Prepared in cooperation with The Nature Conservancy

Gravity Change from 2014 to 2015, Sierra Vista Subwatershed, Upper San Pedro Basin, Arizona

By Jeffrey R. Kennedy

Open File Report 2016-1155

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Director

U.S. Geological Survey, Reston, Virginia: 2016

Suggested citation:
Kennedy, J.R., 2016, Gravity change from 2014 to 2015, Sierra Vista Subwatershed, Upper San Pedro Basin, Arizona: U.S. Geological Survey Open-File Report 2016–1155, 15 p., http://dx.doi.org/10.3133/ofr20161155.

ISSN 2331-1258 (online)

Acknowledgments

Assistance with GPS data collection from The Nature Conservancy volunteers is gratefully acknowledged. Staff at Walnut Gulch Experimental Watershed and the U.S. Army Electronic Proving Ground provided assistance with GPS base-station deployments. Michael Landrum, U.S. Geological Survey, and Brittney Marimow, University of Arizona, assisted with gravity surveys.

Contents

Figures

Tables

Conversion Factors

International System of Units to Inch/Pound

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Acceleration	
microgal (μGal)	10	nanometer per second squared (nm/s^2)
microgal (μGal)	0.328 × 10-9	feet per second squared (ft/s^2)

Datum

Vertical coordinate information is referenced to the Geodetic Reference System of 1980 ellipsoid.
Horizontal coordinate information is referenced to the North American Datum of 1983(2011) epoch 2010.00.

Gravity Change from 2014 to 2015, Sierra Vista Subwatershed, Upper San Pedro Basin, Arizona

By Jeffrey R. Kennedy

Abstract

Relative-gravity data and absolute-gravity data were collected at 68 stations in the Sierra Vista Subwatershed, Upper San Pedro Basin, Arizona, in May–June 2015 for the purpose of estimating aquifer-storage change. Similar data from 2014 and a description of the survey network were published in U.S. Geological Survey Open-File Report 2015–1086. Data collection and network adjustment results are presented in this report, which is accompanied by a supporting Web Data Release (http://dx.doi.org/10.5066/F7SQ8XHX). Station positions are presented from a Global Positioning System campaign to determine station elevation.

Introduction

The Earth's gravitational field, as described by Newton's law of universal gravitation, varies temporally as a result of changes in subsurface and atmospheric mass. In groundwater systems, changes in water storage in unconfined aquifers or in the unsaturated zone between an aquifer and the land surface cause changes in the magnitude of Earth's gravity. Measurements of changes in gravity have proven useful for many applications, including mapping aquifer storage change (Pool and Anderson, 2008) and determining specific yield (Pool and Eychaner, 1995). Previous gravity surveys to monitor aquifer storage change were conducted in the Sierra Vista Subwatershed of the Upper San Pedro Basin from 2005 to 2010 (Kennedy and Winester, 2011). The gravity network was modified in 2014 to better capture changes in aquifer storage in a smaller, more focused network in and around the city of Sierra Vista (Kennedy, 2015). Compared to earlier surveys, additional stations were located along Charleston Road, to the northeast of Sierra Vista, to better capture (1) the evolution of the cone of depression associated with groundwater pumping (Schmerge and others, 2009; Lacher and others, 2014) and (2) the increasing aquifer storage resulting from wastewater recharge at the City's Environmental Operations Park (just west of absolute-gravity station EOP).

Gravity data are reported in units of microgals (µGal). The gal is defined as 1 centimeter per second squared (cm/s^2), or about 1/1,000th of Earth's gravitational field. One µGal is about 1×10^{-9}, or 1 part per billion, of Earth's gravitational field. If the water table in an unconfined aquifer moves vertically up and down without significant horizontal flow (owing to groundwater mounding or pumping, for example), the horizontal infinite-slab model is appropriate to directly convert gravitational units (that is, acceleration in µGal) to an equivalent thickness of free-standing water (Pool, 2008). This model, also known as the Bouguer infinite-slab slab model, indicates that 41.9 µGal of gravity change is equivalent to 1 meter (m) of water in the subsurface, regardless of aquifer or unsaturated-zone porosity (Torge, 1989). The gravity method thus has the advantage of not being sensitive to aquifer porosity because it directly measures the change in the mass of water stored in the aquifer.

In contrast, water levels measured in wells require a porosity estimate to convert the measured change in water level to the amount of water stored in the aquifer; a high-porosity aquifer may store a large amount of water with a relatively small change in water level, whereas a low-porosity aquifer may show a much larger change in water level for the same change in storage. Porosity can be difficult or impossible to measure over a representative portion of the aquifer; therefore, storage-change estimates based on water-level changes alone typically have high uncertainty.

Purpose and Scope

This report presents gravity and Global Positioning System (GPS) data collected in 2015, along with a comparison of 2015 gravity data to previously published data collected in 2014 (Kennedy, 2015). Gravity data were collected using relative- and absolute-gravity meters, and final results were obtained by network adjustment. GPS data were collected to provide survey-grade station positions that can be used in the future to determine and correct for station vertical motion. Gravity change from 2014 to 2015 provides an estimate of aquifer storage change over this period based on the horizontal infinite-slab approximation of subsurface mass change.

Gravity Data

Gravity data were collected using a combination of relative- and absolute-gravity meters. Throughout the report, combined absolute- and relative-gravity stations (referred to as absolute-gravity stations) are denoted by capitalized station names, and relative-only gravity stations are denoted by lowercase station names. Data are provided as three products:

1. Observed absolute-gravity values;
2. Relative-gravity differences between stations; and
3. A single, network-adjusted gravity value at each station.

Absolute-gravity data were collected at 14 stations during the week of May 18–22, 2015, using a Micro-g Lacoste, Inc. A-10 absolute-gravity meter. Additional details about the network and absolute-gravity stations are provided in Kennedy (2015). Time-series plots of the observed absolute-gravity values are shown in figure 1.

