Determining quantitation levels for regulatory purposes

A quantitation level is proposed that should be quantifiable by a majority of laboratories.

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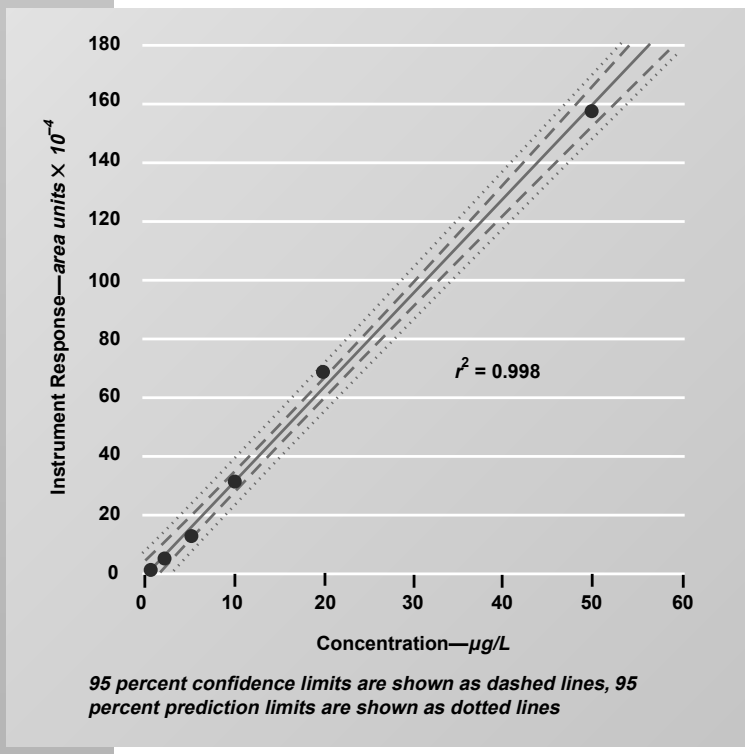
The authors describe an approach for calculating quantitation levels (QLs) that does not require changes in current laboratory practices. The reliable detection level (RDL), when defined as twice the concentration of the method detection limit (MDL), provides adequate protection against both false-positive and false-negative detection decisions. When analyte concentrations are at the RDL, the corresponding precision in the instrument response is adequate for analytical purposes. Therefore, the RDL (as determined by a single laboratory) is a reasonable lower limit of quantitation for that laboratory. To determine an interlaboratory QL suitable for regulatory purposes, median interlaboratory MDLs were multiplied by a variable factor (usually 4–7, determined from actual laboratory performance data). More than 80 percent of the laboratories surveyed had RDLs less than or equal to the calculated QL, indicating that adequate quantitation was attainable at this level and that the QL should be suitable for regulatory purposes.

Recently, water regulatory agencies and providers have shown considerable interest in determining the lowest quantifiable level that is suitable for regulatory purposes.[1–8] Allowable concentration levels for a contaminant in a particular environmental medium (e.g., soil, air, or water) are often based on health-related risk assessments and are sometimes lower than levels that can be quantitated in a laboratory. For this reason, the lowest quantifiable level frequently becomes the de facto regulatory limit for monitoring and compliance purposes.

The lowest quantifiable level has been given many different names. Current terms include the practical quantitation level

FIGURE 1 **Sample calibration curve for 1,1-dichloroethene using method 502.2**



95 percent confidence limits are shown as dashed lines, 95 percent prediction limits are shown as dotted lines

(PQL) defined by the US Environmental Protection Agency[9] (USEPA); the limit of quantitation defined by the American Chemical Society[10] (ACS); the reliable quantitation level (RQL) suggested by the USEPA Office of Ground Water and Drinking Water;[2] the minimum level (ML) used by USEPA Office of Wastewater Enforcement and Compliance;[5] the compliance monitoring quantitation level (Electric Power Research Institute);[11] and the method quality control level.[7]

Behind this array of terms and the conflicting rationales supporting them lies a common need: to establish the lowest quantifiable level that can be used to evaluate regulatory compliance. To be useful in this role, the regulatory level should be adequately quantifiable by the majority of laboratories certified for the particular compound and method of interest. At the same time, the regulatory level should be below the level achievable by poorly performing laboratories in order to provide incentive for these laboratories to improve their detection and quantitation levels. The procedure to calculate the regulatory level therefore needs to take into account actual performance data from the laboratory community.

In the past, three major approaches have been used for determining the lowest quantifiable level. First, interlaboratory studies may be conducted, in which a group of laboratories are challenged with low-level samples.[9,12,13] This approach may be the most defensible because it directly measures the quantitative abilities of an actual laboratory community. The lower limit of quantitation can then be set according to selected criteria of precision and accuracy. However, these studies are time-consuming and expensive; one of the specific goals of this study was to investigate more rapid and cost-effective alternatives to interlaboratory studies.

A second approach to setting the lowest quantifiable level employs statistical techniques based on uncertainties in the calibration curve.[6] This method is perhaps the most theoretically satisfying because a quantitation level can be derived from the same calibration curve used to analyze environmental samples. Related approaches have been described for determining a limit of detection from calibration data.[14,15] However, such approaches would require some changes in current calibration practices.

