Water Quality and the Availability and Sustainability of Water Supplies in the High Plains Aquifer

Chapter 4 of

Water-Quality Assessment of the High Plains Aquifer, 1999–2004

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Contents

Figure

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Introduction

A high-quality water supply is central to the overall health of the High Plains agricultural economy, the viability of its cities and rural communities, and the environmental well-being of the landscape. Ground water is the primary source of water used in the High Plains, thus knowledge about its availability and sustainability are essential for the successful management and future development of this limited resource. In the context of this discussion, the concept of ground-water availability is used when considering the current water resource, whereas ground-water sustainability is used when considering future water resources. Ground-water availability and sustainability are influenced by many factors, one of which is water quality. Water quality generally has been overlooked in the High Plains because the primary focus has been on obtaining a sufficient water supply. In some cases, however, water quality may be a limiting factor for some intended uses such as drinking- or irrigation-water supply. For example, shallow ground water beneath irrigated cropland may not be suitable for human consumption because of elevated concentrations of salt, nitrate, and (or) pesticides (see Chapter 1). Ground water influenced by mixing with brackish surface water or deep formation water may not be suitable for irrigation because of elevated concentrations of dissolved solids (see Chapters 2 and 3). Having a clear understanding of the status and trends in water-quality conditions and the natural and anthropogenic processes that control them facilitates more robust assessments of water availability and sustainability of this aquifer. This chapter summarizes many of the important natural and anthropogenic processes affecting water availability in the High Plains aquifer from a water-quality standpoint and considers some challenges and opportunities for sustaining the water supply in the future.

Assessing Ground-Water Availability and Sustainability

Assessing ground-water availability in the High Plains entails more than just determining the volume of water within the aquifer. The availability of ground water may be limited because not all the water is recoverable or of good quality. Complicating any assessment of ground-water availability is the realization that ground water is only one component of the regional hydrologic budget. For example, small volume changes in the ground-water system can adversely impact ecosystems that develop along riparian corridors by reducing the amount of water discharging to streams and springs (Alley, 2006). In the western CHP and northern SHP, where declines in water levels have been the largest, the volume of water in storage in the aquifer decreased by an average of about 34 percent from predevelopment to 2000 (McGuire and others, 2003). Superimposed on those factors is the realization that water quality can change over time (fig. 55) in response to land-use/land-cover change (see Chapter 1), climate change (see Chapter 1), and pumping stresses (see Chapter 2), among other factors. Scientific assessments of ground-water availability consider all of the interrelated factors outlined above, but society is the ultimate arbitrator and will determine which uses of the ground-water resource have priority. The HPGW study provides insights related to water quality that can inform that decision-making process.

Ground-water resources also are often discussed in terms of their sustainability. As defined by Alley and others (1999), ground-water sustainability is the “development and use of ground water in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences.” Thus, the amount of water allocated to different uses, how those uses may change in the future, and the resulting effects of those uses are all part of assessing the sustainability of an aquifer. For example, withdrawals for irrigation in the High Plains have helped to support a large agricultural economy in the region, but they also have resulted in declining water levels (McGuire, 2007), reduced stream flow (Luckey and Becker, 1998), and even dry channels in some areas. In these instances, agriculture has taken precedence over in-stream flows. This outcome apparently is consistent with societal values at this time and in this place. As time and conditions change, however, the consequences of these choices may no longer be acceptable.

Water-Quality Issues that Influence Ground-Water Availability

To better evaluate ground-water availability, it is necessary to improve understanding of ground-water quality because it has a direct affect on how water can be used. The results presented in Chapters 1 through 3 demonstrate that the interpretation of ground-water quality data in the context of the entire ground-water flow system leads to a more comprehensive understanding than would be obtained by focusing exclusively on a single aspect of the flow system such as the recharge area. As shown in Chapters 1 through 3, water-quality issues that influence ground-water availability can be associated with all parts of the flow system. In this section, some of the most important water-quality issues are summarized that influence water availability in the High Plains aquifer.

The quality of water recharging the High Plains aquifer is controlled by many factors, including land use/land cover, water use, climate, and unsaturated-zone thickness and composition (see Chapter 1). Changes in land use and land cover from natural conditions to agriculture and urbanization are perhaps the most important anthropogenic factors affecting recharge water quality. Agriculture is the more dominant land use/land cover in the High Plains compared to urbanization (38 versus 3 percent of total land area, respectively). Agriculture has a major influence on water quality through the introduction of salts, nitrate, pesticides, and other chemicals in recharge. Processes that promote recharge of agricultural chemicals, such as irrigation and certain other farming practices, can increase the potential for ground-water contamination by increasing chemical fluxes and decreasing chemical transit times to the water table. Other ways recharge water quality has been degraded include infiltration of water from multiple irrigation applications in which concentrations of dissolved solids have increased because of evaporative concentration. These concentrated solutions can drain directly to the aquifer or can drain to streams and subsequently enter the aquifer where ground-water gradients near those streams have been reversed because of irrigation pumping (Whittemore and others, 2001). Furthermore, conversion of rangeland to irrigated cropland has the potential to mobilize natural salt deposits in the unsaturated zone that contain chloride, nitrate, and possibly perchlorate (Rao and others, 2007), which may eventually reach the water table. Mobilization of natural salt deposits has already occurred in some areas of the High Plains, but slow chemical transit times indicate that those salts will continue to migrate to the water table. Thus, the amount of chemical mass entering the aquifer could increase with time as chemicals that still reside in the unsaturated zone reach the water table. Superimposed on those processes is climate variability on annual to interdecadal timescales that can have major influences on the timing and rate of water and chemical movement from land surface to the water table.

Once water recharges the High Plains aquifer it is transported in response to hydraulic gradients to downgradient receptors such as domestic, public-supply, and irrigation wells. During transport, the chemistry of recharge changes as a result of three primary processes—water/rock interactions, redox processes, and mixing of water from different sources (see Chapter 2). Water/rock interactions and redox processes in the High Plains aquifer are, for the most part, natural processes that result in small changes in the concentrations of dissolved constituents as water is transported along flow paths. Denitrification, the redox process that is perhaps most relevant to drinking-water quality in the aquifer because of relatively widespread nitrate contamination, generally cannot be relied upon to substantially attenuate nitrate contamination because electron donors are not available in most areas of the aquifer to support it. Locally, and in some cases over larger areas (Sand Hills eolian deposits and Plio-Pleistocene deposits), however, denitrification can be an important attenuating mechanism. Mixing of water from different sources occurs naturally in the aquifer, particularly in some river valleys that are major discharge areas. In some of those discharge areas, brackish waters from underlying formations enter the aquifer and mix with fresh ground water. In other areas, leakage of poorer quality water from rivers, and possibly saline lakes, mixes with fresh ground water, thereby impairing water quality.

Mixing also is caused by leakage through long well screens and by long-term pumping of high capacity public-supply and irrigation wells. Mixing caused by leakage and pumping is considered to be a major process for moving contaminants from near the water table to deeper zones more rapidly than would occur otherwise under natural hydraulic gradients. Thus, anthropogenic activity not only can be a source of contaminants to the water table, but it also can enhance contaminant transport once the contaminants are in the aquifer. Pumping wells may also induce brackish water from underlying formations to move into the aquifer. In some areas of the High Plains, inputs of water with poor quality near the water table (primarily because of agricultural activities) and near the base of the aquifer (because of inflow of brackish water from below) have the effect of reducing the availability of high-quality water to a zone in the middle of the aquifer. Water availability could be further limited when high-capacity pumping wells vertically mix these zones, as described above. Over time, the operation of these wells can result in a reduction in the thickness of the zone of high-quality water. Of the three primary processes that affect the quality of water as it is transported through the aquifer—water/rock interactions, redox processes, and mixing—mixing related to well design and operation is the only one that could practically be controlled through management.

The quality of water produced by domestic, public-supply, and irrigation wells in the High Plains aquifer generally was acceptable for most uses, although differences in water quality between the assessed hydrogeologic units and between well types are observed (see Chapter 3). Evaluation of domestic-well water quality on the basis of MCL and SMCL exceedances indicates that the SHP Ogallala Formation had the poorest water quality followed by water from the Quaternary and Plio-Pleistocene deposits. The Ogallala Formation in the CHP and NHP had the best water quality. The quality of water from some domestic, public-supply, and irrigation wells is affected by agricultural and urban contaminants in recent recharge (recharged within the past 50 years) and by mixing processes caused by leakage through long well screens and long-term pumping of high-capacity public-supply and irrigation wells. The combination of those source and transport processes has resulted in small but measurable increases in concentrations of anthropogenic contaminants such as nitrate in High-Plains ground water when viewed in the context of a multidecadal timeframe (fig. 77). A statistical comparison of nitrate concentrations, by decade, in water from the High Plains aquifer indicated that median nitrate concentrations were similar from the 1930's to the 1960s, significantly larger in the 1970s, and larger yet in the 1980s and 1990s (Litke, 2001) (fig. 77). The trend becomes even more apparent when viewed in the context of a millennial timeframe (fig. 55). Fogg and LaBolle (2006) pointed out that this type of long-term gradual increase in ground-water contaminant concentrations is generally difficult to separate from "noise" when viewed in the context of short timeframes, indicating the need for long-term monitoring. An important implication of

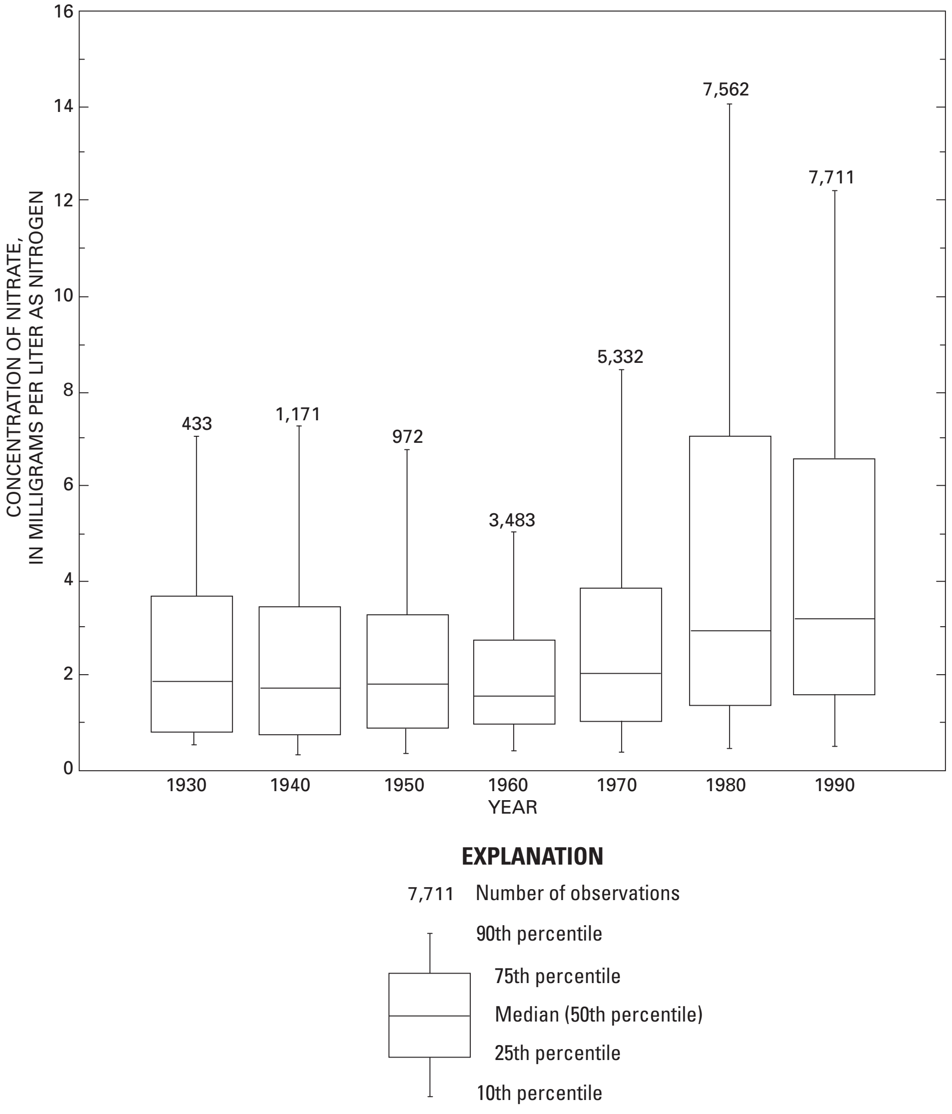

Figure 77. Distribution of nitrate concentrations in the High Plains aquifer, by decade (modified from Litke, 2001).

the trend data illustrated in figures 55 and 77 is that contaminant concentrations in the used resource will increase in the future as the fraction of post-1950 recharge captured by wells used to supply irrigation and drinking water increases. Once contaminated, deep zones in the aquifer in which those wells are screened are not likely to be remediated quickly because of slow recharge rates, long water residence times in the aquifer, and slow rates of contaminant degradation. Thus, this trend could limit water sustainability given current uses and land-use practices, and therefore needs to be factored into future management strategies.

