An investigation into the representativeness of random daytime sampling for lead in drinking water, using computational modelling

C. R. Hayes and T. N. Croft

ABSTRACT

Random daytime (RDT) sampling for lead in drinking water has been used in the UK since 1989 for regulatory compliance assessment and since 2004 in the Netherlands. In 2008, RDT sampling was recommended to the European Commission as the method to be used throughout the European Union but there are concerns about the representativeness of this method, being of relevance to the protection of human health in water supply systems. This issue has been investigated using an established computational modelling system, from which it was concluded that: (i) RDT sampling as practised in the UK is adequately representative of the range of circumstances that occur; (ii) for houses with daytime residency, RDT sampling is not sensitive to the time period of sampling, unless it is constrained to only a few hours; (iii) for houses without daytime residency, RDT sampling of houses elsewhere with daytime residency is adequately representative, for the total periods of water use; (iv) for houses without daytime residency, random sampling just before or after 'normal office hours' will not be representative for checking zonal compliance; (v) it is important that seasonal variation is accommodated; and (vi) adequate reproducibility can be achieved if at least 100 samples are taken annually and if results are aggregated for several years.

Key words | drinking water, lead, modelling, plumbosolvency, random daytime sampling, regulation

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INTRODUCTION

Lead contamination of drinking water arises mainly from the old lead pipes that are still used to connect houses to a water supply system (IWA 2010). In Europe, up to 25% of houses could be affected (Hayes & Skubala 2009) and laboratory testing (Hayes 2008) indicates that all drinking water types can dissolve lead from lead pipes to concentrations that exceed the World Health Organization Guideline Value of 10 μg/L, unless specifically treated to minimise their plumbosolvency characteristics. However, due to sampling inadequacies, the problems with lead in drinking water have been greatly under-estimated in Europe (Hayes 2010). These inadequacies include: (i) no sampling at all (because of the absence of a harmonised monitoring method); (ii) samples being taken from the distribution network (where there are normally no lead pipes); and (iii) samples being taken from consumer points of use (taps) after pipe-work has been flushed. The issue is further complicated as different sampling methods have been used (Hayes & Skubala 2009), spanning random daytime (RDT) sampling, stagnation sampling after 30 minutes or overnight standing, and sampling after full flushing, each method giving different results.

The consequence of these sampling inadequacies is that public health protection in Europe has been undermined (Hayes & Hoekstra 2010), bearing in mind that many health effects have been linked to both acute and chronic lead poisoning (Hayes & Skubala 2009). The severity of health effects, particularly concerns about IQ reduction in children, has recently been confirmed by the World Health Organization (WHO 2010). At the zonal scale

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(i.e. at the level of a water supply system) a sampling method is required that can: (i) identify if zone-wide corrective action is warranted; and (ii) demonstrate the success or otherwise of the zone-wide corrective actions taken. In the UK, RDT sampling has been considered generally successful in meeting these requirements (IWA 2010).

RDT sampling is undertaken in the UK during 'normal office hours' although the allowable time period for daytime sampling has not been prescribed by the UK Government. As practised in the UK since at least 1989, RDT sampling involves (DoE 1989):

- Random selection of the houses to be sampled from billing lists, post-codes, electoral registers or other similar lists.
- Each house being visited by the sampler at a convenient time during normal working hours.
- The sampler taking a first draw sample of 1 L volume from the point of use (normally, the cold water tap in the kitchen), without any prior flushing of the house's pipe-work.

If access to a selected house is not possible, then an adjacent house is sampled where access is possible. Randomness of the sampling is still preserved at the zonal scale. In the UK, compliance with standards is generally assessed annually, thereby accommodating any seasonal variation. The advantages of RDT sampling are that samples can be gathered quickly at each house and that the approach can be efficiently handled by trained sampling personnel, thereby ensuring good levels of quality assurance in the sampling undertaken. The main disadvantage of RDT sampling is that fairly large numbers of samples are required in order to achieve acceptable levels of reproducibility (IWA 2010). It should be noted here that RDT sampling is not an appropriate method for investigating lead emissions at individual properties; in such cases, stagnation or composite sampling can be considered (IWA 2010).

