Total chromium and hexavalent chromium occurrence analysis

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Total and hexavalent chromium occurrence in the United States was investigated using three available datasets. The National Chromium and Boron Occurrence Survey, the US Environmental Protection Agency database of chromium from the Second Six-Year Review, and California Department of Public Health water quality analysis data were obtained and analyzed. The high number of nondetect samples and subsequent nondetect handling had an important effect on the determination of representative chromium concentrations. Chromium was found to occur widely throughout the United States. Total and hexavalent samples were paired, and they indicated that surface water speciation is dominated by trivalent chromium, whereas groundwater speciation is dominated by hexavalent chromium. The potential impact of further chromium regulation ranges more than two orders of magnitude, with as few as 1,000 entry points being affected nationwide at 20 µg/L and as many as 100,000 entry points being affected nationwide at 1 µg/L.

**Keywords:** drinking water regulation, inorganic contaminants, occurrence data and mapping, Six-Year Review 2, UCMR

Regulation of hexavalent chromium in drinking waters is proceeding in California and is a priority for the current US Environmental Protection Agency administration (USEPA, 2011). To regulate at the national level, occurrence, health effects, and treatability must be quantified so that a cost–benefit analysis can be used to determine whether there is a meaningful opportunity for health risk reduction (SDWA, 1996). Hexavalent chromium is not currently regulated in drinking waters, but total chromium has a National Primary Drinking Water Regulation maximum contaminant level (MCL) of 100 µg/L, based on a health effects endpoint of allergic dermatitis. The MCL for total chromium in California is 50 µg/L.

Dissolved chromium typically occurs in two oxidation states—trivalent or hexavalent. Total chromium is the sum of the trivalent and hexavalent species. When chromium occurs in the presence of oxidants such as chlorine or chloramines, the trivalent species may be oxidized to the hexavalent species (Saputro et al, 2011; Lai & McNeill, 2006; Brandhuber et al, 2004; Bartlett, 1997; Clifford & Chau, 1988; Ulmer, 1986; Sorg, 1979). Thus, regulating hexavalent chromium at the entry point of the distribution system without regard to total chromium concentration may not be sufficiently protective of public health. This article summarizes occurrence trends of both total and hexavalent chromium based on currently available data. Additional information can be found elsewhere (Seidel et al, 2012).

Frey et al (2004) provided the most comprehensive study of chromium occurrence to date in the National Chromium and Boron Occurrence Survey. Other studies of chromium occurrence have primarily consisted of reporting naturally occurring chromium concentrations. For instance, Motzer (2005) cited naturally occurring total chromium concentrations of between 0 and 40 µg/L in groundwater and surface water from several sources.

**DATA SOURCES**

Chromium occurrence data were obtained from available sources to guide the development of the national occurrence survey. Three primary datasets are used in this analysis: the National Chromium and Boron Occurrence Survey (NCBOS), USEPA’s Second Six-Year Review (6YR2), and the California Department of Public Health (CDPH) Water Quality Analysis Database (WQAD). A summary of the datasets is shown in Table 1.

**NCBOS.** The NCBOS data were compiled, analyzed, and reported in the Water Research Foundation Report “Occurrence Survey of Hexavalent Chromium and Boron” (Frey et al, 2004). The survey utilities were recruited on a voluntary basis, rather than as a designed survey, to adequately represent regional, system size, and source water occurrence. Field samples were collected in 2003 and transported to a central laboratory where analyses of total and hexavalent chromium were performed. Minimum reporting levels (MRLs) were 0.6 µg/L for total chromium and 0.2 µg/L for hexavalent chromium. In sum, 342 total chromium and 341 hexavalent chromium raw water samples were reported. Total and hexavalent samples were taken at the same relative location for each of 342 sources from 189 systems in 41 states. Only the raw water samples collected by NCBOS were considered in this study.

