Uncertainty of Aquifer-Storage Change Estimated from Temporal Changes in Gravity

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ABSTRACT

Aquifer-storage changes have been estimated from temporal changes of gravity in several studies conducted by the United States Geological Survey, but the uncertainty has never been assessed. If these estimates are to have meaning, an indication of the uncertainty must be included. After reviewing the recently published results to assess the uncertainties, it is apparent that the reported aquifer-storage changes have not always been significant. However, it is also apparent that sometimes the results are significant. For example, in Antelope Valley, California, an aquifer-storage increase of $7 \pm 3 \times 10^5$ m^3 was measured between November 1996 and April 1997. Also, in the Lower Cañada del Oro subbasin in Arizona, an aquifer-storage loss of about $1.3 \pm 0.6 \times 10^8$ m^3 was measured between October 1998 and October 2002; however, there may still be some error that is unaccounted for in this estimate because of the edge problem. In order to measure a significant change in aquifer storage, it is apparent that the average change in gravity should be approximately 10 μGal or greater.

INTRODUCTION

Several studies conducted by the United States Geological Survey have used temporal changes in gravity to estimate aquifer-storage change, but the uncertainty has never been reported. Error propagation has sometimes been completely ignored, and at other times has been only partially considered. Pool and Eychaner (1995), Pool and Schmidt (1997), and Pool (1999) estimated aquifer-storage change in three alluvial basins in Arizona, and discussed some error sources, including relative gravity measurements, deformation, and changes in non-aquifer mass; but the propagation of these errors was not considered. At an injection storage and recovery test near the town of Lancaster, in Antelope Valley, California (figures 1 through 3), Howle and others (2003) used gravity to measure the rate of increase in aquifer storage; the rate was equivalent to only 42 percent of the injection rate, and it was hypothesized that this error was caused by the mound of water extending significantly beyond the monitored area (figure 4). Schmerge (2003) used temporal changes in gravity to estimate aquifer-storage change in the Lower Cañada del Oro subbasin in Arizona (figures 5 through 7), and some sources of error were discussed, including boundary conditions, the assumption that gravity is constant on bedrock, calibration shifts in relative gravimeters, and sampling; some discussion of the propagation of these errors was included, but the total uncertainty was not estimated. Schmerge (2006) reported that significant errors can occur if gravity on bedrock is assumed constant, or if seasonal deformation is ignored.

Purpose and Scope

If estimates of aquifer-storage change are to have meaning, they cannot consist of the estimated value alone; an indication of the uncertainty of the result must also be included. The purpose of this report is to discuss the sources of uncertainty and their propagation in the method of estimating aquifer-storage change from temporal changes in gravity. The scope of the report is examples of temporal changes in gravity (both real and hypothetical), with an emphasis placed on results from Antelope Valley and the Lower Cañada del Oro subbasin.

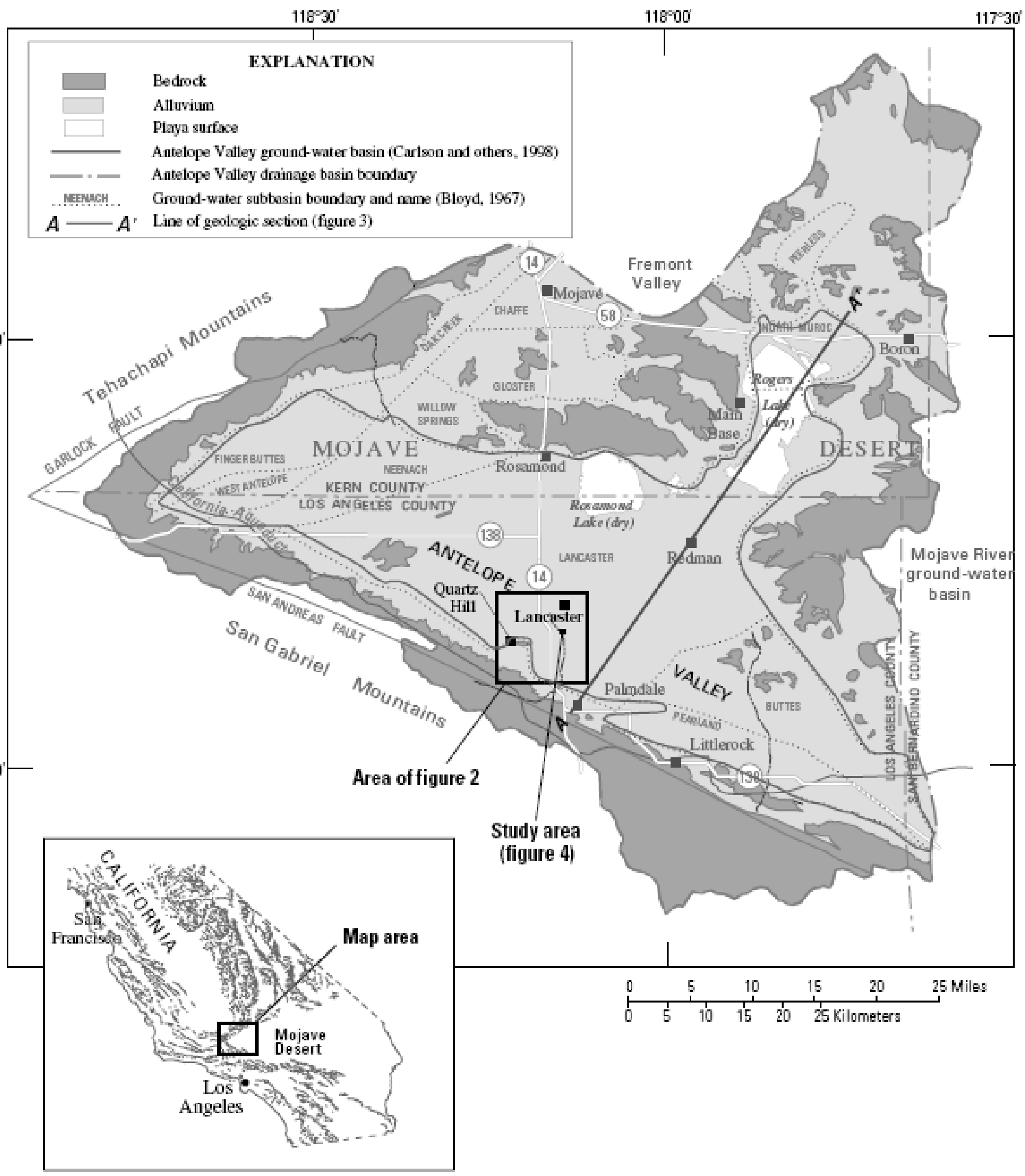


Figure 1. Location of Antelope Valley study area and generalized surficial geology. (From Howle and others, 2003, figure 1).