Challenges and Opportunities for Sustaining the Water Supply

The High Plains aquifer is the most intensively used aquifer in the U.S., producing almost twice the volume of water than any other U.S. aquifer (Maupin and Barber, 2005). Thus, it is important to understand how water quality may affect the sustainability of this ground-water resource. The water-quality assessment provided by the High Plains Regional Ground-Water study establishes a regional baseline against which water-quality conditions can be tracked over time and provides process understanding to help explain changes in those conditions. Although this study was not designed as a long-term monitoring program, results presented here (figs. 55 and 77) demonstrate the importance of collecting long-term monitoring data to detect gradual trends and to provide early warning of water-quality problems for which the aquifer may have limited natural-attenuation capacity (nitrate, for example). The need for long-term water-quality monitoring presents an opportunity for collaboration between local, state, and federal agencies whose goal it is to ensure the sustainability of the High Plains aquifer.

Long-term tracking of factors that control the timing of water-quality trends is needed to better understand the sustainability of the High Plains aquifer. Such factors include changes in chemical use, water use, land use/land cover, and natural factors, such as climate. Understanding changes in these factors is crucial for linking trends in chemical concentrations to processes. Without this process-level understanding to inform the decision-making process, effective best-management practices or remediation strategies are less likely to be developed to address water-quality problems.

Monitoring water quality in all areas of the High Plains aquifer is not possible because of its large area. Moreover, it may not be possible to simultaneously collect long-term water-quality data for numerous constituents such as arsenic, fluoride, nitrate, pesticide compounds, and VOCs. Thus, tools that can extrapolate monitoring data in space and time would represent valuable contributions to the overall goal of sustaining the High Plains aquifer. The development of regional-scale predictive models with quantified uncertainty is increasingly possible for ground-water flow and chemical transport. Expanding this capability is a critical step for assessment and cost-effective management of ground-water resources in the High Plains, because both require more information than can be directly measured under current technology and budget constraints. In addition, the models are critical to evaluate various resource development and management scenarios and the effectiveness of water decisions over time. Model simulations can be used to identify locations that have the greatest likelihood of water-quality problems and therefore, may have the highest priority for continued monitoring and assessment and management strategies. Future success with the development and application of vulnerability and other statistical models—as well as more complex simulation models—will depend upon the integration of monitoring and assessment data with the models. In other words, it is critical that credible, comparable, and comprehensive information continues to be generated—by means of “on-the-ground” monitoring, assessment, and research—that can be used to validate the predictions. This effort needs to be coupled with continued and improved collection of supporting ancillary data on irrigation pumpage, chemical use, land use/land cover, natural features such as climate and ground-water ages, and other explanatory factors needed to update and validate the models.

Summary

Water quality of the High Plains aquifer was assessed for the period 1999–2004 as part of the U.S. Geological Survey's National Water-Quality Assessment (NAWQA) Program. This effort represents the first systematic regional assessment of water quality in this nationally important aquifer. The assessment was based on results from a monitoring program designed in the context of a Source-Transport-Receptor (STR) conceptual model for ground-water quality. A stratified, nested group of studies was designed to assess linkages between the quality of water recharging the aquifer, the effect of transport through the hydrologic system on water quality, and the quality of the resource used for human consumption and agricultural applications. For each component of the STR model, studies were designed to address the NAWQA goals of water-quality assessment (status or baseline) and process understanding. The process component included the study of critical processes or factors of regional importance like recharge, ground-water flow directions and ages, and gradients in land use/land cover and climate that helped to explain baseline conditions. The stratified, nested design facilitated upscaling of monitoring (assessment) results to unmonitored areas of the aquifer as well as upscaling of process understanding from local to regional scales.

The High Plains study was built around four types of studies: unsaturated-zone studies, land-use studies, regional transect studies, and major-aquifer studies. The purpose of the unsaturated-zone studies was to measure chemical storage and transit times in the unsaturated zone beneath rangeland and irrigated cropland. The purpose of the land-use studies was to assess the quality of recently recharged ground water (less than 50 years old) beneath major land-use settings by sampling networks of randomly distributed monitoring wells screened near the water table beneath those targeted land uses/land covers. The purposes of the regional transect studies were to characterize vertical gradients in water chemistry and age and to identify major biogeochemical reactions affecting the quality of water along flow paths from recharge areas to downgradient wells. The purpose of the major-aquifer studies was to broadly assess water-quality conditions in the aquifer by sampling networks of randomly distributed domestic wells in the major hydrogeologic units. By monitoring water and chemical movement from the land surface to the water table and from the water table to the base of the aquifer along flow paths from recharge to discharge areas, the nested design not only facilitated extrapolation of assessment results, it also improved understanding of the timescales at which that movement occurred. Water samples collected from the well networks were sampled for various combinations of field properties, major ions, nutrients, trace elements, pesticides, volatile organic compounds, stable and radioactive isotopes, and dissolved gases.

Irrigated cropland was a direct or indirect source of salts, nitrate, and pesticides in recent recharge (less than 50 years old) to the High Plains aquifer. Urban land was also a source of those constituents, as well as volatile organic compounds, although urban land is much less widespread than agricultural land in the High Plains. Processes that promote recharge in this semiarid area, such as irrigation, increase the potential for ground-water contamination by increasing chemical fluxes and decreasing chemical transit times to the water table. Furthermore, conversion of rangeland to cropland has the potential to mobilize large natural salt deposits in the unsaturated zone that could eventually reach the water table.

Systematic north-to-south regional variations existed in the quality of recently recharged ground water beneath rangeland and irrigated cropland. Those variations were controlled by several interrelated factors that included agricultural water and chemical use, climate gradients, depth to water, chemical transit time to the water table, chemical storage in the unsaturated zone, and crop type. Transport of chemicals from land surface to the water table under irrigated cropland varied from months to decades along fast recharge paths versus decades to centuries along slow recharge paths. Fast recharge probably occurs by several mechanisms including focused recharge beneath topographic depressions in the land surface. However, areas of fast recharge are less extensive on the High Plains than areas where slow recharge occurs. Hence in many areas, despite irrigation, transport of anthropogenic chemicals to the water table has not yet been observed. Implications of these findings with respect to water quality in the aquifer are important because they indicate that the amount of chemical mass reaching the aquifer could increase with time as chemicals beneath this larger area reach the water table because of ongoing irrigation, because of conversion of rangeland to cropland, or because of climate change. Furthermore, long transit times in the unsaturated zone may delay future improvements in water quality that would result from implementation of best management practices.

Logistic regression models were used to extrapolate results from the study of recently recharged ground water to unmonitored parts of the aquifer. Results from the model indicate that 53 percent of the aquifer area has less than a 40-percent predicted probability of containing recently recharged ground water with nitrate concentrations greater than 4 mg/L as nitrogen (the maximum observed background nitrate concentration). Twenty-one percent of the aquifer area has a greater than 60-percent predicted probability of containing recently recharged ground water with nitrate concentrations greater than 4 mg/L as nitrogen. Output from this types of predictive model can be used to identify potentially vulnerable areas for enhanced monitoring and protection.

Once water recharges the aquifer, it is transported in response to hydraulic gradients to downgradient receptors such as domestic, public-supply, and irrigation wells. During transport, the chemistry of recharge changes as a result of three primary processes—water/rock interactions, redox processes, and mixing of water from different sources. Water/rock interactions and redox processes in the High Plains aquifer are, for the most part, natural processes that result in small changes in the concentrations of dissolved constituents. Denitrification, the redox process that is perhaps most relevant to drinking-water quality in the aquifer because of relatively widespread nitrate contamination, generally cannot be relied upon to substantially attenuate nitrate contamination because it occurs very slowly in most areas of the aquifer. Locally, and in some cases in larger areas, however, denitrification was an important attenuating mechanism because of the presence of electron donors in the sediment to support this redox process. Mixing occurs naturally in the aquifer, particularly in some river valleys that are major discharge areas. In some of those discharge areas, brackish waters from underlying formations enter the aquifer and mix with fresh ground water. Mixing also is caused by leakage through long well screens and by long-term pumping of high-capacity public-supply and irrigation wells. Mixing caused by leakage and pumping is considered to be a major process for moving contaminants from near the water table to deeper zones more rapidly than would occur otherwise under natural hydraulic gradients. Thus, anthropogenic activity not only can be a source of contaminants to the water table, but it can also enhance their transport once they are in the aquifer. Pumping wells may also induce the movement of brackish water from underlying formations into the aquifer. Those shallow and deep mixing processes could eventually limit the availability of high-quality water to zones near the middle of the aquifer.

Measured ground-water ages in the aquifer ranged from less than 25 years to more than 15,000 years. That age distribution allowed for the reconstruction of long-terms trends in concentrations of nitrate in recharge. During the past ~12,000 years (late Pleistocene and Holocene), nitrate concentrations in recharge ranged from 0.8 to 4.2 mg/L as N, with a median concentration of 2.2 mg/L as N. During the past 50 to 60 years, nitrate concentrations in recharge have increased compared to concentrations in paleorecharge. An analysis of existing data collected from 1930 to 1999 confirms the relatively recent increase in nitrate concentrations. The increase in recharge nitrate concentrations during the past 50 years appears to be related to the increased use of agricultural fertilizer during that period, although contributions of nitrate from other anthropogenic sources such as human and animal waste may also be important.

The quality of water produced by domestic, public-supply, and irrigation wells in the High Plains aquifer generally was acceptable for most uses, although differences in water quality among the assessed hydrogeologic units and among well types were observed. Evaluation of domestic-well water quality on the basis of exceedances of national primary and secondary drinking-water standards indicates that the Ogallala Formation in the southern High Plains had the poorest water quality followed by the Quaternary and Plio-Pleistocene deposits. The Ogallala Formation in the central and northern High Plains had the best water quality on the basis of this analysis. Most exceedances of primary and secondary drinking-water standards were for arsenic, dissolved solids, fluoride, iron, manganese, and nitrate. The most frequently detected pesticide compounds were atrazine and deethylatrazine, whereas the most frequently detected volatile organic compound was chloroform. None of the pesticide compounds or volatile organic compounds exceeded a primary drinking-water standard.

The quality of water produced by some domestic and public-supply wells was adversely affected by agricultural and urban contaminants in recent recharge and by mixing processes caused by leakage through long well screens and long-term pumping of high-capacity public-supply and irrigation wells. The combination of those processes resulted in small but measurable increases in concentrations of anthropogenic contaminants such as nitrate in High Plains ground water when viewed in the context of decadal and millennial timeframes. One consequence of gradual upward trends in contaminant concentrations is that the contamination problem may go undetected because of a lack of long-term monitoring data. Once contaminated, deep zones in the aquifer in which production wells are screened are not likely to be remediated quickly because of slow recharge rates, long water residence times in the aquifer, and slow rates of contaminant degradation. An important implication of the time-series data is that contaminant concentrations in water from domestic and public-supply wells will increase in the future as the fraction of post-1950s recharge captured by those wells increases.

The availability and sustainability of water supplies in the High Plains aquifer are influenced by many factors, one of which is water quality. This water-quality assessment establishes a regional baseline against which water-quality conditions can be tracked over time and provides process-level understanding to help explain changes. Without process-level understanding to inform the decision-making process, effective best-management practices or remediation strategies are less likely to be developed to address water-quality problems.

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Appendixes

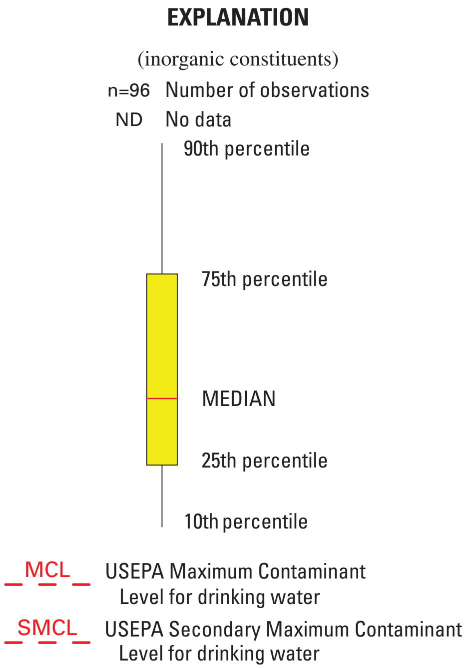
Appendix 1—Reports published as part of, or in cooperation with, the High Plains Regional Ground-Water study.

