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

Survey Technique

Application of gravity theory to the measurement of temporal changes in water mass is conceptually simple. The relative difference in observed gravity is measured between a gravity station on stable bedrock or reference station where mass change is assumed to be minimal and gravity stations overlying an aquifer in which mass change occurs. Reference stations must be sufficiently distant from the aquifer so that the gravitational effects of the mass change in the aquifer are negligible. Possible gravity changes at reference stations were evaluated for this study by monitoring differences in gravity among three reference stations. One of the reference stations was found not suitable as a reference because gravity change relative to the other reference stations was much larger than the survey error.

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 reference station on bedrock, to the stations in the aquifer area that have unknown values and then returning to the bedrock base station to determine closure error. Several closed loops should be made during a survey for the purpose of evaluating the repeatability and accuracy of the measured differences in gravity. Stations are surveyed again after an arbitrary period of time to determine changes in observed gravity resulting from changes in the distribution of water mass.

A Lacoste and Romberg Model D gravity meter (D-127) 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, which is 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 using several algorithms. An algorithm developed by Longman (1959) was used in this study. Surveys were made 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-instrument drift of short duration. 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 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 but 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 spring and capacitance system to stabilize at each station.

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 gravitational 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 near-surface materials affect the absolute value of gravity by an amount equivalent to the local vertical gradient of gravity—about −0.090 mGal/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 gravity stations relative to reference stations was monitored using the Global Positioning System (GPS; Remondi, 1985) to determine possible changes in altitude.

Nonaquifer-mass change can occur through local erosion, deposition, anthropogenic manipulation of the land surface, and storage change above the water table. 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 in tunnels.

Gravity-Station Networks

Three networks of gravity stations were constructed in the Lower Cañada del Oro subbasin for the purpose of monitoring changes in aquifer storage. A regional network of widely spaced stations was designed to monitor changes across the subbasin and included several stations at inactive wells where water levels were monitored and relations between gravity and water levels were developed (fig. 5). A network of closely spaced gravity stations near the Cañada del Oro Wash was designed to monitor changes after streamflow infiltration (fig. 7). A network of closely spaced gravity stations near two withdrawal wells was designed to measure changes resulting from the formation of a cone of depression around the wells (fig. 9). Gravity at each of the networks was referenced to three primary-reference gravity stations—NREF, WREF, and EREF—on or near crystalline bedrock where changes in gravity caused by aquifer-storage change were expected to be minimal (fig. 5). Two stations, NREF and WREF, were on crystalline rock at the base of the Tortolita and Tucson Mountains, respectively. EREF was on alluvium near the base of the Santa Catalina Mountains because exposures of crystalline rock were not accessible.

The vertical and horizontal positions of all stations were surveyed relative to the primary-reference stations with an accuracy of about 1 cm (0.39 in.) using differential GPS technology and geodetic GPS receivers during March 1996. Two stations, MW6 and MW12, were selected for quarterly GPS surveys of position relative to the three primary-reference stations for the purpose of monitoring changes in position, primarily vertical changes, that can cause changes in gravity. A few other stations were resurveyed as well during the study. Variations of more than 1 cm (0.39 in.) in the relative vertical or horizontal position did not occur among the stations.

Differences in gravity between the primary-reference stations and stations in the regional and Cañada del Oro networks were surveyed on a quarterly basis from February 1996 to October 1998. Data were not collected from October 1996 through June 1997 because the instrument was being repaired. A total of eight surveys were made of the regional and Cañada del Oro networks. Differences in gravity between WREF and stations in the network near the withdrawal wells were surveyed frequently during June through November 1998.

Local-reference stations were designated within the Cañada del Oro network and the network near the withdrawal well for the purpose of facilitating the speed of the surveys. Gravity at each network station relative to gravity at the primary-reference stations was determined using two surveys. One survey measured gravity at each network station relative to gravity at the local-reference station and another survey measured gravity at the local-reference station relative to gravity at one or more primary-reference stations. Four local-reference stations were designated within the Cañada del Oro network. One local-reference station was designated for the network near the withdrawal wells.

