Figure 13. Trilinear graph displaying major element chemistry of Tangshan ground water, People's Republic of China. Each scale represents percentage of total milliequivalents per liter. N, nitrogen.

Trilinear graphs of ground water from wells sampled in the western, southern, and eastern parts of the valley are shown in figures 16 through 18. The western San Joaquin Valley is recharged principally by runoff from the Coast Ranges and from irrigation. The anion chemistry of the western San Joaquin Valley ground water is complex with all three types of waters present: bicarbonate, sulfate, and chloride dominated. The cation chemistry is mostly sodium with varying amounts of calcium and magnesium. Ground water of the southern San Joaquin Valley is recharged from a variety of sources, including the Coast Ranges, the Sierra Nevada, various streams, and irrigation. The anion chemistry is basically similar to that of the western San Joaquin Valley, but with a greater dominance of bicarbonate water. The cation chemistry of the natural

ground water is generally similar to that of the western San Joaquin Valley. Ground water of the eastern San Joaquin Valley is recharged mainly from the Sierra Nevada runoff and from irrigation. The anion chemistry of the natural ground water is principally dominated by bicarbonate. The cation chemistry is different from that of the western and southern San Joaquin Valley in that calcium and magnesium tend to be the dominant ions. The ground water of the western San Joaquin Valley and much of the southern San Joaquin Valley tends to be close to saturation or supersaturated with respect to carbonate minerals, but the ground water of the eastern San Joaquin Valley tends to be undersaturated, reflecting the differences in chemistry of recharge water.

Hull (1984) recognized six hydrochemical facies throughout the Sacramento Valley. According to Hull
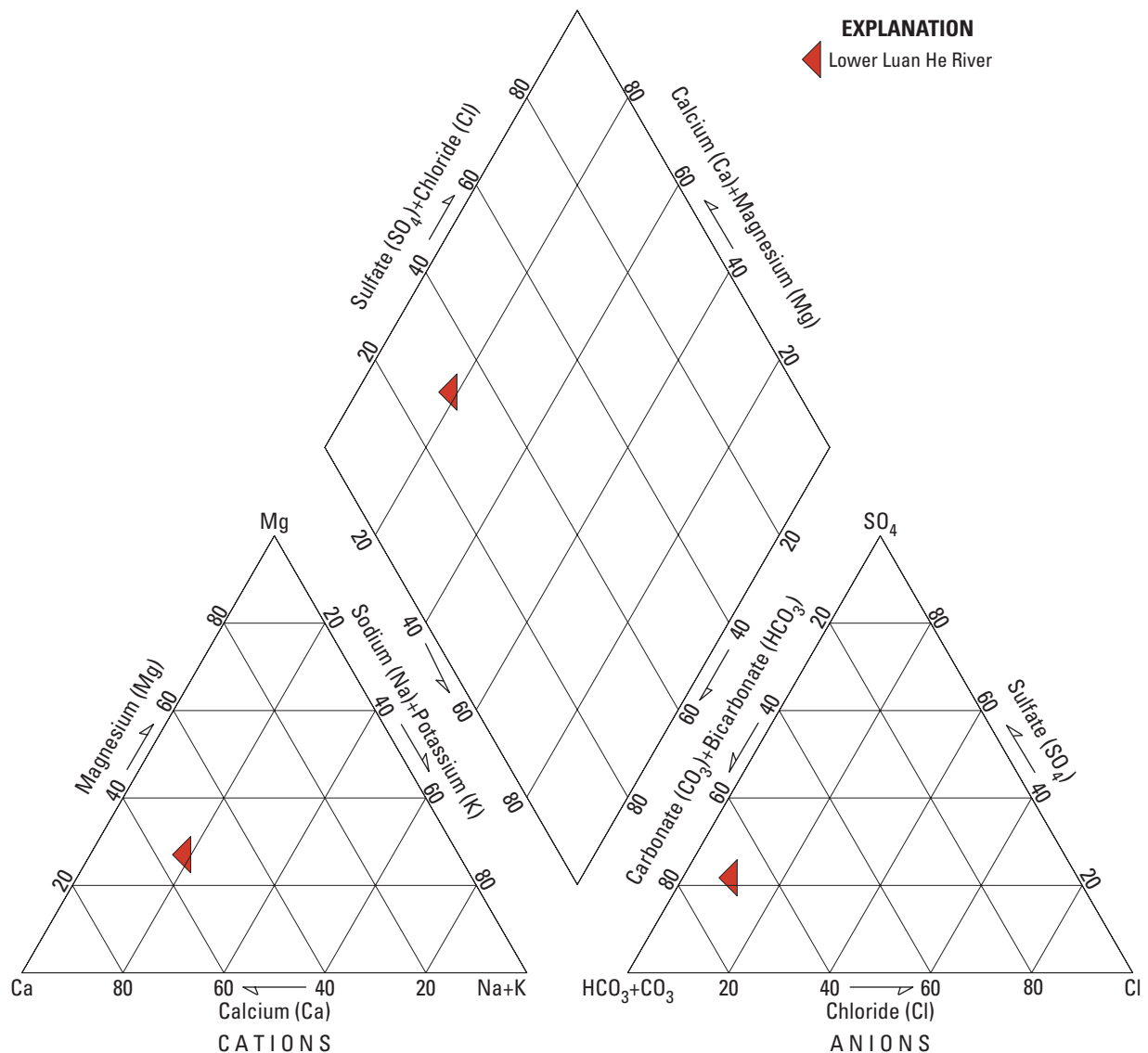
EXPLANATION

◄ Lower Luan He River

Figure 14. Trilinear graph displaying water chemistry of the Luan He River, People's Republic of China. Each scale represents percentage of total milliequivalents per liter.

(1984), the Sacramento subunit comprises two hydrochemical facies whereas the extent of the rice land-use study covers three hydrochemical facies. Under natural conditions, much of the recharge to the Sacramento subunit originates in the Sierra Nevada as dilute sodium or calcium bicarbonate water. Parts of the Sacramento subunit aquifer have areas with low dissolved oxygen and higher concentrations of chloride. The chemistry of the natural ground water of the Sacramento subunit is shown in figure 19. Bicarbonate is the dominant anion for most of the ground water sampled in the Sacramento Valley study with the exception of one well that has high chloride. The cation chemistry shows that the natural ground water is generally calcium and magnesium with varying amounts of sodium. The area of the Sacramento rice land-use study is on both sides of the

Sacramento River and within three of the hydrochemical facies mentioned in Hull (1984). The area of the study unit to the west of the Sacramento River is likely to have higher concentrations of total dissolved solids, chloride, sulfate, and other constituents in ground water relative to the area east of the Sacramento River because of naturally occurring sources of these constituents in the Coast Ranges. The natural water chemistry of the ground water sampled for the Sacramento rice land-use study is shown in figure 20. More wells in the Sacramento rice study have higher sulfate and chloride composition than wells of the Sacramento subunit. The chemistry of the cations in the ground water of the Sacramento rice study is similar to that of the Sacramento subunit.
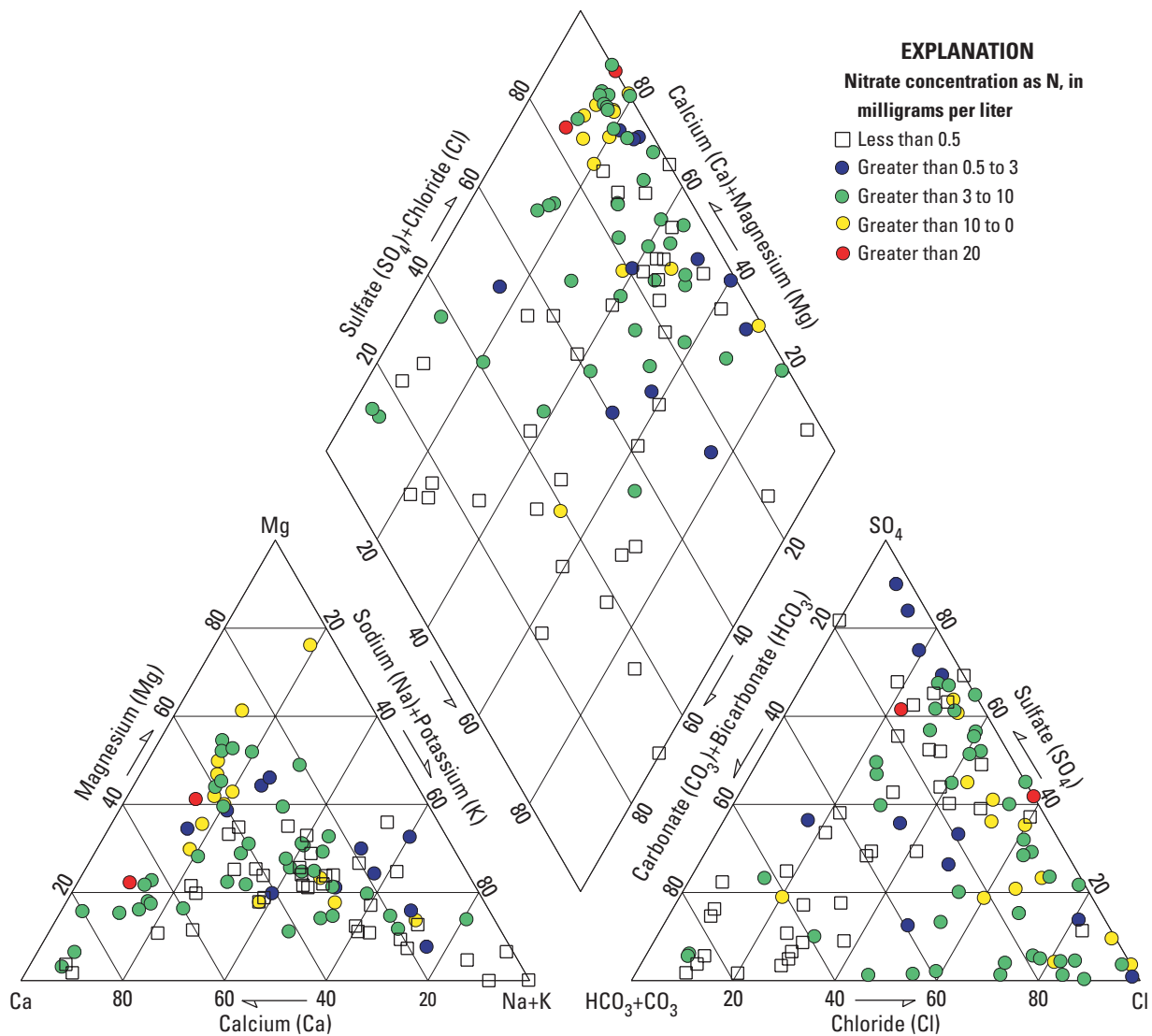
Figure 15. Trilinear graph displaying major element chemistry of ground water of the Delmarva Peninsula, United States. Each scale represents percentage of total milliequivalents per liter. N, nitrogen.

