FACTORS RELATED TO THE WATER-YIELDING POTENTIAL OF ROCKS IN THE PIEDMONT AND VALLEY AND RIDGE PROVINCES OF PENNSYLVANIA

By Debra S. Knopman

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METRIC CONVERSION TABLE

For the use of readers who prefer to use metric units (International System), conversion factors for inch-pound units used in this report are listed below.

Multiply inch-pound unit	*By*	*To obtain metric unit*
inch	25.4	millimeter
foot (ft)	0.3048	meter
gallon (gal)	0.003785	cubic meter
gallon per minute (gal/min)	0.003785	cubic meter per minute

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ABSTRACT

A preliminary classification of the water-yielding potential of hydrogeologic units in the Piedmont and Valley and Ridge provinces of Pennsylvania is based on a set of physical factors readily available in the U.S. Geological Survey data base. Specific capacity was chosen as the measure of yield. The classification is made difficult by the wide range in specific-capacity values within individual hydrogeologic units. Within the study area, 186 hydrogeologic units are represented among the 4,391 well records for which a value of specific capacity has been entered in the data base. Specific-capacity values range from 0.01 to 891 gallons per minute per foot (gpm/ft) with a median value of 0.43 gpm/ft.

The approach taken in this study is to organize a hierarchy of factors available in the data base that relate to differences among hydrogeologic units, with lithology chosen as a starting point. Aggregation of wells according to their lithology can be reduced from 31 separate designations to 5 groups: dolomite-dominated carbonate rocks, limestone-dominated carbonate rocks, siliciclastic rocks, metamorphic and igneous rocks (except diabase), and diabase. Lithology alone can account for about 12 percent of the variation observed in the specific-capacity data. However, a classification of hydrogeologic units based on lithology and also accounting for differences in water use, casing diameter, topographic setting, well depth, and casing depth can explain up to about half the variation in specific-capacity values among carbonate rocks and siliciclastic rocks. The classification appears to be less effective for metamorphic and igneous rocks, in which 40 percent of the variation is explained. Water use and casing diameter are the most important single factors in explaining variation in specific-capacity data (15 percent and 18 percent, respectively), exceeding topographic setting, well depth, casing depth, and even lithology. Results of the study demonstrate the importance of accounting for differences in factors related to well construction before attempting to assess yield potential of hydrogeologic units related to natural factors.

INTRODUCTION

The fractured and soluble rocks in the Appalachian Valley and Ridge, Blue Ridge, and Piedmont physiographic provinces in the eastern United States store the water supply for 10 percent of the United States population. Yet these rocks are among the least understood and quantified major ground-water resources in the Nation. The water-bearing and water-transmitting properties of these rocks are highly variable, even on a local scale. Because of this variability, there is a need to classify hydrogeologic units as to their water-yielding potential.

If the primary factors that control this potential were known and their relative influence quantified, it would be an easy task to develop a logical classification. Indeed, from a geologic perspective, it would be tempting to assume that lithology is the single most important factor and to relate water-bearing and water-transmitting attributes to lithology alone, even in situations where topography, recharge processes, or well construction methods can substantially influence water-yielding potential. One way to avoid this possible bias in approaching the classification problem is to statistically relate a variety of likely factors to a measure of water-yielding potential.

Specific capacity, defined as discharge per unit time per unit drawdown, is a composite measure of the water-yielding potential of a well, and by extension, the surrounding rock. In many ground-water data bases, specific-capacity data are more abundant than more exact measures of water-transmitting ability (transmissivity or hydraulic conductivity). Clearly, in addition to water-transmitting properties, other characteristics need to be considered in evaluating ground-water resources, particularly rock storage capacity (storativity), recharge rates, boundary conditions, hydrogeologic unit thickness, and total volume of ground-water in storage. Nonetheless, specific capacity can be a meaningful response variable in a search for the primary factors that affect water-yielding potential.

Purpose and scope

The purpose of this investigation was to determine through statistical analyses the factors that relate to the water-yielding potential of hydrogeologic units. Use was made of the well records in the U.S. Geological Survey (USGS) Ground-Water Site Inventory (GWSI) data base for the Valley and Ridge, Piedmont, and to a very limited extent, the Blue Ridge provinces of Pennsylvania.

The study was conducted to support the Appalachian Valleys-Piedmont Regional Aquifer System Analysis (RASA) of the USGS, which was initiated in 1988. A fundamental objective of the RASA project is to develop a physical understanding of the storage, flow, and recharge of water in the saturated subsurface environment. The results of the statistical analyses are being used to support a practical classification and regional mapping of ground-water resources, and also assist in the identification of site-specific and physically-based studies of flow dynamics.

Study area

In Pennsylvania, the Appalachian-Piedmont RASA (APRASA) study area includes the Valley and Ridge, Blue Ridge, and Piedmont physiographic provinces (Figure 1). The Valley and Ridge is composed of the Appalachian Mountain and Great Valley sections. The Blue Ridge extends into Pennsylvania in the South Mountain section. The Piedmont province includes nearly all the remaining area in southeastern Pennsylvania.

The study area is characterized by consolidated bedrock that includes carbonate, sandstone, shale, metamorphic, and igneous rocks. Major zones of faulting and folding in the area are indicative of several episodes of tectonic activity. Openings formed during the tectonic episodes and enlarged by chemical weathering and solution account for the secondary permeability of these rocks. Numerous studies of ground-water resources in selected regions of the study area have been published during the last 30 years. Some of the more important of these are listed in the Appendix.

Organization of paper

An overview of the data base is first presented. First, the interpretation of specific capacity as a response variable is discussed and the explanatory variables available in the GWSI data base are given. Biases in the data base are considered and the choice of a subset of all available data is justified. Next, the statistical approach used for the analysis is summarized. Transformations of the specific-capacity data are considered. Non-parametric methods and regression modeling are briefly discussed.

The relation of individual and multiple factors to specific capacity is systematically analyzed for all data from all hydrogeologic units, and then separately for each major lithologic group. In particular, water use, casing diameter, topographic setting, depth of casing, depth of well, and saturated interval are considered individually and simultaneously. The factors affecting yield in each lithologic group are identified, and differences between lithologies are discussed. Finally, hypotheses are tested about appropriate groupings of hydrogeologic units within each major lithologic group.

SPECIFIC CAPACITY AND RELATED FACTORS

Specific capacity as a measure of yield

The use of the variable of specific capacity is a means of standardizing well discharge (volume per unit time) by drawdown within the well. As shown by Theis and others (1963), specific capacity (Q/s, in gallons per minute per foot of drawdown) can be expressed as a function of transmissivity (T, in gallons per minute per foot) of the aquifer, storativity (S, in dimensionless units), effective well radius (r_w, in feet), and time of pumping (t, in minutes) according to the non-equilibrium equation:

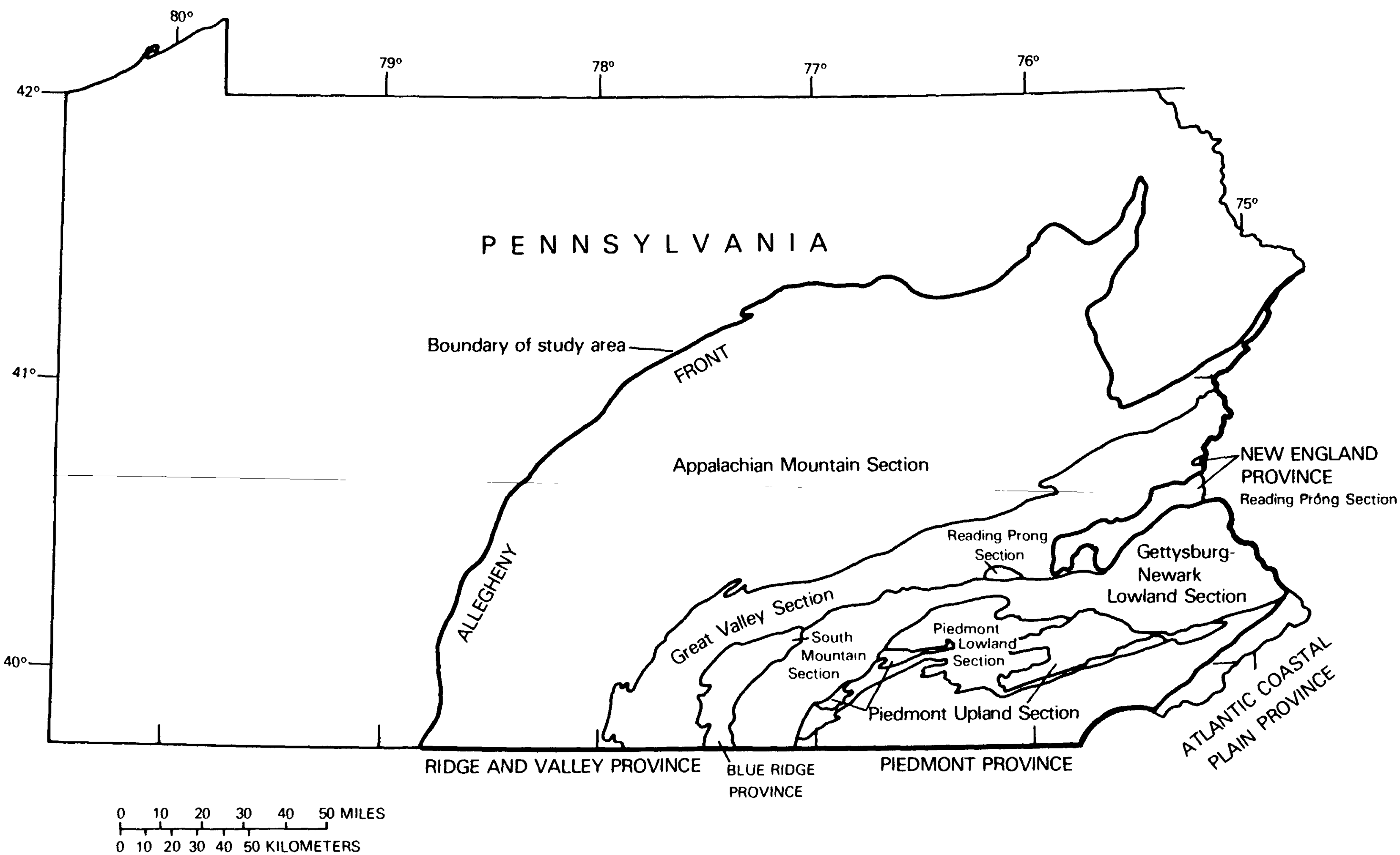


Figure 1.--Study area and physiographic provinces of Pennsylvania (Berg and others, 1989).

$$\frac{Q}{s} = \frac{T}{264 \log(Tt/1.87r_w^2 S) - 65.5} \qquad (1)$$

Thus, it can be seen that specific capacity is directly proportional to transmissivity. The sensitivity of specific capacity to the other terms is much less than to transmissivity (Domenico, 1972). Although transmissivity would be the most desirable variable to use for comparison of water-transmitting potential among hydrogeologic units, it is not reported frequently enough in Pennsylvania to provide a suitably large data base for this investigation. In contrast, specific capacity is reported in records of nearly 6,300 wells in the Valley and Ridge and Piedmont provinces in Pennsylvania.

For comparison among hydrogeologic units, others have recommended that specific capacity should be adjusted for saturated thickness (Walton, 1962; Siddiqui and Parizek, 1971). The term "saturated thickness" is used by these investigators to mean the depth interval over which the well is open to the saturated subsurface. In this paper, the term "saturated interval" is preferred to saturated thickness. The saturated interval may be estimated by taking the difference between the static water level and the well depth when the water level is below the bottom of the casing, or between the depth to the bottom of the casing and the well depth when the water level is above the bottom of the casing. Rather than starting with specific capacity adjusted for the saturated interval, the approach in this work was to investigate the statistical relation between the two composite variables.

Factors that may affect specific capacity

Variables in the GWSI data base can be grouped by their relation to location, well construction, hydrogeologic unit, discharge, and water use (Table 1). Those variables examined in this study are: topographic setting; depth to the bottom of the casing; well depth; primary aquifer; lithology; specific capacity, which is derived from discharge and static water level; and water use. In addition, the saturated interval is derived from casing depth, static water level, and well depth. Specific capacity is also dependent on pumping rate and pumping time, but the influence of these factors was not examined in this study.

It is important to note that in the Pennsylvania data base, the "primary aquifer" is populated with codes that are geologically based, and have not been officially designated as "aquifers". Therefore, throughout this report, the generic term "hydrogeologic unit" is used to refer to an entry listed in the data base as a "primary aquifer".

Topographic setting has been shown (Siddiqui and Parizek, 1971; Daniel, 1987) to relate to specific capacity. The variable of casing depth is hypothesized to indicate thickness of regolith--the unconsolidated material overlying an aquifer that may be partially saturated. Regolith, particularly in carbonate rocks, has been postulated to act as a sponge, slowly feeding precipitation and runoff from storage into the subsurface bedrock. In fact, Le Grand (1967, p. 1) advocates the use of the two factors of topographic setting and soil thickness as a good index for rating the water-yielding potential of a well site in the Piedmont and Blue Ridge provinces: "High-yielding wells

Table 1. Variables used from the Ground Water Site Inventory (GWSI) data base.

Location
- Site identification code
- Topographic setting

Well construction
- Casing diameter
- Depth to bottom of casing
- Depth of well
- Depth to top of open interval

Hydrogeologic unit
- Primary aquifer
- Lithology

Discharge
- Specific capacity
- Static water level

Water use
- Primary use of water

are common where thick residual soils and relatively low topographic areas are combined...."

The specific capacity of a well is usually considered to be correlated with the depth of the well, but the nature of the relation may vary by area and rock type. Cederstrom (1972) states that deeper wells generally yield more water than shallower wells. But in terms of yield per foot of drawdown per foot of well depth, Nutter and Otton (1969) note that wells deeper than 100 feet in the Piedmont (in Maryland) show a decreasing probability of obtaining a given yield with increasing depth. Daniel (1989) found this same relation in the Piedmont and Blue Ridge of North Carolina. A confounding factor in analysis of well depths and specific capacity, however, is that actual depth may reflect a minimum level of effort on the part of the driller to obtain sufficient yield and not an effort to maximize yield.

As exploratory data analysis proceeded, it became increasingly evident that the data base was not a random sample of wells within the study area. In some hydrogeologic units, only large diameter industrial or public water supply wells are included in the data base. In others, small domestic wells dominate. In some hydrogeologic units, the depth to the bottom of the casing and the depth of the well are highly correlated, indicating that as soon as sufficient water for the intended use was found, the well was completed. This is particularly true for domestic wells. Although these factors cannot be entirely eliminated from the data set, they can be controlled in a statistical sense to permit valid comparisons between and among hydrogeologic units.

STATISTICAL APPROACH

Non-parametric methods

Because of the persistent presence of outliers and the occasional violation of the normality assumption when working with small subsets of the data (for example, as few as 10 wells from a single hydrogeologic unit), nonparametric statistics are preferred. Consequently, median, interquartile range, and confidence intervals about the quartiles are better descriptions of central tendency and variability than their parametric counterparts of mean and variance.

Nonparametric summary statistics are estimated by arranging the specific-capacity values in ascending order and then assigning a rank to each value. A sample quantile X_q, where q is between 0 and 1, is defined as the value at which at most a proportion of q of the observations are less than X_q and a proportion of at most 1-q observations are above X_q (Iman and Conover, 1983, p. 113). Hence, $X_{.25}$, $X_{.50}$, and $X_{.75}$ are the 25th percentile (first quartile), the median, and the 75th percentile (third quartile), respectively.

Dependence among variables is often apparent when the data are displayed as a scatterplot. However, it is often useful to quantify the degree of correlation between two variables. Spearman's rho is a correlation coefficient, estimated from the ranks of variables, that gives a measure of monotonic correlation. This measure avoids assumptions about the nature of that dependence (that is, it need not be linear) and is resistant to the influence of outliers (Iman and Conover, 1983, p.126).

When reporting a quartile estimate or correlation coefficient, it is helpful to also note the statistical significance of the estimate. The significance of Spearman's rho is reported as a probability known as a p-value (SAS Institute, 1985, p. 869). It is the smallest level of significance (probability) at which the null hypothesis would be rejected when it is true. In the case of Spearman's rho, the null hypothesis is that the correlation coefficient is zero. A low p-value implies that there is a very small probability that the null hypothesis is in fact true. In general, the p-value is more informative than simply saying that a test is or is not significant at a particular level because it indicates how strongly the case can be made for rejecting the null hypothesis.

Analysis of variance (ANOVA) is a method of testing whether the means of groups of data are statistically different. A one-way ANOVA tests the influence of a single factor on a dependent variable, which in this study is specific capacity. A factorial ANOVA evaluates the influence of multiple factors on a dependent variable. It should be noted that ANOVA is very closely related to a linear regression model in which categorical explanatory variables are represented as combinations of indicator variables taking on values of 0 or 1.

The rank sum tests, Mann-Whitney and Kruskal-Wallis, are the nonparametric equivalent of ANOVA on two groups and more than two groups of a single variable, respectively. The null hypothesis of the Kruskal-Wallis test is that differences in the mean rank of the groups are not statistically significant. The p-value gives the probability of making a Type I error: rejecting the null hypothesis when it is true that the means are about the same. A very low p-value means that it is likely that another sample of a similar size also would show a difference between groups.

If differences between means of more than two groups is detected, the next step is to ascertain which groups differ from one another. A nonparametric multiple comparison test used here is Tukey's honestly significant difference test (SAS, p. 473, 1985). This is a simultaneous inference method appropriate for use when sample sizes among groups are unequal. An overall error rate is set, say at 5 percent, and then the error rate for all pairwise comparisons is constrained to stay within this bound.

Regression modeling

Regression is an optimization method in which a mathematical model is fitted to observations of some response variable. A distance criterion is used to determine the best fit. Typically, the model is a linear function of explanatory variables in addition to an additive error term to account for any random error in the model. It is also most common to use a least squares distance criterion. If explanatory variables are only weakly correlated with the response variable, then a model will be poorly fitted.

Linear regression is also used to estimate and test the significance of each of the factors and interaction of factors in the model and give a cumulative estimate of model fit. For example, the coefficient of determination, R^2, is sometimes used to indicate how much of the variation in the response variable is explained by the model. However, comparisons among models based on R^2 must be done with caution. Simply adding factors or parameters usually increases R^2, but this does not necessarily imply that the more complex model is better (Montgomery and Peck, 1982, p. 34).

Regression has the further advantage of producing residuals from the line fitting procedure. In this study, sources of bias in the data can be partially controlled by regressing on these factors (for example, casing diameter, water use, and topographic setting) and then using the residuals from the regression to test additional hypotheses about differences among groupings of the data (W.M. Alley, U.S. Geological Survey, oral comm., 1990). The residuals may be thought of as "smoothed" specific-capacity values from which some of the exogenous variation in the original data has been removed by regression.

RELATION OF INDIVIDUAL AND MULTIPLE FACTORS TO SPECIFIC CAPACITY

A total of 13,683 well records was available for the Valley and Ridge and Piedmont provinces in Pennsylvania, but only 6,299 contained a value for specific capacity. Not all of these records include entries for all of the variables of interest. To avoid any complications that could arise from a data set with missing values for some of the variables, a decision was made to work with the largest possible data set that was complete in as many of the variables of interest. The variables contained in this data set of 4,391 well records are those listed in Table 1. All references to the "data set" refer to this set.

The specific-capacity values for the full data set are summarized in the form of a histogram (Figure 2a). The distribution of untransformed specific-capacity values is positively skewed, strongly suggesting that some type of log transformation might be appropriate. For statistical purposes, it is more convenient to work with a variable or its transform that is approximately normal in its distribution. It should also be noted that within GWSI, values for specific capacity are stored to only two decimal places, so that data are in effect censored at very low values.