Each network survey comprised subsurveys of 5 to 8 stations that included at least 2 measurements at each network station and at least 3 measurements at a primary-reference station or local-reference station. Accuracies of subsurveys generally were determined by the linearity of drift rates during the surveys. Accuracies of measured differences in gravity among stations in a subsurvey were generally better than ±0.004 mGal on the basis of the standard deviations of three or more measured differences in gravity. Subsurveys that displayed nonlinear drift rates and high variations in repeated gravity differences between stations were discarded and resurveyed. Subsurveys of the regional and Cañada del Oro networks included a reference station and one or more stations in common with another subsurvey. Gravity at the local-reference stations within the the Cañada del Oro network was measured relative to the EREF and NREF stations during the regional-network survey. Most of the quarterly surveys also included an additional subsurvey that directly measured the difference in gravity between the local reference stations and the reference stations EREF and NREF. Gravity at the network near the withdrawal wells was measured relative to gravity at WREF using a subsurvey that included three stations in common with the regional network.

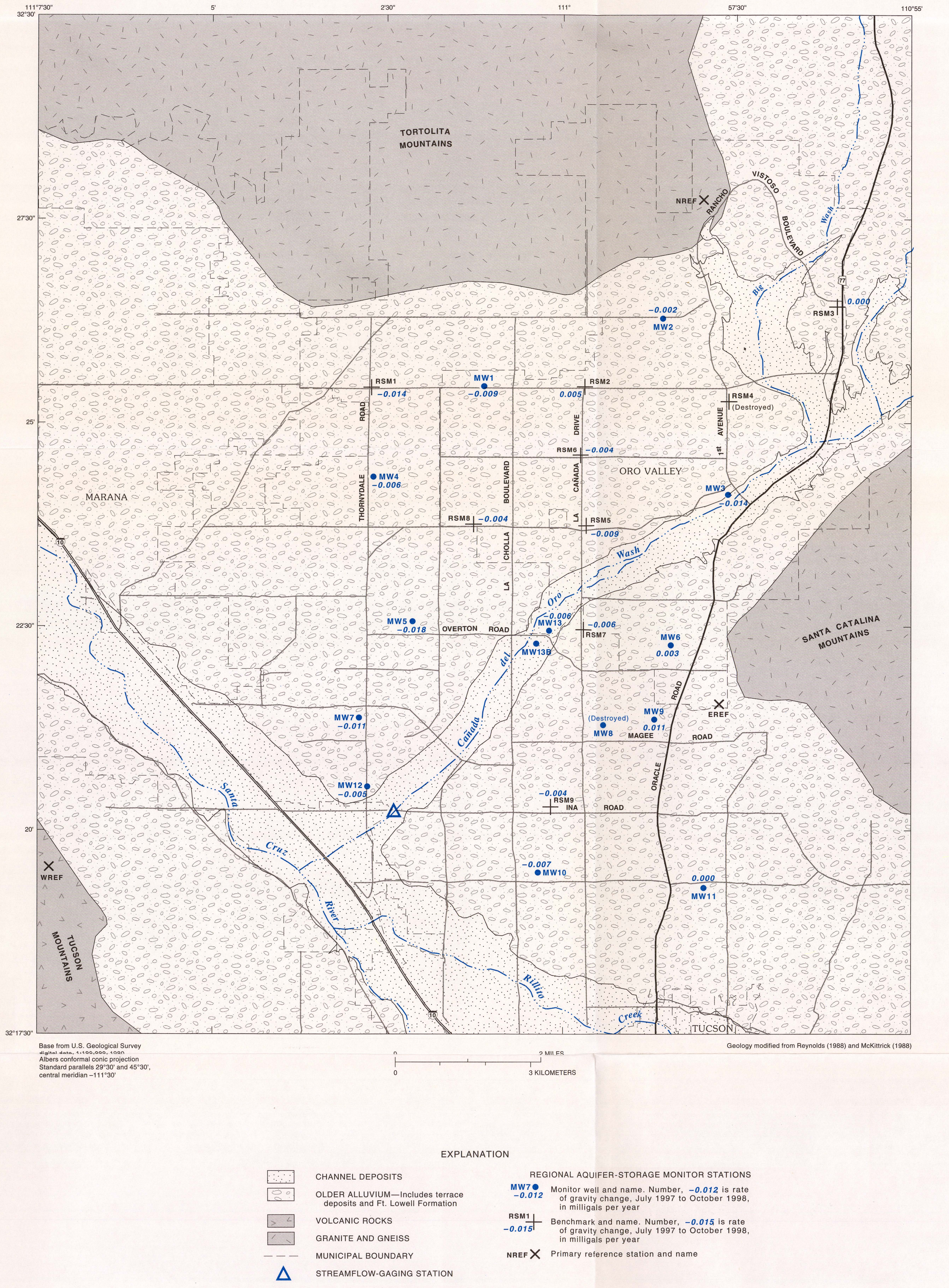


Figure 5. Regional network of aquifer-storage monitor stations and rate of gravity change, July 1997 to October 1998.