Theory

Aquifer-storage change can be estimated using the equation:

$$M = \frac{1}{2\pi G} \cdot \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \Delta g(x, y)\,dxdy\,, \tag{1}$$

where M is the mass flux, G is the universal gravitational constant, and Δg is the temporal change in gravity for the surface area element dxdy (Cole, 1991). If the gravity anomaly

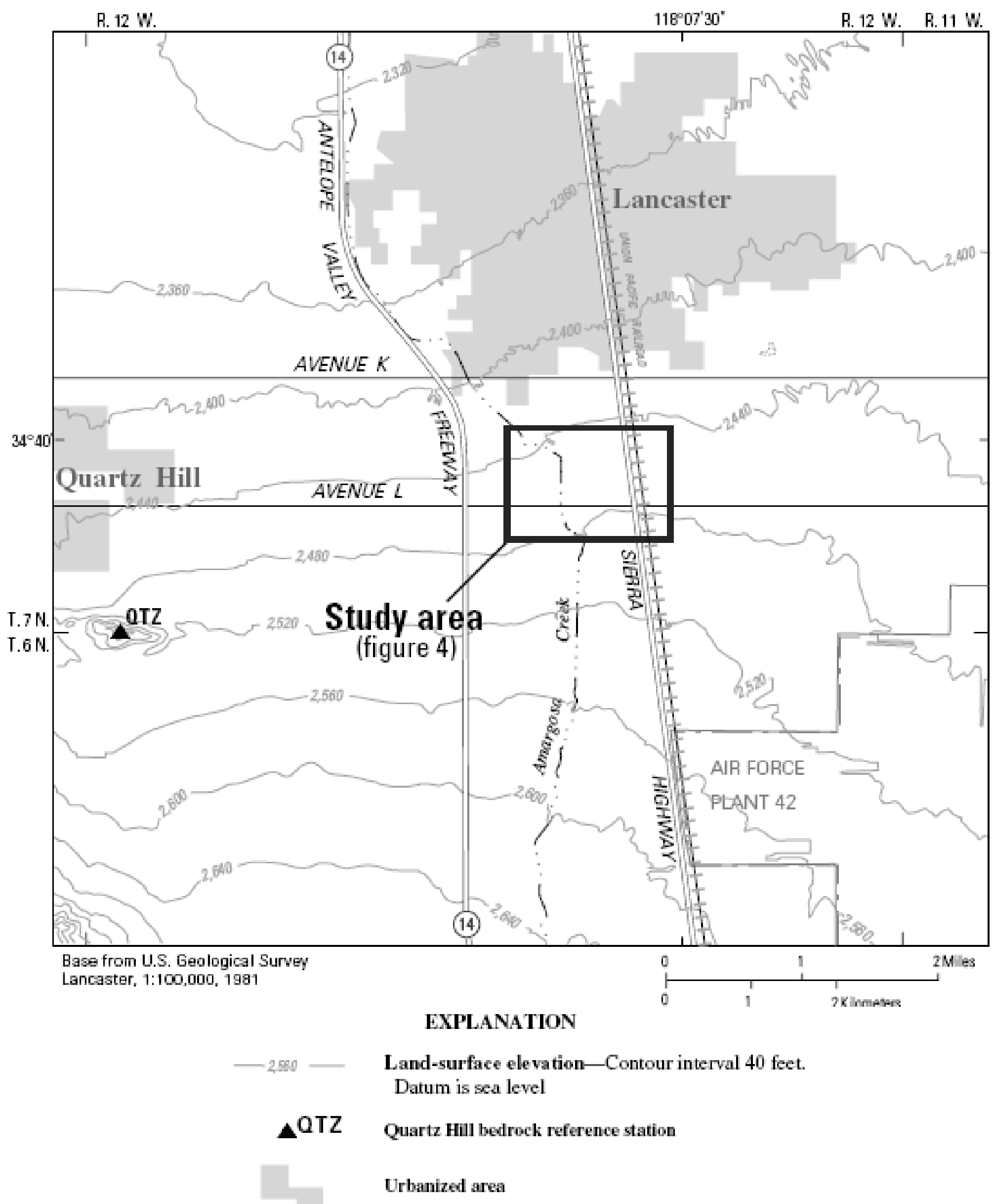


Figure 2. Location of Quartz Hill bedrock reference station and the town of Lancaster, Antelope Valley, California. (From Howle and others, 2003, figure 2).

is contained within the area of summation, then this integral can be approximated as:

$$M \approx \frac{1}{2\pi G} \cdot \sum \left(\Delta g_M \cdot \Delta A\right), \tag{2}$$

where Δg_M is the change in gravity that is caused by the change in mass for the area element ΔA. The change in gravity that is caused by a change in mass can be written as:

$$\Delta g_M = \Delta g - \gamma \cdot \Delta h, \tag{3}$$

where Δg is the change in gravity, γ is the vertical gravity gradient, and Δh is the change in elevation. Inserting this equation into the approximation and dividing by the density (ρ) of the mass gives the volume:

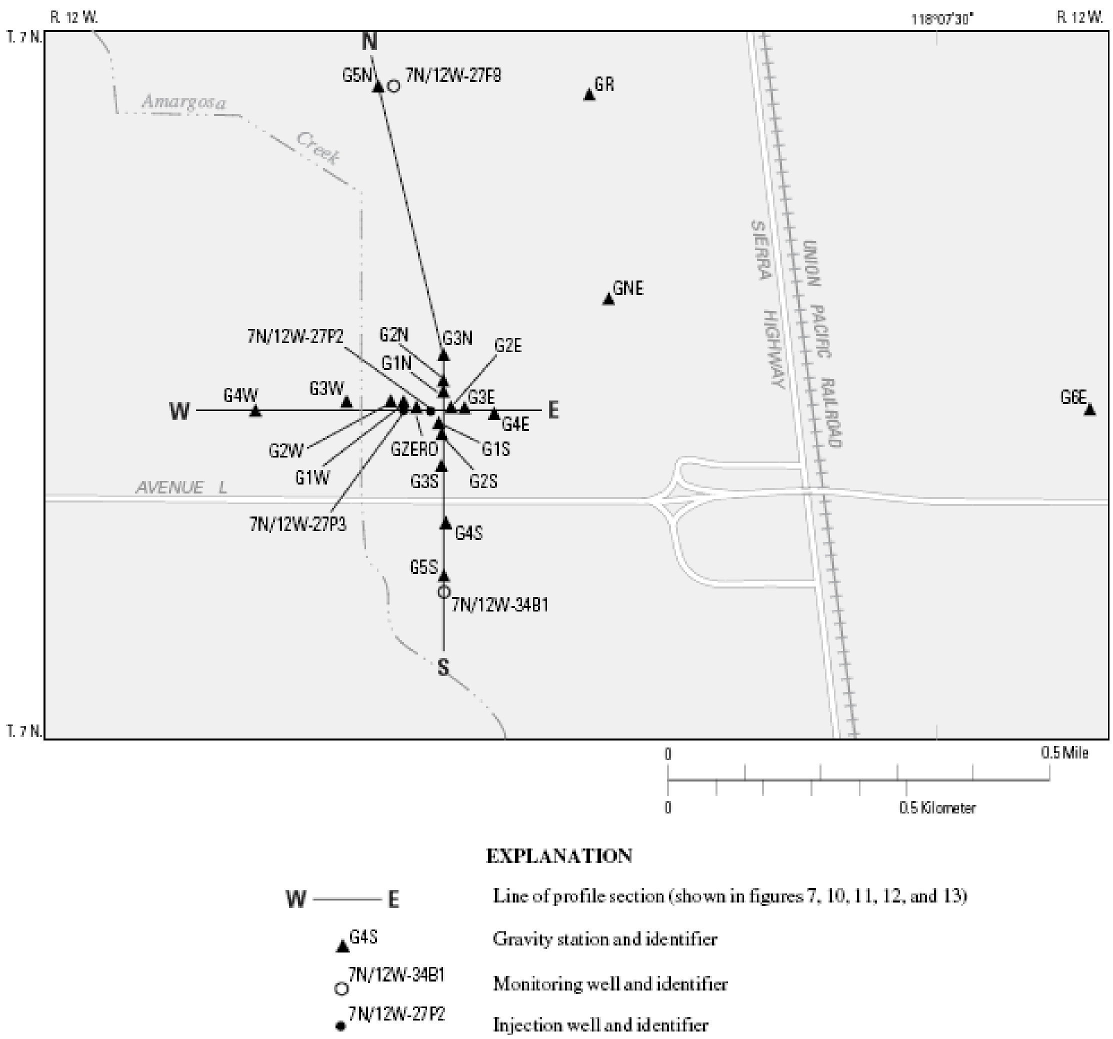


Figure 3. Location of gravity stations, injection wells, and monitoring wells, Lancaster, Antelope Valley, California. (From Howle and others, 2003, figure 4).

$$V \approx \frac{1}{2\pi G} \cdot \frac{1}{\rho} \cdot \sum \left(\left(\Delta g - \gamma \cdot \Delta h \right) \cdot \Delta A \right). \tag{4}$$

