**ENVIRONMENTAL
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PROGRAM**

**Determination of Reference
Concentrations for Inorganic Analytes
in Groundwater
at the Oak Ridge Y-12 Plant,
Oak Ridge, Tennessee**

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**Determination of Reference
Concentrations for Inorganic Analytes
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at the Oak Ridge Y-12 Plant,
Oak Ridge, Tennessee**

Date Issued—March 1996

Prepared by
HSW Environmental Consultants, Inc.,
and Paradigm Data Services, Inc.,
in conjunction with the
Environmental Sciences Division,
the Computer Science and Mathematics Division,
the Office of Environmental Compliance and Documentation,
and the Energy Division at
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PREFACE

This document, *Determination of Reference Concentrations for Inorganic Analytes in Groundwater at the Oak Ridge Y-12 Plant, Oak Ridge, Tennessee (Y/ER-234)*, was prepared in accordance with requirements under the Comprehensive Environmental Response, Compensation, and Liability Act. This work was performed under Work Breakdown Structure 1.1.02.41.10.22 (Activity Data Sheet 2302). Publication of this document helps to meet a Federal Facility Agreement milestone of September 16, 1996. This document provides the Environmental Restoration Program with a description of the methodology used to establish groundwater reference concentrations for nonradionuclides at the Y-12 Plant.

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ABBREVIATIONS

bgs	below ground surface
EPA	U.S. Environmental Protection Agency
ER	Environmental Restoration
GWPP	Groundwater Protection Program (Y-12 Plant)
GWQAR	Groundwater Quality Assessment Report
MCL	maximum concentration limit
ORNL	Oak Ridge National Laboratory
ORR	Oak Ridge Reservation
PC	principal component
PCA	principal components analysis
TDS	total dissolved solids
UST	underground storage tank

EXECUTIVE SUMMARY

Background (or reference) concentrations for inorganics in Oak Ridge Y-12 Plant groundwater were determined by using a combination of statistical cluster analysis and conventional cumulative probability graphing. The objective of the study was to develop a methodology for setting groundwater reference concentrations that uses all site groundwater data instead of only results of sampling upgradient of groundwater contamination. The Y-12 Plant was selected as a prototype for this study because the groundwater data set is very large (430 wells yielding > 4400 sample results) and because the data have been consistently collected and managed by the Y-12 Plant Groundwater Monitoring Program, or their subcontractors, since 1986. Reference concentrations for radiological contaminants were not addressed in this study.

A conceptual framework of groundwater quality at the Y-12 Plant was formulated. As a quality check on the conceptual framework, data were statistically modeled, or clustered. Ten hydrochemical regimes or clusters were identified. Six well clusters closely corresponded to the water-quality framework and to observed water-quality regimes in groundwater at the Y-12 Plant. Four clusters were associated with nitrate, an S-3 Site contaminant, or with nonspecific contaminants that are commonly encountered at shallow depths at industrial sites (e.g., road salt). The four clusters associated with contamination were eliminated from the reference data set.

Cumulative probability graphs were used within a cluster or group of clusters to distinguish contaminated or contamination-affected wells from wells that exhibit ambient water quality. Only the median values of unfiltered samples were plotted. Outlying data points, which were assumed to be contaminated samples, were identified by visual inspection and were eliminated from the data set. When all outliers for a given inorganic had been identified and deleted from the data set, the reference concentration was set at the one-sided upper tolerance limit on the 95th percentile with 95% confidence. The methodology proved very useful in integrating a large amount of data into the Y-12 Plant groundwater conceptual framework and in identifying those wells or groups of wells that have monitoring or sample and analysis problems or that may be monitoring site-related contamination.

1. INTRODUCTION

The goal of site characterization studies of groundwater contamination is to accurately determine the nature and extent of the site-related contamination. When unquestionably anthropogenic chemical constituents such as volatile organic chemicals or polychlorinated biphenyls are present in groundwater, their reliable detection usually provides sufficient evidence of contamination. However, determination of groundwater contamination is not as straightforward when the potential contaminants are inorganic constituents such as arsenic, lead, or chromium—substances that can result from either anthropogenic or natural conditions. Actual site-related groundwater contamination by such constituents cannot be ascertained in the absence of background, or reference, information.

A reference concentration is an uncontaminated background concentration or control state against which contamination can be distinguished (Keith 1988). Like the laboratory reagent blanks that are used to assess whether samples have been tainted in the laboratory by undesired analytes or contamination, a reference concentration represents a constant that can be used to assess varying concentrations of an analyte in groundwater samples. In any study of site-related groundwater contamination, accurate reference concentrations must be determined for all analytes being measured to (1) help establish criteria for characterizing the extent and severity of site-related contamination, (2) furnish the basis for identifying contaminants of potential concern in the baseline risk assessment, and (3) provide information needed to develop and evaluate the suitability of groundwater remediation criteria. The combined reference concentrations for all analytes constitute a reference water quality that is not only free of site-related anthropogenic contamination but also representative of the site's groundwater had it not become contaminated. To accurately characterize water quality at a hydrogeologically complex site, where water types may vary substantially among groundwater flow paths because of the geochemical influence of the matrix through which the groundwater flows, a reference water quality should be determined for each distinct water type.

The conventional approach used in most groundwater studies to determine reference concentrations lacks the sophistication to establish truly representative reference water quality. Although the conventional approach's comparison of contaminant concentrations upgradient and downgradient of source areas [U.S. Environmental Protection Agency (EPA) 1989, 1993a, 1993b] is conceptually simple and well accepted by regulators and industry, locating a sufficient number of upgradient wells that adequately characterize reference conditions is often difficult and expensive, particularly at large, hydrogeologically complex sites. In addition, even when upgradient reference samples can be collected, upgradient reference water quality is not necessarily representative of the reference water quality downgradient and crossgradient of known source areas (Davis 1994). Nonrepresentative reference water quality, particularly for trace-level inorganics, can result in inappropriately high or low contaminant assessments.

The objective of this study was to develop a technically defensible methodology that can consistently determine groundwater reference concentrations that are both free of contamination and representative of groundwater. Although the methodology was designed for general application at any site where groundwater data are sufficiently abundant, the Oak Ridge Y-12 Plant site was selected as a prototype (1) because the groundwater data set is very large; (2) because the data have been consistently collected and managed by the Y-12 Plant Groundwater Monitoring Program, or their subcontractors, since 1986 (Sect. 3.1); and (3) because the reference concentrations determined

from the study could be used immediately by the Y-12 Plant Environmental Restoration (ER) Program in risk assessments or other groundwater remediation activities. In contrast to the conventional approach, the approach used in this study evaluates all site-wide groundwater sample data for inclusion in a groundwater reference data set regardless of whether the samples were collected upgradient, crossgradient, or downgradient of contaminant sources. A site-wide approach to setting reference concentrations has several significant benefits. Because available data have priority, the collection of new data is not always necessary; thus, when the available data are used, the added expense of drilling new wells or sampling old ones is avoided. Furthermore, by not assuming what is contaminated or what is reference, the interpreter of the data can take advantage of the spatial spread or variability of the data. The representativeness of the reference concentrations is thereby optimized. Inclusion of all site-wide data is appropriate, however, only if techniques are available to reliably distinguish groundwater concentrations that appear to be reference concentrations from concentrations that appear to be contamination or affected by contamination. Discrimination of reference from apparent contamination was attempted in this study by a combination of statistical and graphical methods, including cluster analysis and cumulative probability graphing.

2. BACKGROUND

The following sections provide brief descriptions of (1) the results of previous studies that used the conventional approach to determine background concentrations of inorganic compounds in groundwater at the Y-12 Plant and (2) the hydrogeologic framework that was used in the current study to develop a conceptual model for interpretation of the data.

2.1 PREVIOUS EFFORTS TO DETERMINE REFERENCE CONCENTRATIONS IN GROUNDWATER AT THE Y-12 PLANT

Groundwater quality monitoring has been performed at the Y-12 Plant since the early 1980s. Until 1990, monitoring activities were performed under multiple site-specific programs with overlapping regulatory requirements and monitoring objectives. These activities were then combined into a single integrated program described in the *Comprehensive Groundwater Monitoring Plan for the Department of Energy Y-12 Plant* (Geraghty & Miller, Inc., 1990). Under this plan, the Y-12 Plant was divided into three hydrogeologic regimes on the basis of topography, surface water drainage, and groundwater flow patterns: (1) the Bear Creek Hydrogeologic Regime, which encompasses Bear Creek Valley between Gum Hollow Road and a topographic and hydrologic divide located near the west end of the Y-12 Plant; (2) the East Fork Poplar Creek Hydrogeologic Regime, which includes the bulk of the Y-12 Plant in the Bear Creek Valley between the eastern boundary of the Oak Ridge Reservation (ORR) along Scarborough Road and the west end of the plant; and (3) the Chestnut Ridge Hydrogeologic Regime, which includes the section of Chestnut Ridge extending west from Scarborough Road to the west end of the Y-12 Plant and extending south to Bethel Valley Road (Fig. 1). (See Appendix A for all figures.) Although tailored to comply with regulatory requirements applicable to specific waste management sites, groundwater-monitoring activities in each hydrogeologic regime are performed in accordance with standardized protocols established by the Y-12 Plant Groundwater Protection Program (GWPP).

Methods of determining groundwater reference concentrations have evolved in response to changes in the groundwater monitoring programs at the Y-12 Plant. In the mid and late 1980s, site-specific reference concentrations were determined by the conventional approach, by quarterly monitoring one or more wells located hydraulically upgradient of the site. For instance, data reported for samples collected from the monitoring well GW-115 were used to determine reference concentrations for groundwater downgradient of the S-3 Site, a closed hazardous waste disposal site near the western end of the Y-12 Plant. Reference concentrations were not determined for inorganics that already had reference concentrations specified by monitoring program regulations such as those establishing maximum concentration limits (MCLs) for drinking water.

In 1990, after the site-specific monitoring programs were integrated into a comprehensive program that required the issuance of biannual Groundwater Quality Assessment Reports (GWQAR), a modified conventional approach was used to determine reference concentrations applicable to groundwater throughout each of the three hydrogeologic regimes. For the 1992 GWQAR, sophisticated techniques for screening data for quality and for establishing standardized detection limits were developed (HSW Environmental Consultants, Inc., 1992). Reference concentrations for inorganics without MCLs were determined from the pooled data reported for 36 wells located hydraulically upgradient of all known sources of groundwater contamination at the Y-12 Plant. Data were included in the study only if they were in accordance with the decision rule

that the charge balance for a given sample analysis (i.e., the relative percent difference between total cations and total anions expressed in milliequivalents) must fall between +10% and -10%. No other attempt was made to identify and eliminate outlier data. In most cases, parametric or nonparametric tolerance limits were calculated as estimates of the reference values, depending on characteristics of the data and their distribution. The study also investigated whether differences in concentrations of trace metals existed between wells in the Knox formation and those in other formations. If differences were found, two reference concentrations were calculated, one for the Knox wells and one for wells in all other formations.

The same basic process and assumptions were used to recalculate reference concentrations for the 1994 GWQAR. The 1994 study included 2 additional years of data and added 15 new wells to the reference well list (HSW Environmental Consultants, Inc., 1995). None of the original wells were deleted. Two reference values were calculated for each element, one for aquifer wells and one for aquitard wells. At the conclusion of both the 1992 and 1994 studies, researchers noted that the tolerance limits were very sensitive to outliers and deviations from assumptions about the number of unique populations of groundwater present at the site.

By initially including all wells, then identifying and eliminating data from contaminated wells and outliers prior to the calculation of reference values, the current study not only addressed these issues but also overcame the problem of using a limited number of wells to determine reference concentrations for a hydrogeologically heterogeneous site. The current study also added major and minor ions and inorganic analytes such as nitrate for consideration and a statistical water-quality classification step (cluster analysis). Otherwise, the current study's methodology was similar to that of the 1992 study. The same data source and charge-balance criterion ($\pm 10\%$) were used. The only difference occurred when the proportion of values reported as "not detected" for any analyte exceeded 50%. In the 1992 study, the 99th percentile was used as an estimate of the reference value. In the current study, the nonparametric tolerance limit was used as the estimate.

2.2 HYDROGEOLOGIC FRAMEWORK

Before the Y-12 Plant groundwater reference study was begun, a conceptual hydrogeochemical model or framework was developed that describes the predominant hydrogeochemical regimes historically observed in Y-12 Plant groundwater. Hydrogeochemical frameworks are useful at any site or at any scale, but they are particularly useful at hydrogeologically complex sites where it is anticipated that data quality will vary significantly from well to well. In addition to providing a convenient summary of site groundwater conditions, this framework provides insight into the ranges of reference concentrations that will or should occur in the absence of contaminants. All interpretive analysis in the current study was checked against this framework.

2.2.1 Geology

Geology on the ORR is generally characterized by thrust-faulted sequences of southeast-dipping clastic (primarily shale and siltstone) and carbonate (limestone and dolostone) strata of Lower Cambrian to Lower Ordovician age. The Y-12 Plant lies in Bear Creek Valley, which is underlain by the following limestone and shale formations of the Conasauga Group (listed in sequence from youngest to oldest): Maynardville Limestone, Nolichucky Shale, Maryville Limestone, Rogersville Shale, Rutledge Limestone, and Pumpkin Valley Shale. The Maynardville

Limestone is partially exposed along the axis of Bear Creek Valley at the base of Chestnut Ridge, which flanks the southern boundary of the valley and is formed by the Copper Ridge Dolomite formation of the Knox Group; the remaining Conasauga Group formations are partially exposed successively to the north toward Pine Ridge, which is formed by shale and siltstone beds of the Rome Formation (Fig. 2).

Bedrock is overlain by any of several materials, including man-made fill, alluvium, colluvium, fine-grained residuum from the weathering of the bedrock, and saprolite (weathered bedrock), which in some areas retains primary textural features of the bedrock, including fractures (Solomon et al. 1992). The overall thickness of these materials is typically <40 ft in Bear Creek Valley and Pine Ridge but averages ~100 ft on Chestnut Ridge (Geraghty & Miller, Inc., 1987).

Strike and dip of bedding are generally N 55° E and 45° SE, respectively (as referenced to true north); however, small-scale folding and faulting produce locally variable bedding orientations (King and Haase 1987). The bedrock is extensively fractured. Three major fracture orientations are evident: one that roughly parallels bedding and two that dip more steeply, one generally parallel with and one perpendicular to bedding (Dreier et al. 1987). Most fractures are short, usually only tenths of inches to a few feet in length; fracture densities ranging from ~1/ft to 60/ft have been observed in rock outcrops near Oak Ridge National Laboratory (ORNL) (Dreier et al. 1987; Sledz and Huff 1981). Dissolution along fractures in carbonates, particularly in the Copper Ridge Dolomite and the Maynardville Limestone, has produced karst features ranging in thickness from less than an inch to tens of feet.

2.2.2 Groundwater System

Groundwater on the ORR occurs in two general hydrogeologic units with fundamentally different hydrologic characteristics: the Knox Aquifer and the ORR Aquitards. The Knox Aquifer consists of the Knox Group and the underlying Maynardville Limestone formation of the Conasauga Group. The remainder of the Conasauga Group, the Rome Formation, and the Chickamauga Group (exposed in Bethel Valley south of Chestnut Ridge) form the ORR Aquitards.

The groundwater flow system in the ORR Aquitards and the Knox Aquifer basically consists of three subsystems: (1) the stormflow and vadose zones, (2) the groundwater zone, and (3) the aquiclude (Fig. 3). These subsystems are vertically gradational in each hydrogeologic unit and are differentiated by groundwater flux, which decreases successively from the stormflow zone to the aquiclude (Solomon et al. 1992).

2.2.2.1 Stormflow and vadose zones

Groundwater occurs intermittently above the water table in a stormflow zone that extends from ground surface to a depth of ~6 ft below ground surface (bgs). The stormflow zone occurs in regolith and is more permeable near the land surface than at deeper levels. Lateral flow in the stormflow zone is intermittent, lasting only a few days to a few weeks after precipitation; some of the water is lost to evapotranspiration and recharge to the water table, and the remaining water discharges at nearby seeps, springs, and streams. Hydrologic characteristics of the stormflow zone have been identified primarily from information obtained in Bethel Valley and Melton Valley near ORNL (Moore 1988, 1989). Although recently obtained data show that groundwater flow in the stormflow zone also occurs in Bear Creek Valley (Moss 1994), groundwater flux and contaminant transport may be less significant there than in Bethel Valley and Melton Valley.

The vadose zone occurs between the stormflow zone and the water table. Although in some areas the vadose zone includes weathered and fresh bedrock, it typically occurs in regolith, which has an estimated effective porosity (the porosity through which significant advective transport can occur) of 0.01 to 0.15 (Moore 1989). The vadose zone is unsaturated except in the capillary fringe above the water table and within wetting fronts during periods of vertical percolation from the stormflow zone (Moore 1989).

2.2.2.2 Groundwater zone

Groundwater below the stormflow and vadose zones in the ORR Aquitards and Knox Aquifer occurs within orthogonal sets of permeable, planar fractures that form water-producing zones within an essentially impermeable matrix. Water-producing zones commonly develop within a single layer of rock and have an average thickness (an average dip of 35° is assumed) of 2 ft or less (Dreier et al. 1987). Dissolution of carbonates has greatly increased permeability of the water-producing zones in the Knox Aquifer. For example, enlarged fractures and solution cavities in the Maynardville Limestone yield as much as 200 to 300 gal/min (Shevenell et al. 1993), which is several orders of magnitude greater than the typical yield (0.25 gal/min) of water-producing zones in the ORR Aquitards (Solomon et al. 1992). Additionally, stratiform fractures provide the principal flowpaths in the ORR Aquitards and the Knox Aquifer; groundwater flows primarily in the direction of geologic strike (which may or may not correlate with the maximum hydraulic gradient) toward springs, seeps, and crosscutting tributary streams (Moore and Toran 1992).

Because the frequency, aperture, and connectivity of permeable fractures decreases with depth, the bulk hydraulic conductivity of the bedrock in the ORR Aquitards and the Knox Aquifer is vertically gradational. Most of the groundwater flux below the stormflow and vadose zones in each unit occurs in a highly permeable interval (the water table interval) within the transitional horizon between regolith and unweathered bedrock; lower flux (and longer solute residence times) occurs at successively greater depths in the unweathered bedrock. Changes in the geochemistry of the groundwater suggest that active flow in the ORR Aquitards occurs at depths <100 ft bgs. Active groundwater flow occurs at a deeper level in the Knox Aquifer, as indicated by pressure responses to rainfall that are evident in some wells completed at depths of 200 to 400 ft bgs in the Maynardville Limestone (Moss 1994).

The water table interval in the ORR Aquitards and the Knox Aquifer transmits an estimated 90% or more of the groundwater flow below the stormflow and vadose zones. This highly permeable interval is relatively thin in both units (3 to 15 ft thick), and the saturated thickness changes with cyclic variations in the water table elevation (Moore 1989). Transient saturation of permeable flowpaths in the water table interval during and immediately after rainfall causes rapid lateral groundwater movement (i.e., quickflow) toward nearby seeps, springs, and tributaries. Quick flow in the water table interval is reflected by stream hydrographs, which are characterized by rapid responses to rainfall and little or no change in baseflow before and after major storms (Moss 1994). For some wells screened in the water table interval, very low total dissolved solids (TDS) in groundwater samples collected after rainfall also indicate quickflow recharge.

Groundwater flux in the unweathered bedrock below the water table interval in the ORR Aquitards occurs primarily at shallow depths (i.e., <100 ft bgs). However, the permeability of the shallow bedrock varies over several orders of magnitude. For instance, results of 82 hydraulic conductivity tests performed in shallow Nolichucky Shale monitoring wells range from 0.001 to 4.6 ft/d (Geraghty & Miller, Inc., 1986). The higher conductivity values represent permeable,

water-producing intervals and the lower conductivity values represent effectively less permeable matrix intervals (Moore 1989). Results of aquifer-pumping tests suggest strongly anisotropic flow at shallow depths in the ORR Aquitards; each test has generally been characterized by an elliptical cone of depression elongated parallel to geologic strike. Transmissivity values (determined from Theis drawdown analysis) range from ~5 to 530 ft²/d and average ~62 ft²/d (Law Engineering Testing Company 1983; Geraghty & Miller, Inc., 1986; Golder Associates, Inc., 1987). Results for some of the pumping tests showed strike-parallel transmissivities as much as 30 times greater than strike-normal transmissivities (Golder Associates, Inc., 1987).

