ORIGINAL PAPER

# Impact of submersible pumps on Pb constituents in residential wells

W. C. Sidle · P. Li

Received: 6 July 2006/Accepted: 9 March 2007 © Springer Science+Business Media B.V. 2007

Abstract Dissolved Pb in 51 domestic wells screened from 18 to 48 m in glacial tills and outwash deposits were examined in conjunction with the characteristics of their corresponding submersible pump. Pb concentrations, ranging from 0.8 to 24.9  $\mu$ g l<sup>-1</sup>, entering residential water supplies were measured during 2001-2004 in the Royal watershed, Maine. Principal component analyses assisted the weighting of pump age, well screen depth, and draw time variables. Preliminary Pb sequestration significance in the boreholes was predicted from geochemical speciation and synchrotron XAS analyses. Nascent <sup>207</sup>Pb/<sup>206</sup>Pb and <sup>208</sup>Pb/<sup>206</sup>Pb isotope analyses assisted the discrimination of possibly leached Pb from submersible pump materials among geogenic sources.

**Keywords** Lead · Submersible pump · Groundwater wells · Stable Pb isotope · Maine

W. C. Sidle (🖂)

P. Li

## Introduction

Introduction of Pb into well waters from submersible pumps may occur from brass fittings depending on age, material integrity, and the geochemical conditions in the borehole. Health concerns of Pb in US drinking water have been addressed by stringent requirements (USEPA Safe Drinking Water Act Amendment 1996) on materials and performance standards (USEPA National Primary Drinking Water Regulations 2005). Water system components in contact with public drinking water must contain less than 8.0% Pb to be designated lead-free. Furthermore, a drinking water standard (USEPA 2005) of 15  $\mu$ g l<sup>-1</sup> Pb is established for tap water. Additionally, the international consensus of the ANSI/NSF standard 61 is applied to plumbing fixtures and distribution lines in residential water supplies.

Challenges remain in assessing the likelihood of Pb leaching from the ubiquitous submersible pumps used throughout rural water well districts and residential water supplies serviced by individual wells. Today modern well construction relies primarily on steel and thermoplastic casing, screens, leadfree welds, couplings and fittings surrounding the pump housing. However the manufacturing advantages of utilizing brass remain in several pump components. Of course many wells in service are decades old and even newer wells often are not rehabilitated. Poor well and pump maintenance may result in chemical encrustation, biofouling, and

National Risk Management Research Laboratory, Water Supply & Water Resources Division, U.S. Environmental Protection Agency, 26 West Martin Luther King Blvd, Cincinnati, OH 45268, USA e-mail: sidle.william@epa.gov

Department of Chemistry MC 32251, Columbia University, 3000 Broadway Ave, New York, NY 10027, USA

corrosion, particularly where favorable geochemical conditions exist. Sometimes Pb sequestration occurs because of the geochemical sink, thereby reducing dissolved Pb concentrations. That anthropogenic Pb may be masked by mobile naturally occurring Pb entering the screened or open borehole interval at depth from the source lithology.

Representative wells in the Royal watershed, Maine (Fig. 1) were examined to determine if submersible pump age and pump draw cycles impacted on the Pb concentration exiting the pump house or storage tank and entering the distribution lines for the residence(s). A preliminary assessment of the aqueous-phase speciation and solid-phase speciation of Pb is reported for the local geochemical environment. The mobility and bioavailability of either anthropogenic Pb or native environmental Pb will be affected by the prevailing speciation. The source of these Pb constituents need to be determined from their stable Pb isotope composition because ultimately the Pb leaching from pump degradation may be insignificant in comparison to groundwater Pb transport to the pumping interval at depth.

## Methods

Water samples were collected from 51 domestic wells at depths of 18 to 48 m within unconsolidated glacial outwash deposits across the Royal watershed

Fig. 1 Location of wells sampled for Pb across the Royal watershed in Maine. Wells where submersible pumps were removed for inspection are noted by  $\Upsilon$ symbol (361 km<sup>2</sup>) from 2001 to 2002. Field and collection protocols are described in Sidle et al. (2001) and Sidle (2006). All samples were analyzed at the US Environmental Protection Agency (USEPA) isotope hydrology laboratory for dissolved Pb via isotope dilution and also processed for stable isotope analyses. Samples from three wells were split for nondestructive analyses of Pb speciation.