When the specific-capacity values are transformed by their natural logarithm (ln), a histogram of these values is more symmetric (Figure 2b). Based on the strength of this symmetry and the statistical convenience of working with the natural log, exploratory data analysis was carried out on ln specific capacity. The appropriateness of the ln transformation needs to be re-examined when the data set is aggregated by hydrogeologic unit, lithology, topographic setting, or other grouping. The most important feature of Figure 2b is the wide variability of specific-capacity values, spanning several orders of magnitude. Because of this overall variability in the data, a physical and statistical basis was sought for grouping hydrogeologic units according to common hydrogeologic characteristics. A successful classification would show significantly less variability in specific-capacity data within each grouping than in the data set as a whole.

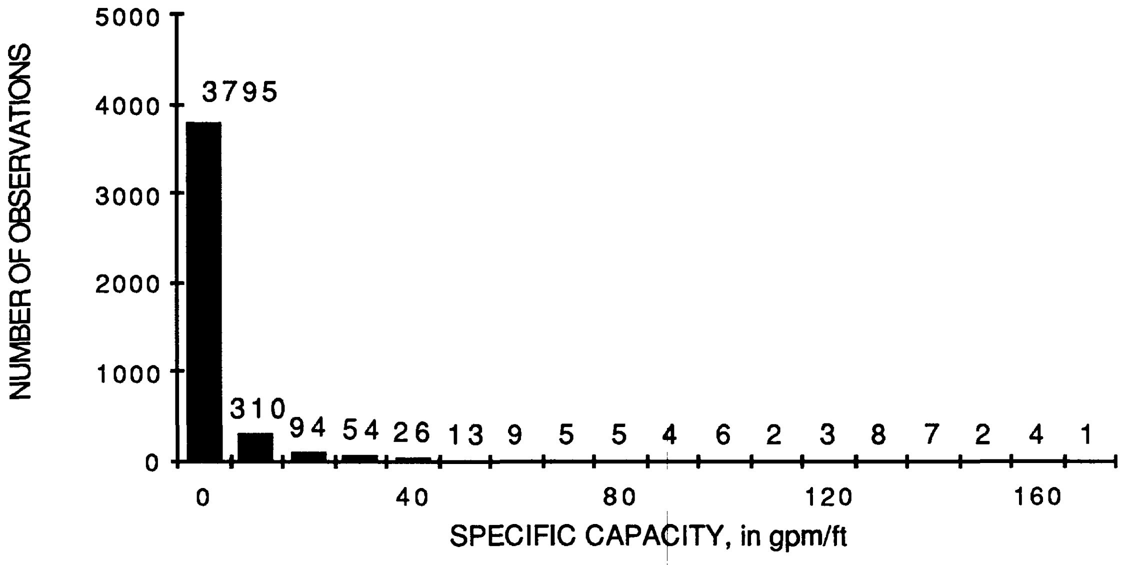
Water use

A potential source of bias is introduced into the data set by the intended use of the ground water. Water use may influence the selection of casing diameter, the depth of the well, the location of the well, and the topographic setting of the well. All of these factors in turn may correlate with the value of specific capacity. For example, wells drilled for domestic use are usually 6 inches in diameter or smaller. Owners are limited in their choice of topography or hydrogeologic unit by virtue of the boundaries of their property. In contrast, industrial and public supply wells tend to be 10 inches in diameter or greater, and are usually located with knowledge of the general hydraulic properties of the underlying hydrogeologic unit.

Boxplots of ln specific capacity for the top 9 of a total of 16 water uses, accounting for 4,330 of the 4,391 wells, were compared (Figure 3a). A boxplot summarizes the distribution of data within a group. The ends of the box are the 25th and 75th percentiles, respectively, and the interquartile range is the length of the box. The median is the line drawn within the box. In Figure 3a, the relative symmetry of the median with respect to the upper and lower quartiles indicates that the ln-transform is still appropriate, even when the data are aggregated by water use.

Boxplots convey other useful information about the data distribution besides the quartiles. Parentheses usually within the box mark the 90 percent confidence interval about the median. A missing parenthesis simply means that it coincided with one of the quartile estimates. The lines from either end of the box extend to the lower and upper adjacent values. These are the lowest and highest values, respectively, within 1.5 times the interquartile range from the ends of the box. Points beyond the adjacent values are plotted individually as either "outside" values or "far out" values. Outside values

a. Untransformed data.



b. Natural log-transformed data.

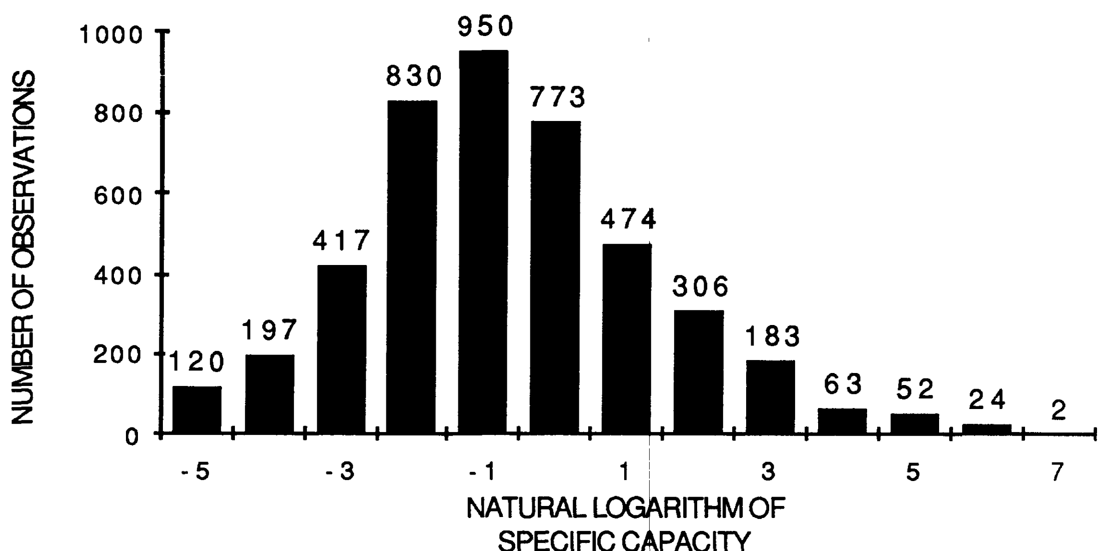


Figure 2.--Histograms showing distribution of specific-capacity data. (a) untransformed, (b) ln-transformed.

are located between 1.5 and 3 times the interquartile range from the ends of the box. Far out values are located more than 3 times the interquartile range from the ends of the box.

A Kruskal-Wallis (KW) test showed that differences among the mean ranks of specific capacity for each of these water uses are highly significant ($p=0.0001$). Tukey's multiple comparison test on the ranks of the ln-transformed specific-capacity data indicated that the mean rank of domestic wells is significantly different than nearly all of the other uses. The Tukey test further suggested that the other uses may be combined into two groups: one for public and industrial wells and the other for commercial, institutional, stock, and unused wells. A KW test on these three combined groups of water use (domestic, public and industrial, and commercial and other uses) was highly significant ($p=0.0001$), and another Tukey test further indicated that each of the mean ranks of these three groups is different than the others.

The ordering from lowest to highest of quartile estimates by category is domestic, commercial, and public supply and industrial (Figure 3b). From a one-way ANOVA on ln specific capacity using the three combined water-use groups, the coefficient of determination (R^2) indicates that about 15 percent of the variation in the specific-capacity data can be explained by differences in water use alone. A similar result was obtained when all 16 water-use groups were considered, implying that very little information is lost in the aggregation process.

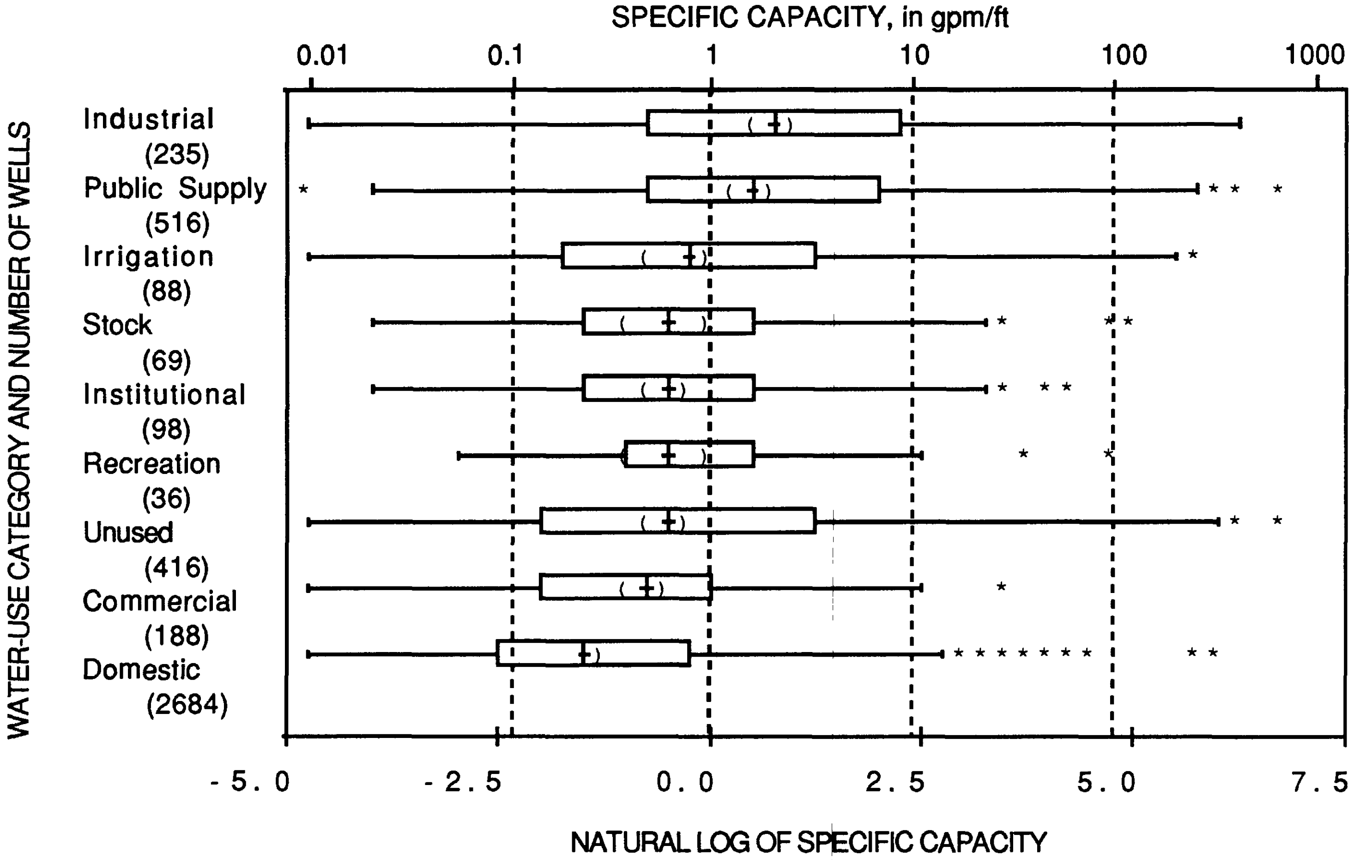
Casing diameter

Another bias in the specific-capacity data is introduced by the variable of casing diameter. Boxplots of the 7 most frequently occurring casing diameters were compared (Figure 4a). As casing diameter increases beyond 6.3 inches, the median of ln specific capacity increases considerably. A KW test showed that these differences are significant ($p=0.0001$). In fact, a one-way ANOVA on casing diameter indicates that 18 percent of the variation in the specific-capacity data can be explained by differences in casing diameter.

A Tukey test further suggested that casing diameters can be combined into 4 groupings: less than 6 inches, between 6 and 7 inches, between 8 and 9 inches, and 10 inches and greater. KW and Tukey tests comparing the mean ranks of specific capacity of these four combined groupings showed that they were significantly different from one another.

An obvious question is whether casing diameter and water use are statistically correlated. The frequency of occurrence for the combined groupings of the two variables (Table 2) seems to confirm the general association between small casing diameters and domestic wells and large casing diameters and public and industrial wells. This same relation was shown by Daniel (1989, p. 16). Nonetheless, both casing diameter and water use are significant factors ($p = 0.0001$) in contrast to an interaction term ($p=0.28$) when a two-way ANOVA on ln specific capacity is run. About 21 percent of the variability in the data can be explained when both factors are considered.

a. All categories



EXPLANATION

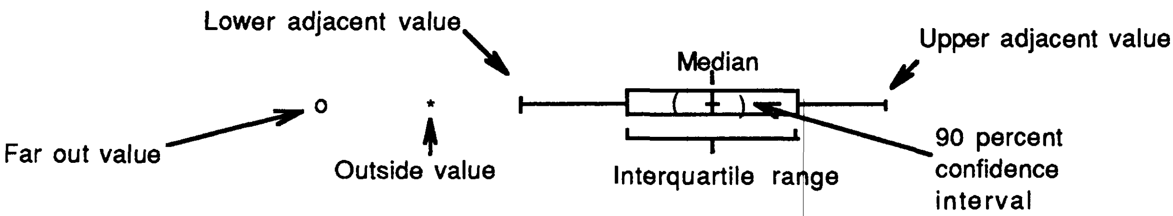
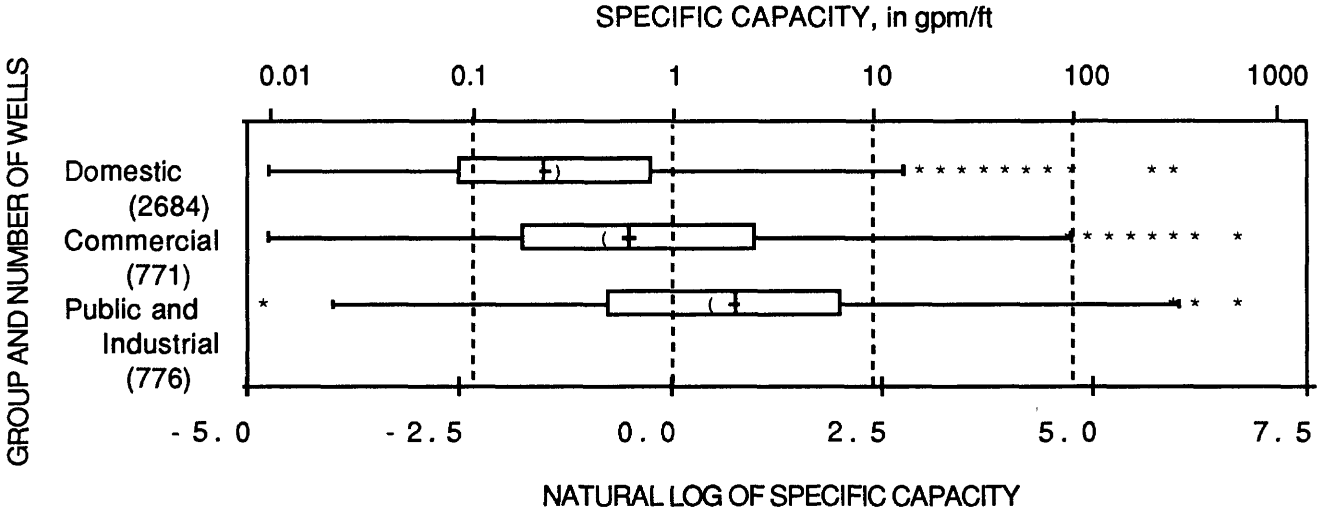


Figure 3.--Boxplots showing specific capacity by water-use category. (a) all categories, (b) combined groups. The number of wells within each designated water use is given under each label, and the 90 percent confidence interval about the median is marked by parentheses.

b. Combined groups



EXPLANATION

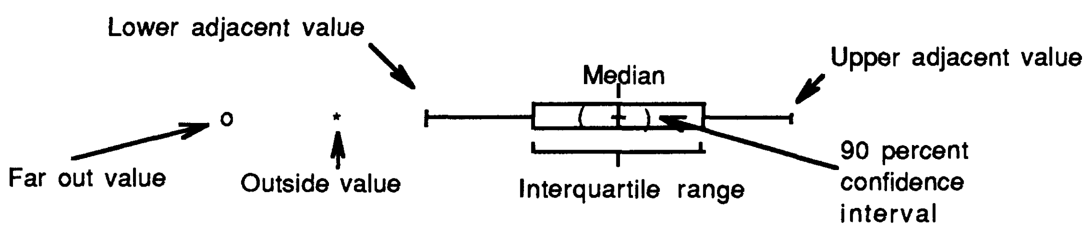
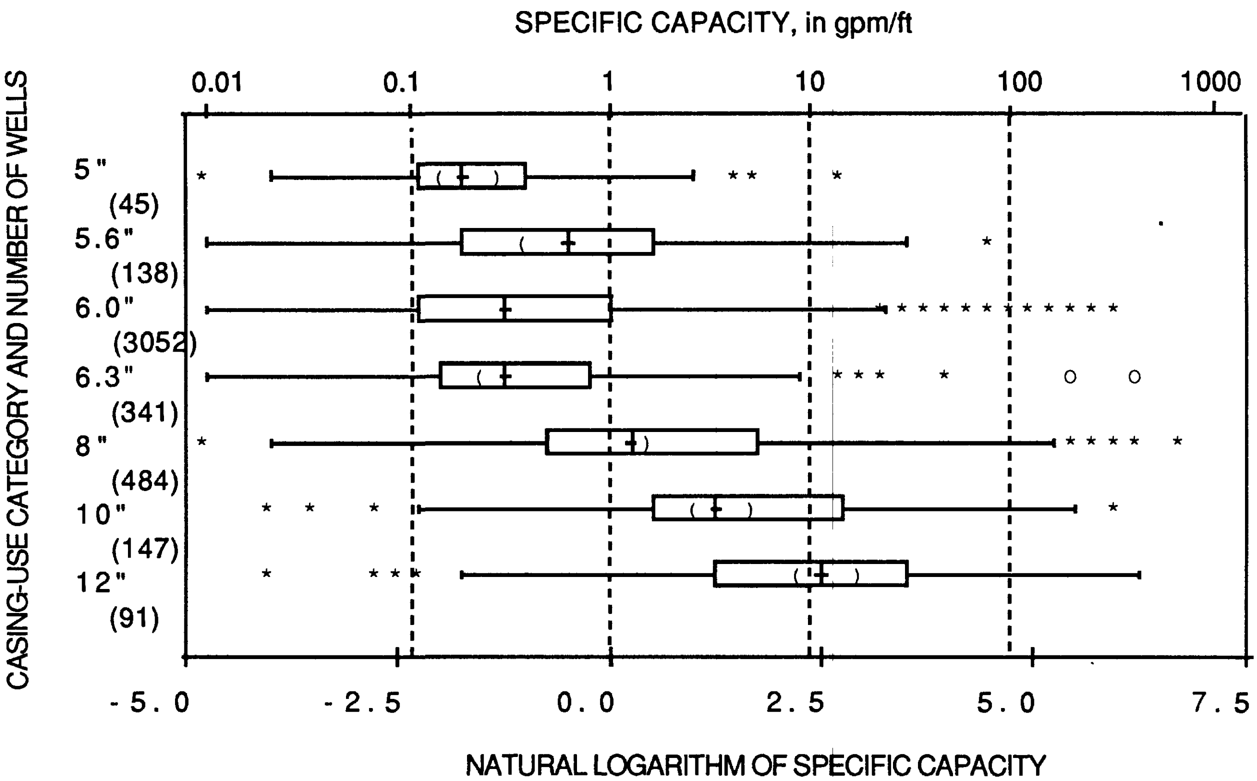


Figure 3.--Boxplots showing specific capacity by water-use category. (a) all categories, (b) combined groups. The number of wells within each designated water use is given under each label, and the 90 percent confidence interval about the median is marked by parentheses.