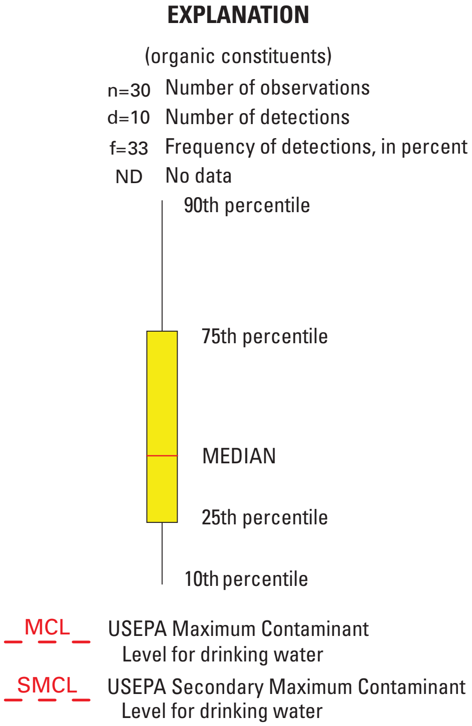
Study component	Report	Region
Major-aquifer studies	Becker, M.F., Bruce, B.W., Pope, L.M., and Andrews, W.J., 2002, Ground-water quality in the central High Plains aquifer, Colorado, Kansas, New Mexico, Oklahoma, and Texas, 1999: U.S. Geological Survey Water-Resources Investigations Report, 02–4112, 64 p.	Central High Plains
	Fahlquist, L., 2003, Ground-water quality of the southern High Plains aquifer, Texas and New Mexico, 2001: U.S. Geological Survey Open-File Report 03–345, 59 p.	Southern High Plains
	Pope, L.M., Bruce, B.W., and Hansen, C.V., 2001, Ground-water quality in Quaternary deposits of the central High Plains aquifer, south-central Kansas, 1999: U.S. Geological Survey Water-Resources Investigations Report, 00–4259, 44 p.	Central High Plains
	Stanton, J.S., and Qi, S.L., 2007, Ground-water quality of the northern High Plains aquifer, 1997, 2002–04: U.S. Geological Survey Scientific Investigations Report 2006–5138, 59 p.	Northern High Plains
Land-use studies	Bruce, B.W., Becker, M.F., Pope, L.M., and Gurdak, J.J., 2003, Ground-water quality beneath irrigated agriculture in the central High Plains aquifer, 1999–2000: U.S. Geological Survey Water-Resources Investigations Report 03–4219, 39 p.	Central High Plains
	Pope, L.M., Bruce, B.W., Rasmussen, P.P., and Milligan, C.R., 2002, Quality of shallow ground water in areas of recent residential and commercial development, Wichita, Kansas, 2000: U.S. Geological Survey Water-Resources Investigations Report, 02–4228, 75 p.	Central High Plains
	Stanton, J.S., and Fahlquist, L., 2006, Ground-water quality beneath irrigated agriculture in the northern and southern High Plains aquifer, Nebraska and Texas, 2003–04: U.S. Geological Survey Scientific Investigations Report 2006–5196, 95 p.	Northern and Southern High Plains
Regional transect studies	McMahon, P.B., 2001, Vertical gradients in water chemistry in the central High Plains aquifer, southwestern Kansas and Oklahoma Panhandle, 1999: U.S. Geological Survey Water-Resources Investigations Report 01–4028, 47 p.	Central High Plains
	McMahon, P.B., Böhlke, J.K., and Christenson, S.C., 2004, Geochemistry, radiocarbon ages, and paleorecharge conditions along a transect in the central High Plains aquifer, southwestern Kansas, USA: Applied Geochemistry, v. 19, p. 1655–1686.	Central High Plains
	McMahon, P.B., Böhlke, J.K., and Lehman, T.M., 2004, Vertical gradients in water chemistry and age in the southern High Plains aquifer, Texas, 2002: U.S. Geological Survey Scientific Investigations Report 2004–5053, 53 p.	Southern High Plains
	McMahon, P.B. and Böhlke, J.K., 2006, Regional patterns in the isotopic composition of natural and anthropogenic nitrate in ground water, High Plains, USA: Environmental Science & Technology, v. 40, p. 2965–2970.	Northern High Plains
	McMahon, P.B., Böhlke, J.K, and Carney, C.P., 2007, Vertical gradients in water chemistry and age in the northern High Plains aquifer, Nebraska, 2003: U.S. Geological Survery Scientific Investigations Report 2006–5294, 35 p.	All regions
Unsaturated-zone studies	McMahon, P.B., Dennehy, K.F., Michel, R.L., Sophocleous, M.A., Ellett, K.M., and Hurlbut, D., 2003, Water movement through thick unsaturated zones overlying the central High Plains aquifer, southwestern Kansas, 2000-2001: U.S. Geological Survey Water-Resources Investigations Report 03–4171, 30 p.	Central High Plains
	McMahon, P.B., K.F. Dennehy, B.W. Bruce, J.K. Böhlke, R.L. Michel, J.J. Gurdak, and D.B. Hurlbut, 2006, Storage and transit time of chemicals in thick unsaturated zones under rangeland and irrigated cropland, High Plains, United States: Water Resources Research, v. 42, W03413, doi:10.1029/2005WR004417.	All regions
	Scanlon, B.R., Reedy, R.C., Stonestrom, D.A., Prudic, D.E., and Dennehy, K.F., 2005, Impact of land use and land cover change on groundwater recharge and quality in the southwestern US: Global Change Biology, v. 11, p. 1577–1593.	Southern High Plains
	Walvoord, M. A., F. M. Phillips, D. A. Stonestrom, R. D. Evans, P. C. Hartsough, B. D. Newman, and R. G. Striegl, 2003, A reservoir of nitrate beneath desert soils: Science, v. 302, p. 1021–1024.	All regions
	Weeks, E.P., and McMahon, P.B., 2007, Nitrous oxide fluxes from cultivated areas and rangeland–U.S. High Plains: Vadose Zone Journal, v. 6, p. 496–510.	All regions
Special studies	Bruce, B.W., and Oelsner, G.P., 2001, Contrasting water quality from paired domestic/public supply wells, central High Plains: Journal of the American Water Resources Association, v. 37, p. 1389–1403.	Central High Plains

Study component	Report	Region
Special studies, continued	Clark, B.R., Landon, M.K., Kauffman, L.J., and Hornberger, G.Z., 2007, Simulations of ground-water flow, transport, age, and particle tracking at the local scale near York, Nebraska for a study of the transport of anthropogenic and natural contaminants (TANC) to public supply wells: U.S. Geological Survey Scientific Investigations Report, 2007–5068, 50 p.	Northern High Plains
	Dennehy, K.F., Litke, D.W., and McMahon, P.B., 2002, The High Plains aquifer; USA – Ground-water development and sustainability, *in* Hiscock, K.M., Rivett, M.O., and Davison, R.M., eds., Sustainable ground-water development: London Geological Society, Special Publication 193, p. 99–119.	All regions
	Dennehy, K.F., 2000, High Plains regional ground-water study: U.S. Geological Survey Fact Sheet FS–091–00, 6 p.	All regions
	Gurdak, J.J., and Qi, S.L., 2006, Vulnerability of recently recharged ground water in the High Plains aquifer to nitrate contamination: U.S. Geological Survey Scientific Investigations Report 2006–5050, 39 p.	All regions
	Gurdak, J.J., Hanson, R.T., McMahon, P.B., Bruce, B.W., McCray, J.E., Thyne, G.D., and Reedy, R.C., 2007, Climate variability controls on unsaturated-zone water and chemical movement, High Plains aquifer: Vadose Zone Journal, doi: 10.2136/vzj/2006.0087.	All regions
	Gurdak, J.J., McCray, J.E., Thyne, G., and Qi, S.L., 2007, Latin hypercube approach to estimate uncertainty in ground water vulnerability: Ground Water, v. 45, p. 348–361.	All regions
	Litke, D.W., 2001, Historical water-quality data for the High Plains Regional Ground-Water study area in Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming, 1930-98: U.S. Geological Survey Water-Resources Investigations Report, 00–4254, 65 p.	All regions
	McMahon, P.B., Bruce, B.W., Becker, M.F., Pope, L.M., and Dennehy, K.F., 2000, Occurrence of nitrous oxide in the central High Plains aquifer, 1999: Environmental Science & Technology, v. 34, p. 4873–4877.	Central High Plains
	McMahon, P.B., 2000, A reconnaissance study of the effect of irrigated agriculture on water quality in the Ogallala Formation, central High Plains aquifer: U.S. Geological Survey Fact Sheet FS–009–00, 6 p.	Central High Plains
	Qi, S.L., Konduris, A., Litke, D.W., and Dupree, J., 2002, Classification of irrigated land using satellite imagery, the High Plains aquifer, nominal date 1992: U.S. Geological Survey Water-Resources Investigations Report, 02–4236, 35 p.	All regions
	Qi, S.L., Konduris, A., Litke, D.W., and Dupree, J., 2002, HPIRRLND_92–Location of irrigated land classified from satellite imagery-High Plains area, nominal date 1992: U.S. Geological Survey Open-File Report 02–441 (GIS dataset).	All regions
	Qi, S.L., and Gurdak, J.J., 2006, Percentage of probability of nonpoint-source nitrate contamination of recently recharged ground water in the High Plains aquifer: U.S. Geological Survey Data Series DS–192 (GIS dataset).	All regions
	Rajagopalan, S., Anderson, T.A., Fahlquist, L., Rainwater, K.A., Ridley, M., and Jackson, W.A., 2006, Widespread presence of naturally occurring perchlorate in High Plains of Texas and New Mexico: Environmental Science & Technology, v. 40, p. 3156–3162.	Southern High Plains
	Torres, J.M., Litke, D.W., and Qi, S.L., 1999, HPBEDROCK--bedrock formations underlying the High Plains aquifer: U.S. Geological Survey Open-File Report 99–214 (GIS dataset).	All regions

Appendix 2—Water Quality of the High Plains Aquifer in a National Context

This appendix includes graphical comparisons of chemical concentrations for some of the most commonly detected inorganic and organic constituents in principal aquifers of the United States (Nolan and Stoner, 2000; Lapham and others, 2005[1]; Gilliom and others, 2006; Zogorski and others, 2006), including the High Plains aquifer. For each constituent, the concentration data are grouped according to four well types: shallow agricultural monitoring wells (agricultural land-use study wells), domestic wells (major-aquifer study wells), shallow urban monitoring wells (urban land-use study wells), and public-supply wells. For each well type, the aquifers also are grouped according to aquifer lithology: basalt and volcanics, carbonate/crystalline, carbonate/sandstone, sand and gravel, and semiconsolidated sand. For organic compounds, graphs show only concentrations detected above a common assessment level and data for a particular compound were not plotted if there were fewer than five detections of the compound. Note that analytical detection limits varied among the constituents; thus, detection frequencies are not comparable between constituents. For a given constituent, however, detection frequencies are comparable between aquifers. The data used in this report for the High Plains are available at URL: *http://co.water.usgs.gov/nawqa/hpgw/index.html*.