A full report of this project, Total Chromium and Hexavalent Chromium Occurrence Analysis (4414), is available for free to Water Research Foundation subscribers by logging on to www.waterf.org.
USEPA 6YR2. The 6YR2 dataset consists of nationwide entry point samples for total chromium. USEPA collected the 6YR2 data by a voluntary call-in of compliance data from state and primary agencies for samples collected between 1998 and 2005 (USEPA, 2010). Data were supplied by all states with the exception of Pennsylvania, Louisiana, Mississippi, and Washington. The samples were analyzed by many different laboratories and methods, resulting in MRLs from 0.02 to 100 µg/L. A total of 162,823 samples were included in the dataset after the USEPA applied a data quality auditing procedure (USEPA, 2010). The USEPA's data cleaning involved standardizing units of concentration for the contaminants and ensuring that parameters such as system type were consistent with data in the federal Safe Drinking Water Information System (SDWIS). Systems classified as groundwater include groundwater sources only. However, systems classified as surface water may include groundwater and groundwater under direct influence of surface water among its sources. Some of the data submissions included source water samples. When possible, the source water data points were removed by the USEPA. Also, each sampling point was inferred to be an entry point to the distribution system. In the USEPA's data-cleaning procedure, nondetects that did not include an MRL were assigned the mode MRL value for that state when other data in the state were available (USEPA, 2010). If no other MRL value was available for that state, the national mode MRL value of 10 µg/L was substituted. Figure 1 shows the distribution of the nondetect results from the 6YR2 dataset and indicates that about half of the nondetect results have an MRL of 10 µg/L; many of these were the result of samples that did not include an MRL. Data from California suggest that approximately 45% of the nondetect samples did not have an associated MRL, resulting in substitution of the mode value.

Of the 162,823 samples in the 6YR2 database, 136,826 (84%) were reported as nondetects. Grouping the data by entry point resulted in 74,672 sample locations, with 58,010 (78%) entry points where total chromium was never detected.

The high percentage of nondetect samples at variable MRLs has a profound effect on the analysis of the data because the concentration of a nondetect sample can be any value from zero up to the MRL. To characterize the effect of the nondetect results, cumulative probability distributions of the dataset were computed under four conditions: (1) zero was substituted for a nondetect result, (2) one quarter of the MRL was substituted for the nondetect result, (3) half of the MRL was substituted for the nondetect result, and (4) the MRL was substituted for the nondetect result. Substituting zero for the nondetects results in a bias toward lower concentrations because some of the nondetects would have had detectable chromium if it had been measured by a more sensitive method (Raucher et al, 1995). Similarly, substituting the MRL for a nondetect results in a bias toward higher concentrations because the actual sample concentrations were likely lower than the MRL.

![FIGURE 1](Histogram of nondetect MRLs of the 6YR2 dataset (all nondetect samples))

![TABLE 1](Summary of occurrence data sources)

<table>
<thead>
<tr>
<th>Database</th>
<th>NCBOSS</th>
<th>6YR2</th>
<th>CDPH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geographic coverage</td>
<td>41 states</td>
<td>46 states and 2 tribes</td>
<td>California</td>
</tr>
<tr>
<td>Source water sampled</td>
<td>Raw drinking water</td>
<td>Treated drinking water</td>
<td>Raw and treated drinking water</td>
</tr>
<tr>
<td>Total chromium data</td>
<td>MRL = 0.6 µg/L, n = 342, 39% &lt; MRL</td>
<td>MRL 0.02–100 µg/L, n = 162,823, 84% &lt; MRL</td>
<td>MRL 1–50 µg/L, n = 108,782, 49% &lt; MRL</td>
</tr>
<tr>
<td>Hexavalent chromium data</td>
<td>MRL = 0.2 µg/L, n = 341, 57% &lt; MRL</td>
<td>None</td>
<td>MRL ≤1 µg/L, n = 27,507, 13% &lt; MRL</td>
</tr>
<tr>
<td>Strengths</td>
<td>Low and consistent MRL</td>
<td>Number and geographic distribution of samples</td>
<td>Number of samples for total and hexavalent chromium</td>
</tr>
<tr>
<td>Weaknesses</td>
<td>Number and geographic distribution of samples</td>
<td>Some high MRL data; no hexavalent chromium data</td>
<td>Some high MRL data; limited geographic distribution</td>
</tr>
</tbody>
</table>

6YR2—Second Six-Year Review, CDPH—California Department of Public Health, MRL—minimum reporting level, NCBOSS—National Chromium and Boron Occurrence Survey

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in most cases. Substituting one quarter or one half of the MRL for the nondetect samples attempts to balance these biases, but the bias is unknown.

