PREPARED IN COOPERATION WITH THE
ARIZONA DEPARTMENT OF WATER RESOURCES, METROPOLITAN DOMESTIC WATER IMPROVEMENT DISTRICT, AND TOWN OF ORO VALLEY

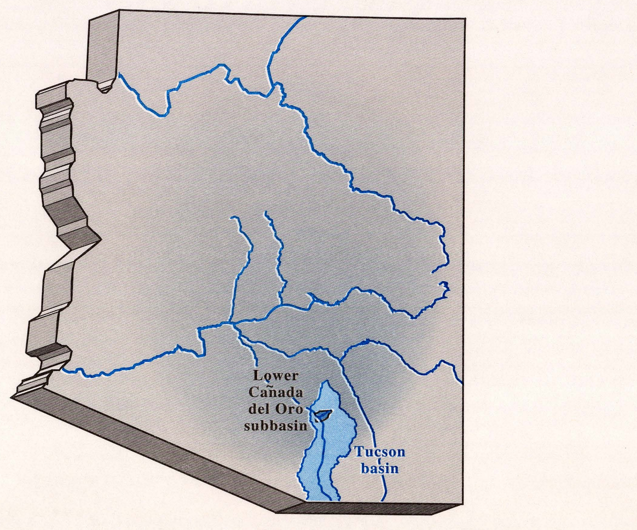

Figure 1. Location of the Lower Cañada del Oro subbasin.

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
gallon (gal)	3.785	liter
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)	0.06309	liter per second

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celcius (°C) as follows:

°C=(°F–32)/1.8

ABBREVIATED GRAVITY UNITS

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

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 the United States and Canada, formerly called Sea Level Datum of 1929. **Altitude**, as used in this report, refers to distance above or below sea level.

Table 1. Estimated average annual ground-water budget, Lower Cañada del Oro subbasin.

Water-budget component and source	Rate, in acre-feet per year
INFLOW:	
Mountain-front recharge[1]:	
Tortolita Mountains	1,880
Santa Catalina Mountains	2,450
Ground-water underflow	5,430
Infiltration along the Cañada del Oro Wash	3,564
Incidental recharge	([2])
TOTAL INFLOW	13,324
OUTFLOW	
Ground-water withdrawals[3]	25,790
Ground-water underflow	0
TOTAL OUTFLOW	25,790
AQUIFER STORAGE CHANGE	-12,466

[1]Hanson and Benedict (1994).
[2]Unknown. Recharge that occurs through downward percolation of excess irrigation water applied to golf courses, parks, and lawns.
[3]Estimated for 1993 (Montgomery and Associates, 1995).

INTRODUCTION

The Lower Cañada del Oro subbasin of the Upper Santa Cruz Basin lies within the Tucson Active Managment Area (TAMA) of the Arizona Department of Water Resources (ADWR) (figs. 1 and 2). Ground water is the primary source of water in the subbasin for the growing communities of the town of Oro Valley, the eastern part of the town of Marana, and the suburbs to the northwest of the city of Tucson. Ground-water demands on the aquifer are causing removal of water from aquifer storage and declining water levels. The ADWR and water providers need accurate water-budget information to assess water-supply management alternatives and mitigate the potential negative consequences of water-level decline. Regional water-supply interests have developed a Northwest Replenishment Program to facilitate development of projects to increase storage in the aquifer and use of renewable water resources to augment the ground-water supply. Information on aquifer-storage properties and the ground-water budget are essential to understand the ground-water system and to design recharge projects in this rapidly developing area of the TAMA. Improved understanding of aquifer-storage properties and the ground-water budget also will contribute to ADWR's TAMA-wide ground-water management efforts including development of programs to achieve a balance of ground-water withdrawal and recharge.

The primary components of the ground-water budget in the Lower Cañada del Oro subbasin are inflow, outflow, and aquifer-storage change. Inflow includes recharge of various types and ground-water underflow from upgradient areas. Outflow includes discharge by wells and ground-water underflow to downgradient areas. Discharge of ground water from wells is the only component of the water budget that can be readily estimated through measurement of withdrawals at public-supply wells and estimation of withdrawals at domestic, agricultural, and stock wells. Accurate estimates of recharge, ground-water underflow, and aquifer-storage change are difficult to obtain using traditional methods. Natural ground-water recharge occurs across a large area and cannot be directly measured. Ground-water underflow, into and out of the basin, can be estimated; however, a high degree of uncertainty is inherent in the estimated values. Aquifer-storage change can be indirectly estimated assuming water-level change is measured and specific yield, which is the amount of water that the aquifer yields per unit change in water level, is known. Indirect estimates of aquifer-storage change using water-level change and specific yield also have a high degree of uncertainty because specific yield is poorly known.

