Hydrologic Implications of Measured Changes in Gravity During Pumping at a Carbonate-Rock Well Near Moapa, Clark County, Nevada

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FIGURES

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer
foot (ft)	0.3048	meter
foot squared per day (ft^2/d)	0.0929	meter squared per day
gallon (gal)	3.785	liter
gallon per minute (gal/min)	0.06309	liter per second
inch (in.)	25.40	millimeter
mile (mi)	1.609	kilometer
pound (lb)	0.4536	kilogram

For temperature, degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by using the formula °F=[1.8(°C)]+32.

The following terms and abbreviations also are used in this report: gram per cubic centimeter (g/cm^3), microGals (μGal), microradians (μrad), millivolts per microradian (mV/μrad), and microGals per hour (μGals/hr).

SEA LEVEL

In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929, formerly called "Sea-Level Datum of 1929"), which is derived from a general adjustment of the first-order leveling networks of both the United States and Canada.

HYDROLOGIC IMPLICATIONS OF MEASURED CHANGES IN GRAVITY DURING PUMPING AT A CARBONATE-ROCK WELL NEAR MOAPA, CLARK COUNTY, NEVADA

By Donald H. Schaefer

ABSTRACT

Changes in the gravity field at a pumping well can be analyzed to provide information about effective porosity of the aquifer adjacent to that well. A gravity decrease of about 13 microGals that occurred during a 30-hour pumping test was estimated after making corrections for Earth tides, barometric pressure changes, and tilt. The test was done in a well drilled in a carbonate-rock aquifer, and pumped at a rate of about 450 gallons per minute, with about 30 feet of drawdown. The reason for the small gravity change is the small density contrast between saturated and unsaturated limestone. On the basis of this gravity change, an effective porosity for the limestone was estimated to be about 12 percent, compared with total porosity estimates for this well of 0.3 to 4.2 percent from geophysical log data.

The pumping test also showed that the gravity measurements at this well are affected by tilting of the concrete pad on which the wellhead rests. The tilting appears to be caused by temperature changes in the surrounding air.

Measurements such as these could prove useful in siting observation wells or gaining information about hydrologic properties around a pumping well. The experiment suggests that this method may be less effective in carbonate-rock aquifers, where the porosity is small, than in alluvial aquifers, where saturated and unsaturated density contrasts are large.

INTRODUCTION

One of the most costly aspects of ground-water investigations to determine hydrologic properties is the drilling and testing of observation wells. A study can benefit, however, from measurements of water levels and other physical properties or characteristics at even one observation well in the vicinity of a production well while that well is being pumped. Measurements at multiple observation wells surrounding the pumped well provide even more benefit. The use of time-series observations of gravity while a change of mass, such as a loss of fluids, occurs is not a new technique. The method has been used in geothermal fields throughout the world to monitor withdrawal of geothermal fluids (Hunt, 1970; Grannell, 1980; Allis and Hunt, 1986). In other applications, high-resolution cryogenic gravity meters are set in place to record changes in the gravitational field associated with geothermal activity (Olson and Warburton, 1979). Other applications have used portable gravity meters to make repeated measurements of gravity at permanent stations for a period of years.

U.S. Geological Survey made a study to determine if the dewatering of a carbonate-rock aquifer at a pumping well could be detected by continuous gravity measurements at the wellhead. The study was made by USGS in cooperation with the State of Nevada and Las Vegas Valley Water District as part of a program to study and test the carbonate-rock aquifers of Nevada.

Purpose and Scope

In this report, a technique is described that may allow a qualitative description of changes in the distribution of mass around a pumping well and allow rough estimates of storage properties to be made without observation wells. If this change in mass could be measured, the porosity of the aquifer material could be calculated on the basis of the density-porosity relation. The gravity meter would serve in place of an observation well by yielding information on aquifer properties. The general method used here for monitoring changes in water levels is similar to methods used in previous investigations, except that the gravity meter is stationary.

Hydrogeologic Setting

Experiments with a gravity meter were made at a public-supply well in northeastern Clark County, approximately 70 mi from Las Vegas (fig. 1). The well, MX-6, was drilled as a test well as part of the U.S. Air Force MX Missile-Siting Program in 1981 (Ertec Western, Inc., 1981) and subsequently was acquired for use by the Moapa Valley Water District. Total depth of the well is 937 ft and all but the upper 87 ft penetrates limestone of the Birdsprings Formation (?) of Paleozoic age. This upper 87 ft penetrates recent alluvial materials. The well is cased with 12-3/4-in. inside-diameter steel casing to a depth of 325 ft; the remaining 612 ft is uncased. The limestone formation has been shown to be fractured in this area, but the fractures are commonly filled with calcite (Alan Preissler, U.S. Geological Survey, written commun., 1989). The open fractures, however, contribute to the transmissivity of 12,600 ft^2/d estimated from drawdowns measured in the well (Dettinger and others, in press).

In much of eastern and southern Nevada, Paleozoic limestone is good aquifer material where fractured. Tests in wells in other areas of eastern and southern Nevada show transmissivities that range from 130 to about 250,000 ft^2/d (Dettinger and others, in press). The ground water around the well is assumed to be under water-table (unconfined) conditions, although no aquifer test information is available to substantiate this. An aquifer test in a well 4 mi to the west, with a similar construction, and penetrating the same formation, indicates a storage coefficient of 0.14. Secondary porosity probably constitutes almost one-half of the total porosity estimated for the limestone; porosities in well MX-6 range from 0.3 to 4.2, on the basis of analysis of geophysical logs (Berger, 1992).

