APPLICATION OF STATISTICAL TECHNIQUES TO THE ESTIMATION OF GROUND-WATER WITHDRAWALS IN NORTHWESTERN KANSAS

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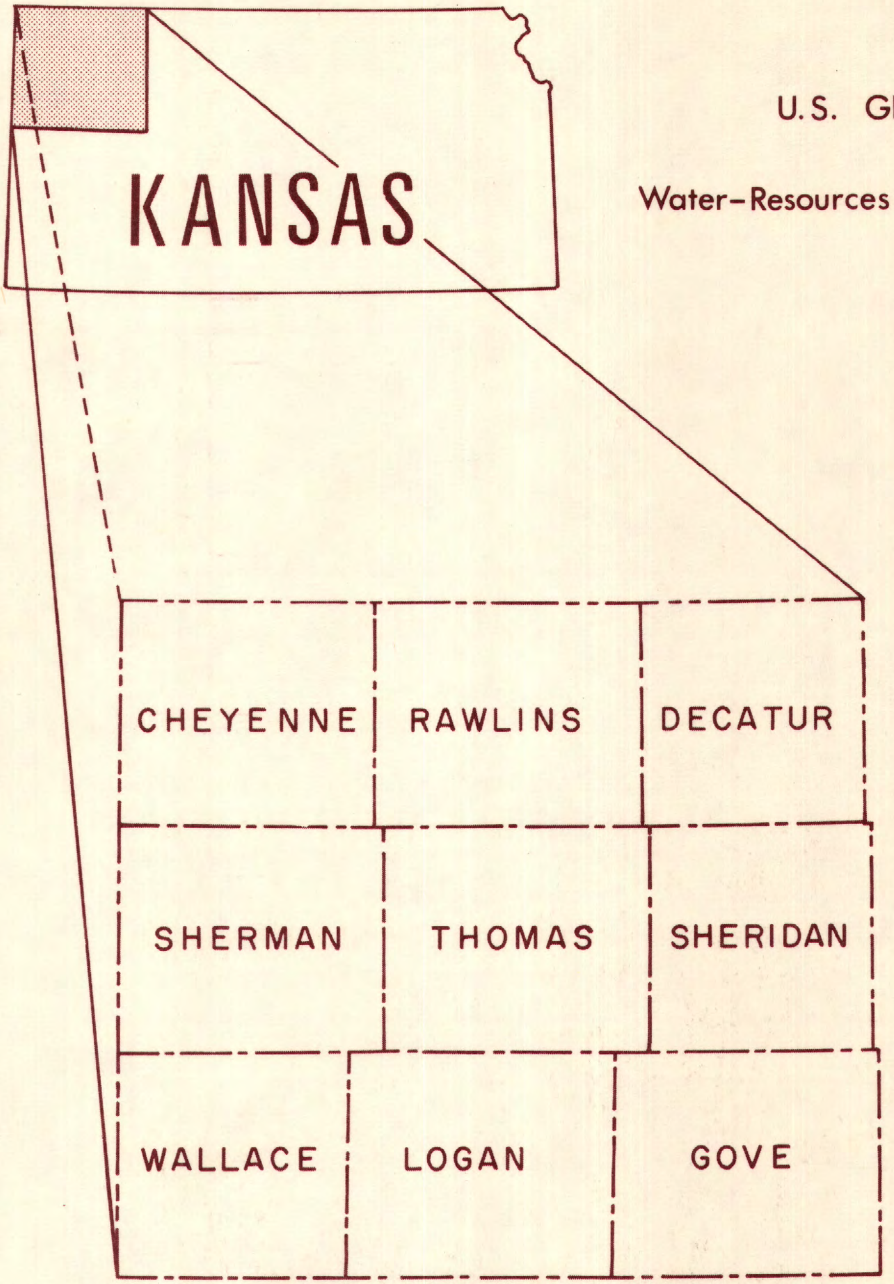

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16. Abstracts This study was made to determine the accuracy of using readily available data with certain statistical techniques to estimate ground-water withdrawals. Data used were from a sample of irrigation wells that can be considered to be typical of data generally available in western Kansas. Withdrawals were obtained by using a power-conversion coefficient to convert records of power consumed to the amount of water pumped. Trend-surface and multiple-regression analyses were performed on the coefficients and on the pumpage per irrigated acre, which was derived from the coefficients. Equations developed using the available data proved to be poor tools for estimating withdrawals. All the expected relationships appeared to be weak or non-existent. A likely conclusion is that the withdrawal values, which were derived from power-conversion coefficients and available data, do not reflect true withdrawals. In future studies, regression and trend-surface techniques might be used with more accurate data, and the reliability and variability of the power-conversion coefficients might be investigated. Continuous metering of a representative sample of wells might also be done to estimate ground-water withdrawals for the total population.