Prepared water samples for dissolved Pb analyses were further filtered in a class-10 fume hood using acid-cleaned 0.1 µm Teflon discs. The resultant 10 g of water was spiked with 204Pb to permit the determination of both Pb concentration and stable Pb isotope ratios. Isotope dilution with an enriched <sup>204</sup>Pb spike (Webster 1960; Galer 1999) was employed and was calibrated against the NIST SRM 981 (common lead) standard. Pb separation included modified washing and digestion sequences of H<sub>2</sub>O-Milli-Q: 6 M HCl:6 M HNO<sub>3</sub> + 6 M HCl + 0.4 M HBr and elution through AG1X8 100-200 mesh anion-exchange columns (Tessier et al. 1979; Bacon et al. 1995; Poimes et al. 1998). Mean total chemical blanks were  $<10 \text{ pg ml}^{-1} \text{ Pb}$ with three replicates. Pb residue (0.7-6.3 ng) was transferred onto an outgassed Re filament with the H<sub>2</sub>PO<sub>4</sub>/SiO<sub>2</sub> (gel) procedure of Tera and Wasserburg (1975). Apart from the clean room, about 60 ng of Pb from aliquots of 2  $\mu$ g l<sup>-1</sup> Pb, derived from concentrated HNO<sub>3</sub> rinsates of selected submersible pump parts, were loaded onto an Re filament.



Pb isotope ratios were determined with a MAT-261A<sup>®</sup> thermal ionization mass spectrometer (TIMS). Reproducibility  $(2\sigma)\%$  of 0.26, 0.18, and 0.18 for <sup>208</sup>Pb/<sup>204</sup>Pb, <sup>207</sup>Pb/<sup>204</sup>Pb, and <sup>206</sup>Pb/<sup>204</sup>Pb, respectively, was achieved. Reported <sup>207</sup>Pb/<sup>206</sup>Pb, <sup>208</sup>Pb/<sup>206</sup>Pb, and <sup>206</sup>Pb/<sup>204</sup>Pb ratios, corrected for isotopic fractionation, had uncertainties (Ludwig 1980) of 0.068, 0.049, and 0.119%, respectively. Total contribution of Pb by reagents and ion exchange resins was about 155 pg. Pb concentrations in water via TIMS had a detection limit of 0.100 pg g<sup>-1</sup>.

A  $N_2(g)$ -filled glove box enabled the 0.1  $\mu$ m filtration of each aliquot for speciation until 1 g of solids was obtained and freeze-dried. Solids were then mounted for synchrotron X-ray absorption spectroscopy (XAS). Detectors were tuned for Pb and collected at the Pb L<sub>III</sub> edge at 13,051 eV. Mineral standards utilized for extended X-ray absorption fine structure (EXAFS) data processing included PbCO<sub>3</sub> (cerrusite, Wards Scientific), PbSO<sub>4</sub> (anglesite, Wards Scientific), PbS (galena, Aldrich), and  $\beta$ -PbO (massicot, Aldrich). Spectra collected from the XAS scans (6-8) were filtered and transformed (Teo 1986; Koningsberger and Prins 1988). Fourier transforms of  $k^2$ -weighted sample data were fitted over the wavevector (k) range 1.45-9.15 Å for Pb and EXFAS fitting was performed over the radial distances of 0.8-2.9 Å.

# **Results and discussion**

# Groundwater Pb

For each of the 51 wells examined, the submersible pump age, the draw times, and the depth to the top of the well screens were recorded with their corresponding dissolved Pb concentrations. As reactive particle Pb such as organocomplexed Pb is not measured, trace Pb is expected to be well below 1 ppb (Davies and Kent 1990). Each of these variables is plotted nonparametrically in Fig. 2a–c. Submersible pump ages ranged from 1 to 23 years. The dissolved Pb concentrations after 30 min pumping were very similar within the 25–75 percentiles, with medians near 5  $\mu$ g l<sup>-1</sup>. The largest Pb concentration measured in the groundwater sampled between 2001 and 2004 within the Royal watershed was 24.9  $\mu$ g l<sup>-1</sup>. Among the wells with newly installed pumps, the 90 percentile Pb was greatest, although the mean only shifted to about 7  $\mu$ g l<sup>-1</sup> (Fig. 2a). At some point in the submersible pump's life, the local geochemical conditions would be expected to impact on the performance, affect Pb sequestration, or even begin to contribute trace Pb to the extracted borehole waters.