If each area element is of equal size, then this can be expressed as:

$$V \approx \frac{1}{2\pi G} \cdot \frac{\Delta A \cdot n}{\rho} \cdot \frac{\sum \left(\Delta g - \gamma \cdot \Delta h \right)}{n}, \tag{5}$$

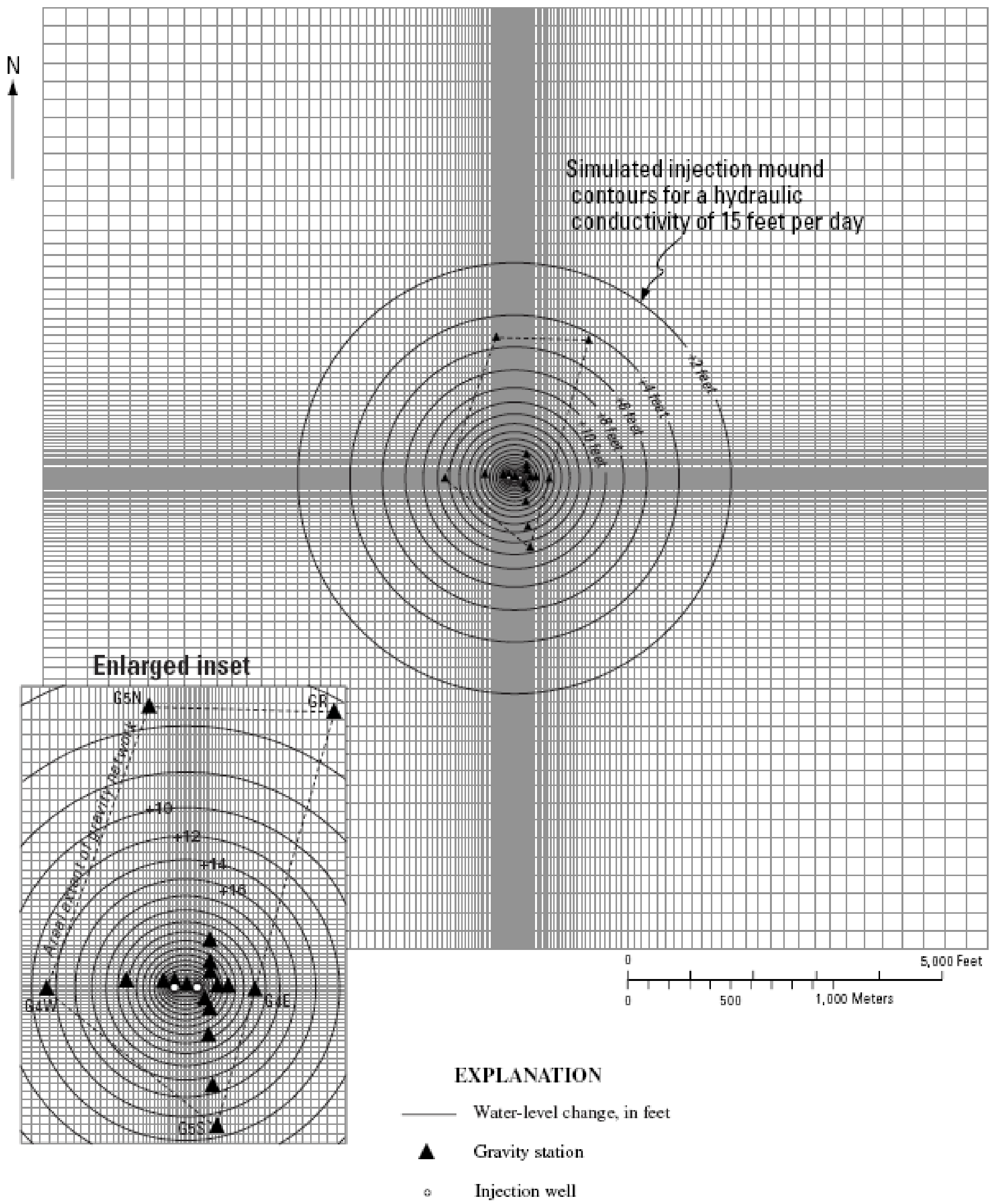


Figure 4. Areal extent of the gravity station network and simulated injection mound contours in Lancaster, Antelope Valley, California. (From Howle and others, 2003, figure 8).

where n is the number of area elements. Finally, it may not be possible to carry out the integration far enough to totally contain the gravity anomaly (Howle and others, 2003; Schmerge, 2003), but this edge problem may be addressed by multiplying by a correction factor (Grant and West, 1965), so:

$$V \approx \frac{1}{2\pi G} \cdot \frac{A}{\rho} \cdot \left(\mu_{\Delta g} - \mu_{\gamma \cdot \Delta h}\right) \cdot C \,, \tag{6}$$

where A is the study area, $\mu_{\Delta g}$ is the average change in gravity, $\mu_{\gamma \cdot \Delta h}$ is the average change in gravity caused by the change in elevation Δh, and C is the correction for the edge problem.

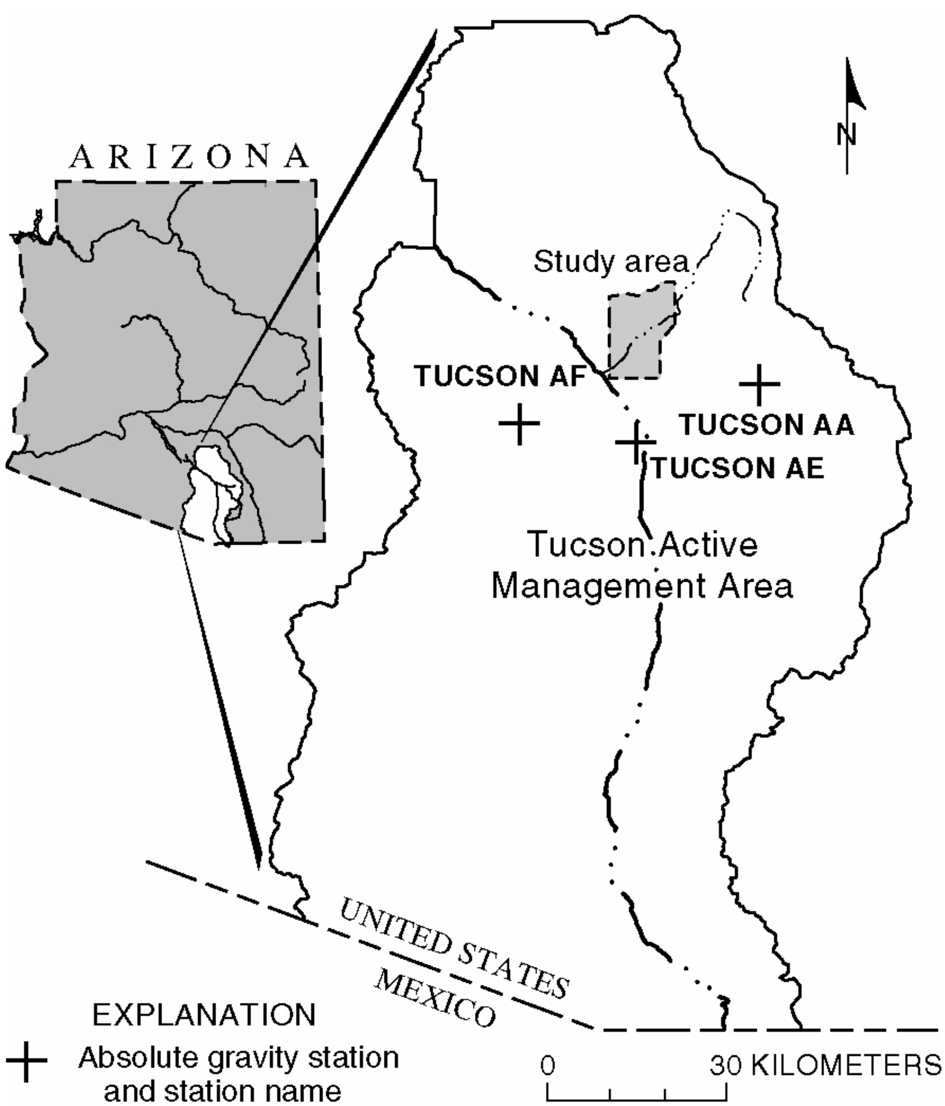


Figure 5. Location of the Lower Canada del Oro subbasin study area, and three nearby absolute gravity stations. (From Schmerge, 2003, figure 1).

