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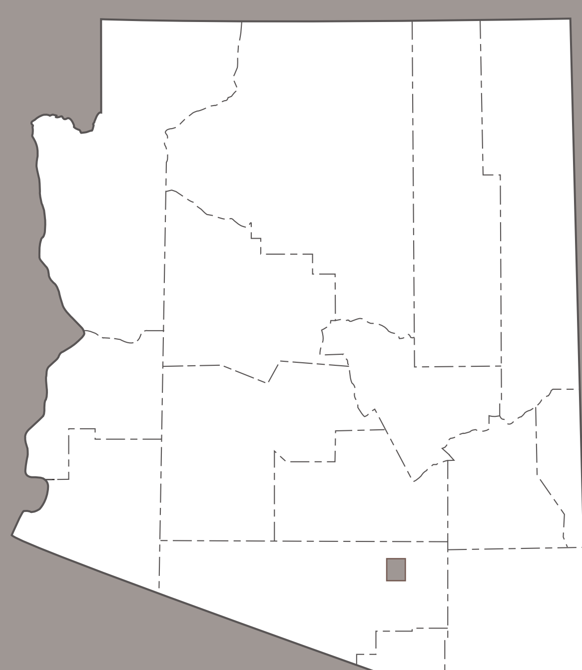
U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 97—4125



Prepared in cooperation with the
PIMA COUNTY DEPARTMENT OF TRANSPORTATION
AND FLOOD CONTROL DISTRICT

U.S. DEPARTMENT OF THE INTERIOR
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By D. R. Pool *and* Werner Schmidt

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Tucson, Arizona
1997

U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS

Multiply	By	To obtain
foot (ft)	0.3048	meter
foot per day (ft/d)	0.0929	meter per day
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
acre-foot (acre-ft)	0.001233	cubic hectometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute (gal/min	3.7854	liter per minute

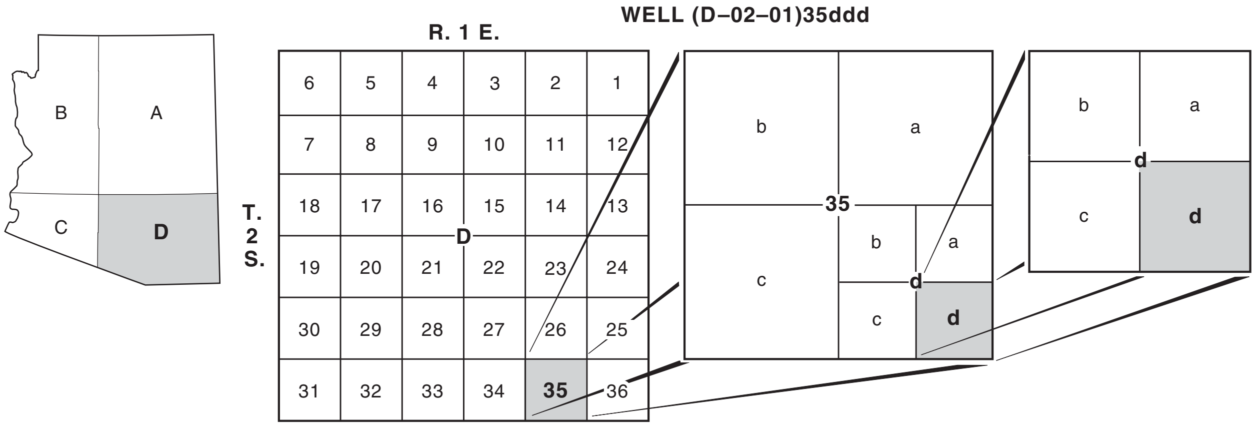
Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°X) as follows:

$$°C=(F-32)/1.8$$

ABBREVIATED GRAVITY UNITS

Milligal (mGal) is defined as 10^{-3} centimeter per second squared and is equal to $3.281x10^{-5}$ feet per second squared. A microgal (μGal) is defined as 10^{-6} centimeter per second squared and is equal to $3.28x10^{-8}$ feet per second squared. Gram per cubic centimeter is a measure of density.

WELL-NUMBERING AND NAMING SYSTEM



Quadrant D, Township 2 South, Range 1 East, section 35, quarter section d, quarter section d, quarter section d

The well numbers used by the U.S. Geological Survey in Arizona are in accordance with the Bureau of Land Management's system of land subdivision. The land survey in Arizona is based on the Gila and Salt River Meridian and Base Line, which divide the State into four quadrants that are designated by capital letters A, B, C, and D in a counterclockwise direction, beginning in the northeast quarter. The first digit of a well number indicates the township, the second the range, and the third the section in which the well is situated. The lowercase letters a, b, c, and d after the section number indicate the well location within the section. The first letter denotes a particular 160-acre tract, the second the 40-acre tract, and the third the 10-acre tract. These letters also are assigned in a counterclockwise direction, beginning in the northeast quarter. If the location is known within the 10-acre tract, three lowercase letters are shown in the well number. Where more than one well is within a 10-acre tract, consecutive numbers beginning with 1 are added as suffixes. In the example shown, well number (D–02–01)35ddd designates the well as being in the SE1/4, SE1/4, SE1/4, section 18, Township 2 South, and Range 1 East.

VERTICAL DATUM

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

Measurement of Ground-Water Storage Change and Specific Yield Using the temporal-Gravity Method Near Rillito Creek, Tucson, Arizona

By D.R. Pool *and* Werner Schmidt

Abstract

The temporal-gravity method was used to estimate ground-water storage and change and specific-yield values at wells near Rillito Creek, Tucson, Arizona, between early December 1992 and early January 1994. The method applies Newton's Law of Gravitation to measure changes in the local gravitational field of the Earth that are caused by changes in the mass and volume of ground water. Gravity at 50 stations in a 6-square-mile area was measured repeatedly relative to gravity at two bedrock stations. Ephemeral recharge through streamflow infiltration during the winter of 1992–93 resulted in water-level rises and gravity increases near Rillito Creek as the volume of ground water in storage increased. Water levels in wells rose as much as 30 feet, and gravity increased as much as 90 microgals. Water levels declined and gravity decreased near the stream after the last major winter flow but continued to rise and increase, respectively, in downgradient areas.

Water levels and gravity relative to bedrock were measured at 10 wells. Good linear correlations between water levels and gravity values at five wells nearest the stream allowed for the estimation of specific-yield values for corresponding stratigraphic units assuming the mass change occurred in an infinite horizontal slap of uniform thickness. Specific-yield values for the stream-channel deposits at three wells ranged from 0.15 to 0.34, and correlation coefficients ranted from 0.81 to 0.99. Specific-yield values for the Fort Lowell Formation at three wells ranged from 0.07 to 0.18, and correlation coefficients ranged from 0.82 to 0.93. Specific-yield values were not calculated for the five wells farthest from the stream because of insufficient water-level and gravity change or poor correlations between water level and gravity. Poor correlations between water levels and gravity resulted from ground-water storage change in perched aquifers and in the unsaturated zone near ephemeral streams.

Seasonal distributions of ground-water storage change since early December 1992 were evaluated from gravity change at all stations using Gauss's Law. Changes in the distribution of gravity are caused by the flow of water into or out of ground-water storage. Gravity along tow profiles was measured frequently to evaluate spatial and temporal distributions of gravity change.

Gravity variations indicated preferential ground-water flow to the south in the western part of the study area where the saturated thickness of the aquifer is greatest. Storage changes from December 1992 through early March 1993, mid-May 1993, late August 1993, and early January 1994 were calculated as increases of 7,900, 8,000, 6,300, and 3,700 acre-feet, respectively. Seasonal variations in storage were caused by ground-water withdrawals, ground-water flow across the boundaries of the gravity-station network, and streamflow infiltration from December 1992 through late April 1993. Most of the estimated recharge of 10,900 acre-feet occurred before mid-May 1993.

INTRODUCTION

Estimation of ground-water storage change and specific yield near Rillito Creek was done in cooperation with the Pima County Department of Transportation and Flood Control District in support of the development of an artificial-recharge facility near Tucson, Arizona (**fig.1**). The facility had been proposed to enhance recharge to the aquifer system in the Tucson Basin. Design of the facility included the capture of periodic low flows in Rillito Creek using an inflatable dam to be constructed between Swan and Craycroft Roads. Impounded water would infiltrate the channel bed. The remainder would be directed to recharge basins in the adjacent flood plain. Funding for this investigation was provided from a grant to Pima County through the Bureau of Reclamation High Plains Groundwater Recharge Demonstration Program.

Efficient design of the recharge basins and subsequent activities requires adequate knowledge of the hydrogeologic system near the proposed site. Important hydrogeologic knowledge includes the transmissivity and storage properties of the aquifer that influence the rates of surface-water infiltration and movement of the recharge water through the aquifer. Transmissivity and storage properties of the aquifer that influence the rates of surface-water infiltration and movement of the recharge water through the aquifer. Transmissivity can be estimated with sufficient accuracy using available information; however, accurate estimates of storage properties require long-term aquifer tests of estimates of the volume of water stored in a given volume of aquifer. Long-term aquifer tests are costly, difficult to perform and analyze, and may result in estimates that do not represent average values for the aquifer. Estimates of changes in the volume of water stored in an aquifer, however, can be determined by measuring changes in gravitational acceleration in the aquifer area and applying Newton’s Law of Gravitation because change sin the volume and mass of water in an aquifer result in an associated change in the local gravitational field of the Earth. Specific-yield values can be estimated for the large volume of aquifer where contemporaneous water-level measurements define the change in aquifer volume.

Purpose and Scope

The purpose of the study was to obtain hydrologic information for the design of the proposed recharge facility by estimating natural changes in aquifer storage and specific yield in the part of the aquifer that includes the proposed artificial-recharge facility. Gravity methods were used in this study on the basis of previous investigations that demonstrated gravity measurements could be made with sufficient accuracy to provide useful hydrologic information in the areas with substantial storage changes (Montgomery, 1971; Zohdy and others, 1974); Strange and Wessels, 1985; Goodkind, 1986; Allis and Hunt, 1986; Pool and Hatch 1990; and Pool and Eychaner, 1995). This study used periodic gravity measurements at a network of stations in a 6-square-mile area that encompassed the proposed location of the recharge facility (fig. 1). The network included gravity stations at 10 wells where water levels were measured. Two of the well sites included three piezometers that are open to the aquifer at different depths. Gravity measurements were used to estimate changes in the volume of water stored in the aquifer system. Specific-yield estimates were made for parts of the aquifer where water-level changes delineated the thickness of aquifer associated with change in ground-water storage.

The study was completed from early December 1992 to early January 1994 and included a period of intense runoff and recharge from January through March 1993. Flows from mountain snowmelt and rainfall continued to occur into early April 1993. Significant streamflow infiltration resulted in an increase in ground-water storage and subsequent redistribution of water in the aquifer system. The report describes changes in the gravitational field caused by changes in water mass, changes in ground-water storage, and estimates of the specific yield of the aquifer where significant water-level changes occurred. Changes in ground-water storage also are correlated with geology and ground-water flow.

Acknowledgments

Fred Barnes, Arizona Department of Water Resources provided Water-level data, and Ralph Marra and Bruce Johnson, Tucson Water, provided water-level, lithologic, well-construction, and ground-water withdrawal data as well as access to wells in the study area. The University of Arizona Department of Geosciences and Department of Hydrology and Water Resources provided equipment, information, and data.

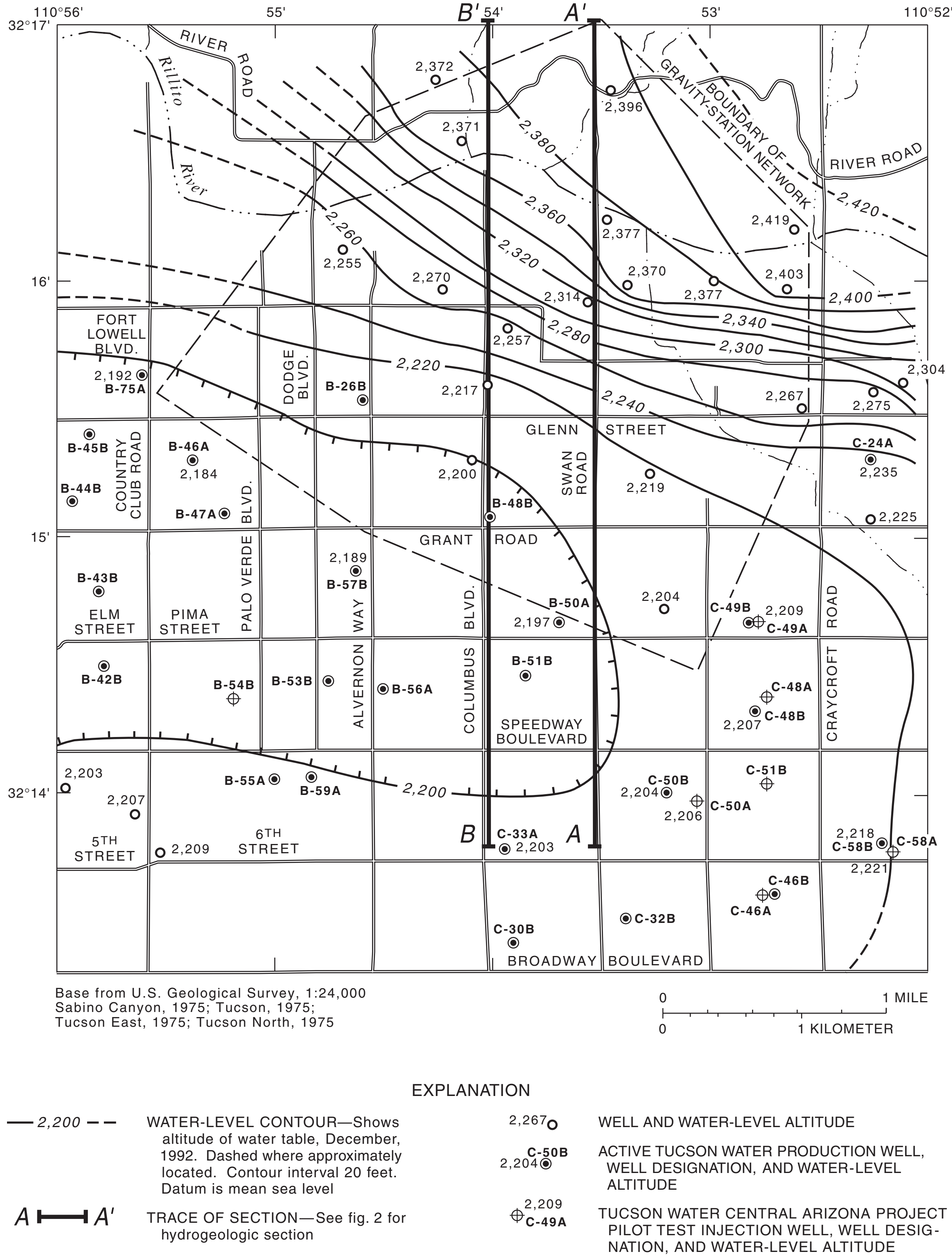


Figure 1. Study area, altitudes of water levels in selected wells, and locations of municipal-supply wells, Rillito Creek, Arizona, December 1992.