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CONTENTS

FACTORS FOR CONVERTING ENGLISH UNITS TO INTERNATIONAL SYSTEM (SI) UNITS

For those readers interested in or accustomed to using the metric system, the U.S. Geological Survey has adopted a policy of giving metric equivalents (in parentheses) of English units of measurements using the following conversion factors:

English units	Multiply by	Metric units
inches (in)	25.4	millimetres (mm)
feet (ft)	.3048	metres (m)
acres	.4047	square hectometres (hm^2)
square miles (mi^2)	2.590	square kilometres (km^2)
cubic feet (ft^3)	2.832×10^{-2}	cubic metres (m^3)
acre-feet	1.233×10^{-3}	cubic hectometres (hm^3)

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William M. Kastner

ABSTRACT

This study was made to determine the accuracy of using readily available data with certain statistical techniques to estimate ground-water withdrawals in western Kansas. The data used in the investigation were from a sample of wells chosen from the total inventoried irrigation wells in nine counties in northwestern Kansas; they can be considered as being typical of the data generally available in western Kansas.

The hypothesis that each of three physical characteristics of the wells had the same distribution in the sample as in the total population was accepted at the 95 percent significance level. These characteristics (saturated thickness of the aquifer, depth to water below land surface, and reported well yield) were assumed to be related to the withdrawal of the wells, and the sample was considered to be representative of the total population in regard to ground-water withdrawals.

Metered withdrawal values for the wells in the test area were not available, so derived withdrawals were obtained by using power-conversion coefficients to convert power records to pumpage. The power-conversion coefficient is the ratio of values obtained in short simultaneous measurements of power use and discharge for a well.

Trend-surface and multiple-regression analyses were performed on the power-conversion coefficients themselves and on the pumpage per irrigated acre derived from the coefficients. The equations developed using the available data proved to be poor tools for estimating withdrawals.

In the analyses, all the expected relationships appeared to be either very weak or non-existent. The expected relations may actually be weak; however, a more likely conclusion is drawn that the withdawal values, which have been derived using the power-conversion coefficients and the available data, do not reflect the true withdrawals.

For future studies, two methods could be used alone or in combination. The first method is to use regression and trend-surface techniques employing more accurate data, and include investigations into the reliability and the variability of the power-conversion coefficients. The second is to use continuous metering of a representative sample of wells to estimate the ground-water withdrawals for the total population.

INTRODUCTION

The amount of ground water withdrawn by wells is a major unknown parameter in quantitative ground-water investigations. This parameter is particularly needed by State and local agencies for planning and management of ground-water resources. The purpose of this project was to test the feasibility of using readily available data with various statistical techniques for estimating withdrawals. The project was conducted as part of the cooperative program between the Kansas Water Resources Board and the U.S. Geological Survey.

The direct procedure in an investigation of methods to estimate ground-water withdrawals would be to use a sample of measured withdrawals in the analyses. However, there are not enough data on measured withdrawals in Kansas to provide a sufficient sample because the discharge of only a few wells is continuously metered. Discharge data that are available most often come from research projects, experimental farms, and other areas where the irrigation practices can not be considered to be typical of those in general use. Therefore, available power data from a chosen test area were used to derive withdrawal data. Errors in the derivation process became an inherent part of the investigation and placed a constraint on the accuracy of the results. Although records of electric power consumption are regarded as being more accurate than records of natural gas consumption, the latter were used in this analysis because of their abundance.

DERIVATION OF WITHDRAWAL DATA

Discharge of a few wells in Kansas has been measured for a short period of time simultaneously with a measurement of the power consumed in operating the pump on the well. The ratio of power usage to discharge provides a ppc (power-conversion coefficient) for converting the generally available power records for the well into pumpage. When natural gas is the power source, the conversion may be in error due to variations in the Btu (British thermal unit) content of the gas or to variations in the line pressure. Additional error is introduced because the pcc is for the short period when simultaneous measurements are made, but is not necessarily representative of the entire period of pumpage record. Shifts in pcc values in time may result from such factors as changes in depth to water or changes in well efficiency.