To calculate cumulative probability distributions, the samples were grouped by entry point to analyze the results on the basis of the drinking water source (all water source types for both community water systems [CWSs] and nontransient, non-CWSs). The cumulative probabilities were calculated at the median (50th percentile), 75th percentile, 95th percentile, and maximum concentration at each entry point. The 75th percentile, 95th percentile, and maximum value yielded very similar curves, with the 95th percentile and the maximum value curves being indistinguishable. The similarity of the 75th, 95th, and maximum curves occurs because the sample size of most entry points is low (162,823 samples divided by 74,672 entry points equals an average of 2.2 samples per entry point). The 75th percentile was used throughout this study to be consistent with the US Geological Survey analysis of arsenic data (USGS, 2012) and its similarity to the 95th percentile results. The median value varied from zero to 10 µg/L as influenced by the nondetects with an MRL of 10 µg/L, many of which would have been assigned a value of 10 µg/L because no MRL was reported with the data.

Another method to analyze the impact of the nondetect results is a Bayesian estimate of the posterior cumulative probability. The USEPA provided a Bayesian analysis of the nondetects from total chromium concentrations between 0.5 and 15 µg/L using WinBUGS software (www.mrc-bsu.cam.ac.uk/bugs/winbugs/contents.shtml) at the mean concentration of each entry-point location.

Figure 2 shows the cumulative probability of the 6YR2 dataset with nondetects substituted with zero, nondetects substituted with one quarter of the MRL, the cumulative probability of the NCBOS dataset, and the Bayesian estimate provided by the USEPA. The NCBOS and USEPA Bayesian curves show similar behaviors. The similarity of these curves was somewhat unexpected because the NCBOS dataset was based on voluntary participation of water utilities willing to sample their source waters and therefore was considered to be biased toward utilities where chromium was suspected or known to occur. NCBOS was generated on a sample-by-sample basis because only one sample was taken per sample location and the samples were raw water samples. Notably, the NCBOS data show the smooth, nearly log-normal curve to the origin, resulting from the low reporting limits used in the study. Raucher et al. (1995) observed that occurrence data often display log-normal behavior. Substitution of one quarter of the MRL in the 6YR2 data is close to the NCBOS and Bayesian estimates while still being conservative, particularly > 5 µg/L. Therefore, substitution of one quarter of the MRL for nondetects was used for all further analyses of total chromium.

CDPH data. CDPH maintains the WQAD, which includes total and hexavalent chromium data for the state of California that were collected between 1974 and 2011 (CDPH, 2011). The limited data collected before 1995 were excluded because they were not of sufficient quality. Data are representative of raw and treated waters from throughout the state. The database included 136,286 results—108,779 for total chromium and 27,507 for hexavalent chromium as of Nov. 18, 2011. Because CDPH provided data for the USEPA 6YR2 database, there is an overlap of up to 23,397 total chromium samples between the CDPH data and 6YR2 datasets for California (22% of the CDPH database, 14% of the 6YR2 database).

The CDPH dataset includes 108,779 total chromium samples, of which 90,560 (83%) were reported as nondetects. Grouping the total chromium data by sample location, the authors found there are 17,847 locations in the CDPH dataset, with 11,104 (62%) locations where total chromium was never detected. The lower percentage of nondetects on a source-location basis can be attributed to two factors. First, the CDPH data are weighted on more recent data with lower detection limits. Second, from a spatial distribution perspective, California has some of the highest levels of chromium. The CDPH dataset also includes 27,507 hexavalent chromium samples, with 11,387 (41%) reported as nondetects. Grouping the hexavalent chromium data by sample point, the authors determined that there are 7,880 hexavalent chromium sample points in the CDPH dataset, with 3,096 (39%) locations where hexavalent chromium was never detected.