Relative-gravity data consist of the difference in gravity between two stations. Because the relative-gravity meter is continually drifting (that is, the zero reference point changes continually), individual observations at a station cannot be used directly. Instead, only the gravity difference between two stations observed in relatively quick succession is used (Kennedy and Ferré, 2016). Relative-gravity observations are made between absolute-gravity stations and the other stations in the network so that all stations share a common datum (the datum is established by the absolute-gravity observations). In this way, relative- and absolute-gravity observations are similar to the relative height differences and known elevation benchmarks that comprise a leveling survey.

Relative-gravity data were collected at 54 stations over 10 days between May 27, 2015, and June 25, 2015, using Zero Length Spring, Inc. Burris relative-gravity meter no. B44. In total, 179 relative-gravity differences were observed. Additional detail about the relative-gravity network is provided in Kennedy (2015). Relative-gravity-meter drift was removed from the observations by modeling drift as a continuous function of time (Kennedy, 2015; Kennedy and Ferré, 2016). Relative-gravity observations are combined with absolute-gravity observations using a least-squares network adjustment procedure to determine a single, best-fit value at each station. Absolute-gravity data can be used as stand-alone time series, or they can be included in the network adjustment with nonzero uncertainty. In the latter case, the network-adjusted value will differ from the observed value.

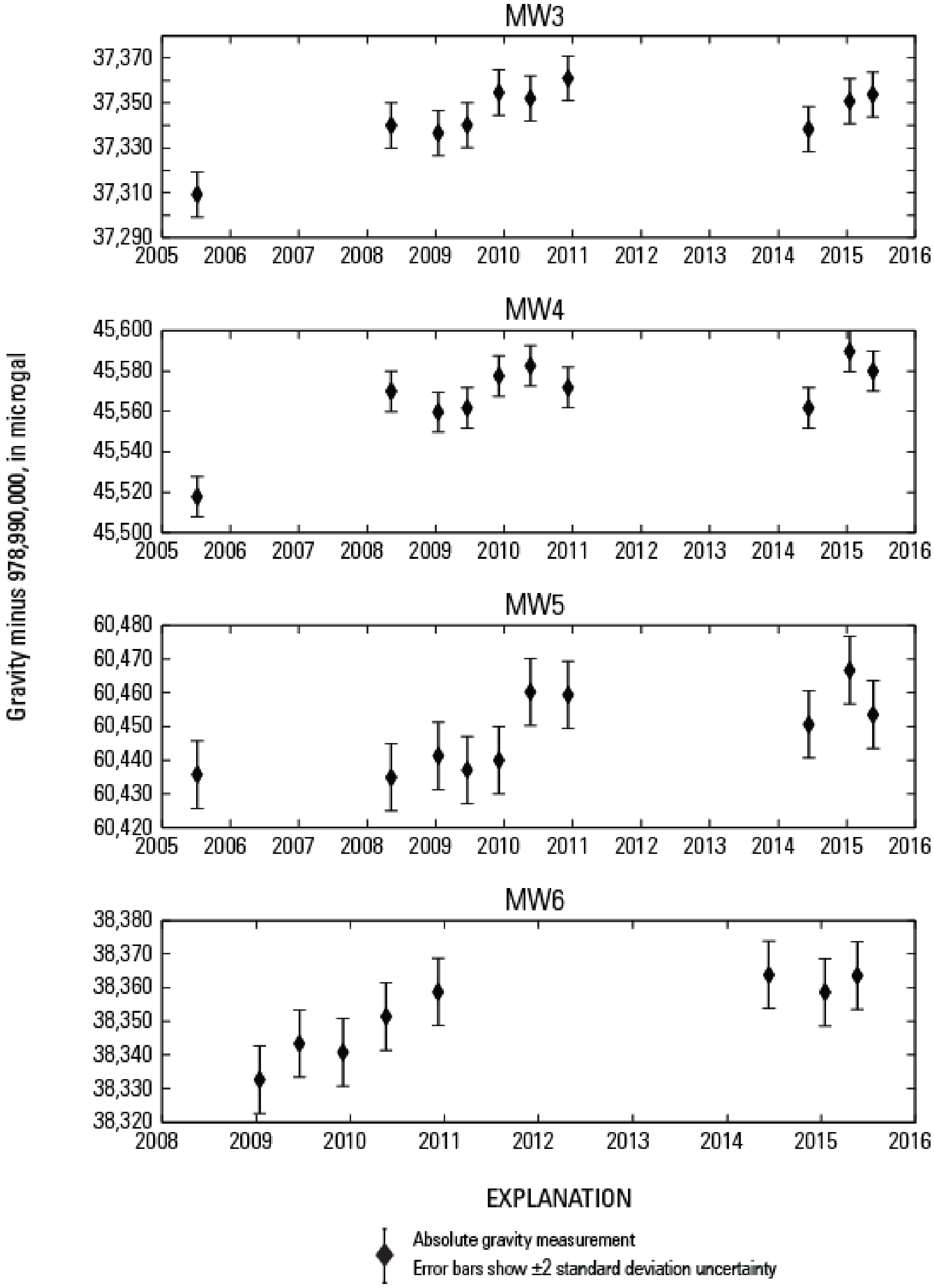

Figure 1. Time-series plots showing gravity change in the Sierra Vista Subwatershed, Upper San Pedro Basin, Arizona, measured using an absolute-gravity meter.