In this project, the pcc values were used to derive the needed withdrawal data. The Btu content and line pressure were assumed to have been stable and the measurements were assumed to have been taken randomly as shifts in the pcc values occurred.

TEST AREA

Data from one area were used to test the feasibility of using statistical techniques for estimating withdrawals. The test area used was the block of counties in northwestern Kansas (see cover) that includes Cheyenne, Rawlins, Decatur, Sherman, Thomas, Sheridan, Wallace, Logan and Gove Counties. The counties comprise an area of about 9,000 square miles (23,000 km^2). Much of the area is irrigated and water-level declines as great as 36 feet (10.9 metres) have occurred since 1950. Because of the extensive irrigation activity, the U.S. Geological Survey, in cooperation with various State agencies, has collected a great deal of information on the area. Data pertinent to this study are included in reports by Keene, Pearl and Pabst (1969) and Keene and Pabst (1971).

The data from this area are more complete than from other areas in western Kansas, but the type of data can be considered to be typical of that generally available.

SAMPLE OF TOTAL POPULATION

Approximately 1,800, or 72 percent, of the 2,500 wells inventoried in the nine-county area are irrigation wells. Of the well yields that are reported, 99 percent of that total can be attributed to irrigation wells. Almost all the wells for which pcc values have been determined are irrigation wells. Because nearly all the pumpage can be attributed to irrigation wells, it was necessary and seemingly within reason to define the total population as the total number of irrigation wells. Wells for other uses were considered to be of little significance in regard to the total ground-water withdrawal for the area.

Eighty-seven wells for which sufficient data were available were selected as a sample from the test area. The wells were chosen using the following criteria:

1. A power-conversion coefficient had been determined for the well.
2. Power records were available for each well.
3. Natural gas was used for power.
4. Irrigated-acreage figures were available for each well.
5. When possible, preference was given to wells located throughout the test area.

Systematic sampling throughout the area was essential because part of the analysis included mapping coefficients or discharge by location.

Natural-gas records were obtained for 1966-71 from the Northern Natural Gas Company and the Peoples' Natural Gas Company, whose cooperation in this study is greatly appreciated. Records were not available for all wells during these years, but 432 well-years of record were obtained from the 87 wells.

ACCEPTANCE OF SAMPLE

As the 87 test wells were not selected randomly, it was necessary to examine the sample to see if it could be considered to be representative of the total population of inventoried irrigation wells. Prior to making the test, three characteristics were defined for each of the 87 test-well sites and also for most of the total population. The chosen characteristics were saturated thickness of the aquifer, depth to water below land surface, and reported well yield. These parameters were expected to be related to the withdrawal of the wells.

The Smirnov-Kolmogrov statistic (Preston, 1970) was used to test the goodness of fit. This nonparametric test consisted of comparing the cumulative frequency distribution of each test-well parameter to the corresponding frequency distribution for the total population. On the distribution curve of each of the three parameters, 100 points were chosen at 0.3 standard deviation spacings. Each point on the test sample curve was compared with the corresponding point on the total population curve, and the variation was small enough to consider the curve equivalent at the 95-percent significance level. Therefore, the test sample was considered to be representative of the total population in regard to ground-water withdrawals.

ANALYSIS AND RESULTS

Two methods were used for estimating well discharge.

Estimating the Power-Conversion Coefficient

In the first method the following general formula was used to estimate ground-water discharge:

$$Q = G/(pcc)_T \tag{1}$$

where Q equals estimated ground-water discharge (acre-feet), G equals power consumption (gas consumption measured in cubic feet for the test area), and $(pcc)_T$ equals the derived power-conversion coefficient that is applicable to the total population. This formula is used to determine values of Q where G is known for an individual well or for an area, and $(pcc)_T$ is estimated using various statistical techniques based on the measured pcc values, $(pcc)_S$ from the 87 wells in the sample population. The statistical analysis is for estimation of a value of pcc; therefore, the standard deviations, standard errors of estimate, and coefficients of determination were on estimates of the pcc rather than on the estimated Q.

The average or mean $(pcc)_S$ value for the test wells is 7,170 cubic feet of natural gas per acre-foot of water (165,000 m^3/hm^3). The standard deviation is 2,015 or 28 percent of the mean value. The mean value of 7,170 could be used for $(pcc)_T$ in equation 1.

