UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
Water Resources Division

A CONTINUING PROGRAM FOR ESTIMATING GROUND-WATER PUMPAGE IN CALIFORNIA--METHODS

Prepared in cooperation with the
California Department of Water Resources

OPEN-FILE REPORT

Menlo Park, California
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By
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ABSTRACT

Municipal and agricultural ground-water pumpage is being estimated for the principal ground-water basins in California. Because of its anticipated use in analog or digital hydrologic models, agricultural pumpage is estimated for unit areas.

Estimated municipal pumpage is based on census figures and population projections and on pumpage reported by organizations in the San Joaquin Valley supplying water to communities. On the average, 0.25 to 0.40 acre-foot of water is used annually per capita, depending upon the population and number of industries in the community. The product of population by appropriate per capita use factor gives an estimated annual pumpage for a municipality.

For agricultural ground-water pumpage estimates, basic data from plant-efficiency tests and annual electric power and gas consumption totals furnished by the major utility companies are punched onto cards. A computer sorts and averages, or totals, the annual data and computes annual ground-water pumpage for units of a quarter of a township. To obtain annual pumpage for larger areal units, such as townships, pumpages for quarter of a township units are summed. Results are cited for areas of 36 square miles.

Several checks are made throughout the program to verify the reliability of the data and computations. Among the checks, there is an average discharge per well per unit area computed from power data. By comparing the average discharge per well to known discharges from pump-efficiency tests, anomalies can be spotted.

Statistical studies indicate that efficiency tests of individual wells probably are representative of wells in a surrounding area. Further, the tests are spaced throughout the pumping season. Although testing may be localized in any one year, over a 5-year period, areal distribution is random.

Under optimum conditions, the difference between metered and computed pumpages is less than 10 percent for areas of a quarter of a township (9 square miles) and for one township (36 square miles). However, pumpage computed for areas of a section (1 square mile) ranged from 37 percent less to 83 percent more per section than metered pumpage.

INTRODUCTION

Increased use of ground water since 1940 has resulted in a notable decline in water levels in many areas of California. Various procedures including water-conservation methods and surface-water imports, have been undertaken to help alleviate the depletion of ground-water resources. Quantitative estimates of ground-water pumpage from the principal ground-water basins in California are necessary for future appraisal studies, for constructing hydrologic models, and for systematic planning of water use and conservation.

This report was prepared by the Geological Survey, Water Resources Division, in cooperation with the California Department of Water Resources, as part of a statewide program of water-resources studies. The work was done under the general supervision of R. Stanley Lord, district chief in charge of water-resources investigations in California, and under the immediate supervision of Williard W. Dean, chief of the Sacramento subdistrict office.

Purpose and Scope

The purpose of this report is to outline a systematic procedure for making estimates of ground-water pumpage and to describe computer techniques for processing pumpage data in California. Because of an anticipated need in model studies, pumpage is determined on a nodal density usable in analog or digital computer models.

This report describes: (1) The collection of basic data; (2) procedures for processing data; (3) techniques used for areas where data coverage is not adequate; and (4) the reliability and representative nature of the data and accuracy of computed pumpage.

Acknowledgments

Appreciation is expressed to the Pacific Gas and Electric Co., Southern California Edison Co., Southern California Gas Co., and Kern County Land Co., and to their engineers, who supplied information on pumpage, pumping-plant efficiency tests, agricultural power, and agricultural power usage. The writers are grateful for the cooperation and assistance received from city and county officials and other federal and state agencies.

MUNICIPAL PUMPAGE

Data on the volume of ground water pumped for municipal use were obtained from 27 communities ranging in population from about 1,000 to 145,000. The reported volume of water used by each community was divided by its population to determine a per capita use factor; the factors are shown in the following table.

Population	Number of samples	Annual per capita use factor, in acre-feet		
		Low	High	Average
Less than 3,000	6	0.14	0.33	0.25
3,000 - 10,000	11	.17	.44	.30
More than 10,000	10	.28	.46	.38

For two communities of more than 10,000 population, in northern San Joaquin Valley (not included in the table above) per capita use averaged only 0.25 acre-foot; however, the communities were served by a private water company and the average use figure did not include pumpage from numerous large industrial wells.