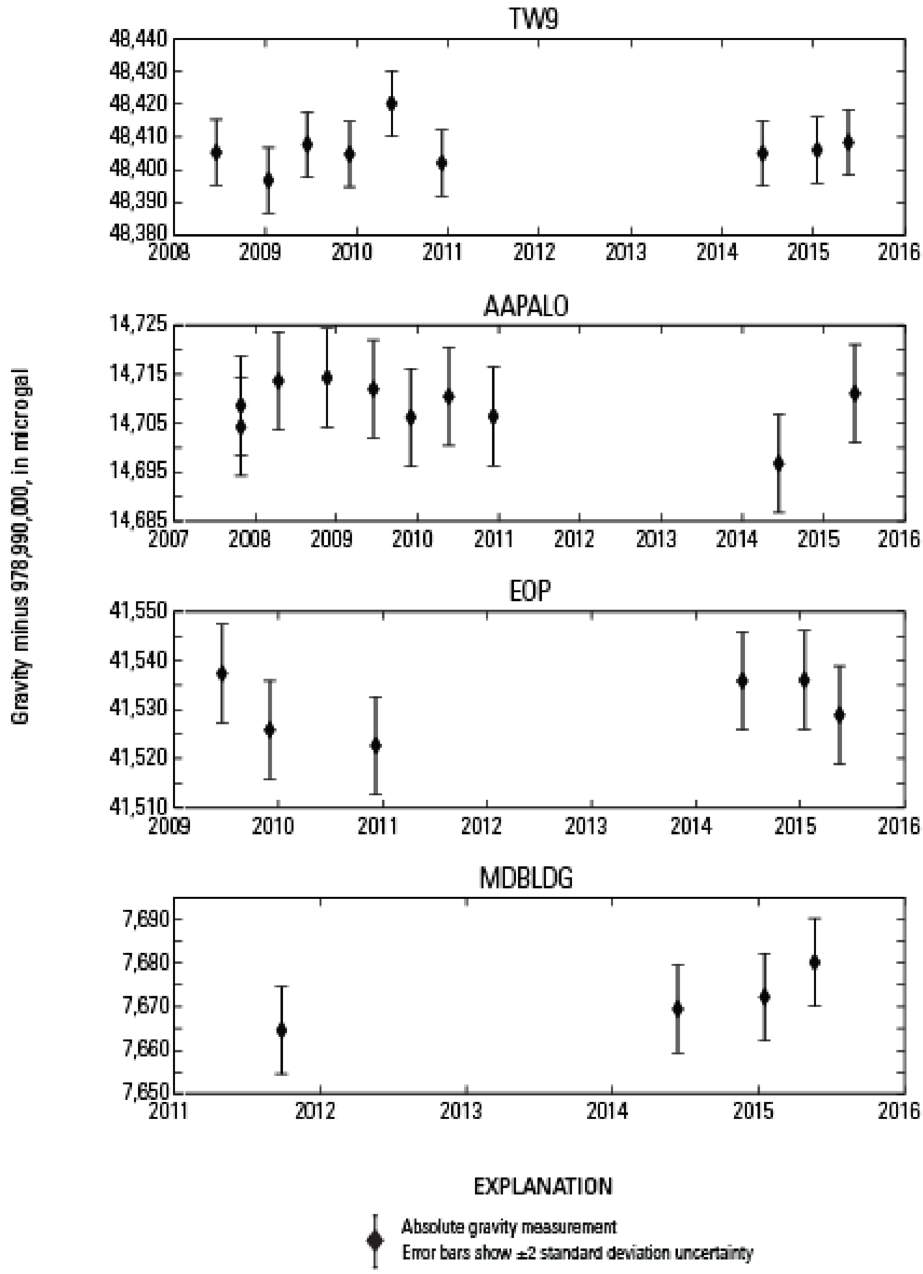

Figure 1. Time-series plots showing gravity change in the Sierra Vista Subwatershed, Upper San Pedro Basin, Arizona, measured using an absolute-gravity meter.—Continued