UNCERTAINTY

The uncertainty of the aquifer-storage change estimated from a temporal change in gravity can be considered in 5 parts: (1) the average change of gravity, (2) the average change of gravity caused by vertical deformation, (3) the density of the mass, (4) the size of the study area, and (5) the edge problem. For an equation of the form:

$$q \pm \delta q = \left(B \cdot \frac{v \pm \delta v}{w \pm \delta w} \cdot \left(x \pm \delta x - y \pm \delta y \right) \cdot \left(z \pm \delta z \right) \right), \tag{7}$$

where B is constant; and v, w, x, y, and z are independent variables, with respective uncertainties of δv, δw, δx, δy, and δz; the uncertainty of q can be expressed as:

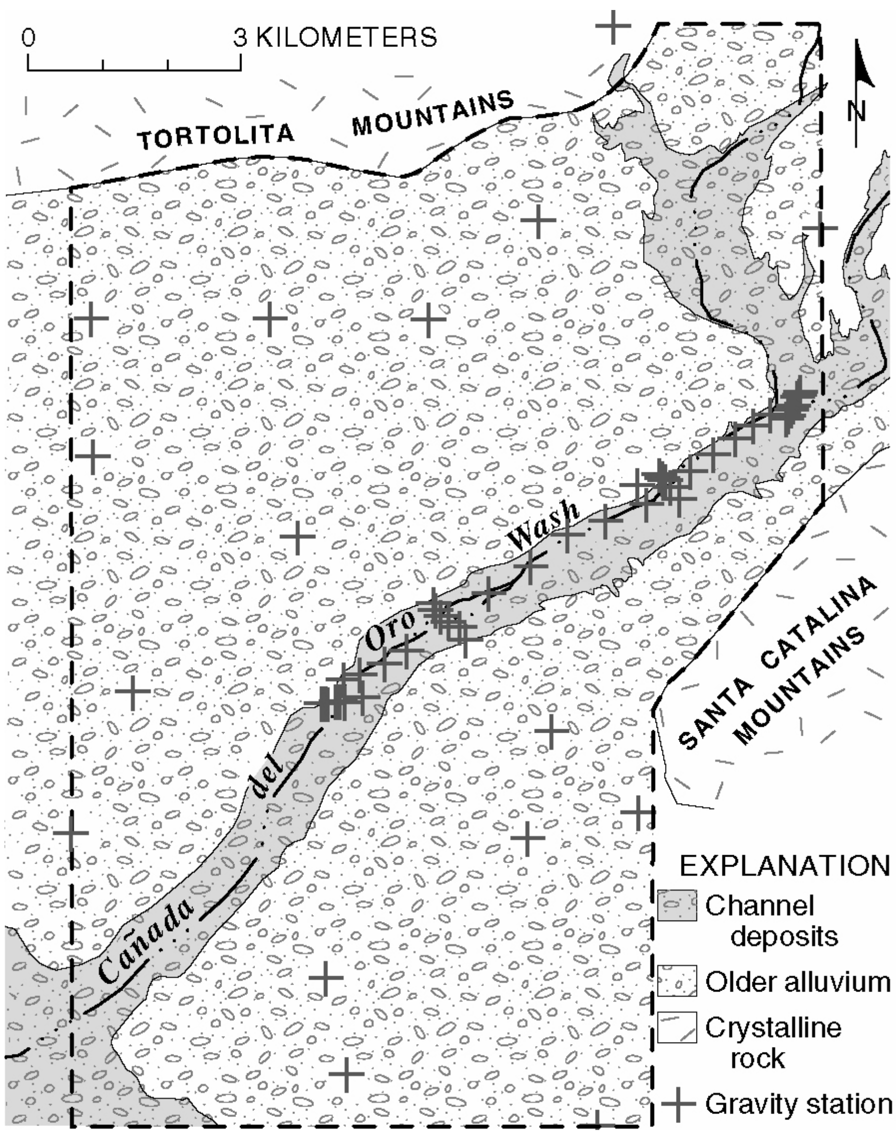


Figure 6. Lower Canada del Oro subbasin. (From Schmerge, 2003, figure 2).

$$\delta q = |q| \cdot \left(\frac{(\delta v)^2}{v^2} + \frac{(\delta w)^2}{w^2} + \frac{(\delta x)^2 + (\delta y)^2}{(x-y)^2} + \frac{(\delta z)^2}{z^2} \right)^{1/2} \qquad (8)$$

(Taylor, 1997). Therefore, assuming the parameters are independent:

$$\delta V = |V| \cdot \left(\frac{(\delta A)^2}{A^2} + \frac{(\delta \rho)^2}{\rho^2} + \frac{(\delta \mu_{\Delta g})^2 + (\delta \mu_{\gamma \cdot \Delta h})^2}{(\mu_{\Delta g} - \mu_{\gamma \cdot \Delta h})^2} + \frac{(\delta C)^2}{C^2} \right)^{1/2} . \qquad (9)$$

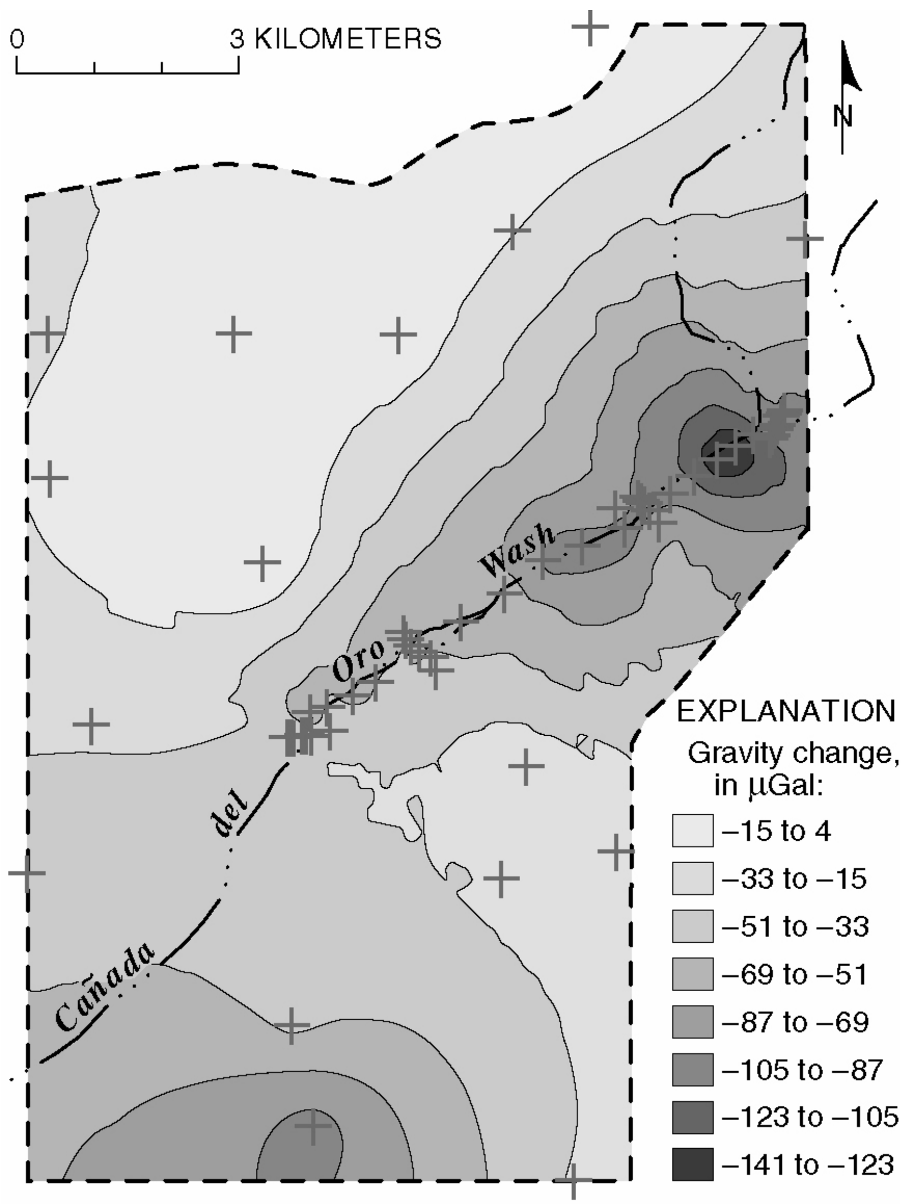


Figure 7. Gravity change in the Lower Canada del Oro subbasin from October 1998 to October 2002. (From Schmerge, 2003, figure 3).