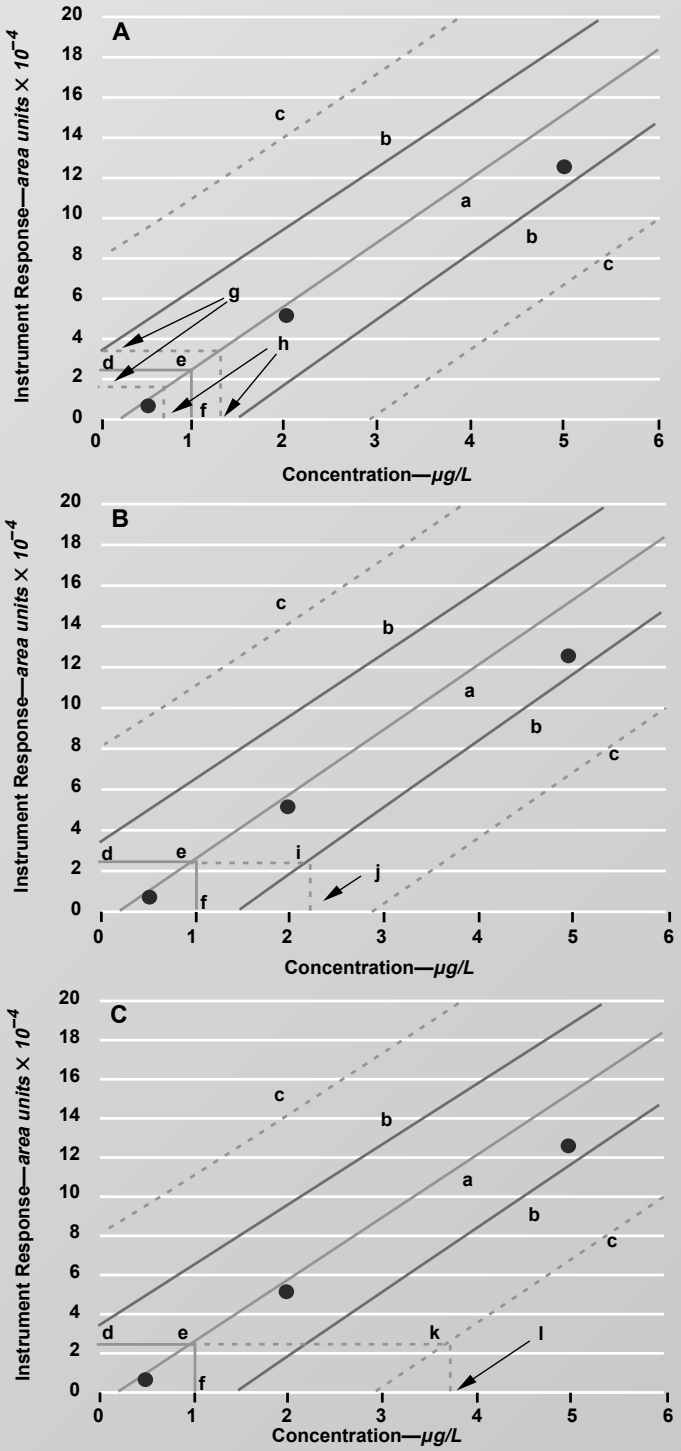
The final approach employs a multiplication factor, typically in the range of 3–10, applied to the detection limit.[2,5,9,10] Because it is widely used and does not require changes in current laboratory practices, the multiplier approach was the method investigated in this study.

The starting point for determining a lower limit of quantitation using the multiplier approach is having a value for the detection limit. For environmental compliance monitoring in the United States under USEPA regulations, a method detection limit (MDL) is currently determined according to specific guidelines.[16] The MDL is not suitable as a regulatory level for the following reasons: (1) it varies from laboratory to laboratory;[17] (2) precision of measurements at this level are generally poor;[18] and (3) although the MDL provides adequate protection against false-positive results, protection against false negatives is inadequate because samples containing contaminants at a concentration near the MDL will not be reported as detected 50 percent of the time.[15,17,19]

The lowest quantifiable level frequently becomes the de facto regulatory limit for monitoring and compliance purposes.

A proposed new parameter, the reliable detection level (RDL), is twice the value of the MDL and is sufficiently above the MDL value to ensure that samples

FIGURE 2 **Close-up of Figure 1, showing uncertainties in predicted concentrations for a sample containing 1,1-dichloroethene at the RDL of 1 µg/L**



a—calibration curve, b—95 percent confidence limit, c—95 percent prediction limit, d—mean value of instrument reading, e—point on calibration curve corresponding to mean instrument reading, f—true concentration of theoretical sample; for part A: points g—upper and lower limits (95 percent confidence level) for instrument response variability, points H—upper and lower limits of estimated concentration based on instrument variability; for part B: trace e–i—confidence interval for instrument reading of d, j—upper limit of established concentration based on confidence interval; for part C: trace e–k—prediction interval for instrument reading of d, l—upper limit of estimated concentration based on prediction interval

at this concentration will be reliably reported as detected; thus, the RDL provides adequate protection against both false positives and false negatives.[17] This parameter, originally proposed as a detection limit by Currie,[19] has recently been considered in discussions among USEPA, ACS, and the American Society for Testing and Materials.[1–4]

The RDL is suitable as a regulatory level provided adequate quantitation at this level is achievable. However, the RDL is derived from the MDL and will still vary among laboratories. Subsequently, each laboratory would report a different quantitation level (QL) for a particular method and compound. To determine a single regulatory level that most laboratories will be able to achieve, performance variations within the laboratory community must be taken into account.

In this article, the authors describe an approach for determining a lower limit of quantitation that most laboratories should be able to achieve, using data readily available from the laboratory community. The derivation of the precision of analytical measurements at the RDL is examined using two fundamental analytical relationships and the USEPA-defined MDL. This precision proves adequate to justify including RDL on the calibration curve as a quantitative level.