a. All diameters



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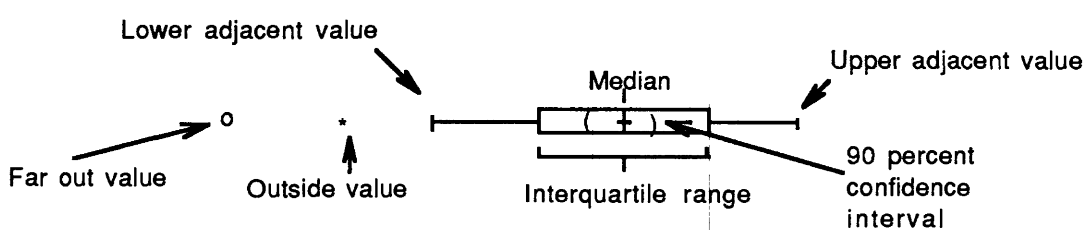
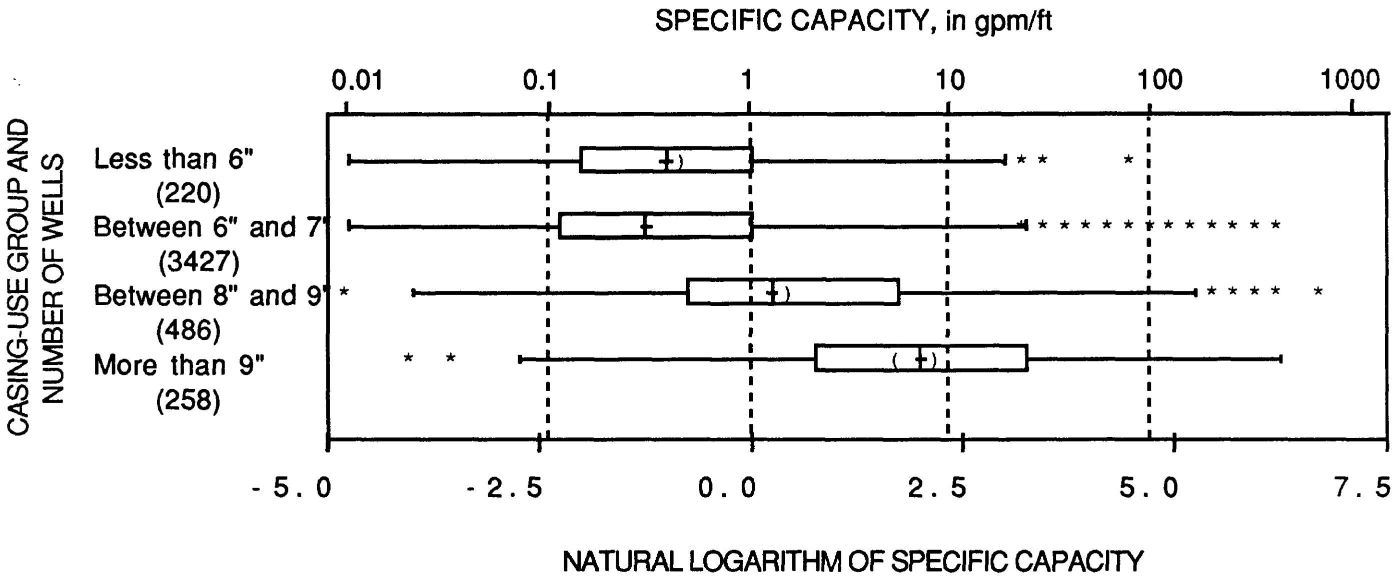


Figure 4.--Boxplots showing specific capacity by casing diameter. (a) all diameters, (b) combined groups. The number of wells within each designated casing diameter is given under each label, and the 90 percent confidence interval about the median is marked by parentheses.

b. Combined groups



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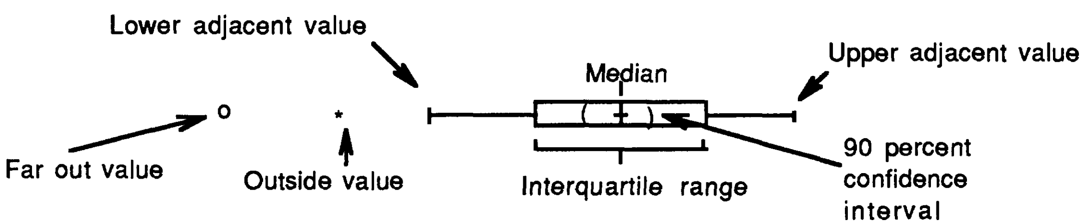


Figure 4.--Boxplots showing specific capacity by casing diameter. (a) all diameters, (b) combined groups. The number of wells within each designated casing diameter is given under each label, and the 90 percent confidence interval about the median is marked by parentheses.

Table 2.--Frequency table of combined casing-diameter groupings versus combined water-use groupings.

	Number of wells in each water-use group			
Casing Diameter (in inches)	Domestic	Commercial	Public Supply and Industrial	Total
Less than 6	155	55	10	220
Between 6 and 7	2512	626	289	3427
Between 8 and 9	14	173	299	486
Greater than 9	3	77	178	258
TOTAL	2684	931	776	4391

Topographic setting

The relation of topographic setting to specific capacity has been reported for a set of 80 wells in carbonate rocks in Nittany and Penns valleys in central Pennsylvania (Siddiqui and Parizek, 1971) and fractured crystalline rocks in the Piedmont and Blue Ridge provinces of North Carolina (Daniel, 1989). Boxplots of 8 topographic settings (Figure 5a) confirm the earlier results that wells located in valley flats and flat surfaces tend to have higher specific-capacity values than wells located on hillsides or hilltops. However, a one-way ANOVA on topographic setting indicates that only about 7 percent of the total variation in the ln specific-capacity data can be explained by this factor alone.

KW and Tukey tests suggest that significant differences among the topographic settings do exist for some pairings. Interestingly, hillsides and hilltops can be treated as one grouping, henceforth referred to as "hills", while all other topographic settings (with the exception of pediments) can be grouped together. This group is referred to as "valleys". Wells located in pediments (literally, at the foot of mountains) are treated as a third category, but only account for 16 wells in the entire data set. KW and Tukey tests on these 3 combined groupings (Figure 5b) show that significant differences do exist between each pairing.

The weak explanatory power of topographic setting is further confirmed when water use and casing diameter are also considered. A three-way ANOVA using the combined groupings of each of the three factors explains 24 percent of the variation in the ln specific-capacity data, compared to 21 percent for casing diameter and water use. Each of the three factors, however, is significant ($p=0.0001$) in the regression.

Lithology

The relation of lithology to specific capacity was considered by itself before controlling for the additional effect on the specific-capacity data introduced by water use, casing diameter, and topographic setting, Boxplots compare the 13 lithologies (Figure 6a) for which more than 20 well records were available (out of a total of 31 lithologies in the data base). As expected, the median and range of values for carbonate rocks exceed those for other rock types. A one-way ANOVA on ln specific capacity using lithology as a single factor produced an R^2 of about 12 percent. When water use, casing diameter, and topographic setting (in the form of their combined groupings) are also considered, 31 percent of the variation in ln specific-capacity values can be explained. Recall that when only the three factors excluding lithology are considered, 24 percent of the variation is explained. Clearly, lithology is an important factor, but without controlling for other factors, it can only explain a portion of the variation in the data.

An effort was made to consolidate the 31 lithologies in the GWSI data base for the study area into a much smaller number of groupings. KW and Tukey tests, in combination with knowledge of similar rock types, led to 5 lithologic groupings (Figure 6b) that were significantly different from one another. The first grouping includes dolomite, interbedded limestone and dolomite, and marble. Wells classified as being in limestone only could not be included in the first group and instead were put in their own group. The third group, defined as siliciclastic rocks, is comprised of sandstone, shale, conglomerates, interbedded limestone and shale, chert, and gypsum. The fourth grouping includes all of the metamorphic and igneous rocks except for diabase, which is the single rock type represented in the fifth group.

Comparison of the results of the factorial ANOVA using the 31 lithologies to the results from using the 5 groupings of lithology indicates that very little information is lost in the aggregation of lithologies: 28 percent of the variation in the ln specific-capacity data (in contrast to 31 percent) is explained when the five lithologic groupings are considered along with the combined groupings of the other three factors. Nonetheless, use of the five groupings (in comparison to the 31 lithologies) does simplify further analysis considerably.

When a KW test was carried out on residuals of ln specific capacity produced by regression on water use, casing diameter, and topographic setting, the five lithologic groupings described above were still significantly different from one another. (A KW test also showed significant differences among the 31 lithologies.) Use of the residuals is a way of controlling for the three factors while comparing different lithologies.

If the basic composition of the lithologic groupings is revisited using the residuals, the results are similar but not identical to ln specific capacity. There are two primary differences in the groupings. First, the Tukey test does not show significant differences between siliciclastic rocks and most of the metamorphic and igneous rocks. Thus, these two groups could be combined. And second, gneiss could be placed in its own group or combined with diabase. This result is ambiguous because the Tukey test shows a significant difference between gneiss and metamorphics generally, but not between gneiss and either schist, granite, gabbro, or igneous rocks. There are no differences in the two groupings of the carbonate rocks. Therefore, 4 combined groupings are justified solely in terms of the results of the Tukey test applied to the residual specific-capacity values.

It should be noted that neither these four groupings nor the five formed from the ln specific-capacity data before regression are the only ones that could have been formed. The lithologic code in the GWSI data base is both subjective and imprecise in terms of water-transmitting properties of the rock. For example, on the basis of hydrogeology, argillaceous limestones with a relatively high clay content and

a. All settings

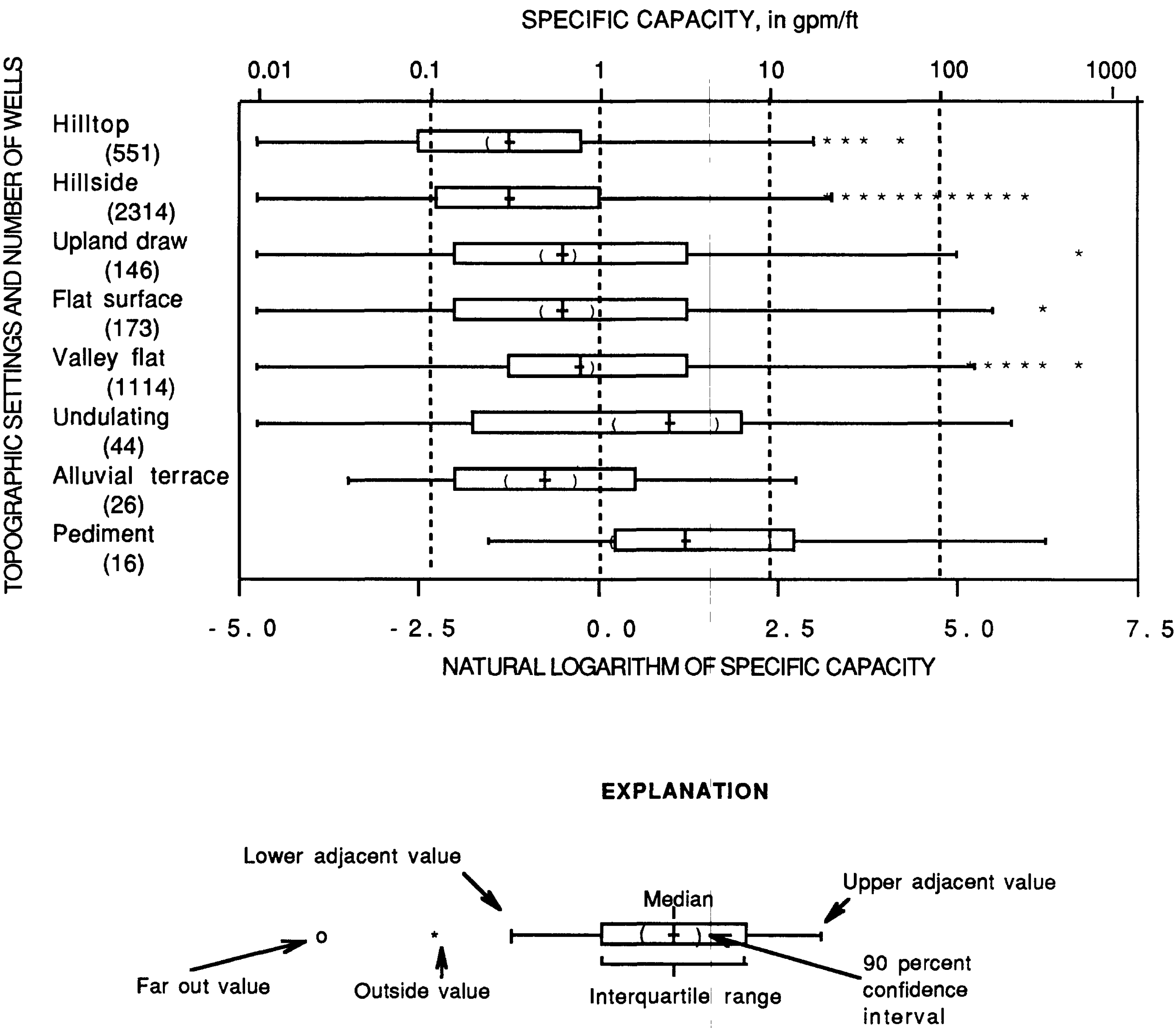
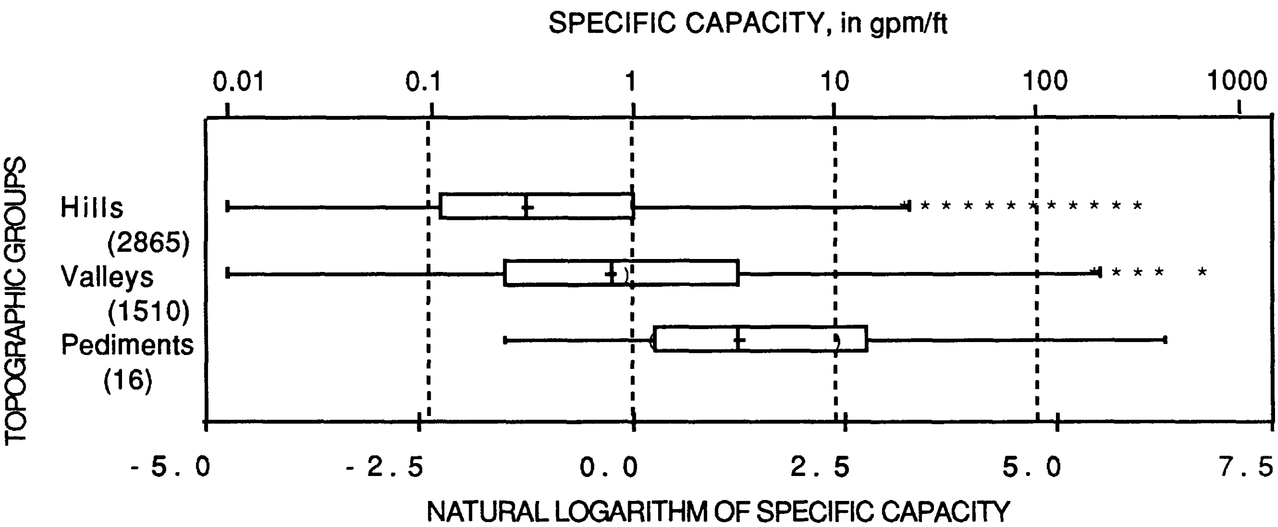


Figure 5.--Boxplots showing specific capacity by topographic setting. (a) all settings, (b) combined groups. The number of wells within each designated topographic setting is given under each label, and the 90 percent confidence interval about the median is marked by parentheses.

b. Combined groups



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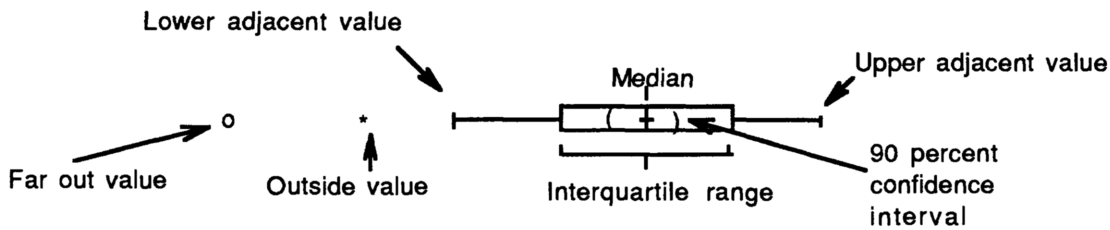
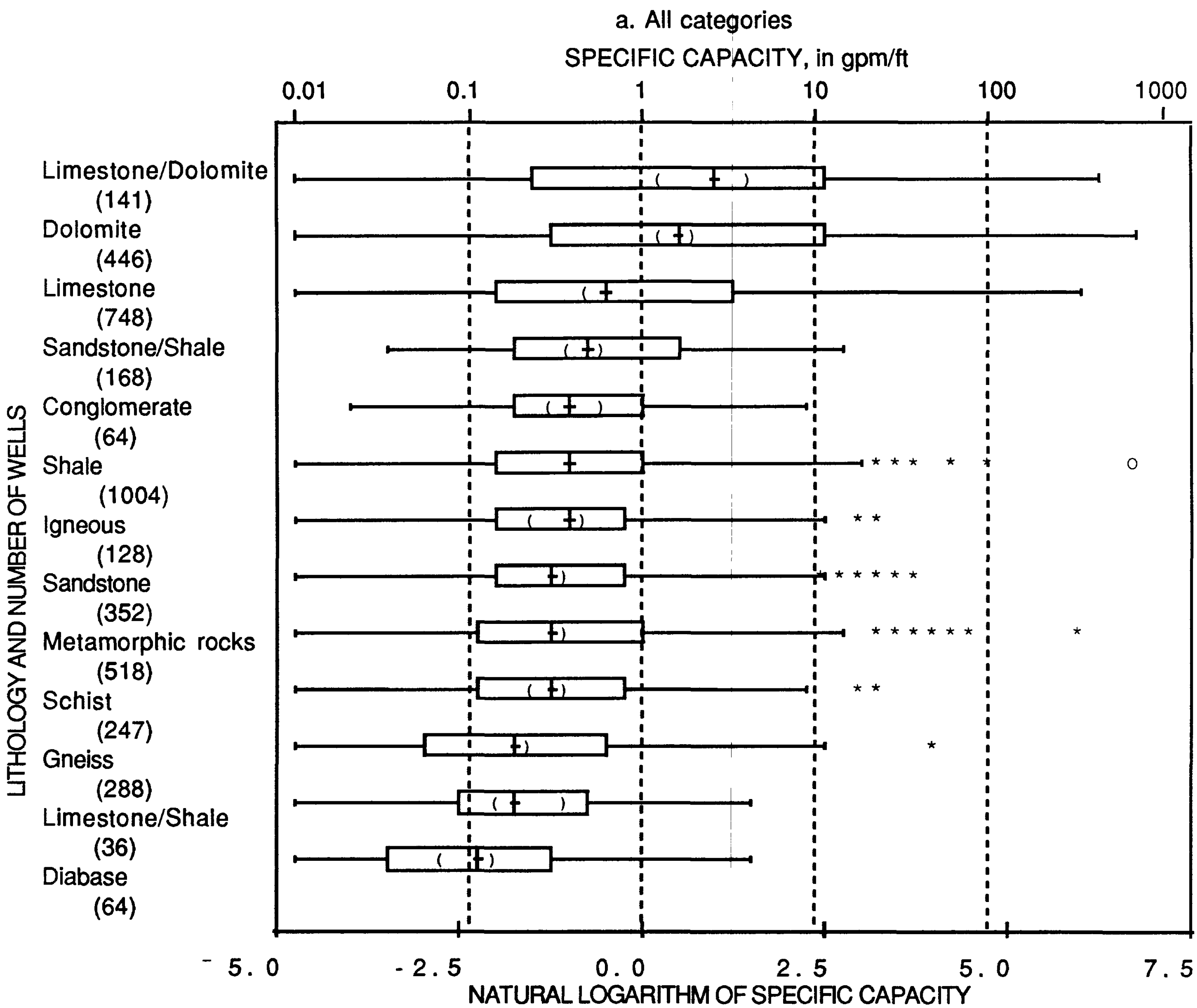


Figure 5.--Boxplots showing specific capacity by topographic setting. (a) all settings, (b) combined groups. The number of wells within each designated topographic setting is given under each label, and the 90 percent confidence interval about the median is marked by parentheses.