The permeability of the shallow bedrock in the Knox Aquifer also varies over several orders of magnitude but is significantly greater overall than in the ORR Aquitards. For example, hydraulic conductivity test results for wells <100 ft bgs in the Maynardville Limestone range from 0.13 to 99 ft/d and average ~22 ft/d (Geraghty & Miller, Inc., 1989a). A comparable flow rate (25 ft/d) also was estimated from results of a dye tracer test performed in the Maynardville Limestone south of the Oil Landfarm Waste Management Area (Geraghty & Miller, Inc., 1989b). Additionally, aquifer pumping tests performed in the Maynardville Limestone produced generally symmetrical cones of depression, indicating potentially lower anisotropy compared with the Conasauga Shales. Transmissivity values obtained from these pumping tests (determined from Theis drawdown analysis) ranged from ~372 to 7690 ft²/d, with storage coefficients between 6×10^{-5} and 0.002 (Golder Associates, Inc., 1988). Results of some of these tests also indicated that strike-parallel transmissivity was substantially greater than strike-normal transmissivity.

Decreasing groundwater flux with depth in the ORR Aquitards is clearly indicated by distinct changes in groundwater geochemistry as well as results of hydraulic conductivity tests. The first transitional flux decrease occurs at ~100 ft bgs and is indicated by a change from calcium-magnesium-bicarbonate groundwater to sodium-bicarbonate groundwater. This geochemical change is probably a function of longer groundwater residence time and reflects lower hydraulic conductivity related to reduced fracture apertures or increased fracture spacings (Solomon et al. 1992). For example, results of several hydraulic conductivity tests reported for wells completed at depths of 132 to 374 ft bgs in the ORR Aquitards range from 3×10^{-5} to 0.01 ft/d and average ~0.004 ft/d (Geraghty & Miller, Inc., 1989a). A second transitional decrease in groundwater flux generally occurs at ~400 ft bgs and is indicated by a change from sodium-bicarbonate groundwater to sodium-chloride groundwater accompanied by higher specific conductance and TDS. Data obtained from straddle packer tests, slug tests, and slow-recovery analyses indicate that hydraulic conductivity of the deep bedrock in the ORR Aquitards is as low as 2.83×10^{-6} ft/d (Solomon et al. 1992).

Decreasing groundwater flux with depth in the Knox Aquifer is generally not indicated by groundwater geochemistry; calcium-magnesium-bicarbonate groundwater occurs in virtually every well completed in the Knox Group and the Maynardville Limestone (some wells monitor calcium-magnesium-sulfate groundwater that probably reflects dissolution of locally disseminated sulfides).

2.2.2.3 Aquiclude

The aquiclude is generally marked by the presence of saline water with TDS concentrations as high as 300,000 mg/L; the water in the aquiclude is a sodium-, calcium-, and chloride-rich brine that is chemically similar to brines associated with major sedimentary basins. Whereas saline water typically occurs at depths of ~600 to 700 ft bgs in Melton Valley (Solomon et al. 1992), it has not been encountered at depth in Bear Creek Valley. However, several wells completed at depths of

~500 to 1000 ft bgs in the ORR Aquitards monitor groundwater with TDS concentrations ranging from several thousand to several tens of thousands of milligrams per liter. This highly mineralized groundwater may represent a mixing or diffusion zone between the fresh and saline groundwater, suggesting that the aquiclude is present at greater depth in the Bear Creek Valley than in Melton Valley (Solomon et al. 1992).

2.2.3 Groundwater Flow Patterns

The potentiometric surface in the Y-12 Plant area under both seasonally high and low flow conditions is a subdued replica of surface topography, with steep gradients down the flanks of Pine Ridge and Chestnut Ridge, and gentle slopes along the axis of Bear Creek Valley. The horizontal hydraulic gradient averages ~0.04 across Bear Creek Valley (strike normal) in the ORR Aquitards and ~0.01 along the axis of Bear Creek Valley (strike parallel) in the Maynardville Limestone.

Groundwater in the ORR Aquitards generally flows parallel to bedding (along strike and dip), which may not coincide with the direction of maximum hydraulic gradient inferred from water level isopleths. Flow tangent to bedding occurs primarily along permeable zones formed by cross cutting fractures or fracture zones (and possibly small faults). Some of these crosscutting structures may act as barriers, possibly causing groundwater from deeper intervals in the ORR Aquitards to upwell and discharge to the shallower flow system.

Groundwater in the Maynardville Limestone flows along geologic strike to the east and west of a slight hydrologic divide located near the western end of the Y-12 Plant. Because of its significantly greater hydraulic conductivity, in conjunction with its location underlying Bear Creek along the base of Chestnut Ridge (the topographic low in Bear Creek Valley), the Maynardville Limestone functions both as a drain for the groundwater flow system and as the principal subsurface pathway for contaminant migration in Bear Creek Valley.

3. TECHNICAL APPROACH

The Y-12 Plant groundwater reference study was conducted in four steps: (1) data set assembly, screening, and evaluation; (2) water quality classification and hydrogeochemical analysis; (3) additional data screening and probability graphing; and (4) tolerance limit and reference calculations (Fig. 4). The following discussion is an overview of the four-step methodology. Detailed descriptions of the methodology are also included in Sects. 4 and 5.

3.1 STEP 1: DATA SET ASSEMBLY, SCREENING, AND EVALUATION

The data used in this study are from analyses of groundwater samples collected from 1986 to 1993 as part of the Y-12 Plant Groundwater Monitoring Program. Nonradionuclide data were analyzed because the objective of the study was to develop a methodology that uses as large and relatively high-quality data set as possible. Because the relatively small size and limited data quality associated with the Y-12 Plant radionuclide database may have complicated method development, only nonradionuclide data (major and minor ions and trace metals) were used in this study. This data set has many advantages, of which the most critical are consistency and size. All samples were collected by the Sampling and Environmental Support Department of the Oak Ridge K-25 Site according to the same standard operating procedure (Procedure SESD-TP-8204 and revisions). All samples were analyzed by the K-25 Site Analytical Chemistry Department. All data for this study were managed by H&R Technical Associates, Inc., Oak Ridge, Tennessee. The data set, a very large one for groundwater, consisted of 4426 observations. An observation is defined as a set of analytical results from samples collected at a well during a sampling event. Samples were collected from 430 wells representing 9 formations. Midpoint monitored depths ranged from 0 to >400 ft. The geologic formations monitored by the wells included in the final data set, as well as the depth of the monitored interval for each well, are summarized in Table 1. (See Appendix B for all tables.)

Because of the statistical nature of the study, the suitability of the data set for subsequent numerical analyses had to be assessed. To assure that the data were appropriate and reasonable, a series of data screens were established: (1) the sample analytical method used for each constituent was evaluated for appropriateness, (2) detection limits were evaluated for reasonableness, (3) samples that exceeded a $\pm 10\%$ analytical charge balance were rejected, and (4) sample pH was checked to confirm that pH was within an acceptable range (4 to 10). Wells with a pH <4.0 were assumed to be in the S-3 pond plume (a contaminant plume with a low pH signature) and were therefore eliminated from the data set, as were wells with a pH >10, which were assumed to be contaminated with grout. In addition to the data screens, a conceptual hydrogeochemical model was developed to describe the predominant hydrogeochemical regimes historically observed in Y-12 Plant groundwater (Sect. 2.2) and to provide plausible hypotheses on how the groundwater data would be geochemically classified or clustered in Step 2.

Comparisons between field and laboratory conductance, sample duplicates, field pH and laboratory alkalinity, and results from filtered and unfiltered elemental samples were also conducted. If any results looked questionable, the laboratory was asked to review its records; determine if an error had occurred during sample handling, analysis, or reporting; and make any necessary changes in the laboratory information system.

Because the data used in this study were not collected to establish reference concentrations but to fulfill a variety of regulatory compliance needs, all wells are not equally represented in the data set. Some wells were sampled many times during the entire sampling period whereas other wells were sampled infrequently over shorter periods of time (Table 2). To ensure that any calculations that use the data would not be influenced by how often a well was sampled or by extreme values resulting from errors in sampling, laboratory testing, or data handling, each well's median value for an analyte was used in all statistical analyses. Reference concentrations calculated from median values are directly comparable to median values and are conservative if compared with individual data points.

3.2 STEP 2: WATER QUALITY CLASSIFICATION AND HYDROGEOCHEMICAL ANALYSIS

Because of the hydrogeological complexity of the Y-12 Plant site and the abundance of available data, representative reference concentrations for each analyte could be best achieved by geochemically organizing, or classifying, the groundwater data according to the chemical patterns that were apparent in the median values of the well sample data (Sect. 4). Reference concentrations could then be calculated for groups, or clusters, of wells that exhibited similar geochemical signatures. Principal component analysis, cluster analysis, and tree-based modeling were used to identify and characterize the groups. The analysis ultimately identified ten clusters of wells.

To validate the statistical analysis, the cluster assignments were evaluated for reasonableness by directly comparing the chemical characteristics of the samples for each well in each cluster with the Y-12 Plant conceptual hydrogeochemical model (Fig. 3). To assess the hydrogeological reasonableness of each cluster's well membership (Sect. 4.2), standard geochemical Piper diagrams (Freeze and Cherry 1979) were used, and well locations were posted for each cluster on a site geology map of the Y-12 Plant.

When a given cluster was dominated by the presence of nitrate (a common contaminant in Y-12 Plant groundwaters) or by other industrial contaminants (e.g., road salt), no further analysis or reference calculations for that cluster were performed. Wells assigned to these affected clusters were reassigned to unaffected, surrogate, clusters according to hydrogeologic criteria (Sect. 4.3). Later, the concentrations of the samples from the wells in the affected clusters were compared with the reference concentrations of the surrogate clusters to which the affected wells had been reassigned. The reference concentrations were determined solely on the basis of the samples from the original wells in the surrogate clusters. If the analyte concentration for a well from an affected cluster was greater than the reference concentration in the cluster to which the well was reassigned, the well sample for that analyte was deemed contaminated. For example, assume that a well assigned to its surrogate cluster, Cluster 1, had a median concentration for barium of 0.75 mg/L. If the reference value for barium in Cluster 1 is set at 0.71 mg/L, then the well would exceed the barium reference concentration and would be judged contaminated. On the other hand, although the well may be contaminated for barium, its median concentration for another analyte, such as chloride, might not exceed the reference value for that analyte for Cluster 1, so the well would be judged to be within the range of the analyte's reference concentration. (For more details on surrogate cluster assignments and how they relate to reference concentrations, see Sect. 4.3.)

3.3 STEP 3: ADDITIONAL DATA SCREENING AND PROBABILITY GRAPHING

The objective of Step 3 was to prepare the data set for the identification of outlier populations and the calculation of reference concentrations as upper tolerance limits.

As a result of the cluster analysis in Step 2, four clusters were characterized by wells contaminated with nitrate or general industrial substances such as road salt. Because nitrate and general industrial contamination were more widespread than anticipated, additional data screening was performed to eliminate other wells that may also adversely affect reference calculations. Outlier wells were identified on the basis of documented or long-suspected site-related contamination and well-construction/well-sampling problems. Data from these wells were deleted from the data set (Sect. 5.1).

Preparation for the identification of outlier populations and the calculation of reference concentrations also involved the following activities: (1) differences in reported detection limits were evaluated, and all analytes were assigned a standard detection limit (Sect. 5.2); (2) median values for each analyte for each well were calculated (Sect. 5.2); and (3) nonparametric Kruskal-Wallis tests were run to test for differences between well clusters in the ranks of the median concentrations for each analyte (Sect. 5.3). In the interest of maximizing the number of observations available for cumulative probability graphing, data from well clusters that could not be distinguished from each other were pooled, and reference concentrations were calculated for the pooled data.

Reference populations were discriminated from apparent site-related contamination (which are regarded as data outliers) through the use of the graphical/visual estimation method of cumulative probability graphing (Sect. 5.4). Median values for each analyte in each well cluster were plotted on cumulative probability graphs. Lognormal cumulative probability graphs were then used to visually identify population outliers (i.e., sample values that were elevated in relation to the bulk analyte distribution). If outliers were identified, the outlier values were deleted and the data set was plotted again. The process was repeated until all outliers were removed from the data set.

The use of normal and lognormal cumulative probability graphs to identify population outliers in groundwater data was modeled on a similar technique commonly used in the mineral exploration industry (Sinclair 1976) and more recently adopted to assist in the determination of remediation standards for contaminated soils (EPA 1994; Fleischhauer and Korte 1990) and groundwater (McBean and Rovers 1992). In addition to the Y-12 Plant, Lockheed Martin Energy Systems sites in the process of completing studies by using this method are the Paducah (Kentucky) Gaseous Diffusion Plant; the Portsmouth (Ohio) Gaseous Diffusion Plant; and the Oak Ridge K-25 Site. Several other U.S. Department of Energy sites, including the Hanford Site, Sandia National Laboratory, and Lawrence Livermore National Laboratory, have also used a similar cumulative probability graphing approach in determining reference concentrations (Carlson 1994; LaGore 1994; Meyers 1994).

The cumulative probability graphing method has been used to solve a common problem in the geochemistry of mineral exploration: distinguishing rock, soil, or water samples enriched in a mineral from other samples containing the same mineral at ambient background concentrations. One way to address the problem of separating enriched samples from background—or reference—samples is to plot the concentration of the data (on the ordinate) against its cumulative percent with an abscissa that is specially scaled to display a probability distribution as a straight line. The power of the probability plot is its simplicity: samples that are normally distributed (or

lognormally distributed following a log transformation of the raw data) will plot very close to a straight line; samples that deviate from normality (i.e., outliers) will deviate from the straight line. In the Y-12 Plant reference study, the outliers are contaminants or analytes affected by contamination.

3.4 STEP 4: TOLERANCE LIMIT AND REFERENCE CALCULATIONS

After all outliers were eliminated from the data set, reference concentrations were determined for each analyte in each cluster (Sect. 6). The method of determining reference concentrations varied depending on the percentage of results that were above the detection limit for a given analyte. Reference concentrations were calculated at the upper 95% tolerance limit with 95% coverage (Sect. 5.3).

4. GROUNDWATER CLASSIFICATION

Because groundwater is influenced by the matrix through which it has flowed, monitoring wells were systematically grouped by their geochemical characteristics before reference concentrations were calculated. To construct meaningful associations among the monitoring wells and to develop a scheme for classifying additional data sets into one of the well groupings, three statistical methods were used in sequence: principal components analysis (PCA), cluster analysis, and tree-based modeling. The analysis was based on the assumption that the variability of the chemical signature within a group will be less than between groups. Median parameter values for each of the wells were used in the analysis to reduce the data to a manageable amount and to remove the influence of atypically large or small values. The stability of the classification system depends on the use of dominant and persistent sources of variation, not anomalous values that will focus the process on unusual results. Seasonal variability has been assessed and determined to be minor compared with variability between groups.

4.1 STATISTICAL TOOLS

The process used was an iterative process involving repeated application of the statistical tools and multiple interactions among the data analysts and subject area experts. The statistical tools are described in the following sections.

4.1.1 Principal Components Analysis

The purpose of using PCA in this study was to identify a few main characteristics of a data set containing a number of interrelated variables. By using an eigenvalue/eigenvector analysis of the correlation matrix of the variables, PCA transforms the original variables into a new set of uncorrelated variables called principal components (PCs)—linear combinations of the original variables ordered so that the first few PCs retain most of the variation present in all of the original variables. If successful, the analysis extracts several PCs that account for a large proportion of the variation present in the data set. These PCs can then be used instead of the original variables in further analyses such as cluster analysis. A comprehensive description of PCA can be found in Jolliffe (1986).

PCA has a number of potential advantages. One advantage is dimension reduction; PCA reduces the dimensions to a few while capturing the bulk of the data's variability. Dimension reduction can be useful for plotting the data to get a visual sense of data groupings. For example, when two PCs represent the bulk of the variability in the data, a plot of the first PC versus the second PC displays that variability. The resulting emphasis on the dominant and persistent variability of the data, rather than on the fine differences that may be there, is important because clustering techniques can be unduly influenced by fine differences, resulting in groupings that may not represent the important, gross features in the data.

The character of groundwater depends on the source of the water, the soil and rock composition through which the water flows, and the time the water is in contact with the surrounding material. This statistical analysis sought well groupings based on the effects of the dominant rock types of the study area. In addition to concentrations of the dominant anions and cations in natural waters in the Oak Ridge area (carbonate and bicarbonate alkalinity, calcium, magnesium, sodium,

chloride, sulfate and nitrate), the geochemical parameters used in the analysis were the field measurements conductivity and pH. Conductivity provides a gross measure of dissolved solids; both conductivity and pH are general water quality measures.

4.1.2 Cluster Analysis

The purpose of cluster analysis is to identify group structure where there is little prior information about the structure. This is accomplished by dividing a set of objects into groups called clusters such that objects within a cluster are more similar to each other than they are to objects in other clusters. Objects in this study are wells described by geochemical parameters. It is assumed that the derived clusters of wells represent distinct water types unique to the surrounding geology.

Two different types of cluster analyses were used in this study: agglomerative hierarchical cluster analysis and partitioning cluster analysis. Hierarchical clustering was used to get indications of the possible number of clusters and starting estimates for the partitioning approach. Results from different starting estimates (i.e., number of clusters and cluster means) were evaluated by subject-area experts for distinctness and validity. Hierarchical clustering was performed in stages; at each stage, the PCs were obtained for the wells contributing to that stage. Clusters were obtained with a reduced set of those PCs that restricted the focus of the cluster analysis, thereby avoiding possible masking by noise variables (Fowlkes et al. 1988). If the directions of greatest variability in the data are associated with group membership, then the first few PCs will capture that information.

The hierarchical technique groups objects into clusters by measuring the Euclidean distance between them with respect to object characteristics. The two objects closest to each other as measured by Euclidean distance are most similar to each other, just as points on a map are similar with respect to distance in map units. Similarity between two clusters (a single object can be a cluster) is defined as the average distance between objects in the clusters. The results of an agglomerative cluster analysis are displayed in a diagram called a cluster dendrogram, which can be visualized as an inverted tree where the tips of the branches represent individual objects and successive forks in the tree show linkage to other objects. A group of objects linked at a lower level in the tree are more similar than a group of objects linked at a higher level. The linking of objects can continue until all objects are connected. Determination of the number of clusters (i.e., where to stop linking objects) is usually guided by the interpretability of the resulting clusters and expert judgment. The inherent conflict between parsimony (too few clusters) and within-cluster homogeneity (too many clusters) must be resolved to make this decision.

Clusters that were derived through applications of the hierarchical method were subsequently refined through a specific partitioning method, that is, by k-means clustering. Partitioning methods, which are far more flexible than hierarchical methods, group objects by optimizing some criterion of similarity. The k-means method uses the intracluster distance around the mean as its criterion. Given there are k clusters, objects are allocated to clusters to minimize the pooled within-cluster sum of squared distances of objects from the respective cluster mean. Important differences between partitioning and hierarchical clustering methods were exploited in this analysis. Partitioning methods allow for relocation of objects among clusters whereas in hierarchical methods an object remains in the cluster to which it is initially assigned. The k-means method also requires specification of the number of clusters and starting estimates of cluster means. Hierarchical methods do not.

Because the data used in this study were derived from a complex system, the resultant clusters of wells probably do not represent exactly some fixed number of water types. Some of the water types may be quite distinct whereas others may be less distinct or even arbitrary. Those less distinguishable types are evidence of water-type mixing and the influence of geologic formation and residence time on the water characteristics. Although identifying the "true" clusters is impossible, a parsimonious partitioning that appears to a subject-area expert as valid and interpretable may be achieved (Solomon 1977).

4.1.3 Tree-Based Modeling

The third statistical technique, tree-based modeling, generates decision rules that unambiguously assign wells to one of the identified clusters on the basis of data from a water sample. Tree-based modeling for classification is based on the multinomial distribution and uses explanatory variables to predict group membership (Clark and Pregibon 1992). Binary recursive partitioning is used to fit a model by successively splitting the data set into increasingly homogeneous subsets until continuing is infeasible. The result of the partitioning is a collection of rules determined from the data. An example of a rule is

If alkalinity > 280 mg/L
and calcium > 65 mg/L,
then water type is most likely to be a limestone water type.

The model is fully specified by a collection of rules and can be displayed in a binary tree. A node in the tree is labeled by and corresponds to the best split of the data in that tree branch with respect to one of the predictors. The likelihood function provides the basis for determining which partition is "best" given the data. The rules may or may not involve all potential predictors. As splitting progresses, nodes become purer. In the limit, there can be as many nodes as observations. The decision to stop is affected by the conflict between accurate classification and model parsimony. Model success can be evaluated empirically by calculating correct classification rates for the data used in the modeling or for new, independent data, when available.

The advantages of the tree-based modeling classification approach over more traditional classification techniques such as linear and quadratic discriminant analysis or logistic discriminant analysis are threefold: it is highly empirical and is relatively free of restrictive assumptions about the underlying distributions, it is invariant under monotone transformation of the predictors, and it can handle missing values.