For purposes of this article, the authors define the QL as the level that is greater than or equal to the RDLs for a majority of laboratories in a certified laboratory community. This definition is similar to the definition of the reliable QL proposed by Keith.[4] The term QL is used to represent the process described here. To calculate the QL, the median interlaboratory MDL is multiplied by a variable multiplier determined from actual laboratory performance data gathered for the compound and method of interest.

MDL and RDL—theoretical considerations

An MDL can be derived from two fundamental concepts of instrumental analysis—the calibration relationship and the minimum distinguishable signal. These two concepts may also be used to determine the precision of measurements made at the USEPA-defined MDL. Throughout this article, it is assumed that a single laboratory is being considered.

The acceptable quantitation range for an analyte in solution is the concentration range for which there is a linear rela-

TABLE 1 **Method 502.2—QLs, laboratory achievability, and current MCLs and PQLs for selected chemicals**

Compound	Number of Labs	Median MDL µgL	Median Spike Level µg/L	Median Calibration Low Point µg/L	Lowest Ratio	QL µg/L	Percentage of Labs Able to Quantify at QL	MCL[23] µg/L	PQL[24,25] µg/L
Benzene	12	0.28	1	1	6	1.6	92	5	
Chlorobenzene	12	0.21	1	1	6	1.3	100	100	5
1,2-Dichlorobenzene	11	0.16	1	1	5	0.87	91	600	5
1,3-Dichlorobenzene	11	0.17	1	1	7	1.2	100	600	
1,4-Dichlorobenzene	11	0.15	1	1	6	0.94	100	75	
1,1-Dichloroethane	11	0.17	1	1	7	1.2	100		
1,2-Dichloroethane	11	0.15	1	1	7	1.0	100	5	
1,1-Dichloroethene	12	0.18	1	1	5	0.88	92	7	
cis-1,2-Dichloroethene	12	0.19	1	1	7	1.3	92	70	5
trans-1,2-Dichloroethene	12	0.22	1	1	6	1.2	92	100	5
Dichloromethane	11	0.50	1	1	4	1.8	91	5	5
Ethyl benzene	12	0.23	1	1	5	1.2	100	700	5
Naphthalene	12	0.28	1	1	5	1.5	92		
Styrene	12	0.28	1	1	5	1.5	92	100	5
1,1,2,2-Tetrachloroethane	11	0.20	1	1	5	1.0	100		
Tetrachloroethene	12	0.28	1	1	5	1.3	92	5	5
Toluene	12	0.20	1	1	8	1.6	100	1,000	5
1,2,4-Trichlorobenzene	12	0.21	1	1	6	1.2	92	70	5
1,1,1-Trichloroethane	11	0.22	1	1	6	1.3	100	200	
1,1,2-Trichloroethane	11	0.17	1	1	9	1.5	100	5	5
Vinyl chloride	10	0.27	1.5	1.5	4	1.2	90	2	
Xylenes	12	0.29	1	1	5	1.4	92	10,000	5

tionship between the instrument response and the concentration of the analyte within the constraints of a specified confidence level (usually 95 percent). This relationship defines the linear calibration curve:[20]

$$S = mC + S_{bl} \quad (1)$$

in which S = the magnitude of the analytical signal, m = the slope of the calibration curve, C = the analyte concentration, and S_{bl} = the magnitude of the analytical signal for a blank sample.

The minimum distinguishable analytical signal has been described as

$$S_{min} = S_{bl} + ks \quad (2)$$

in which S_{min} = the magnitude of the minimum detectable analytical signal, S_{bl} = the magnitude of the analytical signal for a blank sample, s = the standard deviation of the blank signal in instrument response units (such as millivolts), and k = a multiplier applied to the value of the standard deviation.[20]

If S in Eq 1 is set to S_{min}, C will correspondingly be equal to C_{min}, the sample concentration that gives the minimum distinguishable analytical signal. Both Eqs 1 and 2 can then be solved for $S_{min} - S_{bl}$, and the equations can be combined to give

$$ks = mC_{min} \quad (3)$$

Eq 3 provides the basis for determining the MDL and the precision of measurements at this concentration.

USEPA definition of the MDL. Both sides of Eq 3 may be divided by m:

$$ks_C = C_{min} \quad (4)$$

in which s_C = the standard deviation of the instrument response in concentration units. The USEPA defines the MDL as 3.14 times the standard deviation (in concentration units) of seven replicate measurements of a standard concentration (the spike level).[16]

An inherent assumption that is made when using unweighted least-squares calibration curves is that the standard deviation of the instrument response is constant at all concentrations, including blank samples, samples at the MDL, and samples at the MDL spiking level.[14] Although this assumption is not necessarily true for the entire working range of the calibration curve, it is approximately correct at concentrations at the low end of the concentration range.[15,17] Therefore, the magnitude of s_C in Eq 4 for the blank signal is also applicable at the MDL spike level. Substituting the multiplier of 3.14 for k in Eq 4, C_{min} (the concentration that gives a minimum distinguishable signal) becomes the USEPA-defined value for the MDL:

$$3.14s_C = C_{min} = \text{MDL} \quad (5)$$

Eq 5 is identical to the MDL equation appearing in USEPA regulations, and it uses a value for s_C that is calculated from seven replicate measurements of the concentration at a given spike level.