The data indicate that for small communities supplying little or no water to industry, the annual per capita use factor averages about 0.25 acre-foot. For communities supplying water to industry, the average factor ranges from 0.30 to 0.40 acre-foot, depending upon size of the community and number of industries. Thus the volume of ground water pumped for municipal use can be estimated by multiplying the population of a community by the appropriate annual per capita use factor.

AGRICULTURAL PUMPAGE

Data Collection

Total annual consumption of electricity and natural gas for pumping ground water, and data from pumping-plant efficiency tests are acquired from the major utility companies in central California.

In the San Joaquin Valley, data on total annual electric power consumption used for agricultural pumping of ground water are acquired from the Pacific Gas and Electric Co. and the Southern California Edison Co.; total annual consumption of natural gas used for pumping ground water is obtained from the Southern California Gas Co. Data on use prior to 1966 were acquired, where available, from company archives. Gas-consumption records prior to 1965 are not available. Individual accounts of electrical power or natural gas consumption for agricultural use are summed for total energy consumed in unit areas.

Utility companies in California make pumping-plant efficiency tests as a service to customers. These tests provide much of the information required for computing ground-water pumpage, such as the number of kilowatt-hours required to pump 1 acre-foot of water.

Description of Estimation Methods

Agricultural ground-water pumpages are computed on an annual basis per unit area. The unit area selected for the San Joaquin Valley is a quarter of a township; for larger areas pumpages from the unit areas are summed.

Estimates from Electrical Power

Two techniques can be used for estimating ground-water pumpage from electrical power consumption; one uses the efficiency-lift method and the other uses the coefficient of power method. To compute pumpage on an areal basis, the coefficient of power method was used in preference to the efficiency-lift method because more data are available for the coefficient of power method.

Using the equation based on a coefficient of power consumption, annual pumpage is computed as follows:

$$Q_y = \frac{\text{kwhr/yr}}{P_c}$$

$$P_c = \frac{5{,}430\ P_i}{Q}$$

where

Q_y = annual pumpage in acre-feet

P_c = coefficient of power consumption in kilowatt-hours per acre-foot from pump-efficiency tests

P_i = input to motor in kilowatts from pump-efficiency tests

Q = discharge in gpm (gallons per minute) from pump-efficiency tests

$$\frac{\text{kwhr}}{\text{acre-ft}} = \frac{1}{\text{min/hr} \times \text{ft}^3\text{/gal} \times \text{acre-ft/ft}^3} \times \frac{\text{kw}}{\text{gal/min}}$$

$$= \frac{1}{60 \times 1/7.48 \times 1/43{,}560} \times \frac{\text{kw}}{\text{gal/min}}$$

$$= 5{,}430\ \frac{\text{kw}}{\text{gal/min}}$$

Using this technique, data required for calculating areal pumpage include: (1) Total kilowatt-hours of power used per unit area per year from power data, and (2) average coefficient of power consumption per unit area per year. Thus, in each unit area:

$$Q_y = \frac{\Sigma\text{kwhr/yr}}{\dfrac{\Sigma P_c}{nP_c}}$$

where nP_c = number of coefficient of power-consumption tests.

Estimates From Internal-Combustion Engines Using Gas

Most ground water used for agriculture in California is pumped electrically. However, in areas where electricity is not readily available or where there is a ready source of natural gas, pumps may be driven by internal-combustion engines. To lift 1 acre-foot of water 1 foot at 100 percent efficiency requires 1.37 brake hp-hr (horsepower-hours). Therefore, the volume of gas to lift 1 acre-foot of water 1 foot for a single well is:

$$V_Q = \frac{1.37 \text{ hp-hr}}{\text{acre-ft/ft}} \times \frac{\text{cubic feet of gas}}{\text{hp-hr}} \times \frac{100}{E}$$

where

V_Q = volume of gas in cubic feet required to lift 1 acre-foot of water 1 foot

E = efficiency in percentage.