4.2 CLUSTER DESIGNATIONS

The modeling procedure assigned the 430 monitoring wells included in the reference study to 10 different groups designated Clusters 1 through 10 (Fig. 5); the cluster assignment for each well, along with the monitored formation and the depth of the monitored interval, is shown in Table 3. Clusters 1, 2, 3, 4, 6, and 10 are composed of wells that generally monitor groundwater free of inorganic contaminants. However, several inorganic contaminants (primarily nitrate) are known or suspected to be present in the groundwater monitored by wells assigned to Clusters 5, 7, 8, and 9. Characteristics of each cluster are described in the following sections.

4.2.1 Cluster 1: Shallow Groundwater (Maynardville Limestone)

A total of 97 wells were assigned to Cluster 1 (Table 4). These wells share no apparent geographic relationship; they are located throughout the general area of the Y-12 Plant including Bear Creek Valley, Chestnut Ridge, and Bethel Valley (Fig. 6). Cluster 1 is about evenly split between ORR Aquitards wells (47) and Knox Aquifer wells (50), with the bulk of the wells completed in either the Nolichucky Shale (23 wells) or the Maynardville Limestone (41 wells). Well depths range from 10 to 745 ft bgs, although most (74) are <100 ft bgs and just over one-half (49) are <50 ft bgs (the mean depth is 87 ft bgs). Wells assigned to Cluster 1 primarily monitor calcium-magnesium-bicarbonate groundwater (Fig. 7), but some other geochemical characteristics (e.g., sulfate concentrations) are more variable than those of the other clusters.

Cluster 1 contains the largest proportion of the shallow (i.e., <100 ft bgs) Maynardville Limestone wells included in the reference study; 31 (~42%) of the 74 shallow Maynardville Limestone wells were assigned to Cluster 1. Additionally, 12 of the 22 shallow Nolichucky Shale wells assigned to Cluster 1 are in the upper portion of the formation within about 200 ft of the overlying Maynardville Limestone (an average dip of 45° is assumed). These findings suggest that the overall geochemical characteristics of Cluster 1 may be attributed to groundwater quality within the active flow system at shallow depths in the Maynardville Limestone.

One conspicuous characteristic of Cluster 1 is the inclusion of 11 wells that monitor sulfate-enriched groundwater, specifically GW-211, GW-250, GW-303, GW-319, GW-602, GW-646, GW-647, GW-710, GW-711, GW-712, and GW-713 (Fig. 9). Only three of these wells (GW-211, GW-250, and GW-319) are in the ORR Aquitards, and only four (GW-250, GW-319, GW-646, and GW-647) are <200 ft deep. As noted in Sect. 2.2.2.2, sulfate-enriched groundwater in the Knox Aquifer probably results from dissolution of locally disseminated sulfides (Solomon et al. 1992).

Because of the diverse locations, the generally shallow depths, the nearly equal proportion of aquitard/aquifer wells, and the dominant groundwater type monitored by these wells, Cluster 1 was interpreted to represent calcium-magnesium-bicarbonate groundwater at shallow depths in the ORR Aquitards and Knox Aquifer, particularly groundwater in the Maynardville Limestone.

4.2.2 Cluster 2: Recharge Groundwater

Cluster 2 consists of 27 monitoring wells, most of which are located in Bear Creek Valley west of the Y-12 Plant (Fig. 8). Many are located on low hills formed on the Maryville Limestone along the flank of Pine Ridge between northern tributaries to Bear Creek. All of these wells monitor shallow groundwater (the mean depth is 28 ft bgs), and all but two are in ORR Aquitard formations (Table 4). The geochemistry of the groundwater monitored by these wells is fairly variable (Fig. 9); however, the TDS reported for the groundwater samples collected from each of these wells is typically <150 mg/L (TDS reported for wells in other clusters usually exceeds 300 mg/L). Because it is composed of shallow wells that monitor groundwater with low TDS, Cluster 2 was interpreted to represent recharge groundwater with short residence time in the water table interval within the ORR Aquitards.

4.2.3 Cluster 3: Shallow Groundwater (Maryville Limestone)

Cluster 3 shares several characteristics with Cluster 1; it comprises a similar number (100) of mostly shallow wells (the mean depth is 52 ft bgs) that generally monitor calcium-magnesium-bicarbonate groundwater at diverse locations throughout the Y-12 Plant area (Fig. 10). However, Cluster 3 includes a proportionally larger number of ORR Aquitard wells than Cluster 1; 80 of the wells in Cluster 3 are completed in ORR Aquitard formations, primarily the Maryville Limestone (34 wells) and the Nolichucky Shale (29 wells) (Table 4). Additionally, aside from a few wells that monitor sodium-dominated groundwater (e.g., GW-636), wells in Cluster 3 monitor calcium-magnesium-bicarbonate groundwater with less variable geochemistry than Cluster 1 (Fig. 11). The less variable geochemistry indicated for Cluster 3 wells, in comparison with that of Cluster 1 wells, may be a function of greater residence time related to longer flowpaths to groundwater discharge areas.

Of the 52 Maryville Limestone wells that were included in the reference study (~12% of the total wells), 34 (65%) were assigned to Cluster 3. This high proportion of Maryville Limestone wells is analogous to the high proportion of Maynardville Limestone wells assigned to Cluster 1 and is considered a defining characteristic of Cluster 3. Additionally, 14 of the 29 Nolichucky Shale wells assigned to Cluster 3 are completed in the basal portion of the formation within ~200 ft of the contact with the underlying Maryville Limestone (an average dip of 45° is assumed). These findings suggest that the overall geochemical characteristics of Cluster 3 may be attributed to groundwater quality in the Maryville Limestone.

4.2.4 Cluster 4: Knox Group Groundwater

Cluster 4 contains 94 monitoring wells, most of which are located on Chestnut Ridge south of the Y-12 Plant (Fig. 12). Eighty-four of these wells are in the Copper Ridge Dolomite of the Knox Group, and 10 are in the Maynardville Limestone (Table 4). Well depths vary from 35 to about 440 ft bgs, but most (62 wells) are between 100 and 200 ft bgs (bedrock on Chestnut Ridge is overlain by about 100 ft of residuum). The geochemistry of the groundwater monitored by these wells shows little variation and generally reflects a bicarbonate with equal or nearly equal ratios of calcium and magnesium, a characteristic of groundwater in contact with dolomite (Fig. 13). Cluster 4 is clearly representative of groundwater in the Knox Aquifer; about 87% of the 97 Copper Ridge Dolomite wells included in the study were assigned to this cluster, and all of the Maynardville Limestone wells in the cluster are located along the flank of Chestnut Ridge near the contact with the Copper Ridge Dolomite.

4.2.5 Cluster 5: Industrially Contaminated Groundwater

Only 19 wells were assigned to Cluster 5, including 1 Knox Aquifer well and 18 ORR Aquitard wells, 14 of which are completed in the Nolichucky Shale (Table 4). These wells are located in Bear Creek Valley (Fig. 14); most are within industrial areas of the Y-12 Plant, including six wells near underground storage tanks (USTs) containing petroleum fuel (GW-282, GW-505, GW-508, GW-631, GW-632, and GW-659) and four wells near a processing area for waste coolants (GW-331, GW-332, GW-333, and GW-336). Well depths are all <50 ft bgs, and 9 of the wells (primarily those near the USTs) are constructed with very shallow screened intervals (within 5 ft of the ground surface).

Calcium-magnesium-bicarbonate groundwater typical of shallow depths in the ORR Aquitards and the Knox Aquifer is monitored by each of the wells assigned to Cluster 5 (Fig. 15). However, concentrations of some ions reported for the groundwater samples collected from these wells were atypical in comparison with those reported for groundwater samples from shallow wells elsewhere in Bear Creek Valley. For example, elevated sulfate concentrations reported for samples from well GW-333 are unusual for shallow groundwater in the ORR Aquitards and most likely reflect contamination from a nearby industrial source. Additionally, the shallow screened intervals for some of the wells probably allows infiltration of contaminated surface water. Well GW-659, for instance, has a screened interval from 4.6 to 16.7 ft bgs; the sodium-chloride-dominated geochemistry of the groundwater in the well may reflect dissolved salt in the runoff from deiced roadways and other paved areas near the well (which is located near a former fuel-dispensing station).

4.2.6 Cluster 6: Sodium-Chloride-Bicarbonate Groundwater

Seven wells were assigned to Cluster 6, all of which monitor groundwater in the Nolichucky Shale west of the Y-12 Plant (Fig. 16). Monitored intervals for all the wells in Cluster 6 except GW-623 are >400 ft bgs (GW-623 is completed at a depth of 275 ft bgs). These wells monitor sodium-chloride-bicarbonate groundwater; sodium represents nearly 100% of the total cations, but the chloride percentage of total anions ranges from about 15% (GW-123) to >90% (GW-118) (Fig. 17). Because of the depth of the wells and the sodium-chloride-dominated geochemistry, Cluster 6 was considered representative of groundwater in the low permeability bedrock at depth in the ORR Aquitards.

4.2.7 Clusters 7, 8, and 9: Nitrate-Contaminated Groundwater

Clusters 7, 8, and 9 respectively consist of 18, 35, and 12 wells that monitor nitrate-contaminated groundwater (Table 4). The source of the nitrate is the S-3 Site, a closed waste-disposal facility that formerly consisted of four unlined surface impoundments near the west end of the Y-12 Plant. The facility received large volumes of nitric acid wastes during its 34 years of operations. Nitrate contaminations are highest in the groundwater monitored by wells in Cluster 7 (>1000 mg/L) and Cluster 9 (>10,000 mg/L) and lowest (<50 mg/L) in the groundwater monitored by Cluster 8 wells (Figs. 18–20). Differences in the nitrate concentrations are generally a function of distance from the S-3 Site; whereas most of the Cluster 7 and Cluster 9 wells are within 2000 ft of the S-3 Site, all but four of the Cluster 8 wells are more than 2000 ft from the S-3 Site. The relationship between decreased nitrate concentrations and distance from the S-3 Site is in turn reflected by the hydraulic characteristics of the formations monitored by the wells that compose each cluster. All but six of the wells assigned to Clusters 7 and 9 are in the low-permeability Nolichucky Shale, which directly underlies the S-3 Site, whereas 32 of the 35 Cluster 8 wells are in the highly permeable Maynardville Limestone, the principal migration pathway downgradient of the S-3 Site.

High nitrate concentrations totally mask the geochemical characteristics of the groundwater monitored by all of the wells in Cluster 7 except well GW-526, which monitors a sodium-bicarbonate groundwater (Fig. 21). Wells assigned to Cluster 8 generally monitor a nitrate-contaminated calcium-magnesium-bicarbonate groundwater (Fig. 22). Nitrate totally dominates the geochemistry of the groundwater monitored by the Cluster 9 wells (Fig. 23).

4.2.8 Cluster 10: Sodium-Bicarbonate Groundwater

Cluster 10 consists of 21 monitoring wells, all but two of which (GW-232 and GW-385) are located in Bear Creek Valley west of the Y-12 Plant (Fig. 24). Well depths range from 75 ft bgs (GW-363) to >400 ft bgs (GW-232), but 13 of the wells are completed at depths of 100 to 250 ft bgs (Table 4). All but five of the wells monitor groundwater in the Nolichucky Shale; one of these wells (GW-163) is in the Rome Formation, and four (GW-094, GW-095, GW-232, and GW-375) are in the Maynardville Limestone (Table 4).

Each of the wells assigned to Cluster 10 monitors sodium-bicarbonate groundwater (Fig. 25). The deeper wells in Cluster 10 monitor groundwater that occurs in the ORR Aquitards below the first transitional decrease in hydraulic conductivity described in Sect. 2.2.2.2. The sodium-bicarbonate groundwater monitored by the shallow wells (i.e., <100 ft bgs) in Cluster 10 suggests that these wells are completed in less permeable zones within the shallow bedrock, zones in which flow is less active and the groundwater geochemistry resembles that of the groundwater at greater depths. Additionally, monitored intervals for each of the Maynardville Limestone wells assigned to Cluster 10 lie near the contact with the Nolichucky Shale.

4.3 SURROGATE CLUSTER ASSIGNMENTS

As described in the preceding sections, wells composing clusters 1, 2, 3, 4, 6, and 10 (uncontaminated clusters) monitor uncontaminated groundwater, and wells composing clusters 5, 7, 8, and 9 (contaminated clusters) monitor groundwater contaminated by nitrate or otherwise affected by industrial activities at the Y-12 Plant. Because reference concentrations were determined only for the uncontaminated clusters (see Sect. 5) and because the Y-12 Plant ER Program needed a method for identifying which of these reference concentrations should be used to evaluate data for wells assigned to the contaminated clusters, a tree-based model was used to designate one of the uncontaminated clusters as a surrogate cluster for each well originally assigned to the contaminated clusters (Fig. 26). Data for these wells could then be evaluated with respect to the reference concentrations for the designated surrogate cluster (see Table 5 for surrogate cluster assignments).

Assignment to a surrogate cluster is straightforward and entails following the decision process laid out in the surrogate cluster tree model (Fig. 26). For example, suppose that well GW-X, originally assigned to Cluster 9, had a midpoint monitoring interval of 120 ft bgs, was completed in the Knox Group, and had a median sodium concentration constituting >75% of the total cations for the well. If the appropriate decision process were followed, well GW-X should be reassigned to its surrogate cluster, Cluster 1. Although GW-X is now a member of Cluster 1, it should be emphasized that median values for GW-X are not used in any way to establish reference values associated with Cluster 1. In fact, the median concentrations of GW-X are compared with the reference values determined by all other (originally assigned or nonsurrogate) wells in Cluster 1 to determine if median values of GW-X can be regarded as reference concentrations or as contamination. In this sense, median values for GW-X in its reassigned Cluster 1 are treated like new well median data that are to be judged as reference concentrations if and only if GW-X's median values fall below the tolerance limits set for Cluster 1.

5. ADDITIONAL DATA SCREENING AND PROBABILITY GRAPHING

The calculation of the tolerance limits or reference concentrations, began with additional data screening and investigation of differences in reported detection limits for unfiltered samples. Results reported as not detected were replaced with a value equal to one-half the detection limit. Median values were then calculated for each unfiltered analyte for each well. Kruskal-Wallis tests were run to test for differences between well clusters in the ranks of the median concentrations of each analyte. If the Kruskal-Wallis test indicated differences, multiple comparison tests were run to determine which well clusters were different from each other. Data from well clusters that could not be distinguished from each other were pooled. Cumulative probability plots were generated to identify and eliminate outlier data. One-sided upper parametric or nonparametric tolerance limits were then calculated, depending on the percentage of median results above the detection limit, the data distribution, and the presence of outliers.

5.1 ELIMINATION OF ADDITIONAL WELLS

Of the ten well clusters identified by the groundwater classification process (Sect. 4), four were defined primarily by high concentrations of either industrial contaminants or nitrate. The identification of distinct contaminated clusters aided efforts to eliminate from reference value calculations any data associated with contaminated wells; a total of 84 wells from the contaminated clusters were eliminated from the study. Also eliminated were 32 wells that had previously been identified in GWQARs as suspect because of known contamination, well construction problems, turbid samples, corrosion of well materials, or improper well installation.

5.2 EVALUATION OF DETECTION LIMITS AND CALCULATION OF WELL MEDIANS

To fulfill assumptions needed for subsequent calculations, we screened the remaining data to identify deviations from normal detection limits. A normal detection limit is the lowest concentration at which a given analytical method can give and has given reliable, quantifiable information. Those rare instances in which data had a detection limit above the normal detection limit for an analyte were assumed to result from sample dilution required to quantify high concentrations. Because high-concentration samples are unlikely to be reference groundwater samples, data with elevated detection limits were eliminated from further analysis. Results reported below the normal detection limit were set to $<x$, where x = the normal detection limit. For example, if the normal detection limit was 0.5 mg/L and a result was reported as 0.4 or <0.4 , then the result was set to <0.5 mg/L.

A wealth of relevant data existed before the initiation of this study. Because the data were not collected to establish reference concentrations but to meet a variety of regulatory compliance needs, all wells are not equally represented in the data set. Some wells were sampled many times over the entire sampling period whereas other wells were sampled infrequently over shorter periods of time (Table 2). If all data were used, the results would be biased by wells that were sampled most frequently.

To ensure that calculations would not be influenced by well bias of extreme values resulting from errors in sampling, laboratory analysis, or data handling, each well's median value for an analyte was used in the calculation of that analyte's reference value. Reference concentrations calculated from median values are directly comparable to median values and are conservative when compared to individual data points. One drawback to the use of median values is that the within-well variance is not included in the estimate of total variance. However, if between-well variance is much greater than the remaining variance, which includes within-well variance, the increment in the variance estimate caused by the within-well variance will be relatively small. For most analytes, analysis of variance tests, run with well identity as the class variable, indicated that the within-well variance was indeed small relative to the between-well variance and would not lead to severe underestimates of variance.

The percentage of nondetected values must be determined to decide whether an upper parametric or nonparametric tolerance limit should be calculated. Because the median analyte value of a well was used in the reference value calculations, it was necessary to determine if the median value was at the detection limit, was between the detection limit and the first detected result, or constituted a detected result. To make this determination, all nondetected values were set to one-half the detection limit before the median value was calculated (e.g., if a result was reported as <0.5 , the value 0.25 was used in the calculation).

5.3 KRUSKAL-WALLIS TESTS AND MULTIPLE COMPARISON TESTS

Kruskal-Wallis tests were run to test for differences between well clusters in the ranks of the median concentrations of each analyte. If differences were found, a nonparametric multiple comparison test (Helsel and Hirsch 1992) was run to determine which well clusters were different. If median concentrations from some clusters could not be statistically distinguished from each other, the data from these clusters were combined for subsequent calculations. Information on the cluster data used is noted in the third column of Table 8. For instance, the Kruskal-Wallis test did not indicate that there were statistically significant differences in the antimony concentrations of the well clusters. On the other hand, this test did find differences in boron concentrations of the well clusters. The multiple comparison test showed that Cluster 1 boron concentrations were different from those of all other clusters; concentrations from Clusters 2 and 4 could not be distinguished from each other but were different from all other clusters; Cluster 3 concentrations were different from those of all other clusters, and concentrations from Clusters 6 and 10 could not be distinguished from each other but were different from all other clusters.

5.4 CUMULATIVE PROBABILITY GRAPHS

Before upper tolerance limits were calculated, cumulative probability graphs were generated for each unfiltered analyte for each cluster or group of clusters. If outliers were identified by visual inspection, these data were eliminated from further calculations. Outlier identification by cumulative probability graphs is important because an analyte's reference concentration cannot be estimated and its tolerance limit cannot be calculated until the analyte's contaminant population is discriminated from its reference population. The key to separating the reference population from the contaminant population is to estimate (visually) the analyte's threshold concentration. A threshold concentration is the midpoint of overlap between the apparent contaminant population and the apparent reference population. Threshold concentrations indicate both the upper limit of reference and the lower limit

of contamination. Methods described in Fleishhauer and Korte (1990) and Sinclair (1976) were used to estimate threshold concentrations graphically by generating cumulative probability graphs for each analyte for each well for each cluster. For example, on the cumulative probability graph for barium in Cluster 2 (Fig. 28), the abscissa scale is arranged in such a manner that the cumulative distribution for barium will plot as a straight line if the data are normally distributed (or lognormally distributed if the data are transformed to their logarithms). [To avoid compressing 99th percentile values that may have up to four decimal places and that make the x-axis difficult to read in Fig. 28, the abscissa is scaled in equally spaced standard normal deviates or expected values, rather than percentages. The population mean is standardized to zero, with up to 3 standard deviations on either side of the mean (encompassing >99.9% of the population). The population median (and mean, if the distribution is symmetrical) will, by definition, correspond to the expected value of zero.]

If outlier or contaminant populations were present in the well data, they were distinguished as relatively high concentration straight-line segments joined at hinge-shaped threshold concentrations to relatively low concentration reference concentrations, such as zinc in Cluster 10 (Fig. 29). Occasionally, because of geochemical processes or extensive contamination, or both, analytes have a relatively large amount of overlap in the contaminant and reference populations. When this occurs, the threshold is not sharp but curved or curvilinear. Identifying a threshold for these kinds of analytes requires expert judgment. For example, the cumulative probability graph for boron in Cluster 1 seems to indicate an elevated outlier population (Fig. 30). The question, however, is where to mark the lower limit of apparent contamination and the upper limit of reference. When curvilinear graphs like this were generated, a conservative approach was employed, and a threshold was marked at or below the point of maximum curvature.

5.5 OUTLIER INTERPRETATIONS AND DISCUSSION

On the basis of visual inspection of the cumulative probability graphs, 154 outliers were identified for 7 major ions (Table 6) and 11 trace metals (Table 7).