Gravity

Uncertainties in the change of gravity can arise from measurements, assumptions, and sampling. If these uncertainties are independent then:

$$\delta\mu_{\Delta g} = \left((\delta m)^2 + (\delta a)^2 + (\delta s)^2\right)^{1/2}, \tag{10}$$

where δm is the measurement error, δa is the error from assumptions, and δs is the sampling error.

Measurements

Gravity meters that have been used in USGS studies of aquifer-storage change are of two types: (1) absolute gravimeters, which are "absolute" because they are purely metrological, using standards of length and time to measure the acceleration of gravity (g); and (2) relative gravimeters, which are "relative" because they are used to measure differences in gravity. For both relative and absolute gravimeters, the repeatability and change in accuracy are important properties in differential studies like aquifer-storage change. The repeatability is the standard deviation of the measurements from independent setups. The change in accuracy (stability) is important, rather than the accuracy, because the stability affects the uncertainty of the aquifer-storage change, while the accuracy does not. If the uncertainties of the absolute and relative measurements are independent, then:

$$\delta m = \left((\delta m_a)^2 + (\delta m_r)^2\right)^{1/2}, \tag{11}$$

where δm_a is the uncertainty of the absolute measurements, and δm_r is the uncertainty of the relative measurements.

Absolute Gravity

Absolute gravimeters of two types have been used by the USGS: (1) the FG5, and (2) the A10. They are similar instruments in that they are both ballistic, but they have significant differences because they are designed for different purposes. The FG5 is designed to measure g with the greatest possible accuracy; the instrumental uncertainty, in theory, is 1.1 μGal (1 Gal ≡ 1 cm/s^2) (Niebauer and others, 1995). For an FG5, the repeatability is generally considered to be 1 to 2 μGal (Niebauer, and others, 1995; Van Camp and others, 2005; Francis and van Dam, 2006). The FG5 can be – and has been – used in the field, but it is more commonly used in a laboratory setting. The A10 is designed to be a field instrument that is an absolute alternative to relative gravimeters; it is a robust, transportable, quick, absolute gravimeter that can be easily taken into the field. For an A10, the average repeatability is about 3 μGal, with a worst case of about 5 μGal (Schmerge and Francis, 2006).

Absolute gravimeters are compared to other absolute gravimeters to verify that they are working properly and to measure their offset. The offset of an absolute gravimeter is the average difference in the measured value of g compared to other absolute gravimeters. Offsets are measured instead of accuracy because the true value of g is unknown, and therefore, the accuracy is unknown. Numerous absolute gravimeter comparisons have been performed in recent years. An International Comparison of Absolute Gravimeters (ICAG) has recently been held biannually in Europe, with up to 17 absolute gravimeters participating. In 2001, ICAG-2001 was held at the Bureau International des Poids et Mesures (BIPM) (Vitushkin and others, 2002); and in 2003, ICAG-2003 was held at the Underground Laboratory for Geodynamics in Walferdange (WULG) in Luxembourg (Francis and van Dam, 2006). ICAG-2005 was recently held at the BIPM (results are not yet published). Regional or local comparisons consisting of a few absolute gravimeters have also been frequently performed, in addition to the biannual comparisons, because it is often beneficial to verify their working order more frequently than once per 2 years (Niebauer and others, 1995; Van Camp and others, 2003; Wilmes and Falk, 2006; Van Camp, 2006; Šimon and others, 2006; Schmerge and Francis, 2006).

The stability of absolute gravimeters cannot be directly measured, but it is assumed that the change in the measured offset is approximately equal to the stability. Furthermore, it is assumed that the change in the measured offset will more closely approximate the stability as the number of gravimeters participating in a comparison increases. In other words, it is assumed that the accuracy of gravimeters, as a whole, does not change.

For studies of short duration – one absolute gravimeter used throughout the study with no significant change in the instrument caused by wear, repairs, or upgrades – the instrument can be assumed to be stable with no change in the accuracy or the offset; and the uncertainty in the measured change of gravity will be equal to the repeatability of the instrument (table 1).

For studies of long duration – absolute gravimeter with significant wear, repairs, or upgrades; or multiple absolute gravimeters used during the period of study – the measurements are independent; and the uncertainty in the measured change of gravity from absolute gravimeters will be:

$$\delta m_a = \left((\delta m_\alpha)^2 + (\delta m_\omega)^2 \right)^{1/2}, \tag{12}$$

where δm_α is the measurement uncertainty at time α, and δm_ω is the measurement uncertainty at time ω. Ideally, an absolute gravimeter will be compared against

Instrument Type	Short Period	Long Period		
		1st Reference	2nd Reference	Unknown
FG5	1 to 2	1 to 3	2 to 4	3
A10	3 to 5	4 to 7	4 to 10	7

Table 1. Uncertainty estimates (μGal) of the change in gravity from absolute measurements. For the uncertainty of an FG5 secondary reference, it is assumed that the primary reference is an FG5. For the uncertainty of an A10 secondary reference; in the best case, it is assumed that the primary reference is an FG5; and in the worst case, it is assumed that the primary reference is an A10.

numerous others to measure its offset; in this case, the instrument may be thought of as a primary reference, and δm_α and δm_ω will be the repeatability at time α and time ω respectively. Alternatively, an absolute gravimeter may be compared to a primary reference; in this case, the instrument can be thought of as a secondary reference, and δm_α will be the square root of the sum of the squares of the repeatabilities of both gravimeters at time α – and likewise for δm_ω at time ω. Less ideal still would be no measurement of the offset or repeatability; in this case, the estimated system error may be used for δm_α and δm_ω. The estimated system error is 2 µGal for an FG5, and 5 µGal for an A10 (Francis and van Dam, 2006). The uncertainties of the measured change in gravity for long periods for both an FG5 and an A10 are shown in table 1.

Relative Gravity

Relative gravimeters that have been used by the USGS to monitor aquifer-storage change were manufactured by LaCoste & Romberg (L&R); and like absolute gravimeters, the repeatability and stability are important properties. The repeatability is affected by drift and tares, but if the meter is well maintained and operated then these problems can be minimized. The repeatability of L&R measurements was ≤ 6 µGal for Pool and Eychaner (1995), ≤ 9 µGal for Howle and others (2003), and ≤ 5 µGal for Schmerge (2003).

A change in accuracy of an L&R gravimeter can be caused by a calibration shift, and it is therefore considered good practice to check their calibration periodically. Carbone and Rymer (1999) reported several calibration shifts as large as 0.1 percent for L&R gravimeter G513:

> "The data presented in this paper are exceptional because of the very long period of continuous measurements using nearly 4000 mGal of the 7000 mGal available worldwide range of the instrument. On the basis of these data, we have been able to show that large and significant calibration changes can affect L&R instruments and that they have the same percentage extent across the measuring range within experimental error. Over the period covered by this study (nearly 14 years), rather than a continuous, slow calibration drift, two discrete changes of considerable magnitude (≈ 1000 ppm) have occurred over periods of several months."