Precision of instrumental measurements at the MDL. Eq 3 also provides the basis for determining the theoretical precision of instrumental measurements at low concentrations. According to the USEPA approach, the slope m in Eq 3 is approximated by a response factor S/C, which is calculated from an average of seven replicate measurements at the MDL spike level. This calculation ignores the magnitude of the blank signal, S_{bl}, shown in Eq 1. S_{bl} is the y

TABLE 2 **Method 524.2—QLs, laboratory achievability, and current MCLs and PQLs for selected chemicals**

Compound	Number of Labs	Median MDL µgL	Median Spike Level µg/L	Median Calibration Low Point µg/L	Lowest Ratio	QL µg/L	Percentage of Labs Able to Quantify at QL	MCL[23] µg/L	PQL[24,25] µg/L
Benzene	12	0.22	1	2	5	1.1	83	5	
Carbon tetrachloride	21	0.20	1	2	5	1.0	95	5	
Chlorobenzene	12	0.17	1	2	8	1.3	92	100	5
Chloroform	20	0.22	1	2	5	1.1	90		
1,2-Dichlorobenzene	12	0.23	1	2	4	0.96	83	600	5
1,3-Dichlorobenzene	12	0.18	1	2	8	1.4	92	600	
1,4-Dichlorobenzene	12	0.19	1	2	5	1.0	92	75	
1,1-Dichloroethane	11	0.18	1	2	6	1.1	82		
1,2-Dichloroethane	12	0.25	1	2	4	1.0	92	5	
1,1-Dichloroethene	12	0.31	1	2	5	1.6	100	7	
cis-1,2-Dichloroethene	12	0.20	1	2	5	1.1	83	70	5
trans-1,2-Dichloroethene	12	0.17	1	2	5	0.79	75	100	5
Dichloromethane	12	0.41	1	2	3	1.3	92	5	5
1,2-Dichloropropane	21	0.24	1	2	6	1.4	95	5	5
Ethyl benzene	12	0.16	1	2	8	1.2	92	700	5
Naphthalene	11	0.42	1	2	4	1.5	73		
Styrene	12	0.16	1	2	7	1.1	92	100	5
1,1,2,2-Tetrachloroethane	20	0.31	1	2	4	1.2	85		
Tetrachloroethene	12	0.21	1	2	6	1.2	92	5	5
Toluene	12	0.15	1	2	8	1.3	92	1,000	5
1,2,4–Trichlorobenzene	12	0.31	1	2	3	1.0	83	70	5
1,1,1–Trichloroethane	12	0.19	1	2	7	1.4	92	200	
1,1,2–Trichloroethane	19	0.25	1	2	4	1.0	84	5	5
Trichloroethene	22	0.22	1	2	5	1.1	95	5	
Vinyl chloride	12	0.37	1	2	4	1.6	92	2	
Xylenes	11	0.31	2	2	6	1.8	91	10,000	5

TABLE 3 **QLs, laboratory achievability, and current regulatory levels for selected metals, pesticides, and wastewater contaminants**

Method	Compound	Number of Labs	Median MDL µg/L	Median Spike Level) µg/L	Median Calibration Low Point µg/L	Lowest Ratio	QL µg/L	Percentage of Labs Able to Quantify at QL	PQL or ML* µg/L
213.2	Cadmium	28	0.18	1	1	4	0.7	79	2[24,25]
220.2	Copper	15	1.0	5	5	4	4	93	
239.2	Lead	39	1.3	6	5	4	5.2	87	
507	Atrazine	5	0.24	2.3	0.8	2	0.5	80	1[24,25]
	Simazine	5	0.29	2.3	0.95	2	0.6	60	0.7[24,25]
624	Carbon tetrachloride	38	0.73	5	20	7	5.1	95	10[26]
	Chloroform	38	0.74	5	20	8	5.9	95	10[26]
	Dichlorobenzenes	31	1.0	5	20	5	5	84	10[26]
	Tetrachloroethene	40	0.90	5	20	6	5.4	93	10[26]
	1,1,1-Trichloroethane	39	0.83	5	20	6	5	87	10[26]
	Trichloroethene	38	0.89	5	20	6	5.4	97	10[26]
625	Benzo(a)anthracene	38	1.1	10	20	10	11	97	10[26]
	Benzo(a)pyrene	40	1.5	10	20	8	12	95	10[26]
	2,4-Dichlorophenol	33	1.3	10	20	6	8	79	10[26]
	Di(2-ethylhexyl)phthalate	39	2.7	10	20	5	14	90	10[26]
	Pentachlorophenol	37	3.1	20	20	5	16	78	50[26]
	2,4,6-Trichlorophenol	39	1.8	20	20	6	11	79	10[26]

*MLs reported are from the related methods 1624 and 1625.

intercept, and it cannot be determined from analysis at a single concentration point. Although ignoring S_{bl} is invalid if its magnitude is significant, in practice this quantity is generally small because the calibration curve usually passes close to the origin. The response factor is assumed to be constant at all concentrations, including the concentration that gives a minimum distinguishable signal (S_{min}/C_{min}). Eq 3 can then be reexpressed as

$$ks = (S_{min}/C_{min}) \times C_{min} \quad (6)$$

or

$$ks = S_{min} \quad (7)$$

Rearrangement of Eq 7 indicates that the multiplier k is quantitatively equal to the signal-to-noise ratio at the minimum distinguishable signal (S_{min}):

$$k = S_{min}/s \equiv S_{min}/N \quad (8)$$

in which N (noise) has been substituted for s.

The signal-to-noise ratio is also described as the inverse of the relative standard deviation (RSD) of the instrument response:[20]

$$S/N = 1/RSD \quad (9)$$

If S is taken as S_{min}, Eqs 8 and 9 may be combined:

$$k = 1/RSD_{min} \quad (10)$$

in which RSD_{min} = the relative standard deviation of the instrument response for the minimum distinguishable signal. The value of k is therefore inversely proportional to the RSD of the minimum distinguishable signal for a replicate analysis. As discussed earlier, S_{min} is defined as the instrument signal at the MDL when k is set at 3.14. This value for k is selected because it is Student's t value for seven replicate measurements at the 99 percent confidence level, which ensures protection against false-positive detection decisions. The inverse of this value—0.318 or 31.8 percent—is the RSD of the instrument response at the MDL.