A more complete discussion of the general hydrology of the area is given by Eakin (1966), Welch and Thomas (1984), and Dettinger (1989). In brief, the well is near the terminus of a 230-mi-long regional ground-water flow system named the White River ground-water flow system, in the carbonate-rock aquifers of central and southern Nevada (fig. 1). The terminus of the flow system is the Muddy River Springs, about 6 mi southeast of MX-6. These springs discharge about 30,000 acre-ft/yr.

DESCRIPTION OF EXPERIMENT

Theory

The experiment described in the following sections was made on the premise that, as ground water is pumped from a well and removed from storage in the aquifer, a large change in mass will cause a measurable decrease in gravity. This assumes that water-table (unconfined) conditions in the well allow drainage of the pore spaces. A confined aquifer system would not show a change in mass as the well is pumped but rather, a pressure change within the aquifer system.

When a well is pumped, drawdown in the form of a cone of depression develops around the well, with maximum drawdown at the wellbore. The change in water level is not instantaneous; any resultant change in mass also would occur slowly. If the aquifer is isotropic and homogeneous, the cone of depression will be symmetrical. If faults, fractures, or boundaries are present near the well, the cone of depression will be asymmetrical. The cone of depression can be visualized as a series of disks of porous material that change density as the water mass is removed from the pore spaces. The density changes from saturated (ρ_s) to unsaturated (ρ_u). This change from a saturated to an unsaturated state can be used to calculate the porosity of the material, assuming the density of the water filling the pores is 1.0 g/cm^3. For unconsolidated alluvial materials, as well as some limestones, this change in density could be as much as 0.44 g/cm^3 (Telford and others, 1976, p. 25).

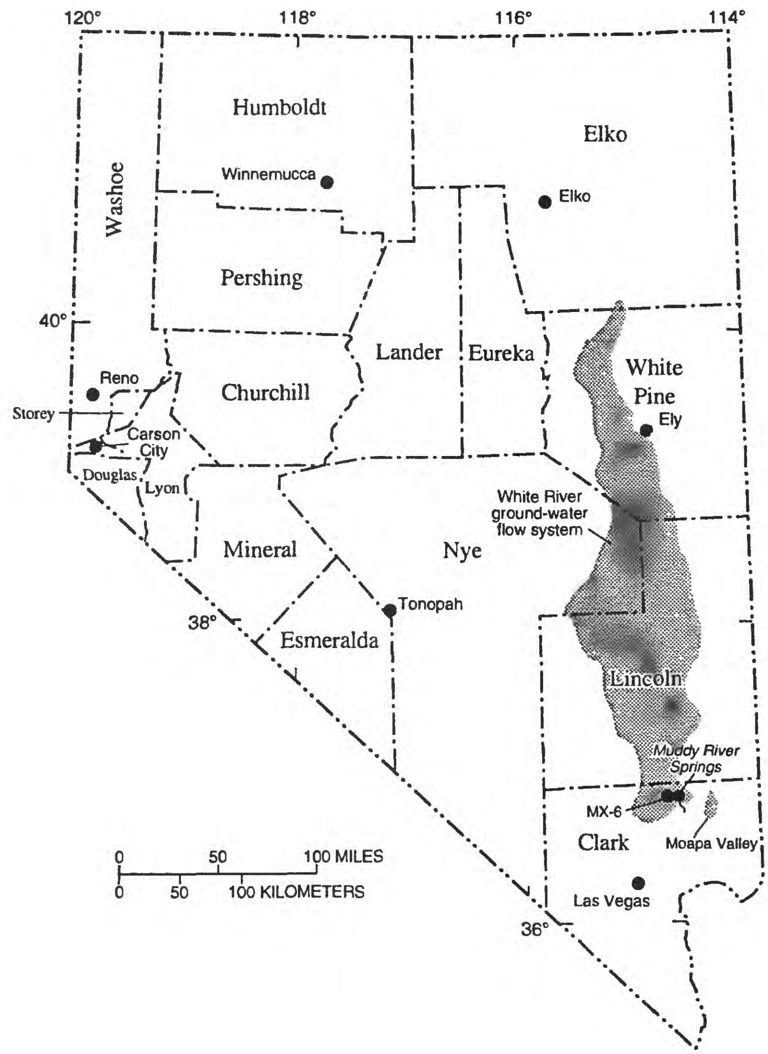


FIGURE 1. Location of White River ground-water flow system and well MX-6.