The CDPH total chromium dataset includes 35,968 nondetect sample results at an MRL of 10 µg/L (39% of all nondetects) and another 40,255 had no reported MRLs and were therefore set to the mode value of the CDPH dataset of 10 µg/L (brining the total to 84% of all nondetects). Thus the CDPH total chromium dataset
Cumulative probability distribution of chromium in CDPH for raw versus treated by sample location (75th percentile concentration per each sample location)

FIGURE 3

Cumulative probability distribution of total chromium data from the three datasets (6YR2 and CDPH data are the 75th percentile concentration per sample location)

FIGURE 4

is similarly influenced by the nondetect results as is the 6YR2 dataset. For comparable analysis, the CDPH chromium data have been analyzed with nondetects substituted, with one quarter of the MRL and missing MRL values set to the mode value of 10 µg/L. The MRL for the CDPH hexavalent chromium is generally ≤ 1 µg/L. The lower MRL adds little bias to the analysis of hexavalent chromium in the range of 1 to 50 µg/L, which is the range of interest in this study. Therefore, nondetect values were set to zero for the CDPH dataset for hexavalent chromium.

Cumulative probability distributions were calculated from the CDPH data for raw and treated waters to determine whether they should be analyzed as a group or separately. Figure 3 shows the cumulative probability for raw and treated waters for both total and hexavalent chromium (not all data included raw or treated identifiers). The analysis was performed with the 75th percentile concentration on a sample-location basis. The data shown in Figure 3 indicate more occurrence of total chromium than hexavalent chromium. Higher total chromium was expected because some occurrence of the trivalent chromium species is probable. Treated water data in Figure 3 show a lower occurrence of both total and hexavalent chromium compared with raw waters. The lower occurrence could be due to treatment removing some chromium, but a more likely explanation is that sources with high concentrations of chromium are not used for drinking water except where they cannot be avoided. In addition, the disparity in the number of samples (i.e., treated waters only account for about 5% of the data) could also result in selection bias. Because the distributions of raw and treated water differ, they are analyzed separately throughout the remainder of this study.

ANALYSIS OF TOTAL AND HEXAVALENT CHROMIUM OCCURRENCE

Comparison of chromium occurrence between datasets. The NCBOS, 6YR2, and CDPH datasets all include total chromium. However, the datasets differ in the number of samples, sample type (raw versus treated), MRLs, and associated proportion of nondetect values. CDPH data include raw and treated waters, the NCBOS data contain only raw waters, and the 6YR2 data contain data from treated drinking waters only. The datasets are compared by plotting the cumulative probability distribution of each (Figure 4). The cumulative probabilities were calculated from the 75th percentile concentration per sample location. The data in Figure 4 indicate the CDPH raw waters exhibited the most occurrence, and the NCBOS exhibited the least occurrence. The 6YR2 and CDPH treated waters showed roughly equivalent occurrence. The difference observed between these two curves is due to the 6YR2 dataset having a proportionately higher number of nondetects with an MRL of 20 µg/L denoted by the vertical step in the 6YR2 data at 5 µg/L (0.25 × 20 µg/L). The treated data indicate about 15% of sample points exceed a total chromium...
concentration of 5 µg/L and < 10% exceed a concentration of 10 µg/L. Comparing the datasets illustrates the influence of managing nondetectable sample results by statistical methods as exhibited by 6YR2 and CDPH versus using detectable sample results as exhibited by NCBOS. Although statistical methods exist to construct an assumed distribution in the nondetectable range (e.g., substitution using 0.25 × MRL or the Bayesian estimate provided by the USEPA), they are less desirable than obtaining detectable sample results in the range of interest.

Figure 5 shows the cumulative probability distributions of hexavalent chromium from the CDPH raw waters and the NCBOS dataset. The analysis was performed with the 75th percentile concentration of hexavalent chromium on a sample-location basis. The California data suggested higher occurrence than the national average, as expected. The CDPH dataset indicates about 20% of sample points with a hexavalent chromium concentration > 5 µg/L, whereas the NCBOS data indicate only about 5% of entry points exceeding 5 µg/L. Both datasets show very little hexavalent chromium occurrence > 20 µg/L.

Analysis of chromium occurrence by system type and source type. Cumulative probability distributions were calculated for the 6YR2 total chromium groundwater data versus surface waters. The concentrations were calculated from the 75th percentile at each sample location, and nondetects were substituted with one quarter of the MRL. Results of the analysis indicate that distributions are similar, with a maximum of about 2% difference between them. As noted previously, some groundwater sources may be labeled as surface waters if they have any surface water or any groundwater under direct influence of sources in the same system. Frey et al (2004) also found no significant difference in distribution of total chromium for groundwaters versus surface waters; thus, the analysis of total chromium data is not separated by source water type.