Boxplots of specific conductance for the wells of each study unit are shown in figure 21. The ground water with the lowest specific conductance is that of the Delmarva Peninsula with a median specific conductance of 203 µS/cm. The sampled ground water of the San Joaquin Valley has the highest specific conductance with a median value of 704 µS/cm. The specific conductance of sampled ground water of the Sacramento Valley is most similar to that of the Tangshan study unit, with median specific conductances of 612 and 625 µS/cm, respectively. Boxplots of specific conductance for wells of the three physiographic regions of Tangshan, including the upper and lower aquifer of the plain region, are shown in figure 22. The wells of the mountain region have the lowest median specific conductance, which is expected because most groundwater recharge is likely to occur under natural conditions in this region. The highest median specific

conductance is shown for the wells of the upper aquifer of the plain region. That specific conductance is significantly higher than the specific conductance of the lower aquifer, which suggests that salts have been added to the water as a result of land use. The specific conductance of the wells of the coastal region are similar to that of the lower aquifer of the plain region. Whereas some of the ground water of the coastal region is known to have high salt content, the water in samples of this region are from parts of the aquifer that have not been affected by saltwater intrusion.

Boxplots of specific conductance for wells of the various regions of the San Joaquin Valley, including the upper and lower aquifers of the western and southern San Joaquin Valley, are shown in figure 23. The highest median specific conductance is about 1,500 µS/cm for the lower western San Joaquin Valley ground water. The western San Joaquin Valley ground water has the
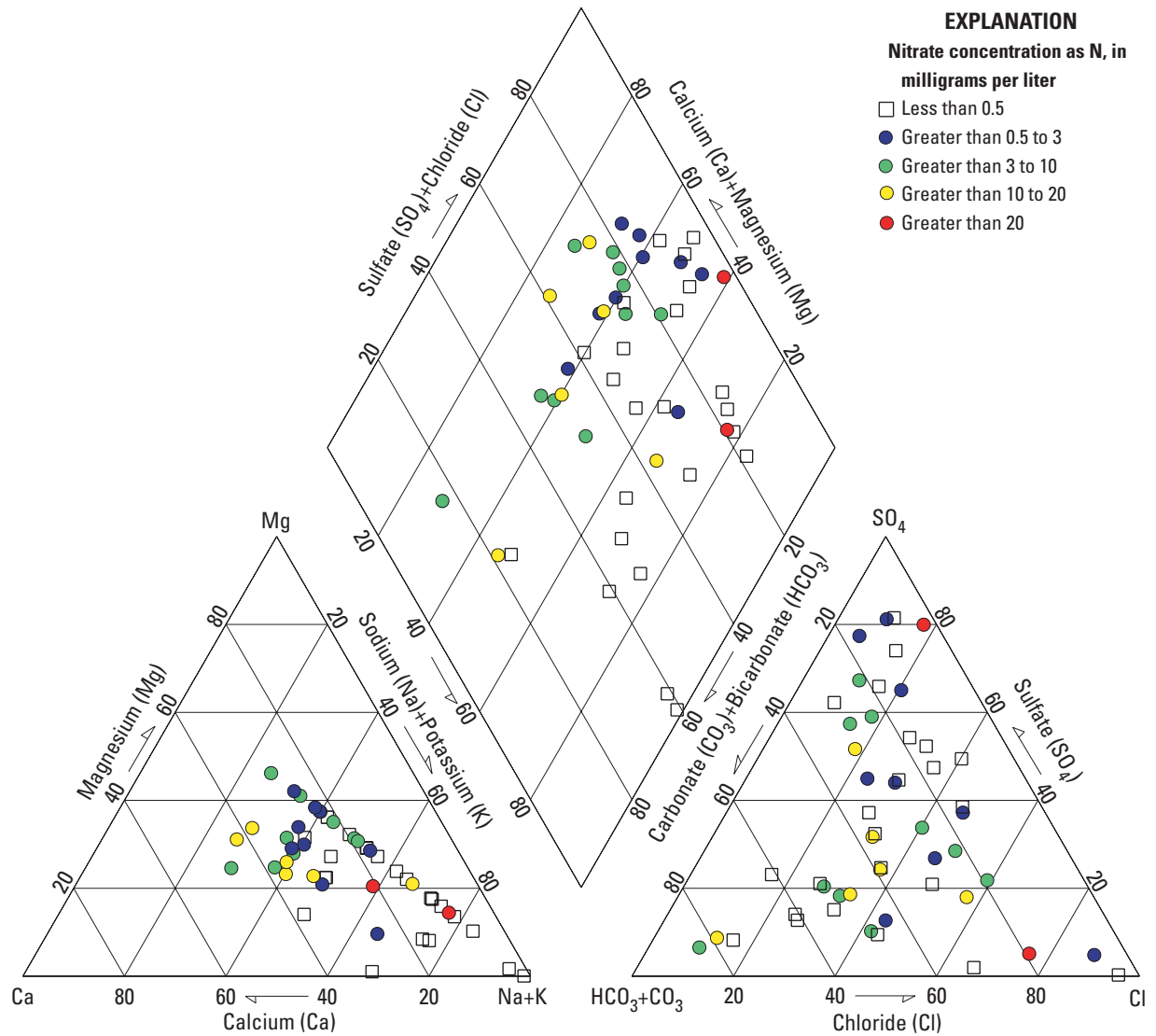
Figure 16. Trilinear graph of ground water of the western San Joaquin Valley, California, United States. Each scale represents percentage of total milliequivalents per liter. N, nitrogen.

highest specific conductance for several reasons. Some of the recharge to the aquifer originates within the Coast Ranges, and that recharge water is relatively high in total dissolved solids. Additionally, some parts of the western San Joaquin Valley have poor soil drainage. Irrigation over poorly drained soils in a semiarid environment can lead to high rates of evaporation, which leave behind salts. The median specific conductance for the other regions of the San Joaquin Valley are lower than those of the western San Joaquin Valley. Ground water of the eastern San Joaquin Valley tends to have the lowest specific conductance because the recharge originates from the Sierra Nevada, which has relatively low concentrations of total dissolved solids.

Boxplots of pH for the wells of each study unit are shown in figure 24. The lowest median pH (5.25) is for the Delmarva Peninsula. Because its aquifer

mineralogy is dominated by quartz, a relatively insoluble mineral, the ground water pH is very similar to that expected for rain.