The measured values of the power-conversion coefficient from the test sample $(pcc)_S$ were located on a map, and the trend expressing geographic variation was contoured using a least-squares trend-surface technique (Esler, Smith and Davis, 1968). The value of $(pcc)_T$ for use in equation 1 could then be chosen from the contour map to represent the pcc for an area or for an individual well. The coefficient of determination on the entire map was 0.20. This low value and a high standard error of estimate on the entire map indicated that there was little geographic trend in the $(pcc)_S$ values detected by the trend-surface program, and that the mean $(pcc)_S$ value could be used as the $(pcc)_T$ value with nearly the same accuracy as picking a value from the trend map. The $(pcc)_S$ values vary in the area. The variations, however, can not be represented by a simple trend.

A pcc value was estimated through regression analysis. The $(pcc)_S$ values were considered as dependent variables and the physical characteristics of the well, such as well depth, depth to water, aquifer thickness, saturated thickness, and depth to bedrock (expressed in feet) and the well diameter, (expressed in inches) were considered as independent variables that might be related to the pcc value. The regression equation

$$(pcc)_T = 3300 + 28D \quad (2)$$

was the most practical equation developed in the analysis. The other variables and various transformations of data resulted in little additional accuracy. In the equation, the $(pcc)_T$ is the derived value applicable to the total population to be used in equation 1 and D is the depth to water. The coefficient of determination for this equation was 0.44 and the estimates had a standard error of estimate of 1,790, or 25 percent of the mean. Judging from the relatively low coefficient of determination and high standard error of estimate, the regression analyses provided equations with poor accuracy for estimating a $(pcc)_T$ value.

Estimating the Ground-Water Withdrawals per Irrigated Acre

In the second method, the general formula used to estimate ground-water withdrawals was

$$Q = (AI)\ (Q)_T \quad (3)$$

where Q equals estimated ground-water discharge in acre-feet, AI equals irrigated acres, and $(Q)_T$ equals the derived ground-water discharge per irrigated acre value. The value of Q is determined where AI is known for a specific well or for an area and $(Q)_T$, which applies to the total population, is estimated using various statistical techniques based on the known ground-water discharge per irrigated acre, $(Q)_S$, figured on the 87 wells in the test sample. The $(Q)_S$ values for each test well were determined as follows:

$$(Q)_S = [(G)_S/(pcc)_S]/(AI)_S \quad (4)$$

where all values are from the wells in the test sample, $(G)_S$ equals the amount of power used, $(pcc)_S$ equals the measured pcc value, and $(AI)_S$ equals the acres irrigated by the test well.

In the second method, the statistical analysis is on derivation of a ground-water discharge per irrigated acre, $(Q)_T$, and all standard deviations, standard errors of estimate, and coefficients of determination are for estimates of this value. The results from the second method are not comparable to those from the first where estimates of $(pcc)_T$ values were analyzed. The inclusion of irrigated acreage and power used in the calculation of $(Q)_S$ introduces additional error.

Because monthly values are available for power usage and for acres irrigated, monthly as well as yearly discharge values can be calculated for $(Q)_S$. The mean ground-water discharge values, in acre-feet per irrigated acre, their standard deviations, and the percentage of the standard deviation to the mean follow:

Period		Mean (acre-feet per irrigated acre)	Standard Deviation	Standard Deviation as Percent of Mean
Annual	$(Q)_S$	1.760	0.960	55
January	$(Q)_S$	.034	.109	321
February	$(Q)_S$	.019	.065	342
March	$(Q)_S$	.061	.130	213
April	$(Q)_S$	.163	.237	145
May	$(Q)_S$	.175	.225	129
June	$(Q)_S$	.069	.120	174
July	$(Q)_S$	.248	.252	102
August	$(Q)_S$	.516	.314	61
September	$(Q)_S$	.355	.285	80
October	$(Q)_S$	.058	.104	179
November	$(Q)_S$	.027	.077	285
December	$(Q)_S$	.031	.087	281

The annual and monthly $(Q)_S$ values were located on a map and contoured using the trend-surface technique. No significant geographic trends were revealed, as the results had high standard errors of estimate and the coefficients of determination were about 0.02.

The $(Q)_S$ values were used as dependent variables in regression analysis and weather characteristics were used as independent variables. Monthly precipitation totals and annual precipitation, P_{period}, are measured in inches; monthly pan-evaporation totals for the months April through September, E_{period}, are measured in inches; and the monthly number of storms with more than 0.5 inch (13 millimetres) of precipitation are given for the months April through October. Discharge values for each well were matched to the climatological data from the precipitation and evaporation station nearest to the well. A correlation between discharge and weather characteristics was anticipated on the premise that, in general, farmers would irrigate more during periods of low rainfall and high evaporation.