The problems with the sampling of metals at consumers' taps have been recognised (Hulsmann & Cortvriend 2006) and recommendations have been made to the European Commission to adopt RDT sampling as the harmonised method (Hoekstra *et al.* 2008) for zonal assessment. Further, in the implementation of the UN/WHO Protocol on Water and Health, RDT sampling has been recommended in guidance on the sampling and monitoring of lead in drinking water (Hoekstra *et al.* 2009). RDT sampling has been shown to be an adequate alternative to composite sampling, for assessing lead in drinking water at the zonal level, in both experimental (Van den Hoven *et al.* 1999) and computational (Hayes 2009) studies. However, the question has been posed (Slaats *et al.* 2008) about whether or not random sampling during 'normal office hours' is adequately representative for assessing metals at consumers' taps. For lead, this question will be very difficult, if not impossible, to answer by experimental methods, because of the variation inherent in random sampling and the uniqueness of every water supply system.

This paper provides the results of an investigation into the representativeness of RDT sampling for lead in drinking water using computational modelling, based on an established modelling system (Van der Leer *et al.* 2002) that has been successfully validated in numerous case studies (Hayes *et al.* 2006, 2008). It provides supplementary information to the earlier computational studies that were published by Hayes (2009) and focuses on the time periods of sampling.

EXPERIMENTAL LIMITATIONS

The results of zonal assessment from random sampling will be determined particularly by:

1. The plumbosolvency of the water.
2. The extent of occurrence of lead pipes and their lengths and diameters.
3. Water use just prior to the time of sampling.
4. The characteristics of the houses that are selected for sampling.

Whilst 1 and 2 will be constant for a zone, unless there are operating changes, 3 and 4 will vary for any particular survey. This means that for any given number of samples taken in a survey, the conclusions will likely vary from survey to survey, purely by chance, because of the variation inherent within the zone. For the numbers of samples likely to be taken in a survey (normally no more than a few hundred), the survey to survey variation can be significant, as illustrated in Table 1, particularly for the period before orthophosphate dosing. The three benchmark concentrations used in Table 1 and elsewhere were: (i) 10 μg/L, the WHO Guideline Value and EU standard from December 2013; (ii) 25 μg/L, the current EU standard; and (iii) 50 μg/L, the earlier EU standard from 1985 to 2003.

The inherent variation of random sampling therefore makes it impossible to use a zone for the experimental investigation of sampling behaviour, such as undertaking a sequence of surveys with each survey having a different sampling protocol. Similarly, it is not possible to select a study zone and control zone for investigating a difference in sampling protocol. However, an approach that can be used for investigating the behavioural characteristics of random sampling is computational modelling.

Table 1 | Observed variation in real RDT sampling results for a water supply system in the UK (adapted from IWA 2010)

Year	N	% >10 μg/L	% >25 μg/L	% >50 μg/L
(a) Before ortho-phosphate dosing				
1990	132	28.0	17.4	9.9
1991	228	24.1	11.0	4.0
1992	61	13.1	6.6	0.0
1993	45	17.8	13.3	2.2
1994	29	10.3	6.9	0.0
1995	14	0.0	0.0	0.0
1990–5[a]	509	21.8	11.8	4.5
Predicted[b]		18.4	11.3	4.8
(b) After ortho-phospate dosing				
1995	11	9.1	0.0	0.0
1996	29	6.9	0.0	0.0
1997	28	3.6	0.0	0.0
1998	28	3.6	0.0	0.0
1999	9	0.0	0.0	0.0
2000	8	0.0	0.0	0.0
2001	26	3.8	3.8	3.8
2002	28	0.0	0.0	0.0
2003	85	0.0	0.0	0.0
1995–2003[a]	252	2.4	0.4	0.4
Predicted[b]		2.8	0.2	0.0

[a] The percentages shown were calculated from the total sample numbers and total failure numbers over the period.

[b] Predicted by computational modelling for this zone (IWA 2010).

METHODOLOGY FOR INVESTIGATING RANDOM DAYTIME SAMPLING

The computational models utilise a single pipe model within a probabilistic framework that mimics the wide variation in factors that determine lead concentrations at the tap across an entire water supply system. A sampling model can then predict the results of different sampling methods. This modelling system is described elsewhere by Van der Leer *et al*. (2002) and Hayes (2009), and is illustrated further in IWA (2010) and Hayes (2010).