Concentrations of iron in ground water provide information on the state of oxidation or reduction of the ground water. Iron is insoluble when oxidized, but is much more soluble in the reduced state. Boxplots of iron for the various zones of study units or for an entire study unit are shown in figure 25. The greatest range in iron concentrations for the Tangshan study unit is for the upper aquifer of the plain zone. The median iron concentration for that part of the aquifer is 290 µg/L. Median iron concentrations are below 250 µg/L in the lower aquifer of the plain zone and also in the mountain zone. Median iron concentrations of the coastal zone of the Tangshan study unit are similar to those of the upper aquifer of the plain zone. The higher iron
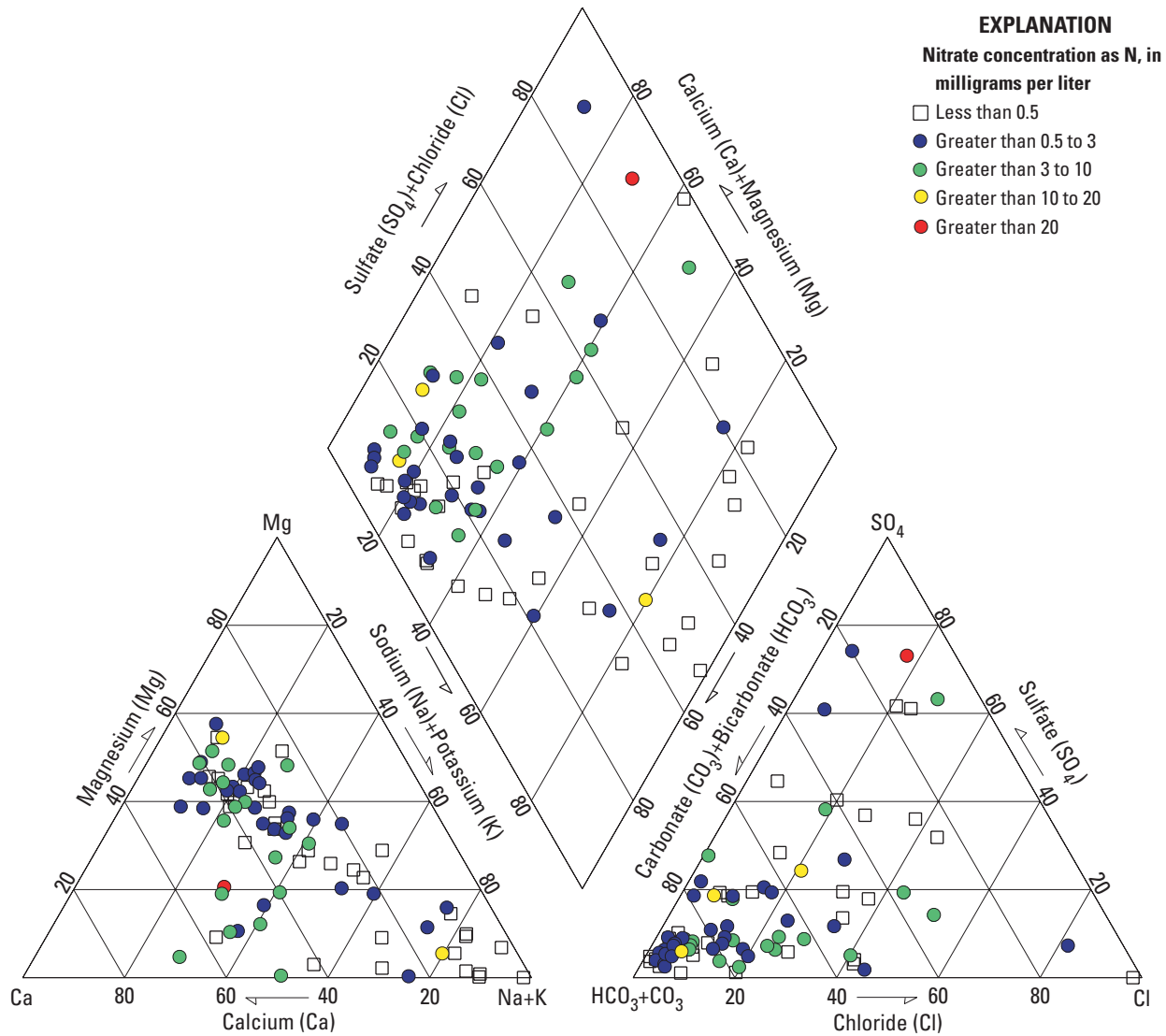
Figure 17. Trilinear graph of ground water of the southern San Joaquin Valley, California, United States. Each scale represents percentage of total milliequivalents per liter. N, nitrogen.

concentrations of the upper aquifer of the plain zone suggest that some processes are affecting the redox potential of the ground water, which is allowing the iron of the aquifer sediment to go into solution. Iron concentrations of the lower aquifer are expected to be highest because the deeper ground water is probably older and has had more time to undergo oxygen-depleting reactions. The wide range and higher concentrations of iron in the upper aquifer suggest that oxygen is being removed from the ground water by some process, which may be related to the use of manure on agricultural land or to the input of sewage waste over the land surface.

The ground water of the Delmarva Peninsula has a wide range of iron concentrations. The median concentration is only 24 µg/L, but the 90th percentile is close to 12,000 µg/L. Iron concentrations in the San

Joaquin Valley tend to be lower than those measured in the Tangshan aquifer. The highest iron concentrations are in the western San Joaquin Valley and the lowest are in the eastern San Joaquin Valley. The aquifer of the eastern San Joaquin Valley is composed of coarser sediments relative to those of the western and southern San Joaquin Valley. Because of the coarser sediment, the aquifer is more open to the atmosphere, and hence the water has a greater amount of dissolved oxygen and less iron. Iron concentrations for the sampled wells of the Sacramento Valley are shown in figure 25. The median concentrations of iron in the ground water in the Sacramento subunit and the Sacramento rice zone (3.0 and 4.2 µg/L, respectively) are similar, but a larger range of concentrations is present in the wells of the rice land-use study. In summary, iron concentrations tend to be highest in the ground water of the Tangshan and
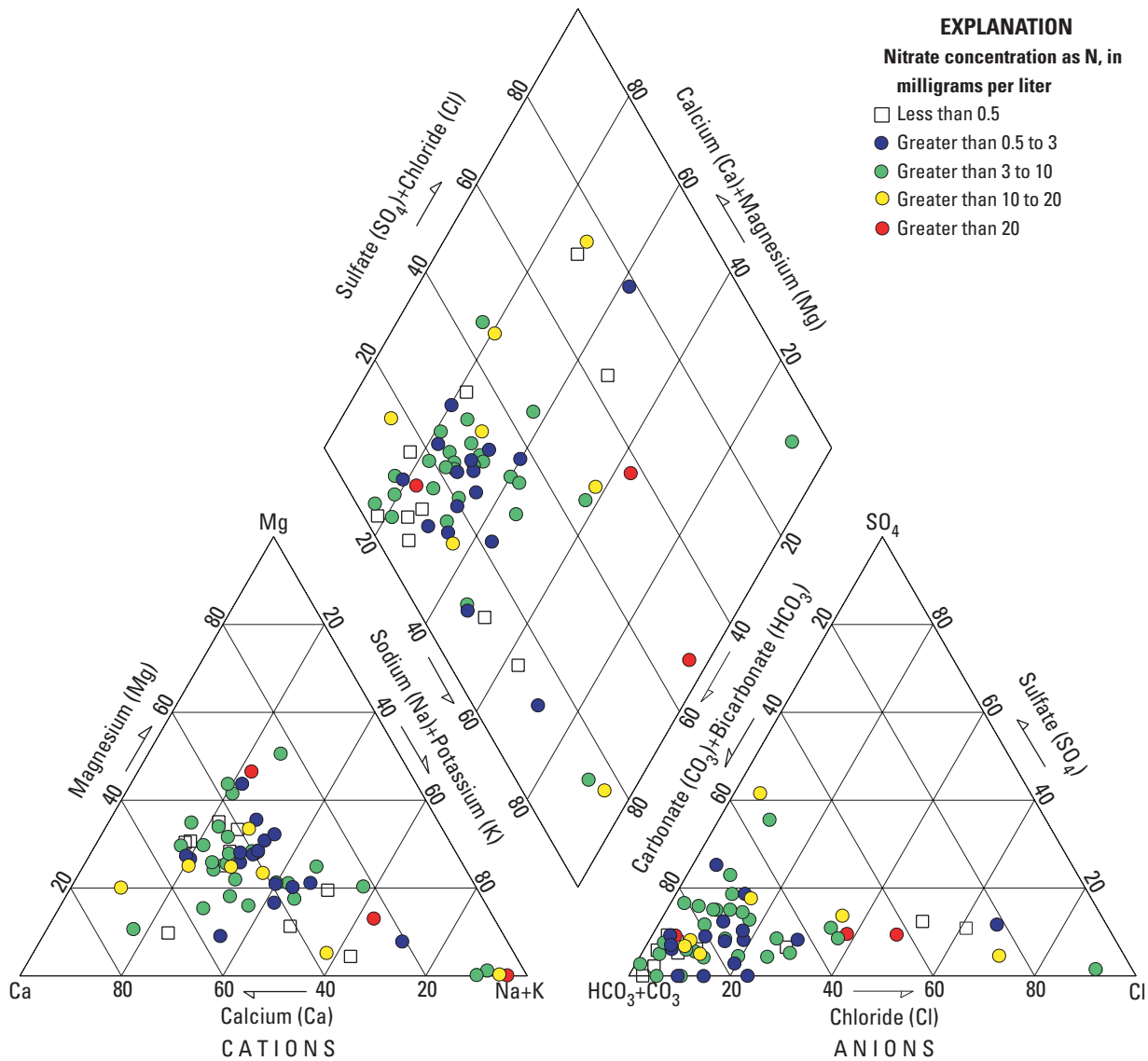
Figure 18. Trilinear graph of ground water of the eastern San Joaquin Valley, California, United States. Each scale represents percentage of total milliequivalents per liter. N, nitrogen.

Delmarva aquifers, relative to the ground water of the other aquifers of this study.