Calibration errors clearly occur in at least some L&R gravimeters. This is an obvious conclusion when several meters are tested simultaneously by measuring the difference in gravity for two points, and the values disagree by more than the expected experimental error. Gravimeters D127 and D209, used by the USGS Arizona Water Science Center, have a manufacturer specified accuracy of 10 µGal. They have been simultaneously tested on several occasions and disagreed by more than the expected experimental error. For an experiment like this, it is uncertain whether the measurement differences reflect the accuracy of the manufacturer, or calibration shifts over time.

The effect of a calibration shift on the measured average change in gravity is dependent upon the gravity range of the network and the choice of the reference station. This can be demonstrated by considering a hypothetical gravity network of stations A, B, C, D, and E; with respective gravities relative to station A of 0, 3, 14, 25, and 28 mGal (table 2). A 0.1 % calibration shift, if A is the reference station, will cause a measured to the mean gravity of the network.

If the Base Station is:		Then the measurement error (μGal) at __ is:					And the mean
Station	g (mGal)	A	B	C	D	E	Δg (μGal) is:
A	0	0	3	14	25	28	14
B	3	-3	0	11	22	25	11
C	14	-14	-11	0	11	14	0
D	25	-25	-22	-11	0	3	-11
E	28	-28	-25	-14	-3	0	-14

Table 2. Measurement errors and average change in gravity resulting from a hypothetical 0.1 % calibration expansion for a relative gravimeter. The gravity (g) for each station is relative to the gravity at station A. The sign for the measurement errors and the average change of gravity would be reversed for a 0.1 % contraction of the calibration.

A calibration shift can introduce a significant error in the estimated aquifer-storage change if it is not detected and corrected. For example, the calibration of L&R gravimeter D127 used by Pool (1999) in the Lower Cañada del Oro subbasin was not checked; so if a shift occurred, then it was not detected and corrected. Gravity varies by about 28 mGal across the basin, and 2 reference stations were used. One reference station has the highest gravity in the network, while the other reference station has the lowest. The relative gravities for each station were reported, so the effect of a 0.1 % calibration shift can be easily calculated. The result is an error in the measured average change in gravity of about 5 μGal. This possible calibration shift results in an error that is the same size as the aquifer-storage change estimated by Pool (1999). Therefore, because it is not possible to say with confidence that no calibration shift occurred, it is not possible to say with confidence that Pool (1999) measured a significant aquifer-storage change.

The uncertainty of the estimated aquifer-storage change caused by a calibration shift of an L&R meter can be made insignificant by taking several precautions. First, the calibration shifts reported by Carbone and Rymer (1999) were of the same percentage across the measured range; so if this is typical of all L&R meters, then a calibration shift can be corrected by multiplying by a single factor. Also, by using a reference station with a gravity value near the mean value of the network, the uncertainty of the estimated aquifer-storage change caused by a calibration error can be made insignificant.

Using a calibrated gravimeter, there is still some uncertainty in the relative measurements, which is dependent upon how the network is tied together. This can be demonstrated by again considering the hypothetical network of stations A, B, C, D, and E (figure 8). Let station A be the reference station. If the relative gravity of AB, AC, AD, and AE are measured, then the errors are random, and the uncertainty of the relative measurements is:

$$\delta m_r = \left(\frac{\sigma_{r\alpha}^{2}}{n_{r\alpha}} + \frac{\sigma_{r\omega}^{2}}{n_{r\omega}} \right)^{1/2}, \qquad (13)$$

where $\sigma_{r\alpha}$ is the repeatability of the relative measurements at time α, $n_{r\alpha}$ is the number of measurements at time α, $\sigma_{r\omega}$ is the repeatability of the relative measurements at time ω,

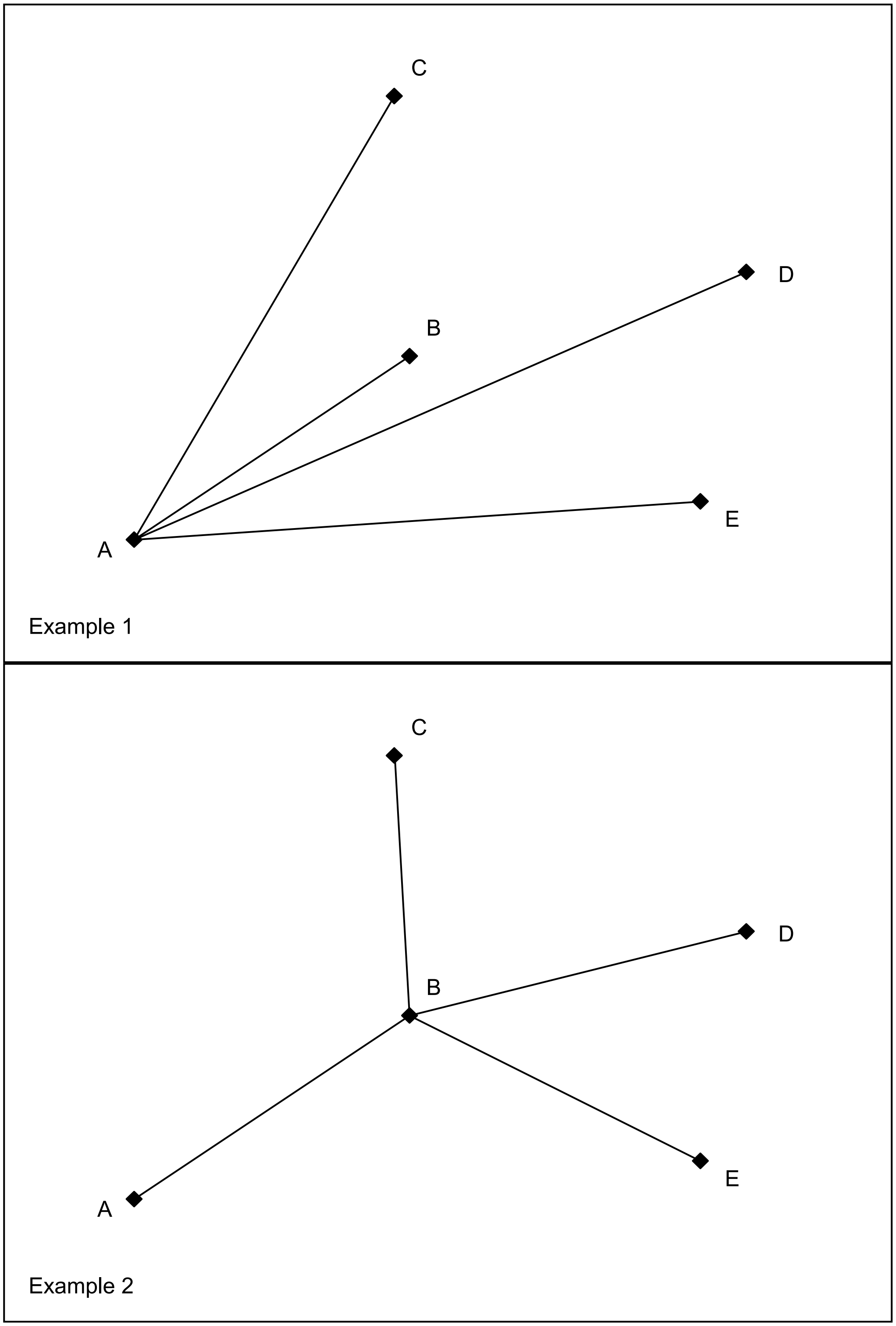


Figure 8. Hypothetical gravity network of stations A, B, C, D, and E. The lines represent relative gravity measurements. The uncertainty of the average change in gravity depends on how the network is tied together. If A is the reference station, then in example 1 all the errors are random, and in example 2 the error of AB will bias the changes in gravity measured at stations C, D, and E.