Well pumping is generally not continuous and drinking water is pumped intermittently either to the point of use or into storage tanks. Some wells are operated seasonally and can remain idle for over six months. Sampling tests were conducted after drawing water for 30 min from wells with draw idle times from continuous operation to only occasional use. In cases where water was pumped continuously, that variable is represented as 30 min in Fig. 2b. The median Pb concentrations and their 25-75 percentiles are similar among the draw times with many outliers. Possibly the 30 min draw time group of wells exhibits the largest range of Pb concentrations. However its mean is only shifted to 8  $\mu$ g l<sup>-1</sup>. It is curious that the idlest wells sampled after 30 min did not show a more marked range of Pb concentrations than observed in Fig. 2b. This might suggest that a steady-state naturally occurring Pb source(s) is flowing into the boreholes at various depths across the watershed.

Among the wells grouped according to their top of well screen depths, the deepest pumped water appeared to contain the greatest Pb concentrations above the median. The 75 percentile of Pb is 18  $\mu$ g l<sup>-1</sup> and the 90 percentile of Pb is 22  $\mu$ g l<sup>-1</sup>. The local geochemical environment impacting on the leaching of deeper submersible pumps could be more severe than at shallower depths, but this is uncertain. More plausible is that the variable glacial till geology in the basin is a source of elevated Pb. Favorable geologic hosts for labile Pb could also be present at other depths. In Fig. 2c, waters pumped from screened wells between 5 and 15 m have a 75 percentile for Pb at 12  $\mu$ g l<sup>-1</sup>. Layered geologic horizons among tills are less likely than isolated lenses. Even so it would seem that atmospheric Pb may possibly be encountered in such shallow wells though local quick recharge events.

Given the large array of dissolved Pb data, and permutations of draw times, age of submersible pumps, and well screen depths a linear transformation was sought to remap the multivariate data into a new coordinate space because the box plots are simply **Fig. 2** Nonparametric box plots of dissolved Pb ( $\mu$ g l<sup>-1</sup>) in groundwater wells grouped according to (**a**) the age of the submersible pumps; (**b**) draw times; and (**c**) the top of the well screen depths (m) within the Royal watershed. Shown are 10, 25, 50, 75, 90 percentiles and outliers. Also noted by dashed line are the means



two-dimensional and cannot discriminate variances among all 15 variables. There are 51 observations for a variable matrix of 15 variables. From the dataset underlying Fig. 2a–c, the 15 × 15 variance–covariance matrix can be generated. A principal component analysis (see, e.g., Dunteman 1989) was developed from this correlation matrix and may assist determination of the underlying structural components of the matrix in *n*-dimensional space. Measured variables  $(x_n)$  are ordered from Fig. 2a–c starting from pump age 0–5 y  $(x_1)$  to well screen depth >45 m  $(x_{15})$ . The calculated eigenvector matrix and its eigenvalues are given in Table 1. The first three eigenvectors account for 98.441% of the total variance contributed by each eigenvalue. Within the 15-dimensional space a coordinate system defined by the likely two principal components can be described by almost 95% of the variation. The loadings of each variable per principal component 1 and 2 are illustrated in Fig. 3. Significant loadings for component 1 are the submersible pump age (0-5 y), 30 min draw from continuous pump operation, and well screen depth (5-15 m). This could suggest that both continuous and new pump operation from shallow groundwater depths may be expectedly associated with elevated trace Pb. Uncertain favor-