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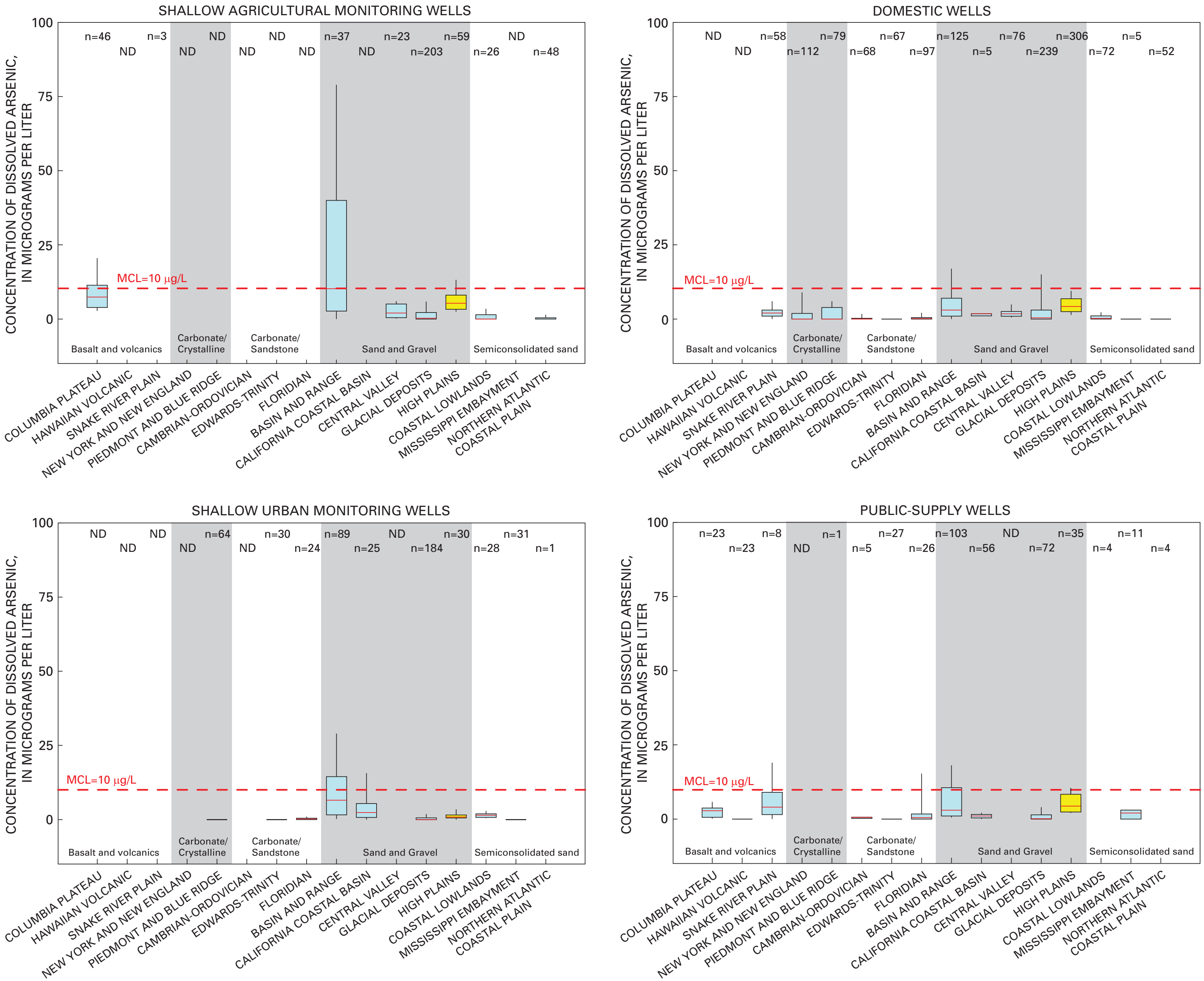
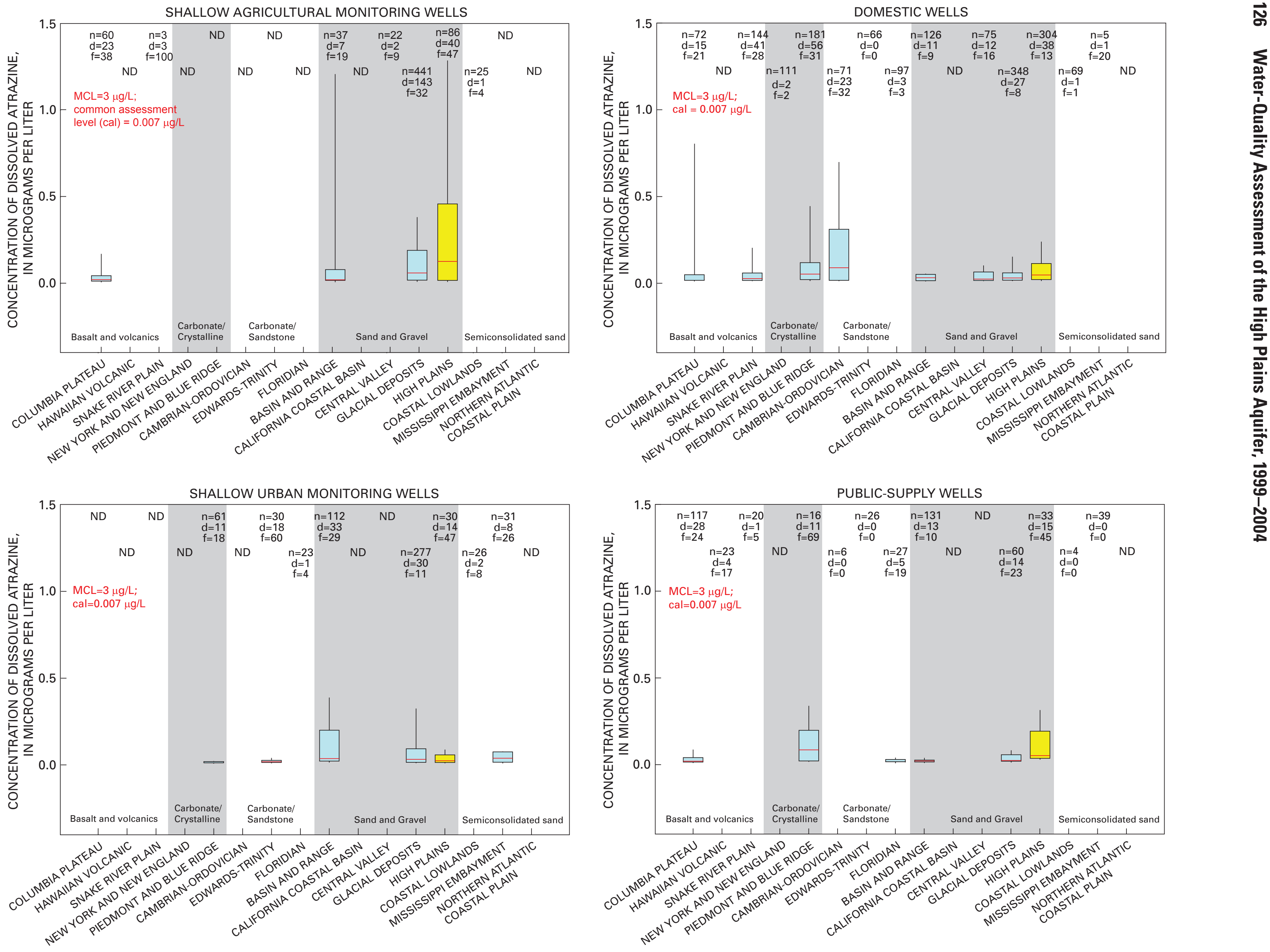
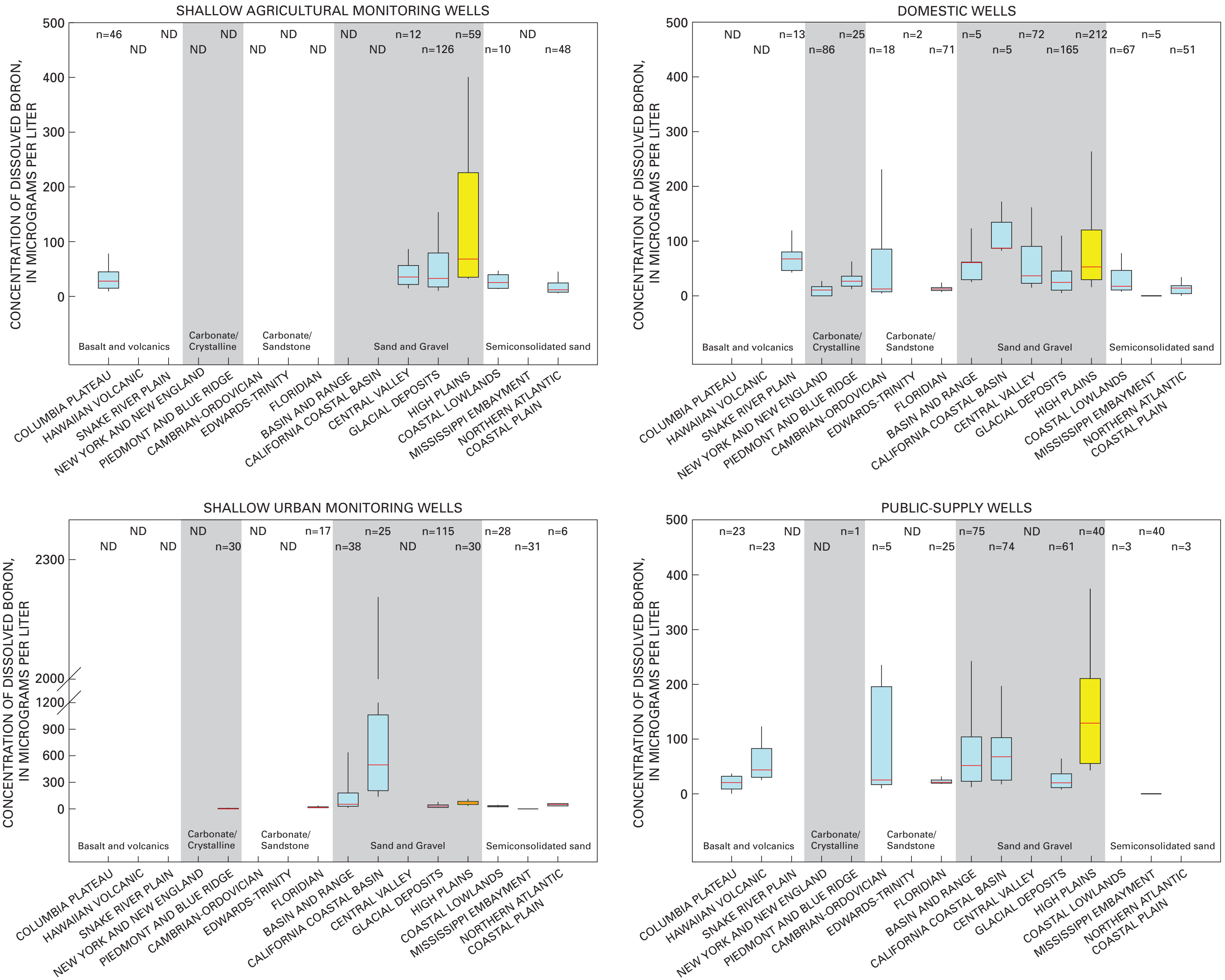
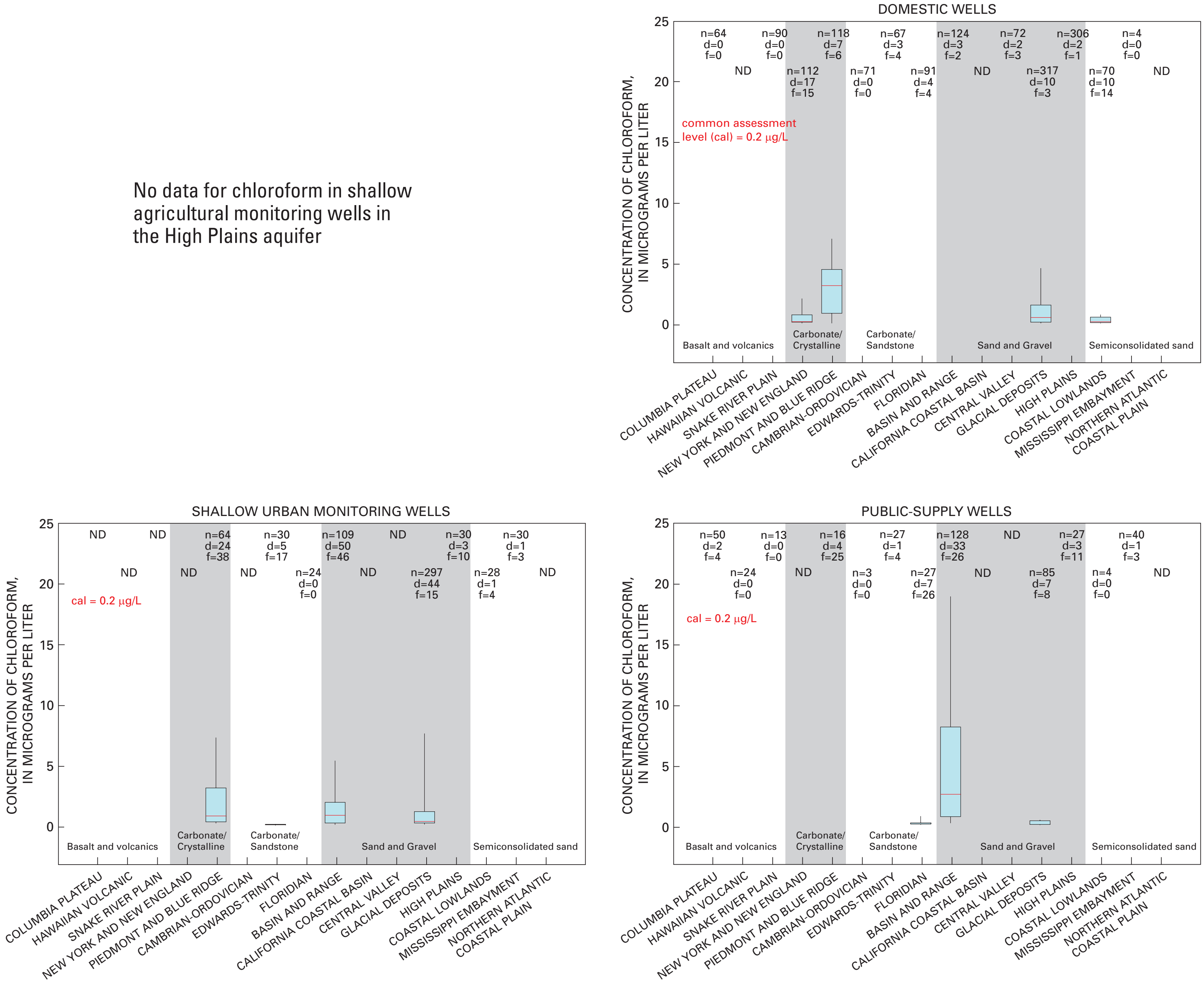
[1] Lapham, W.W., Hamilton, P.A., and Myers, D.N., 2005, National Water-Quality Assessment Program—Cycle II regional Assessments of aquifers: U.S. Geological Survey Fact Sheet 2005–3013, 4 p.


SHALLOW AGRICULTURAL MONITORING WELLS
DOMESTIC WELLS
SHALLOW URBAN MONITORING WELLS
PUBLIC-SUPPLY WELLS
CONCENTRATION OF DISSOLVED ARSENIC, IN MICROGRAMS PER LITER
100
75
50
25
0
MCL=10 µg/L
Basalt and volcanics
Carbonate/ Crystalline
Carbonate/ Sandstone
Sand and Gravel
Semiconsolidated sand
COLUMBIA PLATEAU
HAWAIIAN VOLCANIC
SNAKE RIVER PLAIN
NEW YORK AND NEW ENGLAND
PIEDMONT AND BLUE RIDGE
CAMBRIAN-ORDOVICIAN
EDWARDS-TRINITY
FLORIDIAN
BASIN AND RANGE
CALIFORNIA COASTAL BASIN
CENTRAL VALLEY
GLACIAL DEPOSITS
HIGH PLAINS
COASTAL LOWLANDS
MISSISSIPPI EMBAYMENT
NORTHERN ATLANTIC COASTAL PLAIN
n=46
ND
n=3
ND
ND
ND
ND
ND
n=37
ND
n=23
n=203
n=59
n=26
ND
n=48
ND
ND
n=58
n=112
n=79
n=68
n=67
n=97
n=125
n=5
n=76
n=239
n=306
n=72
n=5
n=52
ND
ND
ND
ND
n=64
ND
n=30
n=24
n=89
n=25
ND
n=184
n=30
n=28
n=31
n=1
n=23
n=23
n=8
ND
n=1
n=5
n=27
n=26
n=103
n=56
ND
n=72
n=35
n=4
n=11
n=4