OXYGEN AND HYDROGEN ISOTOPES IN WATER

Variations in stable isotopes in water and dissolved constituents originate from the natural variation in atomic mass and from fractionation in the environment. Isotope fractionation is defined as the partitioning of isotopes by physical or chemical processes in a manner proportional to the differences in masses (Coplen, 1993). Stable isotopes in water molecules—hydrogen (^{1}H), deuterium (^{2}H), oxygen-16 (^{16}O), and oxygen-18 (^{18}O)—have long been used to help determine ground-water recharge or ground-water flow paths. The ratio of the isotopes is measured with a mass spectrometer. The ratios, expressed as δ notation, are

given in parts per thousand (per mill). The principal fractionation mechanisms of stable isotopes are evaporation and precipitation. Lighter isotopes partition to water vapor, for example, leaving the heavier isotopes enriched in the remaining water. In contrast, rainwater is more enriched in heavier isotopes and becomes progressively lighter as clouds move over landmasses. Isotope ratios in rainwater can be measured and, thus, the pathways of ground-water recharge can be determined by measuring stable isotope ratios along ground-water flow paths. Stable isotope studies or analyses have been completed for wells of the San Joaquin Valley and Sacramento Valley study units from previous studies, but no stable isotope data are available for wells of the Delmarva Peninsula. This study reports on the first analyses of stable isotopes for the Tangshan study-unit ground water.
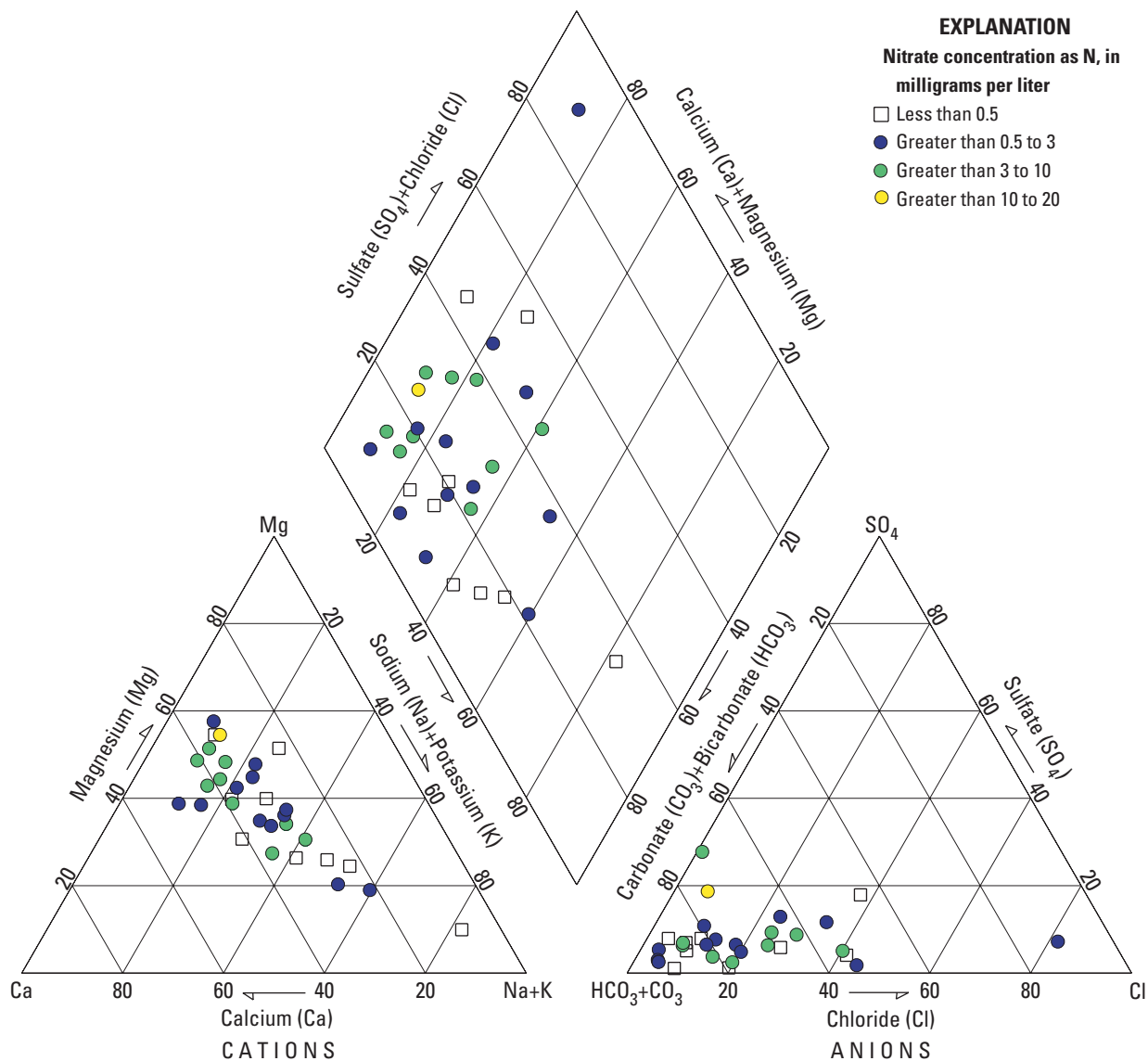
Figure 19. Trilinear graph of subunit ground water, Sacramento, California, United States. Note: Red circles are not shown here because ground water with nitrate greater than 20 milligrams per liter was not detected. Each scale represents percentage of total milliequivalents per liter. N, nitrogen.

The greatest variation in the distribution of stable isotopes is in the San Joaquin Valley ground water (fig. 26) where they vary for several reasons. Precipitation in that region generally results from winter storms that originate over the Pacific Ocean. Rain with heavier isotopes falls on the Coast Ranges, and rain that is relatively depleted in the heavier isotopes falls on the valley floor and the Sierra Nevada. The rain with the lightest isotopes falls on the Sierra Nevada. Groundwater recharge to the San Joaquin Valley aquifer originates from Coast Ranges runoff, precipitation on the valley floor, runoff from the Sierra Nevada, recharge from the San Joaquin River and its tributaries, and irrigation. Irrigation is currently the primary source of ground-water recharge to the aquifer of the San Joaquin Valley (Domagalski and Dubrovsky, 1991, 1992).

Irrigation water is provided by local rivers, water imported from northern California, and ground water. Irrigation also affects the stable isotope pattern in that partial evaporation of the irrigation water leads to enrichment in the heavier isotopes. The isotope ratio patterns for the eastern, western, and southern San Joaquin Valley generally overlap because of the complexity of recharge and other factors that affect the stable isotope patterns (fig. 26). Because of the wide variation in stable isotope ratios of ground water, the use of stable isotope data has aided in the interpretation of previous studies on contaminant chemistry of the San Joaquin Valley ground water (Deverel and Fujii, 1988) and has helped researchers to understand ground water–surface water relations (Phillips and others, 1991). In those cases, stable isotope data were useful
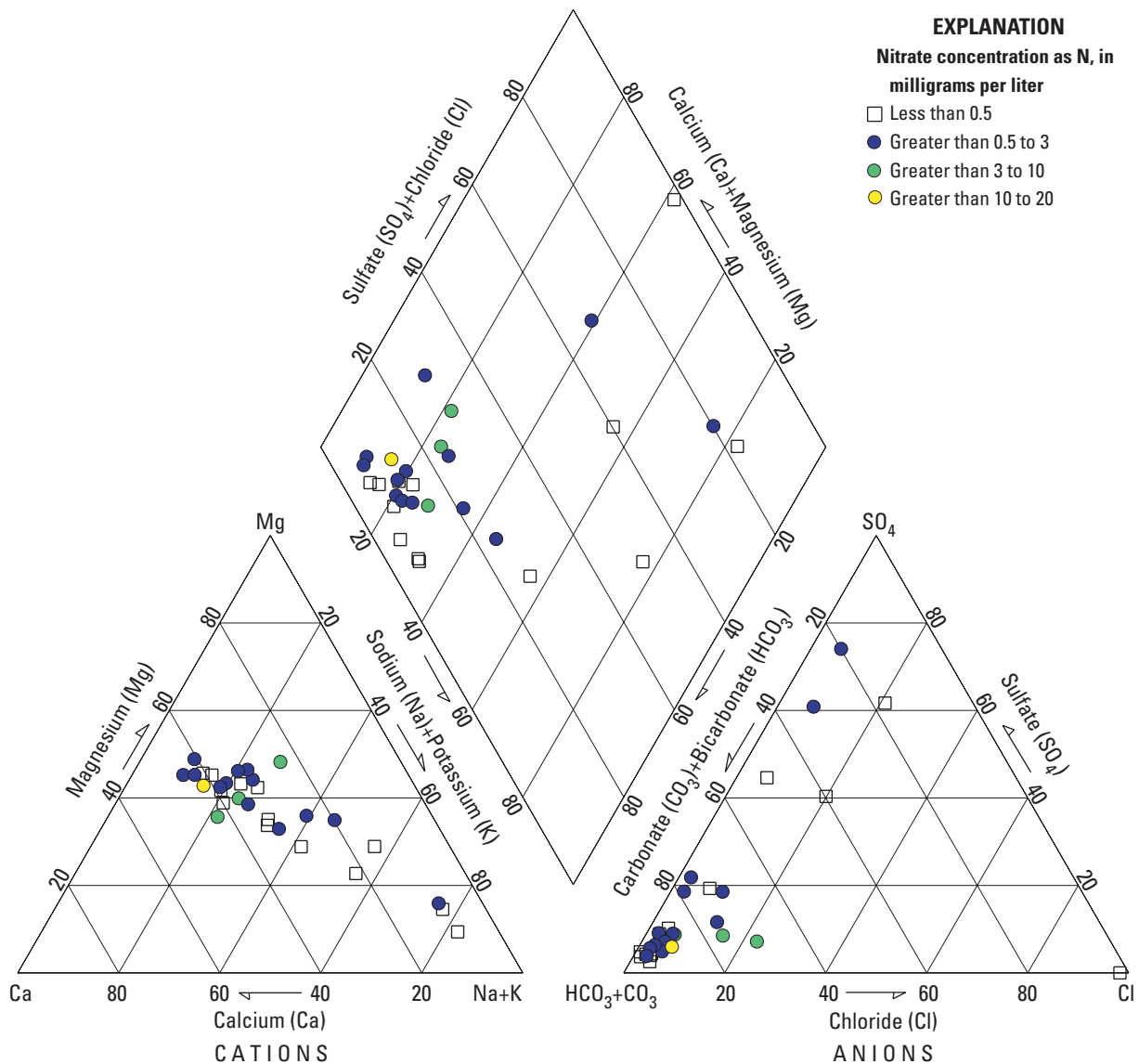
Figure 20. Trilinear graph of the rice land-use ground water, Sacramento, California, United States. Note: Red circles are not shown here because ground water with nitrate greater than 20 milligrams per liter was not detected. Each scale represents percentage of total milliequivalents per liter. N, nitrogen.

because waters originating from different sources, or geochemical processes related to natural phenomenon, such as evaporation, could clearly be distinguished because of the range in values of stable isotope ratios.