Gravity methods were applied to the Lower Cañada del Oro subbasin from 1996 through 1998 for the purpose of directly measuring aquifer-storage change and indirectly estimating recharge. Direct measurement of aquifer-storage change would greatly improve estimates of the overall ground-water budget through elimination of one of two unknowns. Recharge would be the only unmeasured component. Gravity methods have been developed and applied to measure aquifer-storage change in Arizona basins (Montgomery, 1971; Zohdy and others, 1974; Cole, 1990; Pool and Eychaner, 1995; Pool and Schmidt, 1997). Repeat measurement of gravity at specific sites provides a direct measure of gravity change that has occurred in the period between measurements. Integration of gravity change across a network of sites in the basin provides an estimate of aquifer-storage change for the period. The study was done in cooperation with the Arizona Department of Water Resources, Metropolitan Domestic Water Improvement District, and town of Oro Valley.

Purpose and Scope

Aquifer storage was monitored using gravity methods in the Lower Cañada del Oro subbasin from 1996 through 1998 to determine areas of infiltration and amounts of recharge along the Cañada del Oro Wash after major surface flow and to estimate aquifer-storage change and specific-yield values for the regional aquifer. Both purposes were addressed by periodic monitoring of changes in aquifer storage and water levels at a network of gravity stations and monitor wells. Water levels and gravity also were monitored near an active withdrawal well for several months for the purpose of estimating specific yield of the aquifer within the cone of water-level depression at the well.

Description of Study Area

The study area includes about 50 mi^2 within the Lower Cañada del Oro subbasin, which is an area of alluvial deposition that lies within the northwestern part of the Tucson Basin (fig. 1). The extent of alluvial deposits and the study area is partially bounded by crystalline rocks of the Santa Catalina Mountains on the east and the Tortolita Mountains on the north (fig. 2). The north, west, and south boundaries of the study area are the northern limit of Rancho Vistoso Boulevard, Thornydale Road, and Rillito Creek, respectively. Land-surface altitude ranges from about 2,200 ft above sea level at the southwest boundary of the study area to about 3,100 ft at the base of the Tortolita Mountains. Altitudes of mountain peaks are more than 4,500 ft in the Tortolita Mountains and 9,000 ft in the Santa Catalina Mountains. The Cañada del Oro Wash drains most of the study area; the southeastern part of the study area drains south to Rillito Creek.

The climate in the study area generally is semiarid. Average annual precipitation at Tucson is about 12 in. Precipitation at Tucson during the period of investigation was below average during 1996 and 1997, about 10 in., and slightly above average during 1998, about 13.5 in. (National Weather Service, Tucson office monthly climate reports, accessed January 2, 1999).

HYDROGEOLOGIC FRAMEWORK

Surface Water

Most of the streams in the Lower Cañada del Oro subbasin are ephemeral and flow only after sufficient precipitation. The primary ephemeral streams are the Cañada del Oro Wash and Big Wash (fig. 2). Historical records of flow in the Cañada del Oro Wash are available from three streamflow-gaging stations—at Overton Road, below Ina Road, and about 8 mi north of the study area near Oracle Junction.