Precision of instrumental measurements at the RDL. These derivations show that the multiplier k, set to 3.14 by the USEPA, determines both the value for the MDL and describes the precision of the instrument response at this level. As discussed earlier, the RDL is preferable as a concentration level to make a detection decision because it also protects against false-negative detection decisions. Because the RDL has been defined as twice the MDL,[17] the multiplier k to obtain this value would be twice that used for the MDL, or 6.28. If the absolute magnitude of the instrument noise is assumed to be constant at low levels, the RSD of the instrument response would be 1/6.28 or 0.159 (15.9 percent) at the RDL.

Precision of reported concentrations at the RDL. To translate the precision of the instrument response to a precision for a reported concentration at the RDL, a calibration curve must be used. Figure 1 shows a sample calibration curve for 1,1-dichloroethene using method 502.2. The r^2 value for this curve (0.998) is typical from a good laboratory. The confidence intervals shown are routinely used as control limits.

The RSD of the instrument response at the RDL (15.9 percent) represents one standard deviation of the instrument noise and can be multiplied by a factor of 2.45 (Student's t multiplier for seven replicate measurements, two-tailed test) to give an estimate of ±39 percent as the uncertainty of the instrument signal at an equivalent confidence level (95 percent).

The laboratory in this example (Figure 1) reported an RDL of 1 µg/L. It can be shown through example that the precision of the instrument response at the RDL lies within the confines of the confidence interval for the calibration curve and that the uncertainty in the predicted concentration caused by instrument noise will be small relative to the concentration interval bounded by the confidence limits.

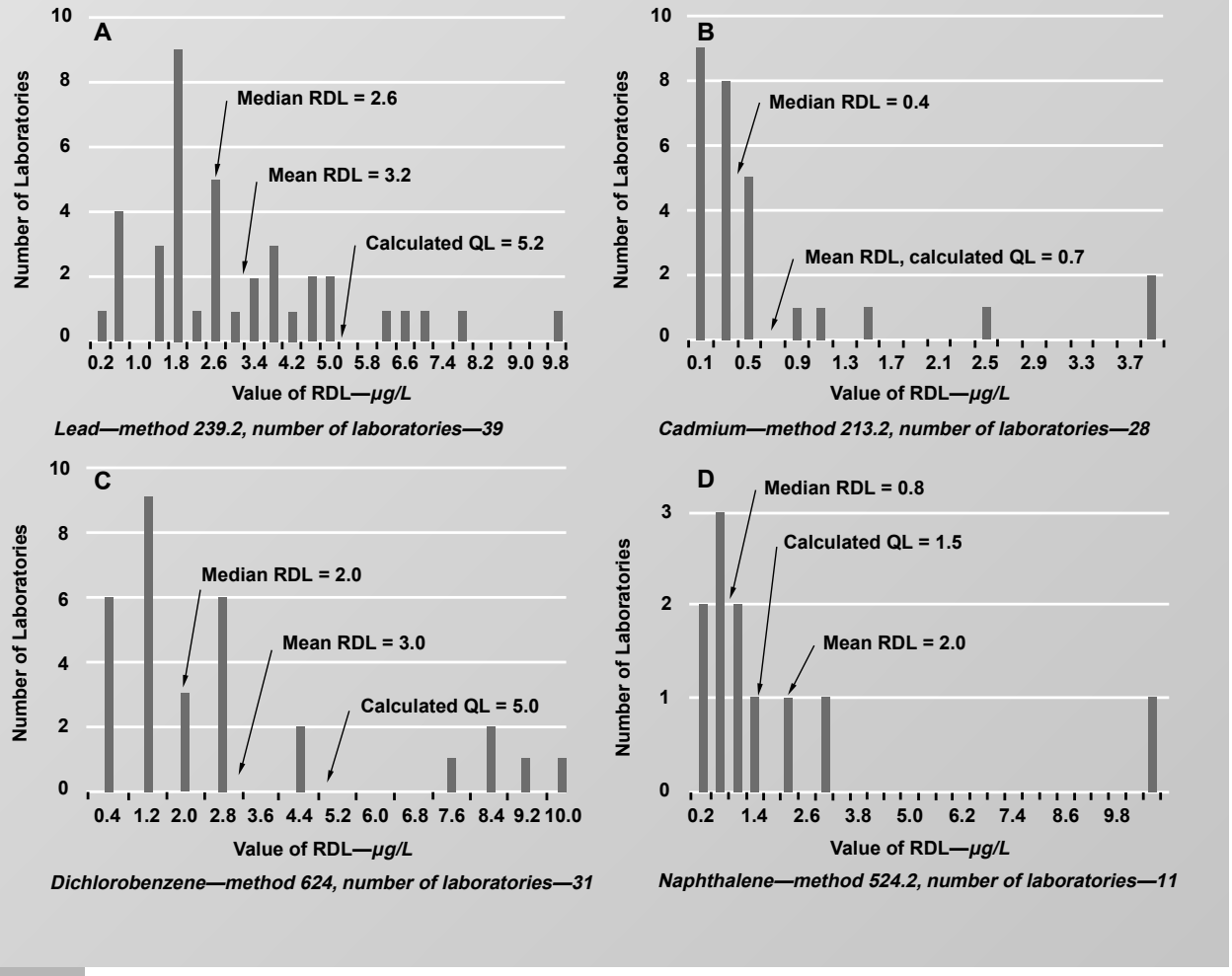
As shown in the closeup of the low end of the calibration curve (parts A–C, Figure 2), the instrument response at the RDL (1 µg/L) is 24,000 area units (trace d–e–f). The 95 percent confidence interval for the signal uncertainty at this level (±39 percent) corresponds to ±9,400 area units (part A of Figure 2, points g). When a 1-µg/L sample is analyzed, this translates to a reported concentration of 1.0 ± 0.3 µg/L (part A of Figure 2, point f ± points h) because of variation in instrument response.