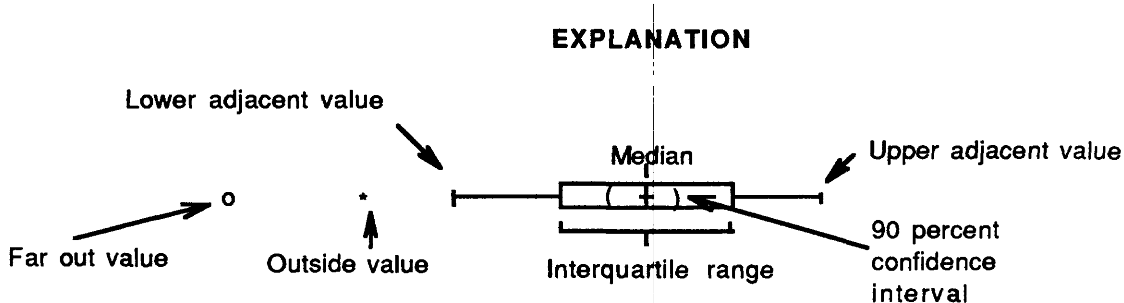
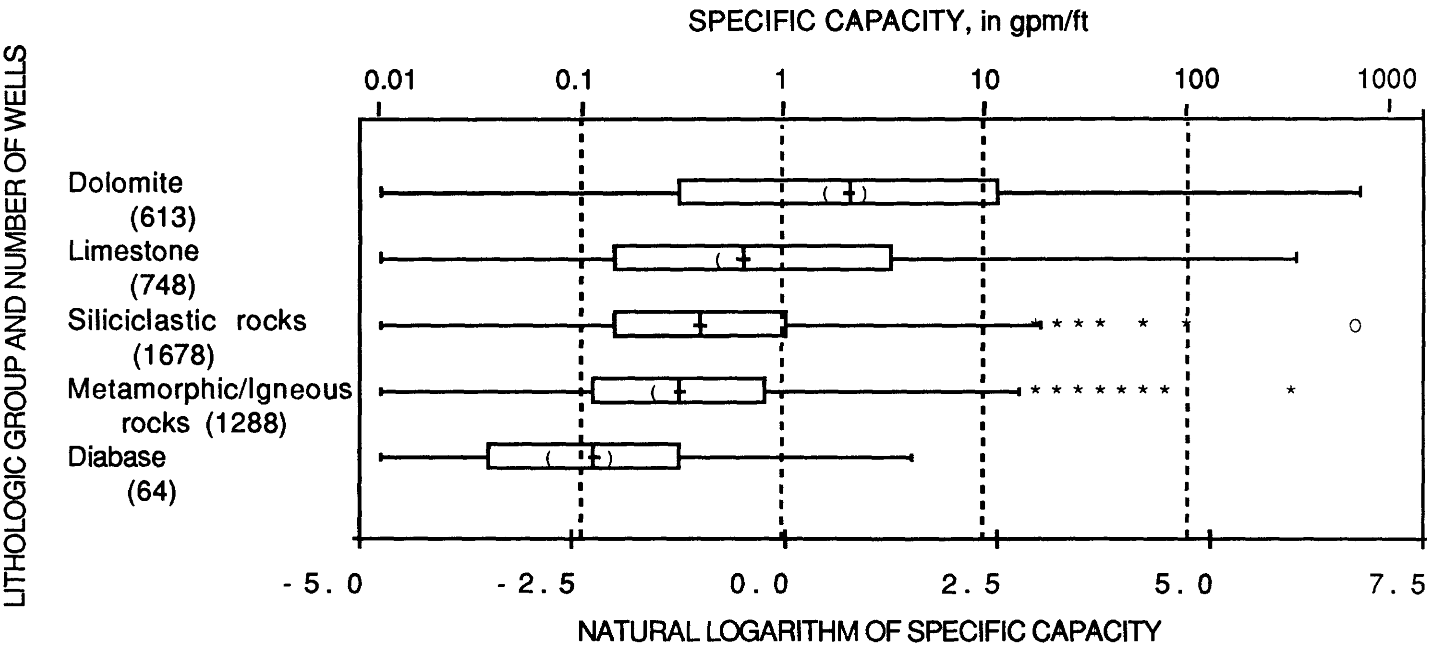


Figure 6.-- Boxplots showing specific capacity by lithology. (a) all lithologies, (b) combined groups. The number of wells within each designated lithology is given under each label, and the 90 percent confidence interval about the median is marked by parentheses.

b. Combined groups



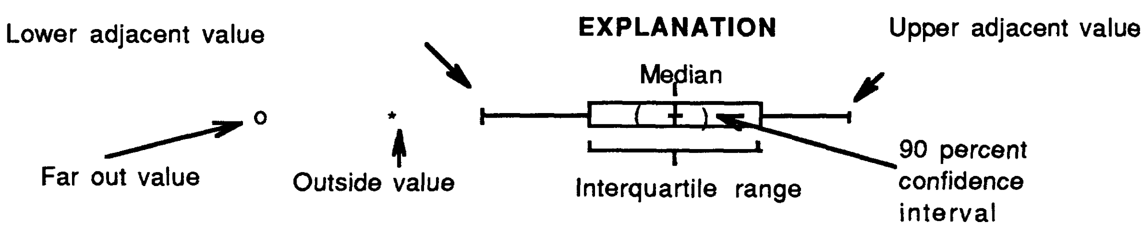


Figure 6.-- Boxplots showing specific capacity by lithology. (a) all lithologies, (b) combined groups. The number of wells within each designated lithology is given under each label, and the 90 percent confidence interval about the median is marked by parentheses.

consequently lower permeability could be placed in a separate grouping below the siliciclastic rocks.

For subsequent analysis, the original five groupings are retained. This is done for three reasons. First, combining siliciclastic rocks with the metamorphic and igneous rocks comprises a very large group of hydrogeologic units with diverse physical properties. If the purpose of the aggregation of lithologies is to simplify analysis, then little advantage is gained by lumping so many diverse rocks types together. Second, differences among the five groupings are significant according to KW and Tukey tests whether the raw specific-capacity values or the residual specific-capacity values are used.

Finally, the classification of gneiss with either the rest of the metamorphic rocks or with diabase is somewhat arbitrary. In the absence of an unambiguous statistical argument for the classification with diabase, gneiss will continue to be grouped with the other metamorphic rocks. (If gneiss were grouped with diabase, then the quartile estimates of diabase increase (Figure 6b). By removing gneiss from the metamorphic and igneous rocks, the quartile estimates for this grouping also increase to the point where no differences can be seen between it and the siliciclastic rocks.) The same basic argument for gneiss also applies to interbedded limestone and shale which is grouped with the siliciclastic rocks.

Depth of casing

It is hypothesized that the depth of casing in some hydrogeologic units may relate to the thickness of regolith. It is further possible that in carbonate rocks, regolith thickness is correlated with specific capacity. However, taking the 4,391 wells in the aggregate, casing depth and specific capacity are weakly correlated (Spearman's rho of 0.15, with $p=0.0001$).

The correlation between casing depth and specific capacity does vary considerably by water use category (Figure 7a). For domestic wells, the correlation coefficient is 0.03 ($p=0.14$). In contrast, commercial wells show a correlation coefficient of 0.13 ($p=0.0001$) and public and industrial wells show a correlation coefficient of 0.28 ($p=0.0001$). These results seem to indicate significant differences in well construction practices across the three primary water uses, consistent with the results of Daniel (1989, p. 16).

A similar trend of increasing correlation between greater casing depth and larger specific capacity is also seen as casing diameter increases (Figure 7b). Correlation is very weak in the small diameter wells and much stronger in wells with diameters between 8 and 9 inches (Spearman's rho of 0.29 and $p=0.0001$). Conversely, correlation between casing depth and specific capacity among wells with casing diameters of 10 inches or greater is very weak. The correlation coefficient is 0.08 ($p=0.22$). Further, as shown in Figure 7c, when topographic setting is considered, using the two combined groupings of hills and valleys, the correlation is only 0.12 ($p=0.0001$) and 0.21 ($p=0.0001$), respectively.

When the three factors of water use, casing diameter, and topographic setting are included in a regression model with casing depth, 24 percent of the variability in the data are accounted for, the same as when casing depth is excluded from the model.

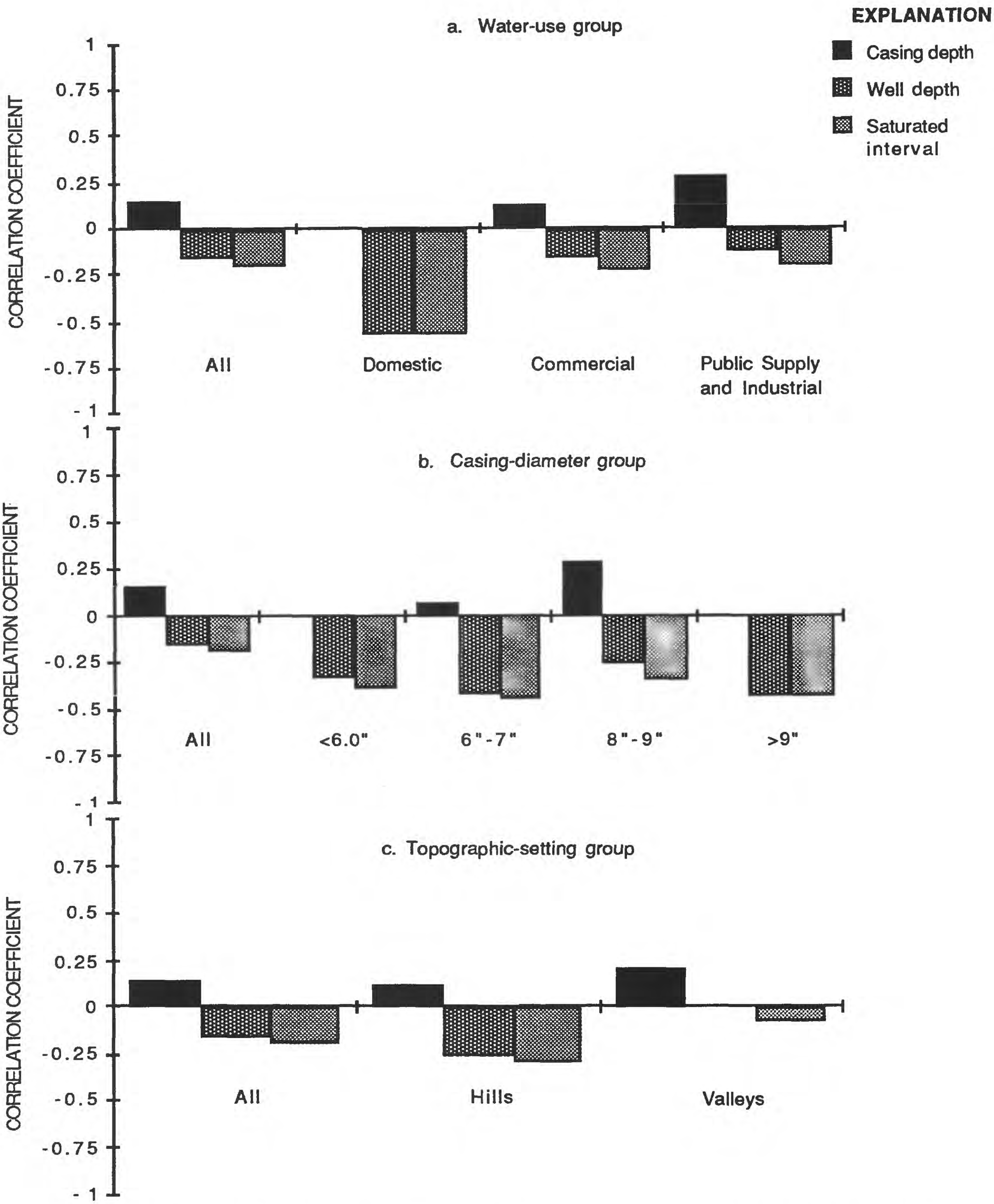


Figure 7.--Graphs showing correlation between specific capacity and casing depth, well depth, and saturated interval. (a) by water-use group, (b) by casing-diameter group, and (c) by topographic-setting group.

Therefore, in the aggregate, casing depth is not a significant factor in explaining variation in specific capacity. When individual lithologies are taken into account, the results are similar, as will be discussed below.

Depth of well

In contrast to the low positive correlation observed between casing depth and specific capacity, correlation between well depth and specific capacity is negative. Considering the data set as a whole, the correlation coefficient is -0.16 (p=0.0001). When the data are grouped by major water-use category (Figure 7a), the variation among the water uses in the correlation between well depth and specific capacity is great. For domestic wells, the correlation coefficient is -0.56 (p=0.0001). For the commercial and industrial and public supply groups, the correlation coefficients are -0.16 (p=0.0001) and -0.13 (p=0.0001), respectively.

No clear pattern emerges among the four groupings by casing diameter (Figure 7b). Correlation coefficients are -0.34 for diameters less than 6 inches, -0.42 for diameters between 6 and 7 inches, -0.26 for diameters between 8 and 9 inches, and -0.43 for diameters of 10 inches and greater. All estimates had p-values of 0.0001. Interestingly, all estimates of correlation are higher than the estimates for the fully aggregated data set of 4,391 wells, further confirming the importance of controlling for casing diameter. Controlling for topographic setting (Figure 7c), the correlation coefficients for hills is -0.27 (p=0.0001). There is virtually no correlation between specific capacity and well depth among wells located in valleys.

When well depth is considered in a regression model with water use, casing diameter, and topographic setting, 38 percent of the variation in the ln specific-capacity data is explained. Thus, well depth is clearly an influential factor on specific capacity in the aggregate, although its effects vary depending on the subset of the data that is examined.

Saturated interval

Saturated interval is highly and positively correlated (0.88) with well depth when all the data are taken in the aggregate. Therefore, where Spearman's rho between specific capacity and well depth is -0.16, the correlation coefficient between specific capacity and saturated interval is -0.20. When the data are grouped by water use, casing diameter, and topographic setting (Figures 7a-c), the magnitude of correlation between specific capacity and saturated interval is very close to that observed between specific capacity and well depth. The direction of the correlation with specific capacity is always negative for saturated interval as it is for well depth. Similarly, a regression model with saturated thickness included with water use, casing diameter, and topographic setting also explains 38 percent of the variation in the specific-capacity data.

Summary

A statistical approach was used on the full data set to analyze the relation of seven factors, both individually and in combination, with specific capacity. For the four categorical factors of water use, casing diameter, topographic setting, and lithology, an effort was made to aggregate the large number of groups for each factor into a much smaller number. The aggregation process is summarized in Figure 8. Using statistical inference drawn from KW and Tukey tests, there was relatively little ambiguity in the aggregation of water use, casing diameter, and topographic setting. Lithologies were aggregated by statistical inference and, in a few cases, by professional judgement to balance the need for an appropriate number of groups against the inconclusiveness of the statistical tests alone.

The factors correlated with specific capacity when all well records from all hydrogeologic units are taken together are: water use, casing diameter, topographic setting, well depth, and lithology. A summary of the variation explained by individual and multiple factors is given in Figure 9. Casing depth is not particularly useful in explaining variation in the specific-capacity data when taken as a whole. Saturated interval proved to be highly correlated with well depth, and thus provided no additional useful information.

RELATION OF INDIVIDUAL AND MULTIPLE FACTORS TO SPECIFIC CAPACITY USING DATA AGGREGATED BY LITHOLOGIC GROUPING

The same factors, excluding lithology, evaluated in the preceding section are evaluated for their relation to specific capacity for each of five aggregated lithologic groupings. These groupings are:

Dolomite, limestone mixed with dolomite, and marble (606 wells);

Limestone (747 wells);

Siliciclastic rocks (1664 wells);

Metamorphic and igneous rocks (1260 wells);

Diabase (64 wells).

The groups are arranged in decreasing order of quartile estimates, with the dolomite group exhibiting the highest quartile estimates.

The choice of lithology as a starting point for a systematic classification is both convenient to implement and justifiable on physical grounds. Lithology is really a summary description of mineral composition, grain size, and packing of grains of

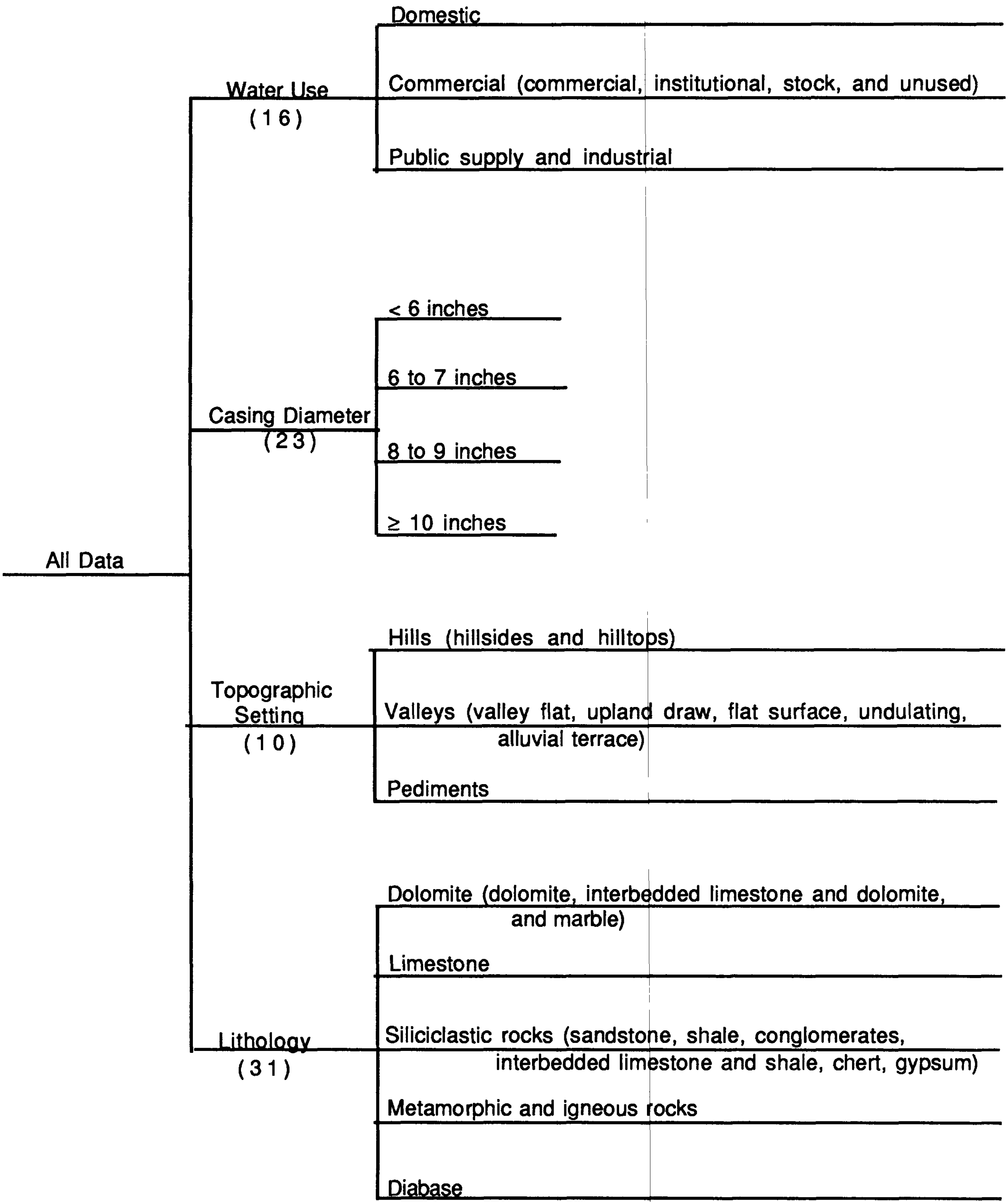


Figure 8.--Diagram showing aggregated groups for the categorical variables of water use, casing diameter, topographic setting, and lithology. Numbers in parentheses are the number of categories prior to grouping.