HYDROGEOLOGY

The hydrogeologic system in the study are is characterized by periodic recharge along the ephemeral stream channel of Rillito Creek, ground-water flow to the south-southwest through basin-fill deposits, and discharge to municipal-supply wells south and west of the study area (**fig. 1**). Periodic streamflow occurs in response to precipitation and snowmelt from the Santa Catalina and Rincon Mountains. Infiltration occurs through the highly permeable stream-channel deposits and flow downgradient through moderately to highly permeable basin-fill deposits.

The geology of the local aquifer described for this investigation generally is based on the framework of the aquifer in the Tucson Basin described by Davidson (1973). The distribution and description of hydrogeologic units in the study area are based on analyses of lithologic logs, particle-size analyses of well cuttings, geophysical logs, and drillers' longs. Geophysical logs included formation density (gamma-gamma), electrical resistivity, neutron porosity, sonic velocity, and temperature. Contacts between units were estimated on the basis of changes in various physical characteristics with depth, which includes density, particle-size distribution, color, degree of cementation, electrical resistivity, porosity, and sonic velocity. Drillers' logs were used to supplement data in some areas.

The aquifer system consists of basin-fill deposits of alluvial sediments underlain by crystalline rocks (**fig. 2**). Sedimentary units from oldest to youngest include the Pantano Formation, lower and upper Tinaja beds (Tsl and Tsu), Fort Lowell Formation (Qf), and surficial deposits of alluvium (Qs) that include the terrace and stream-channel deposits along Rillito Creek. Crystalline rocks and the overlying Pantano Formation generally are impermeable in comparison to overlying sediments and are not penetrated by wells in the study area. The Tinaja beds and Fort Lowell Formation thicken and dip gently to the south.

The main aquifer is the moderately to highly permeable Fort Lowell Formation. HIghly permeable stream-channel deposits also are an important water-bearing unit where the deposits are saturated along the flood plain of Rillito Creek. Ground water also flows through the upper Tinaja beds of moderate to low permeability. The upper Tinaja beds are a minor aquifer in much of the study area except in the southern part where the unit is difficult to distinguish from the Fort Lowell Formation. The lower Tinaja beds are much less permeable than the upper Tinaja beds and are an effective lower boundary of the ground-water flow system. Hydraulic-conductivity values for the Fort Lowell Formation range from 20 to at least 95 ft/d, and well yields range from 500 to 1,500 gal/min in the Tucson Basin (Davidson, 1973). Hydraulic-conductivity values for the upper and lower Tinaja beds range from 1.3 to 53.5 ft/d (Davidson, 1973). The main aquifer generally is unconfined; however, confined condition occur locally.

Lower Tinaja beds typically are comprised of mudstone and clay and contain interbeds of sand, silt, and gravel. Silt-size and smaller particles comprise 58 to 76 percent of the unit. Density of the unit ranges from 2.06 to 2.24 g/cm^3, and electrical resistivity ranges from 15 to 20 ohmmeters. Porosity values from neutron logs range from 35 to 41 percent, and sonic-velocity values range from 5,900 to 7,000 ft/s. Thickness of the lower Tinaja beds is poorly known because no wells are known to penetrate the unit.

Upper Tinaja beds are the main water-bearing unit north of the flood plain of Rillito Creek and at the south boundary of the study area. The unit typically consists of moderately consolidated sand, gravel, clay, and silt and typically is described as conglomerate or cemented sand and gravel in drillers' logs. Silt-size and smaller particles comprise 23 to 45 percent of this unit. Thickness of individual beds averages 66 ft on the basis of drillers' logs. Density of the unit ranges from 2.15 to 2.41 g/cm^3, and electrical resistivity ranges from 17 to 49 ohmmeters. Porosity from neutron logs ranges from 25 to 35 percent, and sonic velocities range from 6,600 to 8,400 ft/s. A greater degree of consolidation of the unit is evident from higher density and sonic velocity and lower porosity than overlying units. The unit grades upward into the Fort Lowell Formation across a thickness of 100 to 200 ft in the southern part of the study area (fig. 2). The base of the upper Tinaja beds forms the base of the main aquifer and generally dips to the south across the study area (**fig. 3**). A local structural high occurs in the north-central part of the study area. The thickness of the upper Tinaja beds generally ranges from 150 to 200 ft near Rillito Creek and increases to more than 500 ft near the south boundary of the study area.

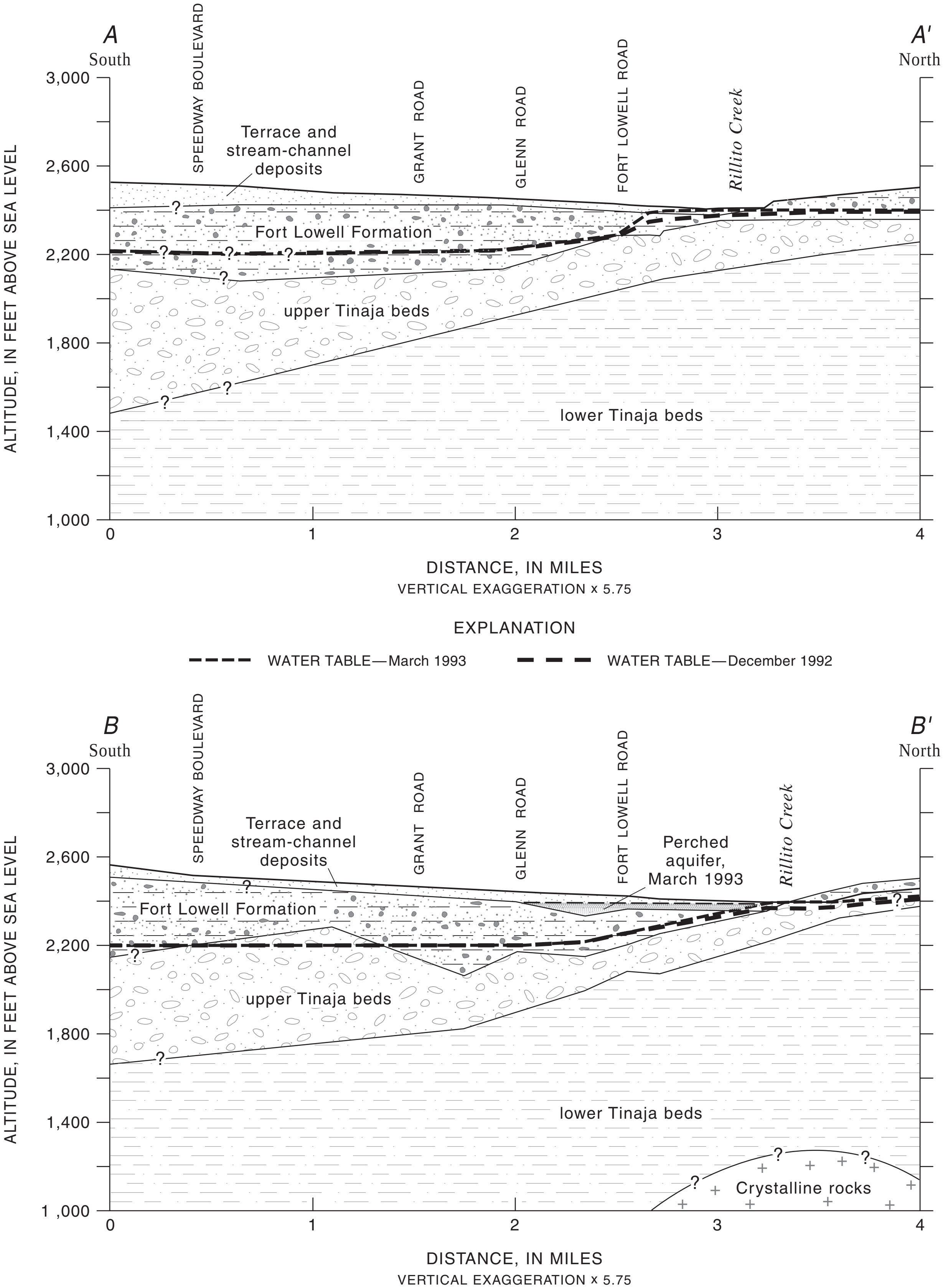


Figure 2. Hydrogeologic section *A–A′* and *B–B′* (see **fig. 1** for trace of section).

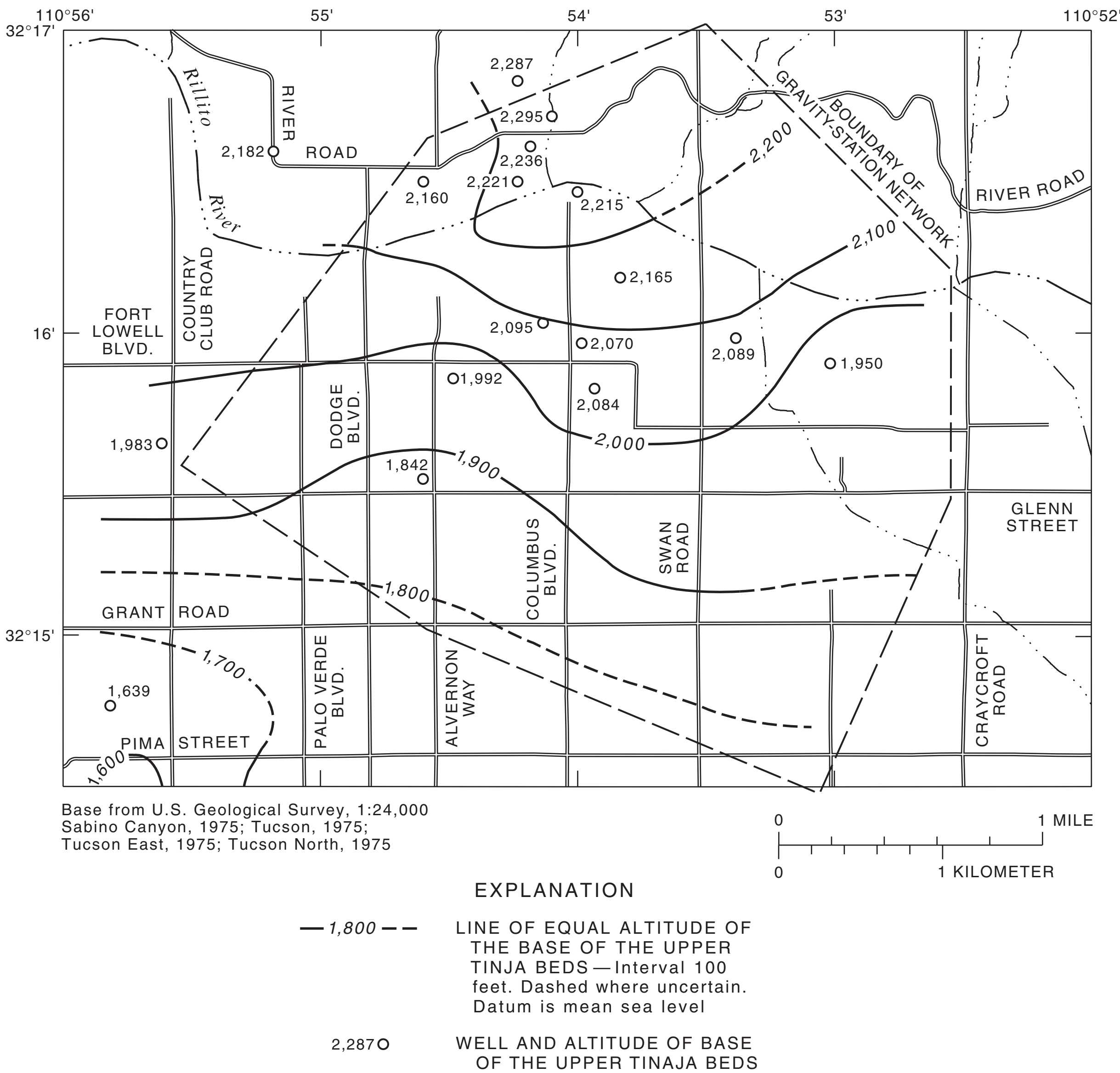


Figure 3. Altitude of the base of the upper Tinaja beds.

The Fort Lowell Formation is the main water-bearing unit south of Rillito Creek. The unit typically consists of interbedded layers of clay, silt, sand, gravel, and boulders. Silt-sized and smaller particles constitute 19 to 37 percent of the unit. Thickness of individual beds averages 47 ft on the basis of drillers' logs. Density of the unit ranges from 2.09 to 2.27 g/cm^3, and electrical resistivity ranges from 18 to 33 ohmmeters. Porosity from neutron logs ranges from 29 to 44 percent, and sonic-velocity ranges from 5,600 to 7,300 ft/s. Saturated thickness in December 1992 typically was about 50 ft towards the south (**fig. 4**). The unit is unsaturated north of Rillito Creek, in a small area east of Swan Road and south of Rillito Creek, and in an area near the southern boundary of the study area where the unit is gradational with the upper Tinaja beds.

The most permeable unit is the stream-channel deposits of the young alluvium along Rillito Creek. The unit generally was unsaturated in December 1992 but became partially saturated during the study.