Forty-six outliers (in 42 wells) for the major ions (calcium, chloride, fluoride, magnesium, nitrate, sodium, and sulfate) were identified in cumulative probability graphs (Table 6). Overall, the locations of outlier wells for the major ions show no clear relationships to potential source areas of contamination. By far the greatest number of outliers were observed for chloride (28, or 61%), and the bulk of these (21) were associated with data from wells assigned to Cluster 4. As noted in Sect. 4.2.4, Cluster 4 consists almost exclusively of wells completed in the Copper Ridge Dolomite on Chestnut Ridge, a formation of the Knox Group. Many of the elevated chloride values are likely a result of site-related contamination, but the unusually large proportion of outliers for chloride relative to other major ions may have another cause. For example, it is not uncommon during installation of wells in the Copper Ridge Dolomite to lose significant volumes of cement grout (containing chloride) to local solution features. Additionally, chemical additives that also contain chloride salts (e.g., calcium chloride) are often used to accelerate grout hardening and reduce grout losses to the formation. The localized geochemical influence of the grout and the chemical additives may help explain why a high proportion of chloride outliers were determined from data reported for wells assigned to Cluster 4.

In 82 wells, 108 outliers for 11 trace metals were identified in cumulative probability graphs (Table 7). Most outliers were observed in Cluster 1 (52, or 48%) or Cluster 3 (34, or 31%). As with the outliers for major ions, no obvious relationships existed between the location of wells associated

with outliers for trace metals and the locations of known groundwater contamination. Wells with boron outliers were most numerous (53, or 65%), followed distantly by wells with lead outliers (15, or 18%). Of all the outliers, boron is exceptional; it is neither generally recognized as a common nor widespread contaminant in Y-12 Plant groundwater, particularly in Clusters 1 or 3, which include wells that monitor shallow groundwater that is generally characterized by low dissolved solids.

Boron's apparently extensive distribution can be explained at least two ways. First, the cumulative probability plot for boron is markedly curvilinear (Fig. 30), indicating a relatively large amount of overlap between the reference and contaminant populations. Any analyte that expresses this degree of curvature would yield a large number of outliers. This is because identifying a distinct threshold value on plots with high curvature is difficult and requires subjective and expert judgment. The approach used in such cases as boron is to mark the threshold approximately at or slightly below the point of maximum curvature. This approach, while conservative, tends to include a relatively large number of high concentration reference data along with similarly high-concentration contamination data. As a result, a disproportionately larger number of outliers are observed for an analyte such as boron relative to an analyte (e.g., zinc; Fig. 29) with very little overlap and a distinct threshold concentration.

Another reason for the large number of boron outliers is that the cumulative probability plots may be indicating hitherto unknown or undocumented site-related contamination. Although groundwater contamination by boron in the shallow wells of Clusters 1 and 3 is possible, it is also possible that boron contamination could be occurring at any step in the sample collection and laboratory analysis process. For example, the widespread commercial use of boron as an ingredient in lubricants and laboratory detergents and glassware raises the possibility that the elevated levels of boron observed in probability plots might just as likely result from sampling or laboratory contamination as result from environmental contamination.

Further discussion of elevated boron and its impact on the tolerance limit calculation step is given in Sect. 6.2.

6. TOLERANCE LIMITS AND REFERENCE CALCULATIONS

To determine if statistically significant evidence exists that a well is contaminated with a particular analyte, the concentration of the analyte in the well must be measured and compared with a reference concentration. In this study, we chose the upper tolerance limit as the estimate of the reference concentration. The upper tolerance limit is a number indicative of the highest concentration that one would expect to measure in an uncontaminated well. Calculated from reference-well measurements, the upper tolerance limit is the upper limit of the concentration range of an analyte within which a particular proportion (coverage = p) of measurements should fall with a high probability (tolerance coefficient = y). The literature (EPA 1989) on this subject recommends a $p = 95\%$ and $y = 95\%$; that is, one can be 95% confident that 95% of measurements of an analyte taken from reference wells will fall between 0 and the upper tolerance limit. Measurements falling above this limit are considered to be statistically significant evidence that the well is contaminated with that analyte.

6.1 UPPER TOLERANCE LIMIT CALCULATIONS

One-sided upper parametric or nonparametric tolerance limits were calculated, as estimates of reference concentrations, in a manner that was determined by the percentage of median values above the normal detection limit, the distribution of the median values, and the presence of outliers, discussed in Sect. 5.2. The decision flow chart is presented in Fig. 27. If <50% of values were nondetects and if the probability plot generated from the remaining data indicated a normal or lognormal data distribution, values were substituted for nondetects through the use of data distribution information from the detected data obtained from the probability plot (Helsel 1990).

The upper parametric tolerance limit with $p = 95\%$ and $y = 95\%$ is calculated as (EPA 1989):

$$TL = \bar{x} + (k \times s),$$

where

$\bar{x}$ = mean of reference well data,

s = standard deviation of reference well data,

k = tolerance factor found in Table 5, Appendix B.

Upper nonparametric tolerance limits were calculated by a process described in Walpole and Myers (1978). Table 8 presents information used in calculating reference concentrations for all analytes in each cluster. Table 9 summarizes tolerance limits for major ions and trace metals in noncontaminated clusters.

6.2 EVALUATION AND MODIFICATION OF TOLERANCE LIMITS

Cumulative probability graphing and the tolerance limit calculations that are based on it assume (1) that the proportion of wells contaminated with any given analyte is small relative to wells with reference concentrations and (2) that the distribution of data values from the contaminated and uncontaminated wells would not have a high degree of overlap. In general, these conditions exist at most industrial sites (Fleishhauer and Korte 1990). However, when tolerance limits determined in this study were compared with results of previous studies (Table 10), questions arose regarding the appropriateness of the relatively high tolerance limit calculated for boron—particularly for the shallow and low dissolved solids Clusters 1 and 2 (Sect. 5.4). Boron had not been considered a potential contaminant at the Y-12 Plant, but a high degree of scatter at an apparent threshold near the 50th percentile, or median, of the probability graph (Fig. 28) indicated that the occurrence of boron as a contaminant in the groundwater may be fairly ubiquitous and that the distribution of boron in the contaminated and uncontaminated wells may significantly overlap.

Probability graphs for all analytes were reevaluated with the objective of finding other analytes that, like boron, appeared to violate the assumptions that underlie the study's approach. Most analytes appeared to meet the study's assumptions; however, 29 of a total of 99 tolerance limits were reconsidered. On the basis of a visual inspection of the cumulative probability graphs, 17 of the 29 reconsidered tolerance limits were recalculated. The tolerance limits resulting from the recalculations were lower than those originally estimated. A decrease would be expected, however, because variance estimates decreased or data at the high concentration end of the distribution were deleted, or both.

7. SUMMARY AND CONCLUSIONS

Reference conditions are critical to any groundwater contamination study because they (1) help establish criteria for characterizing the extent and severity of contamination, (2) furnish a basis for conducting baseline risk assessments, and (3) provide criteria for the cleanup of contaminated groundwater. As important as these goals are, groundwater contamination studies often neglect to thoroughly evaluate representative background or reference conditions against which the severity and extent of contamination can be judged. The objectives of the Y-12 Plant groundwater reference study were (1) to develop a technically defensible and cost-effective methodology that implements a site-wide data-analysis approach and (2) to establish groundwater reference concentrations for inorganics and trace metals that can be used by the Y-12 Plant Environmental Restoration Program for risk assessments or other cleanup activities. Reference concentrations for radiological contaminants were not addressed in this study.

The study was conducted in four steps: (1) data set assembly, screening, and evaluation; (2) water-quality classification and hydrogeochemical analysis; (3) additional data screening and probability graphing; and (4) tolerance limit and reference concentration calculations. The available data consisted of major and minor ion and trace metal chemistry based on >4400 water-quality observations from 430 monitoring wells at the Y-12 Plant. Samples were collected over the period 1986 to 1993.

As a guide to all statistical and interpretive analyses, a hydrogeologic and geochemical conceptual model, or framework, was used to provide insight into the ranges of reference concentrations that will or should occur in Y-12 Plant groundwater in the absence of contamination (Solomon et al. 1992).

Principal component and cluster analyses were used to identify groupings or clusters of wells with similar geochemical signatures. Ten distinct clusters were identified. Six well clusters closely corresponded to the geochemical framework and to observed water-quality regimes in groundwater at the Y-12 Plant. Four clusters were associated with nitrate, an S-3 Site contaminant, or with nonspecific contaminants that are commonly encountered at shallow depths at industrial sites (e.g., road salt). These analyses effectively distinguished the following groundwater types at the Y-12 Plant:

- Intermediate-depth (100 to 200 ft bgs) groundwater of the Knox Group (Cluster 4) was clearly distinguished from shallow groundwater of the Maynardville Limestone (Cluster 1), from shallow recharge or water-table interval groundwater (Cluster 2), and from shallow groundwater of the Maryville Limestone/Nolichucky Shale (Cluster 3).
- Two types of groundwater from the Nolichucky Shale were clearly distinguished: An intermediate-depth sodium-bicarbonate groundwater (Cluster 10) and the deep (>400 ft bgs) sodium-chloride-bicarbonate water characteristic of the low permeability bedrock of the ORR Aquitard (Cluster 6). The intermediate-depth sodium-bicarbonate groundwater of Cluster 10 is interpreted as a geochemical zone that is transitional between the water quality, indicating both relatively shallow groundwater and groundwater from the deep ORR Aquitard.

- Three clusters identified wells known to contain significant levels of nitrate contamination associated with the S-3 Site (Clusters 7, 8, and 9). The degree of nitrate contamination of wells in these clusters is generally a function of the distance of a given well from the S-3 Site. Nitrate contamination dominates the geochemistry of the Cluster 9 wells. The geochemistry of the wells in Clusters 7 and 8 is less affected by nitrate contamination.
- One cluster (Cluster 5) identified wells monitoring shallow (<50 ft bgs) groundwater that is apparently affected by a wide and generally uncharacterized suite of common industrial substances and contaminants (e.g., road salt, sulfate-containing chemicals). As a result of the influences of these industrial materials, Cluster 5 lacks a strong geochemical signature but is most closely related to the shallow water geochemistry of Clusters 1, 2, and 3.

As a final step in the statistical classification of the Y-12 Plant groundwater, a tree-based model was developed that, on the basis of data from a water sample, could assign a given well to a cluster. The Y-12 Plant groundwater tree model was a useful data visualization tool that elucidated the complex geochemical relationships among clusters.

Following groundwater classification, additional data screening was conducted to remove data from wells that appeared to be dominated by the presence of nitrate (wells in Clusters 7, 8, and 9) or that may have had other contamination problems. All data below the normal detection limit for an analyte were assigned a value of one-half the normal detection limit. Median values for each unfiltered analyte for each well were calculated to eliminate sample bias introduced by over sampling at some wells and extreme values caused by errors in sampling, analysis, or data handling. Krusal-Wallis and multiple comparison tests were run to determine if and how cluster data could be pooled. Cumulative probability graphs were then used within each cluster to distinguish contaminated or contamination-affected wells from wells that exhibited ambient water quality. Only the median values of unfiltered samples were plotted. Reference concentration was set at the upper 95% tolerance limit of the reference population.

In general, the proportion of wells contaminated with any analyte was small, and the distribution of data values for the contaminated and uncontaminated wells exhibited little overlap. On the basis of visual inspection of the cumulative probability graphs, 46 outliers were identified for 7 major ions. For 11 trace metals, 108 outliers were identified. No obvious relationships existed between the location of wells associated with the major ion outliers and the locations of known groundwater contamination. Of the 46 outliers for the major ions, the greatest number of outliers were observed for chloride (28, or 61%), and the bulk of these (21) were associated with data from wells assigned to Cluster 4 (Knox Group). The large number of outliers for chloride seems to indicate not only the widespread distribution of this very soluble contaminant in Y-12 Plant groundwaters but also may indicate the residue of large amounts of chloride-containing grout that may have been lost to solutional features in the Copper Ridge Dolomite during well installation.

Similarly, no obvious relationships existed between the location of wells associated with the 108 trace metal outliers and the locations of known groundwater contamination. Wells with boron outliers were the most numerous (53, or 65%), followed distantly by wells with lead outliers (15, or 18%). Boron outliers were most frequent in Cluster 1 (52, or 48%) and Cluster 3 (34, or 31%). The occurrence of elevated levels of boron in Clusters 1 and 3, which include wells that monitor shallow groundwater, is apparently anomalous and may indicate (1) hitherto unknown or undocumented site-related boron contamination or (2) boron contamination occurring somewhere in the sample collection or laboratory analysis process.

On the basis of the apparently anomalous behavior of boron, cumulative probability graphs for all analytes were reevaluated, and 29 of a total of 99 tolerance limits were reconsidered. Of the 29 reevaluated analytes, 17 tolerance limits were recalculated. The tolerance limits resulting from the recalculations were lower than those originally estimated; this discrepancy was anticipated because variance estimates decreased or data at the high concentration end of the distribution were deleted, or both.

In general, combining the methodologies of cluster analysis and cumulative probability plotting proved very useful in setting reference concentrations that are free of discernable contamination and that are representative of groundwater. The case of boron illustrates both the utility of and the limitation of the procedures used in this study. Had the data not been grouped and plotted on a cluster-by-cluster basis, the apparently anomalous behavior of boron would not have been noticed. However, because of the large amount of scatter inherent in the boron data that, in part, gave rise to the large number of outliers, only limited confidence can be attached to the tolerance limit that was calculated for this trace metal. This situation suggests that analysts may have to accept a balance between the use of these techniques to explore data trends vs the use of these techniques to determine reference concentrations.

Future studies of reference concentrations in groundwater at the Y-12 Plant should focus on the more problematic analytes such as boron. In addition, detailed comparisons should be made between previous reference concentrations calculated from an upgradient subset of all wells and reference concentrations calculated from all wells, as were used in this study.

8. REFERENCES

- Carlson, T. 1994. *Background levels at Lawrence Livermore National Laboratory*. Site 300. pp. 2. "In Abstracts of the Sixth National Technology Information Exchange Workshop." U.S. Department of Energy, Office of Environmental Restoration, Kennewick, Wash.
- Clark, L. A., and D. Pregibon. 1992. *Tree-based models*. pp. 377-419. In J. M. Chambers and T. J. Hastie (eds.), *Statistical Models*. S. Wadsworth & Brooks/Cole, Pacific Grove, Calif.
- Davis, C. B. , 1994. *Environmental regulatory statistics*. pp. 817-864. In G. P. Pain and C. R. Roa (eds.), *Environmental statistics*. Elsevier Science B.V., Amsterdam, The Netherlands.
- Dreier, R. B., D. K. Solomon, and C. M. Beaudoin. 1987. *Fracture characterization in the unsaturated zone of a shallow land burial facility*. "In Flow and Transport through Fractured Rock." Am. Geophys. Union Monogr. 42.
- EPA (U.S. Environmental Protection Agency). 1989. *Statistical analysis of groundwater monitoring data at RCRA facilities—Interim final guidance*. EPA/530/SW/89/026.
- EPA (U.S. Environmental Protection Agency). 1993a. *RCRA draft technical guidance for groundwater monitoring*. EPA/530/R/93/001.
- EPA (U.S. Environmental Protection Agency). 1993b. *Statistical analysis of groundwater monitoring data at RCRA facilities—Addendum to interim final guidance*. EPA/530/R/SW/93/003.
- EPA (U.S. Environmental Protection Agency). 1994. *Soil screening guidance*. EPA/540/R-94/101.
- Fleischhauer, H. L., and N. Korte. 1990. "Formulation of cleanup standards for trace elements with probability plots." *Environ. Manage.* 14(1):95-105.
- Fowlkes, E. B., R. Gnanadesikan, and J. R. Kettenring. 1988. "Variable selection in clustering." *J. Classif.* 4:205-28.
- Freeze, R. A., and J. Cherry. 1979. *Groundwater*. Prentice Hall, Englewood Cliffs, N.J.
- Geraghty & Miller, Inc. 1986. *Aquifer test data and design of recovery wells, S-3 Ponds*. Y/SUB/86-00206C/2. Prepared for Martin Marietta Energy Systems, Inc., Oak Ridge, Tenn.
- Geraghty & Miller, Inc. 1987. *Hydrogeologic investigations of the S-3 Ponds area at the Y-12 Plant*. Y/SUB/87-002606C/18. Prepared for Martin Marietta Energy Systems, Inc., Oak Ridge, Tenn.
- Geraghty & Miller, Inc. 1989a. *Development of groundwater flow models for the S-3 waste-management area, Y-12 Plant, Oak Ridge, Tennessee*. Y/SUB/89-00206C/1. Prepared for Martin Marietta Energy Systems, Inc., Oak Ridge, Tenn.

- Geraghty & Miller, Inc. 1989b. *Tracer study of the hydrologic system of Upper Bear Creek, Y-12 Plant, Oak Ridge, Tennessee*. Y/SUB/89-00206C/4. Prepared for Martin Marietta Energy Systems, Inc., Oak Ridge, Tenn.
- Geraghty & Miller, Inc. 1990. *Comprehensive groundwater monitoring plan for the Department of Energy Y-12 Plant*. Y/SUB/90-00206C/5. Prepared for Martin Marietta Energy Systems, Inc., Oak Ridge, Tenn.
- Golder Associates, Inc. 1987. *Aquifer pump tests with tracers*. ORNL/SUB/86-3213612. Prepared for Martin Marietta Energy Systems, Inc.
- Golder Associates, Inc. 1988. *Final report on contaminant transport model validation: Site characterization and groundwater flow computer model application*. Prepared for Martin Marietta Energy Systems, Inc.
- Helsel, D. R. 1990. "Less than obvious: Statistical treatment of data below the detection limit." *Environ. Sci. Technol.* 24:1766-74.
- Helsel, D. R., and R. M. Hirsch. 1992. *Statistical Methods in Water Resources*. Elsevier, Amsterdam.
- HSW Environmental Consultants, Inc. 1992. *Groundwater quality assessment for the Bear Creek Hydrogeologic Regime at the Y-12 Plant: 1991 groundwater quality data interpretations and proposed program modifications*. Y/SUB/92-YP507C/1/P2. Prepared for Martin Marietta Energy Systems, Inc., Oak Ridge, Tenn.
- HSW Environmental Consultants, Inc. 1995. *Calendar year 1994 groundwater quality assessment report for the Bear Creek Hydrogeologic Regime at the Y-12 Plant, 1994 groundwater quality interpretations and proposed program modifications*. Y/SUB/95-EAQ10C/1/P2. Prepared for Lockheed Martin Energy Systems, Inc., Oak Ridge, Tenn.
- Joliffe, I. T. 1986. *Principal Component Analysis*. Springer-Verlag, New York.
- Keith, L. H. (ed.). 1988. *Principles of Environmental Sampling*. American Chemical Society,
- King, H. L., and C. S. Haase. 1987. *Subsurface-controlled geological maps for the Y-12 Plant and adjacent areas of Bear Creek Valley*. ORNL/TM-10112. Oak Ridge National Laboratory, Oak Ridge, Tenn.
- LaGore, T. 1994. *Sitewide background data applications methodology*. p. 24. "In Abstracts of the Sixth National Technology Information Exchange Workshop." U.S. Department of Energy, Office of Environmental Restoration, Kennewick, Wash.
- Law Engineering Testing Company. 1983. *Results of groundwater monitoring studies*. Y/SUB/83-47936/1. Prepared for Union Carbide Corporation, Nuclear Division.
- McBean, E. A., and F. A. Rovers. 1992. "Estimation of the probability of exceedance of contaminant concentrations." *Ground Water Monit. Rev.* Winter:115-19.

- Meyers, J. 1994. *Background concentrations of naturally occurring constituents of concern at Sandia National Laboratories*. pp. 4. In Abstracts of the Sixth National Technology Information Exchange Workshop. U.S. Department of Energy, Office of Environmental Restoration, Kennewick, Wash.
- Moore, G. K. 1988. *Concepts of Groundwater Occurrence and Flow Near Oak Ridge National Laboratory*. ORNL/TM-10969. Oak Ridge National Laboratory, Oak Ridge, Tenn.
- Moore, G. K. 1989. *Groundwater parameters and flow system near Oak Ridge National Laboratory*. ORNL/TM-11368. Oak Ridge National Laboratory, Oak Ridge, Tenn.
- Moore, G. K., and L. E. Toran. 1992. *Supplement to a hydrogeologic framework for the Oak Ridge Reservation, Oak Ridge, Tennessee*. ORNL/TM-12191. Oak Ridge National Laboratory, Oak Ridge, Tenn.
- Moss, P. D. 1994. Letter from P. D. Moss, Science Applications International Corporation, to J. Hodges, Martin Marietta Energy Systems, Inc., dated July 19, 1994.
- Shevenell, L. A., R. B. Dreier, and W. R. Jago. 1993. *Summary of fiscal year 1991 and 1992 construction, hydrologic, and geologic data obtained from the Maynardville Limestone Exit Pathway Monitoring Program*. Y/TS-814. Oak Ridge National Laboratory, Oak Ridge, Tenn.
- Sinclair, A. J. 1976. *Applications of probability graphs in mineral exploration: Special volume 4*. Association of Exploration Geochemists, Richmond, British Columbia, Canada.
- Sledz, J. S., and D. D. Huff. 1981. *Computer model for determining fracture porosity and permeability in the Conasauga Group, Oak Ridge National Laboratory, Tennessee*. ORNL/TM-7695. Oak Ridge National Laboratory, Oak Ridge, Tenn.
- Solomon, H. 1977. *Data dependent clustering techniques*. pp. 155-73. In J. Van Ryzin (ed.), *Classification and Clustering*. Academic Press, Inc., New York.
- Solomon, D. K., G. K. Moore, L. E. Toran, R. B. Dreier, and W. M. McMaster. 1992. *Status report: A hydrologic framework for the Oak Ridge Reservation*. ORNL/TM-12026. Oak Ridge National Laboratory, Oak Ridge, Tenn.
- Walpole, Ronald E. and R. H. Meyers. 1978. *Probability statistics for engineers and scientists*, 2nd edition, MacMillan, New York.