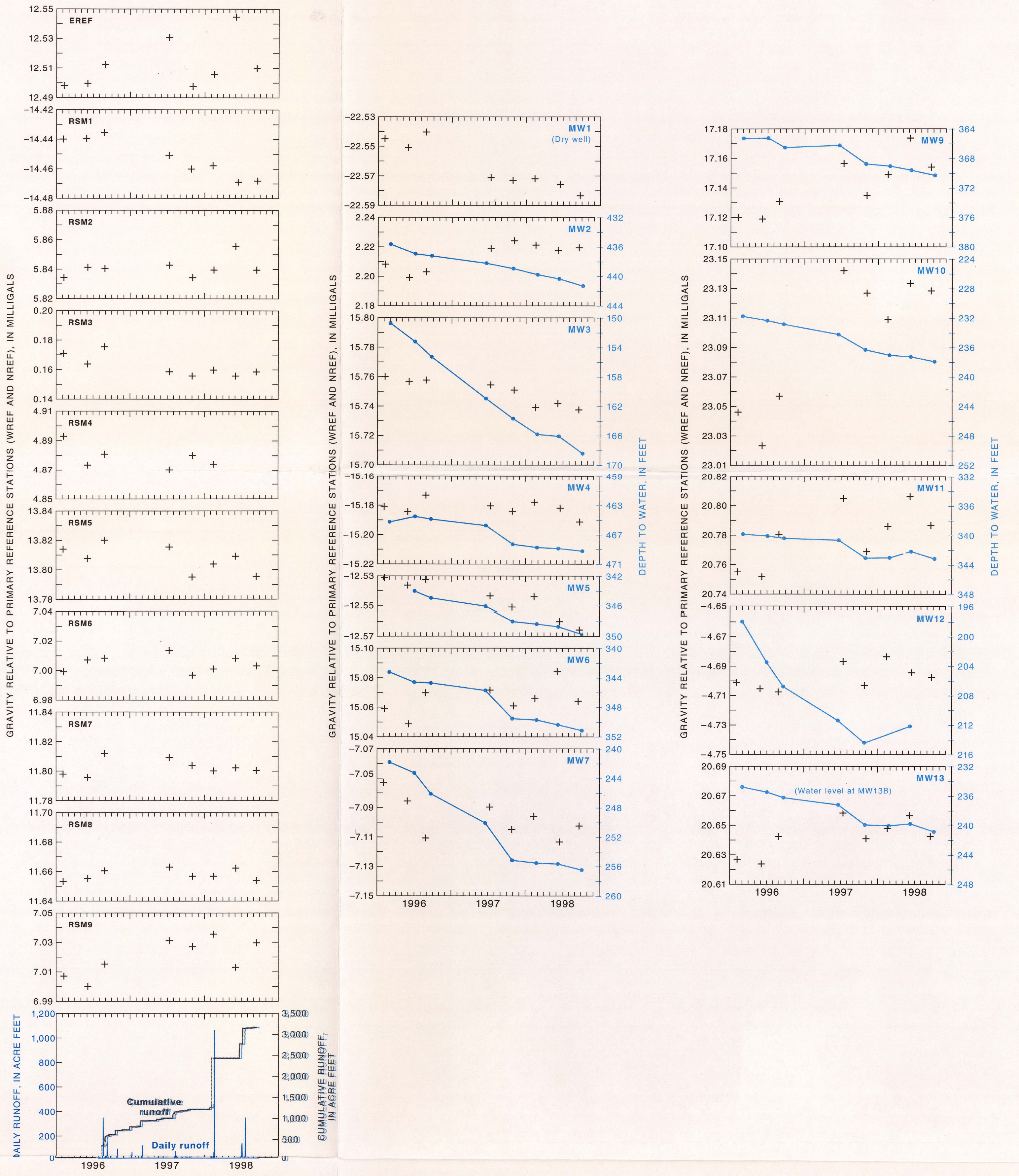


Figure 6. Gravity and water levels at regional aquifer-storage monitor stations and monitor wells and runoff at the streamflow-gaging station below Ina Road, February 1996 through October 1998. Note gap in gravity data during time of instrument repair, October 1996 to June 1997. Gravity data collected after June 1997 should be considered separate data set from data collected prior to that time.

RESULTS

Regional Network

Twenty-two gravity stations were established throughout the Lower Cañada del Oro subbasin to monitor regional changes in aquifer storage and estimate specific yield of the aquifer (fig. 5). The network included 13 stations at monitor wells, MW1 through MW13, where water levels also were measured. Obstructions in wells prevented water-level measurements at MW1 and MW13. Water levels at a nearby well, MW13b, were measured as a replacement for MW13. A well in which water levels could be measured was not available near MW1. The network included nine stations at existing and newly constructed vertical- and horizontal-control benchmarks—RSM1–RSM9. Two stations, MW8 and RSM4, were destroyed by construction equipment during the investigation.

Losses in aquifer storage occurred from February 1996 to October 1998 throughout the Lower Cañada del Oro subbasin on the basis of 4 to 18 ft of water-level decline in the monitor wells (fig. 6). Water levels generally declined 4 to 6 ft throughout the middle part of the study area; however, declines were greater near the northeast margin of the study area at station MW3 and at the southwest margin of the study area at stations MW7 and MW12. The greatest decline, 18 ft, occurred at MW3 near the Cañada del Oro Wash at First Avenue. Declines of about 14 and 16 ft occurred at MW12 and MW7, respectively, at the southwestern boundary of the study area.

Rates of water-level decline during the study were nearly linear in most of the monitor wells, but significant variations correlate with runoff. The greatest rate of water-level decline at most of the wells occurred from July to November of 1997, which was a period of low runoff (fig. 3). Rates of water-level decline generally were lowest during November 1997 to July 1998, which corresponds to a period of high runoff during February and July 1998. Variation in the rate of water-level decline in relation to runoff could be caused by variations in ground-water withdrawals by wells or recharge from infiltrated runoff.