Figure 6 shows the cumulative probability distributions for CDPH hexavalent chromium by groundwater and surface water. Hexavalent chromium occurrence in groundwater is shifted toward higher concentrations than for surface water. Frey et al (2004) found similar results. Figure 6 also shows data with the raw waters separated from the treated waters. The distributions of total and hexavalent chromium are similar in surface water. The low level of occurrence is consistent, with surface water speciation being dominated by trivalent chromium (shown in the (data not shown). Therefore, all data are included in further analysis (rather than limit the data to CWS data only).

Cumulative probability distributions were similarly calculated for the 6YR2 total chromium groundwater data versus surface waters. The concentrations were calculated from the 75th percentile at each sample location, and nondetects were substituted with one quarter of the MRL. Results of the analysis indicate that distributions are similar, with a maximum of about 2% difference between them. As noted previously, some groundwater sources may be labeled as surface waters if they have any surface water or any groundwater under direct influence of sources in the same system. Frey et al (2004) also found no significant difference in distribution of total chromium for groundwaters versus surface waters; thus, the analysis of total chromium data is not separated by source water type.

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following section) and the low solubility of trivalent chromium. The groundwater data, however, indicate higher occurrences in the treated waters < 6 µg/L and higher occurrences in raw waters > 6 µg/L. An increase in hexavalent chromium could result from oxidation of trivalent chromium during disinfection. A decrease in hexavalent chromium could be due to treatment or blending provided at some sites. However, the explanation for the crossover shown in Figure 6 cannot be determined with any certainty and could be due to the disparity in the number of samples (1,242 treated samples versus 14,448 raw samples).

**Analysis of paired total and hexavalent chromium samples.** The CDPH data were used to study the speciation of chromium. A total of 5,976 samples with both total and hexavalent chromium results were paired by matching sample location and date. Figures 7 and 8 show the results by plotting hexavalent chromium versus total chromium by water type and raw versus treated. In Figures 7 and 8, there are several samples that indicate a higher hexavalent chromium concentration than total chromium, which is not truly possible. These points result from analytical issues that are well described and explained by Parks et al (2004) in which total chromium analyses have not accounted for all hexavalent chromium because of incomplete digestion, particularly when chromium is present with iron hydroxide particles.

Analysis of groundwater versus surface water paired samples shown in Figure 7 indicates that surface waters generally have more trivalent chromium than hexavalent chromium. Groundwaters tend to contain much of their total chromium as hexavalent chromium, consistent with other studies (Ball & Izbicki, 2004; Frey et al, 2004). Despite some scatter in the data, the hexavalent chromium concentration is highly correlated with the total chromium concentration. Regression analysis indicates that more than 98% of groundwater total chromium is hexavalent ($R^2 = 0.97$). The average hexavalent chromium concentration in surface water samples with total chromium is 0.12 µg/L, indicating the occurrence of nearly all trivalent chromium in surface waters.

Figure 8 shows groundwater paired samples separated into raw and treated categories. The data in Figure 8 indicate treated waters have lower concentrations of chromium. These lower concentrations may be due to treatment but could also be due to sampling bias created by high chromium sources not being used for drinking water. The disparity in sample sizes between raw and treated waters may also contribute some bias. The treated samples may appear to be more heavily speciated toward hexavalent chromium, as expected, because of chlorination. However, statistical analysis of this dataset does not explicitly support this conclusion.

**Spatial distribution of chromium occurrence.** The 6YR2 dataset was used to calculate the 75th percentile concentration of total chromium at each entry point. The highest 75th percentile entry point concentration per system was mapped by latitude and longitude identifiers assigned to each system from SDWIS data. No data were available for Washington, Pennsylvania, Louisiana, or Mississippi. Figure 9 shows a national pin map of total chromium concentrations between 5 and 10 µg/L, 10 and 20 µg/L, and > 20 µg/L.