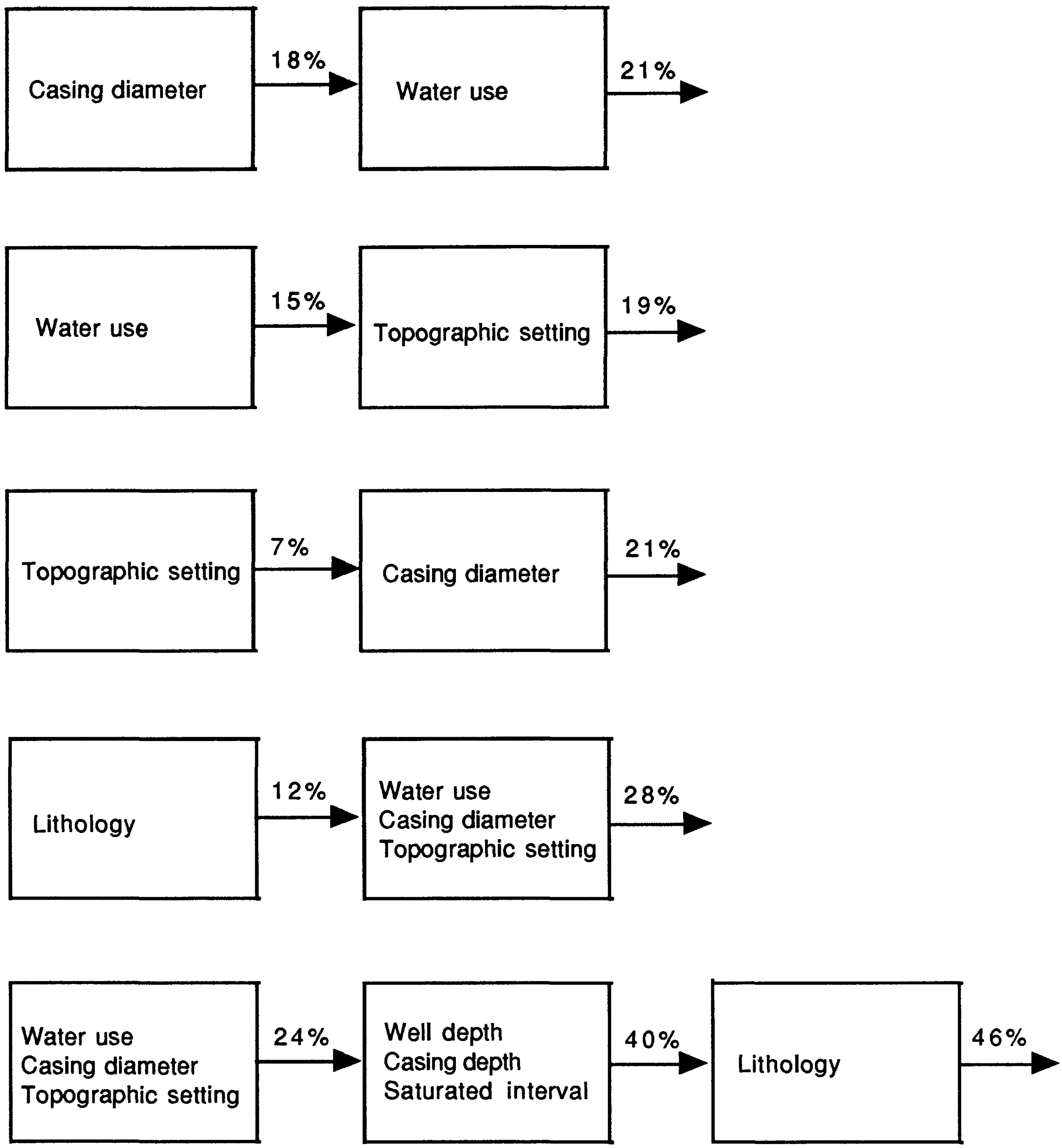


Figure 9.--Diagram showing amount of variation explained in specific-capacity values by regression models with various combinations of explanatory variables.

sediments or rocks (Freeze and Cherry, 1979). Ideally, stratigraphy, structural features, and flow dynamics in combination with lithology would provide the most complete description of the hydrogeologic setting and the best predictor of yield potential. Practically speaking, this additional information is rarely available in adequate quantity and detail to be applied.

Water use

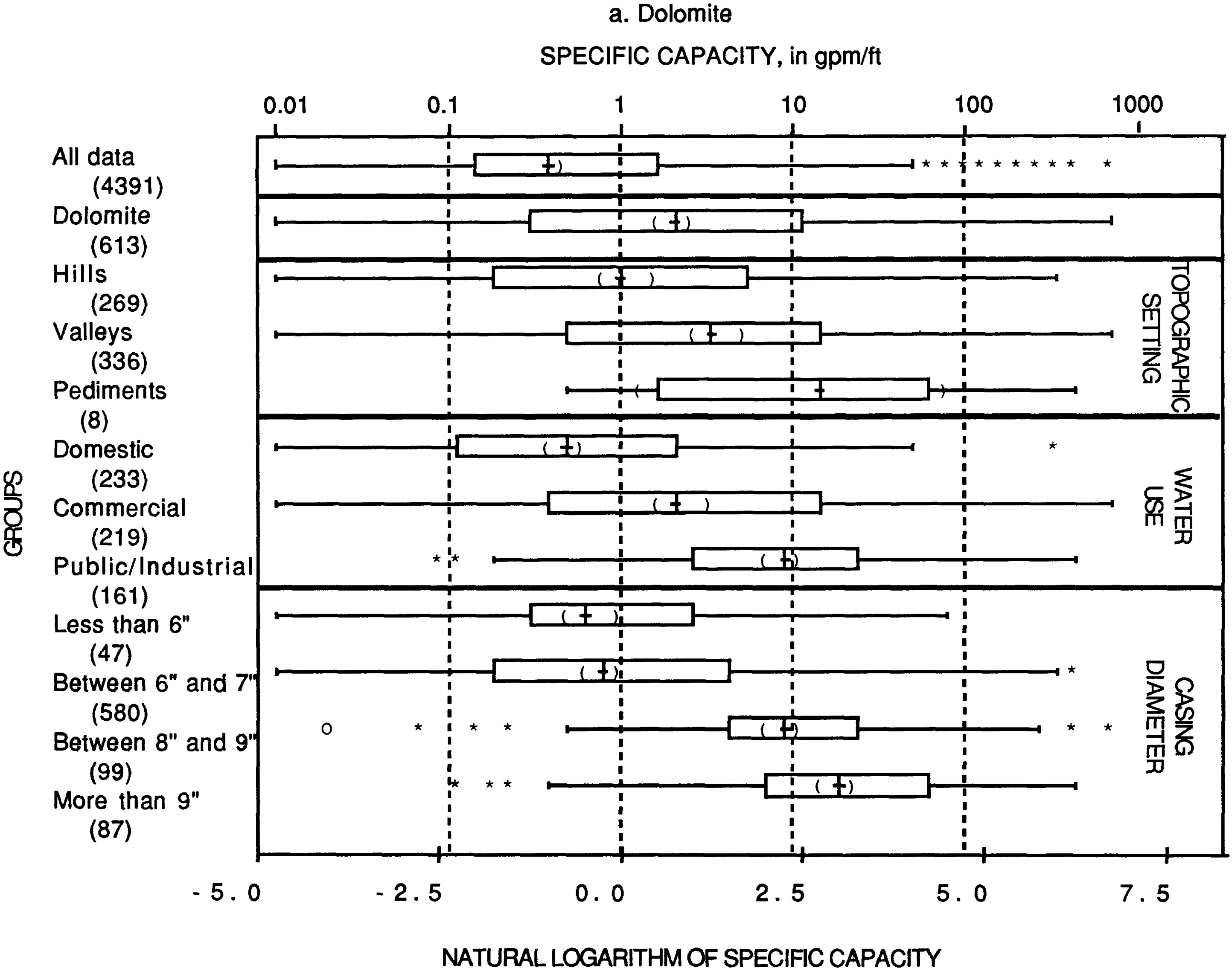
All of the lithologic groups except diabase are sensitive to water use (Figures 10a-e). The pattern in the boxplots is for the quartile estimates to increase in value sequentially from domestic, to commercial, and then to public and industrial uses. Because of the greater number of wells used for domestic purposes, the boxplot for the lithologic group as a whole most closely resembles the boxplot for the domestic wells. Within each water-use group, the same ordering of quartile estimates holds for each of the lithologic groups (from dolomite at the high end to metamorphic and igneous rocks at the low end). However, the difference among medians is much greater for the public supply and industrial group than for the domestic group. Among the carbonate rocks (that is, the dolomite and limestone groups), interquartile ranges vary across water-use groups. In the dolomite group, specific capacity in commerical wells is the most variable. In the limestone group, specific capacity in the domestic wells is the least variable. In the case of the siliciclastic rocks and metamorphic and igneous rocks, variability among the water-use groups is nearly the same.

With the exception of diabase, differences among water uses within each lithologic group were found to be significant using a KW test (p=0.0001). Nearly all the wells in diabase are for domestic use. In terms of percent of variation in the specific-capacity data explained by water use alone for each lithologic group, a one-way ANOVA indicated that there are significant differences among the groups. For example, 22 percent of the variation in the data are explained for the dolomite, 17 percent for the limestones, 13 percent for the siliciclastic rocks, and 5 percent for the metamorphic and igneous rocks. When the data were taken as a whole, water use as a single factor accounted for 15 percent of the variation.

Casing diameter

When wells within a lithologic group are aggregated by casing diameter, strong differences can be seen in the boxplots (Figures 10a-e). The general pattern is for the quartile values to be greater with larger casing diameters. The greatest differences in specific capacity are between wells with casing diameters less than or equal to 7 inches and those with diameters 8 inches and greater. For each lithologic grouping, a KW test between wells with varying casing diameters indicated that all differences were significant (p=0.0001) except for diabase. All wells in the diabase group fall in the same casing diameter category. Within each casing-diameter group, the same ordering of quartile estimates among the lithologic groups generally holds.

In terms of interquartile range, there is considerable variability among the casing diameters for each of the lithologic groups. The general pattern is that wells with casing diameters between 6 and 7 inches show the largest interquartile ranges, whereas the ranges for smaller casings (less than 6 inches) and larger casings (10 inches and greater) are much narrower.



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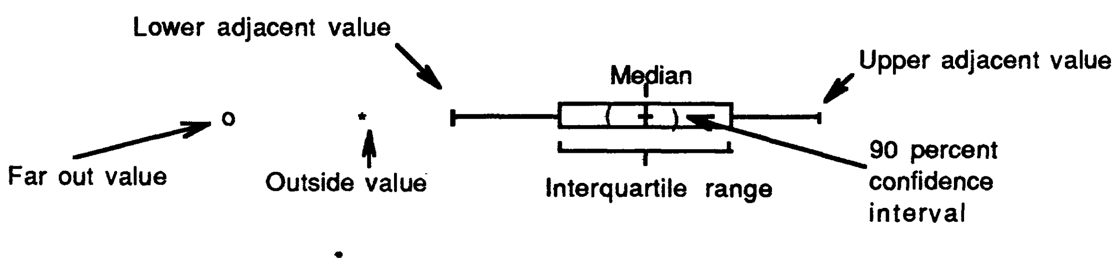
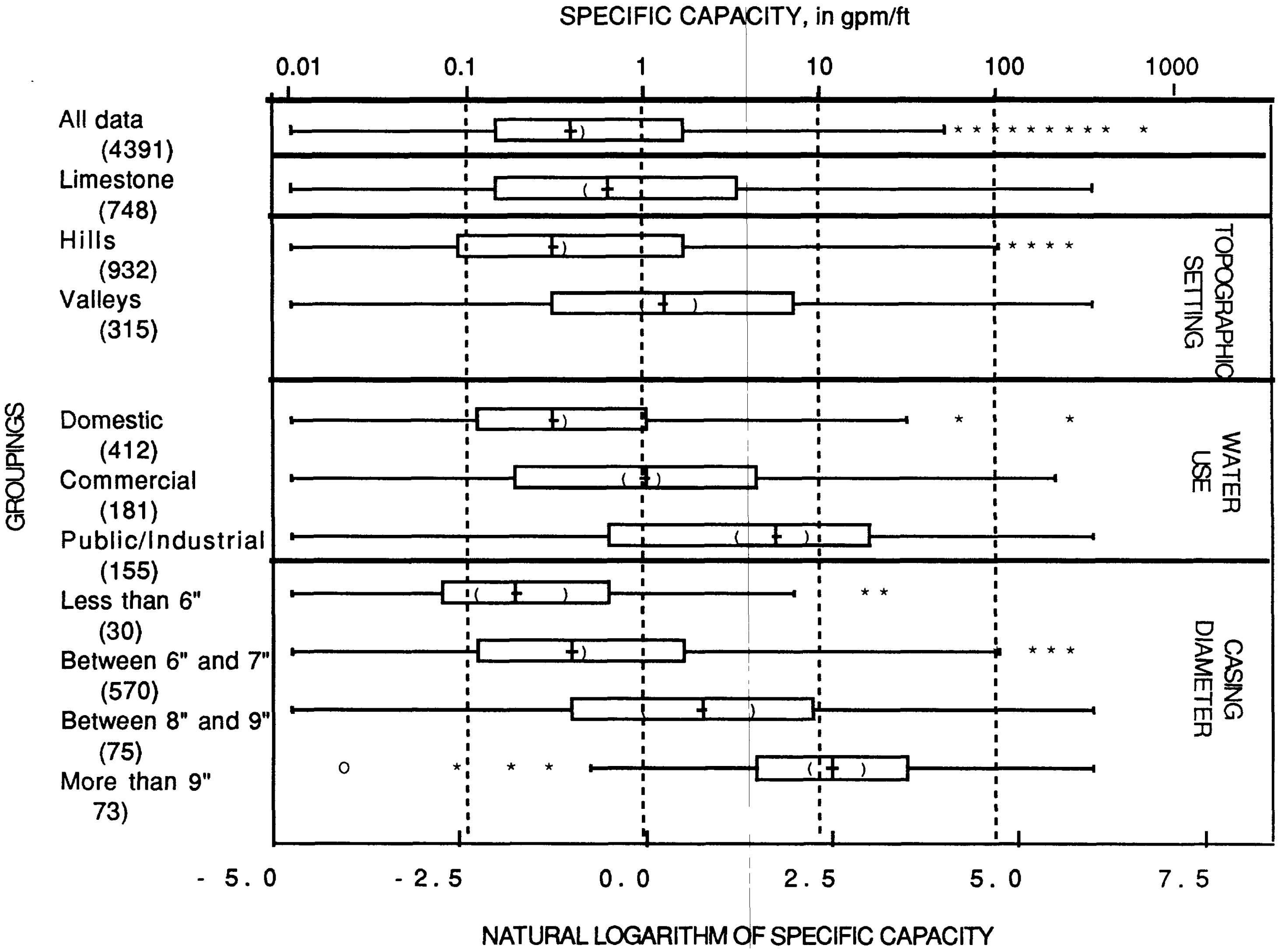


Figure 10.--Boxplots showing specific capacity by lithologic group comparing topographic setting, water use, and casing diameter. (a) dolomite, (b) limestone, (c) siliciclastic rocks, (d) metamorphic and igneous rocks, and (e) diabase. The number of wells within a group is given under each label, and the 90 percent confidence interval about the median is marked by parentheses.

b. Limestone



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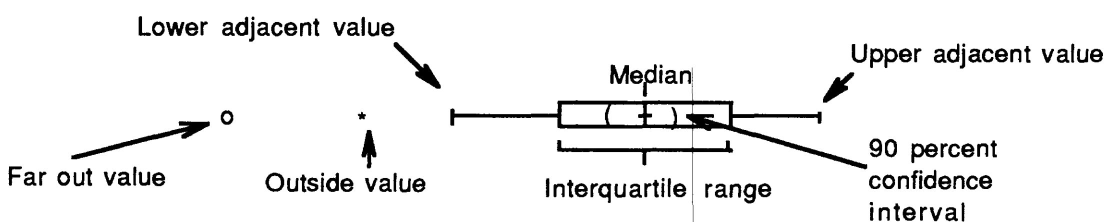
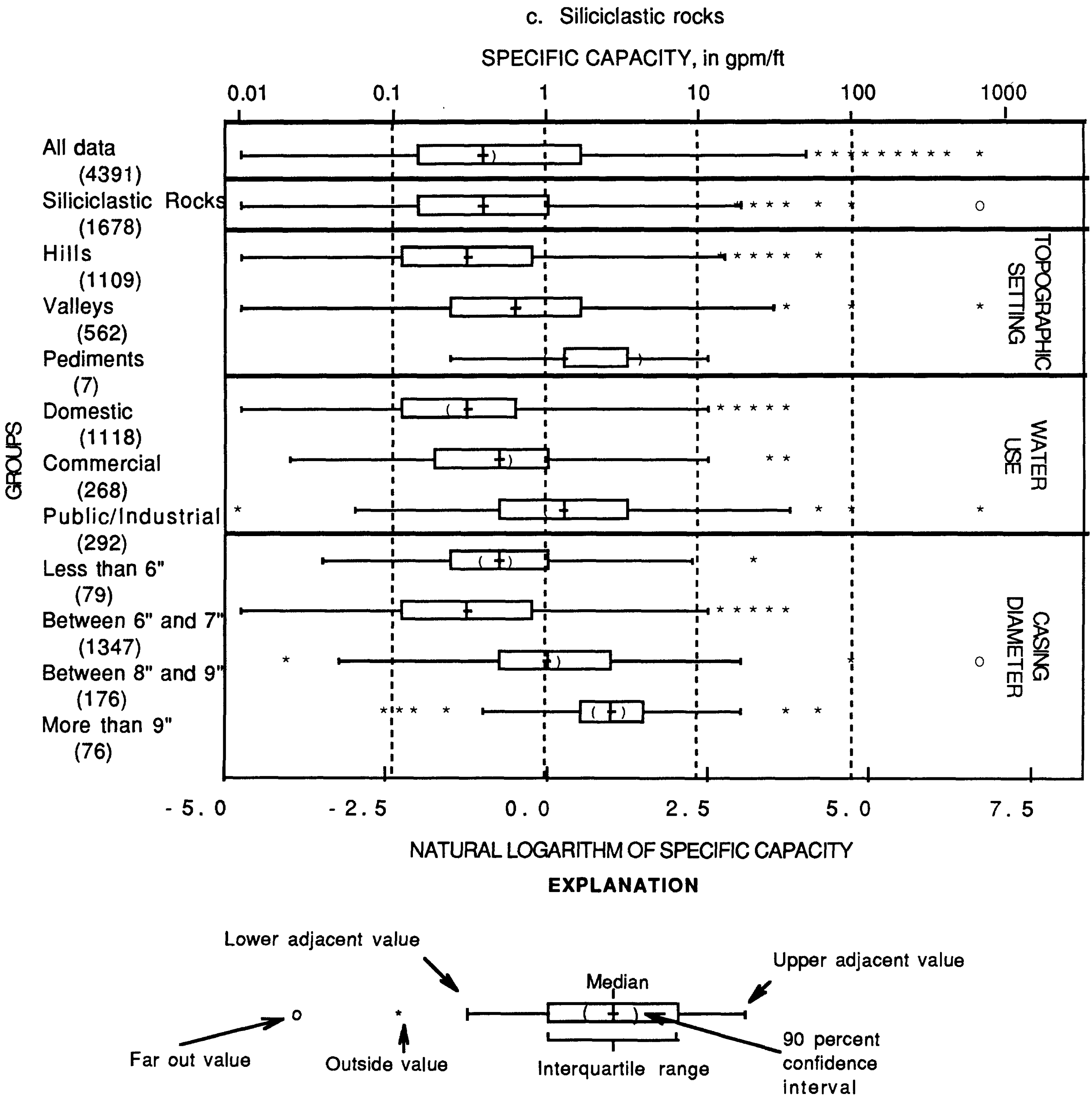


Figure 10.--Boxplots showing specific capacity by lithologic group comparing topographic setting, water use, and casing diameter. (a) dolomite, (b) limestone, (c) siliciclastic rocks, (d) metamorphic and igneous rocks, and (e) diabase. The number of wells within a group is given under each label, and the 90 percent confidence interval about the median is marked by parentheses.