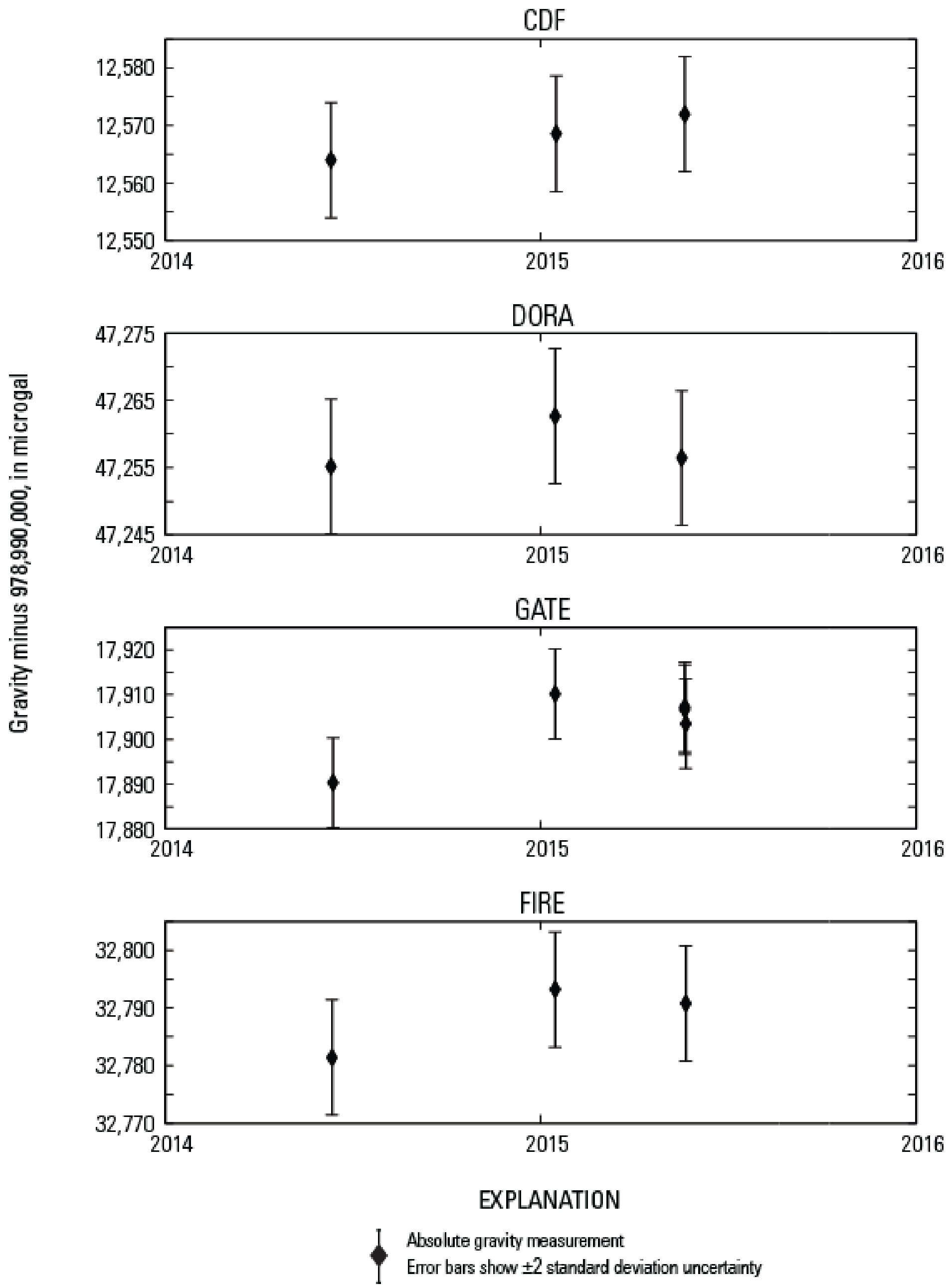

Figure 1. Time-series plots showing gravity change in the Sierra Vista Subwatershed, Upper San Pedro Basin, Arizona, measured using an absolute-gravity meter.—Continued

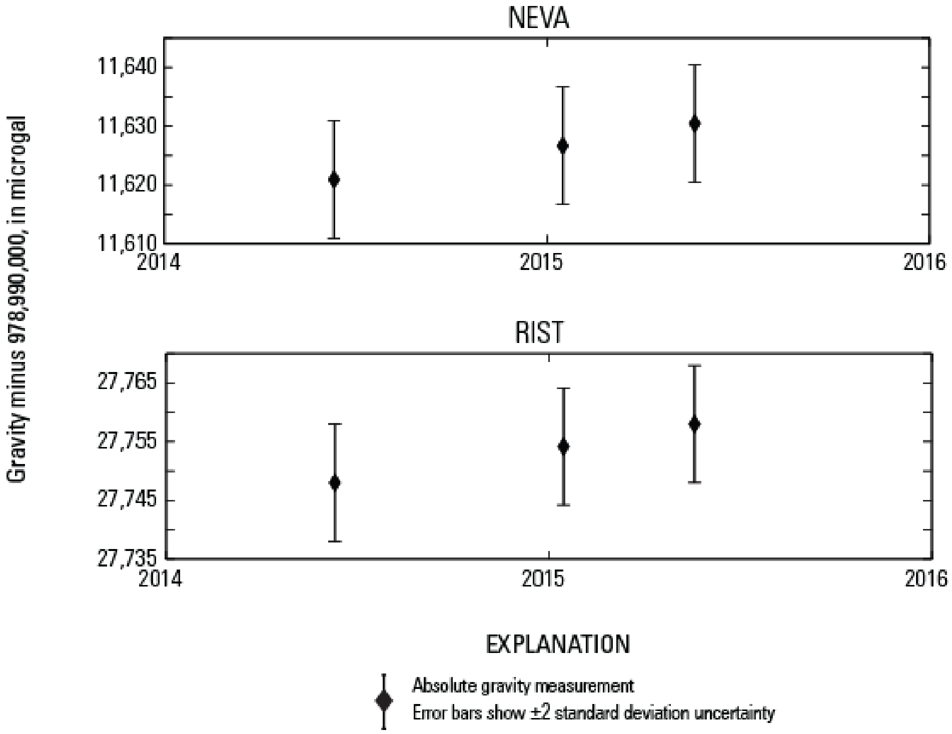

Figure 1. Time-series plots showing gravity change in the Sierra Vista Subwatershed, Upper San Pedro Basin, Arizona, measured using an absolute-gravity meter.—Continued

Global Positioning System Data

Global Positioning System (GPS) data were collected from April 23 to May 1, 2015. Three base stations were used for the duration of the survey: AZCO (part of the National Geodetic Survey [NGS] Continuously Operating Reference Stations [CORS] network), ARS (located on the roof of Quonset 1 at the United States Department of Agriculture [USDA] Walnut Gulch Experimental Watershed Field Station at Tombstone, Arizona), and FORT (located on the roof of the GPS laboratory at Fort Huachuca, Ariz.). Station FORT was a temporary station without a benchmark. Eight daily solutions for FORT and ARS, and 6 for AZCO, were computed using the NGS OPUS (Online Positioning User Service) service. All of the daily solutions at each base station were averaged to determine the position used in the network adjustment. Each gravity-station occupation was approximately 1 hour in length. GPS baselines between each gravity station and the base stations were processed using Trimble Business Center software (v. 2.81). Network adjustment to determine final solutions was also performed in the same software. During the adjustment, stations AZCO, ARS, and FORT were held fixed, using NAD83(2011) epoch 2010.00 positions. Stations bv301, chief, ihop, AAPALO, MW3, MW4, MW5, MW6, and TW9 were not included in the GPS survey. Positions for these stations were determined using autonomous (hand-held) GPS. Station ant3 was not included in the 2015 GPS survey; the position for this station was determined by network-adjusted GPS survey as part of a previous project (Kennedy and Winester, 2011).