Examples of equations developed in the regression analysis, their coefficients of determination (R^2), and their standard errors of estimate as a percentage of the mean follow:

Period	Equation	R^2	Standard Error of Estimate as Percent of Mean
Annual	$(Q)_T = 2.46 - 0.161\ P_{July} - 0.122\ P_{Sept} - 0.082\ P_{Oct}$	0.05	53
May	$(Q)_T = -0.087 - 0.030\ P_{Apr} + 0.036\ E_{Apr}$	.04	126
June	$(Q)_T = 0.005 - 0.017\ P_{May} + 0.011\ E_{May}$	.07	168
July	$(Q)_T = 0.223 - 0.062\ P_{June} + 0.016\ E_{June}$	.07	98
Aug.	$(Q)_T = 0.290 - 0.058\ P_{July} + 0.028\ E_{July}$	.03	60
Sept.	$(Q)_T = 0.081 - 0.021\ P_{Aug.} + 0.026\ E_{Aug.}$	.03	79

In the equations $(Q)_T$ is the annual ground-water discharge or monthly ground-water discharge for the months of the growing season; P_{month} is the monthly precipitation total, and E_{month} is the monthly evaporation total. Various combinations of parameters and data transformations were examined in the analyses. The equations given are for illustration and were chosen for their simplicity and uniformity. A few of the other equations developed had slightly higher coefficients of determination and slightly lower standard errors of estimate. The results of the analyses indicate that the variations in $(Q)_S$ are very poorly correlated to weather characteristics and that regression techniques generally are a poor tool for estimating pumpage in the second method.

The first method using $(pcc)_T$ and the second method using $(Q)_T$ each have distinct advantages and disadvantages. The principal advantage of the first method is the ease and accuracy with which power-consumption data can be converted to ground-water withdrawals. One disadvantage is that data on well or site characteristics, which are independent variables in the regression equations, are commonly missing. Another disadvantage is that different trend maps and regression analyses must be constructed for each kind of power that is used in the area.

The principal advantage in using the second method is that the weather factors, which are independent variables in the regression equation, are generally available. A major disadvantage is that the irrigated-acreage value needed for the computation of $(Q)_S$ may contain extensive error. The data on irrigated acreage per well are often difficult to obtain and generally represent the maximum acreage that can be supplied by the well. The acreage value needed for the computation is the actual acreage irrigated during a specific time.

CONCLUSIONS

The general conclusion reached in this study is that poor estimates of ground-water withdrawals are obtained when the readily available data are used with various statistical techniques.

A definite geographic trend was anticipated when the power-conversion coefficients were mapped and contoured because factors such as depth to water and aquifer thickness differ geographically and were expected to be closely related to the pcc values. A strong correlation was anticipated in regression analysis between the pcc values and the well or site characteristics because these parameters are physically related. A definite geographic trend was anticipated for $(Q)_S$ values because they were expected to show a strong relation to crop type and soil type, which differ geographically. Likewise, a good correlation was anticipated in regression analyses between $(Q)_S$ and weather characteristics because it was assumed that farmers generally irrigate more during dry periods.

All expected relations in this study proved to be very weak or nonexistent. The conclusions that can be drawn are that either the expected relations actually are weak and were not detectable by the statistical techniques, or that the derived data were not reliable and that methods for measuring $(pcc)_S$ values and $(Q)_S$ values are inaccurate. The latter conclusion seems most likely.

DISCUSSION

Alternate methods and the refinement of present methods need to be investigated in view of the poor results obtained in this study for estimating ground-water withdrawals from power-conversion coefficients when using the available data. Metering all wells would provide the most accurate information on ground-water withdrawals. At present, however, extensive metering involves great expense, and less expensive alternatives may provide adequate answers.

One of the more practical alternatives for improving the estimates of ground-water withdrawals would be to use the statistical techniques investigated in this study with a higher quality and different types of data than are presently available and with an improved understanding of the use of pcc values.

The results of this study indicate that discharge values derived from the pcc measurements do not accurately represent discharge. Periodic measurements of pcc values for the same wells at selected locations would help to determine the amount of fluctuation in the value during the irrigation season as the water table is lowered and the pumping lift is increased. Data on changes in the value of the pcc with time would permit better interpretation of available information by showing the amount of error in the derived discharge incurred by use of a single value for pcc.