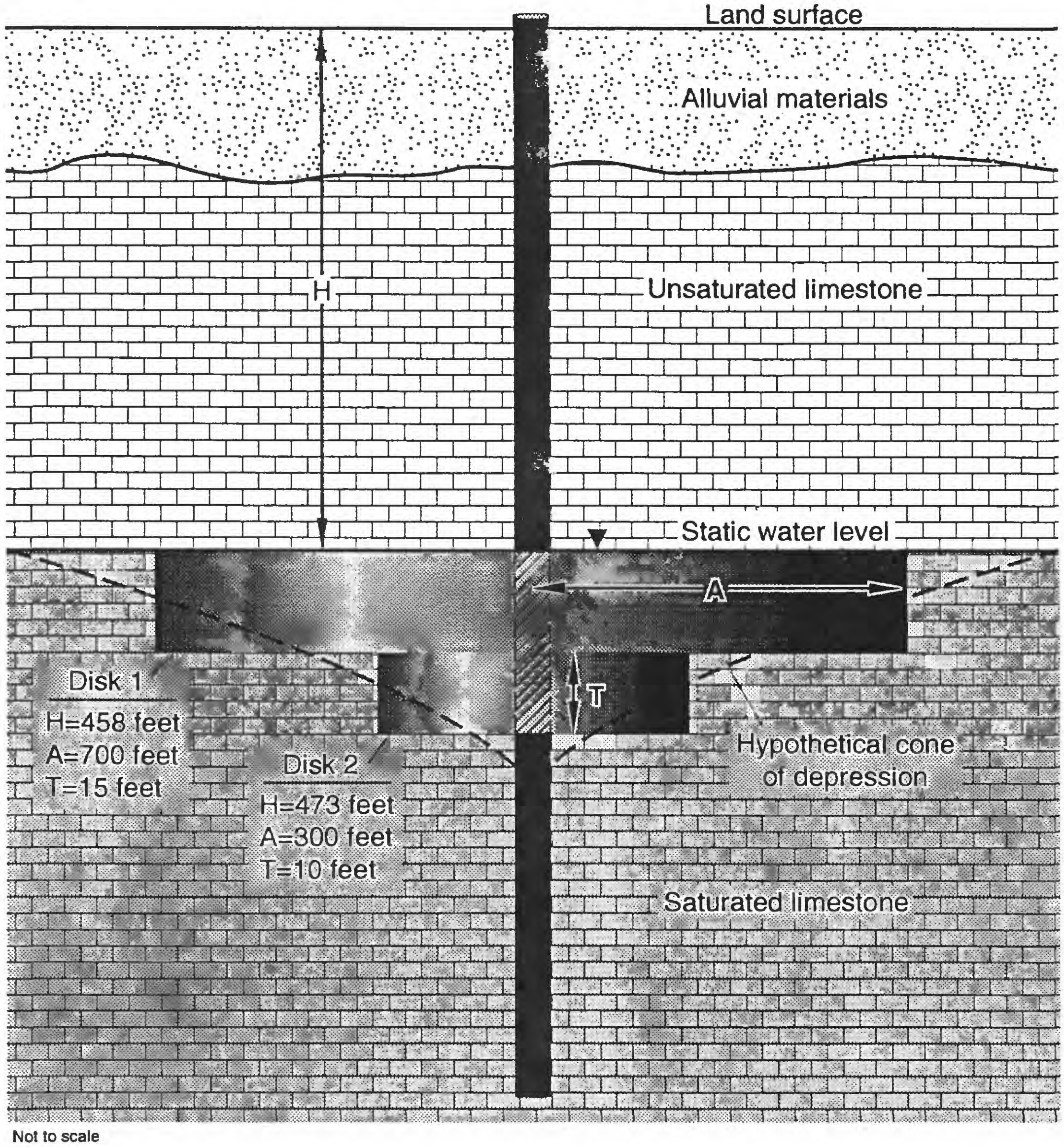
A relatively simple model was used to simulate dewatering around the pumping well. The cone was assumed to be two disks of finite radius and thickness that would have a combined thickness equal to the maximum depth of drawdown in the well. The mathematical model, conceptually illustrated in figure 2, indicates the magnitude of gravitational changes.

The equation for computing the gravitational attraction of a disk-type model is given in Grant and West (1965, p. 295) as:

$$g = 12.77 \Delta\rho T \left[1 - \frac{H}{\sqrt{A^2 + H^2}} \right]$$

where g = gravity, in microGals;
$\Delta\rho$ = density contrast ($\rho_s - \rho_u$), in grams per cubic centimeter;
T = thickness of disk, in feet;
H = depth to top of disk, in feet; and
A = radius of disk, in feet;

A computer program using this equation calculates the resulting gravitational attraction from various disk configurations. This program (appendix 1), written in FORTRAN 77, prompts the user to input the various values and computes the resulting attraction.



EXPLANATION

H DEPTH TO TOP OF DISK, IN FEET

A RADIUS OF DISK, IN FEET

T THICKNESS OF DISK, IN FEET

FIGURE 2. Schematic hydrogeologic section at pumping well MX-6 showing disks.

With the disk-type model, the attraction of both disks is added to give the total gravity change. If the equation assumes (1) a porous limestone with an effective porosity of 15 percent, (2) a density contrast between saturated and unsaturated limestone of 0.15 g/cm^3, and (3) the dimensions shown in figure 2, then gravity change when the well is pumped would be about 16 μGals. Assuming a lower porosity limestone with an effective porosity of 3 percent, a density contrast of 0.03 g/cm^3, and the same model dimensions as the previous example, the gravity change would be about 3 μGals.

Recovery of water levels in the pumped well result in the same gravity change, except that '*g*' would have the opposite sign, as the disk resaturates. This well, on the basis of previous pumping tests, is known to recover quickly once pumping has ceased. The rapid recovery of water levels was expected to result in a measurable recovery of gravity values.

Well Description

Well MX-6 is protected by a brick pump house on an 11-ft by 15-ft concrete slab. The slab itself is approximately 1 ft thick. Static depth to water in the well is about 458 ft below land surface. Currently (1989), the well is pumped seasonally by the Moapa Valley Water District with a 100-horsepower submersible pump set about 500 ft below land surface.