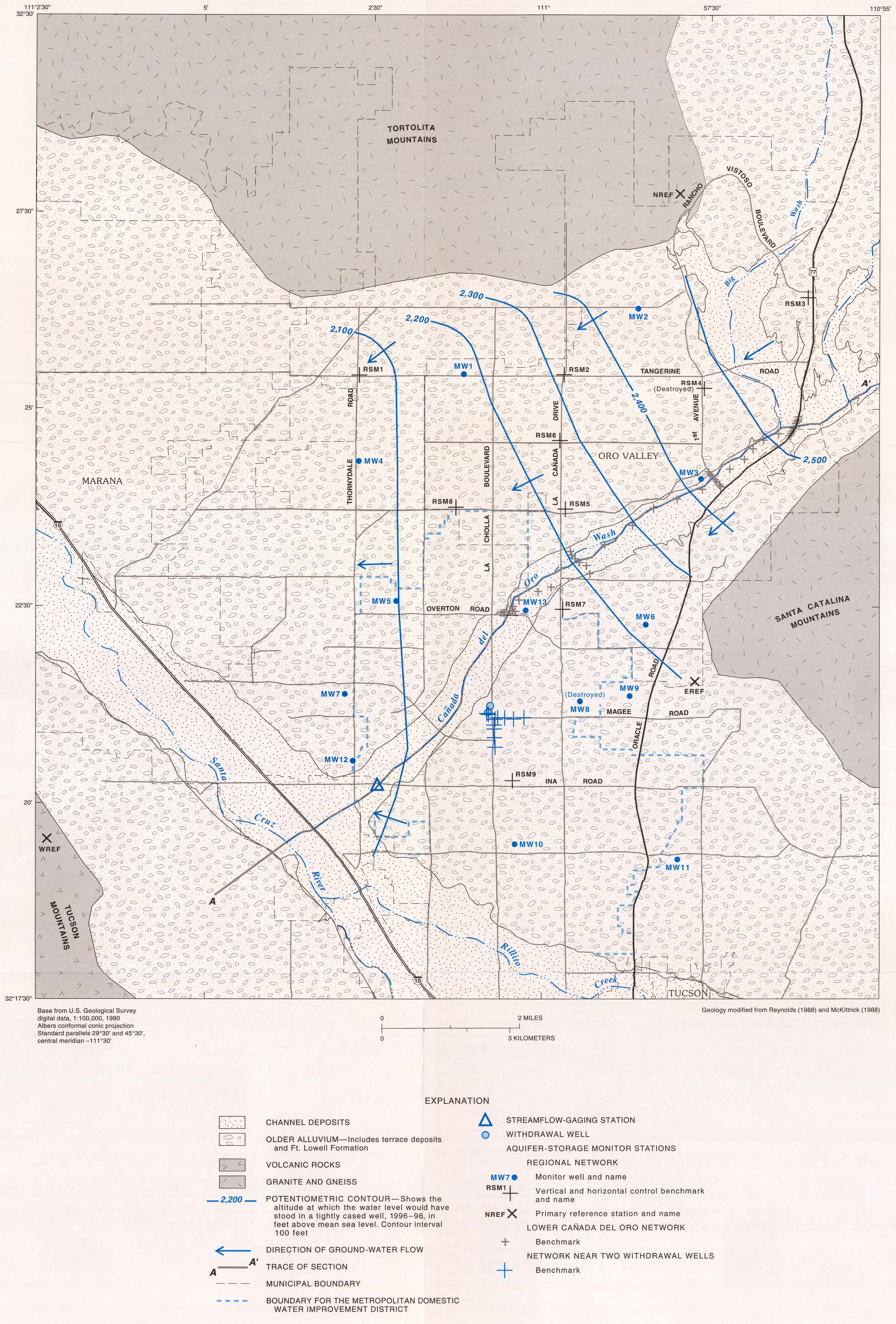

Figure 2. Network of aquifer-storage monitor stations and ground-water conditions, 1996–98, Lower Cañada del Oro subbasin.

The streamflow-gaging station below Ina Road was the only station that was operational during the investigation. Rates of surface flow at the station range from a few cubic feet per second to more than 100 ft^3/s after substantial precipitation. Runoff can occur for a few hours to several days after rainfall, or for longer periods as a result of snowmelt in the Santa Catalina Mountains.

Significant streamflow occurred in the Cañada del Oro Wash below Ina Road on several occasions during the investigation (fig. 3). A large part of the total runoff of 3,168 acre-ft occurred during August 1996, February 1998, and July 1998. The greatest daily runoff of 1,063 acre-ft occurred February 18, 1996. Flow normally occurred for periods of only a few hours, but continuous flow occurred for 2 to 4 days on several occasions. Runoff did not occur from the beginning of the investigation in February 1996 to August 15, 1996. Only 274 acre-ft flowed past the station during March 1997 through January 1998.