The mean network-adjusted uncertainty (standard deviation) for vertical position is 0.033 m. The maximum and minimum uncertainty is 0.015 m and 0.052 m, respectively. Raw GPS data and ancillary files are located in the U.S. Geological Survey (USGS) Arizona Water Science Center Gravity Data

Archive. Elevation uncertainty for each station is provided in the shapefile in the accompanying Web Data Release. Because the first GPS survey was conducted in 2015, 2014 coordinates are not available for comparison to determine station vertical movement. In the future, repeat GPS surveys can be used to check and correct for vertical movement and the resultant effect of gravity measurements. Previous analysis using satellite radar data (InSAR; Kennedy and Winester, 2011) indicated little or no vertical motion in the Sierra Vista Subwatershed.

Network Adjustment

Relative and absolute-gravity data are combined using least-squares network adjustment, a standard method used for all types of survey data (Strang and Borre, 1997). Network adjustment is a least-squares minimization technique that provides a single, best-fit gravity value at each station, while taking into account the variation in uncertainty in the relative- and absolute-gravity observations. The *a priori* standard deviation of the gravity differences (that is, the uncertainty of the relative-gravity data) was estimated by summing in quadrature (the square root of the sum of the station standard deviations squared) the standard deviation reported by the Burris meter at each station.

Network adjustment was performed using Gravnet software (Hwang, 2002) and the provided .txt files (appendix 1) can be used as input files. At first, an unconstrained adjustment was performed, holding one station fixed, to assess the consistency of the observed gravity differences. An iterative procedure was used to flag and remove relative-gravity observations that had unusually high residuals (the difference between the observed value and the network-adjustment-predicted values). The pre-adjustment (*a priori*) standard deviation of the relative-gravity differences, with an original mean value of 2.1 μGal, was revised upward by a factor of 3 based on the *a posteriori* variance of unit weight and chi-square test statistic (table 1). In total, 16 out of 179 observations were excluded from the adjustment.

The final network adjustment incorporated 8 absolute-gravity stations (table 2). Because the absolute-gravity stations have nonzero uncertainty, the final, adjusted values differ from the observed values. The relative-gravity observation residuals (the difference between observed relative-gravity differences and network-adjusted differences) are approximately normally distributed with standard deviation of 4.1 μGal (fig. 2; table 1). The relative-gravity meter calibration factor (a multiplier added to all of the relative-gravity differences to account for error in the meter calibration), determined by the network adjustment, was 1.00049 (table 1). This value is determined by the agreement between relative- and absolute-gravity observations. The mean absolute difference between observed and network-adjusted values at the absolute-gravity stations is 6.51 μGal (fig. 3, table 2). The relatively large differences at stations RIST and FIRE may indicate error in the vertical gradient measurements at these sites (the vertical gradient represents the difference between gravity observed at the height of the absolute-gravity meter and the relative-gravity meter; an incorrect gradient would introduce an offset to the value used in network adjustment). Overall, data quality is similar to previous Upper San Pedro Basin studies (Kennedy and Winester, 2011; Kennedy, 2015).

Table 1. Network-adjustment statistics.

[µGal, microgal]

Number of fixed (absolute-gravity) stations	8	
Degree of polynomial for calibration function	1	
Number of observations	163	
Number of gravity stations	53	
Squared root of *a posteriori* variance of unit weight (reference factor)	1.1	
Global model test statistic	129.7	
Critical chi-square value	143.3	
Estimated accuracy of gravity meter	4.2	µGal
Maximum of residuals	12.6	µGal
Minimum of residuals	-12.2	µGal
Average of residuals	0.004	µGal
Standard deviation of residuals	4.1	µGal
Relative gravity meter calibration factor	1.00049	

Table 2. Absolute-gravity stations and values used in the network adjustment for the Upper San Pedro Basin, Arizona, June 2015.

[g, acceleration due to gravity; µGal; microgal; Std. dev., measurement standard deviation]

Station	Observed g (µGal)	Std. dev. (µGal)	Adjusted g (µGal)	Difference (µGal)
CDF	979002768.7	5.99	979002767.5	–1.2
DORA	979037457.7	5.97	979037452.1	–5.6
RIST	979017955.8	6.08	979017941.6	–14.2
EOP	979031720.4	6.01	979031715.8	–4.6
FIRE	979022989.0	6.25	979023002.7	13.7
NEVA	979001826.0	6.12	979001832.5	6.5
GATE	979008108.8	6.07	979008109.2	0.4
MW5	979050654.7	6.00	979050660.6	5.9

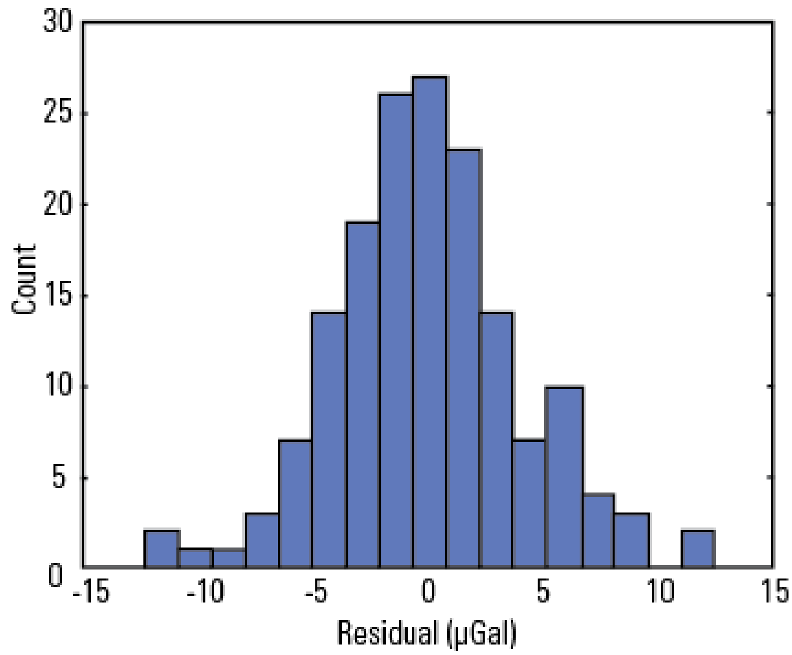

Figure 2. Histogram of network-adjustment residuals (predicted minus observed-gravity differences).