The estimated precision of a measurement of 24,000 area units, based on the uncertainty of the calibration curve, is described by the confidence interval (part B of Figure 2, interval e–i). This would lead to a reported concentration of 1.0 ± 1.2 µg/L (part B of Figure 2, point f ± point j). This concentration range is much larger than the range resulting from variations in the instrument response. Furthermore, although the confidence interval is commonly used in practice, it is theoretically valid only for the mean of replicate measurements.[21] For concentration predictions from individual measurements, it is theoretically more correct to use the prediction interval.[21] The estimated precision of a measurement of 24,000 area units based on the prediction interval can be described by concentration interval e–k (part C, Figure 2). This would lead to a reported concentration of 1.0 ± 2.7 µg/L (part C of Figure 2, point f ± point l).

Behind the array of terms and the conflicting rationales supporting them lies a common need: to establish the lowest quantifiable level that can be used to evaluate regulatory compliance.

Clearly, instrument precision at the RDL is much greater than that associated with the calibration curve in this area. As stated earlier, the calibration curve used in this example is typical and was being used by this laboratory to report concentrations down to its MDL (0.5 µg/L). Obviously, reporting concentrations at the RDL (1.0 µg/L) would be acceptable to this laboratory. The RDL, when defined as twice the USEPA MDL, also offers adequate protection against both false-negative and false-positive detection decision errors; therefore, this para-

FIGURE 3 **Distribution of RDLs for selected contaminants and methods**



meter appears to be a justifiable quantitation level for a single laboratory.

For the purposes of this article, the QL is defined as an interlaboratory parameter, specifically a QL suitable for use by a group of laboratories. The RDL is not in itself adequate as a regulatory level because RDLs will vary from laboratory to laboratory. For this reason, the authors' study incorporated a second component: an investigation of the variability of RDLs determined by different laboratories. Only by comparing a candidate QL with the distribution of the RDLs reported by a representative laboratory community is it possible to determine whether a proposed QL can be quantitated by most laboratories.

Calculation of quantitation levels

Utilization of laboratory performance data. The authors chose 36 environmentally important chemicals that were analytes in one or more of eight standard USEPA methods. Selection was based on either New Jersey regulatory needs or occurrence of these compounds in New Jersey waters (Tables 1–3). The methods chosen were either frequently used or featured state-of-the-art techniques. The methods were suited for water, drinking water, and wastewater analysis.

The 200-series methods are used to determine individual metal analytes in water. The remaining methods determine multiple analytes. The three 500-series methods are used for organic chemicals in drinking water, and the two 600-series methods determine organic compounds in wastewater.

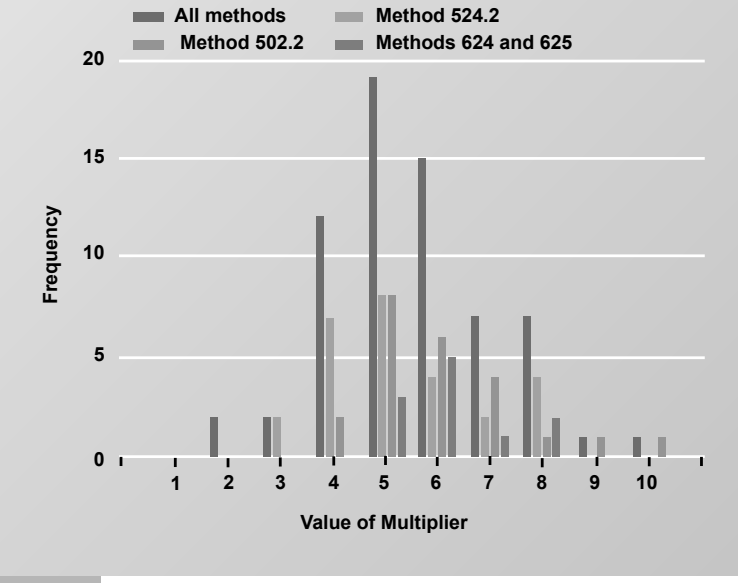
Fifty-one laboratories certified by the states of New Jersey or California were surveyed for information routinely reported for quality assurance purposes. Three types of relevant data were easily obtainable from the various laboratories: the determined MDL value, the low point on the calibration curve, and the spike level used to determine the MDL. The spike levels and calibration curve low points were generally set by analysts, taking into consideration the MDL reported in the method of interest.

Data were rejected for this study if the MDL spike level was greater than 50˘ the reported MDL for a

particular laboratory or if the information provided on the calibration curve range was inconsistent with the cited method. USEPA guidelines suggest that the spike level should be 1–5X the reported MDL and allow a ratio of up to 10;[16] for this study, however, a ratio of up to 50 was allowed in order to minimize the number of rejected laboratories. Using the more conservative 1–10 range would have resulted in discarding several data points. Although the majority of laboratories followed the ratio guidelines, a few laboratories exceeded a ratio of 10, but only rarely did they exceed a ratio of 20.