The same types of weather patterns described for the San Joaquin Valley also affect precipitation in the Sacramento Valley, and so the heaviest isotopes are found in runoff from the Coast Ranges and the lightest in rainfall from the Sierra Nevada and Cascade Mountains. The isotope ratio of the Sacramento River does not vary much because the flow is regulated by releases from large reservoirs that collect snowmelt runoff from high mountains, principally in the northern part of the basin and within the Sierra Nevada. The ratio of deuterium is close to –80 per mill and of ^{18}O is close to

–11.5 per mill. These ratios of the San Joaquin River are similar because most of the flow of the San Joaquin River originates as runoff from the Sierra Nevada. Isotope patterns are more variable for streams that drain the Coast Ranges and tend to be heavier than those of the Sacramento and San Joaquin Rivers. Stable isotopes were used by Davisson and Criss (1993) to map recharge of irrigation water to municipal wells in a region west of Sacramento, California. Davisson and others (1993) were able to document the extent of ground-water recharge to the surficial aquifer of the lower Sacramento Valley from the large rivers (Sacramento and American Rivers) using stable isotope data. In these cases, the difference in isotope abundances was sufficiently great to allow mapping of isotope contours.
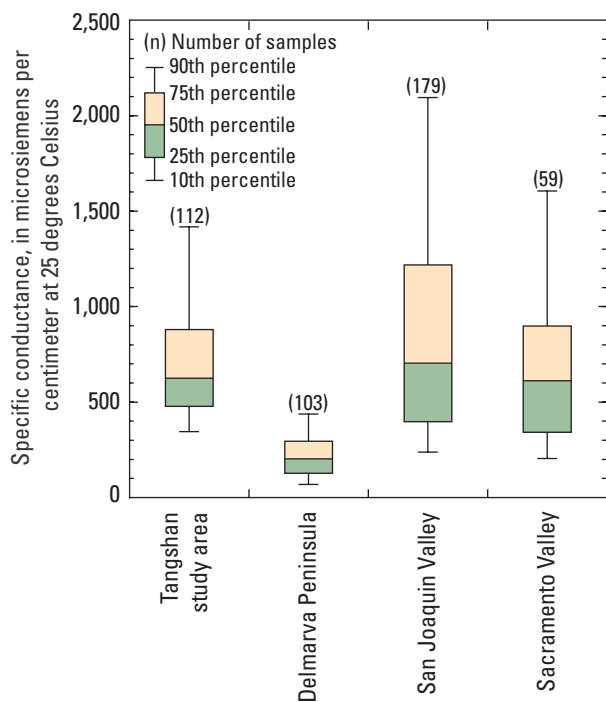
Figure 21. Boxplots of specific conductance for wells within each study unit in the People's Republic of China and the United States.

Agricultural practices may affect the isotope pattern of ground water underlying the rice fields of the Sacramento Valley (fig. 27). Because standing water is on the rice fields during the hottest part of the year, evaporation of water results in some fractionation. The isotope pattern for water underlying the rice fields tends to deviate from the global meteoric water line, a clear indication of the effect of evaporation.

Stable isotope samples were collected from ground water along four selected transects of the Tangshan study unit. Those transects were chosen to provide general information on the regional distribution of stable isotope ratios in this aquifer system. Transect 1 was closest to the Luan He River and was chosen to show how similar the stable isotopes of the ground water system are to those of the largest river. Transect 2 is located near ephemeral streams, such as the Qinglong He River, and was chosen to contrast the stable isotopes of that stream with those of nearby ground water. Transects 3 and 4 were chosen to obtain greater aerial coverage over the study unit. The stable isotope pattern of ground water in the Tangshan study unit (fig. 28 and table 2) varies less than that of the San Joaquin and Sacramento Valleys. This pattern is especially true in the mountain and plain regions where stable isotopes in ground water are very similar to those of the upper and lower Luan He River. Ground water of the coastal region has more variability, which is to be expected because seawater has infiltrated the ground water system. The ^{18}O ratio in the wells sampled in the

mountain and plain regions, and that of the Luan He River, tend to be close to –8 to –8.5 per mill and the deuterium ratio is close to –60 per mill. One sampling site, near the Luan He River (location Lao6), was different. The shallow well (LaoQ6) was slightly enriched in the heavier isotopes, but the deeper well (LaoS6) was more depleted in the heavier isotopes. This was the closest sampling point to the Luan He River. The difference in isotope values may reflect changes in the isotopic chemistry of the Luan He River over time, especially prior to the construction of reservoirs. The stable isotopes of the Qinglong He River were relatively enriched in the heavier isotopes. This enrichment would be expected for an ephemeral stream owing to evaporation. The wells of the upper aquifer sampled closest to the Qinglong He River (sites Ben3 [wells BenQ3-1, BenQ3-2, and BenQ3-3] and Ben4) are slightly enriched in the heavier isotopes, suggesting that some recharge of partially evaporated stream water occurred.

The general uniformity of isotope ratios observed in most of the wells of the mountain and plain regions and the Luan He River probably results from the precipitation pattern. Rainfall originates over the
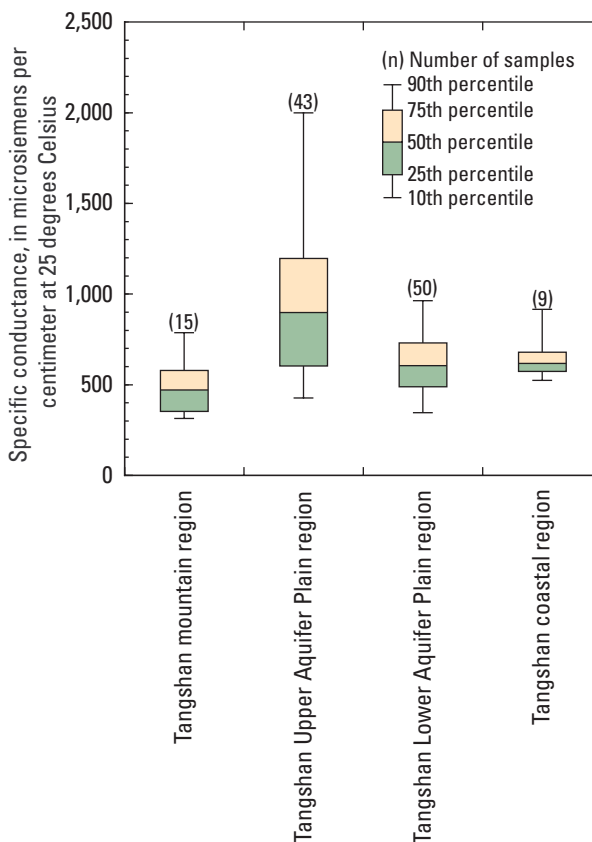

Figure 22. Boxplots of specific conductance for wells in various physiographic regions of the Tangshan study unit, People's Republic of China.
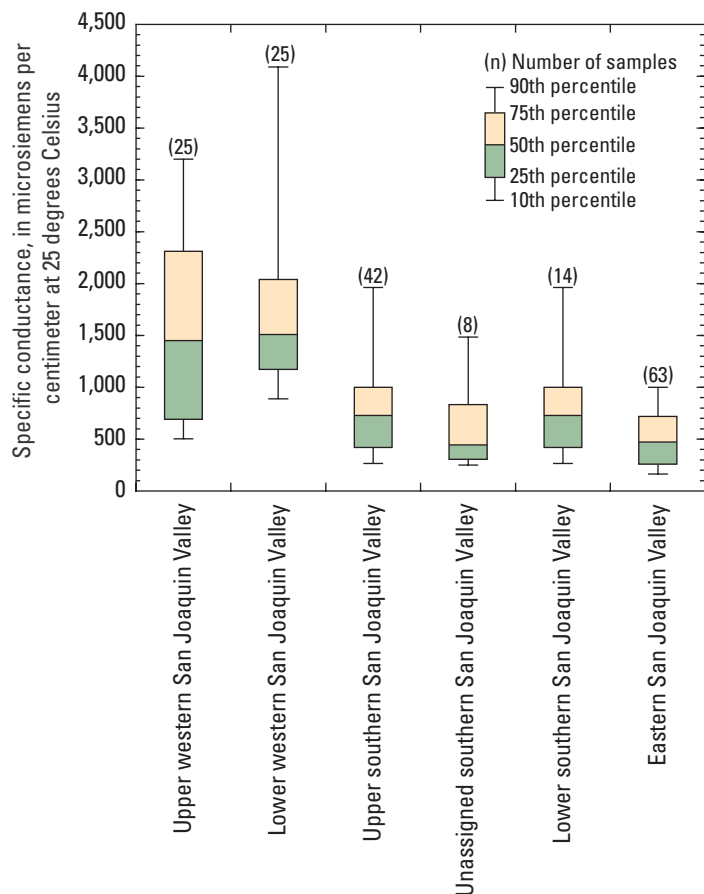
Figure 23. Boxplots of specific conductance for wells in various regions of the San Joaquin Valley, California, United States.