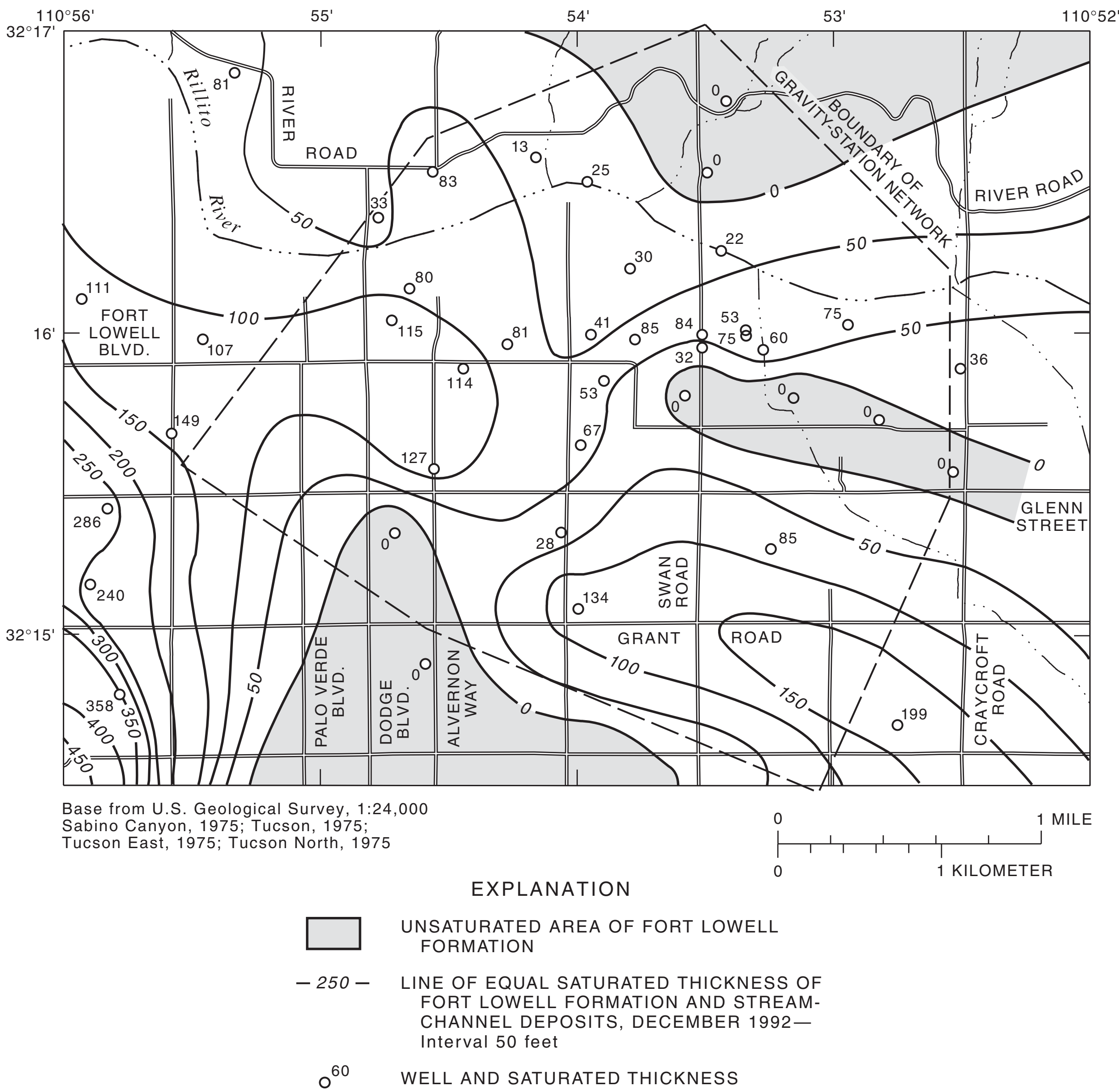


Figure 4. Saturated thickness of the Fort Lowell Formation and stream-channel deposits, December 1992.

The unit consists of sand, gravel and boulders and minor amounts of silt and clay. Samples from wells drilled on the flood plain of Rillito Creek indicate that silt-size and smaller particles comprise 24 to 40 percent of the unit. Deposits along the present stream channel probably contain smaller percentages of silt and clay. Thickness of individual beds averages 20 ft on the basis of drillers' logs. Thickness of the unit exceeds 50 ft in places but generally is about 30 ft. Geophysical logs are not available for the unit; however, the unit is qualitatively characterized as having low density, high electrical resistivity and porosity, and low sonic velocity.

General variations in the thicknesses of the main aquifer also can be inferred from the residual distribution of complete Bouguer gravity-anomaly values (fig. 5). The residual distribution was computed by removing a regional-trend surface from the complete Bouguer gravity-anomaly values to isolate the near-surface effects of variations in thickness of low-density sediments that form the main aquifer.

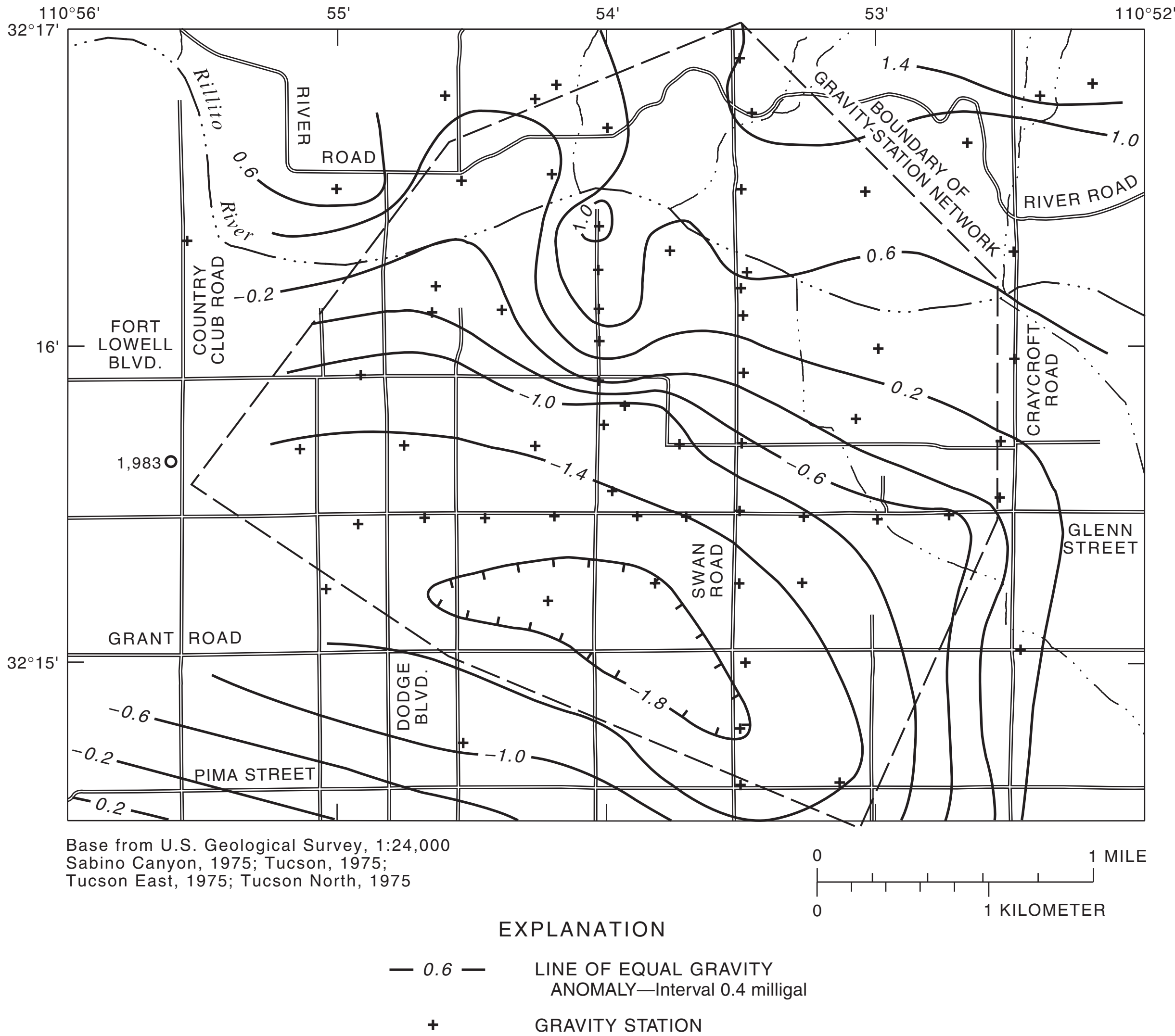


Figure 5. Residual of complete Bouguer gravity-anomaly values.

The regional-trend surface approximates the effects of the regional trend in the depth to bedrock. Areas of low-gravity anomaly values indicate greater thicknesses of low-density sediments. Areas of high-gravity anomaly values indicate greater thicknesses of denser sediments or bedrock structural highs. generally, the gravity- anomaly values trend to higher values in the northern part of the study area and lower values in the southern part of the study area and are similar to the trend in saturated thickness of the Fort Lowell Formation (**fig. 4**). A local gravity high in the north-central part of the study area coincides with a structural high in the base of the upper Tinaja beds (**fig. 3**). The magnitude of the gravity high cannot be explained by a structural high in the upper Tinaja beds alone and probably indicates a local bedrock high in the area. A well near the structural high was drilled to a depth of 863 ft without encountering bedrock, which indicates that bedrock probably is much deeper than 863 ft throughout most of the study area.

METHODS OF TEMPORAL-GRAVITY SURVEYS

Theory

Newton's Law of Gravitation (eq. 1) is the theoretical basis for application of gravity surveys to measurement of aquifer-storage change. Newton's Law state that acceleration due to the gravitational field of a spherically symmetric object is proportional to the mass of the object and inversely proportional to the square of the distance to the center of the object (Telford and others, 1990):

$$g = GM/R^2, \tag{1}$$

where

g	=	acceleration of gravity,
G	=	universal gravitational constant,
M	=	mass of the object, and
R	=	distance to the center of mass of the object.

A linear or one-dimensional approximation to equation 1, the Bouguer slab equation (eq. 2), is useful for discussion and often can be used to approximate the gravitational effect of an object provided the lateral extent of the object is much greater than the distance to the center of the object. The Bouguer slab approximation is expressed mathematically as (Telford and others, 1990):

$$\Delta g = 2\Pi G\rho b, \tag{2}$$

where

Δg	=	gravity effect in milligals (1 gal = 1 cm/s^2)
ρ	=	density of the body in grams per cubic centimeter, and
b	=	thickness of the slab in centimeters.

Converting to gravity units of microgals (μGals), 1μGal = 10^{-6} cm/s^2; density units of grams per cubic centimeter; and thickness, in feet, equation 2 becomes:

$$\Delta g = 12.77\rho b. \tag{3}$$

Equation 3 normally is used to approximate the density or thickness of an anomalous subsurface mass such as a sedimentary basin. The formula also can be applied to temporal changes in density caused by a change in mass of water stored in an aquifer. Approximation error caused by use of the Bouguer slab equation is less than 5 percent for a horizontal disk-shaped body that has a radius of 20 times its depth. The Bouguer slab equation can be used to approximate the gravitational effect of aquifer-storage change in many cases because the assumption of a large lateral extent relative to distance to the center of mass change is often reasonable. Most aquifer-storage change occurs in the interval of water-table fluctuation, which is normally small in comparison to the lateral extent of mass change for regional change in storage. The Bouguer slab equation is not adequate for approximation of the gravitational effect of mass change near the cone of depression around a pumped well.

When Δg is a change in gravity at the land surface in microgals caused by subsurface mass change, the remaining terms of equation 3 represent density change, $\Delta\rho$, in grams per cubic centimeter and thickness of the interval of storage change, b, in feet. For an unconfined aquifer, storage change occurs primarily in the interval of water-table fluctuation; therefore, b is the interval of water-table change. For a confined aquifer, storage change occurs throughout the aquifer, and b is the entire aquifer thickness. Gravity and storage changes are more complex for a confined aquifer because aquifer compaction or expansion may cause a significant change in gravity because of changes in the altitude in gravity because of changes in the altitude of the gravity station.

Density change, $\Delta\rho$, can be computed as:

$$\Delta\rho = S\rho_w, \tag{4}$$

where

S	=	aquifer-storage coefficient, and
ρ_w	=	density of water (1 g/cm^3).

Substituting, and including ρ_w in the constant term, equation 2 becomes:

$$\Delta g = 12.77Sb. \tag{5}$$

The product Sb is the storage change in feet of water.

$$Storage = \Delta g/12.77. \tag{6}$$

The storage coefficient, S, or specific yield of a water-table aquifer, can be calculated provided that the water-table change, b, is known:

$$S = \Delta g / (12.77b) . \qquad (7)$$

In the case of spatially variable mass change where the one-dimensional assumption is invalid, ground-water storage change can be calculated using an excess mass equation. Excess mass is determined through integration of the gravity distribution using Gauss's Law (Telford and others, 1990):

$$\int_s \Delta g ds = 4\Pi GM , \qquad (8)$$

where

ds = an infinitesimally small surface area (direction is outward normal to surface "s"),

Δg = gravity change for the surface area, and

$\int_s$ = surface integral over surface "s."

In the case of ground-water storage change where all changes in mass occur below the land surface, the mass of ground-water storage change is determined by:

$$M = (1/(2\Pi G))\int\int \Delta g(x,y)\Delta x \Delta y , \qquad (9)$$

where

$\Delta x \Delta y$ = an infinitesimally small surface area, and

$\Delta g(x,y)$ = gravity change for the surface area.

In discrete form, equation 9 becomes:

$$M = 1/(2\Pi G)\Sigma\Sigma\Delta g(x,y)\Delta x \Delta y , \qquad (10)$$

where

$\Delta x \Delta y$ = discretized surface area, and

$\Delta g(x,y)$ = average gravity change for the discretized surface area.

Survey Technique

Application of gravity theory to the measurement of temporal changes in water mass is conceptually simple. The relative difference is observed gravity is measured between a gravity station on stable bedrock, where mass change is assumed to be minimal, and gravity stations in aquifer areas where mass change occurs. Bedrock stations must be sufficiently distant from the aquifer that the gravitational effects of the mass change in the aquifer are negligible at the bedrock station. Measurements of the absolute value of gravity at bedrock stations would be preferred to evaluate possible gravity changes in bedrock areas; however, absolute gravity meters are expensive and not sufficiently portable for use in this type of survey. Possible gravity changes at bedrock stations were evaluated for this study by monitoring differences in gravity between the two bedrock stations. Results showed that the measured differences in gravity between the two bedrock stations varied within a range of 12 microgals.

Surveys using relative-gravity meters are in some ways analogous to spirit-level surveys. Closed loops are performed by traversing from a station with a known or constant value, in this case a bedrock base station, to the stations in the aquifer area having unknown values and then returning to the bedrock base station to determine closure error. Several closed loops may be conducted during a survey for the purpose of evaluating the repeatability and accuracy of the measured differences in gravity. The survey is performed again after an arbitrary period of time to determine changes in the difference in observed gravity resulting from changes in the distribution of water mass.

A Lacoste and Romberg Model D gravity meter was used in this investigation. The instrument is a null reading device and uses a test mass attached to a highly sensitive spring to measure the gravitational field of the Earth. Measurements are made by adjusting the spring length to balance the spring tension with the gravitational force of the Earth on the test mass.
The meter includes a screw for coarse adjustment of the spring length and a capacitance system that applies a nulling electrical field. Calibration of the screw and capacitance system is provided by the manufacturer although both can be calibrated by the user.
The capacitance system is calibrated easily with a high degree of accuracy against the calibrated screw or

against theoretical Earth tides. Use of only the capacitance system for measuring temporal changes in gravity is advantageous because circular errors caused by imprecise machining of the screw are eliminated. Screw errors are eliminated by establishing a constant screw position for each station and using it for all subsequent surveys.