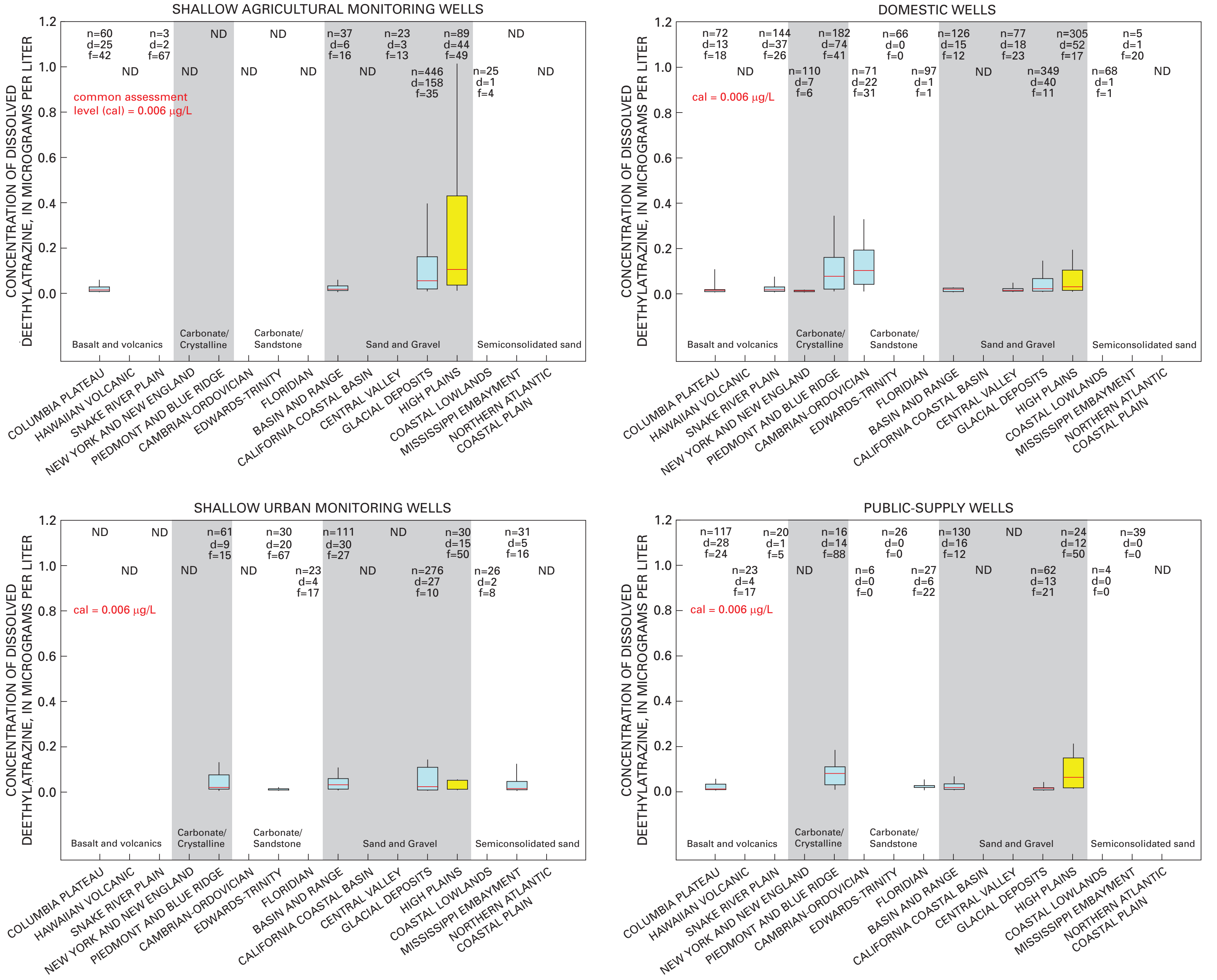
]

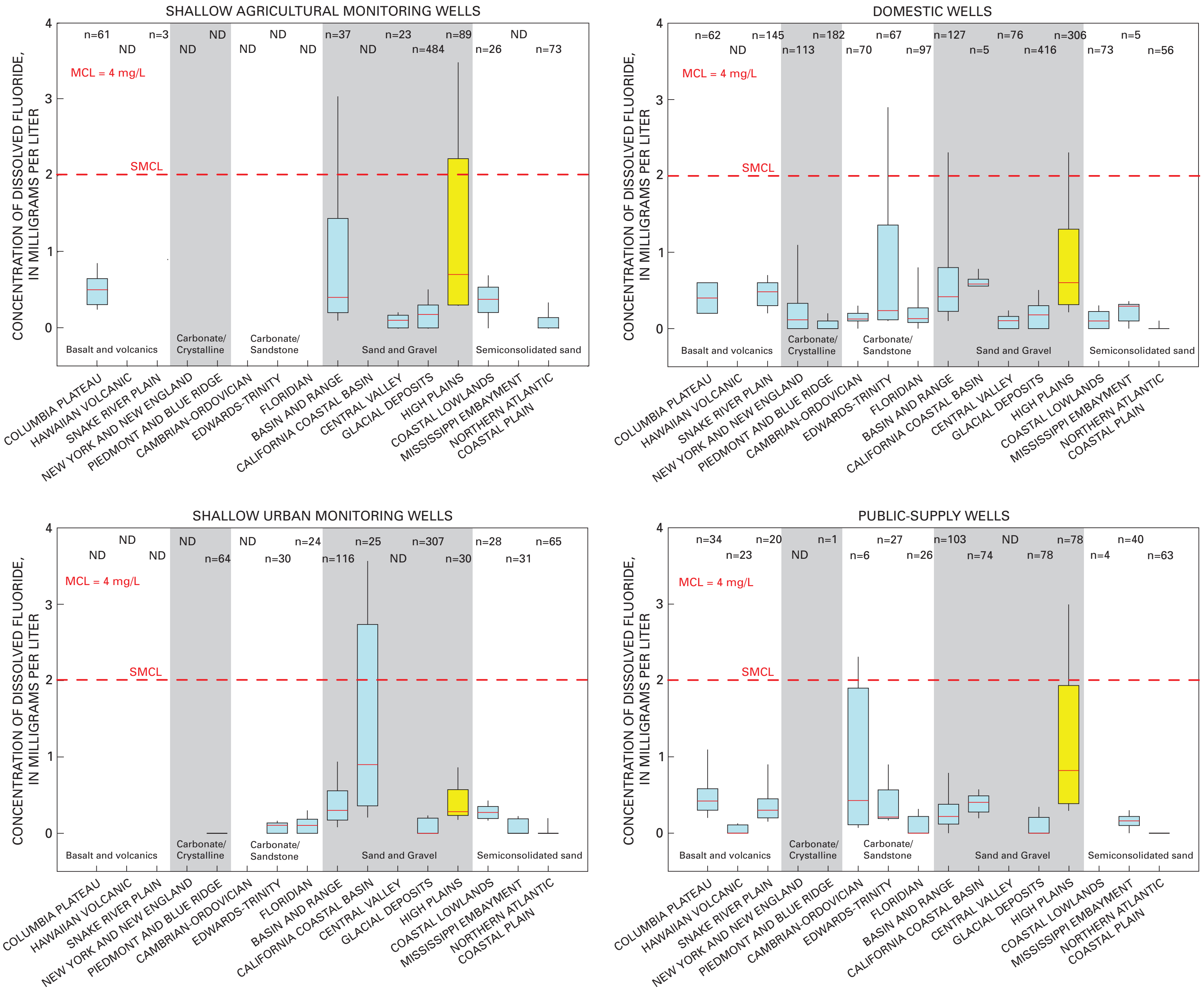

SHALLOW AGRICULTURAL MONITORING WELLS
DOMESTIC WELLS
SHALLOW URBAN MONITORING WELLS
PUBLIC-SUPPLY WELLS
CONCENTRATION OF DISSOLVED ATRAZINE, IN MICROGRAMS PER LITER
1.5
1.0
0.5
0.0
MCL=3 µg/L; common assessment level (cal) = 0.007 µg/L
MCL=3 µg/L; cal = 0.007 µg/L
MCL=3 µg/L; cal=0.007 µg/L
n=60 d=23 f=38
n=3 d=3 f=100
n=37 d=7 f=19
n=22 d=2 f=9
n=86 d=40 f=47
n=441 d=143 f=32
n=25 d=1 f=4
n=72 d=15 f=21
n=144 d=41 f=28
n=181 d=56 f=31
n=66 d=0 f=0
n=126 d=11 f=9
n=75 d=12 f=16
n=304 d=38 f=13
n=5 d=1 f=20
n=111 d=2 f=2
n=71 d=23 f=32
n=97 d=3 f=3
n=348 d=27 f=8
n=69 d=1 f=1
n=61 d=11 f=18
n=30 d=18 f=60
n=112 d=33 f=29
n=30 d=14 f=47
n=31 d=8 f=26
n=23 d=1 f=4
n=277 d=30 f=11
n=26 d=2 f=8
n=117 d=28 f=24
n=20 d=1 f=5
n=16 d=11 f=69
n=26 d=0 f=0
n=131 d=13 f=10
n=33 d=15 f=45
n=39 d=0 f=0
n=23 d=4 f=17
n=6 d=0 f=0
n=27 d=5 f=19
n=60 d=14 f=23
n=4 d=0 f=0
ND
Basalt and volcanics
Carbonate/ Crystalline
Carbonate/ Sandstone
Sand and Gravel
Semiconsolidated sand
COLUMBIA PLATEAU
HAWAIIAN VOLCANIC
SNAKE RIVER PLAIN
NEW YORK AND NEW ENGLAND
PIEDMONT AND BLUE RIDGE
CAMBRIAN-ORDOVICIAN
EDWARDS-TRINITY
FLORIDIAN
BASIN AND RANGE
CALIFORNIA COASTAL BASIN
CENTRAL VALLEY
GLACIAL DEPOSITS
HIGH PLAINS
COASTAL LOWLANDS
MISSISSIPPI EMBAYMENT
NORTHERN ATLANTIC COASTAL PLAIN

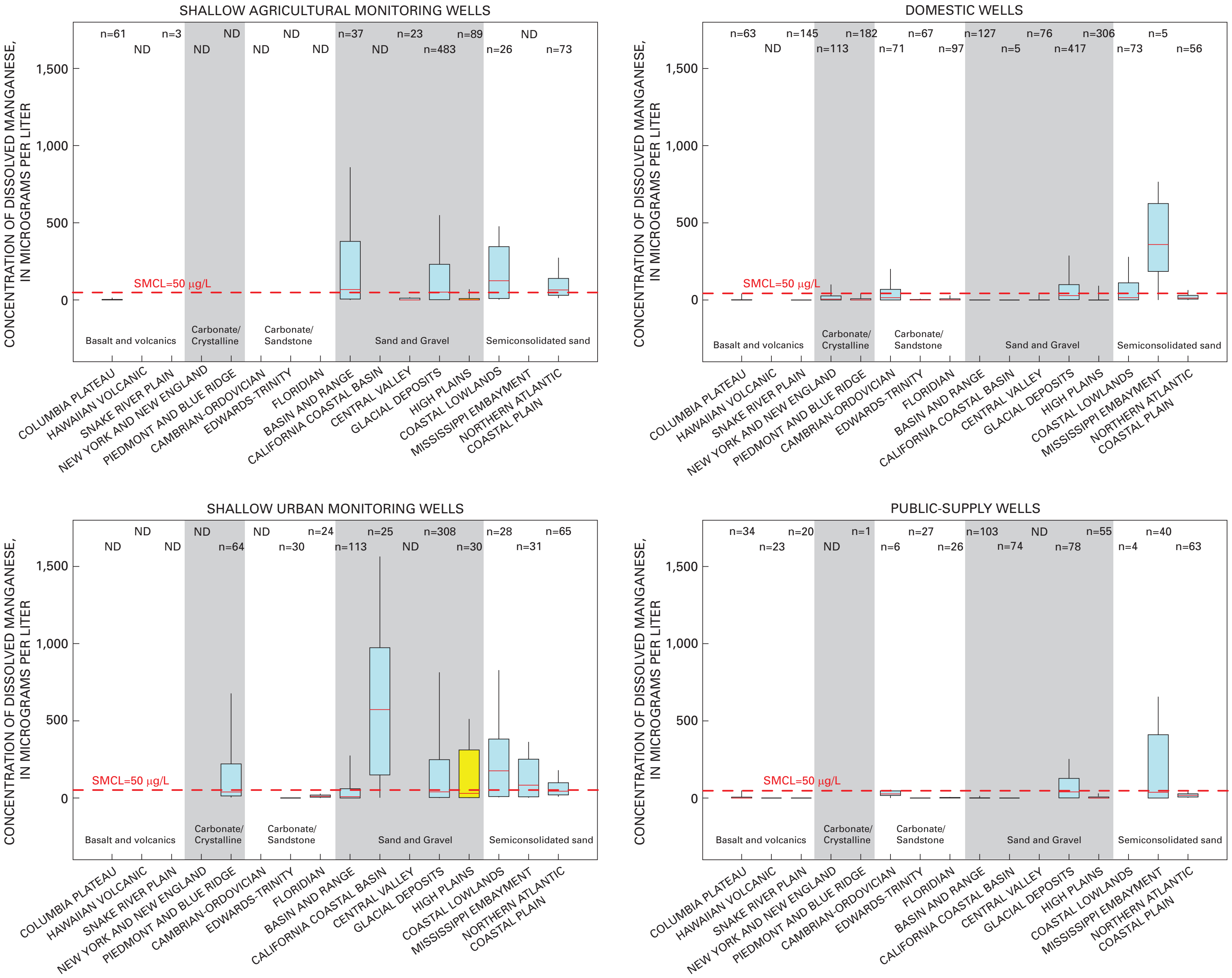

SHALLOW AGRICULTURAL MONITORING WELLS
DOMESTIC WELLS
SHALLOW URBAN MONITORING WELLS
PUBLIC-SUPPLY WELLS
CONCENTRATION OF DISSOLVED BORON, IN MICROGRAMS PER LITER
500
400
300
200
100
0
2300
2000
1200
900
600
300
0
Basalt and volcanics
Carbonate/ Crystalline
Carbonate/ Sandstone
Sand and Gravel
Semiconsolidated sand
n=46 ND ND ND ND ND ND ND ND ND n=12 n=126 n=59 n=10 ND n=48
ND ND n=13 n=86 n=25 n=18 n=2 n=71 n=5 n=5 n=72 n=165 n=212 n=67 n=5 n=51
ND ND ND ND n=30 ND ND n=17 n=38 n=25 ND n=115 n=30 n=28 n=31 n=6
n=23 n=23 ND ND n=1 n=5 ND n=25 n=75 n=74 ND n=61 n=40 n=3 n=40 n=3
COLUMBIA PLATEAU
HAWAIIAN VOLCANIC
SNAKE RIVER PLAIN
NEW YORK AND NEW ENGLAND
PIEDMONT AND BLUE RIDGE
CAMBRIAN-ORDOVICIAN
EDWARDS-TRINITY
FLORIDIAN
BASIN AND RANGE
CALIFORNIA COASTAL BASIN
CENTRAL VALLEY
GLACIAL DEPOSITS
HIGH PLAINS
COASTAL LOWLANDS
MISSISSIPPI EMBAYMENT
NORTHERN ATLANTIC COASTAL PLAIN