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
<i>x</i> <sub>1</sub>	-0.551	0.114	0.237	0.218	0.105	0.151	0.225	0.280	0.382	0.321	-0.204	0.312	0.561	-0.420	0.499
<i>x</i> <sub>2</sub>	0.146	0.683	0.281	0.125	-0.247	-0.034	0.328	0.204	0.326	0.437	-0.035	0.240	0.125	0.451	-0.561
<i>x</i> <sub>3</sub>	0.156	0.239	0.185	0.367	0.540	0.238	-0.248	0.115	0.035	0.121	0.324	0.217	0.117	-0.737	0.335
<i>x</i> <sub>4</sub>	0.145	0.159	0.104	0.259	0.411	0.423	0.115	0.341	0.027	0.118	0.113	0.128	0.112	0.193	0.138
<i>x</i> <sub>5</sub>	0.103	-0.140	-0.193	0.149	0.348	-0.145	0.112	0.125	0.116	0.018	0.114	0.126	0.056	0.173	0.183
$x_6$	0.240	0.182	0.701	0.167	0.326	0.324	0.146	0.164	0.357	0.127	0.103	0.172	0.034	0.128	0.193
<i>x</i> <sub>7</sub>	0.165	0.161	0.174	0.133	0.024	0.126	0.347	0.117	0.724	0.192	0.126	0.125	0.128	-0.629	-0.211
$x_8$	0.125	-0.652	0.183	-0.159	-0.310	0.451	-0.361	0.115	0.225	0.126	0.134	0.173	0.043	0.452	0.440
<i>x</i> 9	0.173	0.167	-0.103	-0.265	0.451	-0.326	0.237	0.112	0.217	0.730	0.125	0.124	0.329	0.121	-0.74
$x_{10}$	0.735	-0.136	0.105	0.045	-0.626	0.561	0.331	0.531	0.101	0.351	0.127	0.366	0.035	0.458	0.124
<i>x</i> <sub>11</sub>	-0.599	0.140	0.492	0.231	-0.450	0.564	0.651	0.251	0.561	0.502	0.016	0.016	0.025	-0.105	0.227
$x_{12}$	0.185	0.182	0.232	0.187	0.103	0.023	0.236	0.102	0.126	0.126	0.340	0.224	0.572	-0.455	0.172
<i>x</i> <sub>13</sub>	0.161	0.109	0.237	0.173	0.216	-0.041	0.023	0.012	0.242	0.113	0.127	0.124	0.721	0.046	0.128
$x_{14}$	0.232	0.153	0.281	0.383	0.573	0.121	-0.420	0.360	0.434	0.430	0.231	0.211	0.328	0.124	0.113
<i>x</i> <sub>15</sub>	0.108	0.544	0.470	0.296	-0.326	0.115	0.126	0.118	0.152	0.114	0.126	0.120	0.392	0.398	0.092
Ev	39.221	21.003	3.901	0.672	0.247	0.192	0.122	0.102	0.009	0.009	0.005	0.003	0.003	0.003	0.003
%	65.021	29.501	3.889	0.461	0.331	0.201	0.182	0.061	0.210	0.040	0.030	0.030	0.020	0.020	0.002

 Table 1
 Matrix of eigenvectors from principal component analysis of 15 variables on submersible pump age, draw times, and well screen depths

Eigenvalues (Ev) and the percentage of total variance or loading contributed by each eigenvalue



Fig. 3 Stacked bar plot of loadings on principal components 1 and 2 from multivariate analysis of groundwater wells in the Royal watershed

able geochemical conditions may not have resulted in any protective corrosive products around the pump housing. Otherwise local shallow geologic hosts for labile Pb may exist along with atmospheric Pb transport to the water table. Significant loadings for component 2 include submersible pump age (5-10 y), 24 h draw time, and screen depths greater than 45 m. Again this suggests that newer pumps, presumably without any corrosive product build up, principally on the shaft and impeller assembly in the pump housing, plus wells having been operated within a day of idling are statistically more likely to account for elevated Pb than older pumps left idle for many months. There may also be other favorable geologic hosts for labile Pb towards the bottom of the Royal basin.