In Kern County, about 11 cubic feet of gas are required to produce 1 brake horsepower-hour, and on the average the engines operate at 60 percent efficiency. Placing these figures in the equation the volume of gas used is:

$$V_Q = \frac{1.37 \text{ hp-hr}}{\text{acre-ft/ft}} \times \frac{11 \text{ ft}^3}{\text{hp-hr}} \times \frac{100}{60}$$

$$= 25.1 \text{ cubic feet of gas per acre-foot per foot.}$$

Utility companies often bill for gas used in units of 1,000 cubic feet (MCF). The equation used to compute pumpage of water in acre-feet is as follows:

$$Q_y = \frac{MCF \times 1{,}000}{V_Q H}$$

and by substitution

$$Q_y = \frac{MCF \times 1{,}000}{25.1\ H} = \frac{39.8\ MCF}{H}$$

where

H = total lift in feet

MCF = gas consumption in units of 1,000 cubic feet reported by utility company. Annual pumpage per unit area is computed as follows:

$$Q_y = \frac{39.8\ \Sigma\ MCF}{H_a}$$

where

ΣMCF = total gas used per unit area

H_a = estimated average total lift in feet per unit area.

Data Processing

Estimates From Electrical Power

The data that are used for computing pumpage from power data are taken from the plant-efficiency tests and records of annual electrical power consumption. Data are punched onto two separate sets of cards of identical format. The mutual data card (fig. 1) consists of 14 fields. A description of the 14 fields follows:

(Fields 1 through 4 are used for both sets of cards)

Field 1, REFERENCE NUMBER. The company account number used to identify the original data.

Field 2, LOCATION. The location of each pumping plant in reference to the California land grid system. Locations are determined to the nearest section.

Field 3, DATE MEASURED. The date of the test, or the year of the annual kilowatt-hour totals.

Field 4, H. P. Horsepower of the pump motor.

(Fields 5 through 13 are used for plant-efficiency test cards only).

Field 5, S.W.L. BELOW LSD (FEET). Static water level below land-surface datum, in feet.

Field 6, S.W.L. BELOW ₵ PUMP (FEET). Static water level below the center of the discharge of the pump head, in feet.

Field 7, DRAWDOWN (FEET). The decline in water level, in feet, resulting from pumping.

Field 8, P.W.L. BELOW ¢ PUMP (FEET). Pumping water level below the center of the discharge of the pump head, in feet.

Field 9, DISCH. L. ABOVE ¢ PUMP (FEET). Discharge level above the center of the discharge of the pump head, or total discharge pressure head, in feet.

Field 10, YIELD OF WELL (GPM). Discharge of the well in gallons per minute.

Field 11, TEMP. (°F). Temperature of the water from the well, in degrees Fahrenheit.

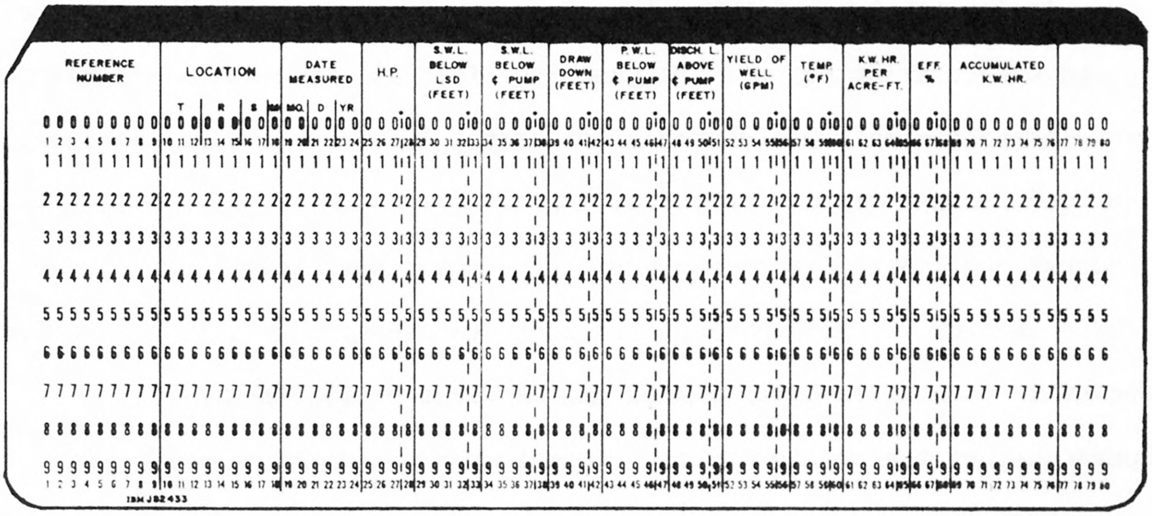
Field 12, K.W.HR. PER ACRE-FT. Number of kilowatt-hours used to pump 1 acre-foot of water--the coefficient of power consumption.