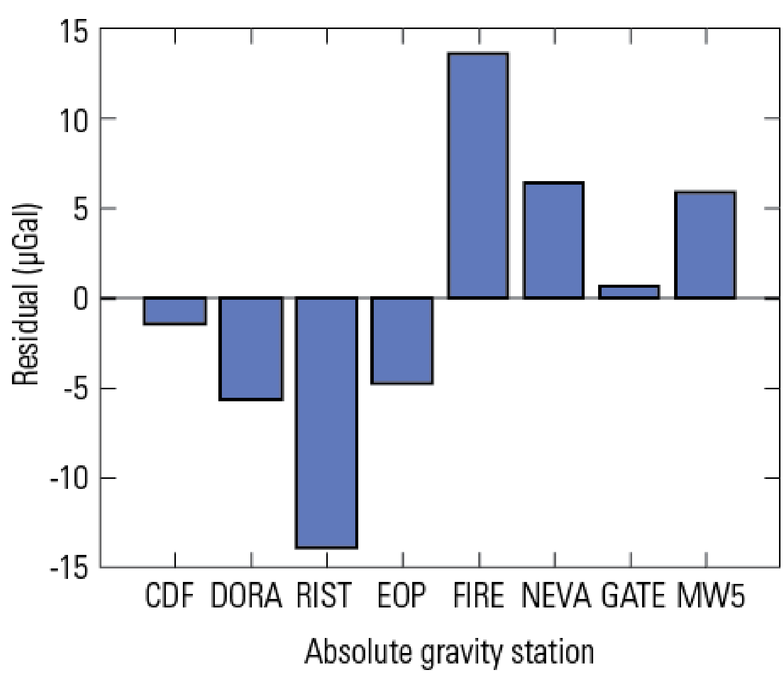

Figure 3. Difference between network-adjusted and observed gravity values at absolute-gravity stations. Positive values indicate the network-adjusted value is greater than the observed value.

Gravity and Storage Change from 2014 to 2015

Network-adjusted gravity values from 2015 were differenced with 2014 values to determine gravity change from June 2014 to June 2015. The accompanying maps show the spatial distribution of gravity change (fig. 4) and storage change (fig. 5). Gravity-change values were converted to 1-dimensional aquifer-storage change using the horizontal infinite-slab approximation, which converts units of acceleration to a thickness of water, regardless of the depth at which storage change occurs (Pool and Eychaner, 1995). Because the conversion from gravity change to storage change is linear (1 m of water is equal to 41.9 µGal of gravity change), figures 4 and 5 show the same information, just at different scales. Storage change is the net increase or decrease in groundwater and unsaturated-zone storage within the region of sensitivity of a particular gravity station; storage change results from an imbalance between inflows (infiltrated rainfall and groundwater subflow) and outflows (losses to evapotranspiration and discharge to wells, springs, and the San Pedro River). Because gravity measurements integrate all storage change in the subsurface, the estimated storage change includes both soil moisture changes in the unsaturated zone (caused by inputs from infiltrated rainfall and losses to evapotranspiration) and saturation/dewatering caused by rise and fall of the water table.

Gravity results are not corrected for elevation change that could be caused by soil shrink/swell processes or subsidence caused by pumping. Future GPS surveys can establish change relative to the positions provided. Previous studies (Kennedy and Winester, 2011; Arizona Department of Water Resources, 2016) using satellite radar have not shown evidence of significant elevation change in the Sierra Vista Subwatershed.