Significant variations in gravity relative to gravity at the primary-reference stations occurred at most of the regional aquifer-storage monitoring stations (fig. 6). Significant long-term variations occurred at many stations; variations at other stations were dominated by quarterly changes. Apparent changes in gravity that occurred between September 1996 and July 1997 (fig. 6), during the time of instrument repair, were caused by a combination of instrument recalibration and variations in gravity. The greatest change after instrument recalibration was observed at MW10 where gravity increased by more than 0.080 mGal relative to gravity at NREF. Some or all of the increase in gravity may have been caused by infiltration of streamflow in the adjacent wash, but the magnitude of increase is suspiciously large. Changes at other stations after instrument recalibration are not as apparent, but observed changes during the period September 1996 to July 1997 must not be interpreted as resulting only from changes in aquifer storage. As a result, surveys before and after the instrument repair and recalibration must be considered as separate data sets. Changes caused by instrument recalibration may be resolved in the future after comparison of other surveys that were made before and after the recalibration.

Gravity at stations in the regional network generally varied about 0.030 mGal (fig. 6) relative to gravity at the primary-reference stations. Most of the stations display long-term decreases in gravity, which indicate decreases in aquifer storage; however, large quarterly variations were common at many stations. The variations are most likely caused by increases in ground-water storage after precipitation, runoff infiltration, and recharge. Increases in gravity that occurred at most monitor wells between November 1997 and July 1998 correlate with runoff and decreases in the rate of water-level decline or water-level recovery (fig. 6). The lack of significant water-level recovery associated with increases in gravity may result from increases in ground-water storage in the unsaturated zone and water levels that are not representative of the water table.

