metals checks, diagnostic assessments, performance monitoring and exposure assessments. There are several advantages: (i) lead in drinking water problems will be tackled properly, providing better health protection for Canadian children; (ii) monitoring burdens and costs will be reduced; (c) the more sophisticated methods will only be used when needed.

CONCLUSIONS

- The Alberta Demonstration Project succeeded in evaluating a range of sampling methods and supporting techniques that can be used in tackling lead in drinking water problems.
- There is a need to clarify the guideline value for lead in drinking water; the numeric value of 10 μg/L should be adopted as a MAC without qualification, consistent with the latest guidelines from the World Health Organization (2011).
- The sampling protocols specified in Health Canada's (2009) guidance do not provide a reliable basis for identifying the need for corrosion control nor for its optimisation.
- Instead, a pragmatic approach based on risk assessment and risk management is proposed, compatible with the DWSPs advocated by the World Health Organization since 2004.
- RDT sampling from homes with a lead service line can be considered as a performance monitoring tool.

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DISCLAIMER

This document has been reviewed in accordance with US Environmental Protection Agency (EPA) policy and approved for external publication. The views expressed in this article are those of the authors and do not necessarily represent the views or policies of EPA.

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