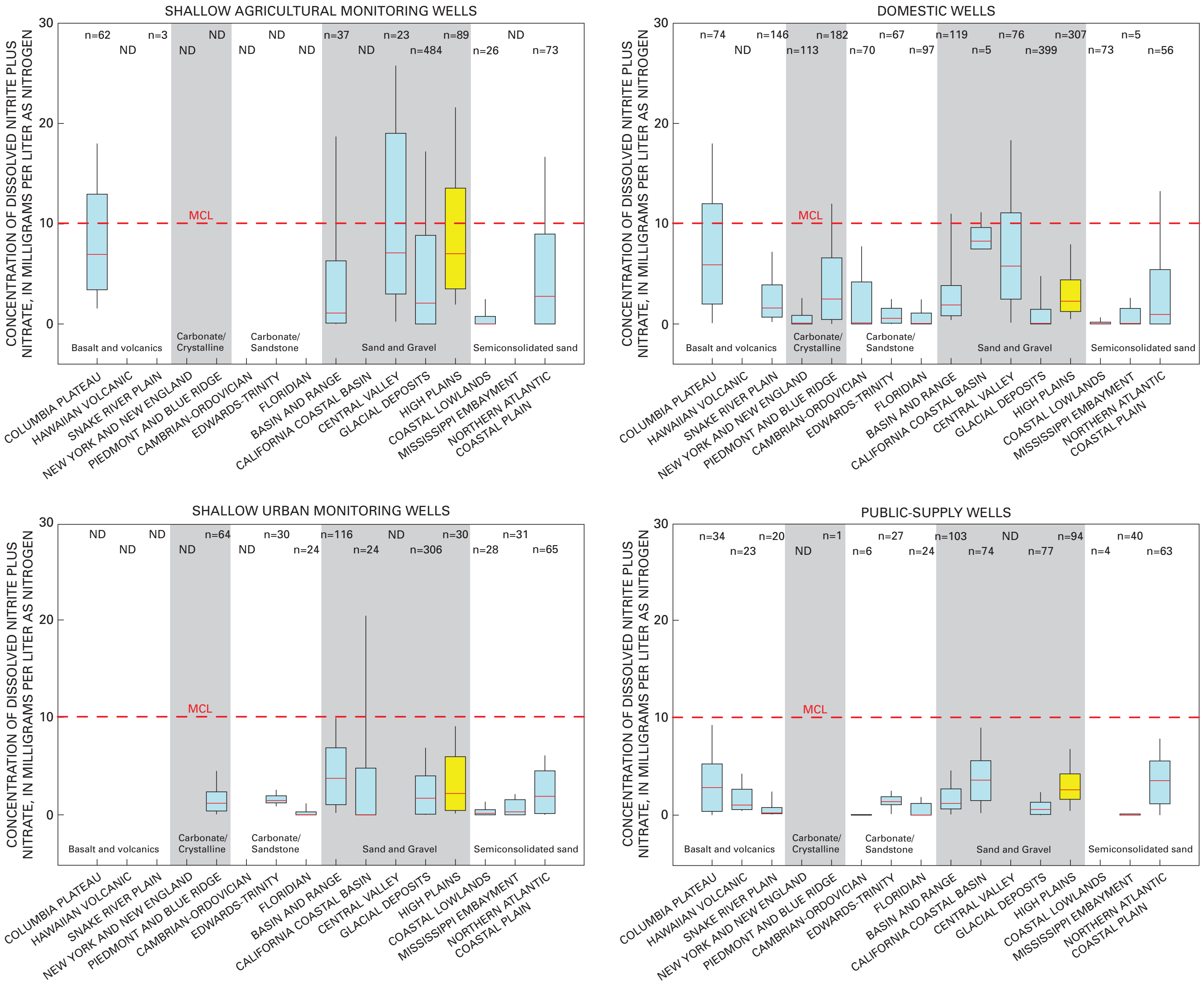


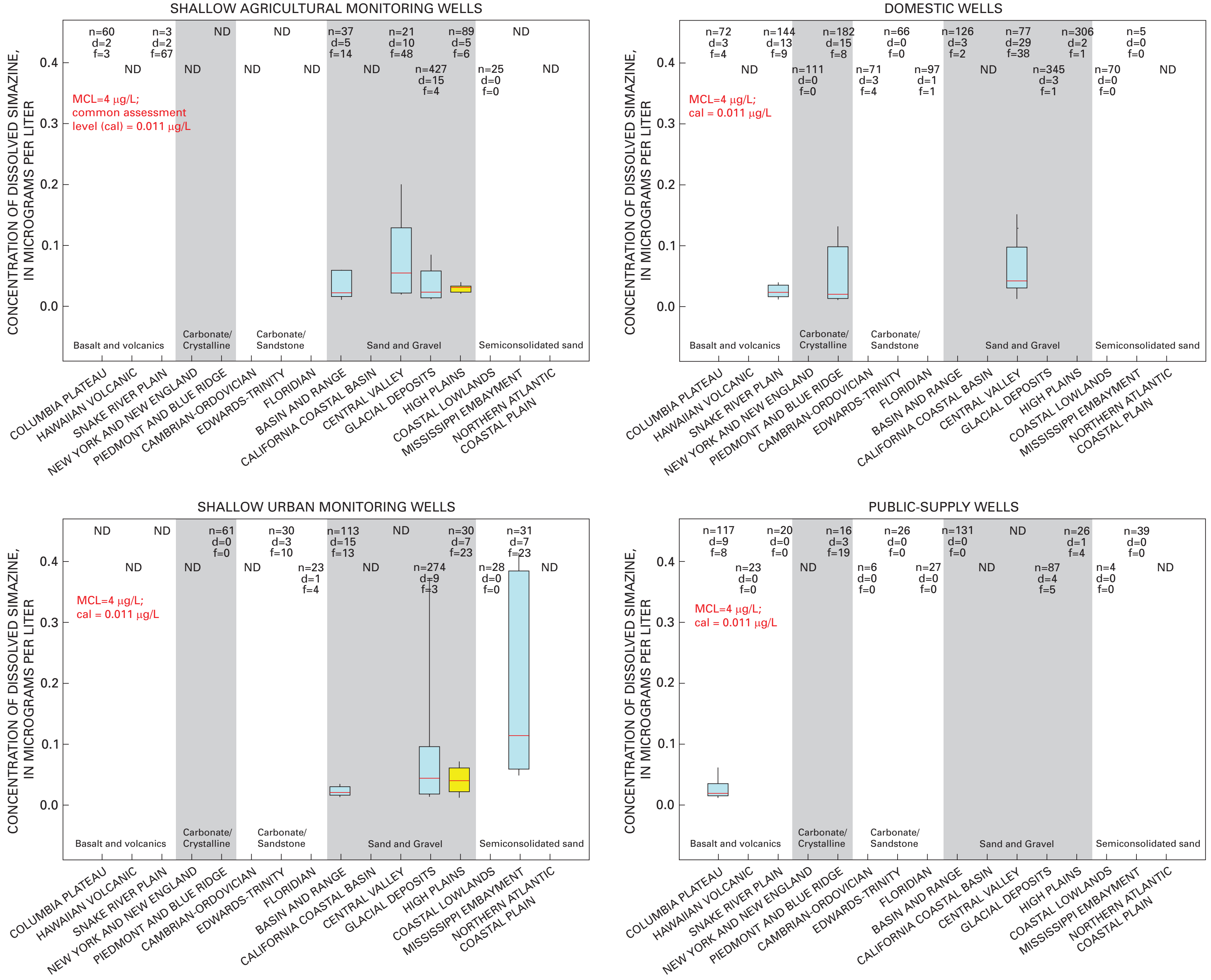
No data for chloroform in shallow agricultural monitoring wells in the High Plains aquifer


SHALLOW AGRICULTURAL MONITORING WELLS
DOMESTIC WELLS
SHALLOW URBAN MONITORING WELLS
PUBLIC-SUPPLY WELLS
CONCENTRATION OF DISSOLVED DEETHYLATRAZINE, IN MICROGRAMS PER LITER
1.2
1.0
0.8
0.6
0.4
0.2
0.0
common assessment level (cal) = 0.006 µg/L
cal = 0.006 µg/L
Basalt and volcanics
Carbonate/ Crystalline
Carbonate/ Sandstone
Sand and Gravel
Semiconsolidated sand
ND
n=60 d=25 f=42
n=3 d=2 f=67
n=37 d=6 f=16
n=23 d=3 f=13
n=89 d=44 f=49
n=446 d=158 f=35
n=25 d=1 f=4
n=72 d=13 f=18
n=144 d=37 f=26
n=182 d=74 f=41
n=66 d=0 f=0
n=126 d=15 f=12
n=77 d=18 f=23
n=305 d=52 f=17
n=5 d=1 f=20
n=110 d=7 f=6
n=71 d=22 f=31
n=97 d=1 f=1
n=349 d=40 f=11
n=68 d=1 f=1
n=61 d=9 f=15
n=30 d=20 f=67
n=111 d=30 f=27
n=30 d=15 f=50
n=31 d=5 f=16
n=23 d=4 f=17
n=276 d=27 f=10
n=26 d=2 f=8
n=117 d=28 f=24
n=20 d=1 f=5
n=16 d=14 f=88
n=26 d=0 f=0
n=130 d=16 f=12
n=24 d=12 f=50
n=39 d=0 f=0
n=23 d=4 f=17
n=6 d=0 f=0
n=27 d=6 f=22
n=62 d=13 f=21
n=4 d=0 f=0
COLUMBIA PLATEAU
HAWAIIAN VOLCANIC
SNAKE RIVER PLAIN
NEW YORK AND NEW ENGLAND
PIEDMONT AND BLUE RIDGE
CAMBRIAN-ORDOVICIAN
EDWARDS-TRINITY
FLORIDIAN
BASIN AND RANGE
CALIFORNIA COASTAL BASIN
CENTRAL VALLEY
GLACIAL DEPOSITS
HIGH PLAINS
COASTAL LOWLANDS
MISSISSIPPI EMBAYMENT
NORTHERN ATLANTIC COASTAL PLAIN


SHALLOW AGRICULTURAL MONITORING WELLS
DOMESTIC WELLS
SHALLOW URBAN MONITORING WELLS
PUBLIC-SUPPLY WELLS
CONCENTRATION OF DISSOLVED FLUORIDE, IN MILLIGRAMS PER LITER
0
1
2
3
4
MCL = 4 mg/L
SMCL
n=61 ND n=3 ND ND ND ND ND n=37 ND n=23 n=484 n=89 n=26 ND n=73
n=62 ND n=145 n=113 n=182 n=70 n=67 n=97 n=127 n=5 n=76 n=416 n=306 n=73 n=5 n=56
ND ND ND ND n=64 ND n=30 n=24 n=116 n=25 ND n=307 n=30 n=28 n=31 n=65
n=34 n=23 n=20 ND n=1 n=6 n=27 n=26 n=103 n=74 ND n=78 n=78 n=4 n=40 n=63
Basalt and volcanics
Carbonate/ Crystalline
Carbonate/ Sandstone
Sand and Gravel
Semiconsolidated sand
COLUMBIA PLATEAU
HAWAIIAN VOLCANIC
SNAKE RIVER PLAIN
NEW YORK AND NEW ENGLAND
PIEDMONT AND BLUE RIDGE
CAMBRIAN-ORDOVICIAN
EDWARDS-TRINITY
FLORIDIAN
BASIN AND RANGE
CALIFORNIA COASTAL BASIN
CENTRAL VALLEY
GLACIAL DEPOSITS
HIGH PLAINS
COASTAL LOWLANDS
MISSISSIPPI EMBAYMENT
NORTHERN ATLANTIC COASTAL PLAIN