Pacific Ocean. Rain with a similar pattern of stable isotopes falls over the plain and mountain regions. Because most of the ground-water recharge comes from mountain runoff and meteoric input over the mountain and plain areas, the stable isotope pattern is very similar throughout. As a result, stable isotopes are not as useful a tool, on a regional pattern, to help determine ground-water flow paths for the mountain and plain regions of the Tangshan aquifer system. However, stable isotopes may be useful in local scale studies, such as near the ephemeral streams or within the coastal region in studies related to seawater intrusion, but that is beyond the scope of the present study.

DATING OF GROUND-WATER RECHARGE

Methods for dating ground-water recharge have been used extensively in the San Joaquin Valley, and more recently in the Sacramento Valley, to interpret the relative age of ground water with depth and to relate the detection frequency of various ground water contaminants to the age of ground water. For example, Domagalski and Dubrovsky

(1991, 1992) showed that pesticide residues in ground water of the San Joaquin Valley were present only in relatively recent water (water with detectable ^3H). Older ground water (^3H below detection limit) had no detectable pesticide residues. Knowledge of the depth distribution of recent water in an aquifer provides a good understanding of which part of the aquifer may be susceptible to contamination from recent land-use practices. Ground water with detectable ^3H is defined for this study as having been recently recharged (from the 1950s to the present).

Prior to this study, there had been no measurements of ^3H or any attempts to establish the age of ground water in the Tangshan aquifer study unit. Results of dating analyses from this study are shown in table 3. The wells selected for these analyses are located along two transects shown in figure 4. The samples were collected in June 1996. ^3H or CFC can be detected to a well depth of 150 m. Ground water sampled from well depths of 212 and 230 m did not have measurable ^3H. Those two samples were collected from the coastal aquifer. The zone of ^3H-free water is probably at or below 150 m below land surface in this aquifer system. Ground water sampled in the lower aquifer of the plain region, at various depths, all had measurable ^3H or CFC, which suggests
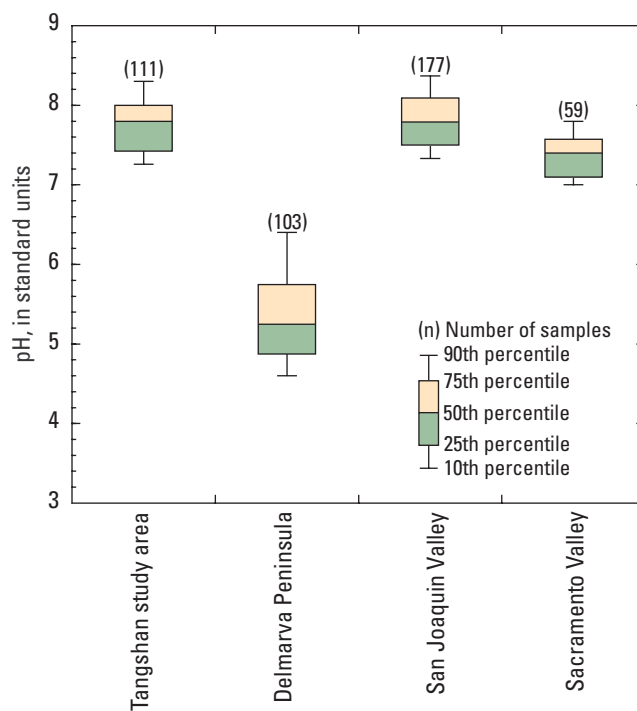

Figure 24. Boxplots of pH for wells within each study unit in the People's Republic of China and the United States.
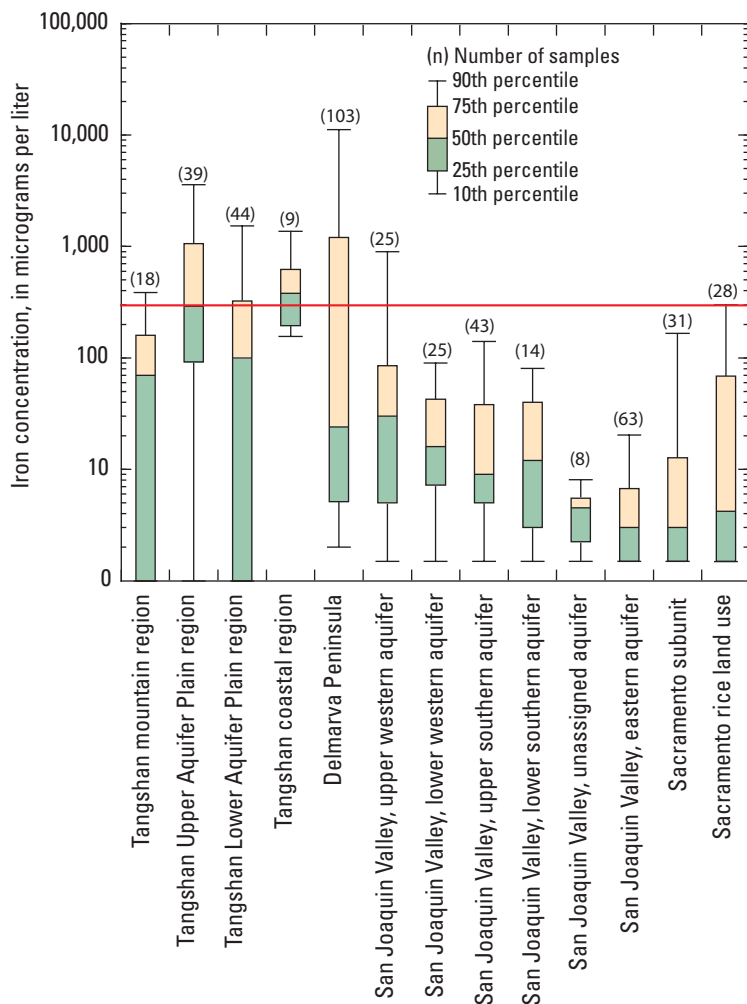
Figure 25. Boxplots of iron concentration for various zones within study units or for an entire study unit, People's Republic of China and the United States. The red line indicates drinking- water standard of China and secondary drinking-water standard of the U.S. Environmental Protection Agency.

surface, which suggests that the ground water system is rapidly recharged either areally by meteoric water (during the Asian monsoon) or by infiltration from rivers, irrigation, or some combination. Water levels measured prior to and after the monsoon season in 1996 are shown in figure 29. Ground water levels were generally closer to land surface in September 1996 relative to May 1996 because the levels for September were measured just after the rainy season (fig. 29). Subsequent pumping of ground water helps to draw the recently recharged water to deeper levels. Soil contaminants, or contaminants present at shallow water levels, such as nitrate, can then be transported to deeper parts of the aquifer system.

ASSESSMENT OF WATER-QUALITY CONDITIONS

Water-quality conditions, with respect to the suitability of ground water as a source of drinking water for each study unit, were assessed on the basis of standards or methods used in the People's Republic of China and water-quality criteria specified in the Safe Drinking Water Act of the United States. In the United States, emphasis is given to meeting standards specified for each constituent that is regulated by the Safe Drinking

that recently recharged water is present to a depth of at least 130 m and perhaps as deep as 150 m in the lower aquifer of the plain region.

Water with undetectable ^3H, such as that collected from wells Xian5 and Xian9, also could not be dated by the $^3H/^3He$ method. There was not close agreement of the ages obtained from the CFC and the $^3H/^3He$ methods, which might be expected because the methods do not work for all ground-water systems. In particular, the CFC method does not work for ground-water systems devoid of dissolved oxygen. Parts of the ground-water system of the Tangshan aquifer are devoid of dissolved oxygen as indicated by the high concentrations of dissolved iron measured at several wells. Therefore, the $^3H/^3He$ method provides a more reliable age for this ground water system.