The probability frameworks are built by randomly ascribing variables which, in addition to the constants used, create a simulated zone made up of simulated houses (in relation to pipe-work circumstances). The simulated houses can then be investigated by a sampling simulator. Each variable is defined by a simple look-up table that determines a discretised distribution. The distributions used in this study were as shown in Figure 1, with amendments as stated. These distributions have been used in earlier studies.

In normal modelling use, the water use Patterns A and B shown in Figure 1 are applied equally for each pattern and use frequency (i.e. 20% each condition). The percentage of daily water flow in each hour is divided evenly to each flow event, dependent on its frequency. The water use frequencies are ascribed in this way with the aim of creating a range of conditions within the probabilistic framework that equate in general terms to the zone. For this study, the simulated zones were established using only Pattern A or Pattern B. Pattern A depicts the situation for a house which has daytime residency, such as elderly residents or a family with children. Pattern B depicts the situation for a house which has no daytime residency, such as one or two people who work elsewhere during the day. The likelihood is that this latter circumstance will be associated with less overall daily water use and this factor was taken into account by amending the 'volume per day' distribution.

In order to simulate an RDT survey, the specified number of simulated houses was selected at random and

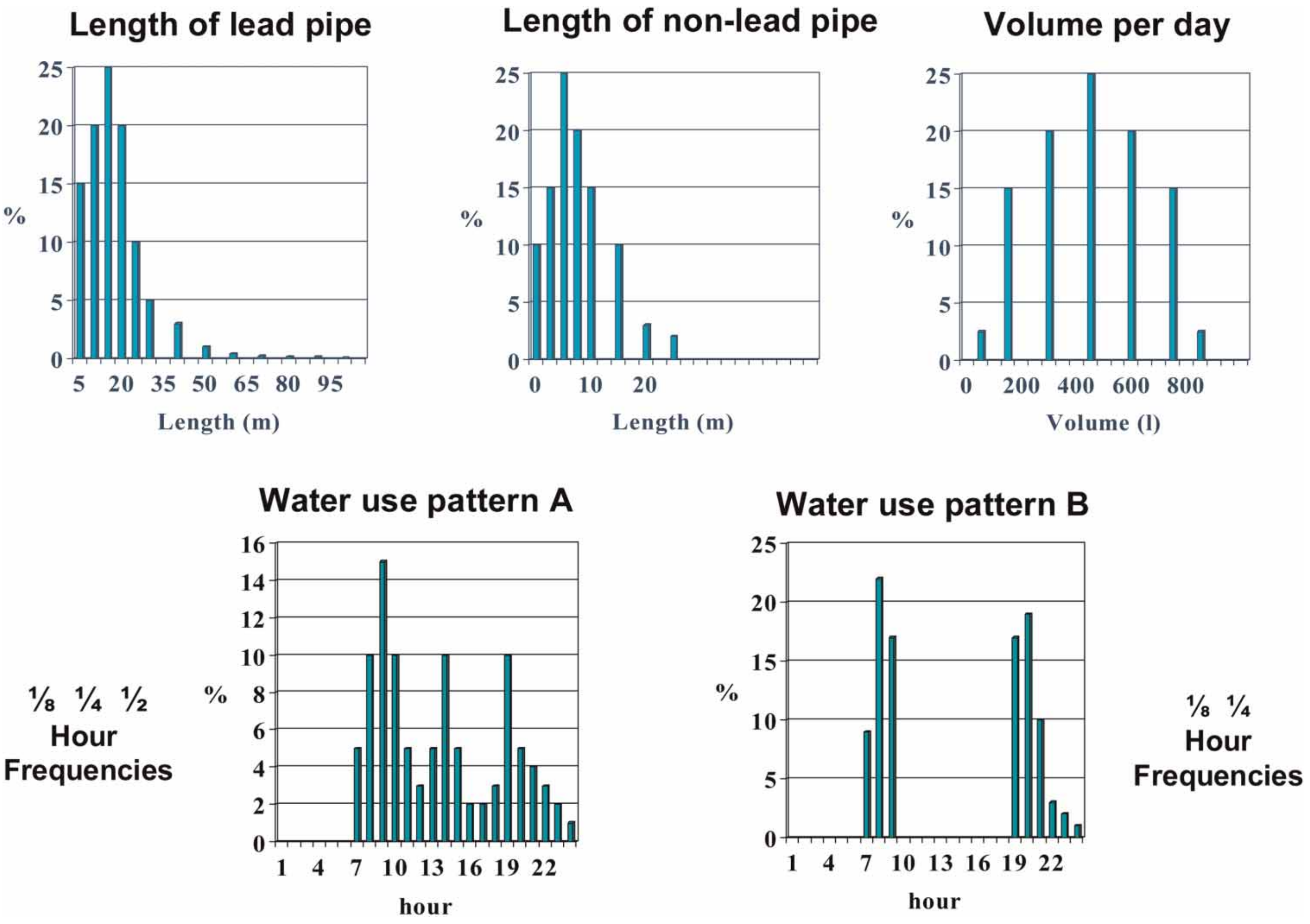

Figure 1 | Statistical distributions used to set up the zonal model (from Hayes 2009).

then a sampling time was selected at random, for each simulated house, between the hours of 0900 and 1700. The RDT sample was simulated by a stirred tank of 1 L capacity as the outlet from the pipe. At the time of simulated sampling, the pattern of water use that had been applied to the simulated house was used to determine the immediately previous water – pipe contact position that determines lead concentration. It is routine to repeat the simulated survey, typically 100 times, in order to be able to understand possible variation.