One problem with allowing a spike ratio greater than 10 is that the standard deviation of the instrument noise may begin to vary between the MDL and the spike level, thereby invalidating the assumptions inherent in Eq 5. The calculated MDL would then be affected by the spike level. However, investigation of the data gathered for this study showed that the reported MDL was independent of the spike ratio, despite the occurrence of ratios greater than 10. This suggested that the assumptions of Eq 5 were not being violated. The goal of this study was to determine a QL that was achievable by most of the certified laboratories; exclusion of data from several of the laboratories would have resulted in a QL that was not reflective of the actual capabilities of the laboratory community as a whole. Therefore, the MDL acceptance criteria for this study was more lenient than that of the USEPA in that higher spike ratios were allowed.

FIGURE 4 Distribution of multiplier values for calculation of QL



Variability of RDLs. For a given chemical and method, RDL distributions from the laboratories were prepared in order to ascertain the variability of this parameter from laboratories certified for that method (parts A–D, Figure 3). The MDLs reported by the laboratories were multiplied by a factor of 2 to obtain the RDLs.

RDL values were not normally distributed. Most were clustered within a well-defined range. However, a few RDLs were reported at significantly higher levels. As demonstrated earlier, an individual laboratory could adequately quantify a concentration at its own RDL. Therefore, for a given compound and method, a QL that most laboratories could achieve would be at or near the upper end of the main RDL distribution. Laboratories with RDLs above the bulk of the distribution (parts A–D, Figure 3) would be considered poorly performing laboratories and may be excluded.

Calculation of QLs from laboratory performance data. Although a QL could be set by visual examination of RDL distributions (such as those shown in parts A–D, Figure 3), such a procedure would be subjective. A reproducible approach needed to be developed. As noted earlier, the approach selected for this study applies a multiplier to the interlaboratory MDL. Alternatively, the multiplier could be divided by a factor of 2 and applied to the interlaboratory RDL; however, laboratories report the MDL, making this the more convenient parameter.

The first step of the process was to select a representative interlaboratory MDL for the group of laboratories surveyed. This study used the median of the individual MDL values from each laboratory for a given compound and method. The nonparametric median value was chosen rather than the mean in order to minimize the influence of values at the upper end of the MDL distributions. The values at the high end of the distributions represent laboratories that performed poorly relative to most of the surveyed laboratories.

To determine a single regulatory level that most laboratories will be able to achieve, performance variations within the laboratory community must be taken into account.

This method of calculating the central tendency of the MDL dataset was tested by several data-rejec-

tion criteria. In each method used, the outlying value was significant at the 10 percent, 5 percent, and 1 percent levels. The outlying value was rejected, and the mean value was recalculated and compared with the median value prior to filtering the dataset. In every instance, the mean value converged to the previously calculated median value. Visually, the advantages of the median over the mean are illustrated in terms of RDL distributions (parts A–D, Figure 3); RDL distributions appear identical to MDL distributions but are at values twice the MDL concentrations. It was visually apparent that when the mean and median RDLs differed significantly, the median RDL better represented the central tendency of the bulk of the distribution.

TABLE 4 Data sheet for trichloroethene—method 524.2*

Lab Code	MDL µg/L	MDL Spike Level µgl	Calibration Low Point µgl	MDL Spike Level—MDL	Calibration Low Point÷ MDL
C010	0.04	0.1	0.5	3	13
77434	0.07	1	4	14	57
18725	0.09	1	2	11	22
C003	0.1	0.5	2	5	20
07059	0.1	1	2	10	20
20044	0.12	0.4	0.5	3	4
74603	0.16	1	1	6	6
55735	0.16	1	2	6	13
C005	0.19	1	0.5	5	3
77360	0.2	2	2	10	10
61667	0.2	0.5	2	3	10
C002	0.23	1	2	4	9
16107	0.24	1	0.3	4	1
73331	0.24	2	0.5	8	2
C001	0.29	1	1	3	3
01289	0.4	2	2	5	5
49529	0.4	1	1	3	3
C008	0.41	2	5	5	12
C009	0.43	2	2	5	5
C007	0.46	2	5	4	11
77166	0.49	2	2	4	4
73469	0.8	4	4	5	5
Mean	0.26	1	2	6	11
Median	0.22	1	2	5	7
Maximum	0.8	4	5	14	57
Minimum	0.04	0.1	0.3	2.5	1
Standard deviation	0.18	0.8	1.4	3	12

*Lowest ratio—5, QL—1.1 µg/L

To calculate a QL, the authors applied a variable multiplier to the median interlaboratory MDL. The multiplier was determined from the MDL spike level and calibration-curve low-point data supplied by the laboratories for this study. Determining the QL for each compound for a given method involved three steps:

(1) For each laboratory, the ratio of the reported MDL spike level to the determined MDL was calculated in order to arrive at the spike ratio. The median ratio was then calculated.

The RDL protects against both false-positive and false-negative detection decisions, but RDLs will vary from laboratory to laboratory.

(2) For each laboratory, the ratio of the calibration-curve low point to the determined MDL was calculated in order to arrive at the calibration ratio. The median ratio was then calculated.

(3) The lower of the two median ratios calculated in steps 1 and 2 was selected as the multiplier of the MDL to determine the QL.

This variable multiplier approach offers two advantages. First, the approach is practical because the data needed for its determination are data routinely reported by laboratories (i.e., the MDL, the MDL spike level, and the low point on the calibration curve). Second, the multiplier is based on actual laboratory performance data rather than on theoretical considerations. Individual calibration and MDL spike ratios for each laboratory represent multipliers that, if used for that particular laboratory, would result in a QL set at either the laboratory's MDL spike level or low point on the calibration curve. The laboratory must adequately measure both of these levels to routinely run the method in a quantitative mode. Therefore, the multiplier for a particular laboratory is known to give a quantitation level that is achievable. In step 3, the median MDL is multiplied by the lowest median ratio that is known to give a quantifiable level. This results in a median QL that is known to be achievable by at least half the laboratories. (Later this article will illustrate that this QL is, in fact, achievable by most of the laboratories.) The procedure results in a QL that is method- and chemical-specific.