The implication for the Tangshan aquifer system is that recent water is present in relatively deep parts of the aquifer, within approximately 150 m below land
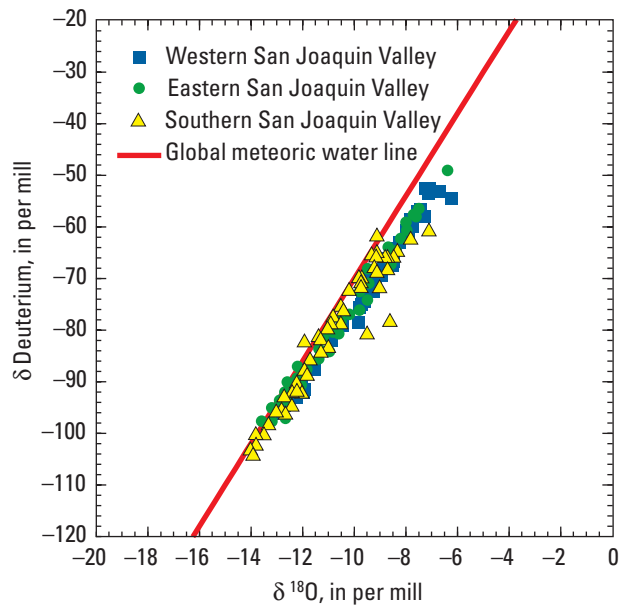

Figure 26. Stable isotopes δ deuterium (^2H) versus $δ^{18}O$ of ground water in the San Joaquin Valley, California, United States. H, hydrogen; O, oxygen; δ, delta. Position of the global meteoric water line from Drever (1982).
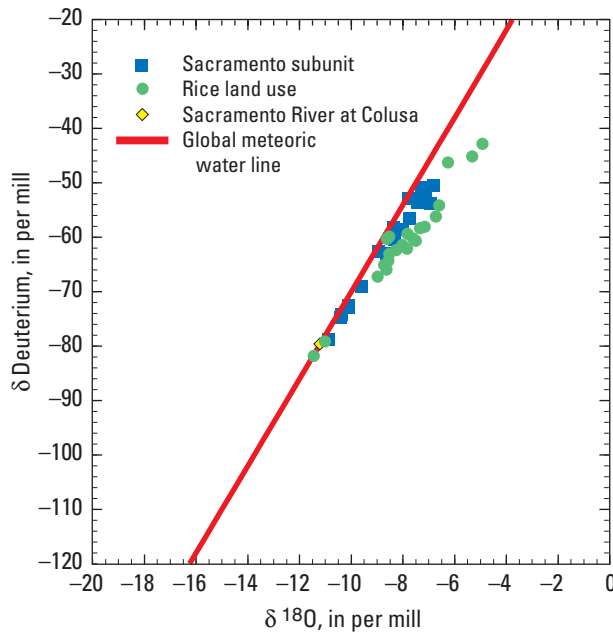
Figure 27. Stable isotopes δ deuterium (^{2}H) versus δ^{18}O of ground water in the Sacramento Valley and of the Sacramento River at Colusa, California, United States. H, hydrogen; O, oxygen; δ, delta. Position of the global meteoric water line from Drever (1982).

Figure 28. Stable isotopes δ deuterium (^{2}H) versus δ^{18}O of ground water in the Tangshan study unit and of the Qinglong and Luan He Rivers, People's Republic of China. H, hydrogen; O, oxygen; δ, delta. Position of the global meteoric water line from Drever (1982).

Water Act of the U.S. Environmental Protection Agency (EPA). When even a single standard is exceeded, there may be sufficient cause to stop the delivery of water supplied by a community well. For example, numerous wells in the San Joaquin Valley have been shut down because concentrations of the pesticide 1,2-dibromo-3-chloropropane (DBCP) exceeded the standard. Meeting individual standards is also important for the regulation of drinking water quality in the People's Republic of China. In addition, the suitability of ground water as a source of drinking water is assessed using a broader method of classification called the "gray pattern method." The results of the gray matrix calculations are presented to show the range of conditions in these aquifers.

Gray Pattern Method of Water-Quality Assessment

To classify the water with respect to a set of chosen water-quality constituents, the gray pattern method assesses the weights of contaminant concentrations, relative to both the National Standards of Groundwater Quality established by the People's Republic of China and to boundary values of various water classes. The assessment of overall water quality according to a set of standards allows water-quality managers in the People's Republic of China to prioritize decisions about the suitability of water for various uses. A set of 21 water-quality constituents regulated by
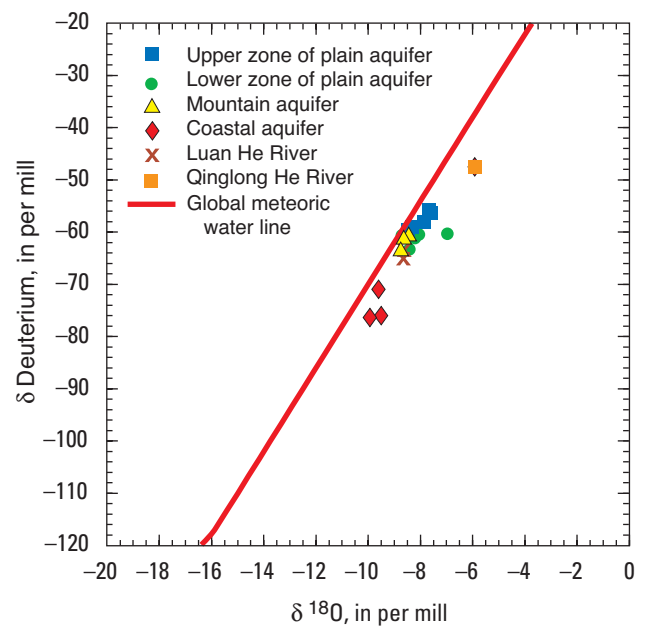
National Standards of Groundwater Quality of the People's Republic of China was selected for this study. Scientists and water-quality specialists of the Hai He River Basin's Water Conservancy Commission, the Tangshan Water Resources Bureau, and the Ministry of Water Resources of the People's Republic of China determined that the 21 water-quality constituents listed in table 4 are the most important for the protection of ground-water quality in the Tangshan study unit. The boundary values of class 3 water, as shown in table 4, are the closest analogy to primary drinking water standards as understood in the United States. These are set for individual constituents. When applicable, the primary and secondary water standards of the EPA are also shown in table 4. Primary standards are enforceable standards that must be met by all public drinking water systems to which they apply. Secondary standards are nonenforceable, but are maintained to protect public welfare and to ensure a supply of pure, wholesome, and potable water. Some states require that all new wells or sources of drinking water meet the secondary standards.

The classes of water, according to the method in the People's Republic of China, represent a gradient of concentrations for each water-quality constituent, indicating suitability for drinking water to nonsuitability of the water. Class 1 water is of highest quality, whereas class 5 represents extremely poor water quality. The boundary values of class 3 (table 4) are most analogous to American drinking water primary standards. Note that the boundary value of class 3 for nitrate is set at

Table 2. Results of stable isotope analyses—δ deuterium and δ¹⁸O in water—for wells of the Tangshan study unit, People's Republic of China

[na, not applicable; O, oxygen; per mill, parts per thousand; Q, shallow well; S, deep well; δ, delta]

Well name	Date sampled	Transect	Aquifer zone or river	δ deuterium (per mill)	δ¹⁸O (per mill)
LuanQ5	23 June 1996	1	Plain upper	–60.2	–8.21
LuanS5	23 June 1996	1	Plain lower	–60.7	–8.75
LaoQ1	24 June 1996	1	Plain upper	–61.7	–8.41
LaoS1	24 June 1996	1	Plain lower	–61	–8.19
LaoQ6	24 June 1996	1	Plain upper	–58	–7.86
LaoS6	24 June 1996	1	Plain lower	–75	–9.61
Xian9	24 June 1996	1	Coastal	–76.2	–9.91
Xian9-1	24 June 1996	1	Coastal	–49.1	–5.93
Shan15	23 June 1996	2	Mountain	–61	–8.62
LuanS1	23 June 1996	2	Plain lower	–60.7	–8.51
BenQ3-1	23 June 1996	2	Plain upper	–56.4	–7.6
BenS3	22 June 1996	2	Plain lower	–60.3	–8.06
BenQ4	25 June 1996	2	Plain upper	–55.8	–7.68
BenS4	25 June 1996	2	Plain lower	–60	–8.3
Xian5	25 June 1996	2	Coastal	–75.8	–9.55
Shan9	23 June 1996	3	Mountain	–63.2	–8.72
Shan10	16 September 1996	3	Mountain	–60.3	–8.42
ShiS2	3 October 1996	3	Plain lower	–60.6	–8.37
NanQ2	3 October 1996	3	Plain upper	–59.7	–8.49
NanS2	3 October 1996	3	Plain lower	–58.2	–7.86
Xian3	4 October 1996	3	Coastal	–60.5	–8.07
RunS1	3 October 1996	4	Plain lower	–59.3	–8.22
RunQ2	24 September 1996	4	Plain upper	–59.9	–8.45
RunS2	16 September 1996	4	Plain lower	–63	–8.45
YuQ7	16 September 1996	4	Plain upper	–58.9	–8.33
YuS7	10 September 1996	4	Plain lower	–58.2	–8.01
RunS4	25 September 1996	4	Plain lower	–61.2	–8.45
Xian1	16 September 1996	4	Coastal	–71.1	–9.62
Upper Luan He River	23 June 1996	na	River	–63.4	–8.65
Lower Luan He River	24 June 1996	na	River	–65	–8.68
Qinglong He River	25 June 1996	na	River	–47.6	–5.91

20 mg/L. The primary (enforceable) American drinking water standard for nitrate is 10 mg/L as N.

The gray pattern method first calculates a pollution index for each constituent relative to the boundary value of the class 3 drinking-water standard. Water with water-quality constituent concentrations less than the boundary values of class 3 water shown in table 4 are ranked low, but as water quality greatly exceeds the boundary values, the ranks are correspondingly higher. Even a single "exceedance" (that is, a value that exceeds the standard) can result in water of overall class 5 if the measured concentrations are very high, that is, if they exceed class 5. A summation of the relative amounts of exceedances and the corresponding factor for each constituent are then calculated, and the matrix of calculations is referred to as the "gray dependency pattern." The output from the gray model is a comprehensive score. Water samples with class of 3 or higher indicate serious water-quality problems or that one or more standards have been exceeded. An examination of the detailed matrix then can provide information on which specific parameter or group of parameters contributed to the ranking.