Sources of Survey Error

Errors in relative-gravity surveys are caused by nonlinear survey drift caused by inaccurate approximation of solid Earth tides, changes in temperature of the instrument housing, atmospheric effects, and jarring of the instrument. Solid Earth tides cause gravity variations that normally are many times larger than the gravitational effects of storage change but can be predicted by several algorithms. An algorithm developed by Longman (1959) was used in this study. Surveys were conducted when possible during linear portions of the tidal curve where the algorithm is most accurate. Temperature variations of the instrument housing can cause linear and nonlinear short-term instrument drift. Thermal drifts are reduced by shielding the instrument from sunlight and taking care to keep the meter housing in equilibrium with the ambient air temperature. Changes in the distribution of atmospheric air mass can result in measurable changes in gravity but are normally small and nearly linear during surveys of a few hours. Offsets in instrument readings also can occur if the instrument is subjected to unnecessary jolting. A soft carrying case was employed to minimize possible jarring of the instrument during transport of the instrument from vehicles to gravity stations and during transport in vehicles between stations. Nonlinear instrument drift can occur when the spring length of the instrument is changed. Nonlinear drift can be minimized by setting the screw position to preset values for each station before leaving the preceding station and allowing a few minutes for the capacitance system to stabilize at each station. The capacitance system generally was allowed to operate for 5 minutes before readings were taken.

Survey drift is approximated linearly on the basis of closure error of repeated measurements at gravity stations. Immediate field reduction of data sets allows for detection of nonlinear drift, general assessment of survey accuracy, and continuation of the survey if the accuracy is not acceptable.

Errors in the measured change in ground-water storage can occur through differential changes in altitude and nonaquifer mass. Regional changes in nonaquifer mass or altitude that affect the gravitation field at all stations in a network equally do not affect differential-gravity measurements among the stations and are not causes of error in this type of survey. Variations in altitude of gravity stations in excess of 0.03 ft will cause significant changes in gravity. Changes in altitude caused by local expansion or contraction of the aquifer or other near-surface materials affect the absolute value of gravity by an amount equivalent to the local vertical gradient of gravity—about 90 μGal/ft in the study area. Bedrock outcrops and concrete slabs at wells are excellent altitude-stable sites for gravity stations that minimize the effects of near-surface expansion and contraction of soils. Altitude changes, however, may result from aquifer compaction or expansion caused by changes in hydrostatic-pressure head in the aquifer. The altitude of two of the gravity stations were monitored using the Global Positioning System (GPS; Remondi, 1985) to evaluate the possible change in altitude.

Nonaquifer-mass change can occur through local erosion, deposition, manmade manipulation of the land surface, and storage change above the water table. Gravity stations were placed at sufficient distance from areas of possible nonaquifer-mass changes to minimize the effect. The maximum effect of observable mass change near a station is easily estimated using gravity models. The gravitational effect of nonaquifer- mass change above the water table cannot be separated from mass change in the aquifer without subsurface-gravity measurements in boreholes or tunnels.

TEMPORAL GRAVITY STATION NETWORK

A network of gravity stations was designed to meet several needs including: (1) estimation of ground-water storage change in the study area, (2) evaluation of temporal and spatial gravity change along profiles, (3) evaluation of water level and gravity relations, and (4) estimation of specific yield. Areal coverage allowed for integration of the gravity change across the study area and estimation of total change in ground-water storage. Detailed information along profiles allowed for evaluation of spatial and temporal variability of gravity changes and general survey accuracy. Gravity stations at wells allowed for the estimation of specific yield for the intervals of water-level change. Most gravity stations were placed on concrete slabs that included well pads, sidewalks, street curbs, and benchmarks. The two bedrock-base stations were established on gneiss at the base of the Catalina Mountains. One station is a chiseled and painted mark about 4 mi north of the study area. The other station, about 5 mi northeast of the study area, is a National Geodetic Survey horizontal-control station, TUC, that is adjacent to an absolute gravity station, TUCSON B, established by the National Oceanic and Atmospheric Administration (NOAA) in 1986. TUCSON B is part of a national network of stations that are periodically monitored by NOAA for changes in the absolute value of gravity. The measured value of absolute gravity at TUCSON B has been transferred to TUC using a relative-gravity meter similar to the meter used for this study.

The original gravity-station network consisted of 46 gravity stations, including 5 stations at wells, that were measured during the initial comprehensive survey of early December 1992 (**fig. 6**). Seven additional stations were added after the initial survey including five at wells. One station was destroyed later by construction equipment, and another station was discontinued in early January 1993. Two north-south profiles along Swan Road and Columbus Boulevard included 12 and 6 stations, respectively. The Swan Road profile (A–A') included stations north and south of Rillito Creek at intervals of about 500 ft near the stream and about 1,000 ft at the ends of the profile. The profile along Columbus Boulevard (B–B') included stations south of Rillito Creek at intervals of about 500 ft. One east-west profile along Glenn Street (C–C') consisted of 10 stations at intervals of about 1,000 ft.

Surveys of the gravity-station network were done in a series of subsurveys that typically included 4 to 13 network stations, a bedrock station, and at least 1 network station in common with other surveys. This system allowed for all network stations to be referenced directly to bedrock stations. Subsurveys generally required 4 to 8 hours to complete and included at least two gravity measurements at each network station and at least three measurements at a bedrock station. Comprehensive surveys of the network were done five times on a quarterly basis including the baseline survey in early December 1992 and were completed in 7 days or less. In addition, stations along Swan Road (A–A') were surveyed several times at a 3- to 4-week interval, and stations along Columbus Boulevard (B–B') also were surveyed several times.

RESULTS OF TEMPORAL-GRAVITY SURVEYS

Substantial streamflow in Rillito Creek occurred from a series of storms between early December 1992 and early March 1993 and was recorded at a streamflow-gaging station at Dodge Boulevard (**fig. 7**). Infiltration of streamflow resulted in substantial changes in water levels and gravity near the stream as the volume of ground water in storage increased. Streamflow continued through early April 1993 but much of the low flow was not recorded at the gaging station. Small flows also resulted from locally intense storms between mid-July and mid-November 1993. Water levels declined and gravity decreased near the stream after the last major winter flow, but gravity continued to increase in much of the remainder of the study area. Measurement of gravity changes across the network at various times allowed for the estimation of ground-water flow directions, calculation of ground-water storage change, and estimates of recharge for each period after accounting for estimated ground-water withdrawals and ground-water flow across boundaries of the network. Data from repeated measurements of gravity and water levels at wells were used to estimate specific yield for several wells where gravity and water levels varied significantly and were correlative.

Distributions of Gravity Change and Inferred Ground-Water Flow

Changes in gravity at each station in the network infer changes in ground-water storage and ground-water flow. Changes in gravity were calculated at all stations on a seasonal basis for the purpose of evaluating storage changes and ground-water flow throughout the network and more frequently at stations along Swan Road and Columbus Boulevard for the purpose of evaluating spatial and temporal changes in detail. Gravity change was calculated by subtracting values of gravity at all stations measured during the initial survey in early December 1992 from values measured later. Gravity surveys of the entire network were made in early March 1993, mid-May 1993, late August 1993, and early January 1994 and were compared to the initial survey (figs. 8*A–D*).

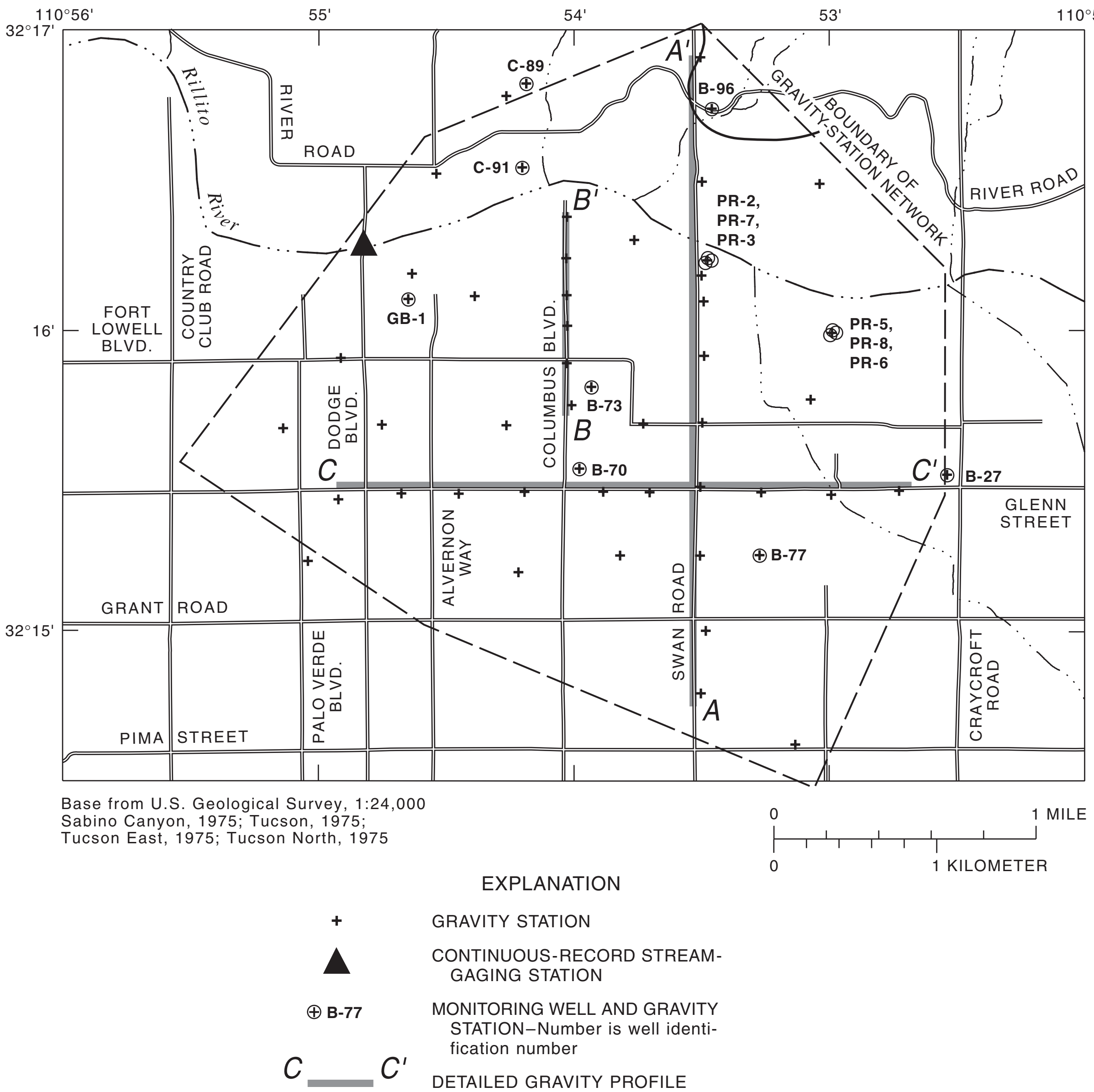


Figure 6. Locations of temporal-gravity stations and monitor wells.

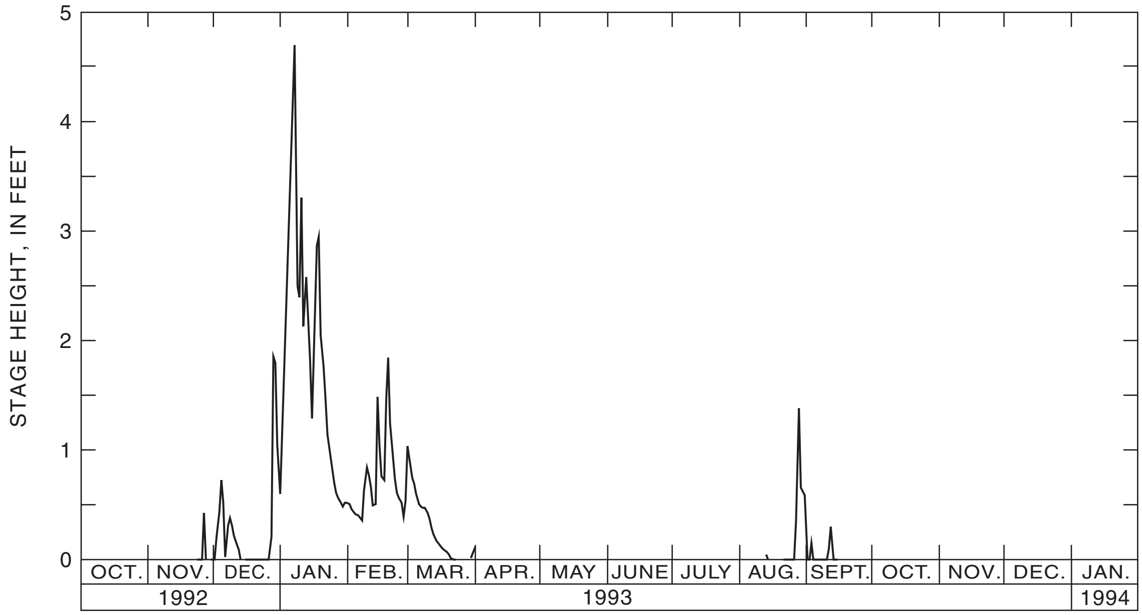


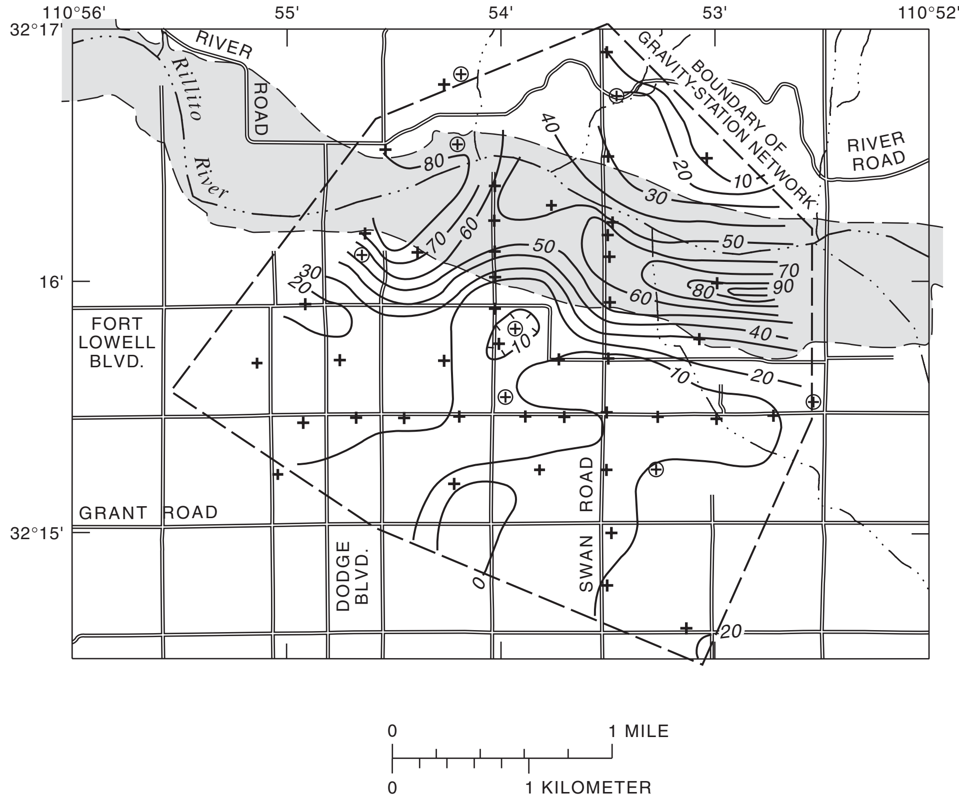
Figure 7. Stage height of Rillito Creek at Dodge Boulevard, October 1992–October 1993.