In all cases, the zone size was set at 10,000 houses. The percentage of houses with a lead pipe was assumed to be 10, 30, 50, 70 or 90%. The lengths of lead pipe followed the distribution shown in Figure 1, assuming 95% were 12 mm and 5% were 18 mm internal diameter. Two plumbosolvency conditions were investigated: (i) M=0.1 and E=150, a reflection of the commonly encountered moderate plumbosolvency; and (ii) M=0.02 and E=30, a reflection of a phosphated water with reduced plumbosolvency. M is the initial mass transfer rate (μg/m^2/s) and E is the equilibrium concentration (μg/L).

The results reported for the simulated zone under investigation are the average survey result from all 100 surveys simulated, each of 100 samples. The standard deviation has been reported where appropriate. The routine simulation of RDT sampling is limited to only those simulated houses that have a Pattern A water use (just as in real life). However, for the purposes of this study, simulated houses with a Pattern B water use were investigated for time periods outside 0900 to 1800, the assumed period of non-residency.

Table 2 | Zonal failure for a range of sampling time periods with daytime residency (Pattern A), standard volume distribution, $M=0.1$, $E=150$ and %Pb=50

Time ranges	% daily flow	Hours when flow occurs	%RDT >10 μg/L	%RDT >25 μg/L	%RDT >50 μg/L
0900–1700 (UK sampling practice)	42	8	20.19	8.32	1.92
0800–1800	60	10	19.81	8.36	2.06
0700–1900	80	12	18.95	7.70	2.00
0600–2000	90	14	18.73	7.29	2.12
0600–2100	94	15	18.89	7.67	2.48
0600–2400 (total period of flow)	100	18	20.87	9.51	2.97
0900–1300 (Slaats *et al.* 2008)	23	4	18.37	6.46	1.19
0600–1800 (Slaats *et al.* 2008)	75	12	18.56	8.44	2.52
1000–1600	30	6	19.64	7.55	1.78
1100–1500	23	4	18.47	6.52	1.44

RESULTS

Influence of sampling time period for houses with daytime residency

Table 2 shows the percentages of simulated samples that exceeded three bench-mark concentrations for lead (10, 25 and 50 μg/L) for the moderate plumbosolvency condition and a zone in which 50% of houses have a lead pipe. These results indicated that:

- RDT sampling during the period 0900–1700 hrs was adequately representative of the assumed total water use period of 0600–2400 hrs.
- Extending or shortening the RDT sampling period, to the extents shown in Table 2, had a limited effect on the simulated results.

Slaats *et al.* (2008) published information on the time of RDT sampling in the Netherlands for the period 2004–2006, from which it was apparent that 77% of samples were collected between 0900 and 1300 hrs, and that 100% of samples were collected between 0600 and 1800 hrs. The simulated results in Table 2 for these periods were found to be slightly lower than or similar to the 0900–1700 hrs period assumed for the UK, depending on the benchmark concentration used.