### Pb speciation

Since the solubility products for metal sulfides are substantially lower than those of oxides or hydroxides under reducing conditions, the role of Pb sequestration would have an impact on the trace Pb concentrations provided such local geochemical conditions prevail. Further, the limits of solubility would be controlled by the variability of redox, sulfur species, and iron-manganese oxyhydroxides. In a simplified Pb-CO<sub>2</sub>-S-O-H<sub>2</sub>O system at STP (Fig. 4) and ignoring TOC, the groundwater samples throughout the Royal watershed (Fig. 1) plot in equilibria with largely PbCO<sub>3</sub>, with the remainder of samples in the Pb<sup>2+</sup> field. Some divalent Pb may be freely associated but most are likely to be complexed. Pb<sup>2+</sup> would occur in inner-sphere complexes, which are stronger than ion pairs as water-rock interactions of dissolved solids increase. Field determined ph and calculated pe (Maine Public Health 2000) values support a slightly oxidizing environment although some local reducing conditions may occur sporadically at depth associated with sulfide mineralization among granitic materials in the glacial tills.

In order to substantiate the placement of Royal watershed samples in this solubility-equilibria diagram, a preliminary XAS assessment of three groundwater samples was examined. Figure 5 shows the stacked Fourier transforms of the radial structure functions in the EXFAS spectra (Manceau et al. 1996) for Pb in the standards and groundwater samples. The highest-amplitude peak of each spectrum represents the position of the first orbital shell in the bond of the species. Sample spectra are readily distinguished from the background signal. In two samples (RW-14 and RW-36) the average bond lengths of 2.21 Å and the first-shell peak of 2.03 Å are consistent with PbCO<sub>3</sub>. Pb–O bonding is recognized in sample RW-21 with a first-shell peak of 1.61 Å. The  $P_{\rm CO2}$  may not be pervasively low to support PbO (litharge) formation. Rather it appears that the expected equilibrium solubility reactions would be

$$\begin{aligned} & Pb_{3}(CO_{3})_{2}(OH)_{2} + 6H^{+} \\ & \Leftrightarrow 3Pb^{2+} + 2CO_{2(g)} + 4H_{2}O \ LogK = 4.65 \\ & PbCO_{3} + 2H^{+} \\ & \Leftrightarrow Pb^{2+} + CO_{2(g)} + H_{2}O \ LogK = 17.51 \end{aligned}$$

such that over time submersible pump shaft and impellers would be become encrusted with hydrocerrusite  $[Pb_3(CO_3)_2 (OH)_2]$  and cerrusite  $[PBCO_3]$ . Under the apparently slightly oxidizing conditions with the known Pb species, over time the trace Pb might actually be reduced by aging submersible pumps in groundwater wells. However significant natural sources of Pb may obviate any role played by sequestration.



Fig. 4 Groundwater from Royal watershed plotted on the Pb–CO<sub>2</sub>–S–O–H<sub>2</sub>O stability diagram at STP for Pb<sup>2+</sup>  $\alpha = 10^{-6}$ ,  $P_{CO2} = 10^{-2}$  atm, and S  $\alpha = 10^{-2}$ . Dashed boundary represents carbonate stability in the absence of S species



Fig. 5 Stacked radial structure functions for Pb  $L_{III}$ -EXFAS in standards and solids from groundwater samples in the Royal watershed. The phase shift is uncorrected with approximate bond lengths

Stable Pb isotope composition

Isotope Pb ratios, with uncertainties, from the screened intervals of 20 m from 18 wells across the Royal watershed are reported in Table 2. Pb isotopes do not fractionate perceptibly in nature because of their high mass values. Therefore the measured Pb isotopes represent real sources but under long residence times and/or multiple flow pathways may mix sufficiently in an aquifer, disguising their original provenance.

The preliminary assessment of this solute isotope supports the origin of trace Pb in these wells being not from significant leaching via submersible pumps (Fig. 6). Smelted Pb derived from regional Pb ore deposits have long been known to have distinctive Pb isotope compositions. Generally, all pump fittings originated from USA manufacturers prior to the mid 1980s and the Pb source regions are known from analyses of the manufacturer's Pb-containing metals. Dashed regions on Fig. 6 represent the approximate ranges of those Pb isotope signatures observed from the predominant Joplin smelter of the tri-state Pb–Zn deposits and from the Bunker Hill smelter of the Coeur d'Alene Pb–Zn–Ag deposits (Rabinowitz 2002). As global manufacturing increases, the source-region isotopic Pb values would need to be known. From Sidle (2006), it is known that three representative submersible pump parts in Royal watershed wells have a source origin as plotted in Fig. 6. They plot within two distinct  $^{207}$ Pb/ $^{206}$ Pb and  $^{208}$ Pb/ $^{206}$ Pb signatures from earlier Pb smelting products.