SHALLOW AGRICULTURAL MONITORING WELLS
DOMESTIC WELLS
SHALLOW URBAN MONITORING WELLS
PUBLIC-SUPPLY WELLS
CONCENTRATION OF DISSOLVED MANGANESE, IN MICROGRAMS PER LITER
0
500
1,000
1,500
SMCL=50 µg/L
Basalt and volcanics
Carbonate/ Crystalline
Carbonate/ Sandstone
Sand and Gravel
Semiconsolidated sand
n=61
ND
n=3
ND
ND
ND
ND
ND
n=37
ND
n=23
n=483
n=89
n=26
ND
n=73
n=63
ND
n=145
n=113
n=182
n=71
n=67
n=97
n=127
n=5
n=76
n=417
n=306
n=73
n=5
n=56
ND
ND
ND
ND
n=64
ND
n=30
n=24
n=113
n=25
ND
n=308
n=30
n=28
n=31
n=65
n=34
n=23
n=20
ND
n=1
n=6
n=27
n=26
n=103
n=74
ND
n=78
n=55
n=4
n=40
n=63
COLUMBIA PLATEAU
HAWAIIAN VOLCANIC
SNAKE RIVER PLAIN
NEW YORK AND NEW ENGLAND
PIEDMONT AND BLUE RIDGE
CAMBRIAN-ORDOVICIAN
EDWARDS-TRINITY
FLORIDIAN
BASIN AND RANGE
CALIFORNIA COASTAL BASIN
CENTRAL VALLEY
GLACIAL DEPOSITS
HIGH PLAINS
COASTAL LOWLANDS
MISSISSIPPI EMBAYMENT
NORTHERN ATLANTIC COASTAL PLAIN


SHALLOW AGRICULTURAL MONITORING WELLS
DOMESTIC WELLS
SHALLOW URBAN MONITORING WELLS
PUBLIC-SUPPLY WELLS
CONCENTRATION OF DISSOLVED NITRITE PLUS NITRATE, IN MILLIGRAMS PER LITER AS NITROGEN
0
10
20
30
MCL
Basalt and volcanics
Carbonate/ Crystalline
Carbonate/ Sandstone
Sand and Gravel
Semiconsolidated sand
COLUMBIA PLATEAU
HAWAIIAN VOLCANIC
SNAKE RIVER PLAIN
NEW YORK AND NEW ENGLAND
PIEDMONT AND BLUE RIDGE
CAMBRIAN-ORDOVICIAN
EDWARDS-TRINITY
FLORIDIAN
BASIN AND RANGE
CALIFORNIA COASTAL BASIN
CENTRAL VALLEY
GLACIAL DEPOSITS
HIGH PLAINS
COASTAL LOWLANDS
MISSISSIPPI EMBAYMENT
NORTHERN ATLANTIC COASTAL PLAIN
n=62
ND
n=3
ND
ND
ND
ND
ND
n=37
ND
n=23
n=484
n=89
n=26
ND
n=73
n=74
ND
n=146
n=113
n=182
n=70
n=67
n=97
n=119
n=5
n=76
n=399
n=307
n=73
n=5
n=56
ND
ND
ND
ND
n=64
ND
n=30
n=24
n=116
n=24
ND
n=306
n=30
n=28
n=31
n=65
n=34
n=23
n=20
ND
n=1
n=6
n=27
n=24
n=103
n=74
ND
n=77
n=94
n=4
n=40
n=63


SHALLOW AGRICULTURAL MONITORING WELLS
CONCENTRATION OF DISSOLVED SIMAZINE, IN MICROGRAMS PER LITER
0.4
0.3
0.2
0.1
0.0
MCL=4 µg/L; common assessment level (cal) = 0.011 µg/L
n=60 d=2 f=3
ND
n=3 d=2 f=67
ND
ND
ND
ND
ND
n=37 d=5 f=14
ND
n=21 d=10 f=48
n=427 d=15 f=4
n=89 d=5 f=6
n=25 d=0 f=0
ND
ND
Basalt and volcanics
Carbonate/ Crystalline
Carbonate/ Sandstone
Sand and Gravel
Semiconsolidated sand
COLUMBIA PLATEAU
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CENTRAL VALLEY
GLACIAL DEPOSITS
HIGH PLAINS
COASTAL LOWLANDS
MISSISSIPPI EMBAYMENT
NORTHERN ATLANTIC COASTAL PLAIN
DOMESTIC WELLS
CONCENTRATION OF DISSOLVED SIMAZINE, IN MICROGRAMS PER LITER
0.4
0.3
0.2
0.1
0.0
MCL=4 µg/L; cal = 0.011 µg/L
n=72 d=3 f=4
ND
n=144 d=13 f=9
n=111 d=0 f=0
n=182 d=15 f=8
n=71 d=3 f=4
n=66 d=0 f=0
n=97 d=1 f=1
n=126 d=3 f=2
ND
n=77 d=29 f=38
n=345 d=3 f=1
n=306 d=2 f=1
n=70 d=0 f=0
n=5 d=0 f=0
ND
Basalt and volcanics
Carbonate/ Crystalline
Carbonate/ Sandstone
Sand and Gravel
Semiconsolidated sand
COLUMBIA PLATEAU
HAWAIIAN VOLCANIC
SNAKE RIVER PLAIN
NEW YORK AND NEW ENGLAND
PIEDMONT AND BLUE RIDGE
CAMBRIAN-ORDOVICIAN
EDWARDS-TRINITY
FLORIDIAN
BASIN AND RANGE
CALIFORNIA COASTAL BASIN
CENTRAL VALLEY
GLACIAL DEPOSITS
HIGH PLAINS
COASTAL LOWLANDS
MISSISSIPPI EMBAYMENT
NORTHERN ATLANTIC COASTAL PLAIN
SHALLOW URBAN MONITORING WELLS
CONCENTRATION OF DISSOLVED SIMAZINE, IN MICROGRAMS PER LITER
0.4
0.3
0.2
0.1
0.0
MCL=4 µg/L; cal = 0.011 µg/L
ND
ND
ND
ND
n=61 d=0 f=0
ND
n=30 d=3 f=10
n=23 d=1 f=4
n=113 d=15 f=13
ND
ND
n=274 d=9 f=3
n=30 d=7 f=23
n=28 d=0 f=0
n=31 d=7 f=23
ND
Basalt and volcanics
Carbonate/ Crystalline
Carbonate/ Sandstone
Sand and Gravel
Semiconsolidated sand
COLUMBIA PLATEAU
HAWAIIAN VOLCANIC
SNAKE RIVER PLAIN
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HIGH PLAINS
COASTAL LOWLANDS
MISSISSIPPI EMBAYMENT
NORTHERN ATLANTIC COASTAL PLAIN
PUBLIC-SUPPLY WELLS
CONCENTRATION OF DISSOLVED SIMAZINE, IN MICROGRAMS PER LITER
0.4
0.3
0.2
0.1
0.0
MCL=4 µg/L; cal = 0.011 µg/L
n=117 d=9 f=8
n=23 d=0 f=0
n=20 d=0 f=0
ND
n=16 d=3 f=19
n=6 d=0 f=0
n=26 d=0 f=0
n=27 d=0 f=0
n=131 d=0 f=0
ND
ND
n=87 d=4 f=5
n=26 d=1 f=4
n=4 d=0 f=0
n=39 d=0 f=0
ND
Basalt and volcanics
Carbonate/ Crystalline
Carbonate/ Sandstone
Sand and Gravel
Semiconsolidated sand
COLUMBIA PLATEAU
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SNAKE RIVER PLAIN
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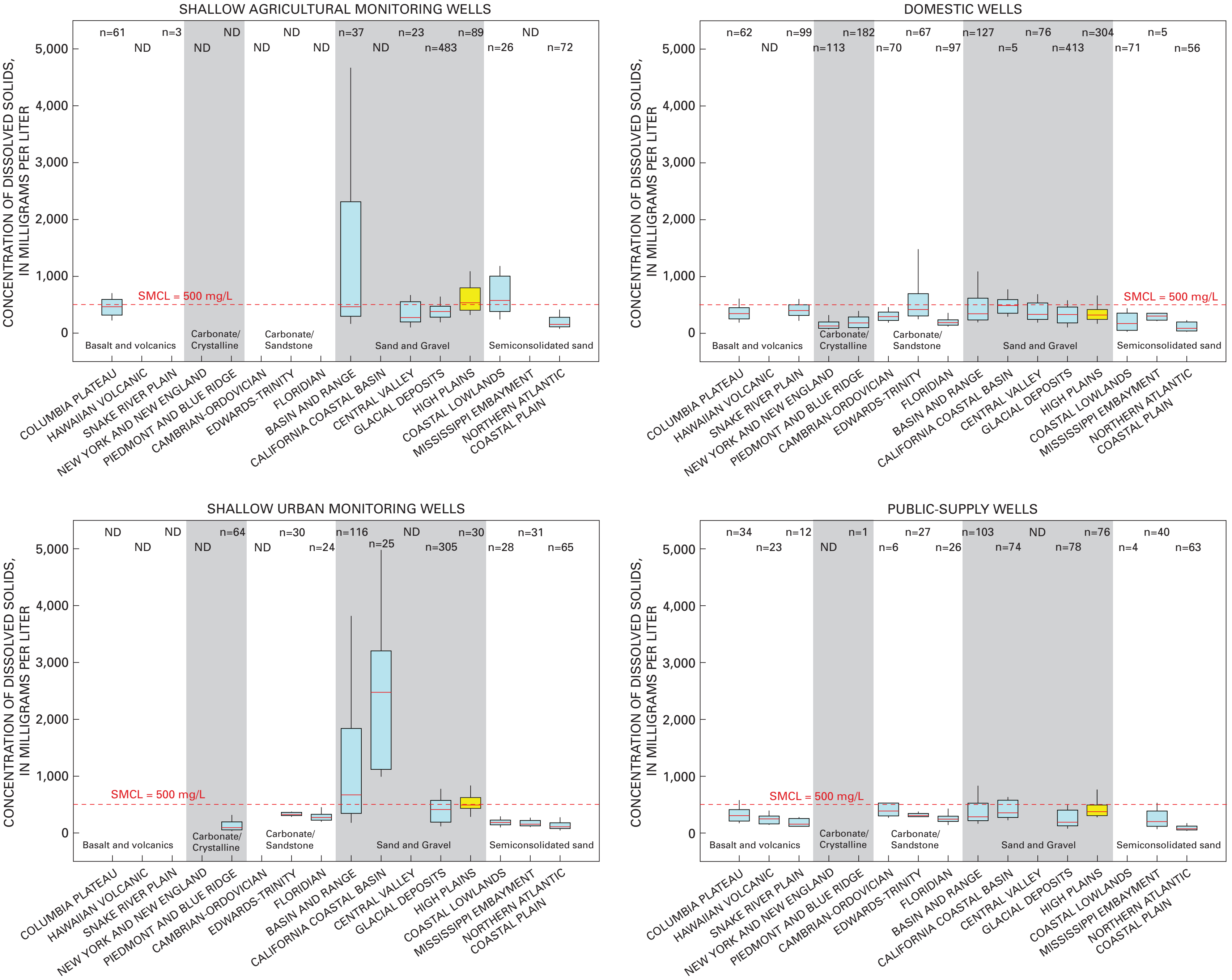
GLACIAL DEPOSITS
HIGH PLAINS
COASTAL LOWLANDS
MISSISSIPPI EMBAYMENT
NORTHERN ATLANTIC COASTAL PLAIN