Ground Water

Ground water in the Lower Cañada del Oro subbasin occurs in alluvial deposits that fill the structural basin overlying the crystalline rocks of the mountains that include granite, gneiss, and volcanic rocks (figs. 2 and 4). Depths to water range from a few feet along the Cañada del Oro Wash east of Oracle Road to more than 400 ft near the Tortolita Mountains. The primary aquifer includes channel deposits, the Fort Lowell Formation, and the upper Tinaja beds (Davidson, 1973). Channel deposits are primarily sand and gravel within stream channels and beneath the flood plains of streams. The Fort Lowell Formation and upper Tinaja beds are primarily coarse-grained deposits of sand and gravel; thin intervals of silt and clay occur locally. Underlying the units of the primary aquifer are the lower Tinaja beds and Pantano Formation, which are hydraulically connected to the primary aquifer and generally are more consolidated, more structurally deformed, and less permeable than the overlying units. Crystalline rocks that crop out in the mountains around the basin form the boundary of the ground-water system and include granite and gneiss in the Santa Catalina and Tortolita Mountains and volcanic rocks in the Tucson Mountains (fig. 2). The saturated thickness of each alluvial unit is not well defined; however, the greatest saturated thickness, of as much as 200 ft, is in the upper Tinaja beds (Anderson, 1987). Saturation of the Fort Lowell Formation is limited to a few tens of feet near the subbasin axis. Saturation of the channel deposits may occur locally near the mountains where the aquifer is thin and depths to water are less than 100 ft, especially after water levels rise in response to streamflow infiltration.

The ground-water budget in the subbasin is not well defined. Most recharge to the ground-water system occurs naturally as ground-water underflow from the north, infiltration of runoff in stream channels near the mountains (mountain-front recharge), and infiltration of runoff in major stream channels throughout the subbasin (fig. 2, table 1). Some incidental recharge probably occurs through downward percolation of excess irrigation water applied to golf courses, parks, and lawns. Ground-water discharges from the subbasin as ground-water underflow to the west and as withdrawals from wells (fig. 2). A ground-water deficit exists in the subbasin on the basis of measured ground-water withdrawals that are in excess of estimated rates of recharge and on the basis of declining water levels in wells, which indicate removal of water from aquifer storage.

The rate of ground-water recharge in the subbasin is difficult to quantify but has been estimated through indirect means. Rates of natural recharge probably vary significantly on an annual and seasonal basis in response to changes in climate. Recent estimates of average annual natural recharge by Hanson and Benedict (1994) include 5,430 acre-ft of ground-water underflow, 3,564 acre-ft of streamflow infiltration along the Cañada del Oro Wash, 188 acre-ft of infiltration along each mile of the front of the Tortolita Mountains, and 175 acre-ft along each mile of the front of the Santa Catalina Mountains. Direct infiltration of precipitation elsewhere in the subbasin probably is insignificant as a source of recharge. Mountain-front recharge along 10 mi of the base of the Tortolita Mountains and along 14 mi of the base of the Santa Catalina Mountains is 1,880 and 2,450 acre-ft/yr, respectively. Total average annual natural recharge in the study area is about 13,324 acre-ft on the basis of data from Hanson and Benedict (1994). Recharge probably was below average during below-average precipitation of 1996 through 1997 but above average during the above-average precipitation of 1998.

Discharge from the ground-water system was estimated on the basis of measured ground-water withdrawals from wells and estimated ground-water underflow out of the subbasin. Evapotranspiration from the ground-water system in the study area probably is insignificant. Ground-water underflow is difficult to estimate; however, most underflow that occurred before water was withdrawn from wells probably is captured by wells in the current system. Ground-water withdrawal in the study area during 1993 from municipal, private, and commercial wells was about 25,790 acre-ft (Montgomery and Associates, 1995). The annual ground-water deficit in the study area is about 12,500 acre-ft/yr minus the amount of incidental and artificial recharge on the basis of the estimated rates of natural recharge by Hanson and Benedict (1994) and ground-water withdrawals during 1993.

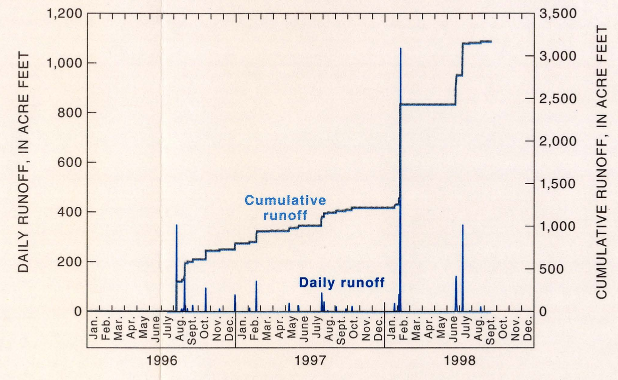

Figure 3. Runoff at the streamflow-gaging station on the Cañada del Oro Wash below Ina Road, 1996–98.