and $n_{r\omega}$ is the number of measurements at time ω. In this example, both $n_{r\alpha}$ and $n_{r\omega}$ are 4, so if the repeatabililty is 5 µGal, then δm_r is about 3.5. Alternatively, if the relative gravity of AB, BC, BD, and BE are measured, then the error of AB will bias the results of the other stations, so the uncertainty is:

$$\delta m_r = \left(\frac{\sigma_{s\alpha}{}^2}{n_{s\alpha}} + \frac{\sigma_{r\alpha}{}^2}{n_{r\alpha}} + \frac{\sigma_{s\omega}{}^2}{n_{s\omega}} + \frac{\sigma_{r\omega}{}^2}{n_{r\omega}} \right)^{1/2}, \tag{14}$$

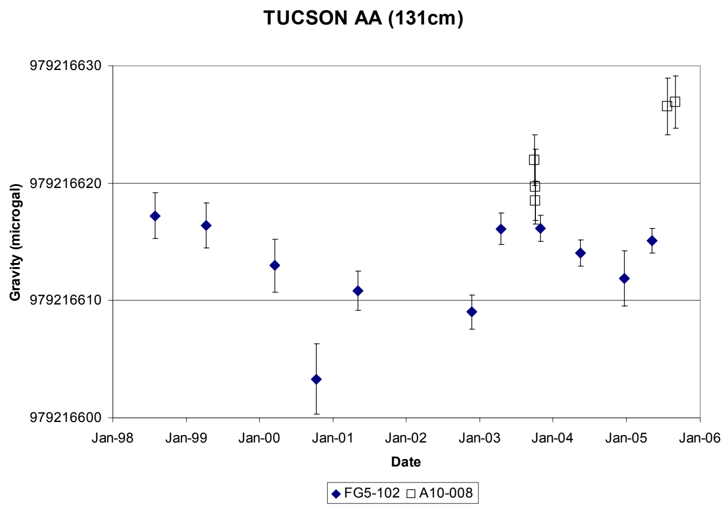
where $\sigma_{s\alpha}$ is the standard deviation of AB at time α, $n_{s\alpha}$ is the number of measurements of AB at time α, $\sigma_{s\omega}$ is the standard deviation of AB at time ω, and $n_{s\omega}$ is the number of measurements of AB at time ω. In this example, again assuming the repeatabililty of all the measurements is 5 µGal, if two loops of AB are completed at both time α and ω, then both $n_{s\alpha}$ and $n_{s\omega}$ are 3, and δm_r will be about 3.4. For this simple network, the uncertainties from the two examples are about the same. However, for a larger network, the uncertainty will be smaller if the errors are all random as opposed to if there is a bias. For example, for 100 stations and assuming $n_{s\alpha}$ and $n_{s\omega}$ are equal to 3, δm_r will be about 1 µGal if the errors are all random, and about 3 µGal if there is a bias. Therefore, it is generally preferable to tie all the relative measurements directly to the reference station. However, if for logistical reasons this is not feasible, then the bias can be reduced by increasing the number of measurements.

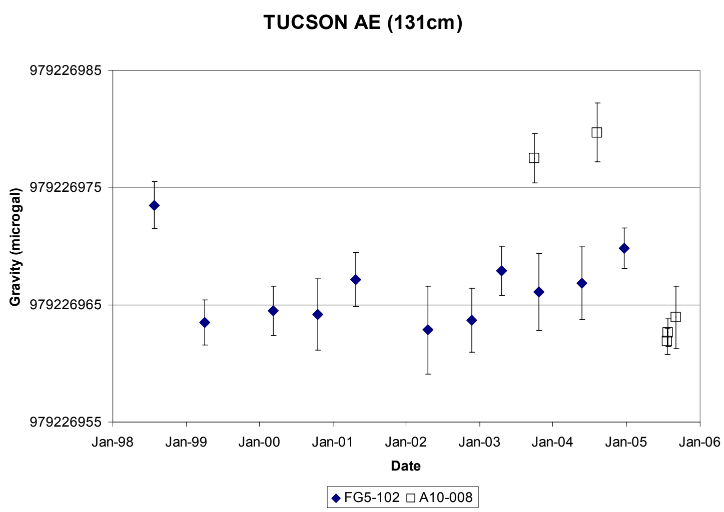
Assumptions

The assumption that gravity is constant on bedrock can cause a significant error in the estimated aquifer-storage change. Cole (1991) concluded that it would be necessary to measure absolute gravity for this method to yield accurate results. However, without measuring absolute gravity, Pool (1999) and Schmerge (2003) used a relative gravimeter to estimate aquifer-storage change in the Lower Cañada del Oro subbasin by assuming that gravity on bedrock was constant. Absolute gravity was measured at 3 sites on bedrock within about 20 km of the Lower Cañada del Oro subbasin between 1998 and 2005 (figure 9); the average change in gravity at these sites between measurements was about 0.0 ± 5.5 µGal (Schmerge, 2006). Using the standard deviation of 5.5 µGal from these 3 sites to estimate the uncertainty in the assumption that gravity on bedrock is constant, Schmerge (2006) concluded that the estimated aquifer-storage change of Pool (1999) was smaller than the uncertainty.

The variability of gravity at the 3 sites in Arizona is similar to that observed on bedrock at other sites in the world, where gravity does not simply remain constant, or vary at a constant rate. Seasonal variability has been seen in the gravity signal at places like: a low-porosity argillaceous sandstone at Membach, Belgium, with a variation of about 12 µGal in 7 years (Francis and others, 2004; Van Camp, 2006); a schist in Bad Homburg, Germany, with a variation of about 17 µGal over a period of 12 years (Wilmes and Falk, 2006); and on metamorphic rock at the Geodetic Observatory Pecný in the Czech Republic, with a variation of about 9 µGal in 4 years (Šimon and others, 2006).

Significant changes in gravity can occur on bedrock in periods as small as a few weeks. At the WULG, an old gypsum mine, gravity varied by 3.6 µGal in just 23 days (Schmerge and Francis, 2006). Consider, for example, if this amount of change occurred





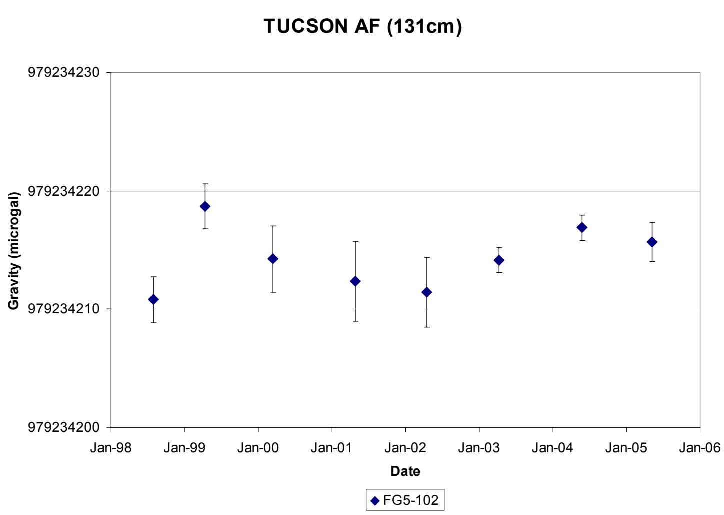


Figure 9. Absolute gravity measurements by FG5-102 and A10-008 at three sites on bedrock in southern Arizona.

at a reference station during a gravity survey, with an absolute measurement at the start of the period, and relative measurements at the end of the period. The assumption that there was no change in gravity at the base station during this interval would cause a bias in the change of gravity of 3.6 μGal for the relative stations. To minimize this potential error, all gravity measurements should be performed in as short of a time period as possible.

Sampling

Sampling error is inevitable, because the change in gravity cannot be measured at every point in the study area. The sampling error will be:

$$\delta s = \mu_{\Delta g} - \overline{\Delta g}, \tag{15}$$

where $\mu_{\Delta g}$ is the average change in gravity and $\overline{\Delta g}$ is the average change in gravity of the sampled points.