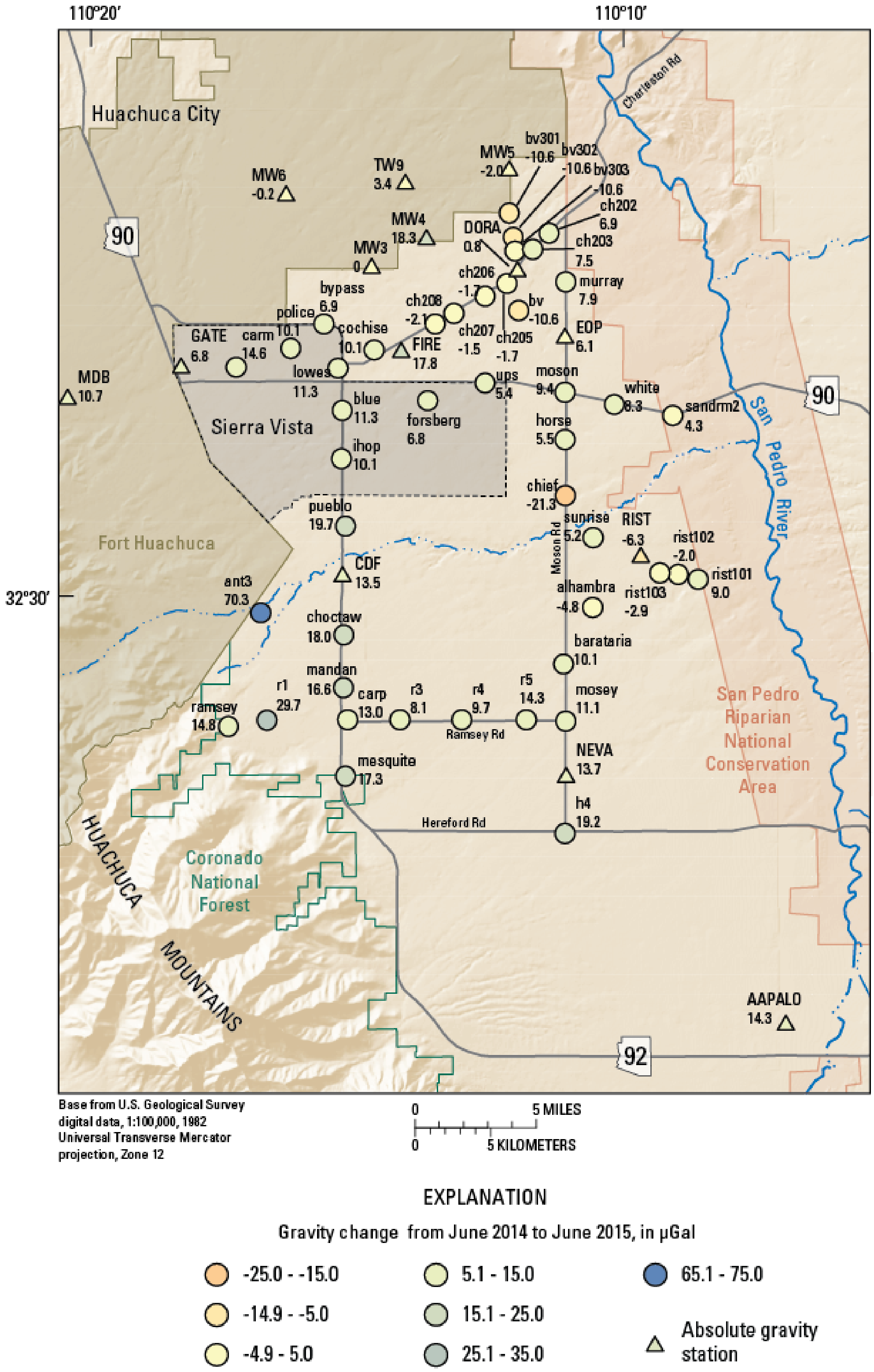

Figure 4. Map showing the change in gravity from 2014 to 2015 in the Sierra Vista Subwatershed, Upper San Pedro Basin, Arizona.

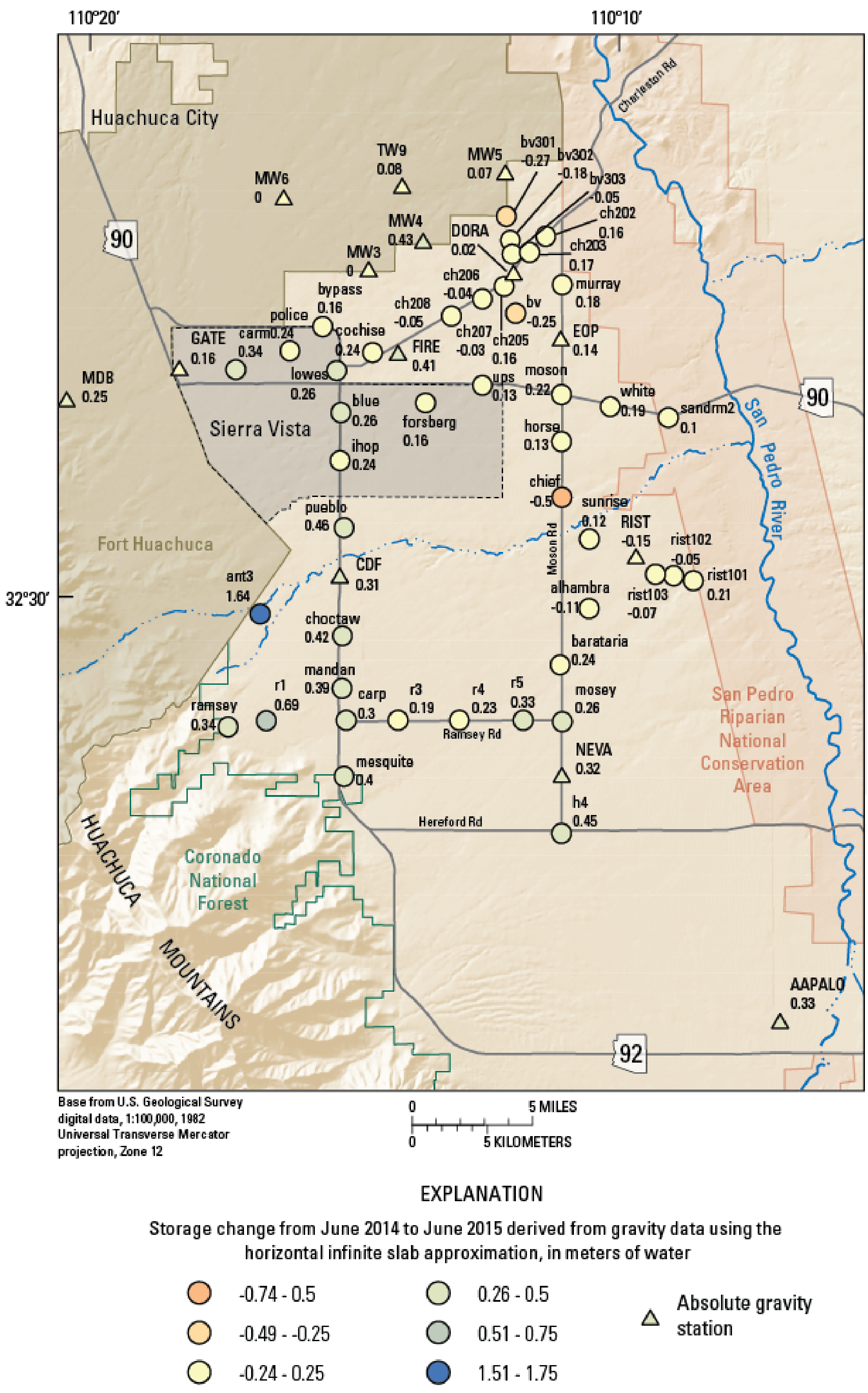

Figure 5. Map showing the change in aquifer storage from 2014 to 2015 in the Sierra Vista Subwatershed, Upper San Pedro Basin, Arizona.