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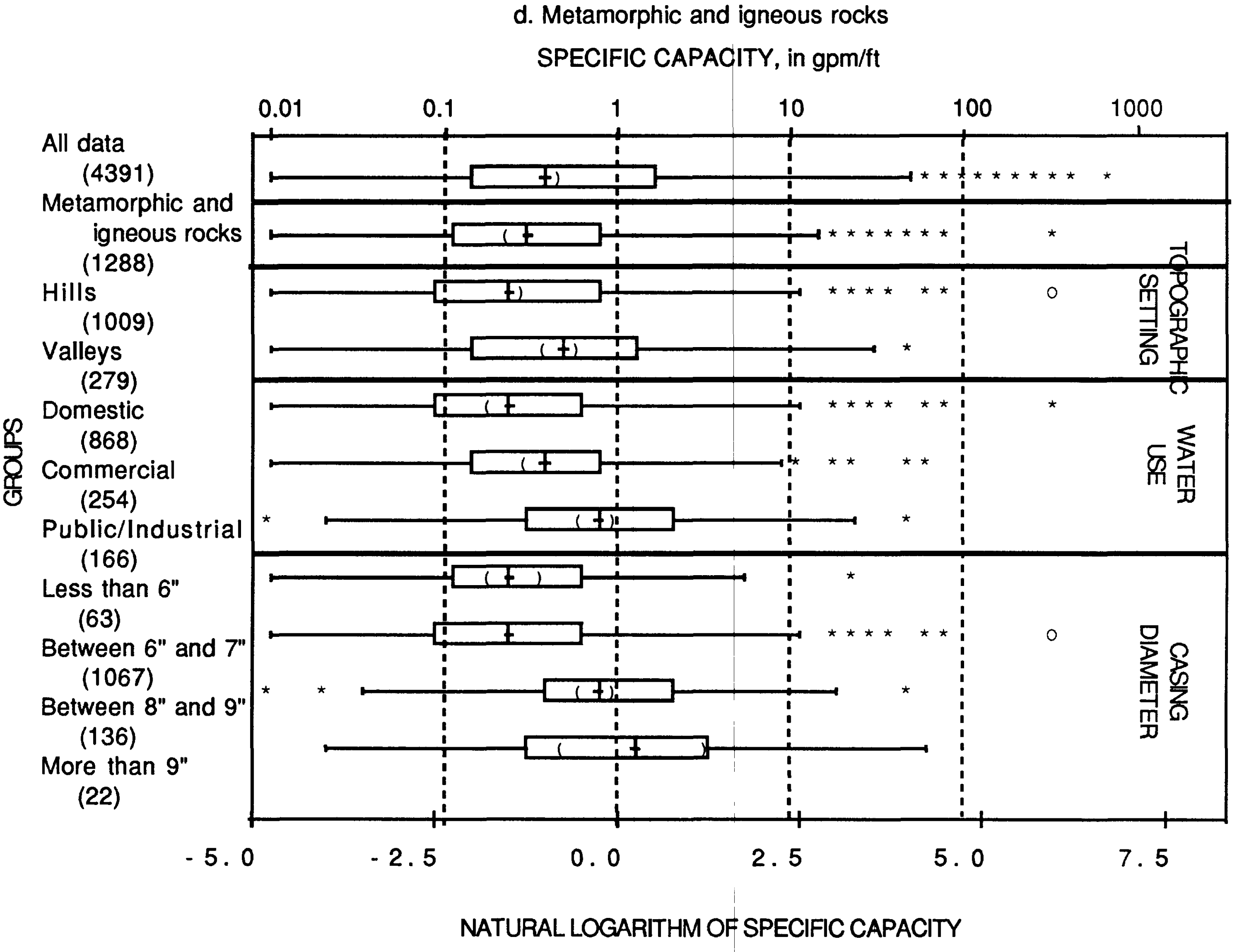

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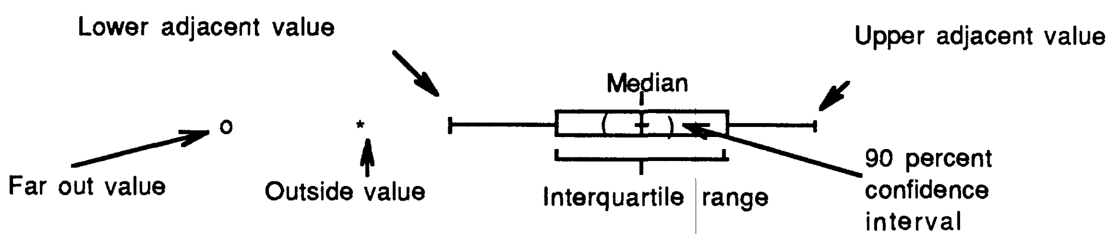

Figure 10.--Boxplots showing specific capacity by lithologic group comparing topographic setting, water use, and casing diameter. (a) dolomite, (b) limestone, (c) siliciclastic rocks, (d) metamorphic and igneous rocks, and (e) diabase. The number of wells within a group is given under each label, and the 90 percent confidence interval about the median is marked by parentheses.

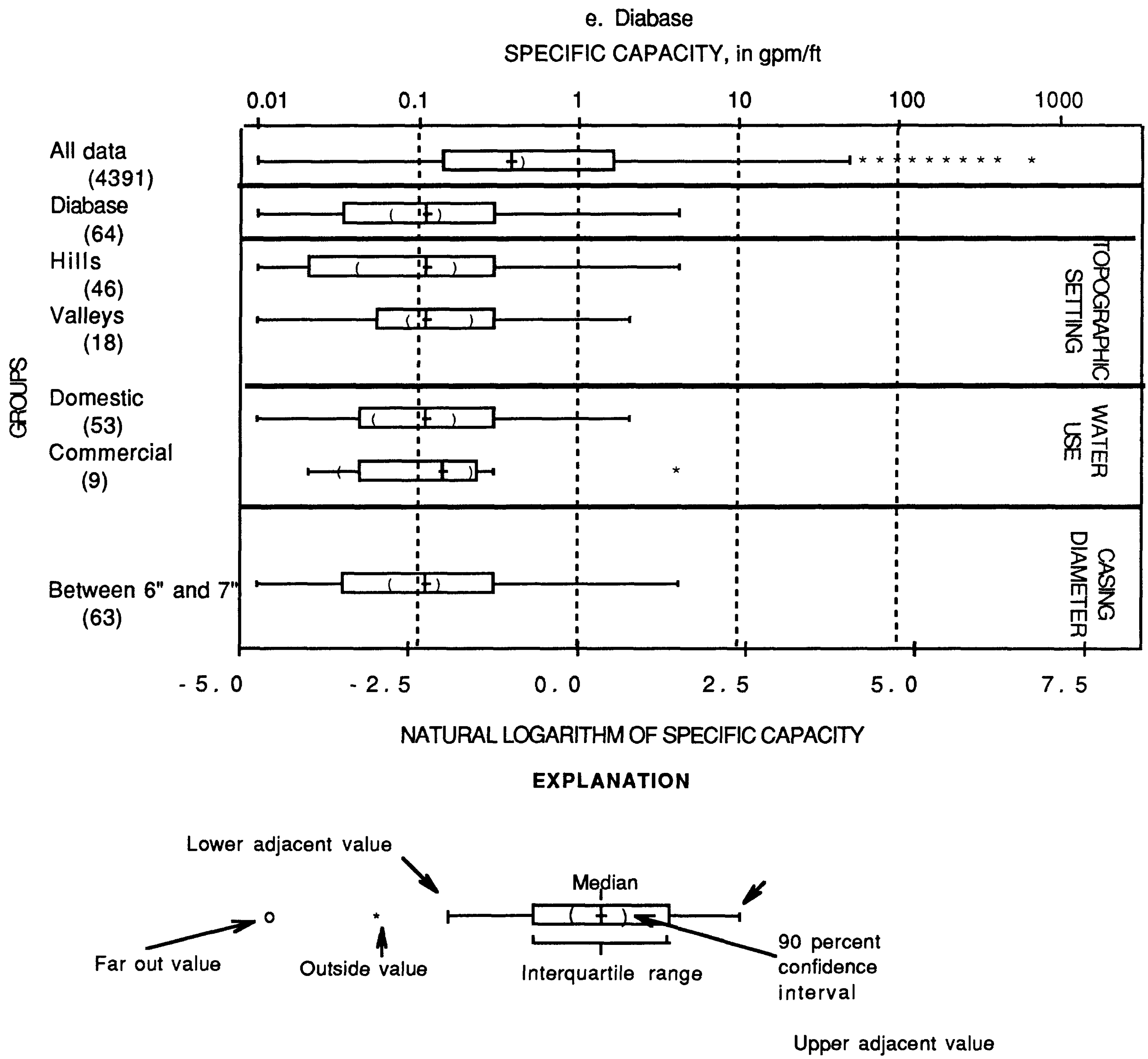

Figure 10.--Boxplots showing specific capacity by lithologic group comparing topographic setting, water use, and casing diameter. (a) dolomite, (b) limestone, (c) siliciclastic rocks, (d) metamorphic and igneous rocks, and (e) diabase. The number of wells within a group is given under each label, and the 90 percent confidence interval about the median is marked by parentheses.

Casing diameter as a single factor can explain about 25 percent of the variability in the specific-capacity data when wells located in dolomite are aggregated. For limestones, 20 percent of the variability is explained, for the siliciclastic rocks 14 percent, and only 5 percent for the metamorphic and igneous rocks. In comparison, when the full data set was used, casing diameter alone explains 18 percent of the variation. When both water use and casing diameter are considered together, 30 percent of the variation in dolomite-based wells is explained, 23 percent in limestones, 17 percent in siliciclastic rocks, 7 percent in metamorphic and igneous rocks, and 3 percent in diabase.

Topographic setting

For all of the lithologic groups except diabase, quartile estimates of specific capacity are significantly different between the two dominant topographic settings of hills and valleys. Too few wells are located in pediments to allow any meaningful comparisons. Boxplots (Figures 10a-e) clearly show these differences. As with water use and casing diameter, within each topographic-setting group, the same ordering of quartile estimates among the lithologic groups holds. The spread in the data, as represented by the interquartile range, is roughly the same within each lithologic group.

A regression model that includes only topographic setting as a single factor has very low explanatory power among all the lithologic groups (5 percent for dolomite, 8 percent for limestones, 4 percent for siliciclastic rocks, and 2 percent for metamorphic and igneous rocks and diabase). Consistent with these results, when the full data set was considered, topographic setting accounted for only 7 percent of the variation in the specific-capacity data. When topographic setting is considered with water use, about 25 percent of the variation for the dolomite is explained, a slight improvement over the 22 percent for water use alone. The same magnitude of change in R^2 is evident among the other lithologic groups. It is also the same magnitude of change in R^2 observed when topographic setting and casing diameter are included in a two-way ANOVA on the ln specific-capacity data.

When topographic setting is considered in the context of a regression model that also includes water use, casing diameter, casing depth, and well depth, the parameter associated with the topographic setting variable is not statistically significant for the dolomite or diabase groupings. (For dolomite, such a model explains 45 percent of the variation in the specific-capacity data.) Topographic setting is significant ($p \leq 0.05$) for the other three lithologic groupings.

Depth of casing

Correlation between specific capacity and casing depth among the five lithologic groups appears to be minimal (Figure 11a). Only coefficients with p values less than or equal to 0.05. are given. When the data are grouped by water use, correlation between specific capacity and casing depth is still quite low. The same is true when the data are grouped by casing diameter or topographic setting. When water use, casing diameter, and topographic setting are controlled simultaneously, correlation between casing depth and specific capacity is insignificant for all of the lithologic groupings with the exception of diabase. For example, Spearman's rho for diabase is 0.50 ($p=0.05$) when

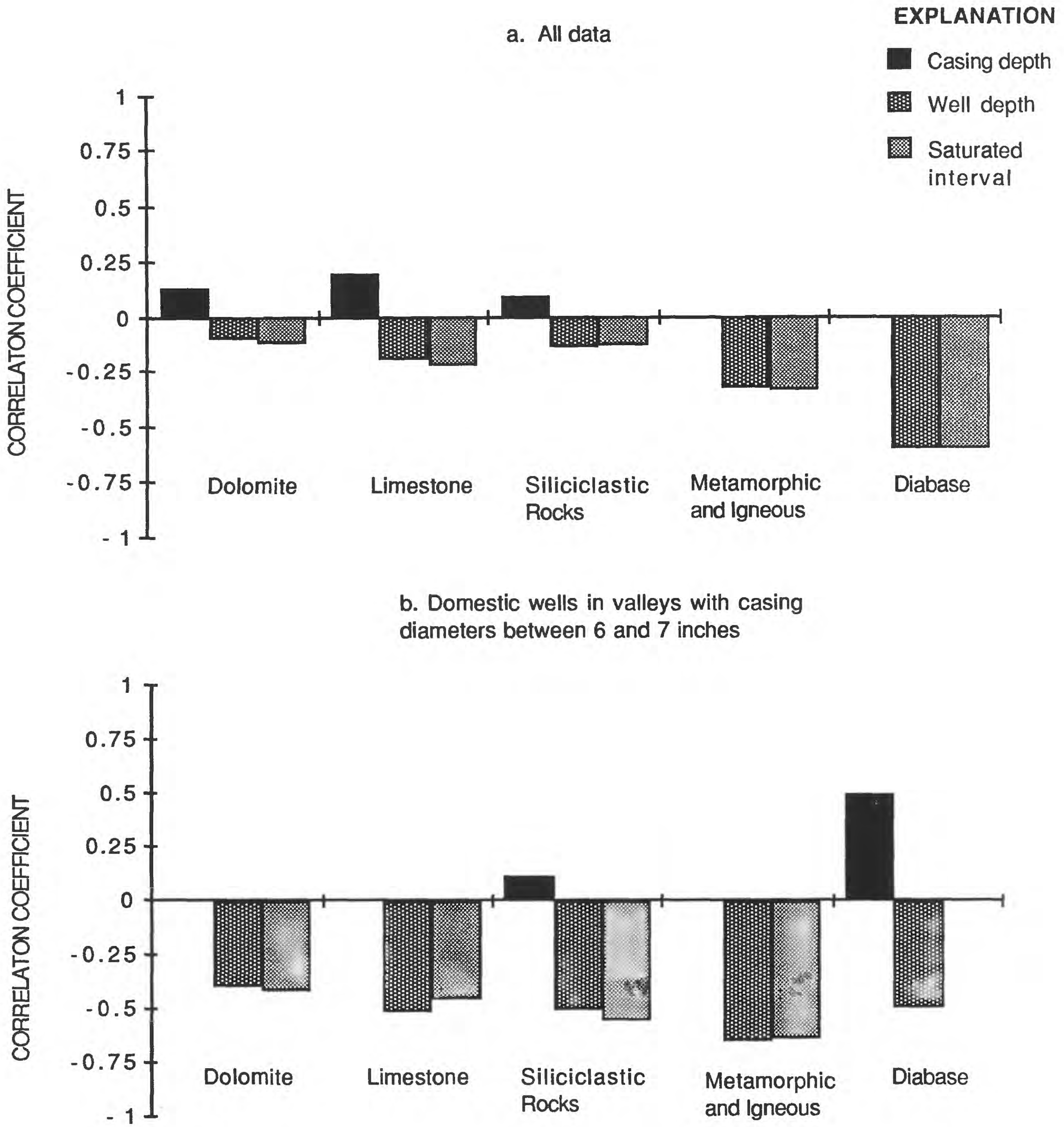

Figure 11.--Graphs showing correlation coefficients by lithologic group between specific capacity and casing depth, well depth, and saturated interval. (a) all data, (b) domestic wells with casing diameters between 6 and 7 inches located valleys.

considering only domestic wells with diameters between 6 and 7 inches which are located in valleys (Figure 11b). In contrast, no significant correlation is found between casing depth and specific capacity for public and industrial wells of similar diameter and topographic setting.

When casing depth is considered in the context of a regression model that also includes topographic setting, water use, casing diameter, well depth, and saturated interval, casing depth is a significant parameter for the dolomite, limestones, and siliciclastic rocks, but not for either the metamorphic and igneous rocks or diabase. For the dolomite and limestones, 45 and 44 percent, respectively, of the variability in the specific-capacity data are explained by models that include all of the above variables except saturated thickness. For the siliciclastic rocks, only 36 percent of the variability is explained by a similar model. This result reflects both the differences in rock properties and the differences in well construction practices for the different lithologic groups (C.C. Daniel, U.S. Geological Survey, oral comm., 1990).

Depth of well

Considering all data, correlation between well depth and specific capacity does vary with lithologic group (Figure 11a). Spearman's rho is highest for the diabase (-0.60) and metamorphic and igneous groups (-0.33), and relatively low for dolomite, limestone, and the siliciclastic rocks. When water use alone is controlled, there are significant differences in the extent of correlation (which is always negative). Among domestic wells, correlation coefficients for the five lithologic groups ranges from -0.48 (dolomite) to -0.65 (metamorphic and igneous rocks). In contrast, none of the other lithologic groups showed any significant correlation between specific capacity and well depth, with the exception of the metamorphic and igneous rocks (correlation coefficient of -0.21).

When casing diameter is controlled, similar patterns in correlation are observed among the lithologic groups for wells with diameters between 6 and 7 inches. Among wells with casing diameters between 8 and 9 inches, the correlation coefficient between well depth and specific capacity was only significant at the 5 percent level for limestone (-0.32) and the metamorphic and igneous rocks (-0.36).

When only wells located on hills are considered, correlation between well depth and specific capacity increases among the lithologic groups, beginning with the carbonate rocks and ending with diabase. Spearman's rho is -0.14 for dolomite, -0.27 for limestone, -0.28 for the siliciclastic rocks, -0.41 for the metamorphic and igneous rocks, and -0.63 for diabase. In contrast, no significant correlation was found between well depth and specific capacity for wells in valleys for the dolomite, limestone, and siliciclastic groups. For this topographic setting, however, metamorphic and igneous rocks showed a correlation coefficient of -0.14 and diabase showed a coefficient of -0.52.

Saturated interval

Saturated interval shows all the same patterns in correlation with specific capacity as did depth of well (Figure 11a). This is true even when the factors of water use, casing diameter, and topographic setting are controlled individually and together. When saturated interval is included in a regression model with all the other variables, the associated parameter estimate is not statistically significant among the dolomite, limestones, and siliciclastic rocks. Consistent with the correlation results, saturated thickness in these lithologic groups is not contributing any more information about variability in the specific-capacity data than well depth already provides. This is not the case for the metamorphic and igneous rocks for which saturated interval is a significant parameter but casing depth is not significant. A regression model for this lithologic group that includes topographic setting, casing diameter, water use, well depth, and saturated thickness only explains about 35 percent of the variation in the specific-capacity data.

Summary

Water use and casing diameter were shown to be the most important factors related to the specific-capacity data and are also the most important factors when the specific-capacity data are aggregated by lithologic grouping (Figure 12). Topographic setting alone is not particularly significant for any of the lithologic groups, but does make some contribution, particularly among limestone, when considered with casing diameter and water use. Casing depth only emerges as a significant factor among the carbonate rocks and siliciclastic rocks when topographic setting, water use, and casing diameter are controlled.

The factor of well depth increases in importance from the carbonate rocks down to diabase when only wells from hills are considered. In general, specific capacity is negatively correlated with well depth among all of the lithologic groups. Saturated interval is not any more informative than well depth in statistically explaining variation in the specific-capacity data among the carbonate rocks and siliciclastic rocks. In contrast, among wells located in metamorphic and igneous rocks, saturated interval does appear to be a significant factor in accounting for variability in the specific-capacity data.

TESTING HYPOTHESES ABOUT DIFFERENCES AMONG HYDROGEOLOGIC UNITS WITHIN EACH LITHOLOGIC GROUPING

The complexity of the Valley and Ridge and Piedmont provinces is indicated by the fact that 186 distinct hydrogeologic units are represented among the 4,391 well records. About 35 percent (68) of the 186 hydrogeologic units represented in the study area have 19 or more well records, and 13 percent (24) have 50 or more records. In most hydrogeologic units, nearly all the wells are classified by the same lithology, but this is not always the case. The boxplots of residual ln specific capacity for these 68 hydrogeologic units (Figures 13a-d) are arranged by lithologic group and by median, in descending order. Hydrogeologic units with a mixed lithology appear in more than one of the figures; only wells with the appropriate lithology are represented in a boxplot for a given hydrogeologic unit.