The measurements indicated that changes in gravity were primarily caused by increases in ground-water storage as a result of recharge by streamflow infiltration during the winter of 1993, the subsequent redistribution of water in storage through ground-water flow, and loss of storage from ground-water withdrawals and flow across network boundaries. Ground-water withdrawals in the study area occurred through two municipal wells and many private wells. Ground-water inflow probably occurred through Tinaja beds along the north boundary of the network and stream-channel deposits along the east boundary. Ground-water outflow probably occurred through the Fort Lowell Formation and Tinaja beds along the south boundary and stream-channel deposits along the west boundary. Distributions of gravity change also were affected slightly by streamflow infiltration from local summer thunderstorms during August and September of 1993 (fig. 7).

The largest increases in gravity of 50 to 90 μGal occurred before surveys in March and April 1993 (**figs. 8***A*, **9***A*, and **10***A–B*) following most of the winter streamflow and were associated with the stream-channel deposits in the flood plain of Rillito Creek (figs. 9*A*, and 10*A–B*). Ground water generally flowed south from the stream during and after streamflow in the direction of decreasing hydraulic head (**fig. 1**). The southward movement of ground water also resulted in southward movement of the largest increase in gravity with successive surveys. Smaller values of maximum gravity change also occurred with successive surveys (figs. 8*B–D*, 9*A–B*, and 10*A–B*) as the storage increase dispersed laterally. Gravity values and the amount of ground water in storage near Rillito Creek had returned to near initial conditions by January 1994 as water in storage had flowed away from the recharge area; however, a residual increase in gravity of 10 to 20 μGal remained throughout the area south of Rillito Creek (figs. 8*D*, 9*B*, and 10*B*), which indicates a residual increase in storage. The residual increase in gravity south of Rillito Creek correlated with rising water levels in wells in the area.

Increases in gravity in the western part of the study area that were greater than those in the eastern part for each survey (figs. 8*A–D*) indicate preferential southward flow of ground water from the recharge area along the western part of Rillito Creek in the study area. Lithologic data support the occurrence of a better hydraulic connection between the stream-channel deposits and the Fort Lowell Formation in the western part of the study area than in the eastern part.

A Early December 1992 to early March 1993



B Early December 1992 to mid-May 1993

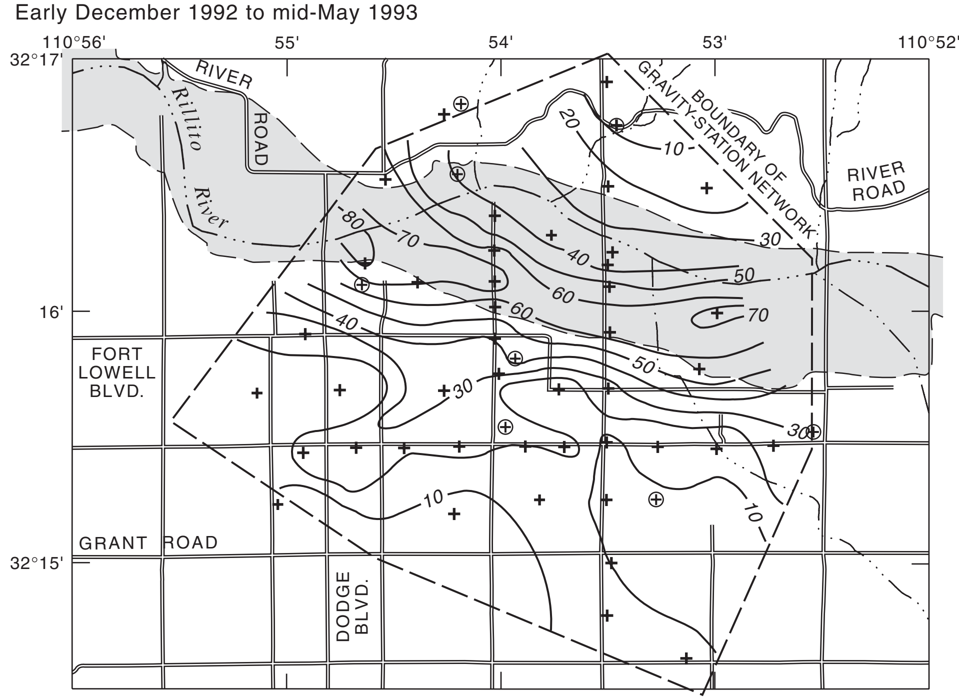


Figure 8. Gravity change from early December 1992 to early January 1994. *A*, Early December 1992 to early March 1993. *B*, Early December 1992 to mid-May 1993. *C*, Early December 1992 to late August 1993. *D*, Early December 1992 to early January 1994.

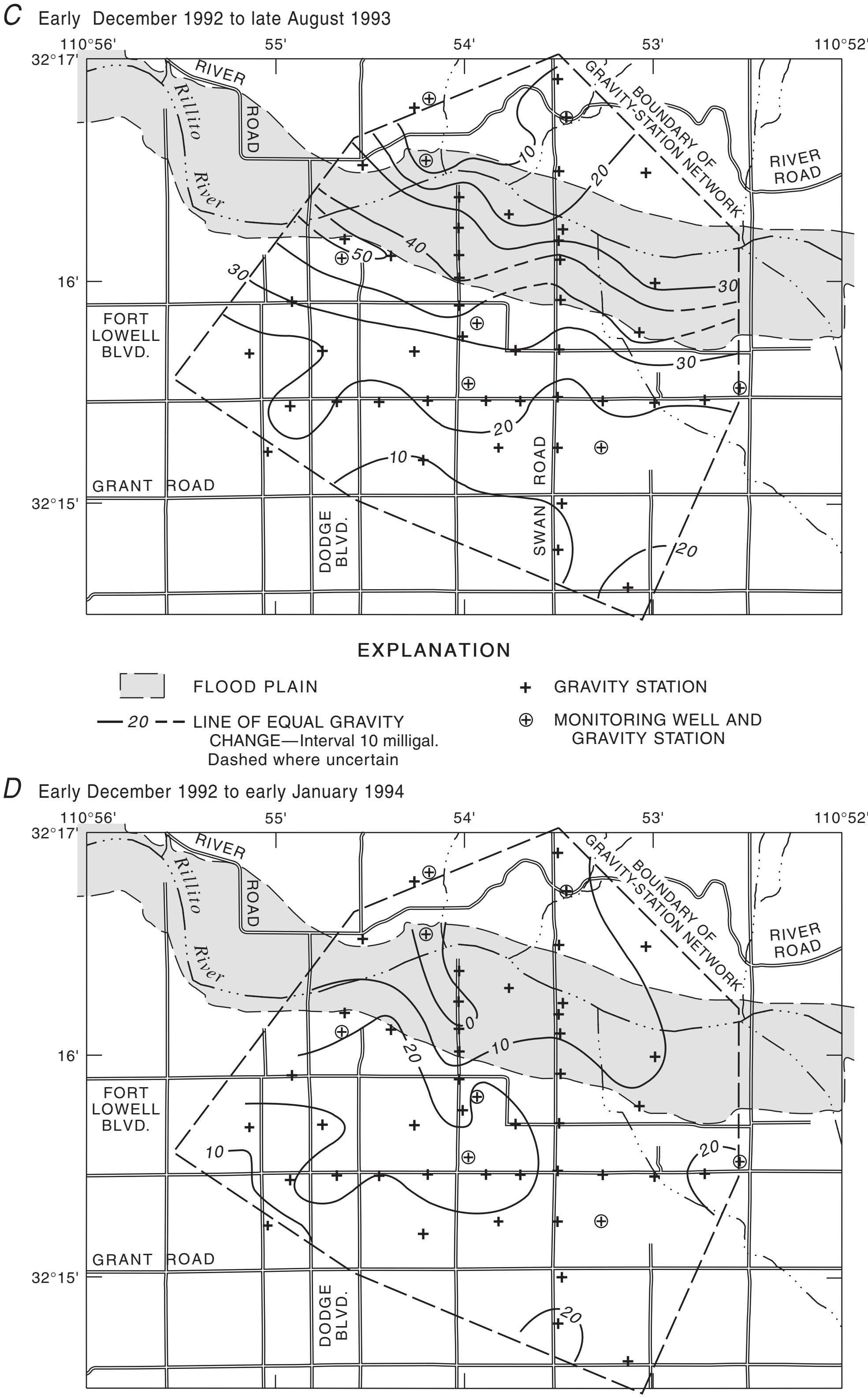


Figure 8. Continued.

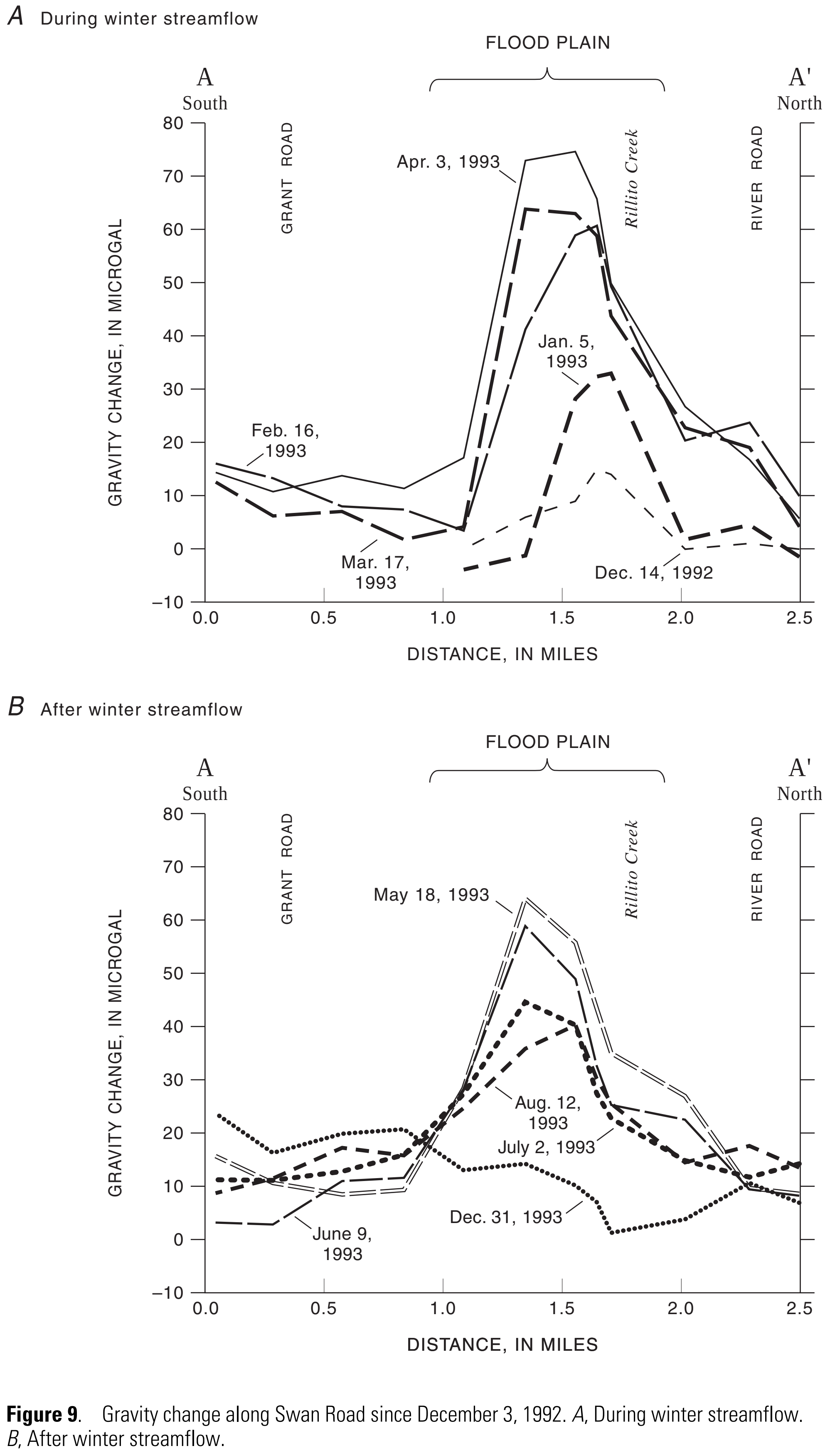


Figure 9. Gravity change along Swan Road since December 3, 1992. *A*, During winter streamflow. *B*, After winter streamflow.