References Cited

Arizona Department of Water Resources, 2016, Land Subsidence in Arizona: Arizona Department of Water Resources, Hydrology Division, accessed June 20, 2016, at http://www.azwater.gov/AzDWR/Hydrology/Geophysics/LandSubsidenceInArizona.htm.

Hwang, C., Wang, C., and Lee, L., 2002, Adjustment of relative gravity measurements using weighted and datum-free constraints: Computers and Geosciences, v. 28, p. 1005–1015.

Kennedy, J.R., and Winester, D., 2011, Gravity data from the San Pedro River Basin, Cochise County, Arizona: U.S. Geological Survey Open-File Report 2011–1287, 11 p. and data files, available at http://pubs.usgs.gov/of/2011/1287/.

Kennedy, J.R., 2015, Gravity data from the Sierra Vista Subwatershed, Upper San Pedro Basin, Arizona: U.S. Geological Survey Open-File Report 2015–1086, 26 p., http://dx.doi.org/10.3133/ofr20151086.

Kennedy, J.R., and Ferré, T.P.A., 2016, Accounting for time- and space-varying changes in the gravity field to improve the network adjustment of relative-gravity data: Geophysical Journal International, v. 204, p. 892–906, doi:10.1093/gji/ggv493.

Lacher, LJ., Turner, D.S., Gungle, Bruce, Bushman, B.M., and Richter, H.E., 2014, Application of hydrologic tools and monitoring to support managed aquifer recharge decision making in the Upper San Pedro River, Arizona, USA: Water, v. 6, p. 3495–3527, accessed December 1, 2014, at http://dx.doi.org/10.3390/w6113495.

Pool, D.R., 2008, The utility of gravity and water-level monitoring at alluvial aquifer wells in southern Arizona: Geophysics, v. 73, p. WA49–WA59.

Pool, D.R., and Eychaner, J.H., 1995, Measurements of aquifer-storage change and specific yield using gravity surveys: Ground Water, v. 33, no. 3, p. 425–432.

Schmerge, D., Corkhill, F., and Flora, S., 2009, Water-level conditions in the Upper San Pedro Basin, Arizona, 2006: Arizona Department of Water Resources, ADWR Water Level Change Map Series Report No. 3, 3 plates.

Strang, G., and Borre, K., 1997, Linear algebra, geodesy, and GPS: Wellesley, Mass., Wellesley-Cambridge Press, 624 p.

Torge, W., 1989, Gravimetry, Berlin, De Gruyter, 465 p.

Appendix 1. Data Files

Data files included in the OFR provide observed, minimally processed observations. Network-adjusted, final gravity values for each station are provided in

- USGS_OpenFileReport_2016-1155_SanPedroGravity2014-2015_AdjustedGravity.csv
    - Contains 2015 network-adjusted gravity values in units of microgals. Also included are 2014 values from Kennedy (2015), and the change in gravity from 2014 to 2015 is calculated. These data are also provided in the shapefile at the accompanying Web Data Release. Coordinates for most points are taken from the GPS network described in this report.
    - Fields:
        - Latitude (NAD83(2011) epoch 2010.00)
        - Longitude (NAD83(2011) epoch 2010.00)
        - Height (relative to GRS 80 ellipsoid), in m
        - Height error (determined from network adjustment; --, station not included in the 2015 GPS network), in m
        - g_2014: Network-adjusted 2014 gravity from Kennedy (2015), µGal
        - sd_2014: Standard deviation of 2014 network adjusted gravity from Kennedy (2015), µGal
        - g_2015: Network-adjusted 2015 gravity, in µGal
        - sd_2015: Standard deviation of 2014 network adjusted gravity, in µGal
        - dg_uGal: Change in gravity, 2014 to 2015, in µGal
        - dg_sd_uGal: Standard deviation of the 2014 to 2015 change in gravity, in µGal, calculated as the square root of the sum of the squared 2014 and 2015 standard deviations
        - dg_mH2O: Change in gravity, 2014 to 2015, converted to aquifer-storage change using the horizontal infinite-slab approximation. The value represents a thickness of free-standing water, in m.
        - dg_mH2O: Standard deviation of the change in gravity, 2014 to 2015, converted to aquifer-storage change using the horizontal infinite-slab approximation. The value represents a thickness of free-standing water, in m.
- USGS_OpenFileReport_2016-1155_SanPedroGravity2014-2015_RelativeGravity.txt
    - Drift- and tide-corrected relative gravity differences used in the network adjustment. Tab-separated file format can be used with the adjustment program Gravnet (Hwang and others, 2002).
    - Fields:
        - sta1: Station 1 name
        - sta2: Station 2 name
        - dg: Gravity difference, in mGal
        - sta1_t: Observation time at station 1, in MATLAB format
        - sta2_t: Observation time at station 2, in MATLAB format
        - reading_from: Meter reading at station 1, in counter units
        - reading_to: Meter reading at station 2, in counter units
        - sd: *a posteriori* gravity difference standard deviation, in µGal (determined from chi-square test and network adjustment)

- USGS_OpenFileReport_2016-1155_SanPedroGravity2014-2015_AbsoluteGravity.txt
    - Absolute-gravity observations used in the network adjustment. Tab-separated file format can be used with the adjustment program Gravnet (Hwang and others, 2002).
    - Fields:
        - Station name
        - Observed absolute gravity, in mGal
        - Standard deviation, in mGal