The quantity and quality of data used in the analysis could be increased by recording all data on a well that might directly or indirectly relate to the use of irrigation water. Data that might be included would be the physical characteristics of the well, aquifer characteristics, soil conditions, type of irrigation, whether tail water is re-used, type of crop and acreage, type of pump, and type of power and method of metering. These data could be used as additional independent variables in regression analyses for estimating the pcc or discharge and might prove to be better correlated with the dependent variables than the parameters used in the present study. In the present study, the independent variables used in the regression anlayses were limited to parameters that were available for a large number of wells in northwestern Kansas. They were typical of parameters generally available for wells throughout Kansas.

In this study a strong relationship between well discharge and weather parameters is not indicated by regression analyses. The lack of correlation probably is due, in part, to the fact that discharge for irrigation of all crops is treated together in one analysis. There may be periods during the growing season when irrigation of many crops is not governed by weather conditions. Because periods of irrigation not dependent on weather occur at different times for different crops, correlation is likely to be poor in any analysis that includes data for all crops together.

Subdivision in regression by crop could be expected to improve results if detailed crop information in relation to irrigation were available. Similar improvements also might be obtained with subdivision in separate regressions by type of irrigation used, by aquifer pumped, or by soil type irrigated.

Much of the data that could be used to improve the statistical analysis is being collected, but is not in the form needed for analysis. As an example, irrigated acreage commonly is being measured according to the crop irrigated. This information seldom is related to the well that is the source of the irrigation water. Therefore, there is no tie between irrigated acreage and the amount of water used.

The discharge of new wells is measured in the process of establishing a water right, but a simultaneous measurement of the power consumed during the well test generally is not made. As a result, a power-conversion coefficient is not determined even though the major part of the work involved in obtaining the coefficient has been done.

Power records are obtained through the voluntary cooperation of individual power companies. The records, which generally are compiled by account number or by landowner, may include a total value for several wells. A cross-reference system relating power consumption to a specific well would eliminate many errors that occur in assigning pumpage.

Another alternative for estimating ground-water withdrawals would be to meter continuously a small sample of wells. If the sample is tested and shown to be representative of all the wells, values determined from the sample could be projected to the total population. A random sampling technique might be used to insure that the test sample is representative of the total population.

The number of wells that should be in a randomly selected sample depends primarily on the degree of accuracy desired. By measuring the discharge from a small number of wells, the variability associated with the discharge can be used to estimate the accuracy that can be obtained at a desired confidence level. If the accuracy is not as high as that desired, the number of wells in the sample can be increased and the accuracy test repeated. By this procedure, the smallest sample that will give the desired accuracy and confidence level can be chosen.

The type of ground-water investigation that is planned in an area may dictate whether statistical techniques, metering a random sample of wells, or a combination of methods is chosen to estimate withdrawals. The method using the tested statistical techniques would probably be preferred when withdrawal estimates are desired for a period of time different from the period when the investigation will be in progress. Examples of such periods are when estimates of past withdrawals are needed or when future withdrawals are to be postulated. Changes in depth to water, weather conditions, or other factors that affect withdrawals could be accounted for by including these factors as parameters in the regression equations. Power-conversion coefficients taken under a variety of conditions would be needed to form the equations, and power records for the period of interest would have to be available or would have to be postulated.

Metering a random sample of wells might be the preferred method when the metering could be done in the same period of time for which estimates were desired. As an example, the total withdrawal from an area would be estimated for a period of years using data collected from a sample of wells during the same period of time. Hydrologic changes that affect the total withdrawal, such as lowering of the water table, would be reflected in data from the sample wells.

A combination of methods may be appropriate in future studies. Random-sampling techniques could be used to select a representative sample of wells to be metered for determination of the power-conversion coefficients. The coefficients could be remeasured periodically and checked against the meters to provide data on the variability of the coefficients. Parameters determined from the sample could be used with the tested statistical techniques for estimating historical or future withdrawals and withdrawals in areas where metering would be impractical or where power records were unavailable.

As the need for information on ground-water withdrawal becomes increasingly apparent, the State and Federal agencies that deal with irrigation and ground water use will find it necessary to exchange additional data and to work closely to meet the need. An adequately funded and coordinated data-collection program could insure that optimal data on ground-water withdrawals are collected properly and at a minimum cost.

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