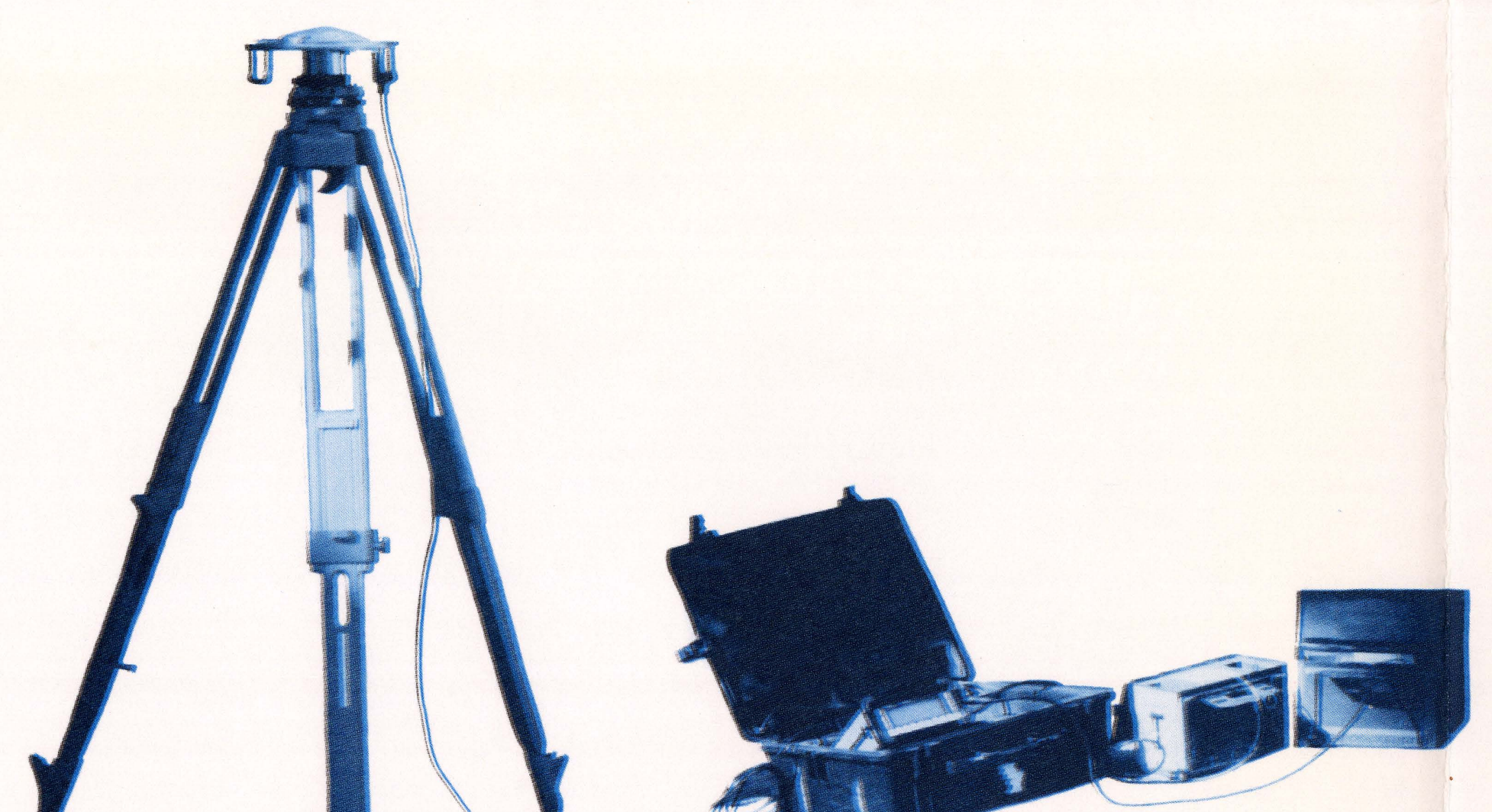
After November 1997, the greatest change in gravity—0.020 mGal or more—occurred at stations MW6, MW9, MW10, MW11, MW12, MW13, RSM2, RSM5, RSM6, and RSM9. Most of these stations are in the southeastern part of the study area near the Santa Catalina Mountains. Only one station (RSM8) southeast of the Cañada del Oro Wash did not display large gravity variations; although moderate variations of about 0.010 mGal at RSM7 display a pattern similar to that at the other southeast stations. The proximity of the Santa Catalina Mountains to the southeast stations may have resulted in greater precipitation and infiltration of runoff; however, gravity variation at many of the southeast stations may have been biased by infiltration along major ephemeral streams near MW6, MW10, MW11, and along the Cañada del Oro Wash near MW13.