How the period of RDT sampling influences results was investigated further by limiting the sampling time period to each hour during the total period of assumed flow. Table 3 shows a clear relationship between the percentage of flow allocated to each hourly time period and

Table 3 | Influence of time of day on RDT compliance results[a]

Sampling period	% flow	% >10 μg/L	% >25 μg/L	% >50 μg/L
0600–0700	5	22.71	13.00	10.51
0701–0800	10	12.53	3.33	0.68
0801–0900	15	8.89	1.87	0.10
0901–1000	10	11.08	2.53	0.24
1001–1100	5	15.84	4.87	0.63
1101–1200	3	24.55	10.49	2.09
1201–1300	5	18.67	7.74	1.91
1301–1400	10	12.23	3.35	0.59
1401–1500	5	16.84	5.00	0.77
1501–1600	2	28.66	13.85	2.84
1600–1700	2	31.99	18.84	6.27
1701–1800	3	27.77	13.63	4.14
1801–1900	10	13.40	4.63	1.23
1901–2000	5	16.94	5.15	0.66
2001–2100	4	20.35	7.19	1.28
2101–2200	3	24.26	10.67	2.43
2201–2300	2	31.28	16.98	4.91
2301–2400	1	39.26	27.94	9.89
0600–2400	100	20.87	9.51	2.97

[a] Other than time periods, same modelling conditions as relate to Table 2, with daytime residency (Pattern A), standard volume distribution, $M=0.1$, $E=150$ and %Pb=50.

Table 4 | Zonal failure for a range of sampling time periods with daytime residency (Pattern A), standard volume distribution, $M=0.02$, $E=30$ and %Pb=50

Time ranges	% Daily flow	Hours when flow occurs	%RDT >10 μg/L	%RDT >25 μg/L	%RDT >50 μg/L
0900–1700 (UK sampling practice)	42	8	2.16	0.01	0.00
0800–1800	60	10	2.23	0.01	0.00
0700–1900	80	12	1.99	0.03	0.00
0600–2000	90	14	2.10	0.21	0.00
0600–2100	94	15	2.46	0.35	0.00
0600–2400 (total period of flow)	100	18	2.64	0.14	0.00
0900–1300 (Slaats *et al.* 2008)	23	4	1.35	0.00	0.00
0600–1800 (Slaats *et al.* 2008)	75	12	2.50	0.33	0.00
1000–1600	30	6	1.48	0.04	0.00
1100–1500	23	4	1.34	0.00	0.00

the extent of failure against 10, 25 and 50 μg/L (for each hour shown the results are the average of 100 surveys each of 100 samples); the lower the percentage of flow, the greater was the level of failure.

It can be concluded that the precise daytime period used by water companies is not particularly important in determining RDT sampling results if the period of sampling extends to more than 4 hrs and includes the 1100–1300 hrs period when water consumption has been assumed to be lower. If water companies obtained all their RDT samples before 1100 hrs, the results would likely be lower. Sampling between 0900 and 1700 hrs adequately captures the variations in lead emissions that are expected to occur throughout a day. It can be concluded that RDT sampling should be spaced over as much of the working day as is logistically possible. The results also indicate that flushing the tap first thing in the morning is, by itself, inadequate for protecting consumers from lead concentrations that exceed the WHO Guideline Value of 10 μg/L. Table 4 summarises the results for a reduced plumbosolvency condition, from which broadly similar conclusions can be drawn to those from Table 2.

To further explore the representativeness of RDT sampling, Table 5 provides the results for 0900–1700 hrs and 0600–2400 hrs for zones which have different percentages of houses with a lead pipe. The representativeness of 0900–1700 hrs is confirmed over the wide range of percentages of houses with a lead pipe that were investigated.

Influence of sampling time period for houses without daytime residency

Table 6 shows the effect of sampling outside normal office hours for reducing time periods from both Pattern A and B houses. RDT sampling of Pattern A houses between 0600–0900 hrs and 1800–2400 hrs gave similar results to RDT sampling of Pattern B houses for the same time periods when the reduced volume distribution was applied to

Table 5 | Comparing RDT sampling during ‘normal office hours’ to the total period of simulated flow in Pattern A, for a range in the percentage of houses with a lead pipe ($M=0.1$, $E=150$, standard volume distribution)