Field 13, EFF %. The percentage efficiency for the wire to water relation of power output to power input X 100.

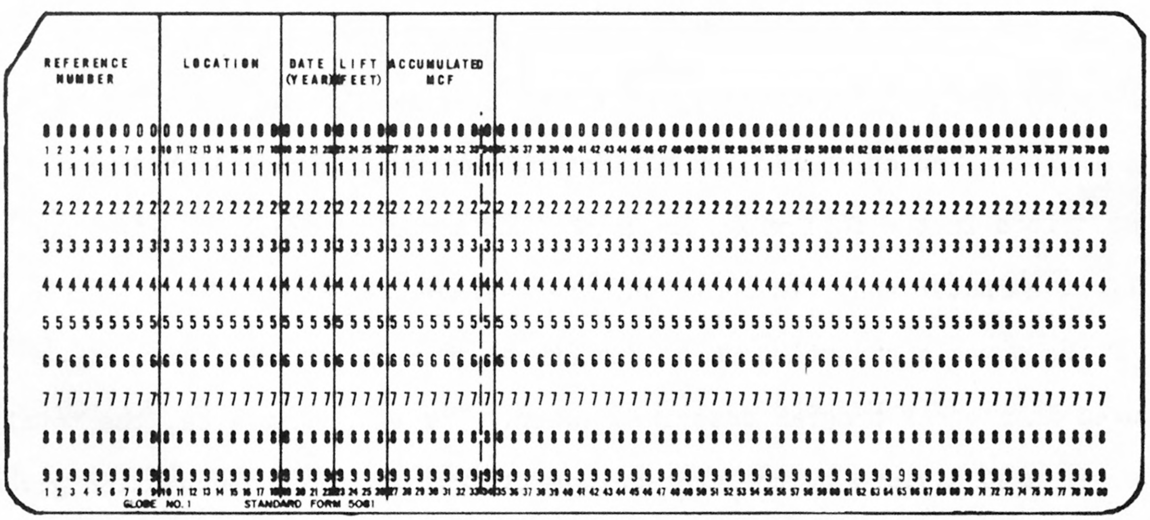
(Field 14 is used on electric power consumption cards only).

Field 14, ACCUMULATED K.W.HR. The annual total kilowatt-hours of electric power used.

Entries in field 12 and field 13 are edited on the basis of inspection, before punching, to delete some data that are notably different than other tests in a given area. Plant-efficiency tests where the efficiencies are very low compared to other tests (less than 40 percent for example), or where the discharge levels above the pumps are very high (more than 30 feet for example, due to sprinklers or other reasons), the listed coefficients of power consumption probably are too high.



A.--Used for electric-power data and efficiency tests.



B.--Used for gas-consumption data.

FIGURE 1.--Data cards

Agricultural power (nonextractive power) not used for ground-water pumpage is eliminated prior to punching field 14. Records available for some areas indicate use of power for shops, lift pumps, wind machines, and other nonextractive purposes. For other accounts, the service address and listed horsepower are clues to nonextractive use of power. Where records are not available to indicate use of power, nonextractive power is identified or estimated on the basis of discussions with personnel of the public utility companies.