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**FIGURE 7** CDPH paired-sample analysis of GW and SW

![Graph showing CDPH paired-sample analysis of GW and SW](image1)

**FIGURE 8** CDPH paired-sample analysis of GW grouped by raw and treated waters

![Graph showing CDPH paired-sample analysis of GW grouped by raw and treated waters](image2)
Figure 9 shows that total chromium is distributed across the United States. The greatest number of high chromium concentrations appears to be in the southwestern United States from California to Texas. The region surrounding the Great Lakes also appears to have widespread occurrence. Figure 10 shows the CDPH occurrence of hexavalent chromium in California. Because of the lower detection limit for hexavalent chromium concentration, ranges of 1–5, 5–10, 10–20, and > 20 µg/L are shown. Hexavalent chromium appears to be distributed across California and corresponds closely with both population density and use of groundwaters.

**ESTIMATED EXTENT OF POTENTIAL FUTURE REGULATION**

One of the objectives of this occurrence survey was to determine to what extent a potential future regulation may affect drinking water systems. Thus the number of entry points greater than a given threshold total chromium concentration was estimated for CWSs nationally and for hexavalent chromium in California. Because the 6YR2 database does not represent a census of all entry points, the total number of entry points was estimated nationally. The number of nationwide CWS entry points was estimated by comparing the 6YR2 data with the SDWIS database of CWSs (retrieved December 2011), broken down by system size. For California, the WQAD was considered a census of California entry points; however, not all entry points had hexavalent chromium sample results. Therefore, the number of affected California entry points was determined by multiplying the percent of entry points above the threshold value (with hexavalent chromium results) by the total number of entry points in the WQAD dataset. Table 2 shows the results of the national and California estimations. The second and third columns show the number of systems in the SDWIS and chromium databases, respectively. The table also shows that the chromium database includes about 60–90% of the SDWIS totals. To project the number of entry points nationally, the number of entry points included in the 6YR2 database was divided by the frac-
tion of systems represented. Comparisons were made by system size and summed for the national and California estimates. Last, the average number of entry points per system was calculated as a check on reasonableness. The numbers generally increase with system size from ~2 to 14.5 for the largest systems nationally and 25 entry points per Public Water Safety Identification information for large systems in California.

The number of entry points greater than the threshold values was estimated by multiplying the total number of entry points by the percent of entry points exceeding the threshold concentration. Table 3 shows the national results for total chromium concentrations of 1, 2, 5, 10, 20, and 50 µg/L. The national number of entry points above the threshold concentration has been estimated based on using the 6YR2 database with nondetects set to one quarter of the MRL and the NCBOS database with nondetects set to zero. Given their similar distributions, it would be expected that the estimated number of entry points using the USEPA Bayesian approach would be similar to the NCBOS estimate. Table 4 shows the California results for hexavalent chromium at threshold concentrations of 1, 2, 5, 10, and 20 µg/L. A California estimate at 50 µg/L was not prepared because that is the state's MCL for total chromium. The California number of entry points above the threshold concentration has been estimated based on using the CDPH database, with nondetects set to zero.

The results of Table 3 show the number of entry points exceeding the threshold concentration increases steeply <10 µg/L, which is largely the result of the uncertainty associated with nondetect handling. For instance, at 5 µg/L, between 10,783 and 24,609 entry points would require further treatment, which represents between 9 and 21% of entry points nationally. Figure 11 shows the number of entry points affected by aggregating all system sizes. For instance, the estimated number of entry points with concentrations above 10 µg/L range from 1,971 (NCBOS) to 8,829 (6YR2 with nondetects set to one quarter of the MRL). Thus, even at a concentration greater than most of the influence of the nondetect results, more than a fourfold difference is estimated depending on which dataset is selected. This uncertainty in systems affected by potential regulation indicates the need for better occurrence data before an accurate evaluation of these systems can be made. Unregulated Contaminant Monitoring Rule 3 data are expected to fill in these data gaps with the sampling period being completed at the end of 2015 and data being made available to the public in 2016.