Equipment

The primary instrument used for the experiment at the MX-6 well site was a LaCoste and Romberg 'D' model gravity meter (D-19) equipped with an analog linear force feedback system. The feedback system circumvents the error that can be introduced when continuous measurements are taken with the gravity meter: the elasticity of the spring that balances the proof mass within the meter may not be linear when the meter is continuously recording changes in gravity. The feedback system maintains the spring in a null position with the output signal of the meter proportional to the force required to keep the mass nulled. The net effect is a more stable and consistent measurement (Valliant and others, 1986). Output from the gravity meter was recorded on data loggers and strip-chart recorders.

Other instruments used in the test included a downhole pressure transducer to record changes in water level before, during, and after pumping, an on-surface pressure transducer to record changes in barometric pressure, and several thermocouples to measure changes in temperature during the test. Barometric-pressure data were required to calculate the effect of barometric change on gravity readings.

A two-axis tiltmeter was used to record possible tilt of the concrete slab of the pump house of MX-6. Previous gravity work at this site indicated that the concrete slab under the pump house could be tilting. It was postulated that the tilting may result from a slight subsidence of the pump-house slab caused by withdrawal of water from the limestone. The tiltmeter was oriented along the long and short axes of the pump-house slab about 1.7 ft from the gravity meter (figs. 3 and 4). The tiltmeter has a range of ±800 μrad in both the X and Y directions and a gain of about 10 mV/μrad. A thermocouple imbedded in the tiltmeter recorded air temperature in the pump house. These data were recorded by data loggers.

GRAVITY CHANGES AND HYDROLOGIC ANALYSES

The gravity meter was placed in the northwest corner of the pump house of well MX-6 (fig. 3). Indentations were chipped into the concrete slab to fit the legs of the gravity meter tripod to ensure that the meter was always in the same orientation. The meter was connected to a data logger and a strip-chart recorder for continuous recording.

The test was started on May 2, 1989, when all instruments were set up in the pump house; data recording began about 10:30 a.m. Static (nonpumping) conditions were recorded for about 22 hours to calibrate the instruments to calculated earth tides.

Pumping began the morning of May 3 at 8:35 a.m. Pumping rates were monitored intermittently using an inline flowmeter in the pump discharge pipe. Discharge rates from the well averaged about 450 gal/min during the test. The test continued until 2:35 p.m. on May 4, 1989 (30 hours of pumping). During that time, about 820,000 gal (6,800,000 lbs) of water were pumped. Data continued to be collected during the recovery phase of the test, which continued until 8:35 the following morning (May 5, 1989). The recovery phase lasted 18 hours.

The data collected from the gravity meter were converted to microGal readings and corrected for Earth tides. The procedure for calculating Earth tides (developed by Longman, 1959) assumed a compliance factor of 1.16. No correc-