Both sets of cards are sorted by year and by unit area. The data in fields 4 to 13 of both sets of cards are averaged and in field 14 of the power-consumption cards, data are summed. However, only the results from fields 12 and 14 (averaged coefficient of power consumption from efficiency test cards and total kilowatt-hours from the power-consumption cards) are used by the computer for estimating pumpage. Data in fields 4 to 11 and field 13 are averaged at the request of the cooperator and as an aid for estimating pumpage for certain unit areas described in the following paragraph that are not computed during the first computer run. In addition, the average horsepower from field 4 of the power-consumption cards and annual pumpage per unit area are used in a check program described later. For each unit area, the total power used divided by the average coefficient of power consumption gives annual pumpage.

Because the areal distribution of plant-efficiency tests is not uniform, some unit areas for which there are power totals (from the power-consumption cards) lack values for average coefficient of power consumption (from plant-efficiency test cards). Consequently, pumpages are not estimated for those unit areas during the first computer run. For each of those unit areas and for areas in which the coefficient of power values are averaged from three efficiency tests or less or where sprinklers predominate, an average coefficient of power consumption and a value for pumpage is determined in the following manner: (1) For a given area, such as power district or county, a least-squares regression relation is computed between total lift and kilowatt-hours per acre foot using data from the listed plant-efficiency tests; (2) lift for the unit areas is determined from maps showing either static or pumping water levels. An estimated drawdown is added to static water levels in order to get an estimated pumping level. Average pmmping lift in each unit area is considered to be the average pumping depth to water plus an estimated head due to sprinklers--if present. The head due to sprinklers is estimated by averaging the values greater than 50 feet for discharge level above the reference point listed in the plant-efficiency test records; (3) an estimated value for average kilowatt-hours per acre-foot for each unit area then is determined from the least-squares relation. The coefficients of power consumption for the unit areas are punched onto cards which are keyed to sections lying within the unit areas. These cards are combined with the efficiency-test cards and the pumpages for all unit areas are recomputed in a second computer run.

Estimates From Gas Consumption

Data used for computing pumpage by internal-combustion engines are punched onto one set of cards (fig. 1) having five fields as follows:

Field 1, REFERENCE NUMBER. The company account number used to identify the original data.

Field 2, LOCATION. The location of each pumping plant in reference to the California land grid system. Locations are determined to the nearest section.

Field 3, DATE. The year of annual gas-consumption totals.

Field 4, LIFT (FEET). The total lift from the pumping water level to the discharge level, in feet.

Field 5, ACCUMULATED MCF. The total annual gas consumption, in thousands of cubic feet.

Data taken from gas-consumption records are punched onto fields 1, 2, 3, and 5. Values for lift for each unit area are estimated from maps showing static or pumping water levels, and punched onto field 4 of cards keyed to the proper year and to sections within the unit areas. The cards are combined and pumpage computed as described on page 10.

Reliability of Estimation Methods

Quality Control

Before and after pumpage is computed, checks are made to verify the reliability of the data and the data decks. The data decks are checked for (1) punching errors, (2) location descriptions, (3) water levels and associated drawdowns, and (4) any anomalies occurring among lift, kilowatt-hours per acre-foot, and kilowatt-hours per acre-foot per foot. Also random-sample computations of pumpage are made manually to verify machine computations. In addition, through a subsidiary program, the average discharge per well is computed and checked against known discharges from tested wells in the area. The equation that is used to compute average discharge per well is as follows:

$$Q_{avg} = \frac{KQ_y}{\frac{nL}{100}}$$

where:

Q_{avg} = average discharge per well in gallons per minute

Q_y = pumpage in acre-foot per year

$$K = \frac{325,850 \text{ gal/acre-ft}}{365 \text{ day/yr} \times 1,440 \text{ min/day}} = 0.62 \frac{\text{gal/yr}}{\text{acre-ft/min}}$$

n = number of accounts

L = load factor (approximate percentage of time wells operate in year)