The 21 constituents that were used to assess the quality of ground water according to the National Standards of the People's Republic of China were total dissolved solids, chloride, sulfate, total hardness, ammonia, nitrite, nitrate, chemical oxygen demand (permanganate index), cyanide, arsenic, phenol, chromium (VI), mercury, cadmium, lead, copper, iron, fluoride, manganese, zinc, and coliform bacteria. The coliform bacteria measurements were completed only

Table 3. Results of dating analyses for wells of the Tangshan study unit, People's Republic of China

[The ^{3}H/^{3}He results column shows samples tested for dating on the basis of years elapsed since recharge. CFC, chlorofluorocarbon; ^{3}H, tritium; ^{3}H/^{3}He, tritium/helium-3; L, liter; m, meters; pCi, picocuries; Q, shallow wells; S, deep wells. —, sample not taken]

Well name	Well depth (m)	Aquifer zone	^{3}H (pCi/L)	^{3}H/^{3}He results	CFC recharge date (period)
LuanQ5	27	Plain upper	34.2	—	—
LuanS5	48	Plain lower	46.46	—	Early 1970s
LaoQ1	21	Plain upper	34.7	6.08	Early 1960s or older
LaoS1	80	Plain lower	21.8	—	—
LaoS6	150	Plain lower	—	—	Mid-1940s
Xian9	212	Coastal	0	Old water[1]	—
Shan15	25	Mountain	98.79	7.36	Mid-1980s
LuanS1	130	Plain lower	38.75	20.71	—
BenQ3-1	13	Plain upper	97.6	—	—
BenS3	60	Plain lower	6.53	20.56	Mid-1960s
BenQ4	20	Plain upper	35.8	—	—
BenS4	120	Plain lower	10.2	—	—
Xian5	230	Coastal	0	Old water[1]	—

[1]Recharged before 1960.

for the wells of the upper aquifer (plain region) and only for the May 1996 sampling. The gray matrix summaries for the wells of the Tangshan study unit are shown in tables 5 through 13. The number of wells for each classification is shown in tables 5 through 13, and for each case, a median classification is presented. In each case, the median classification refers only to that individual grouping.

The highest median gray matrix results (table 5) were calculated for the upper aquifer (plain region) of the Tangshan study unit for the May 1996 sampling. May 1996 was the only time—and the wells selected during this time were the only wells—for which a complete set of coliform bacteria data was available. When the gray matrix is calculated without the coliform data,

Figure 29. Water levels measured in May and September 1996, Tangshan study unit, People's Republic of China.

the result is a lower median gray matrix score (table 6). The median classification drops from 4.19 to 3.68, which indicates that coliform bacteria significantly degrades the water quality of the upper aquifer. The May 1996 score, without coliform data, is very similar to the median score calculated for the September 1996 sampling of the upper aquifer in the plain region. This similarity indicates that general water quality conditions did not change appreciably following the monsoon season. A total of 29 out of 39 wells of the upper aquifer (plain region) of the Tangshan study unit, sampled during May 1996, were scored in class 3 on the basis of this gray matrix classification. Exceedances of total dissolved solids, total hardness, ammonia, nitrate, and coliform bacteria contributed to these high scores. A total of 28 out of 39 wells of the upper aquifer (plain region) of the Tangshan study unit, sampled in September 1996, were scored in class 3 on the basis of this gray matrix classification. Therefore, even without the coliform analyses, most wells of the upper aquifer were in a relatively high classification, which indicates poor water-quality conditions. The median classification for each sampling of the upper aquifer was a value corresponding to class 3 or higher water.

Water quality of the lower aquifer (plain region) of the Tangshan study unit is better because fewer ground-water samples were in the highest rating (poorest water quality). The median classification was slightly below that of an overall class 3 water. Although the gray matrix calculations suggest that the water of the lower aquifer is of higher general quality relative to that of the upper, some serious water-quality problems are still present. The constituents that contributed to the higher rankings were ammonia, nitrate, iron, manganese, and total hardness.
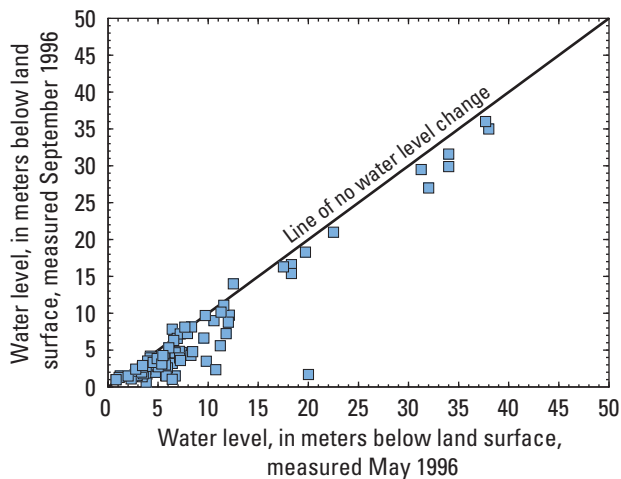
Table 4. Classification of representative values of National Standards of Groundwater Quality in the People's Republic of China, and of primary and secondary standards of the U.S. Environmental Protection Agency in the United States

[Values of constituents are in milligrams per liter, unless otherwise noted. Primary Standard: Enforceable standard that must be met for drinking water. Secondary Standard: Nonenforceable, but recommended for drinking water. Class 1 to 5: Classification of water according to a gradient of highly suitable (class 1) to highly unsuitable (class 5) with respect to the use of the water as a source of drinking water. Boundary values of class 3: Analogous to an enforceable standard of the EPA. $CaCO_3$, calcium carbonate; Cr, chromium; Cr^{+6}, chromate ion; EPA, U.S. Environmental Protection Agency; N , nitrogen; NH_3, ammonia. —, no available standard]

| Water-quality constituent | People's Republic of China | | | | | | United States | |
	Class 1	Class 2	Class 3	Class 4	Class 5	Boundary values of Class 3	EPA primary standard	EPA secondary standard
Total dissolved solids	300	400	750	1,500	2,000	1,000	—	500
Chloride	50	100	200	300	350	250	—	250
Sulfate	50	100	200	300	350	250	—	250
Total hardness (as $CaCO_3$)	150	225	375	500	550	450	—	—
Ammonia (nitrogen as NH_3)	0.02	0.02	0.11	0.35	0.5	0.2	—	—
Nitrate (nitrogen as N)	2	3.5	12.5	25	30	20	10	—
Nitrite (nitrogen as N)	0.001	0.0055	0.015	0.06	0.1	0.02	1	—
Permanganate index	1	1.5	2.5	6.5	10	3	—	—
Cyanide	0.001	0.0055	0.03	0.075	0.1	0.05	0.2	—
Arsenic	0.005	0.0075	0.03	0.05	0.05	0.05	0.05	—
Phenol	0.001	0.001	0.0015	0.006	0.01	0.002	—	—
Chromium (as Cr^{+6})	0.005	0.0075	0.03	0.075	0.1	0.05	0.1 as total Cr	—
Mercury	0.00005	0.00028	0.00075	0.001	0.001	0.001	0.002	—
Cadmium	0.0001	0.00055	0.0055	0.01	0.01	0.01	0.005	—
Lead	0.005	0.0075	0.03	0.075	0.1	0.05	0.015	—
Copper	0.01	0.03	0.525	1.25	1.5	1	—	1
Iron	0.1	0.15	0.25	0.9	1.5	0.3	—	0.3
Fluoride	1	1	1	1.5	2	1	4.0	—
Manganese	0.05	0.05	0.075	0.55	1	0.1	—	0.05
Zinc	0.05	0.275	0.75	3	5	1	—	5
Coliforms	3	3	3	52	100	3	—	—

As indicated by the gray matrix scores, water quality of the mountain region was considerably better than that of the aquifer of the plain region. Relatively few samples had scores in the higher classes. The source of ground-water recharge to the plain region lies, at least in part, in the mountain region. Water quality may be better in this region because of less intensive agriculture. However, as will be shown later, nitrate may be a developing problem for ground water in that region.

Water-quality problems are also evident for the coastal region as indicated by a median gray score above or near that of class 3 water. The water-quality constituents most responsible for the loadings are ammonia and nitrite, but not nitrate, iron, and manganese.

The gray matrix summary of the Delmarva Peninsula ground water samples is shown in table 14. A total of 36 of 103 samples are of class 3 or higher. The presence of nitrate and iron contributed most to those

higher water-quality class rankings. The median classification is that of class 2 water.

Gray matrix summaries for the San Joaquin Valley ground water are shown in tables 15 through 20. The upper and lower zones of the aquifer of the western San Joaquin Valley have relatively poor water quality as indicated by the gray matrix scores. Eighteen out of 25 wells of the upper aquifer are in class 3 or higher, and 14 out of 25 wells of the lower aquifer are in class 3 or higher. The water-quality constituents contributing to the higher gray matrix scores, for the upper and lower aquifer, are total dissolved solids, chloride, sulfate, total hardness, iron, and manganese. A total of 11 of 43 wells of the southern San Joaquin Valley, upper aquifer, had scores in class 3 or higher. The median score was lower than that of the western San Joaquin Valley. The lower aquifer of the southern San Joaquin Valley has much better water quality relative to that of the lower aquifer of the western San Joaquin Valley. Total dissolved solids, chloride, sulfate, and total hardness contribute to