CONCLUSIONS

Results of this analysis of occurrence data indicate that total and hexavalent chromium occur in drinking water entry points sampled throughout the United States. California, Arizona, and
### TABLE 2  
**Estimation of the national and California EP inventory**

<table>
<thead>
<tr>
<th>System Population Served</th>
<th>SDWIS CWS PWSID Census</th>
<th>PWSID Inventory</th>
<th>6YR2/SDWIS—%</th>
<th>Dataset EP Inventory</th>
<th>Projected EPs</th>
<th>Average EPs per PWSID</th>
</tr>
</thead>
<tbody>
<tr>
<td>National</td>
<td>50,936</td>
<td>32,810</td>
<td>64</td>
<td>74,672</td>
<td>114,710</td>
<td>2.3</td>
</tr>
<tr>
<td>0–100</td>
<td>11,460</td>
<td>8,217</td>
<td>72</td>
<td>20,116</td>
<td>28,055</td>
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<tr>
<td>101–500</td>
<td>16,333</td>
<td>10,509</td>
<td>64</td>
<td>20,977</td>
<td>32,602</td>
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<tr>
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<td>5,707</td>
<td>3,432</td>
<td>60</td>
<td>7,085</td>
<td>11,781</td>
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<tr>
<td>1,001–3,300</td>
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<td>57</td>
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<td>63</td>
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<td>50,001–100,000</td>
<td>97</td>
<td>85</td>
<td>87.6</td>
<td>971</td>
<td>1,108</td>
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<td>100,001–1,000,000</td>
<td>81</td>
<td>74</td>
<td>91.4</td>
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### TABLE 3  
**Number of national CWS EPs higher than threshold total chromium concentrations**

<table>
<thead>
<tr>
<th>System Population Served</th>
<th>Threshold Concentration</th>
<th>1 µg/L</th>
<th>2 µg/L</th>
<th>5 µg/L</th>
<th>10 µg/L</th>
<th>20 µg/L</th>
<th>50 µg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>All EPs</td>
<td>6YR2 ND = 0.25 × MRL</td>
<td>96,628</td>
<td>78,977</td>
<td>24,609</td>
<td>8,623</td>
<td>1,933</td>
<td>209</td>
</tr>
<tr>
<td></td>
<td>NCBOS</td>
<td>50,015</td>
<td>29,480</td>
<td>10,783</td>
<td>1,950</td>
<td>1,033</td>
<td>0</td>
</tr>
<tr>
<td>0–100</td>
<td>6YR2 ND = 0.25 × MRL</td>
<td>23,022</td>
<td>19,135</td>
<td>5,957</td>
<td>2,178</td>
<td>432</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>NCBOS</td>
<td>12,232</td>
<td>7,210</td>
<td>2,637</td>
<td>477</td>
<td>252</td>
<td>0</td>
</tr>
<tr>
<td>101–500</td>
<td>6YR2 ND = 0.25 × MRL</td>
<td>27,254</td>
<td>22,268</td>
<td>7,248</td>
<td>2,539</td>
<td>516</td>
<td>71</td>
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<tr>
<td></td>
<td>NCBOS</td>
<td>14,215</td>
<td>8,379</td>
<td>3,065</td>
<td>554</td>
<td>293</td>
<td>0</td>
</tr>
<tr>
<td>500–1,000</td>
<td>6YR2 ND = 0.25 × MRL</td>
<td>9,969</td>
<td>7,817</td>
<td>2,554</td>
<td>825</td>
<td>197</td>
<td>27</td>
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<tr>
<td></td>
<td>NCBOS</td>
<td>5,137</td>
<td>3,028</td>
<td>1,107</td>
<td>200</td>
<td>106</td>
<td>0</td>
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<tr>
<td>1,001–3,300</td>
<td>6YR2 ND = 0.25 × MRL</td>
<td>13,553</td>
<td>10,811</td>
<td>3,101</td>
<td>881</td>
<td>181</td>
<td>15</td>
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<tr>
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<td>NCBOS</td>
<td>7,012</td>
<td>4,133</td>
<td>1,512</td>
<td>273</td>
<td>145</td>
<td>0</td>
</tr>
<tr>
<td>3,301–10,000</td>
<td>6YR2 ND = 0.25 × MRL</td>
<td>9,424</td>
<td>7,733</td>
<td>2,144</td>
<td>724</td>
<td>208</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>NCBOS</td>
<td>4,790</td>
<td>2,823</td>
<td>1,033</td>
<td>187</td>
<td>99</td>
<td>0</td>
</tr>
<tr>
<td>10,001–50,000</td>
<td>6YR2 ND = 0.25 × MRL</td>
<td>8,769</td>
<td>7,136</td>
<td>2,231</td>
<td>800</td>
<td>221</td>
<td>15</td>
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<tr>
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<td>NCBOS</td>
<td>4,352</td>
<td>2,565</td>
<td>938</td>
<td>170</td>
<td>90</td>
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<tr>
<td>50,001–100,000</td>
<td>6YR2 ND = 0.25 × MRL</td>
<td>2,055</td>
<td>1,787</td>
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<td>88</td>
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<td>NCBOS</td>
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<td>586</td>
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<td>100,001–1,000,000</td>
<td>6YR2 ND = 0.25 × MRL</td>
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<td>2,001</td>
<td>749</td>
<td>299</td>
<td>77</td>
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<tr>
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<td>NCBOS</td>
<td>1,144</td>
<td>674</td>
<td>247</td>
<td>45</td>
<td>24</td>
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<tr>
<td>&gt; 1,000,000</td>
<td>6YR2 ND = 0.25 × MRL</td>
<td>304</td>
<td>289</td>
<td>149</td>
<td>132</td>
<td>13</td>
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<tr>
<td></td>
<td>NCBOS</td>
<td>139</td>
<td>82</td>
<td>30</td>
<td>5</td>
<td>3</td>
<td>0</td>
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</table>