In the above equation the load factor L is computed as follows:

$$L = \frac{\Sigma \text{kwhr per unit area/yr}}{\frac{\Sigma \text{hp per unit area} \times 0.7457 \text{ kw/hp}}{8,760 \text{ hr/yr}}} \times 100$$

$$= 0.01531 \frac{\Sigma \text{kwhr}}{\Sigma \text{hp}}$$

Accuracy of Results

A statistical analysis of pumpage in selected areas of Kern County by Allison (1967, p. 44-61) is based on records of power used for pumping and results of pumping-plant efficiency tests. Results of that analysis include: (1) The variance in efficiency is small relative to the number of tests available and the mean value of efficiency for any given area can be estimated accurately; (2) the primary factor in the variation of efficiency is the variation of pumping lift; (3) the tests are spaced throughout the pumping season and are indicative of dynamic conditions; (4) measurements of lift and efficiency are integrated in the computation of the coefficient of power consumption; (5) the probable error in the estimation of pumpage is a function of the number of tests on which the coefficient of power consumption are made; and (6) the number of tests made is closely related to the number of pumping plants in any given area and to the total volume of water pumped. In an example for one township (Allison, 1967, p. 53), where the number of tests ranged from 4 to 49, the probable error in estimation of pumpage ranged from 12.5 to 4.0 percent.

Because the major cause of change in the power-consumption coefficient is the pumping lift, the most precise method for estimating pumpage probably would be one incorporating more information on pumping lift and fewer efficiency tests. However, there are few areas in California where pumping levels are measured frequently enough to define the mean pumping lift during the irrigation season.

In order to determine the accuracy of pumpage computations from electric-power consumption, computed pumpage was compared with metered pumpage for selected wells in Santa Clara County (table 1) and in Fresno County. The comparison indicates that, the difference between computed and metered pumpage is less than 10 percent. One- and 5-year averages are shown because instances occur where a 1-year average in a single township will not include enough tests to provide a reliable value for coefficient of power consumption.

Ground-water pumpage from about 200 wells in T. 6 S., R. 1 W., Santa Clara County, was computed by using average pumping-plant efficiency and average pumping lift per township as determined from efficiency tests and a depth to water map. The water meters used to measure pumpage were new and were calibrated at the factory to record within a maximum error of 2 percent. As shown in table 1, the computed pumpage was about 1 percent larger than metered pumpage from the same wells in T. 6 S., R. 1 W., and about 11 percent larger in T. 6 S., R. 1 E.

A further comparison of computed and metered pumpage was made for Santa Clara County by using average coefficients of power consumption per township. Pumpage computed by using the average power-consumption coefficient for 1966 was about 2.6 percent larger than metered pumpage; pumpage computed by using the average 5-year power consumption coefficient (1962-66) was 4.0 percent larger than metered pumpage in T. 6 S., R. 1 W., and 9.2 percent larger in T. 6 S., R. 1 E.

Table 1.--Comparison of computed and metered pumpage

Santa Clara County, 1966

[Using average pumping-plant efficiency and average lift per township]

Township and range	Metered pumpage (acre-ft)	Computed pumpage (acre-ft)	Difference between metered and computed pumpage (percent)
6S/1E	4,390.4	4,854.2	10.6
6S/1W	9,020.4	9,098.4	.87

Using average coefficient of power consumption per township

Township and range	Metered pumpage (acre-ft)	Computed pumpage (acre-ft)		Difference between metered and computed pumpage (percent)	
		1 year	5 years	1-year average	5-year average
6S/1E	4,390.4	4,505.6	4,796.0	2.6	9.2
6S/1W	9,020.4	9,264.3	9,381.0	2.7	4.0

A similar comparison was made in T. 13 S., R. 20 E., Fresno County, using 1960 data for selected wells of the Fresno County Waterworks. The computed pumpage was 5.4 percent larger than metered pumpage.

In Madera County, pumpage computed by use of the average coefficient of power consumption per township for 1960 and that computed by use of the 5-year average coefficient (1960-64) differed by only 4 percent. The small difference may indicate that where distribution of plant-efficiency tests is limited and where changes in average lift are not great, pumpage probably can be computed by using either a 1- or 5-year average coefficient.

Regardless of the method used, pumpage computed per township is reasonably close to metered pumpage. However, when power consumption is totaled by section and divided by an average coefficient of power consumption per township, computed pumpage ranges from 37 percent less to 83 percent more than metered pumpage in the Santa Clara County test area.

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