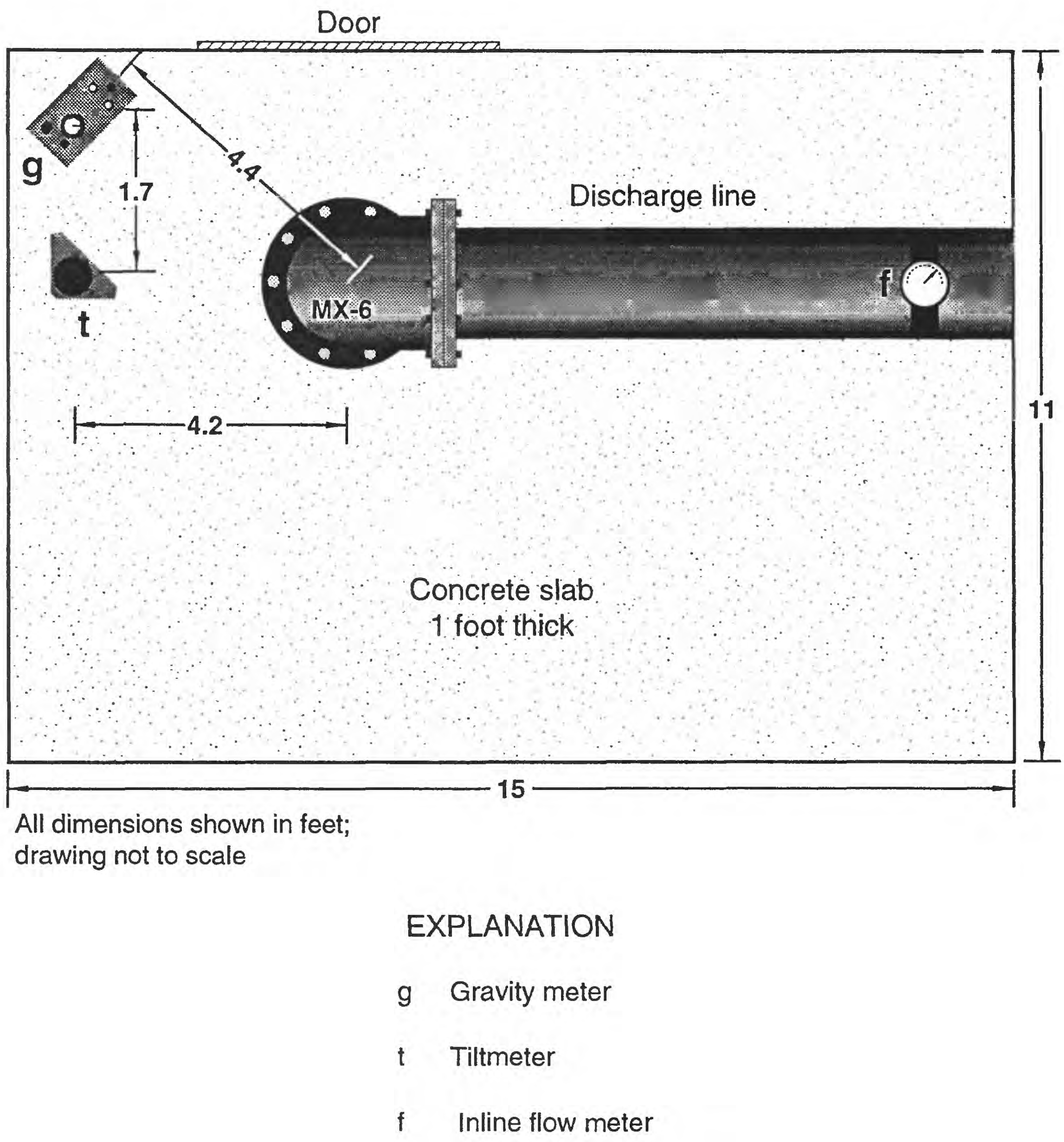


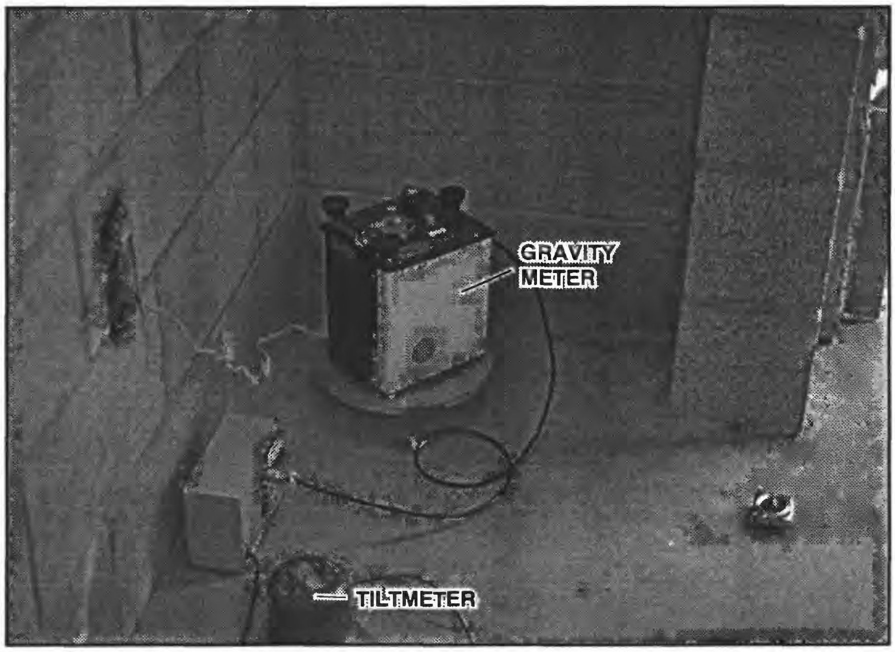
FIGURE 3. Plan view of equipment layout.

tions were made for terrain, which was assumed to remain constant during the test, or for any other change in elevation at this station.

The results of the test are shown in figure 5. The curves shown are based on corrected values at various scales. The residual gravity (fig. 5G) was corrected for Earth tides, tilt, and barometric pressure. Corrections for changes in the gravity caused by tilt were made by regressing the tiltmeter signal into the measured gravity curve. Barometric corrections were from Levine and others (1986).

The tiltmeter signal (fig. 5C) shows a satisfactory correlation with temperature (fig. 5D). Diurnal changes in temperature are believed to cause movement of the concrete slab by thermal expansion and contraction of the underlying alluvial materials. The tiltmeter signal shows no correlation with changes in the water level of the well, so it is unlikely that movement of the pumphouse slab was caused by subsidence in response to withdrawal of water.

A.



B.