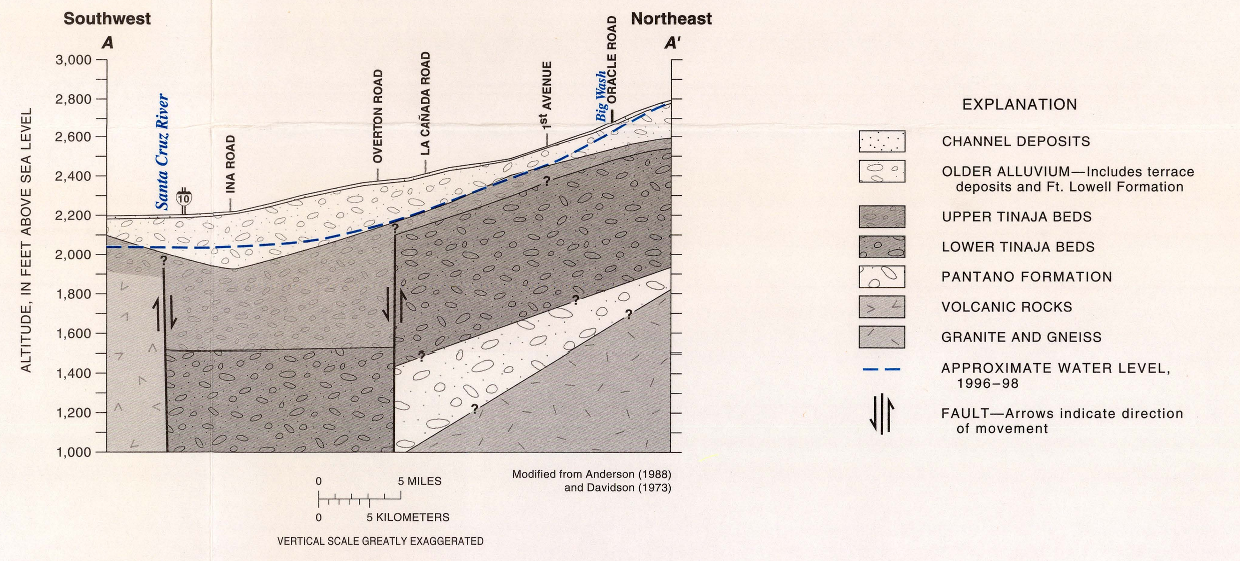

Figure 4. Generalized hydrogeologic section along Cañada del Oro Wash.

APPROACH

Theory

Newton's laws of gravitation are the theoretical basis for application of gravity surveys to measurement of aquifer-storage change. Newton's laws 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 (mGal), 1 mGal = 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 typically 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 the use of the Bouguer slab equation is less than 5 percent for a horizontal disk-shaped body that has a radius 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. The Bouguer slab equation is not adequate for approximation of the gravitational effect of mass change near the cone of depression around a pumping well or in areas where a thick unsaturated zone receives significant amounts of water from streamflow infiltration.

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 in grams per cubic centimeter, $\Delta\rho$, and thickness of the interval of storage change in feet, b. 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 as a result of changes in the altitude of the gravity station. Measurement of aquifer-storage change in areas of land subsidence requires accurate monitoring of the vertical position of the gravity station.

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

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

where

S = aquifer-storage coefficient, for the interval of water-table change, b 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:

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

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

$$S = \Delta g/(12.77b). \tag{7}$$

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):

$$\int_s \Delta g ds = 4\pi GM, \tag{8}$$

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:

$$M = 1/(2\pi G)\iint \Delta g(x,y)dxdy, \tag{9}$$

where

$dxdy$ = an infinitesimally small surface area, and
$\Delta g(x,y)$ = gravity change for the surface area.

GROUND-WATER FLOW SYSTEM AND AQUIFER-STORAGE MONITORING NETWORKS

AQUIFER-STORAGE CHANGE IN THE LOWER CAÑADA DEL ORO SUBBASIN, PIMA COUNTY, ARIZONA, 1996–98

By D.R. Pool