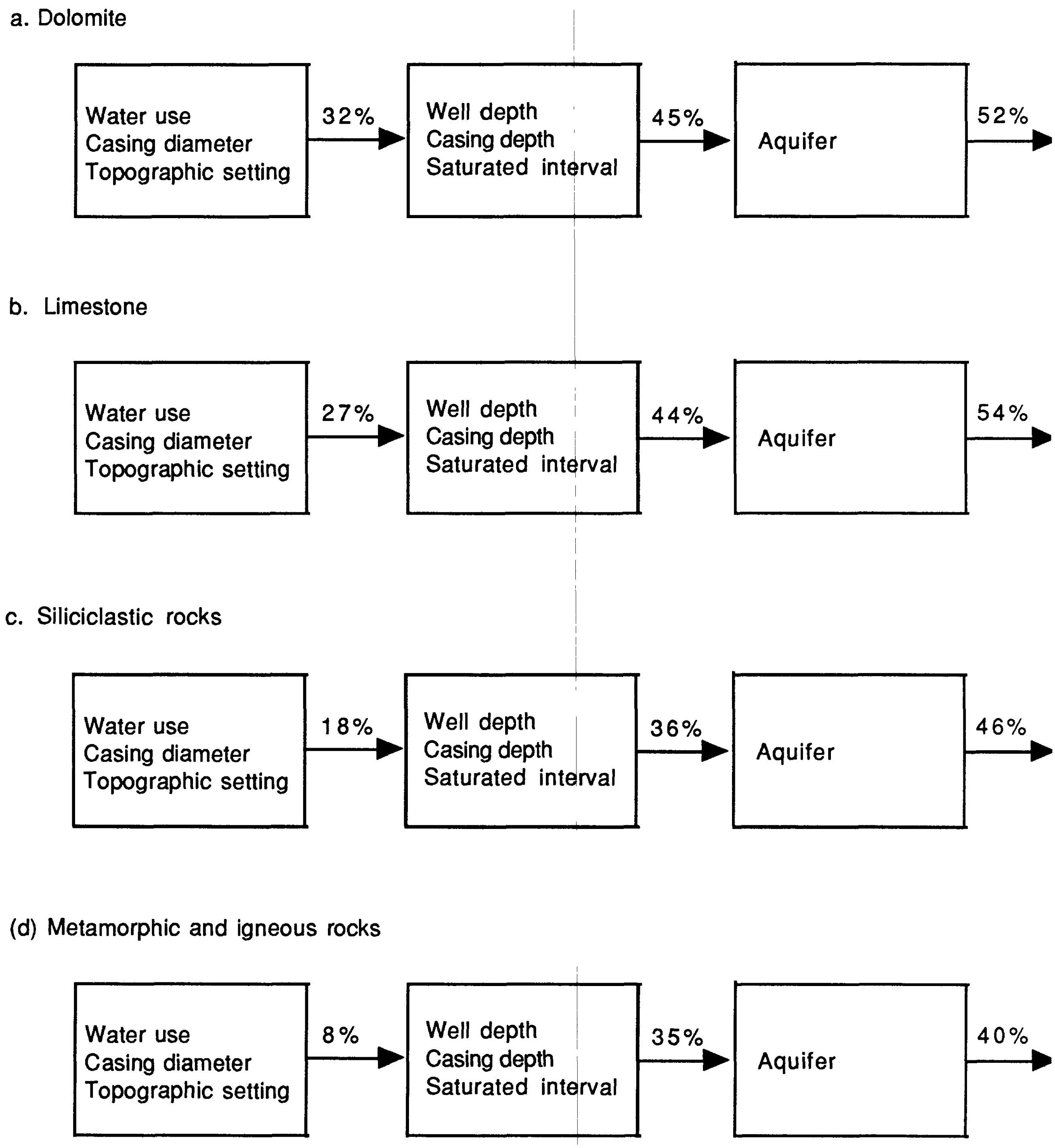

Figure 12.--Diagram showing summary by lithologic group of the amount of variation explained in specific-capacity values by regression models with various combinations of explanatory variables. (a) dolomite, (b) limestone, (c) siliciclastic rocks, and (d) metamorphic and igneous rocks.

Comparisons among hydrogeologic units are made by first controlling for water use, casing diameter, and topographic setting. As described previously, a regression model with these three factors used ln specific-capacity values for all 4,391 wells. The residuals from the regression are, in a sense, filtered ln specific-capacity values in which the main effects of water use, casing diameter, and topographic setting have been removed. Then, KW and Tukey tests on the residuals of ln specific capacity were used to test for differences among hydrogeologic units within a given lithologic grouping. The general result of using the residuals rather than the "uncontrolled" specific-capacity values are to slightly reduce the interquartile range and shift the quartile estimates up or down to adjust for the dominance of one type of well or another within the given hydrogeologic unit.

In spite of the complexity added by the inclusion of the hydrogeologic unit as another factor that correlates with specific capacity, the variable can make some contribution to the overall goal of explaining variation in the data. In the aggregate, 50 percent of the variation in the specific-capacity data is explained by a model that accounts for hydrogeologic unit, lithologic group, water use, casing diameter, topographic setting in addition to casing depth, well depth, and saturated interval. All of these factors are significant in a regression on ln specific capacity. In contrast, when a model is hypothesized that includes all of the above factors except the hydrogeologic unit classification, 46 percent of the variation is explained. Within a given lithologic grouping, the hydrogeologic unit classification may add more or less information, as summarized in Figure 12 and described in the following sections. Stratigraphic nomenclature used in this report mainly is that of the Pennsylvania Geological Survey and does not necessarily follow that of the U.S. Geological Survey.

Dolomite

A KW test for differences among the mean ranks of specific capacity for the 22 hydrogeologic units with at least 1 well classified as being located in dolomite or interbedded limestone and dolomite was highly significant ($p=0.0001$). When pairwise comparisons were made using the Tukey test, the Bellefonte Formation and Nittany-Larke Formations (undivided) appeared to be significantly different than five others: Rockdale Run Formation, Elbrook Formation, Maiden Creek Member of Allentown Formation, Gatesburg Formation (upper sandy member), and Zooks Corner Formation. The boxplots (Figure 13a) show that these hydrogeologic units are the lowest and highest, respectively, among the hydrogeologic units with wells described as being located in either dolomite, interbedded limestone and dolomite, or marble. (Note that Figure 13a only shows the boxplots for 18 of the 22 hydrogeologic units with 10 or more wells.)

Within this lithologic grouping, a regression model that includes hydrogeologic unit, water use, casing diameter, topographic setting, in addition to casing depth, well depth, and saturated thickness explains 52 percent of the variation in the specific-capacity data. When the hydrogeologic unit classification is not included in the model, only 45 percent of the variation is explained. In either case, neither topographic setting nor saturated interval appear to be significant factors.

In summary, the Nittany-Larke and Bellefonte hydrogeologic units emerge as significantly different than five other hydrogeologic units containing dolomite. These two hydrogeologic units show a lower median of ln specific capacity than the other 20

a. Dolomite

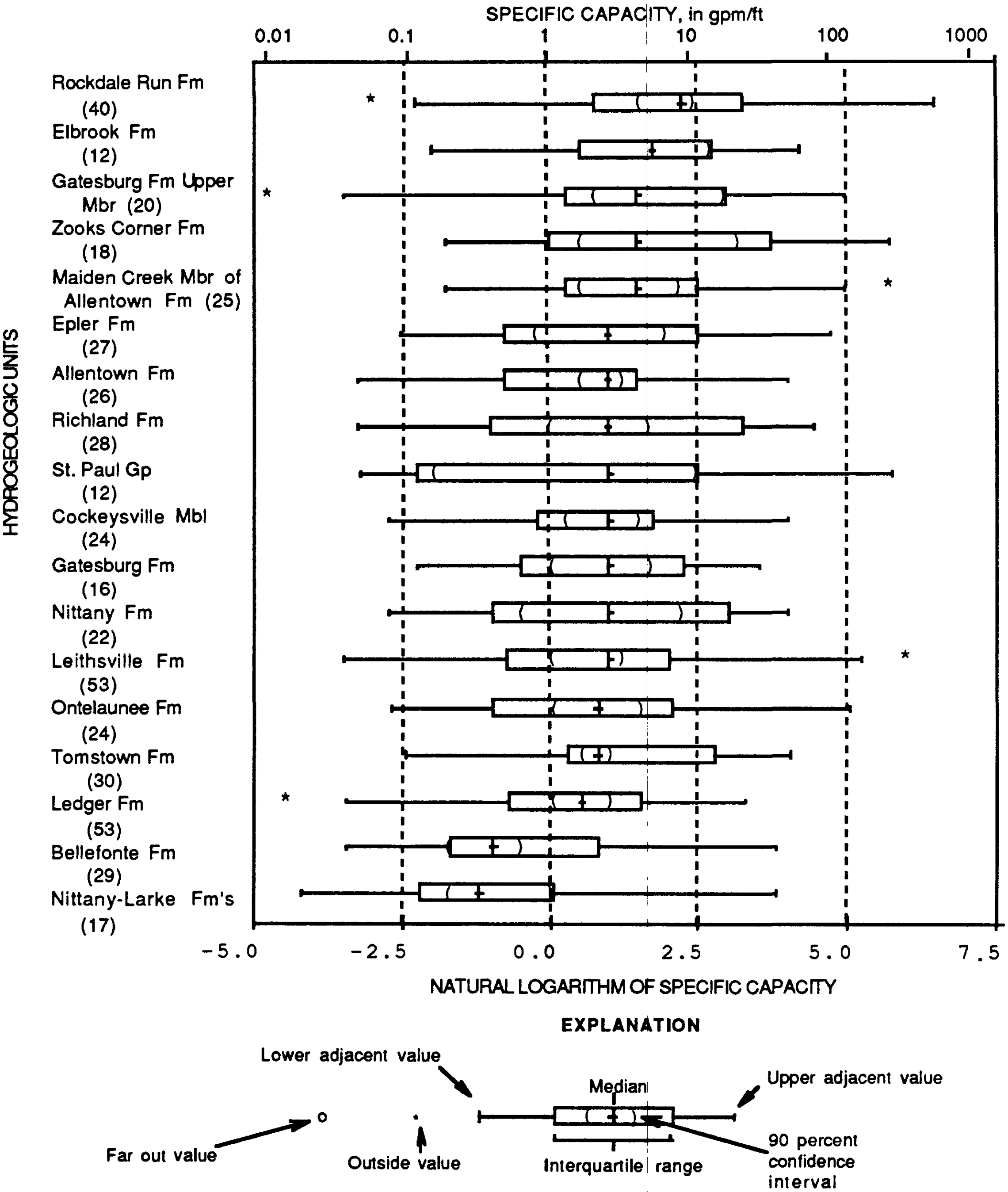

Figure 13--Boxplots showing residual specific capacity for hydrogeologic units within each lithologic group. (a) dolomite, (b) limestone, (c) siliciclastic rocks, (d) metamorphic and igneous rocks, and (e) diabase. Residual values of ln specific capacity, obtained from a regresion on all of the data, are independent of the effects of water use, casing diameter, and topographic setting. The number of wells within a group is given under each label, and the 90 percent confidence interval about the median is marked by parentheses. Hydrogeologic unit abbreviations: Gp=Group, Fm=Formation, Mbl=Marble, Mbr=Member. (No stratigraphic order implied in arrangement of units).

hydrogeologic units that fall within this lithologic grouping. Among these other 20 hydrogeologic units, additional groupings cannot be distinguished on the basis of a Tukey test on the residual ln specific-capacity values. Indeed, the similarity of the medians from the Epler hydrogeologic unit down to the Ledger hydrogeologic unit (Figure 13a) is quite striking.

Limestone

As with the dolomite group, a KW test shows that significant differences do exist among some of the hydrogeologic units within the limestone group, when the factors of casing diameter, water use and topographic setting are controlled. The Tukey multiple comparison test indicates that the Stonehenge, Keyser, and Allentown Formations are significantly different than Bellefonte Formation and St. Paul Group. Stonehenge Formation is also significantly different than Coburn, Salona, and Nealmont Formations (undivided) and Conestoga Formation. No other comparisons are significant within the overall 5 percent level.

The Stonehenge Formation (Figure 13b) seems to be an outlier whose median and upper quartile estimates of residual ln specific capacity are more consistent with some of the higher yielding dolomite units. On the lower end, Jacksonburg Formation, Elbrook Formation, Chambersburg Limestone, Coburn, Salona, and Nealmont Formations (undivided), and Wills Creek Formation are argillaceous limestones (E.F. Hollyday, U.S. Geological Survey, oral comm., 1990). In addition to the range among the median estimates, there is also substantial variation in the width of the interquartile ranges of the limestone hydrogeologic units. However, the interquartile ranges for most of the limestones are narrower than most of the dolomite.

A regression model that includes the hydrogeologic unit classification, water use, casing diameter, and topographic setting, in addition to casing depth and well depth explains 54 percent of the variation in the specific-capacity data. Saturated interval was not a significant factor. In contrast, a similar model with all but the hydrogeologic unit classification explains only 44 percent of the variation. Clearly, the hydrogeologic unit classification is an important factor in explaining the pattern of specific capacity observed among limestones.

Siliciclastic rocks

Within this lithologic grouping, 1,332 wells are identified in 35 hydrogeologic units. Figure 13c shows the boxplots for 22 of these hydrogeologic units; 13 of the 35 hydrogeologic units had fewer than 10 wells and are thus not shown. (In the analysis in section 5, 1,664 wells were used from 93 hydrogeologic units, many with only 1 or 2 wells described as being located in siliciclastic rocks.) Among all 35 hydrogeologic units, a KW test was significant (p=0.0001), indicating that there are differences among the hydrogeologic units in terms of the mean ranks of specific capacity.

A Tukey test was carried out on the specific-capacity data (controlling for water use, casing diameter, and topographic setting) to determine which hydrogeologic units differed from one another. Using Figure 13c as a guide, the Tukey test indicated the following significant differences at the 5 percent level:

b. Limestone

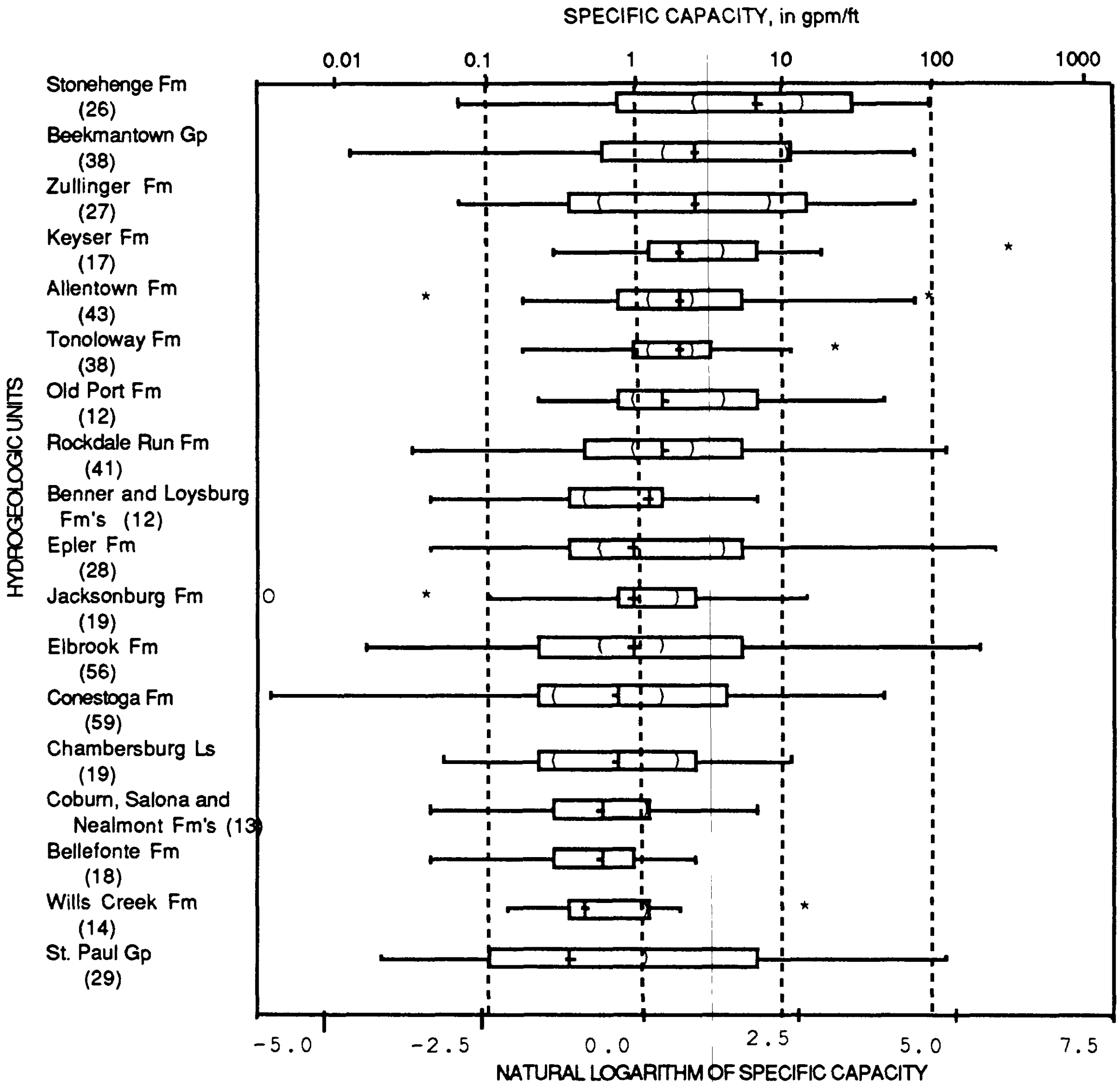

Figure 13.--Boxplots showing residual specific capacity for hydrogeologic units within each lithologic group. (a) dolomite, (b) limestone, (c) siliciclastic rocks, (d) metamorphic and igneous rocks, and (e) diabase. Residual values of ln specify capacity, obtained from a regression on all of the data, are independent of the effects of water use, casing diameter, and topographic setting. The number of wells within a group is given under each label, and the 90 percent confidence interval about the median is marked by parentheses. Hydrogeologic unit abbreviations: Gp=Group, Fm=Formation, Ls=Limestone (no stratigraphic order implied in arrangement of units).

c. Siliciclastic rocks

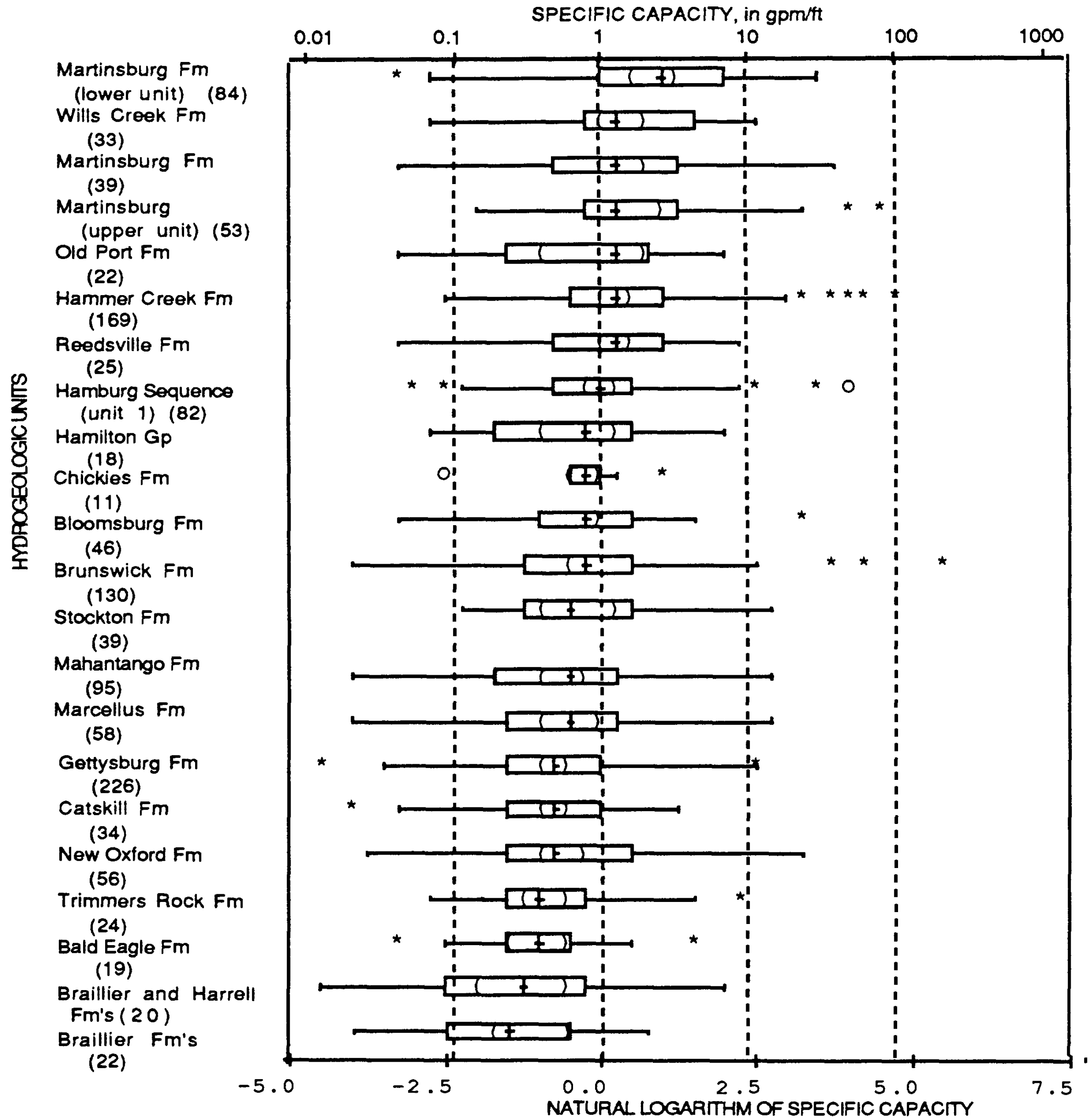

Figure 13.--Boxplots showing residual specific capacity for hydrogeologic units within each lithologic group. (a) dolomite, (b) limestone, (c) siliciclastic rocks, (d) metamorphic and igneous rocks, and (e) diabase. Residual values of ln specific capacity, obtained from a regression on all of the data, are independent of the effects of water use, casing diameter, and topographic setting. The number of wells within a group is given under each label, and the 90 percent confidence interval about the median is marked by parentheses. Hydrogeologic unit abbreviations: Gp=Group, Fm=Formation (no stratigraphic order implied on arrangement of units).