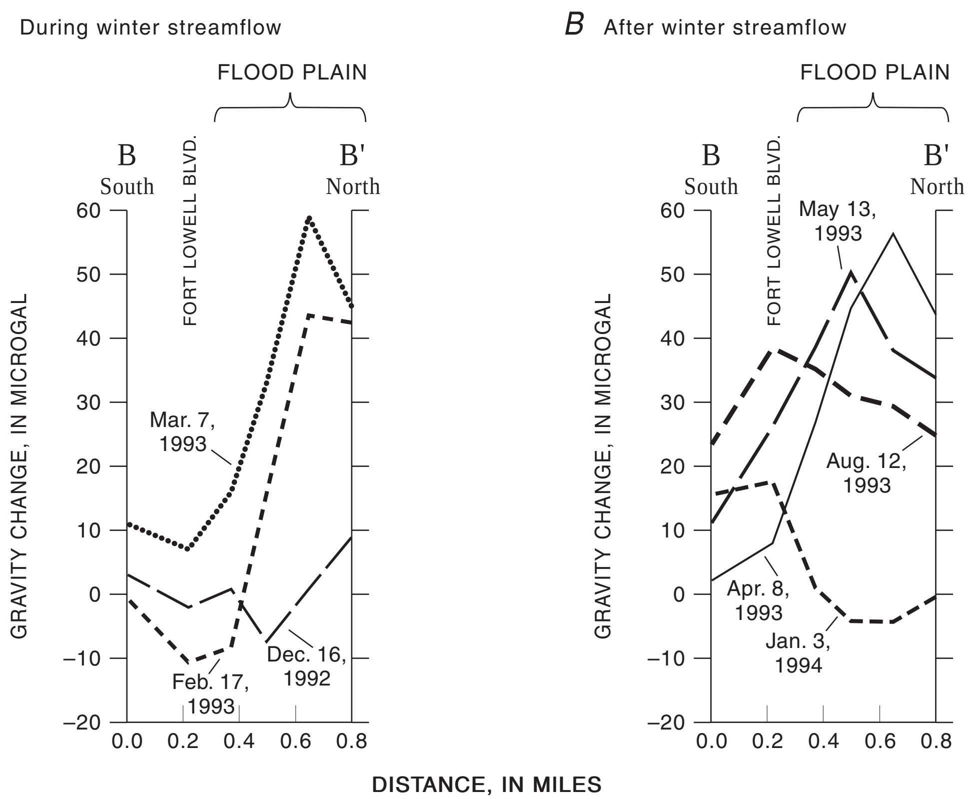


Figure 10. Gravity change along Columbus Boulevard since December 1, 1992. *A*, During winter streamflow. *B*, After winter streamflow.

The Fort Lowell Formation is thickest in the western part of the study area, and lithologic data from two wells indicate that the Fort Lowell Formation was unsaturated during December 1992 in an area south of Rillito Creek and east of Swan Road (**fig. 4**). Greater initial depths to water beneath Rillito Creek in the western part of the study area also resulted in a greater volume of unsaturated zone that was available for accepting infiltrated water into storage in comparison to the eastern part of the study area.

Estimates of Ground-Water Storage Change and Recharge

Estimates of ground-water storage change and recharge within the boundaries of the gravity-station network were determined for the periods between the initial gravity survey in early December 1992 and later surveys of the entire network in early March 1993, mid-May 1993, late August 1993, and early January 1994 by integrating the gravity changes (**figs. 8***A–D*) using equation 10. The maximum value of storage change (8,000 acre-ft) occurred in mid-May 1993 (**table 1**). Storage change decreased thereafter because of ground-water withdrawals and net ground-water outflow across the network boundaries. Recharge within network boundaries for the period of study was estimated to be 10,900 acre-ft (table 1).

Most recharge occurred before early March 1993, and no significant recharge occurred between mid-May 1993 and early January 1994. Evapotranspiration from the aquifer was considered negligible because phreatophytes occur only adjacent to Rillito Creek, and the depth to the water table remained greater than 15 ft for most of the study period. Recharge was assumed to be the only source of water to the network area because ground-water inflow through Tinaja beds of low permeability north of Rillito Creek probably was insignificant.

Table 1. Estimation of ground-water storage change for selected periods since early December 1992, Rillito Creek, Arizona

[Dashes indicate no data]

Period	Measured change in ground-water storage, in acre-feet		Estimated ground-water component, in acre-feet			
	Change in storage	Block kriging standard deviation, in acre-feet	Withdrawals[1]	Net flow across boundary since December 1992	Recharge	Withdrawals within 0.5 mile from south boundary since December 1992[1]
Early March 1993	+7,900	2,000	-600	-1,000	9,500	---
Mid-May 1993	+8,000	2,000	-1,200	-1,700	10,900	-600
Late August 1993	+6,300	1,000	-1,900	-2,700	10,900	-2,100
Early January 1994	+3,700	900	-2,800	-4,400	10,900	-4,000

[1]Wells that are exempt and wells that produce less than 30 gallons per minute are excluded.

Integration of gravity changes across the network required the discretization of the study area and assignment of gravity-change values to grid blocks. The area of the gravity-station network was discretized on a grid of 328 by 328 ft (100 by 100 m), and gravity-change values were assigned to grid blocks using ordinary block kriging applied to the measured values (**figs. 8***A–D*). Ordinary block kriging allows for the calculation of standard deviations that depend on gravity-change variances and on block-estimation variances. Block-estimation variances were similar for each period because block estimation depends on the distribution and density of gravity stations and the size of the estimated block, all of which were similar for each period.

Increased ground-water storage since early December 1992 was estimated as 7,900 acre-ft through early March 1993, 8,000 acre-ft through mid-May 1993, 6,300 acre-ft through late August 1993, and 3,700 acre-ft through early January 1994 (table 1). Block-kriging values of the standard deviation of storage change were about one-quarter of the storage-change values but are probably not representative of the error of the estimate. The standard deviation of the estimate is probably much smaller because block kriging assumes that the measurements are point values. Gravity measurements actually are influenced by the mass present in a large volume of aquifer. In this case, the volume increases with depth to the interval where storage change occurs. Standard gravity models for a radially symmetric mass (Telford, 1990) can be used to estimate the gravitational effect of storage change at various depths and distances from the gravity station. The sample volume is small in areas along the flood plain of Rillito Creek, which has shallow depths to water (10 to 30 ft) where only about 6 percent of the gravity signal results from storage change that is more than 328 ft laterally from the gravity station.
The sample volume is much greater south of the flood plain where depths to water are from 225 to 235 ft, and about 58 percent of the gravity signal results from storage change that is more than 328 ft from the gravity station.

Recharge volumes were estimated by a water-budget approach using the estimated ground-water storage change and accounting for ground-water withdrawals and ground-water flow across network boundaries. Estimated recharge volumes for the periods from early December 1992 were 8,500 acre-ft through early March 1993 and 10,900 acre-ft for each period thereafter (table 1). The increase in recharge from early March 1993 to mid-May 1993 of 700 acre-ft is attributed to continued streamflow infiltration through early April 1992. Ground-water withdrawals were estimated by summing reported weekly withdrawals from two municipal wells (Tucson Water, 1994) and apportioning reported withdrawals for the year from many private wells during the period of study. Wells that do not yield more than 30 gal/min were considered insignificant and were not included in the estimate. Estimated ground-water withdrawals were about 200 to 300 acre-ft per month and totaled 2,800 acre-ft for the period of study. Ground-water flow across the network boundaries was estimated using Darcy's Law applied to flow across the south boundary and along the east and west boundaries where transboundary flow could occur through the highly permeable stream alluvium and Fort Lowell Formation. Ground-water flow across network boundaries was estimated as a net loss of 4,400 acre-ft for the period of study. The estimated discharge of 7,200 acre-ft from the system during the study period was 66 percent of the estimated recharge.

Water-Level and Gravity Relations at Wells

Water levels and gravity were monitored at 10 wells in the study area for the purpose of evaluating water level and gravity relations and estimating specific yield. Good linear correlations between water level and gravity at five wells allowed for the estimation of specific-yield values using the modified Bouguer slab equation for storage change in an unconfined aquifer (eq. 7). Moderate to poor correlations occurred at the other wells. Good correlations generally occurred at wells nearest Rillito Creek and on the flood plain where large water-level and gravity changes (more than 15 ft and 30 μGal, respectively) resulted from ground-water storage changes in the stream-channel deposits. Moderate to poor correlations generally occurred at the wells beyond the flood plain where water-level and gravity changes were smaller. Also, gravity and water-level responses were different north and south of the flood plain. Specific-yield values were estimated for the stream-channel deposits, which had values from about 0.20 to 0.30, and the Fort Lowell Formation, which had values from 0.07 to 0.18. Storage changes within the Tinaja beds were of insufficient magnitude to result in linear correlation of water levels and gravity and estimates of specific-yield values.

Assumptions necessary for the estimation of specific yield through application of equation 7 include: (1) storage change in an interval of aquifer that closely approximates an infinite slab, (2) uniform values of specific yield throughout the slab, and (3) water-level changes measured in wells closely approximate the thickness of the slab. Significant deviations from these assumptions can occur near a recharge mound where delayed saturation and drainage occur, in areas of spatially variable specific yield where significant vertical hydraulic gradients or perched aquifers occur, and where significant variations in ground-water storage occur in the unsaturated zone.

Deviations from these assumptions were found to various degrees in the study area. Although there was evidence of effects of a recharge mound and delayed saturation and drainage at wells near Rillito Creek, these factors did not prevent good correlation of water-level and gravity changes. Changes in the unsaturated zone and the presence of perched aquifers subsequent to streamflow probably caused moderate to poor correlations between water-level and gravity changes at the wells beyond the flood plain. The four wells south of the flood plain displayed gravity increases that preceded water-level increases. The delayed water-level increases probably were caused by the development of a perched aquifer that was not registered in wells that are open to deeper aquifers. Brief increases in gravity at two wells north of the flood plain following major streamflow were much larger than would be expected from the measured water-level increase. The two wells are near small ephemeral washes that are underlain by tens of feet of unsaturated zone. The brief but abnormally large increases in gravity probably were caused by short-term increases in ground-water storage in the unsaturated zone beneath the washes.

Wells on the Flood Plain

Wells PR-2A, PR-7A, and PR-3A.— Frequent measurements at wells PR-2A, PR-7A, and PR-3A near Rillito Creek at Swan Road (**fig. 6**) provided data on vertical-hydraulic gradients, on the development of a recharge mound, and on delayed saturation and drainage. The wells are about 80 ft south of Rillito Creek. Well PR-2A is screened at depths of 15–35 ft in the stream-channel deposits and the Fort Lowell Formation. Well PR-7A is screened at depths of 45–80 ft in the Fort Lowell Formation and the upper Tinaja beds. Well PR-3A is screened at depths of 90–130 ft in the upper Tinaja beds. Well PR-2A was initially dry in December 1992; the well screen became submerged after water levels rose.

Water level and gravity are visually correlated at wells PR-2A, PR-7A, and PR-3A (**fig. 11*A***). Only the water level for well PR-7A is shown because the altitude of the water level in the wells was similar. Water levels rose and gravity increased about 29 ft and 60 μGal, respectively, from initial conditions corresponding with extended streamflow from January through March before gradually declining to near initial conditions by January 1994. A small gravity increase in August 1993 corresponded to a water-level rise associated with streamflow caused by locally intense rainfall (**fig. 7**).

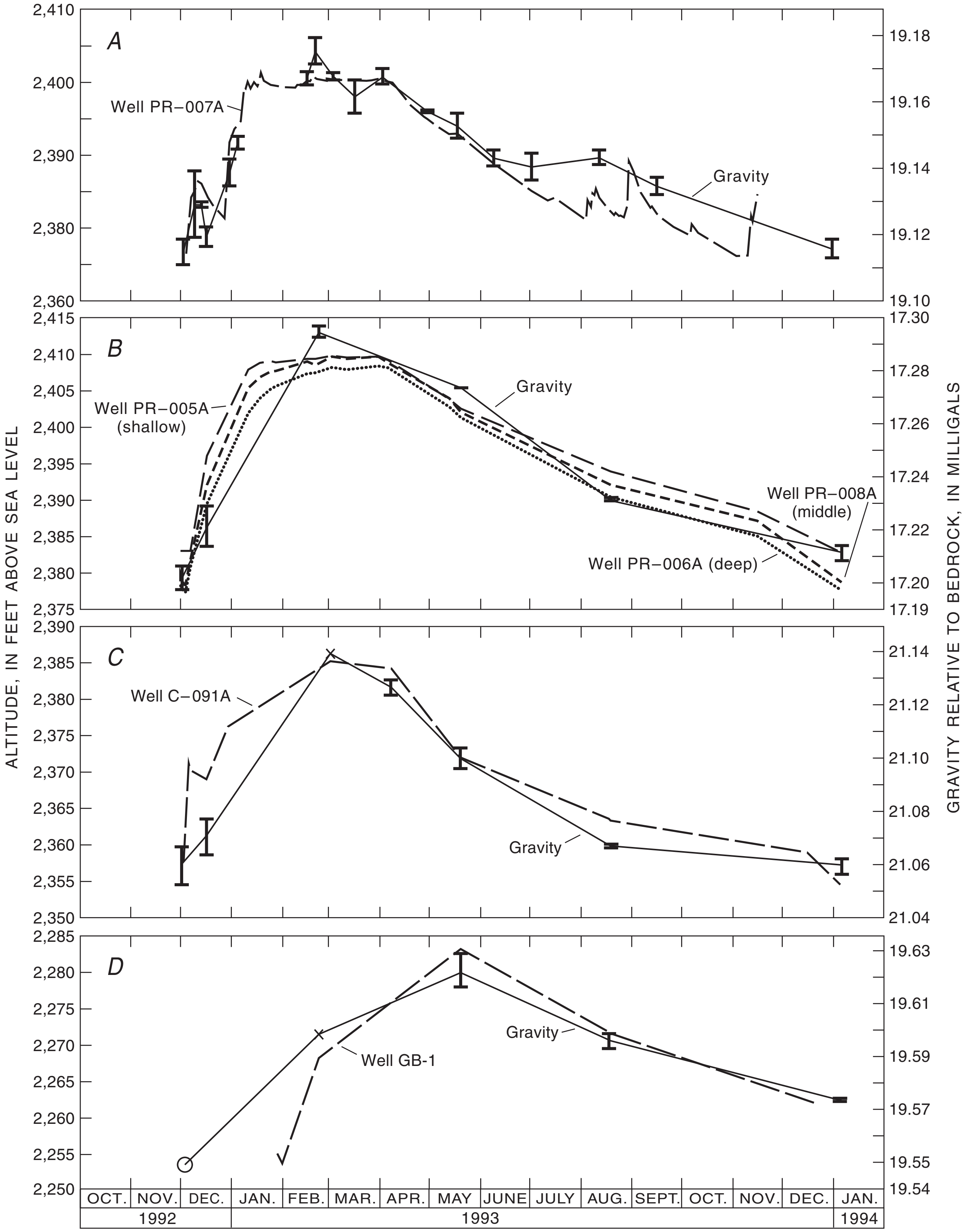


Figure 11. Water levels and gravity at selected wells, October 1992–January 1994. *A*, Well PR–7A. *B*, Wells PR–5A, PR–8A, and PR–6A. *C*, Well C–91A. *D*, Well GB–1A. *E*, Well B–73A. *F*, Well B–70A. *G*, Well B–77A. *H*, Well B–27B. *I*, Well B–96A. *J*, Well C–89A.