% Houses with Pb	Time ranges	%RDT >10 μg/L	%RDT >25 μg/L	%RDT >50 μg/L
10	0900–1700	4.24	1.71	0.21
	0600–2400	4.21	2.04	0.61
30	0900–1700	12.58	5.30	1.11
	0600–2400	12.58	5.50	1.68
50	0900–1700	20.19	8.32	1.92
	0600–2400	20.87	9.51	2.97
70	0900–1700	27.86	11.14	2.63
	0600–2400	29.83	13.58	4.26
90	0900–1700	35.87	14.45	3.54
	0600–2400	37.96	16.70	4.93

emphasise one and two person residency. These results were also fairly similar to the RDT sampling of Pattern A houses between 0900–1700 hrs and also 0600–2400 hrs (Table 2). These results indicate that RDT sampling during normal office hours from Pattern A houses is representative of Pattern B houses if reduced water consumption is assumed for the latter. As the time periods were reduced to increasingly exclude the early and late periods associated with lower water consumption (and therefore exclude greater water stagnation and higher lead concentrations), the failure rates reduced. The results indicate that lead emissions are lower when proportionally more water flows during fewer hours. It can also be concluded from Table 6(c) that random sampling of houses where there is no daytime residency, just before 0900 hrs or just after 1800 hrs, will give non-representative results compared to random samples obtained from houses during 'normal office hours' (Table 2).

Time of year when RDT sampling is undertaken

Table 7 shows the RDT failure rates for four scenarios that extend to moderate and phosphate treated plumbosolvency conditions, as an average condition and for assumed summer and winter conditions where the seasonal difference in plumbosolvency is a factor of two, for two percentages of houses with lead pipes. This difference in summer to winter plumbosolvency relates to UK conditions and has been determined by laboratory testing and general observation (IWA 2010). It can be noted that the plumbosolvency of the water and the extent of occurrence of houses with a lead pipe are major drivers of zonal compliance. For scenario 1, the seasonal variation around the average was quite marked. However, in the UK context, the Government's criterion for optimising plumbosolvency control by treatment measures was 5% or more of RDT samples exceeding 10 μg/L (DWI 2000, 2001). In this context, the seasonal variation shown by the scenario has limited significance. In contrast, the seasonal variation shown in scenario 2 was significant and would influence whether or not optimisation was required. The DWI's target for optimisation was that no more than 2% RDT samples exceed 10 μg/L. In scenario 3, the seasonal variation was significant in relation to this target but not in scenario 4. It can be concluded that seasonal effects can strongly influence regulatory assessment in some cases and therefore

Table 6 | Zonal failure for a range of sampling time periods outside normal office hours

Time ranges	% Daily flow	Hours when flow occurs	%RDT >10 μg/L	%RDT >25 μg/L	%RDT >50 μg/L
(a) With daytime residency (Pattern A), standard volume distribution, M=0.1, E=150 and %Pb=50					
0600–0900 and 1800–2400	55	9	19.80	9.26	3.51
0600–0900 and 1800–2100	49	6	15.22	5.76	2.43
0700–0900 and 1800–2000	40	4	12.21	3.70	0.70
0800–0900 and 1800–1900	25	2	11.47	3.13	0.69
(b) Without daytime residency (Pattern B), with standard volume distribution, M=0.1, E=150 and %Pb=50					
0600–0900 and 1800–2400	100	9	14.62	6.78	2.71
0600–0900 and 1800–2100	94	6	8.40	2.46	1.69
0700–0900 and 1800–2000	73	4	6.11	1.70	1.16
0800–0900 and 1800–1900	34	2	7.85	2.66	2.15
(c) Without daytime residency (Pattern B), with reduced volume distribution, M=0.1, E=150 and %Pb=50[a]					
0600–0900 and 1800–2400	100	9	19.80	10.39	4.72
0600–0900 and 1800–2100	94	6	11.49	3.14	2.00
0700–0900 and 1800–2000	73	4	8.34	1.81	1.09
0800–0900 and 1800–1900	34	2	9.68	3.00	2.32

[a] The reduced volume distribution was as follows: 50 L/d=2.5%; 150 L/d=40%; 300 L/d=50%; 450 L/d=5%; 600 L/d=2.5%, to reflect the lower water use in houses with one and two person residency.