Appendix A

FIGURES

FIGURE 1
HYDROGEOLOGIC REGIMES
AT THE OAK RIDGE
Y-12 PLANT.

LOCATION:	Y-12 PLANT OAK RIDGE, TN
DATE:	2/14/96
DWG ID.:	OR321-HC

SOURCE: King, H. L., and C. S. Hoase, 1987. Subsurface-controlled geological maps for the Y-12 Plant and adjacent areas of Bear Creek Valley. ORNL/TM-10112. Oak Ridge National Laboratory, Oak Ridge, Tenn.

SYSTEM GROUP	HYDRO UNIT	FORMATION	MAP SYMBOL	THICKNESS (ft)
CAMBRIAN	UPPER	COPPER RIDGE DOLOMITE	Ock	NOT DETERMINED
	MIDDLE	MAYNARDVILLE LIMESTONE	Cmn	418-450
CONASAUGA	RESERVATION AQUITARDS	NOLCHUCKY SHALE	Cn	422-550
		MARYVILLE LIMESTONE	Cm	346-445
		ROGERSVILLE SHALE	Crg	90-120
		ROUTEVILLE LIMESTONE	Crt	90-120
		PUMPKIN VALLEY SHALE	Cpv	260-320
LOWER		ROME	Cr	NOT DETERMINED

FIGURE 2

TOPOGRAPHY AND BEDROCK GEOLOGY
AT THE OAK RIDGE
Y-12 PLANT.

LOCATION:	Y-12 PLANT OAK RIDGE, TN
DATE:	2/14/96
DWG ID.:	OR006-HC

PROPOSED HYDROSTRATIGRAPHIC UNITS *

* Proposed by Solomon, D. K., G. K. Moore, L. E. Toran, R. B. Dreier, and W. M. McMaster. 1994. Status report: A hydrologic framework for the Oak Ridge Reservation. ORNL/TM-12026. Oak Ridge National Laboratory, Oak Ridge, Tenn.

Approximate depths are for Oak Ridge Reservation Aquitards; depths in the Knox Aquifer will be greater.

Drawing is not to scale.

LOCATION:	Y-12 PLANT OAK RIDGE, TN	FIGURE 3 SCHEMATIC PROFILE OF HYDROGEOLOGIC UNITS AT THE OAK RIDGE Y-12 PLANT.
	DATE: 2/14/95	
	DWG ID.: OR007-HC

LOCATION:		Y-12 PLANT OAK RIDGE, TN	FIGURE 4 OVERVIEW OF METHODOLOGY.
DATE:		2/14/96	
DWG ID.:		ORG3

LOCATION:	Y-12 PLANT OAK RIDGE, TN	FIGURE 5 ORIGINAL CLUSTER ASSIGNMENT MODEL.
DATE:	2/14/96	
DWG ID.:	OR465-HC

SYSTEM GROUP	CAMBRIAN			ORDOVICIAN			HYDRO UNIT	FORMATION	MAP SYMBOL	THICKNESS (ft)
	LOWER	MIDDLE	UPPER	LOWER	MIDDLE	UPPER				
		CONASAUGA		KNOX		CHICKAMAUGA	OAK RIDGE RESERVATION AQUITARDS	CHICKAMAUGA (Undifferentiated)	Och	1500-2000
		OAK RIDGE RESERVATION AQUITARDS		KNOX AQUIFER		MISSING SECTION (Subaerial Erosion)		KNOX (Undifferentiated)	Ock	2500-3000
			MAYNARDVILLE LIMESTONE						Cmn	418-450
			NOLCHUCKY SHALE						Cn	422-550
			MARYVILLE LIMESTONE						Cm	346-445
			ROGERSVILLE SHALE						Crg	90-120
			RUTLEDGE LIMESTONE						Crl	90-120
			PUMPKIN VALLEY SHALE						Cpv	260-320
			ROME						Cr	NOT DETERMINED

EXPLANATION

- — LESS THAN 100 FT DEEP
- — 100 TO 400 FT DEEP
- — GREATER THAN 400 FT DEEP
- ▼ — UNDEFINED DEPTH
- - - - - APPROXIMATE GEOLOGIC CONTACT

LOCATION: Y-12 PLANT OAK RIDGE, TN		FIGURE 6	
DATE:	2/14/96	LOCATION OF CLUSTER 1 WELLS (SHALLOW GROUNDWATER).	
DWG ID.:	MAPONE

EXPLANATION

- — LESS THAN 100 FT DEEP
- — 100 TO 400 FT DEEP
- — GREATER THAN 400 FT DEEP
- ▲ — UNDEFINED DEPTH

LOCATION:	Y-12 PLANT OAK RIDGE, TN	FIGURE 7 GEOCHEMISTRY OF GROUNDWATER MONITORED BY CLUSTER 1 WELLS.
DATE:	2/14/96	
DWG ID.:	2P1

EXPLANATION

- — LESS THAN 100 FT DEEP
- — 100 TO 400 FT DEEP
- — GREATER THAN 400 FT DEEP
- ▲ — UNDEFINED DEPTH
- - - - - APPROXIMATE GEOLOGIC CONTACT

LOCATION:	Y-12 PLANT OAK RIDGE, TN	FIGURE 8 LOCATION OF CLUSTER 2 WELLS (RECHARGE GROUNDWATER).
DATE:	2/14/96	
DWG ID.:	MAPTWO

SYSTEM	GROUP	HYDRO UNIT	FORMATION	MAP SYMBOL	THICKNESS (ft)
ORDOVICIAN	UPPER	CHICKAMAUGA	CHICKAMAUGA (Undifferentiated)	Och	1500-2000
	MIDDLE		MISSING SECTION (Subaerial Erosion)		
	LOWER	KNOX	KNOX (Undifferentiated)	Ock	2500-3000
CAMBRIAN	UPPER	OAK RIDGE RESERVATION AQUITARDS	MAYNARDVILLE LIMESTONE	Cmn	418-450
	MIDDLE		NOLICHUCKY SHALE	Cn	422-550
	MIDDLE	OAK RIDGE RESERVATION AQUITARDS	MARYVILLE LIMESTONE	Cm	346-445
			ROGERSVILLE SHALE	Crg	90-120
			RUTLEDGE LIMESTONE	Crl	90-120
			PUMPKIN VALLEY SHALE	Cpv	260-320
	LOWER		ROME	Cr	NOT DETERMINED

EXPLANATION

- — LESS THAN 100 FT DEEP
- — 100 TO 400 FT DEEP
- — GREATER THAN 400 FT DEEP
- ▲ — UNDEFINED DEPTH

FIGURE 9

GEOCHEMISTRY OF GROUNDWATER
MONITORED BY CLUSTER 2 WELLS.

LOCATION:	Y-12 PLANT OAK RIDGE, TN
DATE:	2/14/96
DWG ID.:	2P2

EXPLANATION

- — LESS THAN 100 FT DEEP
- — 100 TO 400 FT DEEP
- — GREATER THAN 400 FT DEEP
- ▲ — UNDEFINED DEPTH
- - - - - APPROXIMATE GEOLOGIC CONTACT

LOCATION:	Y-12 PLANT OAK RIDGE, TN	FIGURE 10 LOCATION OF CLUSTER 3 WELLS (SHALLOW GROUNDWATER).
DATE:	2/14/96	
DWG ID.:	MAPTHREE

SYSTEM	GROUP	HYDRO UNIT	FORMATION	MAP SYMBOL	THICKNESS (ft)
ORDOVICIAN	UPPER	CHICKAMAUGA	OAK RIDGE RESERVATION AQUITARDS	Ch	1500-2000
	MIDDLE		MISSING SECTION (Subaerial Erosion)		
	LOWER	KNOX	KNOX (Undifferentiated)	Oek	2500-3000
CAMBRIAN	UPPER	CONASAUGA	MAYNARDVILLE LIMESTONE	Emn	418-450
	MIDDLE		NOLICHUCKY SHALE	En	422-550
	MIDDLE		MARYVILLE LIMESTONE	Em	346-445
	LOWER	OAK RIDGE RESERVATION AQUITARDS	ROGERSVILLE SHALE	Erg	90-120
			RUTLEDGE LIMESTONE	Ert	90-120
			PUMPKIN VALLEY SHALE	Epv	260-320
			ROME	Er	NOT DETERMINED

FIGURE 11

**GEOCHEMISTRY OF GROUNDWATER
MONITORED BY CLUSTER 3 WELLS.**

LOCATION:	Y-12 PLANT OAK RIDGE, TN
DATE:	2/14/96
DWG ID.:	2P3

11

11

EXPLANATION

- — LESS THAN 100 FT DEEP
- — 100 TO 400 FT DEEP
- — GREATER THAN 400 FT DEEP
- ▲ — UNDEFINED DEPTH
- - - - - APPROXIMATE GEOLOGIC CONTACT

LOCATION:	Y-12 PLANT OAK RIDGE, TN	FIGURE 12 LOCATION OF CLUSTER 4 WELLS (KNOX GROUP GROUNDWATER).
DATE:	2/14/96	
DWG ID.:	MAPFOUR

SYSTEM	GROUP	HYDRO UNIT	FORMATION	MAP SYMBOL	THICKNESS (ft)
ORDOVICIAN	UPPER	CHICKAMAUGA	OAK RIDGE RESERVATION AQUITARDS	Och	1500-2000
	MIDDLE				
	LOWER	KNOX	KNOX AQUIFER	Ock	2500-3000
CAMBRIAN	UPPER	CONASAUGA	MAYNARDVILLE LIMESTONE	Cmn	418-450
	MIDDLE		NOLICHUCKY SHALE	Cn	422-550
			MARYVILLE LIMESTONE	Cm	346-445
			ROGERSVILLE SHALE	Crg	90-120
			RUTLEDGE LIMESTONE	Crt	90-120
			PUMPKIN VALLEY SHALE	Cpv	260-320
	LOWER			ROME	Cr

EXPLANATION

- — LESS THAN 100 FT DEEP
- — 100 TO 400 FT DEEP
- — GREATER THAN 400 FT DEEP
- ▲ — UNDEFINED DEPTH

LOCATION:	Y-12 PLANT OAK RIDGE, TN	FIGURE 13 GEOCHEMISTRY OF GROUNDWATER MONITORED BY CLUSTER 4 WELLS.
DATE:	2/14/96	
DWG ID.:	2P4

EXPLANATION

- — LESS THAN 100 FT DEEP
- — 100 TO 400 FT DEEP
- — GREATER THAN 400 FT DEEP
- ▲ — UNDEFINED DEPTH
- — APPROXIMATE GEOLOGIC CONTACT

FIGURE 14

LOCATION OF CLUSTER 5 WELLS
(INDUSTRIALLY CONTAMINATED GROUNDWATER).

LOCATION:	Y-12 PLANT OAK RIDGE, TN
DATE:	2/14/96
DWG ID.:	MAPFIVE

EXPLANATION

- — LESS THAN 100 FT DEEP
- — 100 TO 400 FT DEEP
- — GREATER THAN 400 FT DEEP
- ▲ — UNDEFINED DEPTH

LOCATION:

Y-12 PLANT
OAK RIDGE, TN

DATE:

2/14/96

DW ID.:

2P5

FIGURE 15

**GEOCHEMISTRY OF GROUNDWATER
MONITORED BY CLUSTER 5 WELLS.**

SYSTEM	GROUP	HYDRO UNIT	FORMATION	MAP SYMBOL	THICKNESS (ft)
ORDOVICIAN	UPPER	CHICKAMAUGA	CHICKAMAUGA (Undifferentiated)	Och	1500-2000
	MIDDLE		MISSING SECTION (Subaerial Erosion)		
	LOWER	KNOX	KNOX (Undifferentiated)	Ock	2500-3000
CAMBRIAN	UPPER	OAK RIDGE RESERVATION AQUITARDS	MAYNARDVILLE LIMESTONE	Cmn	418-450
	MIDDLE		NOLICHUCKY SHALE	Cn	422-550
	MIDDLE	OAK RIDGE RESERVATION AQUITARDS	MARYVILLE LIMESTONE	Cm	346-445
			ROGERSVILLE SHALE	Crg	90-120
			RUTLEDGE LIMESTONE	Crt	90-120
			PUMPKIN VALLEY SHALE	Cpv	260-320
	LOWER		ROME	Cr	NOT DETERMINED

EXPLANATION

- — LESS THAN 100 FT DEEP
- — 100 TO 400 FT DEEP
- — GREATER THAN 400 FT DEEP
- ▲ — UNDEFINED DEPTH
- - - - - APPROXIMATE GEOLOGIC CONTACT

FIGURE 16

LOCATION OF CLUSTER 6 WELLS
(SODIUM-CHLORIDE-BICARBONATE GROUNDWATER).

LOCATION:	Y-12 PLANT OAK RIDGE, TN	FIGURE 16 LOCATION OF CLUSTER 6 WELLS (SODIUM-CHLORIDE-BICARBONATE GROUNDWATER).
DATE:	2/14/96	
DWG ID.:	MAP16

SYSTEM	GROUP	HYDRO UNIT	FORMATION	MAP SYMBOL	THICKNESS (ft)
ORDOVICIAN	UPPER	CHICKAMAUGA	CHICKAMAUGA (Undifferentiated)	Och	1500-2000
	MIDDLE		MISSING SECTION (Subaerial Erosion)		
	LOWER	KNOX	KNOX (Undifferentiated)	Ock	2500-3000
CAMBRIAN	UPPER	OAK RIDGE RESERVATION AQUITARDS	MAYNARDVILLE LIMESTONE	Cmn	418-450
	MIDDLE		NOLICHUCKY SHALE	Cn	422-550
	MIDDLE	OAK RIDGE RESERVATION AQUITARDS	MARYVILLE LIMESTONE	Cm	346-445
			ROGERSVILLE SHALE	Crg	90-120
			RUTLEDGE LIMESTONE	Crt	90-120
			PUMPKIN VALLEY SHALE	Cpv	260-320
	LOWER		ROME	Cr	NOT DETERMINED

EXPLANATION

- — LESS THAN 100 FT DEEP
- — 100 TO 400 FT DEEP
- — GREATER THAN 400 FT DEEP
- ▲ — UNDEFINED DEPTH

FIGURE 17

GEOCHEMISTRY OF GROUNDWATER
MONITORED BY CLUSTER 6 WELLS.

LOCATION:	Y-12 PLANT OAK RIDGE, TN
DATE:	2/14/96
DWG ID.:	2P6

EXPLANATION

- — LESS THAN 100 FT DEEP
- — 100 TO 400 FT DEEP
- — GREATER THAN 400 FT DEEP
- ▲ — UNDEFINED DEPTH
- - - - - APPROXIMATE GEOLOGIC CONTACT

LOCATION:	Y-12 PLANT OAK RIDGE, TN	FIGURE 18 LOCATION OF CLUSTER 7 WELLS (NITRATE-CONTAMINATED GROUNDWATER).
DATE:	2/14/96	
DWG ID.:	MAP17

SYSTEM	GROUP	HYDRO UNIT	FORMATION	MAP SYMBOL	THICKNESS (ft)
ORDOVICIAN	UPPER	CHICKAMAUGA	CHICKAMAUGA (Undifferentiated)	Och	1500-2000
	MIDDLE		MISSING SECTION (Subaerial Erosion)		
	LOWER	KNOX	KNOX (Undifferentiated)	OEk	2500-3000
CAMBRIAN	UPPER	OAK RIDGE RESERVATION AQUITARDS	MAYNARDVILLE LIMESTONE	Cmn	418-450
	MIDDLE		NOLICHUCKY SHALE	Cn	422-550
	MIDDLE	OAK RIDGE RESERVATION AQUITARDS	MARYVILLE LIMESTONE	Cm	346-445
			ROGERSVILLE SHALE	Crg	90-120
			RUTLEDGE LIMESTONE	Crl	90-120
			PUMPKIN VALLEY SHALE	Cpv	260-320
	LOWER		ROME	Cr	NOT DETERMINED

SYSTEM	GROUP	HYDRO UNIT	FORMATION	MAP SYMBOL	THICKNESS (ft)		
ORDOVICIAN	UPPER	CHICKAMAUGA	OAK RIDGE RESERVATION AQUITARDS	Chickamauga (Undifferentiated)	Och	1500-2000	
	MIDDLE			MISSING SECTION (Subaerial Erosion)			
	LOWER	KNOX	KNOX AQUIFER	KNOX (Undifferentiated)	Ock	2500-3000	
CAMBRIAN	UPPER	CONASAUGA		MAYNARDVILLE LIMESTONE	Cmn	418-450	
	MIDDLE			NOLICHUCKY SHALE	Cn	422-550	
				MARYVILLE LIMESTONE	Cm	346-445	
				ROGERSVILLE SHALE	Crg	90-120	
				RUTLEDGE LIMESTONE	Crt	90-120	
				PUMPKIN VALLEY SHALE	Cpv	260-320	
	LOWER				ROME	Cr	NOT DETERMINED

EXPLANATION

- — LESS THAN 100 FT DEEP
- — 100 TO 400 FT DEEP
- — GREATER THAN 400 FT DEEP
- ▲ — UNDEFINED DEPTH
- - - - - APPROXIMATE GEOLOGIC CONTACT

LOCATION:	Y-12 PLANT OAK RIDGE, TN	FIGURE 19	
DATE:	2/14/96	LOCATION OF CLUSTER 8 WELLS (NITRATE-CONTAMINATED GROUNDWATER).	
DWG ID.:	-MAPEIGHT

EXPLANATION

- — LESS THAN 100 FT DEEP
- — 100 TO 400 FT DEEP
- — GREATER THAN 400 FT DEEP
- ▲ — UNDEFINED DEPTH
- - - - - APPROXIMATE GEOLOGIC CONTACT

LOCATION:	Y-12 PLANT OAK RIDGE, TN	FIGURE 20
DATE:	2/14/96	LOCATION OF CLUSTER 9 WELLS (NITRATE-CONTAMINATED GROUNDWATER).
DWG ID.:	MAP19

SYSTEM	GROUP	HYDRO UNIT	FORMATION	MAP SYMBOL	THICKNESS (ft)
ORDOVICIAN	UPPER	CHICKAMAUGA	CHICKAMAUGA (Undifferentiated)	Och	1500-2000
	MIDDLE		MISSING SECTION (Subaerial Erosion)		
	LOWER	KNOX	KNOX (Undifferentiated)	Ock	2500-3000
CAMBRIAN	UPPER	OAK RIDGE RESERVATION AQUITARDS	MAYNARDVILLE LIMESTONE	Cmn	418-450
	MIDDLE		NOLICHUCKY SHALE	Cn	422-550
			MARYVILLE LIMESTONE	Cm	346-445
			ROGERSVILLE SHALE	Crg	90-120
			RUTLEDGE LIMESTONE	Crt	90-120
			PUMPKIN VALLEY SHALE	Cpv	260-320
	LOWER		ROME	Cr	NOT DETERMINED

EXPLANATION

- — LESS THAN 100 FT DEEP
- — 100 TO 400 FT DEEP
- — GREATER THAN 400 FT DEEP
- ▲ — UNDEFINED DEPTH

FIGURE 21

GEOCHEMISTRY OF GROUNDWATER
MONITORED BY CLUSTER 7 WELLS.

LOCATION: Y-12 PLANT
OAK RIDGE, TN

DATE: 2/14/96

DWG ID.: 2P7

A-24

EXPLANATION

- — LESS THAN 100 FT DEEP
- — 100 TO 400 FT DEEP
- — GREATER THAN 400 FT DEEP
- ▲ — UNDEFINED DEPTH

FIGURE 22

GEOCHEMISTRY OF GROUNDWATER
MONITORED BY CLUSTER 8 WELLS.

A-25

EXPLANATION

- — LESS THAN 100 FT DEEP
- — 100 TO 400 FT DEEP
- — GREATER THAN 400 FT DEEP
- ▲ — UNDEFINED DEPTH

FIGURE 23

GEOCHEMISTRY OF GROUNDWATER
MONITORED BY CLUSTER 9 WELLS.