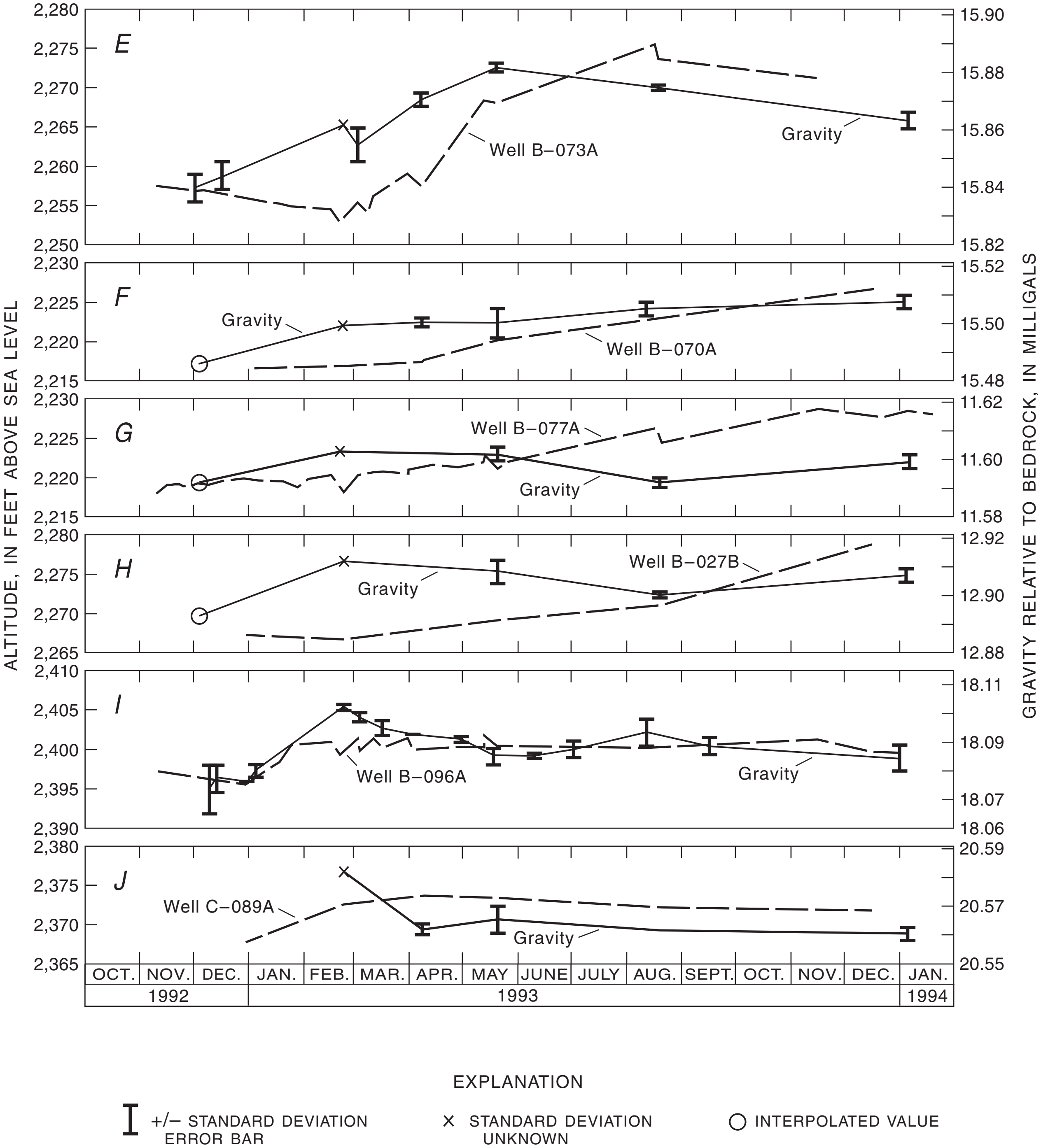


Figure 11. Continued.

Wells PR-5A, PR-8A, and PR-6A.—Water levels and gravity also are visually correlated at wells PR-5A, PR-8A, and PR-6A (**fig. 11***B*), which are about 400 ft south of Rillito Creek (**fig. 6**). Water levels rose and gravity increased about 31 ft and 90 μGal, respectively, and corresponded with streamflow. Decreasing water-level altitude with depth at these wells, however, indicated vertical-hydraulic gradients of as much as 5 ft between the deep and shallow wells and downward flow of ground water. The three wells are screened at depths of 15–40 ft, 50–70 ft, and 80–120 ft, respectively. Well PR-5A is screened in the stream-channel deposits and the Fort Lowell Formation. Well PR-8A is screened only in the Fort Lowell Formation. Well PR-6A is screened in the Fort Lowell Formation and the upper Tinaja beds. The well screen of PR-5A was above the water table at the beginning and end of the study.

Well C-91A.—A water-level rise of about 28 ft is correlated with a gravity increase of about 80 μGal at well C-91A (fig. 11*C*). The well is about 300 ft north of Rillito Creek (fig. 6) and is screened from 49 to 200 ft below land surface in the stream-channel deposits, the Fort Lowell Formation, and the upper and lower Tinaja beds. The interval of water-level change primarily occurred in the stream-channel deposits.

Well GB-1A.—A water-level rise of about 29 ft is correlated with a gravity increase of about 80 μGal at well GB-1A (fig. 11*D*). The well is about 800 ft south of Rillito Creek and about 100 ft south of the flood plain (fig. 6). The well is open to the upper Tinaja beds through an uncased and open hole from 311 to 365 ft below land surface. The interval of water-level change primarily occurred in the Fort Lowell Formation. The initial gravity measurement was interpolated from nearby gravity stations because the well was added to the network in February 1993. Maximum water-level and gravity changes occurred during mid-May 1993, which was later than at the other wells near the river.

Wells South of the Flood Plain

Poor to moderate correlations between gravity and water levels occurred at the four well sites south of the flood plain. Each of the data sets displayed water-level rises that lagged behind gravity increases. The early gravity increase probably was caused by storage increases in one or more perched aquifers before storage and water levels changed in the primary aquifer. Corroborating evidence for perched aquifers is found in the driller's logs of well B-73A that were made in 1977 when the well was deepened. Ground water was found above the existing water level in as many as four sand-and-gravel, and sandy clay beds. These beds are below the altitude of the Rillito Creek channel and may have provided a conduit for lateral ground-water flow from the stream-channel deposits above the regional water table (**fig. 2***B*).

Well B-73A.—Water-level rises of about 21 ft lagged behind gravity increases of about 40 μGal at well B-73A (fig. 11*E*). Well B-73A is about 3,200 ft south of Rillito Creek (fig. 6) and is perforated from 120 to 446 ft below land surface in the Fort Lowell Formation. Gravity increases during late February 1993 preceded significant water-level rises in mid-March 1993. Maximum gravity changes during mid-May 1993 also preceded the maximum water level that occurred during June through August 1993. Gravity decreased and water levels declined from August through January 1994.

Well B-70A.—Gravity increases of about 20 μGal preceded water-level rises of about 10 ft at well B-70A (fig. 11*F*). The well is about 4,200 ft south of Rillito Creek and 1,000 ft south of well B-73A (fig. 6). The well is perforated from 90 to 430 ft below land surface in the Fort Lowell Formation. The initial gravity measurement was interpolated from nearby stations because the station was added to the network in February 1993. Unlike well B-73A, gravity continued to increase and the water level continued to rise through January 1994. Comparison of the relations of well B-73A and well B-70A (figs. 11*E* and *F*) shows the effect of downgradient migration of the storage change as it dissipates in basin-fill deposits. The magnitude of gravity and water-level increases are less at well B-70A and occur later than at well B-73A.

Well B-77A.—Gravity increases of about 10 μGal preceded water-level rises of about 10 ft (fig. 11*G*). The well is about 5,000 ft south of Rillito Creek and is perforated from 91 to 432 ft below land surface in the Fort Lowell Formation. A slight drop in gravity during August may have been caused by nearby ground-water withdrawals. Three withdrawal wells owned and operated by Tucson Medical Center are about 0.5 mi east of well B-77A and have withdrawal capacities between 500 and 1,300 gal/min—the largest of all private wells in the study area. The withdrawal wells are perforated from 166–250 ft and 330–400 ft at well (B-02-01)35dbd, 201–511 ft at well (B-02-01) 35ddd, and 360–520 ft at well (B-02-01)35dac. Ground-water withdrawal from these wells totaled 312 acre-ft for calendar year 1993. Pumping schedules for these wells were not available, but it was assumed that withdrawal rates were greatest during the summer.

Well B-27B.—Gravity increases of about 20 μGal preceded water-level rises of about 12 ft at well B-27B (**fig. 11***H*). The well is about 3,500 ft south of Rillito Creek (**fig. 6**) and is perforated from 324 to 617 ft. A slight drop in gravity during August may have been caused by the nearby ground-water withdrawals similar to those that affected well B-77A. The withdrawal wells are about 0.5 mi south of well B-27B.

Wells North of the Flood Plain

Water levels and gravity at two well sites north of the flood plain of Rillito Creek are moderate to poorly correlated. The gravity changes are characterized by short duration and relatively large increases in relation to the water-level rise. But the long-term correlation between water levels and gravity during the project appears good. Water-level changes occurred in the upper Tinaja beds at both wells. The short-duration gravity increases probably are caused by ground-water storage increases in the unsaturated zone following substantial rainfall and infiltration of streamflow in the nearby washes. Both wells are within 100 ft of small washes that periodically flowed during the study period. The increased storage in the unsaturated zone migrated down to the water table and spread laterally leaving a residual gravity increase that correlated well with the residual water-level rise.

Well B-96A.—Well B-96A is about 2,300 ft north of Rillito Creek and within 20 ft of a small wash (fig. 6). Data indicate that two gravity increases with subsequent decreases occurred along with a small water-level rise associated with streamflow after a major rainfall (fig. 11*I*). A gravity increase of about 25 μGal in late February 1993 corresponded to a 5-foot rise in water level after most of the winter rainfall had occurred. Gravity values subsequently decreased through May 1993. A second gravity increase of about 10 μGal occurred in early August 1993 following a brief but intense period of rainfall.

Well C-89A.—Well C-89A is about 1,500 ft north of Rillito Creek and within 100 ft of a small wash (fig. 6). The first gravity measurement at well C-89A in late February 1993 probably was preceded by an initial gravity increase in January 1993 that was similar to the initial increase observed at well B-96A (fig. 11*J*). Gravity and water levels remained roughly unchanged after early April 1993.

Estimates of Specific Yield

Estimates of specific yield were calculated from the water level and gravity relations at five well sites—wells PR-2A, PR-3A, and PR-7A; wells PR-5A, PR-8A, and PR-6A; well C-91A; well GB-1; and well B-70A. Water levels and gravity at these wells were sufficient to result in good linear correlations. All estimates of specific yield were determined on the basis of linear regression of the water-level and gravity data and the modified Bouguer slab formula (eq. 7; **figs. 12***A*–*E* and **table 2**). Estimates of specific yield were not made for the remaining wells because of moderate to poor correlations and small changes in water levels and gravity. Estimates of specific yield were calculated for the stream-channel deposits and the Fort Lowell Formation at three well sites. Results indicate specific-yield values for stream-channel deposits and the Fort Lowell Formation were significantly different and ranged from 0.15 to 0.34 and from 0.07 to 0.18, respectively. Specific-yield values were not calculated for the upper and lower Tinaja beds because of insufficient data at wells where the water-level change was below the top of the Tinaja beds. Detailed data collection at wells PR-2A, PR-3A, and PR-7A was used to analyze the effects of Bouguer slab assumptions near the recharge source on water level and gravity relations. Significant vertical-hydraulic gradients at wells PR-5A, PR-8A, and PR-6A resulted in well-dependent specific-yield values.

A large amount of data collected at wells PR-2A, PR-7A, and PR-3A allowed for a detailed analysis of the water level and gravity relations near the recharge source where the assumptions necessary for application of the modified Bouguer slab equation are most likely to be invalid. Results indicate that the effects of delayed saturation or development of a recharge mound at the site significantly influenced the water level and gravity relations (fig. 12*A*). A considerable amount of scatter exists among the data shown in figure 12*A* resulting in low correlation coefficients.Specific-yield values calculated for the stream-channel deposits at the well nest were 0.21, 0.21, and 0.22 (table 2), respectively, using the water-level data for each well. Correlation coefficients were calculated as 0.83, 0.85, and 0.81, respectively. Slightly different values of specific yield are calculated depending on the use of data from the period of ascending or descending water levels.

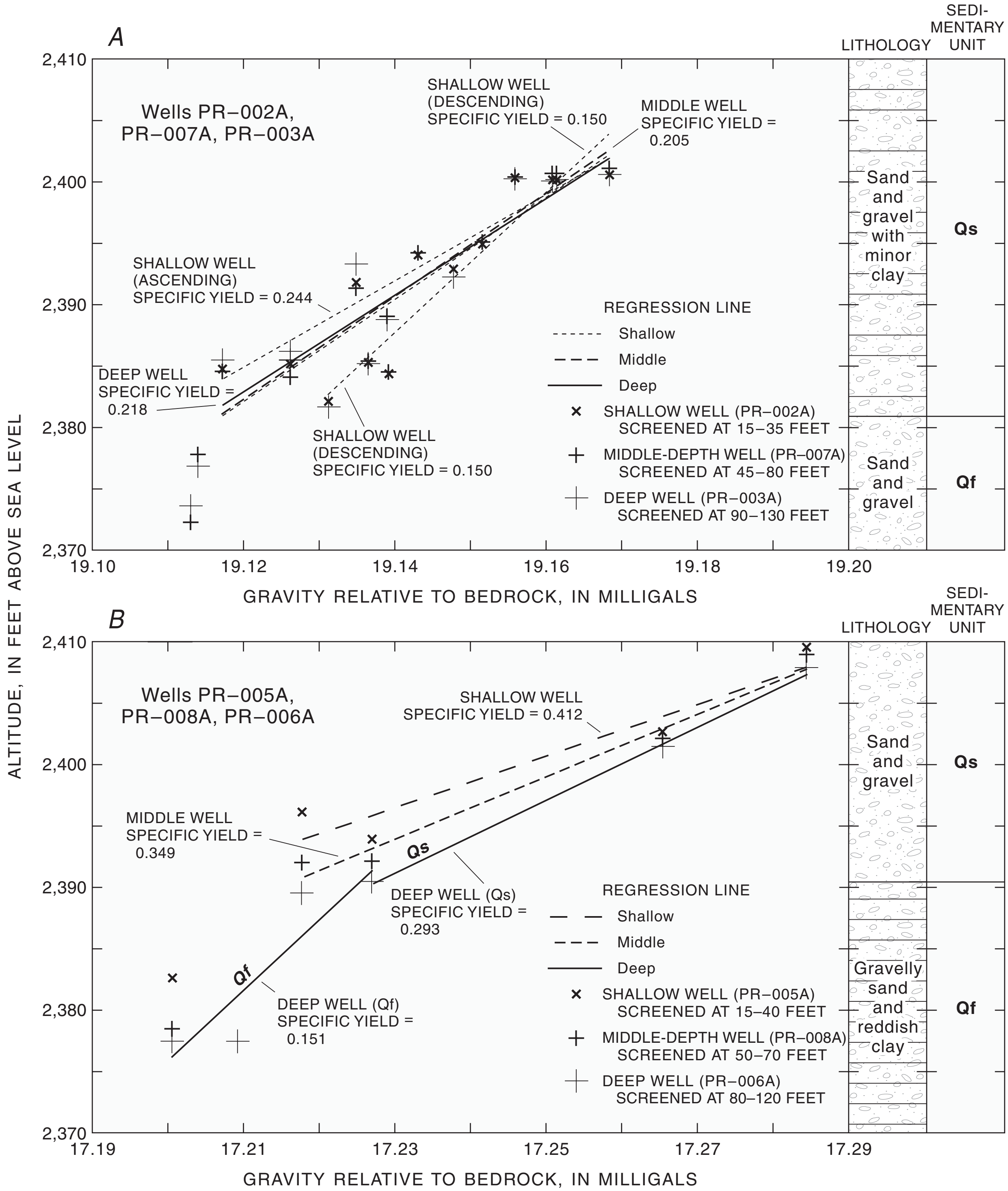


Figure 12. Specific yield determined by water level and gravity relations at selected wells October 1992–January 1994. *A*, Wells PR–2A and PR–3A. *B*, Wells PR–5A, PR–8A, and PR–6A. *C*, Well C–91A. *D*, Well GB–1A. *E*, Well B–70A.