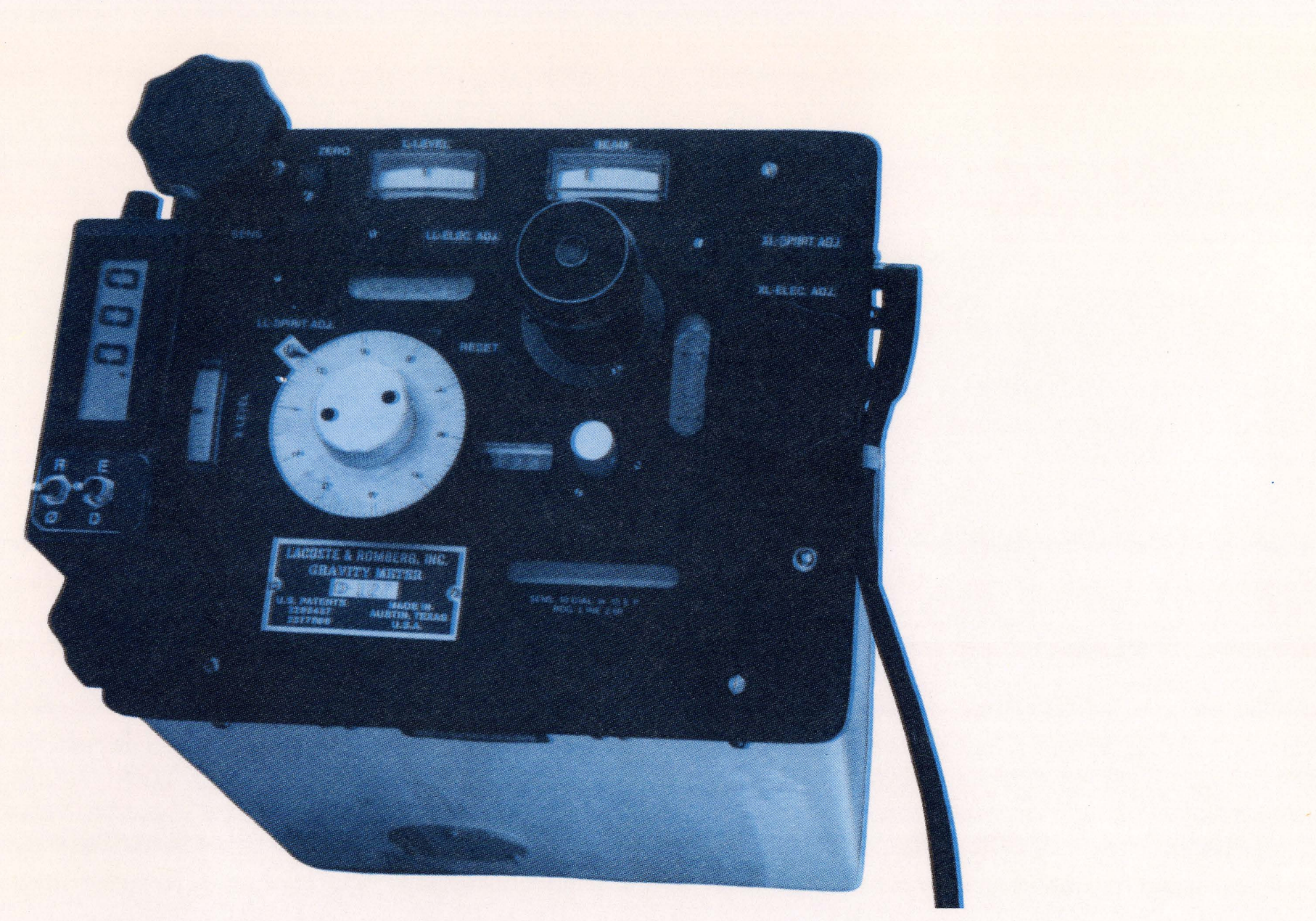
Significant changes in gravity relative to gravity at NREF also were observed at EREF from November 1997 through September 1998 (fig. 6) on the basis of several subsurveys that directly measured the difference in gravity between the two stations. Several indirect surveys that included one of the primary-reference stations and a common network station indicated similar changes at EREF relative to WREF. Most of the changes are assumed to have occurred at EREF and not at NREF and WREF because EREF is not on crystalline rock. Gravity at EREF during late February to June 1998 was about 0.030 mGal greater than during November 1997; however, gravity decreased about 0.008 mGal during June to October 1998. The measured changes are consistent with increases in aquifer storage near the mountains that may have occurred after infiltration of runoff during February and July 1998. Observation of changes in gravity at EREF indicate that changes in aquifer storage near the mountains can be significant and may result in undetected changes in gravity at stations on crystalline rock near the aquifer. The gravitational effect of changes in aquifer storage at WREF and NREF probably are small because the edge of the aquifer is more than several hundred feet from the stations. Uncertainty of changes in gravity at reference stations in areas of crystalline rock cannot be resolved without repeated measurements of the absolute value of gravity at the stations. These measurements, however, were not within the scope of this investigation.