Table 7 | Seasonal effects on RDT results

Scenario	Seasonal condition	% Pb	*M*	*E*	%RDT >10 μg/L	%RDT >25 μg/L	%RDT >50 μg/L
1	Summer	50	0.133	200	23.70	11.44	3.64
	Winter	50	0.067	100	14.83	3.88	0.48
	Annual average	50	0.100	150	20.02	8.26	2.00
2	Summer	12.5	0.133	200	6.06	2.95	0.90
	Winter	12.5	0.067	100	3.58	0.83	0.12
	Annual average	12.5	0.100	150	4.76	1.75	0.39
3	Summer	50	0.0266	40	4.08	0.28	0.00
	Winter	50	0.0134	20	0.54	0.00	0.00
	Annual average	50	0.0200	30	1.93	0.01	0.00
4	Summer	12.5	0.0266	40	0.98	0.01	0.00
	Winter	12.5	0.0134	20	0.22	0.00	0.00
	Annual average	12.5	0.0200	30	0.56	0.00	0.00

monitoring assessment periods should extend to multiples of years.

Reproducibility

Lead emissions at the tap, across a water supply system, are highly variable, both spatially and over time (Hayes 2009; IWA 2010). This is due to the variation in pipe-work circumstances across a system and due to frequently changing contact periods between the water and the pipes through which it flows. Variation in RDT sampling results, year by year, is much greater before ortho-phosphate dosing, as illustrated in Table 1. Averaging the results from the pre-dosing period of 1990–2005 should give a more robust assessment and in the example given the average failure rates were matched closely by the predicted average failure rates from the modelling system. After the commencement of ortho-phosphate dosing, the extent of variation, year by year, is less, particularly after the first few years. Predicted failure rates for an 85% reduction in plumbosolvency match the averaged failure rates for the post-dosing period 1995–2003.

It can be concluded from the close matching of averaged data that it is beneficial to bulk RDT sampling results for several years, if there have been no operational changes during the period under assessment. The variation exhibited in the pre-dosing period was of limited significance given that the Government's criterion for action was 5%. The variation during the post-dosing period, in relation to the Government's target of no more than 2% exceeding 10 μg/L, was more significant in compliance terms.

Computer simulation can investigate this more closely and indicates the magnitude of possible variation in RDT sampling and how this is dependent on the numbers of samples taken. Figure 2 shows the predicted extent of variation for a zone with 50% of houses with a lead pipe and moderate plumbosolvency, based on 100 surveys each of 100 samples; this is shown as a distribution of the survey failure rates against 10 μg/L. Inspection of this distribution indicated that 69% of the simulated surveys were within ±20% of the averaged result of 20.72% exceeding 10 μg/L and 99% of the simulated surveys were within ±50%. The latter is comparable to the variation shown in Table 1 for the pre-phosphated condition over the period 1990–1994

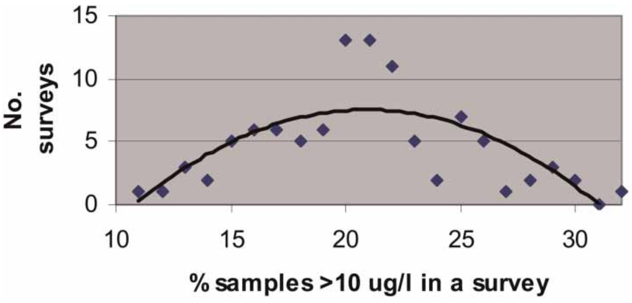

Figure 2 | Variation in simulated RDT survey results from 100 surveys (100 samples each) with daytime residency (Pattern A), standard volume distribution, $M=0.1$, $E=150$ and %Pb=50.

(1995 is clearly inconsistent and may be due to samples being taken at the beginning of the year when water temperatures were lower).

In Table 8, the results from three sample sizes (10, 100 and 1,000 per survey) demonstrate that as the sampling number per survey increases, reproducibility improves. It can be concluded that surveys of at least 100 samples (and preferably more) will be required to minimise reproducibility problems. In the UK, this was achieved by 'opportunistic' sampling for lead. The RDT sampling frequencies for bacteriological parameters are much higher than for lead and for several years water companies took advantage of their sampler being at a house and also sampled for lead. Bulking data for several years will also minimise reproducibility problems.