The <sup>207</sup>Pb/<sup>206</sup>Pb and <sup>208</sup>Pb/<sup>206</sup>Pb isotope compositions of groundwater Pb do not overlap with the isotopic compositions of the Pb contained in these submersible pump parts. This strongly suggests that trace groundwater Pb from these wells originates from other sources. Investigations to discriminate among potential natural sources have yet to be carried out. Key considerations among water-rock interactions, for example, would include lithologic controls, mineral dissolution, reaction kinetics, residence times, and fluid pathways. A starting point would consider the range of stable Pb isotope values among the predominant glacial till and outwash deposits that fill the Royal basin. Early analyses from two bedrock samples in this catchment have a mean <sup>207</sup>Pb/<sup>206</sup>Pb ratio of 0.7981 and <sup>208</sup>Pb/<sup>206</sup>Pb ratio of 1.9490 (Fig. 6) and thus may

Well (20 m)	$Pb \ (\mu g \ l^{-1})$	<sup>207</sup> Pb/ <sup>206</sup> Pb	Error (SD)	<sup>208</sup> Pb/ <sup>206</sup> Pb	Error (SD)	<sup>206</sup> Pb/ <sup>204</sup> Pb	Error (SD)	
RW1	8.8	0.7833	0.0003	1.9350	0.0002	18.63	0.30	
RW2	4.8	0.8502	0.0030	2.0366	0.0003	22.22	0.09	
RW9	13.8	0.7880	0.0003	1.9624	0.0002	18.75	0.12	
RW10	4.5	0.8233	0.0008	2.0421	0.0003	21.05	0.12	
RW13	7.2	0.8173	0.0007	2.0068	0.0009	20.42	0.12	
RW14	0.8	0.7831	0.0010	1.9411	0.0002	18.42	0.14	
RW16	5.8	0.7908	0.0003	1.9449	0.0003	18.33	0.13	
RW19	23.6	0.7830	0.0007	1.9468	0.0011	18.71	0.21	
RW23	9.3	0.7880	0.0010	1.9471	0.0008	18.71	0.13	
RW28	6.8	0.7881	0.0010	1.9650	0.0003	19.01	0.13	
RW30	4	0.7844	0.0008	1.9232	0.0002	18.46	0.10	
RW31	5	0.7849	0.0008	1.9500	0.0003	18.74	0.13	
RW37	0.8	0.7801	0.0010	1.9694	0.0003	18.44	0.13	
RW38	11.7	0.8002	0.0021	1.9446	0.0005	19.01	0.14	
RW44	8.3	0.7839	0.0010	1.9692	0.0002	18.74	0.13	
RW45	23.8	0.7877	0.0010	1.9512	0.0002	18.24	0.12	
RW48	20.2	0.7863	0.0010	1.9380	0.0002	19.80	0.15	
RW50	0.8	0.7945	0.0013	1.9477	0.0010	18.42	0.13	

Table 2 Isotope dilution Pb and stable Pb isotope composition of selected 20 m screened groundwater wells in the Royal watershed



Fig. 6 Isotopic composition of selected 20 m screened wells, submersible pump parts, and bedrocks in the Royal watershed. Dashed areas are approximate isotope signatures of known Pb smelted ore sources (Rabinowitz 2002)

be a local source for some groundwater Pb. However outwash deposits could also be Pb sources that are variably transported from past glacial transport into the basin.

#### Conclusions

Contributions of Pb from submersible pumps into groundwater appear to be less significant than that

from other sources within the Royal watershed. Pump ages, screen depth, pump operations, geochemical sequestration may partly mask local natural sources of Pb being transported. Leaching Pb from idle decades-old pumps differ little from recently installed pumps. Evidently, Pb sources from principally glacial lithologies and possibly atmospheric sources could account for the ubiquitous trace Pb being pumped from domestic wells across the watershed.