This method offers two additional useful features. First, the QL value is derived from laboratory performance data, which means that it serves as a baseline for monitoring the improvement of analytical

sensitivities over time. Second, this QL is useful to the regulatory community in that it is indicative of the current analytical capabilities for a particular compound and method.

Results and discussion

Table 4 is an example of the data worksheet for trichloroethene, method 524.2, showing data collected from the laboratories and the calculation of the QL using the floating multiplier approach. In this example, the median MDL (0.22 µg/L) was slightly lower than the mean (0.26 µg/L). The median spike ratio (5) was lower than the median calibration ratio (7). The median MDL was multiplied by 5, resulting in a QL of 1.1 µg/L for this compound.

As shown in Table 4, individual laboratory multipliers usually ranged from 3 to 10. There were also a few multipliers between 10 and 20. Only occasionally did the ratio exceed 20. The median multiplier used for QL calculation usually ranged from 4 to 7 (Tables 1–3, Figure 4). For methods 502.2 and 524.2, the mode of the multiplier distribution was 5. When only wastewater methods were considered (600 series), the mode of the multiplier was 6. This results from the somewhat higher spike levels and calibration-curve low-point values typically used in the 600-series methods (the higher levels being used in order to allow for matrix effects in these wastewater methods).

The final step in assessing the suitability of the calculated QLs is to ascertain what percentage of the laboratories could adequately quantify at these levels. As discussed earlier, the variable multiplier approach results in a median QL that, by definition, should be quantifiable by at least half of the laboratories because the multiplier links the MDL to the calibration-curve low point or to the MDL spiking level. However, both of these analytical levels are typically above the minimum quantifiable level because they are usually somewhat greater than the RDL, which is a factor of only twice the MDL. Because the RDL represents a suitable minimum quantifiable level, the calculated QL must be compared with the RDL distributions of the individual laboratories to determine what percentage of laboratories have RDLs less than or equal to the calculated QLs. As shown in parts A–D of Figure 3, the QL typically fell at or near the upper end of the main RDL distribution and eliminated the outlying values reported by poorly performing laboratories. The percentage of laboratories reporting RDLs less than or equal to the calculated QLs for all methods and compounds are tabulated in Tables 1–3. With only a few exceptions, more than 80 percent of the laboratories were able to adequately quantify at the QL based on their value for the RDL.

Tables 1–3 also list USEPA maximum contaminant levels (MCLs), PQLs, and draft MLs for the compounds studied. The MCLs and PQLs are applicable to drinking water and are shown for methods 502.2, 524.2, and 507 and for cadmium. The MLs are applicable to wastewater and are shown with the two wastewater methods (624 and 625). All QLs reported in this study were below the applicable MCLs for the compounds studied. The QLs were also lower than the PQLs reported by USEPA. The QLs typically were in the range of 1–2 µg/L for the drinking water methods, whereas the PQLs were reported as 5 µg/L. The QLs are lower than the USEPA PQLs for two reasons: (1) quantitation levels have improved (decreased) since the USEPA PQLs were published and (2) the procedure for determining QLs described in this article differs from that used by the USEPA in calculating PQLs. The USEPA used multiple approaches, including interlaboratory studies, a multiple of 5˘ the MDL, and a multiple of 10˘ the MDL.[6]

Maximum contaminant level goals (MCLGs) for several of the contaminants in Tables 1 and 2 are 0 because the contaminants have been classified as carcinogens.[22] Benzene, carbon tetrachloride, 1,2-dichloroethane, dichloromethane, 1,2-dichloropropane, tetrachloroethene, and trichloroethene all have MCLs or PQLs of 5 µg/L but MCLGs of 0. The study presented in this article suggests that the laboratory community may be able to quantitate these compounds at levels of 1–2 µg/L if the MCLs were decreased to these levels.

A suitable QL would be a level that is at or above the RDLs of most laboratories certified for the method and compound of interest.

Draft MLs reported in Table 3 were approximately twice as high as the QLs for method 624 but are roughly comparable to the QLs for method 625 (except for pentachlorophenol). (The draft MLs were not specifically developed for methods 624 and 625 but for the related methods 1624 and 1625.)[26]

Conclusions

Multiplication of MDLs or RDLs by an appropriate factor to determine a suitable QL has been a commonly employed technique. It is still being considered by agencies such as USEPA and ACS, as in their recent discussions of the RQL and the ML.[1–5] This study analyzed quality assurance data from 51 certified laboratories in California and New Jersey in order to develop a variable multiplication factor for calculating QLs from existing data.

The authors arrived at a QL that was quantifiable by a majority of the analytical laboratories partici-

pating in the study. This QL, which is compound- and method-specific, most frequently is in the range of 4–6X the median interlaboratory MDL. Based on this study, data for a particular compound and method from as few as five laboratories may provide meaningful results.

The data needed for the QL calculation procedure described in this article are available without any changes in current laboratory analytical practices. The procedure could be used to calculate compound-specific multipliers to determine QLs as illustrated in this study. Alternatively, the observed clustering of multiplier values in the range of 4 to 7 could be used to justify selection of a constant multiplier in this range. This procedure should be applicable to any standard method and chemical for which adequate data are available. The procedure provides a basis for judging the current state-of-the-art quantitative ability of the laboratory community and a scientific basis for regulations that require an actual reportable concentration value for standards use.

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