Small variations in gravity of about 0.010 mGal or less at regional aquifer-storage monitoring stations MW1, MW2, RSM1, RSM3, and RSM7 probably are indicative of areas where little recharge occurred during the study. A lack of a long-term change in gravity at RSM3 and MW2 indicate that the local ground-water system is in equilibrium with respect to inflow and outflow, the aquifer is not present in the area, or the storage capacity of the aquifer is low. Declining water levels at MW2 probably occur in an aquifer that has low storage capacity. Drillers' logs are not available for MW2. The well, however, is near crystalline bedrock outcrops in the Tortolita Mountains.

Regional changes in aquifer storage can be estimated through integration of gravity change throughout the subbasin and conversion to mass and volume of water using equation 9. Changes can be estimated for the period between each quarterly survey; however, many quarterly changes are approximately equal to or less than the accuracy of surveys, ±0.004 mGal, and regional integration of the gravity change for such changes in aquifer storage would not yield a meaningful value. A more accurate estimate of average rates of aquifer-storage change can be derived from long-term trends in gravity.

Rates of change in aquifer storage from July 1997 to October 1998 were estimated by calculating a best-fit linear trend through the quarterly gravity data at each station in the regional network and integrating the change across the network. Rates of gravity change ranged from decreases of 0.018 mGal/yr at MW5 to increases of 0.011 mGal/yr at MW9 (fig. 5). The average rate of change was a decrease of about 0.003 mGal/yr. Rates of gravity change can be grouped into three areas—west, north, and southeast. The greatest rates of decrease in gravity occurred at stations near the west margin of the study area where decreases in gravity averaged about 0.011 mGal/yr. Rates of change at stations north of the Cañada del Oro Wash and east of La Cholla Boulevard had an average decrease of about 0.003 mGal/yr. Stations southeast of the Cañada del Oro Wash had the lowest average rate of decrease—about 0.001 mGal/yr. Trends of increasing gravity occurred at MW6, MW9, MW11, and EREF, which are stations nearest the Santa Catalina Mountains. Integration of gravity change throughout the study area results in an average loss in aquifer storage of about 9,500 acre-ft/yr. This value is similar to the estimate of 12,500 acre-ft/yr minus incidental and artificial recharge that was derived using water-budget methods. The estimate from this investigation does not include an increase in storage that occurred along the Cañada del Oro Wash during 1998.


Global Positioning System equipment


Gravity meter

AQUIFER-STORAGE CHANGE AT THE REGIONAL NETWORK OF MONITORING STATIONS

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

By D.R. Pool