LOCATION:	Y-12 PLANT OAK RIDGE, TN
DATE:	2/14/96
DWG ID.:	2P9

EXPLANATION

- — LESS THAN 100 FT DEEP
- — 100 TO 400 FT DEEP
- — GREATER THAN 400 FT DEEP
- ▼ — UNDEFINED DEPTH
- - - - - APPROXIMATE GEOLOGIC CONTACT

LOCATION:	Y-12 PLANT OAK RIDGE, TN	FIGURE 24 LOCATION OF CLUSTER 10 WELLS (SODIUM-BICARBONATE GROUNDWATER).
DATE:	2/14/96	
DWG ID.:	MAP20

SYSTEM	GROUP	HYDRO UNIT	FORMATION	MAP SYMBOL	THICKNESS (ft)
ORDOVICIAN	UPPER	CHICKAMAUGA	OAK RIDGE RESERVATION AQUITARDS	Och	1500-2000
	MIDDLE		MISSING SECTION (Subaerial Erosion)		
	LOWER	KNOX	KNOX (Undifferentiated)	Ock	2500-3000
CAMBRIAN	UPPER	CONASAUGA	MAYNARDVILLE LIMESTONE	Cmn	418-450
	MIDDLE		NOLICHUCKY SHALE	Cn	422-550
	LOWER	OAK RIDGE RESERVATION AQUITARDS	MARYVILLE LIMESTONE	Cm	346-445
			ROGERSVILLE SHALE	Crg	90-120
			RUTLEDGE LIMESTONE	Crt	90-120
			PUMPKIN VALLEY SHALE	Cpv	260-320
	LOWER		ROME	Cr	NOT DETERMINED

EXPLANATION

- — LESS THAN 100 FT DEEP
- — 100 TO 400 FT DEEP
- — GREATER THAN 400 FT DEEP
- ▲ — UNDEFINED DEPTH

FIGURE 25

GEOCHEMISTRY OF GROUNDWATER
MONITORED BY CLUSTER 10 WELLS.

LOCATION: Y-12 PLANT
OAK RIDGE, TN

DATE: 2/14/96

DWG ID.: 2P10

Depth of MP Monitored Interval < 100 ft bgs?

A-28

Decision criteria:

- * depth of midpoint (MP)
- * total dissolved solids (TDS)
- * aquifer (AQF) or aquitard (AQT)
- * Knox Group
- * Na as a percentage of total cations

FIGURE 26

TREE MODEL OF SURROGATE
CLUSTER ASSIGNMENTS.

LOCATION:

Y-12 PLANT
OAK RIDGE, TN

DATE:

2/14/96

DWG ID.:

OR466-HC

A-29

LOCATION:

Y-12 PLANT
OAK RIDGE, TN

DATE:

2/14/96

DWG ID.:

ORFL

FIGURE 27

FLOW CHART OF THE PROCESS FOR
ASSIGNING REFERENCE CONCENTRATIONS.

FIGURE 28

CUMULATIVE PROBABILITY PLOT OF BARIUM
CONCENTRATIONS FOR CLUSTER 2 WELLS.

LOCATION:

Y-12 PLANT
OAK RIDGE, TN

DATE:

2/14/96

DWG ID.:

29

LOCATION:

Y-12 PLANT
OAK RIDGE, TN

DATE:

2/14/96

DWG ID.:

30

FIGURE 29

CUMULATIVE PROBABILITY PLOT OF ZINC
CONCENTRATIONS FOR CLUSTER 10 WELLS.

FIGURE 30

CUMULATIVE PROBABILITY PLOT OF BORON
CONCENTRATIONS FOR CLUSTER 1 WELLS.

Appendix B

TABLES

Table 1. Geologic formations and depth intervals monitored by wells included in the final data set

Monitored formation			Monitored interval depths		
Geologic unit	Number of wells	Percentage of wells	Depth (ft bgs)	Number of wells	Cumulative percentage of wells
Chickamauga Group	6	2	0-49	183	43
Knox Group	97	23	50-99	88	64
Maynardville Limestone	112	26	100-149	62	80
Nolichucky Shale	125	29	150-199	46	90
Maryville Limestone	52	12	200-249	13	92
Rogersville Shale	10	2	250-299	8	94
Rutledge Limestone	2	<1	300-349	9	95
Pumpkin Valley Shale	9	2	350-399	7	97
Rome Formation	10	2	400-449	4	98
Not specified	7	2	450+	10	100
Total	430		Total	430	

Table 2. Variations in sampling frequency for wells included in the final data set

Number of sampling events	Number of wells
1-3	57
4-7	125
8-11	79
12-15	84
16-19	30
20-23	43
24-26	12
	430 total

Table 3. Well cluster assignments

Cluster designation	Well number	Monitored formation ^a	Depth (ft bgs) ^b
1	1085	Ock	114.0
1	GW-005	Cn	7.8
1	GW-010	Cn	10.2
1	GW-014	Cn	9.1
1	GW-021	Cn	9.9
1	GW-027	Cm	24.5
1	GW-053	Cmn	22.1
1	GW-056	Cmn	52.2
1	GW-057	Cmn	20.2
1	GW-058	Cmn	41.9
1	GW-067	Cmn	11.9
1	GW-068	Cn	76.8
1	GW-097	Cn	14.3
1	GW-098	Cn	90.3
1	GW-143	Ock	229.0
1	GW-145	Ock	98.0
1	GW-146	Ock	205.0
1	GW-148	Cmn	7.9
1	GW-149	Cmn	43.3
1	GW-151	Cmn	90.8
1	GW-152	Cmn	14.1
1	GW-153	Cmn	52.5
1	GW-154	Cmn	8.0
1	GW-167	Cmn	27.6
1	GW-168	Cn	119.7
1	GW-170	Cmn	130.5
1	GW-172	Cmn	119.4
1	GW-183	NS	17.8

Table 3 (continued)

Cluster designation	Well number	Monitored formation ^a	Depth (ft bgs) ^b
1	GW-186	Och	156.5
1	GW-187	Och	150.5
1	GW-188	Och	58.5
1	GW-193	Cmn	12.0
1	GW-199	Crg	19.5
1	GW-204	NS	11.9
1	GW-206	Cr	13.5
1	GW-207	Cr	104.8
1	GW-208	Cr	408.4
1	GW-211	Cr	407.0
1	GW-220	Cmn	38.1
1	GW-222	Cmn	21.5
1	GW-223	Cmn	84.8
1	GW-226	Cmn	50.0
1	GW-229	Cmn	47.5
1	GW-230	Cmn	373.7
1	GW-240	Cmn	25.3
1	GW-242	Cpv	13.0
1	GW-250	Cm	55.6
1	GW-263	Cm	26.9
1	GW-264	Cm	64.8
1	GW-271	Cn	50.1
1	GW-279	Cmn	69.0
1	GW-283	Cn	12.0
1	GW-284	Cn	10.0
1	GW-295	Ock	138.2
1	GW-303	Ock	310.5
1	GW-318	Och	73.6

Table 3 (continued)

Cluster designation	Well number	Monitored formation ^a	Depth (ft bgs) ^b
1	GW-319	Och	16.7
1	GW-335	Cn	11.7
1	GW-364	Cmn	53.7
1	GW-365	Cmn	138.4
1	GW-380	Cmn	9.2
1	GW-381	Cmn	54.9
1	GW-382	Cmn	149.0
1	GW-383	Cn	20.1
1	GW-384	Cn	45.6
1	GW-602	Cmn	204.3
1	GW-603	Cmn	69.3
1	GW-605	Cmn	34.1
1	GW-606	Cmn	163.4
1	GW-618	Cmn	31.5
1	GW-624	Cn	20.8
1	GW-638	Cn	7.0
1	GW-646	Cmn	69.6
1	GW-647	Cmn	84.5
1	GW-656	Cn	14.9
1	GW-657	Cmn	10.6
1	GW-685	Cmn	113.4
1	GW-695	Ock	56.6
1	GW-707	Cmn	15.8
1	GW-710	Ock	642.1
1	GW-711	Cmn	641.1
1	GW-712	Ock	449.5
1	GW-713	Cmn	310.1
1	GW-715	Cmn	38.0

Table 3 (continued)

Cluster designation	Well number	Monitored formation ^a	Depth (ft bgs) ^b
1	GW-735	Cn	73.4
1	GW-745	Cpv	27.0
1	GW-748	Cm	21.0
1	GW-749	Cm	10.5
1	GW-750	Cn	67.0
1	GW-758	Crt	44.0
1	GW-759	Crg	24.0
1	GW-760	Cm	54.0
1	GW-762	Cn	52.5
1	GW-763	Cn	10.0
1	GW-765	Crg	26.0
1	GW-769	Cn	54.0
1	GW-776	Cn	17.0
2	1096	Ock	62.5
2	GW-007	Cn	12.6
2	GW-018	Cn	15.5
2	GW-042	Cpv	20.8
2	GW-043	Cm	25.0
2	GW-047	Cn	19.0
2	GW-080	Crg	25.3
2	GW-209	Cr	45.1
2	GW-265	Cm	19.4
2	GW-266	Cm	21.3
2	GW-269	Cm	26.0
2	GW-289	Cm	34.9
2	GW-325	Cn	11.5
2	GW-342	Cpv	68.0
2	GW-531	Cm	30.3

Table 3 (continued)

Cluster designation	Well number	Monitored formation ^a	Depth (ft bgs) ^b
2	GW-533	NS	24.1
2	GW-613	Cn	36.0
2	GW-634	Cn	9.3
2	GW-640	Cn	41.2
2	GW-641	Cn	17.7
2	GW-642	Crg	27.7
2	GW-643	Cm	22.5
2	GW-644	Cn	16.9
2	GW-649	Cn	14.6
2	GW-653	Cn	32.7
2	GW-655	Cpv	56.4
2	GW-767	Cm	12.5
3	GW-003	Cn	23.0
3	GW-013	Cn	10.0
3	GW-037	Cm	55.4
3	GW-044	Cm	56.3
3	GW-045	Cmn	9.1
3	GW-054	Cmn	34.2
3	GW-073	Cn	73.4
3	GW-076	Cn	74.1
3	GW-077	Cn	93.9
3	GW-078	Cn	16.4
3	GW-079	Crg	57.4
3	GW-082	Cm	31.9
3	GW-083	Cn	24.7
3	GW-084	Cm	23.2
3	GW-089	Crt	22.5
3	GW-115	Cm	45.3

Table 3 (continued)

Cluster designation	Well number	Monitored formation ^a	Depth (ft bgs) ^b
3	GW-150	Cmn	8.4
3	GW-162	Cpv	108.5
3	GW-164	Cr	387.5
3	GW-169	Cmn	31.7
3	GW-184	Och	115.8
3	GW-190	NS	17.1
3	GW-191	Cm	52.8
3	GW-192	Cm	12.0
3	GW-194	Cm	9.6
3	GW-195	Cm	20.0
3	GW-210	Cr	114.0
3	GW-248	Cm	55.6
3	GW-252	Cmn	44.6
3	GW-257	Cm	26.4
3	GW-258	Cm	43.5
3	GW-259	Cm	27.3
3	GW-261	Cm	20.2
3	GW-262	Cm	64.2
3	GW-267	Cm	23.4
3	GW-268	Cm	30.8
3	GW-272	Cn	12.5
3	GW-278	Cmn	17.6
3	GW-281	Cn	9.5
3	GW-285	Cn	12.3
3	GW-286	Cm	25.9
3	GW-287	Cm	9.1
3	GW-288	Cm	53.0
3	GW-290	Cm	28.9

Table 3 (continued)

Cluster designation	Well number	Monitored formation ^a	Depth (ft bgs) ^b
3	GW-291	Cm	13.2
3	GW-304	OCk	157.8
3	GW-311	Cmn	33.0
3	GW-324	Cn	73.3
3	GW-334	Cn	23.5
3	GW-337	Cn	18.6
3	GW-338	Cn	14.4
3	GW-343	Cr	177.5
3	GW-344	Cr	308.5
3	GW-347	Cmn	18.7
3	GW-349	Cmn	14.7
3	GW-350	Cmn	35.9
3	GW-370	Cm	27.1
3	GW-371	Cm	117.5
3	GW-372	Cm	45.7
3	GW-376	Cm	140.5
3	GW-532	Cm	19.9
3	GW-534	NS	37.8
3	GW-535	Cn	11.3
3	GW-536	Cn	11.5
3	GW-538	NS	33.9
3	GW-614	Cn	80.9
3	GW-619	Cmn	33.8
3	GW-620	Cmn	68.4
3	GW-621	Cmn	31.9
3	GW-622	Cn	13.7
3	GW-626	Cn	70.5
3	GW-630	NS	21.7

Table 3 (continued)

Cluster designation	Well number	Monitored formation ^a	Depth (ft bgs) ^b
3	GW-636	Cn	107.8
3	GW-637	Cn	21.0
3	GW-651	Cmn	45.9
3	GW-652	Cmn	22.3
3	GW-654	Cm	9.8
3	GW-658	Cn	13.0
3	GW-708	Cmn	8.2
3	GW-714	Cmn	130.0
3	GW-733	Cmn	248.3
3	GW-744	Cpv	62.3
3	GW-747	Cm	73.5
3	GW-751	Cn	55.0
3	GW-753	Cm	65.5
3	GW-754	Cn	18.5
3	GW-755	Crg	55.0
3	GW-757	Ock	150.5
3	GW-761	Cm	9.5
3	GW-764	Crg	59.5
3	GW-766	Cm	41.0
3	GW-768	Crg	59.0
3	GW-770	Cn	13.5
3	GW-771	Crg	48.0
3	GW-773	Cm	53.0
3	GW-774	Cm	20.0
3	GW-775	Cn	50.5
3	GW-793	Cn	23.0
3	GW-794	Cn	32.5
3	GW-795	Cn	14.0

Table 3 (continued)

Cluster designation	Well number	Monitored formation ^a	Depth (ft bgs) ^b
4	1080	Ock	170.5
4	1086	Ock	148.0
4	1090	Ock	NS
4	1091	Ock	NS
4	1095	Ock	117.5
4	GW-099	Ock	119.8
4	GW-141	Ock	148.5
4	GW-142	Ock	271.8
4	GW-144	Ock	171.5
4	GW-147	Ock	60.5
4	GW-155	Ock	171.5
4	GW-156	Ock	151.5
4	GW-157	Ock	139.5
4	GW-158	Ock	398.5
4	GW-159	Ock	151.5
4	GW-160	Ock	220.0
4	GW-161	Ock	375.0
4	GW-165	Ock	300.5
4	GW-166	Ock	382.5
4	GW-173	Ock	159.5
4	GW-174	Ock	139.5
4	GW-175	Ock	157.5
4	GW-176	Ock	139.5
4	GW-177	Ock	138.5
4	GW-178	Ock	125.3
4	GW-179	Ock	111.5
4	GW-180	Ock	135.0
4	GW-181	Ock	161.5

Table 3 (continued)

Cluster designation	Well number	Monitored formation ^a	Depth (ft bgs) ^b
4	GW-203	Ock	150.0
4	GW-205	Ock	159.0
4	GW-217	Ock	172.6
4	GW-221	Ock	152.5
4	GW-231	Ock	28.9
4	GW-233	Ock	161.0
4	GW-241	Ock	90.5
4	GW-255	Cmn	73.9
4	GW-292	Ock	179.1
4	GW-293	Ock	205.5
4	GW-294	Ock	120.5
4	GW-296	Ock	140.7
4	GW-298	Ock	180.6
4	GW-299	Ock	160.5
4	GW-300	Ock	139.5
4	GW-301	Ock	156.0
4	GW-302	Ock	128.2
4	GW-305	Ock	172.5
4	GW-313	Cmn	105.6
4	GW-316	Cmn	73.8
4	GW-317	Cmn	124.5
4	GW-320	Ock	106.3
4	GW-321	Ock	91.3
4	GW-322	Ock	160.5
4	GW-323	Ock	101.0
4	GW-339	Ock	107.5
4	GW-366	Cmn	94.5
4	GW-367	Cmn	137.5

Table 3 (continued)

Cluster designation	Well number	Monitored formation ^a	Depth (ft bgs) ^b
4	GW-511	Ock	146.9
4	GW-512	Ock	54.5
4	GW-513	Ock	118.2
4	GW-514	Ock	184.5
4	GW-521	Ock	129.6
4	GW-522	Ock	189.2
4	GW-539	Ock	146.2
4	GW-540	Ock	165.0
4	GW-541	Ock	95.6
4	GW-542	Ock	67.8
4	GW-543	Ock	84.9
4	GW-544	Ock	100.2
4	GW-546	Ock	75.3
4	GW-557	Ock	125.5
4	GW-560	Ock	57.1
4	GW-562	Ock	48.0
4	GW-564	Ock	66.5
4	GW-604	Cmn	106.3
4	GW-607	Ock	144.7
4	GW-608	Ock	184.0
4	GW-609	Ock	262.7
4	GW-610	Ock	111.3
4	GW-611	Ock	111.6
4	GW-612	Ock	244.5
4	GW-645	Cmn	71.7
4	GW-648	Cmn	72.6
4	GW-709	Ock	74.7
4	GW-731	Ock	171.4

Table 3 (continued)

Cluster designation	Well number	Monitored formation ^a	Depth (ft bgs) ^b
4	GW-732	Ock	184.2
4	GW-740	Cmn	177.8
4	GW-742	Ock	385.0
4	GW-743	Ock	155.6
4	GW-796	Ock	130.0
4	GW-797	Ock	126.0
4	GW-798	Ock	128.5
4	GW-799	Ock	85.5
4	GW-800	Ock	25.5
4	GW-801	Ock	182.5
5	GW-040	Cpv	25.0
5	GW-046	Cn	12.7
5	GW-086	Cn	25.3
5	GW-087	Cn	13.3
5	GW-249	Cm	31.8
5	GW-282	Cn	8.5
5	GW-331	Cn	26.6
5	GW-332	Cn	20.5
5	GW-333	Cn	19.4
5	GW-336	Cn	17.3
5	GW-505	Cn	7.5
5	GW-508	Cn	8.2
5	GW-617	Cmn	12.4
5	GW-631	Cn	10.0
5	GW-632	Cn	9.3
5	GW-659	Cn	10.7
5	GW-746	Cpv	9.2
5	GW-752	Cn	10.5

Table 3 (continued)

Cluster designation	Well number	Monitored formation ^a	Depth (ft bgs) ^b
5	GW-756	Cm	11.0
6	GW-117	Cn	505.0
6	GW-118	Cn	550.0
6	GW-119	Cn	485.0
6	GW-123	Cn	547.0
6	GW-125	Cn	527.0
6	GW-239	Cn	418.7
6	GW-623	Cn	256.2
7	53-1A	Cn	19.1
7	GW-085	Cn	53.6
7	GW-100	Cmn	12.3
7	GW-101	Cn	13.8
7	GW-105	Cn	13.3
7	GW-106	Cn	64.2
7	GW-122	Cmn	117.0
7	GW-124	Cmn	125.0
7	GW-253	Cmn	43.1
7	GW-254	Cmn	50.9
7	GW-256	Cmn	14.4
7	GW-270	Cn	14.8
7	GW-273	Cn	28.0
7	GW-345	Cn	20.8
7	GW-346	Cn	58.2
7	GW-526	Cn	112.0
7	GW-537	Cn	14.1
7	GW-633	Cn	9.3
8	GW-052	Cmn	11.8
8	GW-061	Cmn	21.1

Table 3 (continued)

Cluster designation	Well number	Monitored formation ^a	Depth (ft bgs) ^b
8	GW-063	Cmn	30.2
8	GW-064	Cmn	49.8
8	GW-107	Cn	10.3
8	GW-127	Cn	19.0
8	GW-225	Cmn	175.0
8	GW-227	Cmn	35.0
8	GW-228	Cmn	90.0
8	GW-251	Cmn	43.0
8	GW-280	Cmn	140.3
8	GW-306	Cmn	52.4
8	GW-307	Cmn	35.2
8	GW-308	Cmn	29.9
8	GW-309	Cmn	31.5
8	GW-310	Cmn	23.3
8	GW-314	Cmn	108.0
8	GW-315	Cmn	97.0
8	GW-348	Cmn	74.5
8	GW-368	Cmn	235.0
8	GW-369	Cmn	133.0
8	GW-601	Cmn	337.3
8	GW-683	OCk	165.4
8	GW-684	Cmn	117.4
8	GW-694	Cmn	179.3
8	GW-703	Cmn	158.5
8	GW-704	Cmn	251.0
8	GW-706	Cmn	169.8
8	GW-723	Cmn	392.6
8	GW-724	Cmn	295.6

Table 3 (continued)

Cluster designation	Well number	Monitored formation ^a	Depth (ft bgs) ^b
8	GW-725	Cmn	137.5
8	GW-736	Cmn	98.5
8	GW-737	Cmn	84.3
8	GW-738	Cmn	75.8
8	GW-739	Cmn	304.6
9	GW-108	Cn	49.8
9	GW-109	Cn	112.6
9	GW-243	Cn	60.1
9	GW-244	Cn	60.0
9	GW-245	Cn	50.7
9	GW-246	Cn	55.1
9	GW-247	Cn	54.8
9	GW-274	Cn	30.4
9	GW-275	Cn	59.4
9	GW-276	Cn	14.9
9	GW-277	Cn	69.8
9	GW-615	Cn	233.8
10	GW-069	Cn	89.1
10	GW-072	Cn	91.5
10	GW-074	Cn	194.0
10	GW-075	Cn	188.1
10	GW-094	Cmn	100.9
10	GW-095	Cmn	143.1
10	GW-120	Cn	155.0
10	GW-126	Cn	130.0
10	GW-163	Cr	216.5
10	GW-232	Cmn	406.4
10	GW-363	Cn	62.5

Table 3 (continued)

Cluster designation	Well number	Monitored formation ^a	Depth (ft bgs) ^b
10	GW-373	Cm	140.5
10	GW-374	Cn	137.4
10	GW-375	Cmn	143.3
10	GW-385	Cn	151.2
10	GW-502	Cn	241.9
10	GW-616	Cn	244.0
10	GW-627	Cn	262.0
10	GW-629	Cn	287.2
10	GW-639	Cn	110.5
10	GW-705	Cn	272.0

^aJones, S. B, B. K. Thompson, and S. M. Field. 1994. Updated subsurface data base for Bear Creek Valley, Chestnut Ridge, and parts of Bethel Valley on the U.S. Department of Energy Oak Ridge Reservation. Y/TS-881/R2. Oak Ridge Y-12 Plant, Oak Ridge, Tenn.