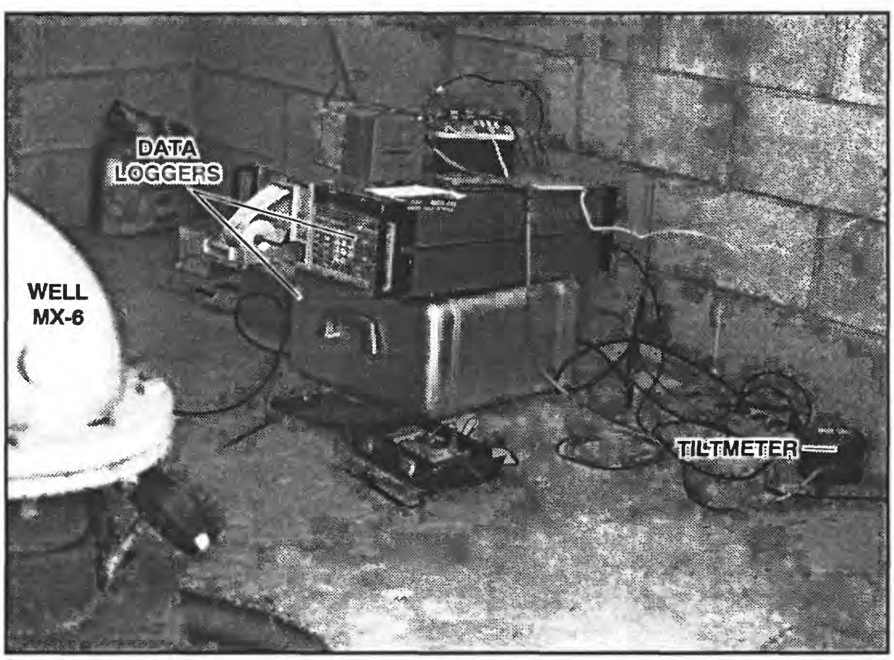


FIGURE 4. Equipment layout in pump house for well MX-6, May 2, 1989. *A*, Gravity and tiltmeter, and *B*, same tiltmeter and data loggers.

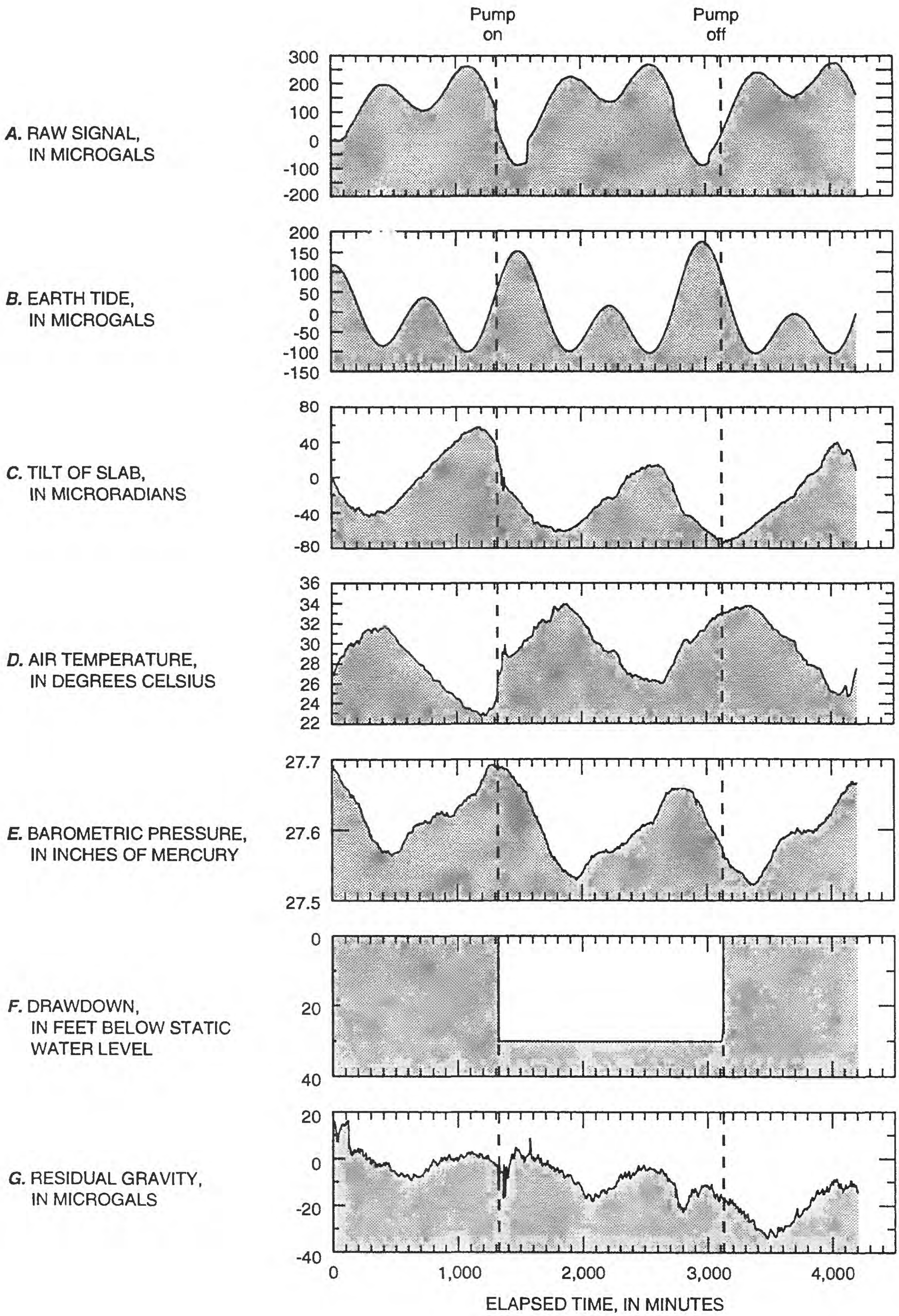


FIGURE 5. Changes in selected measured parameters with time during pumping test at well MX-6.