SHALLOW AGRICULTURAL MONITORING WELLS
DOMESTIC WELLS
SHALLOW URBAN MONITORING WELLS
PUBLIC-SUPPLY WELLS
CONCENTRATION OF DISSOLVED SOLIDS, IN MILLIGRAMS PER LITER
0
1,000
2,000
3,000
4,000
5,000
SMCL = 500 mg/L
Basalt and volcanics
Carbonate/ Crystalline
Carbonate/ Sandstone
Sand and Gravel
Semiconsolidated sand
COLUMBIA PLATEAU
HAWAIIAN VOLCANIC
SNAKE RIVER PLAIN
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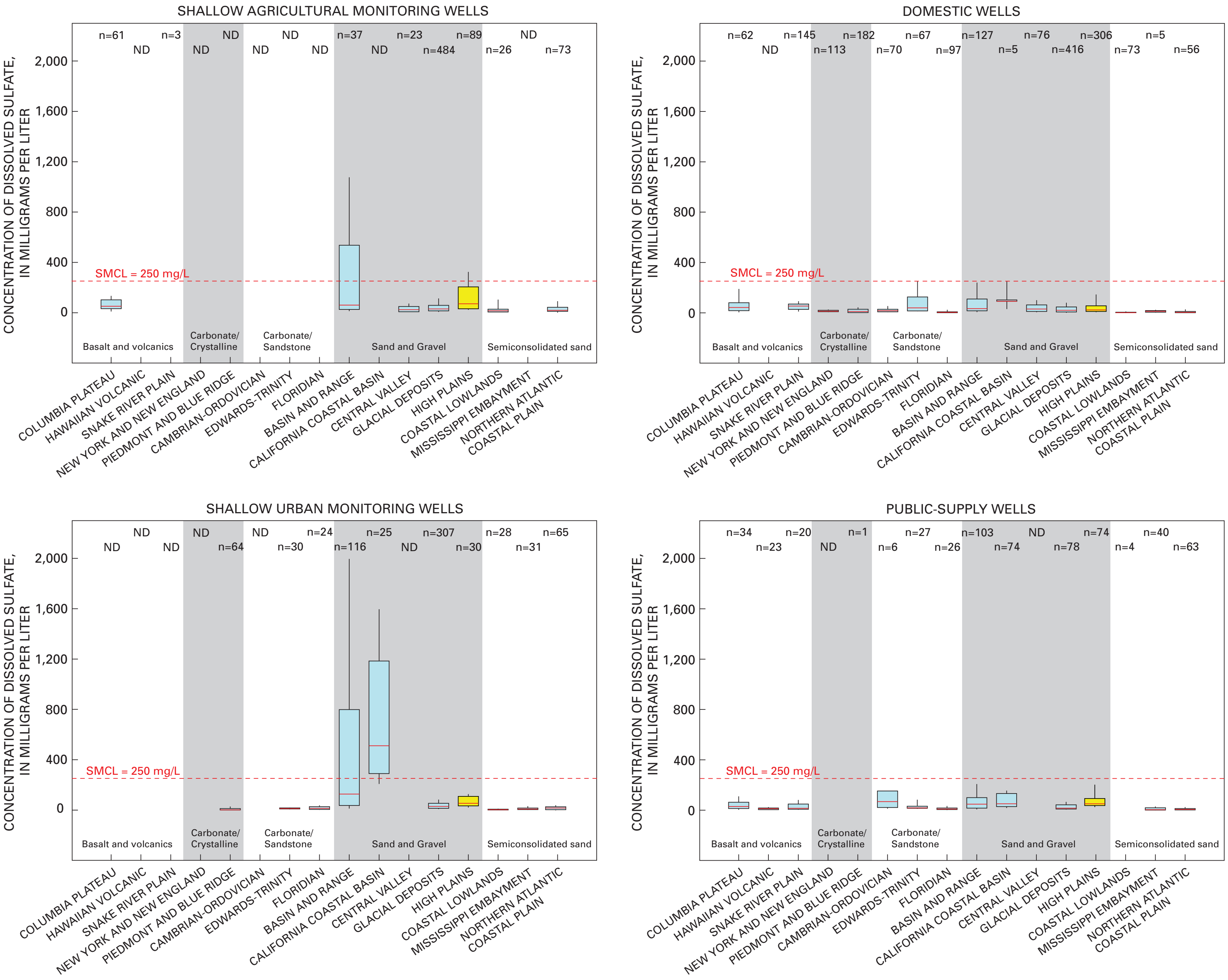
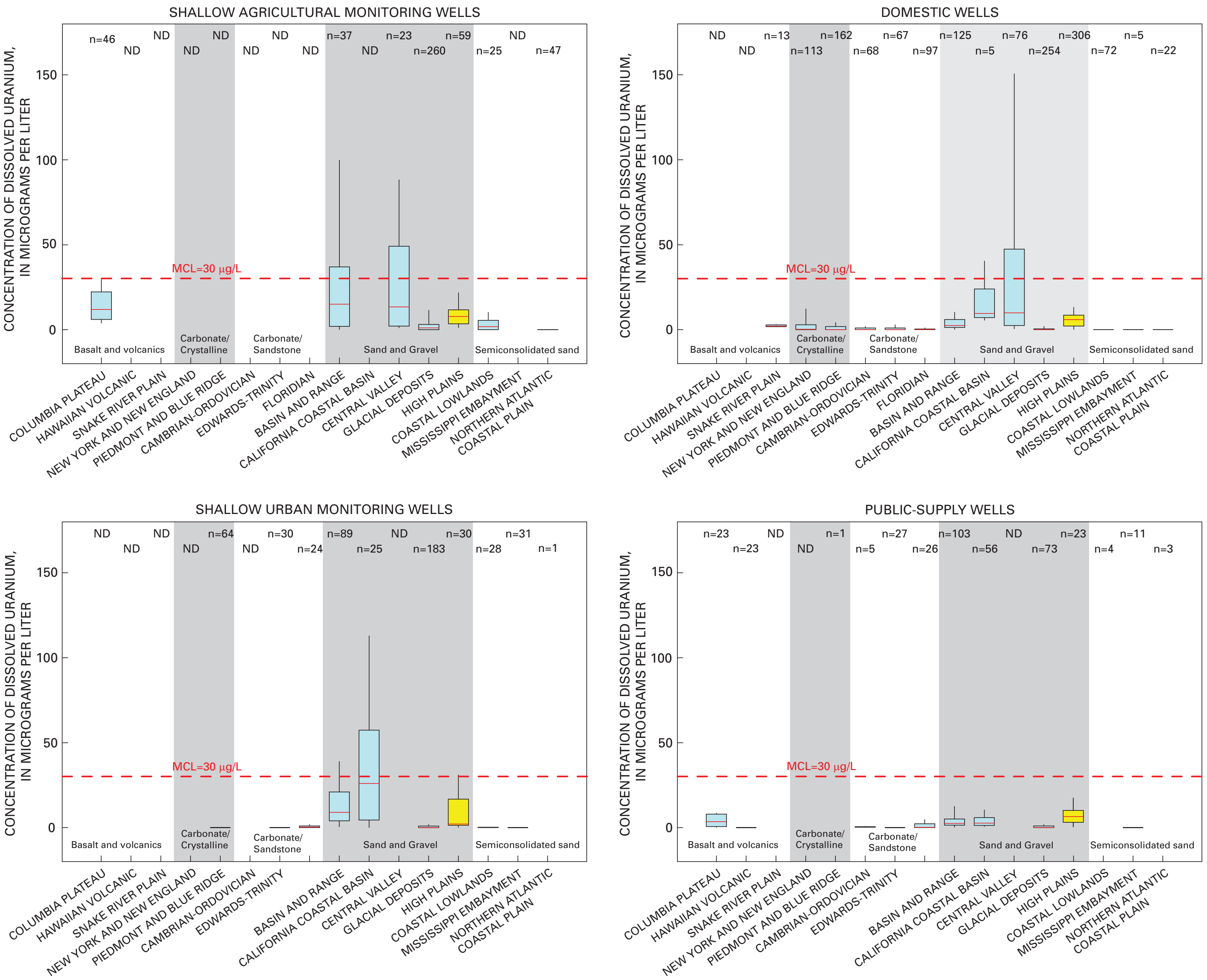
CALIFORNIA COASTAL BASIN
CENTRAL VALLEY
GLACIAL DEPOSITS
HIGH PLAINS
COASTAL LOWLANDS
MISSISSIPPI EMBAYMENT
NORTHERN ATLANTIC COASTAL PLAIN
n=61 ND n=3 ND ND ND ND ND ND n=37 ND n=23 n=483 n=89 n=26 ND n=72
n=62 ND n=99 n=113 n=182 n=70 n=67 n=97 n=127 n=5 n=76 n=413 n=304 n=71 n=5 n=56
ND ND ND ND n=64 ND n=30 n=24 n=116 n=25 ND n=305 n=30 n=28 n=31 n=65
n=34 n=23 n=12 ND n=1 n=6 n=27 n=26 n=103 n=74 ND n=78 n=76 n=4 n=40 n=63


SHALLOW AGRICULTURAL MONITORING WELLS
DOMESTIC WELLS
SHALLOW URBAN MONITORING WELLS
PUBLIC-SUPPLY WELLS
CONCENTRATION OF DISSOLVED SULFATE, IN MILLIGRAMS PER LITER
2,000
1,600
1,200
800
400
0
SMCL = 250 mg/L
Basalt and volcanics
Carbonate/ Crystalline
Carbonate/ Sandstone
Sand and Gravel
Semiconsolidated sand
COLUMBIA PLATEAU
HAWAIIAN VOLCANIC
SNAKE RIVER PLAIN
NEW YORK AND NEW ENGLAND
PIEDMONT AND BLUE RIDGE
CAMBRIAN-ORDOVICIAN
EDWARDS-TRINITY
FLORIDIAN
BASIN AND RANGE
CALIFORNIA COASTAL BASIN
CENTRAL VALLEY
GLACIAL DEPOSITS
HIGH PLAINS
COASTAL LOWLANDS
MISSISSIPPI EMBAYMENT
NORTHERN ATLANTIC COASTAL PLAIN
n=61 ND n=3 ND ND ND ND ND n=37 ND n=23 n=484 n=89 n=26 ND n=73
n=62 ND n=145 n=113 n=182 n=70 n=67 n=97 n=127 n=5 n=76 n=416 n=306 n=73 n=5 n=56
ND ND ND ND n=64 ND n=30 n=24 n=116 n=25 ND n=307 n=30 n=28 n=31 n=65
n=34 n=23 n=20 ND n=1 n=6 n=27 n=26 n=103 n=74 ND n=78 n=74 n=4 n=40 n=63


SHALLOW AGRICULTURAL MONITORING WELLS
DOMESTIC WELLS
SHALLOW URBAN MONITORING WELLS
PUBLIC-SUPPLY WELLS
CONCENTRATION OF DISSOLVED URANIUM, IN MICROGRAMS PER LITER
0
50
100
150
MCL=30 µg/L
Basalt and volcanics
Carbonate/ Crystalline
Carbonate/ Sandstone
Sand and Gravel
Semiconsolidated sand
n=46
ND
n=37
n=23
n=59
n=260
n=25
n=47
n=13
n=162
n=113
n=67
n=68
n=97
n=125
n=5
n=76
n=254
n=306
n=72
n=22
n=64
n=30
n=24
n=89
n=25
n=183
n=28
n=31
n=1
n=23
n=1
n=27
n=26
n=103
n=56
n=73
n=11
n=4
n=3
COLUMBIA PLATEAU
HAWAIIAN VOLCANIC
SNAKE RIVER PLAIN
NEW YORK AND NEW ENGLAND
PIEDMONT AND BLUE RIDGE
CAMBRIAN-ORDOVICIAN
EDWARDS-TRINITY
FLORIDIAN
BASIN AND RANGE
CALIFORNIA COASTAL BASIN
CENTRAL VALLEY
GLACIAL DEPOSITS
HIGH PLAINS
COASTAL LOWLANDS
MISSISSIPPI EMBAYMENT
NORTHERN ATLANTIC COASTAL PLAIN

Back Cover:

Drilling a monitoring
well, southern
High Plains.

Photograph by
L. Fahlquist
(U.S. Geological Survey)

Development of a new
monitoring well.

Photograph by
P.B. McMahon
(U.S. Geological Survey)

Sampling a regional
transect study monitoring
well, southern High Plains.

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P.B. McMahon
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Typical set of sample bottles used
during ground-water quality sampling.

Photograph by
J.J Gurdak (U.S. Geological Survey)

Flame sealing a glass vial
containing a sample of
gas from an unsaturated-
zone study monitoring
site.

Photograph by
J.J Gurdak
(U.S. Geological Survey)

Collecting a ground-water
sample for analysis of
pesticides.

Photograph by
P.B. McMahon
(U.S. Geological Survey)

Alkalinity titration on a
sample of ground water.

Photograph by
P.B. McMahon
(U.S. Geological Survey)

Installing instruments at an unsaturated-
zone study monitoring site, central High
Plains rangeland setting.

Photograph by
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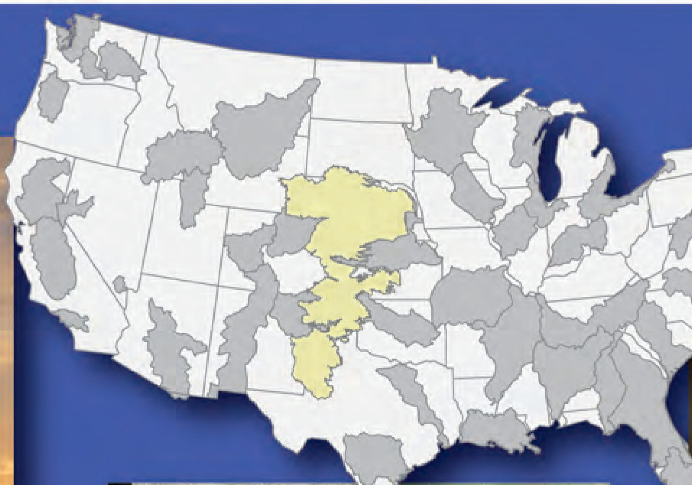
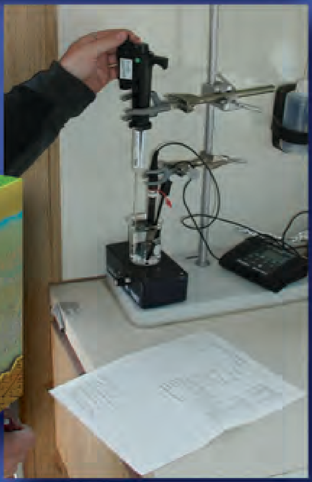
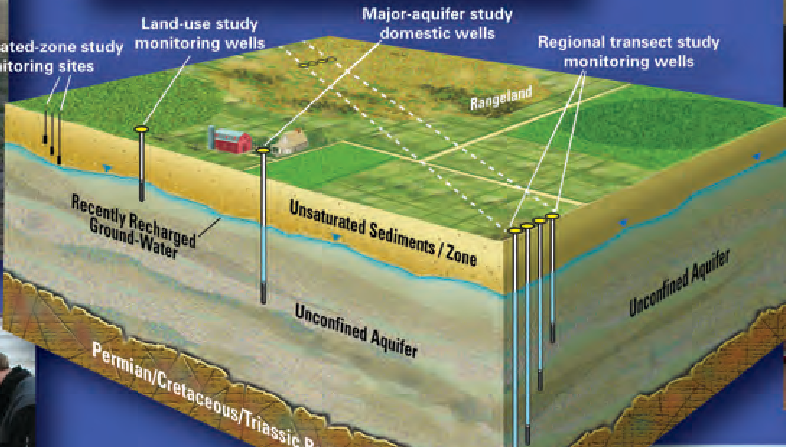
National Water-Quality Assessment (NAWQA) Program
High Plains Regional Ground-Water Study







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