Och=Chickamauga Group

Ock=Knox Group (Copper Ridge Dolomite)

Cmn=Maynardville Limestone

Cn=Nolichucky Shale

Cm=Maryville Limestone

Crg=Rogersville Shale

Crt=Rutledge Limestone

Cpv=Pumpkin Valley Shale

Cr=Rome Formation

NS=Not specified

^bDepth to the monitored interval midpoint in feet below ground surface (bgs).

Table 4. Well cluster characteristics

Cluster 1: Shallow Groundwater (Maynardville Limestone)											
Monitored formation ^a	Number of monitoring wells at various monitored interval depths (ft bgs) ^b										Total
	0-49	50-99	100-149	150-199	200-249	250-299	300-349	350-399	400-449	450+	
Chickamauga Group	1	2	0	2	0	0	0	0	0	0	5
Knox Group	0	2	2	0	2	0	1	0	1	1	9
Maynardville Limestone	20	11	5	1	1	0	1	1	0	1	41
Nolichucky Shale	15	7	1	0	0	0	0	0	0	0	23
Maryville Limestone	4	3	0	0	0	0	0	0	0	0	7
Rogersville Shale	3	0	0	0	0	0	0	0	0	0	3
Rutledge Limestone	1	0	0	0	0	0	0	0	0	0	1
Pumpkin Valley Shale	2	0	0	0	0	0	0	0	0	0	2
Rome Formation	1	0	1	0	0	0	0	0	2	0	4
Not Specified	2	0	0	0	0	0	0	0	0	0	2
Total	49	25	9	3	3	0	2	1	3	2	97

Table 4 (continued)

Cluster 2: Recharge Groundwater											
Monitored formation ^a	Number of monitoring wells at various monitored interval depths (ft bgs) ^b										Total
	0-49	50-99	100-149	150-199	200-249	250-299	300-349	350-399	400-449	450+	
Chickamauga Group	0	0	0	0	0	0	0	0	0	0	0
Knox Group	0	1	0	0	0	0	0	0	0	0	1
Maynardville Limestone	0	0	0	0	0	0	0	0	0	0	0
Nolichucky Shale	11	0	0	0	0	0	0	0	0	0	11
Maryville Limestone	8	0	0	0	0	0	0	0	0	0	8
Rogersville Shale	2	0	0	0	0	0	0	0	0	0	2
Rutledge Limestone	0	0	0	0	0	0	0	0	0	0	0
Pumpkin Valley Shale	1	2	0	0	0	0	0	0	0	0	3
Rome Formation	1	0	0	0	0	0	0	0	0	0	1
Not specified	1	0	0	0	0	0	0	0	0	0	1
Total	24	3	0	0	0	0	0	0	0	0	27

Table 4 (continued)

Cluster 3: Shallow Groundwater (Maryville Limestone)											
Monitored formation ^a	Number of monitoring wells at various monitored interval depths (ft bgs) ^b										Total
	0-49	50-99	100-149	150-199	200-249	250-299	300-349	350-399	400-449	450+	
Chickamauga Group	0	0	1	0	0	0	0	0	0	0	1
Knox Group	0	0	0	2	0	0	0	0	0	0	2
Maynardville Limestone	15	1	1	0	1	0	0	0	0	0	18
Nolichucky Shale	20	8	1	0	0	0	0	0	0	0	29
Maryville Limestone	23	9	2	0	0	0	0	0	0	0	34
Rogersville Shale	1	4	0	0	0	0	0	0	0	0	5
Rutledge Limestone	1	0	0	0	0	0	0	0	0	0	1
Pumpkin Valley Shale	0	1	1	0	0	0	0	0	0	0	2
Rome Formation	0	0	1	1	0	0	1	1	0	0	4
Not specified	4	0	0	0	0	0	0	0	0	0	4
Total	64	23	7	3	1	0	1	1	0	0	100

Table 4 (continued)

Cluster 4: Knox Group Groundwater											
Monitored formation ^a	Number of monitoring wells at various monitored interval depths (ft bgs) ^b										Total
	0-49	50-99	100-149	150-199	200-249	250-299	300-349	350-399	400-449	450+	
Chickamauga Group	0	0	0	0	0	0	0	0	0	0	0
Knox Group	3	12	30	27	3	2	1	4	0	2	84
Maynardville Limestone	0	5	4	1	0	0	0	0	0	0	10
Nolichucky Shale	0	0	0	0	0	0	0	0	0	0	0
Maryville Limestone	0	0	0	0	0	0	0	0	0	0	0
Rogersville Shale	0	0	0	0	0	0	0	0	0	0	0
Rutledge Limestone	0	0	0	0	0	0	0	0	0	0	0
Pumpkin Valley Shale	0	0	0	0	0	0	0	0	0	0	0
Rome Formation	0	0	0	0	0	0	0	0	0	0	0
Not specified	0	0	0	0	0	0	0	0	0	0	0
Total	3	17	34	28	3	2	1	4	0	2	94

Table 4 (continued)

Cluster 5: Industrially Contaminated Groundwater											
Monitored formation ^a	Number of monitoring wells at various monitored interval depths (ft bgs) ^b										Total
	0-49	50-99	100-149	150-199	200-249	250-299	300-349	350-399	400-449	450+	
Chickamauga Group	0	0	0	0	0	0	0	0	0	0	0
Knox Group	0	0	0	0	0	0	0	0	0	0	0
Maynardville Limestone	1	0	0	0	0	0	0	0	0	0	1
Nolichucky Shale	14	0	0	0	0	0	0	0	0	0	14
Maryville Limestone	2	0	0	0	0	0	0	0	0	0	2
Rogersville Shale	0	0	0	0	0	0	0	0	0	0	0
Rutledge Limestone	0	0	0	0	0	0	0	0	0	0	0
Pumpkin Valley Shale	2	0	0	0	0	0	0	0	0	0	2
Rome Formation	0	0	0	0	0	0	0	0	0	0	0
Not specified	0	0	0	0	0	0	0	0	0	0	0
Total	19	0	0	0	0	0	0	0	0	0	19

Table 4 (continued)

Cluster 6: Sodium-Chloride-Bicarbonate Groundwater											
Monitored formation ^a	Number of monitoring wells at various monitored interval depths (ft bgs) ^b										Total
	0-49	50-99	100-149	150-199	200-249	250-299	300-349	350-399	400-449	450+	
Chickamauga Group	0	0	0	0	0	0	0	0	0	0	0
Knox Group	0	0	0	0	0	0	0	0	0	0	0
Maynardville Limestone	0	0	0	0	0	0	0	0	0	0	0
Nolichucky Shale	0	0	0	0	0	1	0	0	1	5	7
Maryville Limestone	0	0	0	0	0	0	0	0	0	0	0
Rogersville Shale	0	0	0	0	0	0	0	0	0	0	0
Rutledge Limestone	0	0	0	0	0	0	0	0	0	0	0
Pumpkin Valley Shale	0	0	0	0	0	0	0	0	0	0	0
Rome Formation	0	0	0	0	0	0	0	0	0	0	0
Not specified	0	0	0	0	0	0	0	0	0	0	0
Total	0	0	0	0	0	1	0	0	1	5	7

Table 4 (continued)

Cluster 7: Nitrate-Contaminated Groundwater											
Monitored formation ^a	Number of monitoring wells at various monitored interval depths (ft bgs) ^b										Total
	0-49	50-99	100-149	150-199	200-249	250-299	300-349	350-399	400-449	450+	
Chickamauga Group	0	0	0	0	0	0	0	0	0	0	0
Knox Group	0	0	0	0	0	0	0	0	0	0	0
Maynardville Limestone	3	1	2	0	0	0	0	0	0	0	6
Nolichucky Shale	8	3	1	0	0	0	0	0	0	0	12
Maryville Limestone	0	0	0	0	0	0	0	0	0	0	0
Rogersville Shale	0	0	0	0	0	0	0	0	0	0	0
Rutledge Limestone	0	0	0	0	0	0	0	0	0	0	0
Pumpkin Valley Shale	0	0	0	0	0	0	0	0	0	0	0
Rome Formation	0	0	0	0	0	0	0	0	0	0	0
Not specified	0	0	0	0	0	0	0	0	0	0	0
Total	11	4	3	0	0	0	0	0	0	0	18

Table 4 (continued)

Cluster 8: Nitrate-Contaminated Groundwater											
Monitored formation ^a	Number of monitoring wells at various monitored interval depths (ft bgs) ^b										Total
	0-49	50-99	100-149	150-199	200-249	250-299	300-349	350-399	400-449	450+	
Chickamauga Group	0	0	0	0	0	0	0	0	0	0	0
Knox Group	0	0	0	1	0	0	0	0	0	0	1
Maynardville Limestone	9	8	5	4	1	2	2	1	0	0	32
Nolichucky Shale	2	0	0	0	0	0	0	0	0	0	2
Maryville Limestone	0	0	0	0	0	0	0	0	0	0	0
Rogersville Shale	0	0	0	0	0	0	0	0	0	0	0
Rutledge Limestone	0	0	0	0	0	0	0	0	0	0	0
Pumpkin Valley Shale	0	0	0	0	0	0	0	0	0	0	0
Rome Formation	0	0	0	0	0	0	0	0	0	0	0
Not specified	0	0	0	0	0	0	0	0	0	0	0
Total	11	8	5	5	1	2	2	1	0	0	35

Table 4 (continued)

Cluster 9: Nitrate-Contaminated Groundwater											
Monitored formation ^a	Number of monitoring wells at various monitored interval depths (ft bgs) ^b										Total
	0-49	50-99	100-149	150-199	200-249	250-299	300-349	350-399	400-449	450+	
Chickamauga Group	0	0	0	0	0	0	0	0	0	0	0
Knox Group	0	0	0	0	0	0	0	0	0	0	0
Maynardville Limestone	0	0	0	0	0	0	0	0	0	0	0
Nolichucky Shale	2	8	1	0	1	0	0	0	0	0	12
Maryville Limestone	0	0	0	0	0	0	0	0	0	0	0
Rogersville Shale	0	0	0	0	0	0	0	0	0	0	0
Rutledge Limestone	0	0	0	0	0	0	0	0	0	0	0
Pumpkin Valley Shale	0	0	0	0	0	0	0	0	0	0	0
Rome Formation	0	0	0	0	0	0	0	0	0	0	0
Not specified	0	0	0	0	0	0	0	0	0	0	0
Total	2	8	1	0	1	0	0	0	0	0	12

Table 4 (continued)

Cluster 10: Sodium-Bicarbonate Groundwater											
Monitored formation ^a	Number of monitoring wells at various monitored interval depths (ft bgs) ^b										Total
	0-49	50-99	100-149	150-199	200-249	250-299	300-349	350-399	400-449	450+	
Chickamauga Group	0	0	0	0	0	0	0	0	0	0	0
Knox Group	0	0	0	0	0	0	0	0	0	0	0
Maynardville Limestone	0	0	3	0	0	0	0	0	1	0	4
Nolichucky Shale	0	3	3	4	2	3	0	0	0	0	15
Maryville Limestone	0	0	1	0	0	0	0	0	0	0	1
Rogersville Shale	0	0	0	0	0	0	0	0	0	0	0
Rutledge Limestone	0	0	0	0	0	0	0	0	0	0	0
Pumpkin Valley Shale	0	0	0	0	0	0	0	0	0	0	0
Rome Formation	0	0	0	0	1	0	0	0	0	0	1
Not specified	0	0	0	0	0	0	0	0	0	0	0
Total	0	3	7	4	3	3	0	0	1	0	21

^aJones, S. B, B. K. Thompson, and S. M. Field. 1994. Updated subsurface data base for Bear Creek Valley, Chestnut Ridge, and parts of Bethel Valley on the U.S. Department of Energy Oak Ridge Reservation. Y/TS-881/R2. Oak Ridge Y-12 Plant, Oak Ridge, Tennessee.

Och=Chickamauga Group

Ock=Knox Group (Copper Ridge Dolomite)

Cmn=Maynardville Limestone

Cn=Nolichucky Shale

Cm=Maryville Limestone

Crg=Rogersville Shale

Crt=Rutledge Limestone

Cpv=Pumpkin Valley Shale

Cr=Rome Formation

NS=Not specified

^bDepth to the monitored interval midpoint in feet below ground surface (bgs).

Table 5. Surrogate cluster assignments

Well number	Original cluster	Surrogate cluster ^a
53-1A	7	2
GW-040	5	3
GW-046	5	2
GW-052	8	2
GW-061	8	1
GW-063	8	1
GW-064	8	1
GW-085	7	3
GW-086	5	3
GW-087	5	3
GW-100	7	2
GW-101	7	3
GW-105	7	3
GW-106	7	3
GW-107	8	3
GW-108	9	3
GW-109	9	3
GW-122	7	1
GW-124	7	1
GW-127	8	3
GW-225	8	1
GW-227	8	1
GW-228	8	1
GW-243	9	3
GW-244	9	3

Table 5 (continued)

Well number	Original cluster	Surrogate cluster ^a
GW-245	9	3
GW-246	9	3
GW-247	9	3
GW-249	5	3
GW-251	8	1
GW-253	7	1
GW-254	7	1
GW-256	7	1
GW-270	7	2
GW-273	7	3
GW-274	9	3
GW-275	9	3
GW-276	9	3
GW-277	9	2
GW-280	8	1
GW-282	5	3
GW-306	8	2
GW-307	8	1
GW-308	8	1
GW-309	8	1
GW-310	8	1
GW-314	8	1
GW-315	8	1
GW-331	5	2

Table 5 (continued)

Well number	Original cluster	Surrogate cluster ^a
GW-332	5	3
GW-333	5	2
GW-336	5	3
GW-345	7	2
GW-346	7	3
GW-348	8	2
GW-368	8	1
GW-369	8	1
GW-505	5	3
GW-508	5	2
GW-526	7	10
GW-537	7	3
GW-601	8	1
GW-615	9	3
GW-617	5	1
GW-631	5	3
GW-632	5	3
GW-633	7	3
GW-659	5	3
GW-683	8	4
GW-684	8	1
GW-694	8	1
GW-703	8	1
GW-704	8	1

Table 5 (continued)

Well number	Original cluster	Surrogate cluster ^a
GW-706	8	1
GW-723	8	1
GW-724	8	1
GW-725	8	1
GW-736	8	1
GW-737	8	1
GW-738	8	1
GW-739	8	1
GW-746	5	3
GW-752	5	3
GW-756	5	3

^aSee tree model for surrogate cluster assignments (Fig. 26). The model illustrates the series of decision criteria for making surrogate cluster assignments.

Table 6. Major ion data outliers, arranged according to frequency^a

Well number	Well cluster	Chloride	Magnesium	Calcium	Sodium	Sulfate	Fluoride	Nitrate
1095	4	■						
1090	4	■						
GW-014	1	■						
GW-057	1	■						
GW-069	10		■					
GW-118	6		■					
GW-119	6		■					
GW-120	10		■					
GW-144	4							
GW-156	4	■		■				
GW-157	4	■						
GW-160	4	■						
GW-166	4	■						
GW-173	4	■						
GW-174	4	■						
GW-177	4	■						
GW-192	3			■				
GW-211	1					■		
GW-230	1	■						
GW-255	4	■						
GW-292	4	■						
GW-293	4	■						
GW-294	4	■						
GW-296	4	■						
GW-313	4			■				
GW-339	4	■						
GW-367	4	■						
GW-511	4	■						
GW-544	4	■						

Table 6 (continued)

Well number	Well cluster	Chloride	Magnesium	Calcium	Sodium	Sulfate	Fluoride	Nitrate
GW-604	4	■						
GW-610	4	■						
GW-616	10							■
GW-636	3				■			
GW-644	2	■						
GW-708	3			■				
GW-711	1	■	■	■	■	■		
GW-740	4	■						
GW-755	3				■			
GW-757	3						■	
GW-760	1	■						
GW-767	2	■						
GW-768	3				■			
Total wells:	42	28	5	5	4	2	1	1

■ signifies that the data for the specific ion contain outliers.

Table 7. Trace metal data outliers, arranged according to frequency^a

[illegible]

Table 7 (continued)[illegible]

Table 7 (continued)

Well number	Well cluster	B	Pb	Cu	Zn	Cr	Ni	V	U	Sr	Mo	Si
GW-619	3	■										
GW-620	3	■										
GW-636	3	■										
GW-645	4									■		
GW-646	1	■										
GW-651	3	■										
GW-654	3	■										
GW-656	1			■		■						
GW-705	10			■								
GW-708	3	■										
GW-711	1	■										
GW-712	1	■										
GW-714	3	■										
GW-744	3	■										
GW-747	3	■										
GW-755	3	■										
GW-762	1	■										
GW-764	3	■										
GW-765	1							■				
GW-768	3	■										
GW-770	3	■										
GW-776	1					■	■					
GW-794	3	■										
Total wells:	82	53	15	11	8	6	4	4	3	2	1	1

■ signifies that the data for the specific metal contain outliers.