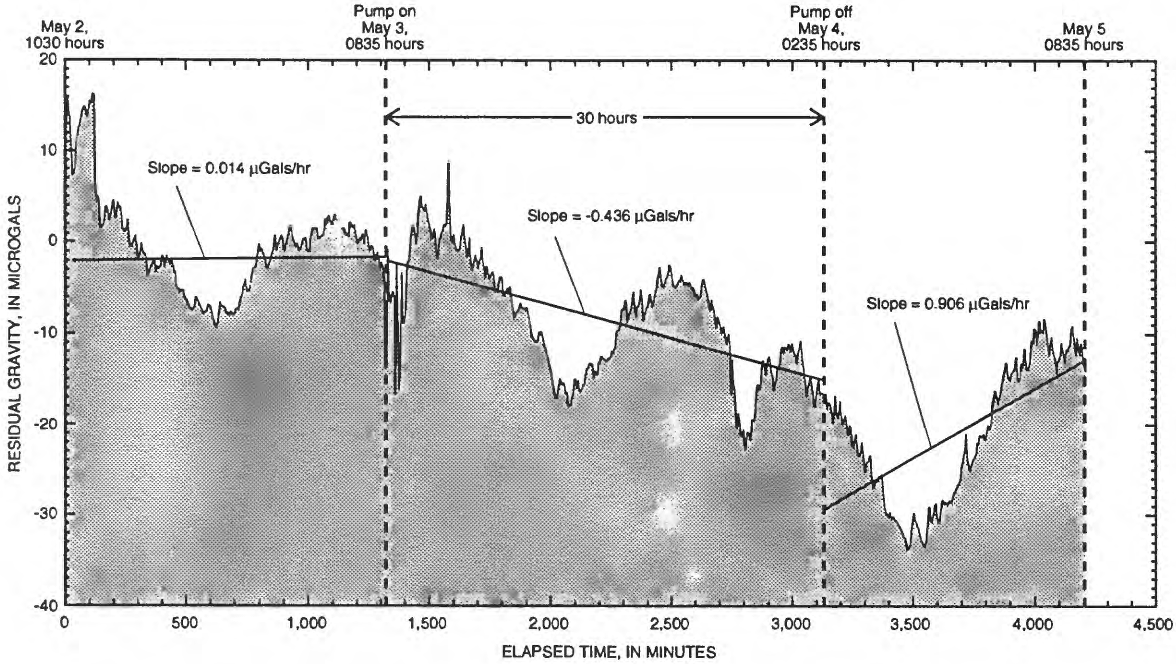


FIGURE 6. Changes in residual gravity and trends with time during pumping test at well MX-6. Abbreviation: µGals/hr, microGals per hour.

The corrected residual-gravity curve (fig. 5G) shows significant cyclic fluctuation, and trends that correspond to periods of pumping. Figure 6 is an enlargement of figure 5G. Trend lines through three segments of the curve are based on a least-squares fit of the data in each segment. The early segment of the curve (before pumping) has a slope of 0.014 µGals/hr. The slope of the segment representing the pumping period is -0.436 µGals/hr. The slope of the segment representing the recovery period is reversed and increased to 0.906 µGals/hr. The slope of the curve during the pumping phase of the test indicates that, after 1,800 minutes of pumping, the maximum gravity change would be 13 µGals. If this value is put back into the model, the resulting density contrast is about 0.12 g/cm^3. On the basis of a generalized error analysis of the various components, this value of density has a range of about ±0.03 g/cm^3.

This density contrast is equivalent to an effective porosity of about 12 percent, somewhat higher than total porosity determined from geophysical log analyses. Geophysical logs, however, sample only the sidewall of a borehole. The sidewall can be easily damaged during drilling, thus affecting porosity.

The residual-gravity curve in figure 6 exhibits a relatively high level of background noise along with the signal. The noise may result from poorly determined correction factors (Earth tides and tilt) and uncertainty in the gravity measurements. In this experiment, the gravity meter measures only small changes in acceleration. If the gravity anomaly caused by dewatering the aquifer material had been twice as large, the signal probably would have been more obvious.

DISCUSSION AND CONCLUSIONS

This study indicates that measurements of gravity and other associated physical properties at a pumping well can provide information about aquifer properties. Several refinements could be made to improve the method. First, a longer duration test probably would produce a more conspicuous and larger residual gravity change. Second, additional monitoring before and after pumping would make analysis of the data easier and would provide more data from which to construct trends. Finally, the test at MX-6 indicated that stability of land surface is an important factor that can seriously affect high-precision gravity surveys in hydrologic work. The stability of land surface, including concrete slabs, can be monitored with tiltmeters to detect changes in altitude of land surface of gravity stations during pumping tests. All environmental factors that may affect the results need to be monitored to determine which factors are significant and to provide data to use for correcting the gravity data.

This method probably could be more successfully applied in porous alluvial aquifers that have relatively large drawdowns and porosity values. The limestone tested in this experiment had a relatively small porosity. The resulting density contrast between saturated and unsaturated conditions in the limestone was not high enough to easily measure. Results of tests in an alluvial aquifer potentially could be used to develop an empirical relation between porosity and gravity change. Once the relation at a well is established, additional tests with the gravity meter located farther from the pumping well could be made to qualitatively map drawdown around the well. A series of measurements at different distances could indicate major nonconformities, anisotropies, or barriers within the aquifer. A qualitative map of drawdown could add to the understanding of the aquifer with minimal test-well drilling, and could be useful in siting additional wells.

REFERENCES CITED

Allis, R.G., and Hunt, T.M., 1986, Analysis of exploitation-induced gravity changes at Wairakei Geothermal Field: Geophysics, v. 51, no. 8, p. 1647-1660.