Table 8 | Reproducibility as a function of sample numbers

	>10 μg/L	>25 μg/L	>50 μg/L
(a) 100 surveys each of 1,000 samples			
Average % of samples	20.21	8.25	1.93
Average number of samples	202.05	82.51	19.27
Minimum number of samples	172	63	10
Maximum number of samples	241	109	34
Standard deviation relating to the average number of samples	13.34	8.49	3.85
Standard deviation as % of number of samples	1.33	0.85	0.39
(b) 100 surveys each of 100 samples			
Average % of samples	20.72	8.72	2.17
Average number of samples	20.72	8.72	2.17
Minimum number of samples	11	2	0
Maximum number of samples	32	17	5
Standard deviation relating to the average number of samples	4.32	3.12	1.40
Standard deviation as % of number of samples	4.32	3.12	1.40
(c) 100 surveys each of 10 samples			
Average % of samples	21.70	8.60	2.50
Average number of samples	2.17	0.86	0.25
Minimum number of samples	0	0	0
Maximum number of samples	5	4	1
Standard deviation relating to the average number of samples	1.25	0.92	0.43
Standard deviation as % of number of samples	12.5	9.2	4.3

Sensitivity

In the UK context in which an average of 40% of houses have a lead pipe (IWA 2010), RDT sampling has clearly differentiated between pre- and post-phosphate dosing conditions. This is illustrated by data from England and Wales (DWI 1992, 1996, 2011): (i) over the period 1989–1994 before ortho-phosphate dosing was widespread, 19.6% of RDT samples exceeded 10 μg/L and 8.4% RDT samples exceeded 25 μg/L (based on a total of 326,554 samples); (ii) over the period 2005–2010 after ortho-phosphate dosing had become widespread, 1.2% RDT samples exceeded 10 μg/L and 0.2% of RDT samples exceeded 25 μg/L (based on a total of 111,553 samples).

Table 9 summarises the results of an investigation into the sensitivity of RDT sampling to differentiate pre- and post-phosphate dosing conditions for zones in which there are fewer houses with lead pipes. The average percentage of houses with a lead pipe in the US is 2–3% (IWA 2010), although Renner (2010) reports 27% of houses in Providence, Rhode Island have a lead service pipe. The modelling results indicate an approximate 10-fold difference in the percentage of samples exceeding 10 μg/L, even though the failure rates for 1% of houses with a lead pipe are below 0.5%. It is concluded that RDT sampling should be sufficiently sensitive in most cases.

Table 9 | Zonal failure levels for systems with low numbers of houses with lead pipes

Plumbosolvency condition	% Pb	% >10 μg/L	% >25 μg/L	% >50 μg/L
Moderate ($M = 0.1$, $E = 150$)	10	4.08	1.76	0.42
	5	1.86	0.66	0.18
	1	0.47	0.14	0.04
Phosphated ($M = 0.02$, $E = 30$)	10	0.45	0.00	0.00
	5	0.21	0.00	0.00
	1	0.04	0.00	0.00

DISCUSSION AND CONCLUSIONS

The sampling protocol used to assess lead in drinking water across a water supply system is not only relevant to regulatory compliance but also to health protection, particularly children who are the most susceptible to chronic lead poisoning and consequential IQ reduction (WHO 2010). The question about the representativeness of RDT sampling is therefore important, particularly as this sampling method has been recommended to the European Commission (Hoekstra *et al.* 2008) for incorporation in the next revision of the EU drinking water directive.

Due to inherent variation in the behaviour of random sampling, an experimentally based investigation into representativeness is not possible. Fortunately, computational modelling methods are available that have already been validated in numerous case studies concerning the optimisation of plumbosolvency control. It is entirely reasonable to use such modelling in these circumstances to overcome the experimental limitations. The results from the modelling reported in this paper demonstrate behavioural characteristics and provide the deeper insight into random sampling that is required.

It can be concluded from the modelling investigations that:

1. RDT sampling as practised in the UK is adequately representative of the range of house circumstances that occur.
2. For houses with daytime residency, RDT sampling is not particularly sensitive to the time of sampling, unless it is constrained to only a few hours.
3. For houses without daytime residency, RDT sampling of houses elsewhere with daytime residency is adequately representative, for the total periods of water use.
4. For houses without daytime residency, random sampling just before or just after 'normal office hours' will not be representative.
5. It is important that seasonal variation is accommodated.
6. If at least 100 samples are taken from a zone annually and if data for several years are aggregated, then reproducibility in RDT sampling is adequate.
7. RDT sampling has sufficient sensitivity to differentiate plumbosolvency conditions in zones with low numbers of lead pipes, at least down to 1% of houses having a lead pipe.

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