**Table 8. Reference concentrations used in 1996 evaluation of
groundwater quality at the Oak Ridge Y-12 Plant**

Element	Well cluster ^a	Data used ^b	N ^c	Percentage of ND ^d	Outliers (well numbers)		Distribution	Mean variance	Type ^e	Detection limit (mg/L)	Tolerance limit (mg/L) ^f
Aluminum	1, 3, 4, 6, 10	1, 3, 4, 6, 10	282	12	—	—	Lognormal	-1.01393 0.77645	PTL	0.02	2.4
	2	2	23	0	—	—	Lognormal	-0.35179 0.48917	PTL	—	6.1
Antimony	All	All	305	99	—	—	?	—	NPTL	0.05	<0.05
Arsenic	All	All	276	99	—	—	?	—	NPTL	0.05	0.078
Barium	1	1, 2, 3	196	0	—	—	Lognormal	-0.89917 0.40678	PTL	0.001	0.71
	2	1, 2, 6, 10	126	0	—	—	Lognormal	-1.02107 0.45026	PTL	—	0.68
	3	1, 3	173	0	—	—	Approximate lognormal	-0.87054 0.41534	PTL	—	0.79
	4	4, 6	93	0	—	—	?	—	NPTL	—	0.34
	6	2, 4, 6, 10	134	0	—	—	?	—	NPTL	—	0.34
	10	2, 6, 10	47	0	—	—	Lognormal	-1.20699 0.36146	PTL	—	0.35
Beryllium	All	All	305	95	—	—	?	—	NPTL	0.0003	0.00045

Table 8 (continued)

Element	Well cluster ^a	Data used ^b	N ^c	Percentage of ND ^d	Outliers (well numbers)		Distribution	Mean variance	Type ^e	Detection limit (mg/L)	Tolerance limit (mg/L) ^f
Boron	1	1	79	3	GW-014 GW-053 GW-098 GW-143 GW-145 GW-146 GW-148 GW-149 GW-152 GW-186 GW-187 GW-188 GW-193	GW-207 GW-208 GW-211 GW-229 GW-318 GW-319 GW-364 GW-365 GW-383 GW-646 GW-711 GW-712 GW-762	Lognormal	-1.44466 0.25002	PTL	0.004	0.12
	2, 4	2, 4	110	3	GW-147 GW-176 GW-217 GW-612	—	Normal	0.016074 0.006012	PTL	—	0.028
	3	3	92	0	GW-076 GW-089 GW-162 GW-210 GW-272 GW-278 GW-290 GW-291 GW-371 GW-619 GW-620 GW-636	GW-651 GW-654 GW-708 GW-714 GW-744 GW-747 GW-755 GW-764 GW-768 GW-770 GW-794	Lognormal	-1.70919 0.16275	PTL	0.004	0.041
	6, 10	6, 10	24	0	—	—	Lognormal	-0.29568 0.33846	PTL	—	3.1
Cadmium	1	1, 3, 4, 6, 10	282	99	—	—	?	—	NPTL	0.002	<0.002

Table 8 (continued)

Element	Well cluster ^a	Data used ^b	N ^c	Percentage of ND ^d	Outliers (well numbers)		Distribution	Mean variance	Type ^e	Detection limit (mg/L)	Tolerance limit (mg/L)
	2	2, 3, 4, 6, 10	227	98	—	—	?	—	NPTL	—	0.0028
	3, 4, 6, 10	All	304	99	—	—	?	—	NPTL	—	0.0025
Calcium	1	1	80	0	GW-711	—	Lognormal	1.89948 0.20729	PTL	?	203
	2	2	23	0	—	—	Lognormal	0.95065 0.37265	PTL	—	66
	3	3	96	0	GW-192 GW-708	—	Normal	52.8883 18.8637	PTL	—	89
	4	4	87	0	GW-156 GW-313	—	Approximate lognormal	1.56408 0.10791	PTL	—	60
	6, 10	6, 10	28	0	—	—	Lognormal	0.32581 0.30460	PTL	—	10
Chloride	1	1	80	0	GW-014 GW-057 GW-230 GW-711 GW-760	—	?	—	NPTL	1	100
Chloride (continued)	2, 4	2, 4	110	20	1090 1095 GW-144 GW-157 GW-160 GW-166 GW-173 GW-174 GW-177 GW-255 GW-292 GW-293	GW-294 GW-296 GW-339 GW-367 GW-511 GW-544 GW-604 GW-610 GW-644 GW-740 GW-767	?	—	NPTL	1	2.0

Table 8 (continued)

Element	Well cluster ^a	Data used ^b	N ^c	Percentage of ND ^d	Outliers (well numbers)		Distribution	Mean variance	Type ^e	Detection limit (mg/L)	Tolerance limit (mg/L) ^f
	2	2, 3, 4, 6, 10	227	98	—	—	?	—	NPTL	—	0.0028
	3, 4, 6, 10	All	304	99	—	—	?	—	NPTL	—	0.0025
Calcium	1	1	80	0	GW-711	—	Lognormal	1.89948 0.20729	PTL	?	203
	2	2	23	0	—	—	Lognormal	0.95065 0.37265	PTL	—	66
	3	3	96	0	GW-192 GW-708	—	Normal	52.8883 18.8637	PTL	—	89
	4	4	87	0	GW-156 GW-313	—	Approximate lognormal	1.56408 0.10791	PTL	—	60
	6, 10	6, 10	28	0	—	—	Lognormal	0.32581 0.30460	PTL	—	10
Chloride	1	1	80	0	GW-014 GW-057 GW-230 GW-711 GW-760	—	?	—	NPTL	1	100
Chloride (continued)	2, 4	2, 4	110	20	1090 1095 GW-144 GW-157 GW-160 GW-166 GW-173 GW-174 GW-177 GW-255 GW-292 GW-293	GW-294 GW-296 GW-339 GW-367 GW-511 GW-544 GW-604 GW-610 GW-644 GW-740 GW-767	?	—	NPTL	1	2.0

Table 8 (continued)

Element	Well cluster ^a	Data used ^b	N ^c	Percentage of ND ^d	Outliers (well numbers)		Distribution	Mean variance	Type ^e	Detection limit (mg/L)	Tolerance limit (mg/L) ^f
	3, 10	3, 10	117	10	—	—	Lognormal	0.52398 0.46912	PTL	—	26
	6	6	7	0	—	—	Lognormal	2.47731 0.74765	PTL	—	1.0 × 10 ⁵
Chromium	1	1, 2, 3, 6	200	88	GW-010 GW-263 GW-283	GW-531 GW-656 GW-776	?	—	NPTL	0.01	0.029
	2	1, 2, 6	106	83	GW-010 GW-263 GW-283	GW-656 GW-776	?	—	NPTL	—	0.041
	3	1, 3, 4, 6, 10	282	92	GW-010 GW-263 GW-283	GW-531 GW-656 GW-776	?	—	NPTL	—	0.041
	4, 10	3, 4, 6, 10	205	95	—	—	?	—	NPTL	—	0.029
	6	All	304	91	GW-010 GW-263 GW-283	GW-531 GW-656 GW-776	?	—	NPTL	0.01	0.043
Cobalt	All	All	305	96	—	—	?	—	NPTL	0.005	0.019
Copper	1	All	305	64	GW-067 GW-080 GW-179 GW-195 GW-272	GW-278 GW-291 GW-531 GW-656 GW-705	?	—	NPTL	0.004	0.012

Table 8 (continued)

Element	Well cluster ^a	Data used ^b	N ^c	Percentage of ND ^d	Outliers (well numbers)		Distribution	Mean variance	Type ^e	Detection limit (mg/L)	Tolerance limit (mg/L) ^f
	2, 3, 6, 10	1, 2, 3, 6, 10	218	58	GW-067 GW-080 GW-195 GW-272 GW-278	GW-291 GW-531 GW-656 GW-705	?	—	NPTL	—	0.012
	4	1, 4	166	72	GW-067 GW-179 GW-656	—	?	—	NPTL	—	0.012
Fluoride	1	1	80	35	—	—	Lognormal	-0.9296 0.6550	PTL	0.1	2.3
	2	2, 3, 4	205	70	GW-757	—	?	—	NPTL	—	0.55
	3	2, 3	118	57	GW-757	—	?	—	NPTL	—	0.22
	4	2, 4	110	85	—	—	?	—	NPTL	0.1	0.55
	6	6	6	0	—	—	Normal	4.75833 1.89774	PTL	—	12
	10	10	19	5	—	—	Lognormal	0.00256 0.57278	PTL	—	25
Iron	1, 2, 3	1, 2, 3, 10	212	0	—	—	Approximate lognormal	-0.2948 0.6750	PTL	0.004	8.7
	4	4, 10	105	0	—	—	Approximate lognormal	-0.72226 0.72306	PTL	—	4.6
	6	6	6	0	—	—	Normal	4.1325 1.7714	PTL	—	11

Table 8 (continued)

Element	Well cluster ^a	Data used ^b	N ^c	Percentage of ND ^d	Outliers (well numbers)		Distribution	Mean variance	Type ^e	Detection limit (mg/L)	Tolerance limit (mg/L)
	10	1, 2, 3, 4, 10	299	0	—	—	Approximate lognormal	-0.43619 0.70857	PTL	—	6.9
Lead	1, 3, 4, 6	All	314	77	GW-003 GW-010 GW-014 GW-067 GW-089 GW-150 GW-152 GW-160	GW-209 GW-241 GW-257 GW-318 GW-342 GW-364 GW-531	?	—	NPTL	0.004	0.0096
	2	1, 2, 3, 4, 6	293	76	GW-003 GW-010 GW-014 GW-067 GW-089 GW-150 GW-152 GW-160	GW-209 GW-241 GW-257 GW-318 GW-342 GW-364 GW-531	?	—	NPTL	—	0.0096
Lead (continued)	10	1, 3, 4, 6, 10	291	78	GW-003 GW-010 GW-014 GW-067 GW-089 GW-150 GW-152	GW-160 GW-241 GW-257 GW-318 GW-364	?	—	NPTL	—	0.0090
Magnesium	1	1	80	0	GW-711	—	Lognormal	1.24875 0.22312	PTL	0.005	49
	2	2, 6	30	0	—	—	Lognormal	0.28061 0.37199	PTL	—	13

Table 8 (continued)

Element	Well cluster ^a	Data used ^b	N ^c	Percentage of ND ^d	Outliers (well numbers)		Distribution	Mean variance	Type ^e	Detection limit (mg/L)	Tolerance limit (mg/L) ^f
	3	3	96	0	—	—	Lognormal	0.84854 0.22810	PTL	—	19
	4	4	87	0	—	—	Lognormal	1.32709 0.11634	PTL	—	36
	6	2, 6, 10	51	0	—	—	Approximate lognormal	0.03303 0.48385	PTL	—	11
	10	6, 10	28	0	GW-069 GW-118 GW-119 GW-120	—	Lognormal	-0.38066 0.27082	PTL	—	1.8
Manganese	1, 2, 3, 6	1, 2, 3, 6	200	2	—	—	Lognormal	-1.17150 0.75972	PTL	0.001	1.7
	4, 10	4, 10	105	14	—	—	Lognormal	-2.25817 0.70717	PTL	—	0.13
Mercury	All	All	307	99	—	—	?	—	NPTL	0.0002	0.0003
Molybdenum	1, 2, 3, 4, 10	1, 2, 3, 4, 10	299	97	GW-319	—	?	—	NPTL	0.01	0.018
	6	6	6	50	—	—	?	—	ID	—	NA
Nickel	1	1, 2, 6	108	74	GW-263 GW-283 GW-603 GW-776	—	?	—	NPTL	0.01	0.060
	2	1, 2, 3, 6, 10	218	83	GW-263 GW-283 GW-603 GW-776	—	?	—	NPTL	—	0.060

Table 8 (continued)

Element	Well cluster ^a	Data used ^b	N ^c	Percentage of ND ^d	Outliers (well numbers)		Distribution	Mean variance	Type ^e	Detection limit (mg/L)	Tolerance limit (mg/L) ^f
	3, 10	2, 3, 4, 6, 10	226	91	—	—	?	—	NPTL	—	0.020
	4	3, 4, 6, 10	203	93	—	—	?	—	NPTL	—	0.020
	6	All	305	87	GW-263 GW-283 GW-603 GW-776	—	?	—	NPTL	—	0.060
Nitrate-N	1	1, 3, 6, 10	203	76	GW-616	—	?	—	NPTL	0.2	6.9
	2	2, 3, 6, 10	147	82	GW-616	—	?	—	NPTL	—	6.9
	3, 6, 10	1, 2, 3, 6, 10	226	77	GW-616	—	?		NPTL	—	5.3
	4	4	85	40	—	—	Lognormal	-0.62959 0.54323	PTL	—	2.7
Potassium	1	1	80	0	—	—	Lognormal	0.56802 0.28696	PTL	0.6	14
	2	2	23	30	—	—	Lognormal	-0.06026 0.29501	PTL	—	4.2
	3, 10	3, 10	117	0	—	—	Lognormal	0.30386 0.23005	PTL	—	5.5
	4	4	87	5	—	—	Approximate lognormal	0.15380 0.28182	PTL	—	5.0
	6	6	7	0	—	—	Lognormal	1.03324 0.28923	PTL	—	100
Selenium	All	All	276	100	—	—	?	—	—	0.05	<0.05

Table 8 (continued)

Element	Well cluster ^a	Data used ^b	N ^c	Percentage of ND ^d	Outliers (well numbers)	Distribution	Mean variance	Type ^e	Detection limit (mg/L)	Tolerance limit (mg/L) ^f
Silicon	1	1	60	0	—	—	Lognormal 0.77042 0.21336	PTL	0.03	16
	2, 3	2, 3	91	0	GW-195	—	Normal 8.97278 3.31813	PTL	—	15
	4, 10	4, 10	90	0	—	—	?	NPTL	—	9.0
	6	6	6	0	—	—	Lognormal -0.02468 0.33771	PTL	—	17
Silver	All	All	305	100	—	—	?	NPTL	0.006	<0.006
Sodium	1	1	80	0	GW-711	—	Lognormal 1.07627 0.37285	PTL	0.02	64
	2, 3	2, 3	119	0	GW-636 GW-755 GW-768	—	Lognormal 0.75356 0.31161	PTL	—	22
Sodium (continued)	4	4	87	0	—	—	?	NPTL	—	9.7
	6	6	7	0	—	—	Lognormal 2.80675 0.26759	PTL	—	5200
	10	10	21	0	—	—	Lognormal 2.20150 0.21972	PTL	—	530
Strontium	1	1	79	0	—	—	Lognormal -0.34682 0.50513	PTL	0.0004	4.4
	2, 4	2, 4	110	1	GW-147 GW-645	—	Lognormal -1.62181 0.27182	PTL	—	0.079
	3, 6, 10	3, 6, 10	116	0	—	—	Lognormal -0.76826 0.38543	PTL	0.0004	0.92

Table 8 (continued)

Element	Well cluster ^a	Data used ^b	N ^c	Percentage of ND ^d	Outliers (well numbers)		Distribution	Mean variance	Type ^e	Detection limit (mg/L)	Tolerance limit (mg/L)
Sulfate	1, 6, 10	1, 6, 10	108	0	GW-211 GW-711	—	Lognormal	1.33957 0.47026	PTL	1	170
	2, 4	2, 4	110	9	—	—	Lognormal	0.49097 0.40800	PTL	—	19
	3	3	96	1	—	—	Lognormal	0.99916 0.29431	PTL	—	37
Thorium	All	All	305	100	—	—	?	—	NPTL	0.2	<0.2
Uranium	1	1, 2, 6	110	62	GW-058 GW-145 GW-229	—	?	—	NPTL	0.001	0.012
	2, 6	All	314	73	—	—	?	—	NPTL	—	0.0040
	3, 4, 10	2, 3, 4, 6, 10	234	78	—	—	?	—	NPTL	—	0.0050
Vanadium	All	All	305	96	GW-160 GW-195 GW-319 GW-765	—	?	—	NPTL	0.005	0.0044
Zinc	1, 3, 4, 6	All	305	2	GW-119 GW-172 GW-178 GW-208	GW-210 GW-230 GW-232 GW-366	Lognormal	-1.93746 0.30855	PTL	0.001	0.041
	2	1, 2, 3, 4, 6	287	2	GW-119 GW-172 GW-178 GW-208	GW-210 GW-230 GW-366	Lognormal	-1.92705 0.30988	PTL	—	0.043

Table 8 (continued)

Element	Well cluster ^a	Data used ^b	N ^c	Percentage of ND ^d	Outliers (well numbers)		Distribution	Mean variance	Type ^e	Detection limit (mg/L)	Tolerance limit (mg/L) ^f
	10	1, 3, 4, 6, 10	282	1	GW-119 GW-172 GW-178 GW-208	GW-210 GW-230 GW-232 GW-366	Lognormal	-1.95198 0.30398	PTL	—	0.040

^aNumber s indicate clusters for which the reference concentration (i.e., tolerance limit) was calculated.

^bNumbers indicate clusters from which data was used in calculating the tolerance limits.

^cNumber of data points.

^dPercentage of nondetect data.

^eID = insufficient data; NA = not applicable; NPTL = non-parametric tolerance limit; PTL = parametric tolerance limit.

^fLimit with 95% coverage and 95% confidence that 95% of the data are less than the limit.

Table 9. Reference values determined from cluster-specific data

Major ions	Cluster-specific tolerance limits (mg/L)					
	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 6	Cluster 10
Calcium	203	66	89	60		
Chloride	100				1×10^5	
Fluoride	2.3				12	25
Magnesium	49			36		
Nitrate				2.7		
Potassium	14	4.2		5.0	100	
Sodium	64			9.7	5200	530
Sulfate			37			
Trace metals	Cluster-specific tolerance limits (mg/L)					
	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 6	Cluster 10
Aluminum		6.1				
Boron	0.12		0.15			
Iron					11	
Molybdenum					?	
Silicon	16				17	
Strontium	4.4					

Table 10. Reference values used to evaluate groundwater quality at the Oak Ridge Y-12 Plant in previous studies

Analyte	Historical reference value (mg/L)								Maximum historical reference value (mg/L)	
	1989 ^a		1990 ^b		1991–1993 ^c		1993–1994 ^d			
	Knox Aquifer	ORR Aquitards	Knox Aquifer	ORR Aquitards	Knox Aquifer	ORR Aquitards	Knox Aquifer	ORR Aquitards	Knox Aquifer	ORR Aquitards
Aluminum	36	15	24	15	8.3	8.3	9.5	7.9	36	15
Antimony	<0.05	<0.05	<0.05		0.11	0.11	0.058	0.05	0.11	0.11
Arsenic	0.05	<0.005	<0.005						0.05	0
Barium	0.43	0.48							0	0.48
Beryllium	0.0091	<0.001		0.0017	0.0066	0.0066	0.0066	0.0019	0.0091	0.0066
Boron	0.59	0.064	0.17	1.2	1.1	1.1	1.3	0.57	1.3	1.2
Cadmium	0.01	0.02							0.01	0.02
Calcium	88	170	100	150					100	170
Chloride		13	11	30					11	30
Chromium	0.05	0.16							0.05	0.16
Cobalt	0.012	0.0083	0.0066	0.011	0.012	0.012	0.011	0.025	0.012	0.025
Copper	0.064	0.025	0.28	0.094	0.11	0.44	0.1	0.3	0.28	0.44
Fluoride			0.5	1.6					0.5	1.6
Iron	60	31	31	31	13.91	13.91	14	13	60	31
Lead	0.079	0.4	0.17						0.17	0.4
Magnesium	49	45	55	45					55	45
Manganese	0.79	2.4	0.34	3.6	0.49	2.4	0.32	2.7	0.79	3.6
Mercury	0.00023	0.0011	0.0021						0.0021	0.0011
Molybdenum	0.017	<0.01	<0.01	0.024	0.023	0.023	0.023	0.01	0.023	0.024

Table 10 (continued)

Analyte	Historical reference value (mg/L)								Maximum historical reference value (mg/L)	
	1989 ^a		1990 ^b		1991–1993 ^c		1993–1994 ^d			
	Knox Aquifer	ORR Aquitards	Knox Aquifer	ORR Aquitards	Knox Aquifer	ORR Aquitards	Knox Aquifer	ORR Aquitards	Knox Aquifer	ORR Aquitards
Nickel	0.43	0.032	0.39	0.98	0.18	0.18	0.18	0.33	0.43	0.98
Nitrate			0.9	0.6					0.9	0.6
Potassium	11	10	12	5.9					12	10
Selenium	<0.05	0.065	<0.05						0	0.065
Silicon	31	33	11	19					31	33
Silver	<0.006	<0.006							0	0
Sodium	6.6	110	4.8	110					6.6	110
Strontium			0.12	0.0095	1.5	0.88	2.8	0.83	2.8	0.88
Sulfate			15	178					15	178
Thorium	<0.2	<0.2	<0.2	<0.2	0.2	0.2	0.2	0.2	0.2	0.2
Uranium	0.018	0.028	0.003	0.028	0.01	0.01	0.007	0.015	0.018	0.028
Vanadium	0.14	0.016	0.067	0.016	0.064	0.064	0.064	0.058	0.14	0.064
Zinc	0.84	0.18	0.27	0.43	0.14	0.14	0.18	0.079	0.84	0.43

^aGeraghty & Miller, Inc. 1989a. Groundwater quality assessment report 1988 Chestnut Ridge Security Pit Hazardous Waster Disposal Unit at the Y-12 Plant. Y/SUB/89-00206C/6. Prepared for Martin Marietta Energy Systems, Inc., Oak Ridge, Tenn.

Geraghty & Miller, Inc. 1989b. Grounwater quality assessment report 1988 S-3 Ponds Waste Management Area at the Y-12 Plant. Y/SUB/89-00206C/7. Prepared for Martin Marietta Energy Systems, Inc., Oak Ridge, Tenn.

^bHSW Environmental Consultants, Inc. 1991a. Grounwater quality assessment report 1990 Chestnut Ridge Security Pit Hazardous Waster Disposal Unit at the Y-12 Plant. Y/SUB/91-YP507C/1.

HSW Environmental Consultants, Inc. 1991b. Groundwater quality report for the Bear Creek Hydrogeologic Regime: 1990 data interpretations and proposed program modifications. Y/SUB/91-YP507C/1/P2. Prepared for Martin Marietta Energy Systems, Inc., Oak Ridge, Tenn.

^cHSW Environmental Consultants, Inc. 1992. Groundwater quality assessment for the Bear Creek Hydrogeologic Regime at the Y-12 Plant: 1991 groundwater quality data interpretations and proposed program modifications. Y/SUB/92-YP507C/1/P2. Prepared for Martin Marietta Energy Systems, Inc., Oak Ridge, Tenn.

^dHSW Environmental Consultants, Inc. 1994. Groundwater quality report for the Bear Creek Hydrogeologic Regime: 1994 data interpretations and proposed program modifications. Y/SUB/94-EAQ10C/3/P2. Prepared for Martin Marietta Energy Systems, Inc., Oak Ridge, Tenn.

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