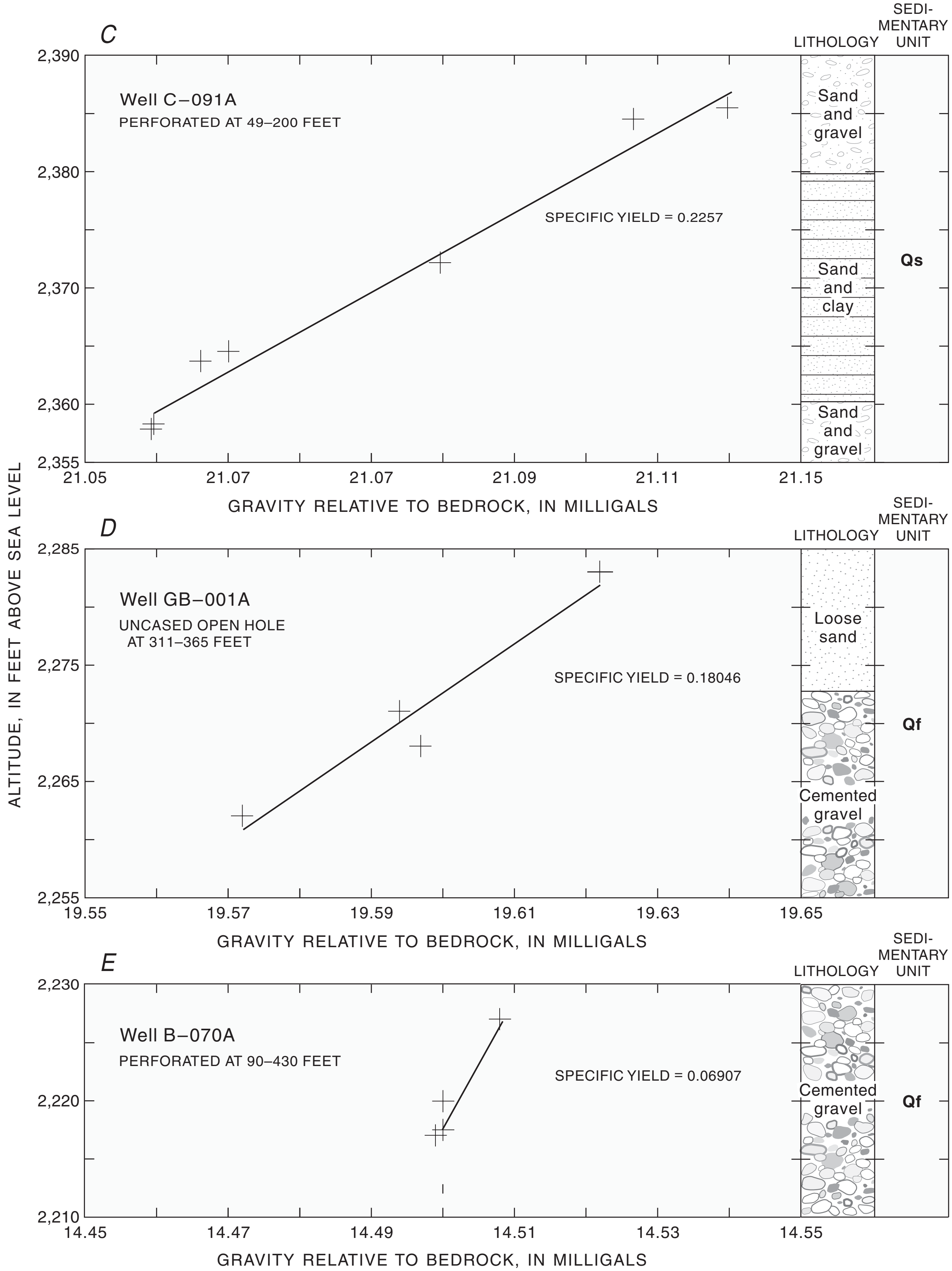


Figure 12. Continued.

Table 2. Estimates of specific yield at selected wells, Rillito Creek, Arizona

[Open interval: screen, perforations, or open hole, in feet. Dashes indicate no data]

Sedimentary unit	Well	Open interval, in feet: Below land surface From	Open interval, in feet: Below land surface To	Open interval, in feet: Altitude, above sea level From	Open interval, in feet: Altitude, above sea level To	Lithology	Interval of water-level change, in feet: Below land surface From	Interval of water-level change, in feet: Below land surface To	Interval of water-level change, in feet: Altitude, above sea level From	Interval of water-level change, in feet: Altitude, above sea level To	Estimates of specific yield	Correl-ation coeffi-cient
Stream-channel deposits	PR-2A	15	35	2,396	2,376	Sand and gravel with minor clays	10.40	28.95	2,400.51	2,381.96	0.206	0.83
	PR-2A[1]	15	35	2,396	2,376	Sand and gravel with minor clays	25.85	10.40	2,385.06	2,400.51	.244	.96
	PR-2A[2]	15	35	2,396	2,376	Sand and gravel with minor clays	10.40	28.95	2,400.51	2,381.96	.150	.92
	PR-7A	45	80	2,366	2,331	Sand and gravel with minor clays	9.60	26.57	2,401.03	2,384.06	.205	.85
	PR-3A	90	130	2,320	2,280	Sand and gravel with minor clays	9.70	28.80	2,400.59	2,381.49	.218	.81
	PR-5A	15	40	2,408	2,383	Sandy gravel	13.63	28.95	2,409.24	2,393.92	.412	.92
	PR-8A	50	70	2,373	2,353	Sandy gravel	13.97	30.44	2,408.58	2,392.11	.341	.98
	PR-6A	80	120	2,342	2,302	Sandy gravel	14.90	31.92	2,407.53	2,390.51	.293	.99
	C-91A	49	200	2,351	2,200	Sand Sand and clay Sand and gravel	14.90 21 40	17 40 42.59	2,385.30	2,357.61	.226	.98
Fort Lowell Formation	PR-6A	80	120	2,342	2,302	Gravelly sand and reddish clay	31.92	44.85	2,390.51	2,377.58	.151	.82
	GB-1A	311	365	2,082	2,028	Loose sand Cemented gravel	109.59 120	120 130.73	2,283.19	2,262.05	.180	.93
	B-70A	90	430	2,339	1,999	Cemented gravel, very hard	202.74	212.52	2,226.69	2,216.91	.069	.93
	PR-2A, PR-7A, PR-3A					Reddish sand and minor clays	30	38.57	2,380	2,372.30	([3])	---
	PR-5A, PR-8A					Gravelly sand and reddish clay	32	44.52	2,390	2,378.03	([3])	---
	B-73A	120	446	2,304	1,978	Sandy clay	150.10	171.20	2,273.72	2,252.62	([3])	---
	B-77A	91	432	2,363	2,022	Gravel	225.30	235.86	2,228.70	2,218.14	([3])	---
	B-27 B	324	617	2,131	1,838	Sandy brown conglomerate	176.50	188.61	2,278.80	2,266.69	([3])	---
Upper Tinaja beds	B-96 A	90	195	2,377	2,272	Cemented gravel	66.75	71.78	2,400.54	2,395.51	([3])	---
	C-89 A	98	355	2,327	2,070	Hard grey conglomerate	46.65	53.29	2,378.45	2,371.81	([3])	---

[1]Ascending water levels.
[2]Descending water levels.
[3]Insufficient data.

The specific-yield value of 0.24 was calculated using ascending water levels for well PR-2A and a correlation coefficient of 0.96. Descending water levels, however, resulted in a value of 0.15 and a correlation coefficient of 0.92. The discrepancy probably was caused by incomplete saturation of a uniform slab because of a recharge mound or delayed saturation of sediments during recharge. Specific-yield values that were calculated using descending water levels probably are more representative of the sediments because the water-level decline probably occurred gradually across a large area and approximated a slab of uniform thickness.

Using the water-level data from individual wells, specific-yield values for the stream-channel deposits at wells PR-5A, PR-8A, and PR-6A were calculated as 0.41, 0.34, and 0.29 (**table 2**), respectively. Correlation coefficients were 0.92, 0.98, and 0.99, respectively. The variation in calculated specific yield was most likely caused by vertical-hydraulic gradients that occurred during winter streamflow. Water levels in the shallow well, PR-5A, were more than 5 ft higher than water levels in the deep well, PR-6A, after the first major winter streamflow in December. The vertical gradients indicate that a recharge mound or delayed saturation of sediments probably occurred at this site. The specific-yield value calculated using the water-levels from the shallow well, PR-5A, probably is in error because water levels from early periods of recharge probably were above the water table. Water levels in the deep wells may more closely represent the water table during early periods of recharge, and the specific-yield values of 0.34 and 0.29 probably are representative of the stream-channel deposits at the site.

Specific-yield values estimated for the stream-channel deposits correlated well with lithology. The sandy gravel at wells PR-5A, PR-8A, and PR-6A had the largest grain size of sediments encountered in the unit and also had the largest estimate of specific yield of 0.29 to 0.34. Smaller estimates of specific yield of 0.15 at wells PR-2A, PR-7A, and PR-3A of correlated with a reported lithology of sand, gravel, and minor clays. The estimated specific yield of 0.23 at well C-91A correlates with a sequence of sand, gravel, and clay.

Specific-yield values were calculated for the interval of water-level change associated with the Fort Lowell Formation in wells PR-6A, GB-1A, and B-70A. Specific yield estimated from the relation at well PR-6A was calculated as 0.15 and the correlation coefficient was 0.82. Specific-yield estimates from the relations at wells GB-1A and B-70A were calculated as 0.18 and 0.07, respectively, and the correlation coefficient was 0.93. Early water-level changes in this unit also occurred at wells PR-2A, PR-7A, and PR-3A; however, the data collected were inadequate to derive a relation. Specific-yield values were not determined for the Fort Lowell Formation at wells PR-5A or PR-8A because most water-level changes occurred above the unit.

Specific-yield values estimated for the Fort Lowell Formation correlated with lithology. The smallest specific-yield value of 0.07 correlated with a very hard, cemented gravel at well B-70A. Lithology at well PR-6A, which is a gravelly sand and reddish clay, correlated with a larger estimated specific yield of 0.15. A somewhat larger estimate of specific yield of 0.18 correlated with a sequence of cemented gravel and loose sand at well GB-1A.

Values of specific yield estimated for this study compare favorably with previous estimates and values used in ground-water models. Montgomery (1971) used temporal-gravity techniques to estimate specific-yield values at wells about 2 mi west of the study area near Rillito Creek. Estimated values ranged from 0.25 to 0.29 percent and represented composite values for stream alluvium and basin fill in the area. Hanson and Benedict (1994) used values of 0.18 for the upper and lower layers of a ground-water flow model of the area. Davidson (1973) estimated the average specific yield for the upper 500 ft of aquifer in the Tucson Basin to be about 0.15 for the Fort Lowell Formation and Tinaja beds and 0.25 for the stream-channel deposits.

CONCLUSIONS

The temporal-gravity method was used to estimate ground-water storage change for periods between early December 1992 and early January 1994 and to estimate specific-yield values near Rillito Creek near Tucson, Arizona. The method applies Newton’s Law of Gravitation to measure changes in the local gravitational field of the Earth caused by changes in the mass and volume of ground water. Gravity values were measured repeatedly in relation to bedrock at 43 stations in a 6-square-mile study area. The volume of ground water stored in the study area increased during the period of investigation because of recharge through streamflow infiltration along Rillito Creek. Water levels in wells in the flood plain of Rillito Creek rose as much as 30 ft and gravity increased as much as 90 μGal. Water levels declined and gravity decreased near the stream after the last major winter flow, but gravity continued to increase in downgradient areas as ground water flowed away from storage near the stream.

Seasonal distributions of gravity and ground-water storage change were estimated by measuring gravity at each station in relation to bedrock in early March 1993, mid-May 1993, late August 1993, and early January 1994 and subtracting the values measured in early December 1992. Estimated increases in ground-water storage from December 1992 through early March 1993, mid-May 1993, late August 1993, and early January 1994 were calculated as 7,900, 8,000, 6,300, and 3,700 acre-ft, respectively. Ground-water recharge for the study period is estimated to be 10,900 acre-ft using a water-budget approach that accounted for estimated ground-water withdrawals and ground- water flow across the study-area boundaries. Most of the recharge occurred before early March 1993. Distributions of gravity change indicate that downgradient areas at the southern extent of the study area are well connected hydraulically with the part of the recharge area west of Swan Road. A partial barrier to the southward flow of ground water is indicated by distributions of gravity change in the area east of Swan Road near Fort Lowell Road. The contrast in the ability of the aquifer to transmit water downgradient on either side of Swan Road is consistent with geology inferred from well logs and geophysical information.

Water levels and gravity were measured at 10 wells for the purpose of evaluating water level and gravity relations and estimating specific yield. Good correlations between water levels and gravity values at five of the wells allowed for the calculation of specific yield for the interval of water-level change. Specific-yield values for the stream-channel deposits at three well sites ranged from 0.15 to 0.34. Specific-yield values for the Fort Lowell Formation at three well sites ranged from 0.07 to 0.18. Moderate to poor correlations between water levels and gravity at five wells are attributed to ground-water storage changes in a perched aquifer and in the unsaturated zone.

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