Acknowledgements The cooperation of Maine Public Health is appreciated. Thanks to M. Cvetic of Groundwater Research Co., Lewiston for completing the field logistics. Also without the full cooperation of homeowners across Cumberland and Androscoggin counties, this research would not be possible. Special thanks are given to the field crews through the years for completing an uninterrupted sampling record through all seasons. Thanks to the USEPA Isotope Hydrology Laboratory (Cincinnati); D. Andrews, Dartmouth College; and V. Johnson, Brookhaven National Laboratory. Any opinions expressed in this paper are those of the authors and do not, necessarily, reflect the official positions and policies of the USEPA. Any mention of products or trade names does not constitute recommendation by the USEPA.

#### References

- Bacon, J. R., Berrow, M. L., & Shand, C. A. (1995). Isotopic characterization of lead in the Scottish upland environment. *International Journal of Environmental Analytical Chemistry*, 59, 253–264.
- Davies, J. A., & Kent, D. B. (1990). Surface complexation modeling in aqueous geochemistry. In M. F. Hochella & A. F. White (Eds.), *Reviews in mineralogy (Vol. 23): Mineral-water interface geochemistry* (pp. 177–260). Washington D.C.: Mineralogical Society of America.
- Dunteman, G. H. (1989). *Principal component analysis* (*Quantitative applications in the social sciences*). Boston: Sage.
- Galer, S. G. (1999) Optimal double and triple spiking for high precision lead isotopic measurement. *Chemical Geology*, 157, 255–274.
- Koningsberger, D. C., & Prins, R. (1988). X-ray absorption: Principles, applications, techniques of EXFAS, SEXAFS and XANES. New York: John Wiley & Sons.

- Ludwig, K. R. (1980). Calculation of uncertainties of U-Pb isotope data. *Earth Planetary Science Letters*, 46, 212– 220.
- Maine Public Health. (2000). Water well records database, Cumberland and Androscoggin counties.
- Manceau, A., Boisset, M. C., Sarret, G., Hazemann, J. L., Mench, M., Cambier, P., & Prost, R. (1996). Direct determination of lead speciation in contaminated soils by EXFAS spectroscopy. *Environmental Science & Technology*, 30, 1540–1552.
- Poimes, C., Cocherie, A., Guerrot, C., Marcoux, E., & Lancelot, J. (1998) Assessment of the precision and accuracy of lead-isotope ratios measured by TIMS for geochemical applications: example of massive sulphide deposits (Rio Tinto, Spain). *Chemical Geology*, 144, 137–149.
- Rabinowitz, M. B. (2002). Isotopic characterization of various brands of corroding grade refined lead metal. *Bulletin Environmental Contamination Toxicology*, 69, 501–508.
- Sidle, W. C., Roose, D. L., & Barndt, P. (2001) Isotopic evaluation of Pb occurrences in the riverine ecosystems of the Kankakee watershed, Illinois-Indiana. *Journal of the American Water Resources Association*, 37, 379–393.
- Sidle, W. C. (2006). Diagnosis of trace Pb in domestic wells, upper Gloucester catchment, Maine. Environmental Geology. DOI 10.1007/s00254-006-0448-1.
- Tera, F., & Wasserburg, G. J. (1975). Precise isotopic analysis of lead in picomole and subpicomole quantities. *Analyti*cal Chemistry, 47, 2214–2220.
- Teo, B. K. (1986). *EXAFS: Basic principles and data analysis.* Berlin: Springer-Verlag.
- Tessier, A., Campbell, P. C., & Bisson, M. (1979) Evaluation of the APDC-MIBK extraction method for the atomic absorption analysis of trace metals in river water. *International Journal of Environmental Analytical Chemistry*, 7, 41–54.
- USEPA. (1996). United States Environmental Protection Agency, Amendments to the Safe Drinking Water Act of 1974, from http://www.epa.gov/safewater/sdwa/text.html.
- USEPA. (2005). United States Environmental Protection Agency, National Primary Drinking Water Regulations, from http://www.epa.gov/safewater/standards/standards.html.
- Webster, R. K. (1960). Mass spectrometric isotope dilution analysis. In A. A. Smales & L. R. Wager (Eds.), *Methods* in geochemistry (pp. 202–246). New York: Interscience.