Nevada seem to be the areas of highest occurrence, followed by the area surrounding the Great Lakes. Surface waters tend to be more speciated toward trivalent chromium, whereas groundwaters tend to be heavily speciated in hexavalent chromium. However, little difference was found in the distribution of total chromium between groundwaters and surface waters.

The total chromium data are limited by MRLs, making predictions of systems affected subject to a high degree of uncertainty when < 10 µg/L. A suitable dataset is not available for predicting hexavalent chromium occurrence on a national basis. Preliminary analysis of systems affected at different chromium concentrations indicates the potential for a large number of systems to be affected by potential regulation.

ACKNOWLEDGMENT

The authors acknowledge the Water Research Foundation as joint owner of certain technical information on which this article is based. The authors thank the foundation for its financial, technical, and administrative assistance in funding project 4414, through which this information was discovered. Rajiv Khera of the US Environmental Protection Agency provided the Bayesian estimate of the Second Six-Year Review data and helpful comments throughout.

ABOUT THE AUTHORS

Chad J. Seidel is manager of water technology at Jacobs Engineering Group, 707 17th St., Ste. 2400, Denver, CO 80202; chad.seidel@jacobs.com. He has been involved with chromium occurrence research since 2001 as a co-principal investigator for the Water Research Foundation-funded National Chromium and Boron Occurrence Survey. His dissertation research, completed in 2006 at the University of Colorado–Boulder, focused on chromium occurrence, treatment, and regulatory implications. Christopher J. Corwin is a water process engineer at Jacobs Engineering Group.

PEER REVIEW

Date of submission: 11/02/12
Date of acceptance: 01/29/13

REFERENCES


Table 4: Number of California EPs estimated to be higher various threshold hexavalent chromium concentrations

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<tr>
<th>System Population Served</th>
<th>1 µg/L</th>
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<th>5 µg/L</th>
<th>10 µg/L</th>
<th>20 µg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>All EPs</td>
<td>4,747</td>
<td>3,445</td>
<td>1,694</td>
<td>681</td>
<td>168</td>
</tr>
<tr>
<td>0–100</td>
<td>450</td>
<td>311</td>
<td>186</td>
<td>70</td>
<td>0</td>
</tr>
<tr>
<td>101–500</td>
<td>643</td>
<td>468</td>
<td>254</td>
<td>111</td>
<td>36</td>
</tr>
<tr>
<td>501–1,000</td>
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<td>110</td>
<td>70</td>
<td>20</td>
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<tr>
<td>1,001–3,300</td>
<td>296</td>
<td>188</td>
<td>76</td>
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<td>3,301–10,000</td>
<td>457</td>
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<td>611</td>
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EP—entry point

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EP—entry point