Berger, D.L., 1992, Lithologic properties of carbonate-rock aquifers at five test wells in the Coyote Springs Valley area, southern Nevada, as determined from geophysical logs: U.S. Geological Survey Water-Resources Investigations Report 91-4167, 27 p.

Dettinger, M.D., 1989, Distribution of carbonate-rock aquifers in southern Nevada and the potential for their development--Summary of findings, 1985-88: Carson City, Nev., Program for the Study and Testing of Carbonate-Rock Aquifers in eastern and southern Nevada, Summary Report No. 1, 37 p.

Dettinger, M.D., Schmidt, D.L., Harrill, J.R., and Hess, J.W., (in press), Distribution of carbonate-rock aquifers and the potential for the development, southern Nevada and parts of Arizona, California, and Utah: U.S. Geological Survey Water-Resources Investigations Report 91-4146.

Eakin, T.E., 1966, A regional interbasin groundwater system in the White River area, southeastern Nevada: Water Resources Research, v. 2, no. 2, p. 251-271.

Ertec Western, Inc., 1981, MX Siting Investigation Water Resources Program, Results of regional carbonate aquifer testing, Coyote Springs Valley, Nevada: Unpublished report to U.S. Department of the Air Force Ballistic Missile Office, Norton Air Force Base, Calif., 190 p.

Grannell, R.B., 1980, The use of surface gravity methods in monitoring subsurface reservoir changes with case studies at Cerro Prieto, Mexico, and Heber, California: Geothermal Resources Council Annual Meeting, Salt Lake City, Utah, 1980, Transactions, v. 4, p. 49-52.

Grant, F.S. and West, G.F., 1965, Interpretation theory in applied geophysics: New York, McGraw-Hill, 584 p.

Hunt, T.M., 1970, Gravity changes at Wairakei geothermal field, New Zealand: Geological Society of America Bulletin, v. 81, no. 2, p. 529-536.

Levine, Judah, Harrison, J.C., and Dewhurst, Warren, 1986, Gravity tide measurements with a feedback gravity meter: Journal of Geophysical Research, v. 91, no. B12, p. 12,835-12,841.

Longman, I.M., 1959, Formulas for computing the tidal accelerations due to the Moon and Sun: Journal of Geophysical Research, v. 64, no. 12, p. 2351-2355.

Olson, J.J., and Warburton, R.J., 1979, Continuous gravity observations at the Geysers--A preliminary report: Geothermal Resources Council Annual Meeting, Reno, Nev., 1979, Transactions, v. 3, p. 519-522.

Telford, W.M., Geldart, C.P., Sheriff, R.E., and Keys, D.A., 1976, Applied geophysics: Cambridge, England, Cambridge University, 860 p.

Valliant, H.D., Gagnon, C., and Halpenny, J.F., 1986, An inherently linear electrostatic feedback method for gravity meters: Journal of Geophysical Research, v. 91, no. B10, p. 10463-10469.

Welch, A.H., and Thomas, J.M., 1984, Aqueous geochemistry and isotope hydrology of the White River system, eastern Nevada [abs.]: Geological Society of America, Abstracts with Programs, v. 16, no. 6, p. 689

APPENDIX--Computer program to calculate the gravitational attraction from a series of disks.

```
C  PROGRAM TO CALCULATE GRAVITY EFFECT OF A SERIES OF DISKS
C  STACKED UPON ONE ANOTHER MAXIMUM NUMBER OF DISKS 20
C  VARIABLES   P(N)=  DENSITY CONTRAST OF DISK (GM/CC)
C            T(N)=  THICKNESS OF DISK (FEET)
C            H(N)=  DEPTH TO TOP OF DISK (FEET)
C            A(N)=  RADIUS OF DISK (FEET)
C            G(N)=  ATTRACTION OF DISK (MICROGALS)
C           TOTAL=  ATTRACTION OF ALL DISKS (MICROGALS)
C***********************************************************************
C     WRITTEN 8/2/89  D.H. SCHAEFER
      DIMENSION P(20),G(20),T(20),H(20),A(20)
      TOTAL=0.0
      WRITE(1,*) 'ENTER NUMBER OF DISKS (MAX=20)'
      READ(1,'(BN,I2)') N
      WRITE(1,*) '  '
      DO 100 I=1,N
      PRINT*, 'ENTER RADIUS OF DISK NO.  ',I,' IN FEET'
      READ(1,'(F7.3)') A(I)
      PRINT*, 'ENTER THICKNESS OF DISK NO.  ',I,' IN FEET'
      READ(1,'(F7.3)') T(I)
      PRINT*, 'ENTER DEPTH TO TOP OF DISK NO.  ',I,' IN FEET'
      READ(1,'(F8.3)') H(I)
      WRITE(1,*) 'ENTER DENSITY CONTRAST FOR THIS DISK (GM/CC)'
      READ(1,'(F6.3)') P(I)
      G(I)=12.77*P(I)*T(I)*(1-(H(I)/(SQRT(A(I)**2+H(I)**2))))
      TOTAL=TOTAL+G(I)
      PRINT*, 'CONTRIBUTION FOR DISK NO.  ',I, '  EQUALS  ',G(I)
100   CONTINUE
      WRITE(1,*) '  '
      WRITE(1,'(A,I2,A,F9.3,A)') 'TOTAL GRAVITY FOR ',N,' DISKS   ',
     1 TOTAL, 'MICROGALS'
      STOP
      END
```