Martinsburg Formation (lower unit) and all hydrogeologic units between Hamburg sequence (lithotectonic unit 1) and Braillier Formation;

Wills Creek Formation and all hydrogeologic units between Mahantango and Braillier Formations.

Martinsburg Formation and all hydrogeologic units between Gettysburg and Braillier Formations.

Martinsburg (upper unit) and Hammer Creek Formations and all hydrogeologic units between Brunswick and Braillier Formations.

Reedsville and Braillier Formations.

With the exception of Martinsburg (lower unit) at the high end and Braillier and Braillier-Harrell at the low end, there is relatively little variation among the siliciclastic rocks. Martinsburg (lower unit) does contain some limestone, which accounts for its relatively high quartile estimates. The confidence intervals about the estimates of the medians, shown in Figure 13c as parentheses (most are inside the box itself), are also quite narrow for nearly all of the siliciclastic rocks. In statistical terms, there is not sufficient evidence on which to base a classification scheme for the siliciclastic rocks. With prior information about the mineralogy of the hydrogeologic units, Figure 13c does generally indicate (with some exceptions) that the coarse-grain siliciclastic rocks are in the high end and fine-grain siliciclastic rocks in the low end (E.F. Hollyday, U.S. Geological Survey, oral comm., 1990).

A regression model that includes the hydrogeologic unit classification, water use, casing diameter, and topographic setting in addition to casing depth and well depth explains 46 percent of the variation in the specific-capacity data. In contrast, a similar model with all but the hydrogeologic unit classification explains only 36 percent of the variation. As with the limestones, the hydrogeologic unit is an important factor in explaining the pattern of specific capacity observed among the siliciclastic rocks.

Metamorphic and igneous rocks

A KW test for significant differences among the 19 hydrogeologic units (or undifferentiated material) with wells classified as being located in metamorphic and igneous rocks indicates that differences are indeed significant (p=0.0001). Figure 13d shows the boxplots for 16 of the 19 hydrogeologic units with 10 or more wells. The results of a Tukey test on the ranks of the specific-capacity data suggest that only the lowest yielding hydrogeologic unit of pyroxene-bearing mafic gneiss can be distinguished as significantly different than the other hydrogeologic units and undifferentiated material. Both the interquartile ranges and the confidence intervals about the medians are relatively narrow in most of these boxplots. Daniel (1989) reports that some of the variation among these hydrogeologic units can be accounted for by differences in precipitation and the saturated thickness of the regolith.

Within this lithologic grouping, a regression model that includes hydrogeologic unit, water use, casing diameter, and topographic setting, in addition to casing depth, well depth, and saturated interval explains only 40 percent of the variation in the specific-capacity data. This is considerably less than the 52, 54 and 46 percent for

d. Metamorphic and igneous rocks, including diabase

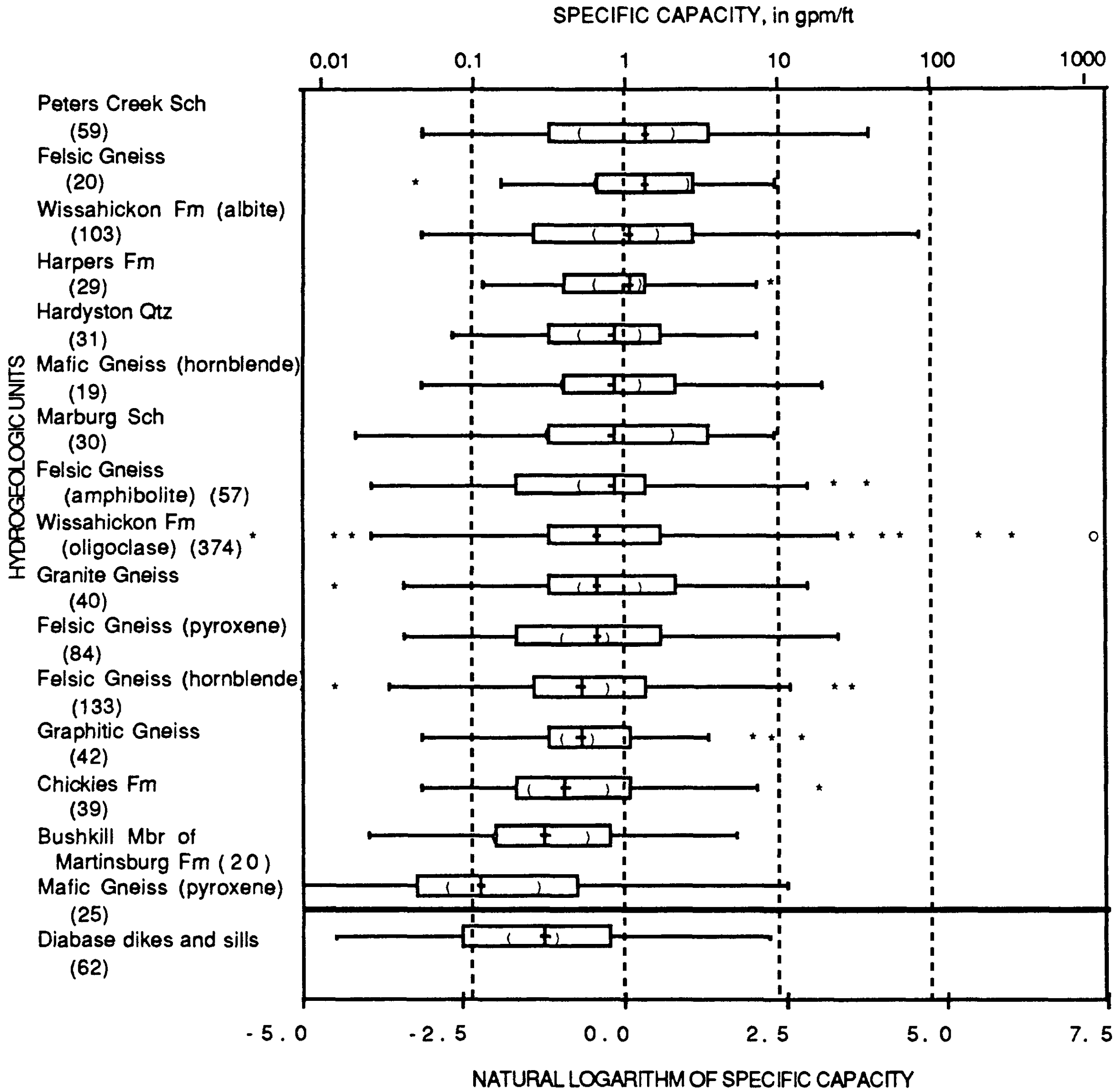

Figure 13.--Boxplots showing residual specific capacity for hydrogeologic units within each lithologic group. (a) dolomite, (b) limestone, (c) siliciclastic rocks, (d) metamorphic and igneous rocks, and (e) diabase. Residual values of ln specific capacity, obtained from a regression on all of the data, are independent of the effects of water use, casing diameter, and topographic setting. The number of wells within a group is given under each label, and the 90 percent confidence interval about the median is marked by parentheses. Hydrogeologic unit abbreviations: Fm=Formation, Sch=Schist, Qtz=Quartzite, Mbr=Member (no stratigraphic order implied in arrangement of units).

dolomite, limestones, and siliciclastic rocks, respectively. In fact, when all the above factors are considered in a regression model except the hydrogeologic unit, 35 percent of the variation is explained. Thus, the variable of hydrogeologic unit is adding less information in this lithologic grouping than it did for the others. In both cases (with and without the hydrogeologic unit classification), the variable of casing depth was not significant at the 0.05 level.

Diabase

Only one hydrogeologic unit classified as diabase dikes and sills (within Upper Triassic rocks) includes wells in this lithologic group, and only 62 wells are located within it (Figure 13d). With the notable exception of some of the pyroxene-bearing mafic gneiss, the diabase dikes and sills have the lowest median ln specific capacity among all of the other hydrogeologic units. It should be noted that nearly all of the wells in these two hydrogeologic units are for domestic use.

SUMMARY OF RESULTS

Within the study area, 186 hydrogeologic units are represented among the 4,391 well records for which a value of specific capacity has been entered. Specific-capacity values range from as low as 0.01 gpm/ft to as high as 891 gpm/ft with a median value of 0.43 gpm/ft. Following are the most important (significant) results of statistical analyses of factors that might influence well yield as measured by specific capacity.

(1) Lithology alone can account for only about 12 percent of the variation observed in the specific-capacity data. A lithology-based classification of hydrogeologic units, accounting for differences in water use, casing diameter, topographic setting, well depth, and casing depth can explain about half the variation in specific-capacity values among carbonate rocks and siliciclastic rocks. The classification appears to be less effective for metamorphic and igneous rocks.

(2) Aggregation of wells according to their lithology, as described coarsely by a single code in the data base, can be reduced from 31 separate designations to 5 groups: dolomite-dominated carbonate rocks, limestone-dominated carbonate rocks, siliciclastic rocks, metamorphic and igneous rocks, and diabase.

(3) Casing diameter and water use are the most important single factors in explaining variation in specific-capacity data (15 to 18 percent, respectively), exceeding topographic setting, well depth, casing depth, and even lithology. Casing diameter is not a surrogate for water use. Although the two variables are related to one another, they are both significant factors in explaining variation in specific-capacity data.

(4) Water use, casing diameter, and topographic setting are categorical variables that can be reduced from many groups into a few combined groups. Sixteen water uses designated in the data base can be combined into three groups: domestic,

public supply and industrial, and a miscellaneous group that includes commercial wells, unused, unknown, or other non-domestic wells. From 23 casing diameters represented in the data base, 4 combined groups can be identified: less than 6 inches, between 6 and 7 inches, between 8 and 9 inches, and 10 inches and greater. From as many as 10 separate designations, topographic settings can be combined into 3 groups: hillsides and hilltops, valleys and flat surfaces, and pediments (accounting for less than 0.4 percent of the total).

(5) Topographic setting taken as a single factor is not a particularly effective variable in explaining some of the variation in the specific-capacity data. However, with the exception of the dolomite, topographic setting is a contributing factor among the other four lithologic groupings in explaining variation in the specific-capacity data in conjunction with the other variables.

(6) Specific capacity is negatively correlated with well depth, although the degree of correlation varies considerably with water use and topographic setting. For example, Spearman's rho is -0.56 among all domestic wells, regardless of lithology or hydrogeologic unit or any other factor. In contrast, among public supply and industrial wells, the correlation is only -0.13. One possible explanation for the high negative correlation between depth and specific capacity among the domestic wells is that the deeper wells are failures, to the extent that a location was selected without much information about the underlying hydrogeologic unit. Holes were drilled deeper in search of sufficient yields, but only to a point, after which the well owner gave up and settled for a low-yielding well. Correlation between specific capacity and well depth also varies by lithologic group. It is relatively low for dolomite, limestones, and siliciclastic rocks and higher for metamorphic and igneous rocks (-0.33) and diabase (-0.60).

(7) Casing depth is not a particularly useful variable when the specific-capacity data are taken as a whole. As a single factor when lithology is controlled, casing depth still does not appear to be significant. Only in the context of a regression model that includes all other factors (except saturated interval) does casing depth contribute to the percent of variation in the specific-capacity data that can be explained; this is true for the carbonate rocks and, to a lesser extent, the siliciclastic rocks.

(8) Among the carbonate rocks and siliciclastic rocks, saturated interval does not contribute any more information than well depth in explaining variation in specific-capacity data. Saturated interval is a significant variable in explaining variation among metamorphic and igneous rocks.

(9) Specific capacity among the carbonate rocks has great variability. The interquartile ranges among the siliciclastic rocks, the metamorphic and igneous rocks, and diabase are about one half that of the carbonate rocks.

(10) A number of hydrogeologic units have wells classified in more than one lithologic group. This may indicate interbedding, mixed lithologies, and subjective judgement on the part of drillers and field hydrologists.

(11) Among the dolomite-dominated hydrogeologic units, only the undivided Nittany-Larke Formations and Bellefonte Formation can be shown to be significantly different than the other hydrogeologic units.

(12) Hydrogeologic units classified with limestone or some mix of limestone and other carbonate rocks fall roughly into three groups. The Stonehenge, Keyser, and

Allentown Formations are examples of the higher yielding units among the limestones. The undivided Coburn, Salona, and Nealmont Formations, Bellefonte Formation, Wills Creek Formation, and St. Paul Group are among the lowest yielding limestones. The remaining limestone hydrogeologic units cannot be differentiated from one another.

(13) There is insufficient statistical evidence on which to base a classification of the siliciclastic-dominated hydrogeologic units. The lower yielding units tend to be those that are known to be fine-grained in texture, and the higher yielding units tend to be those known to be coarse-grained.

(14) The metamorphic and igneous rocks include a wide range of hydrogeologic units. With a few exceptions, there is surprising uniformity in the boxplots among these hydrogeologic units and undifferentiated material.

DISCUSSION AND CONCLUSIONS

The goal of this work was to classify hydrogeologic units on the basis of their potential yield, and to base this classification on a set of physical factors that are related to yield. Specific capacity was chosen as the measure of yield. The problem of classification was made difficult by the enormous variation in specific-capacity values within a given hydrogeologic unit. For example, in a dolomite-dominated carbonate hydrogeologic unit such as the Leithsville Formation, specific-capacity values range from 0.02 gpm/ft to 891 gpm/ft with a median of 2.7 gpm/ft. Even in the Wissahickon Formation (schist), values range from 0.01 gpm/ft to 400 gpm/ft with a median of 0.3 gpm/ft.

The variation may be attributed to a number of sources. First, there is the natural spatial heterogeneity in the fracturing, solution channels, and bedding planes of the hydrogeologic units. Local effects in the immediate vicinity of a well can exert considerable influence on the observed discharge and drawdown. Second, the effort to withdraw water on the part of the driller is not necessarily maximized in any absolute sense, but rather pursued as far as the owner and intended use require. This point is supported by the degree to which both water use and casing diameter can explain variation in the specific-capacity data. Indeed, results show that within a given hydrogeologic unit, significant differences in specific capacity can exist between both water use and casing diameter. Finally, the siting of the well in relation to topography, proximity to recharge areas, saturated regolith thickness, boundary conditions, and other physical factors that may affect storage and transmissivity within a localized area of an hydrogeologic unit can also influence specific capacity.

While acknowledging the importance of these constraints, there is still a need to find some physical basis on which to lump together the many hydrogeologic units within the study region. The approach taken in this study was to organize a hierarchy of factors that could reflect some of the causes of differences among hydrogeologic units. The large number of hydrogeologic units and possible factors required that a systematic approach of this type be taken.

Once the dominant lithology of hydrogeologic units was determined, the next step was to examine the relation of specific capacity to factors available in the ground water data base. These factors, representing both categorical and continuous variables, included: water use, casing diameter, topographic setting, well depth, casing depth, and casing diameter. From static water levels, casing depths, and well depths, an estimate of saturated interval was derived. This is the interval of the hydrogeologic unit intercepted by the well (or well screen).

Water use and casing diameter have the strongest relation to specific capacity of the factors when considered individually. They also may be considered to be subjective factors selected by the driller or owner independently of the physical properties of the underlying hydrogeologic unit. To some extent, topographic setting may be put in the same category. Although the influence of topographic setting on specific capacity is a genuine physical effect, the actual siting of a well is often determined by land ownership and structural constraints for the vast majority of domestic wells.

Therefore, water use, casing diameter, and topographic setting were identified as three factors whose influence needed to be filtered out of the specific-capacity values before meaningful comparisons between hydrogeologic units could be made. By regressing specific capacity on these three factors and then working with the residuals from the regression, the effects of water use, casing diameter, and topographic setting were controlled to some extent. In the aggregate, 24 percent of the variation in the specific-capacity data can be explained by these three factors alone.

When nonparametric tests for differences between hydrogeologic units were performed within each major lithologic grouping, distinctions could be made between hydrogeologic units at the extremes of median specific capacity. But for the majority of hydrogeologic units within a lithologic group, no statistically significant differences were detected. This suggests that there is at least a statistical basis for grouping of hydrogeologic units by lithology. Within each lithologic group, there are hydrogeologic units at the lower and upper extremes of the quartile estimates that are comparable in magnitude with hydrogeologic units in other lithologic groups. The divisions between lithologic groups on the basis of specific capacity is a useful, but imprecise means of classification.

The results of this study are, of course, predicated on the quality of the data base. Wells in the GWSI data base are not a random sample of wells in the study area. By identifying some of the primary sources of non-randomness in the data such as water use and casing diameter, some of the systematic bias can be removed. There are clearly other important structural factors such as local fault zones, fracture size and concentration, dip of the rock, and folding patterns that affect specific capacity. The influence of these factors needs to be investigated on the regional scale with high-resolution geologic maps in the framework of a geographic information system. In practical terms, however, the factors considered in this study are the ones most likely to be available in other areas and therefore provide a reasonable starting point for exploratory data analysis and hypothesis testing.

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APPENDIX

Below are listed selected references for past ground-water resource evaluation studies conducted in the study area. All reports are publications of the Pennsylvania Geological Survey and are available by mail from the Department of General Services, State Book Store, P.O. Box 1365, Harrisburg, PA 17105.

Becher, A.B., and S.I. Root, 1981, Groundwater and geology of the Cumberland Valley, Cumberland County: Report W50, 95 p.

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Lloyd, O.B., Jr., and D.J. Growitz, 1977, Ground-water resources of central southern York County: Report W42, 93 p.

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