In the Lower Cañada del Oro subbasin (figure 7), Schmerge (2003) broke the study area into area elements of 10^4 m^2 and used geostatistics to estimate the change in gravity and the error for each element, and then estimated the sampling error using the equation:

$$\delta s = \left(\sum_{i=1}^{n} \delta s_i \cdot \Delta A \right)^{1/2}, \tag{16}$$

where δs_i is the error of the estimated change in gravity for area element ΔA. However, this assumes that δs_i is independent for each area element; an assumption that is not necessarily valid, because there is some spatial correlation in the change in gravity – and the standard error – for the area elements. Instead, it is more appropriate to break the study area into squares of equal size with one randomly selected measurement from each element, and then estimate the sampling error as:

$$\delta s = \sigma / \sqrt{n}, \tag{17}$$

where σ is the standard deviation of the measurements, and n is the number of sampled points. Using a grid of 14 squares and randomly selecting one measurement from each square gives $\overline{\Delta g}$ equal to about 41 μGal, and σ equal to about 40 μGal; so the sampling error is about 11 μGal.

Vertical Deformation

The uncertainty associated with vertical deformation can be significant. Land-surface deformation commonly occurs in alluvial basins due to ground-water withdrawal and recharge. Both permanent and reversible deformation can occur. Reversible deformation commonly results in land surface displacements of several centimeters in the vertical direction (Amelung and others, 1999; Galloway and others, 1999; Bawden and others, 2001). The vertical gravity gradient is about -3 μGal/cm; therefore, vertical deformation that is not measured will cause an error in the estimation of aquifer-storage change.

In the Lower Cañada del Oro subbasin, vertical deformation was, until recently, assumed to insignificant based on the results of GPS measurements of a few sites (Pool, 1999; Schmerge, 2003. However, it was hypothesized that significant deformation may be occurring, because these few sites were not necessarily representative of the entire area. Also, the GPS measurements were not conducted simultaneously with the gravity measurements; therefore, even if there was no significant change in elevation between the GPS surveys, it is possible that there was a significant change in elevation between the gravity surveys. Recently, multiple GPS surveys of all the sites in the Lower Cañada del Oro subbasin revealed an average deformation of -1.6 cm between February 2004 and January 2005, and -0.7 cm between January 2005 and September 2005 (Schmerge, 2006). It is not certain whether this deformation is permanent, reversible, or some combination of both; but based upon this evidence, it is now assumed that it is possible that some significant reversible deformation has been occurring for years. Schmerge (2006) reported that an uncertainty of 1 cm for the average change in elevation results in an uncertainty that is more than half the size of the estimated aquifer-storage change of Pool (1999).

The uncertainty of the measured average deformation from the recent GPS surveys in the Lower Cañada del Oro subbasin still needs to be determined. Trimble Geomatics Office (TGO) was used to determine the ellipsoid heights, and Trimble Navigation Limited (2001) recommends using TGO to perform a "fully constrained adjustment" of the data, which means fixing the horizontal positions of at least 2 points and the vertical positions of at least 3 points. However, in this application, it is recommended by G. Blewitt (oral commun., 2005) to hold only one point on bedrock fixed, to assume that all the stations on bedrock are moving at the same rate, and to estimate the uncertainty of the average vertical deformation as the standard deviation of the change in elevation of the non-fixed points on bedrock.

Density

The uncertainty of the density must be considered, because significant non-aquifer mass flux may also occur in the study area. Mass flux from geologic processes may include magma, ice, and sedimentation; and human activities to consider include construction and mining. In some settings, it may be necessary to monitor non-aquifer mass flux and correct for it, in order to obtain a significant estimate of the aquifer-storage change. Also, in some settings, it may not be possible to accurately separate the non-aquifer mass from the aquifer mass.

Magma and ice flux have been monitored from temporal changes in gravity in several studies. For example, magma intrusion was detected beneath Long Valley Caldera in California; after correcting for the effects of deformation and water table fluctuations, the density of the intruding material was estimated to be 2.7 to 4.1 x 10^3 kg/m^3 at 95 percent confidence (Battaglia and others, 1999). Also, cyclic movement of magma – both intrusion and drainage – was detected under Mt Etna; after correcting for the effects of deformation and water table fluctuations, the volume of magma was estimated to range between 3 and 10 x 10^8 m^3 (Carbone and others, 2003). Mass variations of the Antarctic ice sheet were monitored from 2002 to 2005 using temporal gravity measurements from the Gravity Recovery and Climate Experiment; after correcting the data for contamination from several geophysical processes, the rate of mass loss was estimated to be about $1.52 \pm 80 \times 10^{11}$ m^3 per year (Velicogna and Wahr, 2006).

Sedimentation should be considered as a possible source of error. For example, the major washes in the lower Cañada del Oro subbasin are about 24 km long (figure 6), and perhaps ¼ km wide. They are usually dry, but deposition or erosion may occur after a flood. Generally, the sediment flux is probably near equilibrium, with approximately equal amounts of sediment being washed into and out of the study area. However, numerous benchmarks are located within the wash, and it is not unusual to occasionally find some of them buried by about 1 cm of sediment. If sediment is deposited 1 cm deep across the major washes in the study area, the total volume would be about 6×10^4 m^3. There are also numerous smaller washes leading directly into the study area from the surrounding mountains; and if they make a significant contribution, then perhaps the total would be doubled. An equivalent mass of water would have a volume of about 1×10^5 to 2×10^5 m^3. This volume is about 1 or 2 percent of the aquifer-storage change reported by Pool (1999), and about 0.1 to 0.2 percent of the aquifer-storage change reported by Schmerge (2003).

Construction is rapidly occurring in the Cañada del Oro subbasin, a primarily urban environment with a growing population that contains most of the town of Oro Valley, and parts of the town of Marana and the city of Tucson. Part of the area is unincorporated, but it too is being developed. It is not simple to accurately estimate the amount of mass flux from construction, but even a crude estimate may be helpful in estimating $\delta\rho$. There is about 6×10^4 kg of mass in an average house (Franklin Associates, 1998); and the town of Oro Valley, covering about half the study area, issued 1,445 new building permits in 2004 (Arizona Department of Commerce, 2005). Assuming there were twice this many permits in the entire study area, and assuming the new buildings in the study area are equivalent in size to an average house, then the construction mass added to the study area in 2004 is about 1.6×10^8 kg. Some of the new buildings will of course be nonresidential, which tend to be larger than residential buildings, so perhaps the total should be doubled to 3.2×10^8 kg. About ⅔ of the construction is above ground, and the rest is below ground (Franklin and Associates, 1998), so only about ½ of the above ground mass will contribute to the total mass flux. This mass is equivalent to a volume of about 1×10^5 m^3 of water. This is about 1 percent of the aquifer-storage change reported by Pool (1999) and about 0.1 percent of the aquifer-storage change reported by Schmerge (2003).

Mining might include oil, natural gas, coal, gravel, and ore. Within Antelope Valley and the Lower Cañada del Oro subbasin, there is no mining activity. Therefore, the effect of mining is not considered in detail. However, in some settings mining activity may cause contamination of the data that will need to be corrected.

Study Area and Edge Problem

It is a practical difficulty that, in theory, the integration is to be carried out over the entire horizontal plane, while data exist only within a limited area (Cole, 1991; Howle and others, 2003; Schmerge, 2003). Assuming the entire mass is concentrated at the center point, and the measurements are sufficiently far away, then for a mass of any shape, this edge problem can be solved by applying the correction:

$$C = \frac{\pi}{2} \cdot \left(\tan^{-1} \frac{XY}{Z\sqrt{X^2 + Y^2}} \right)^{-1} \tag{18}$$

where 2X and 2Y are the dimensions of a rectangular study area with the gravity anomaly near the center, and Z is the depth of the anomaly (Grant and West, 1965).

At an injection storage and recovery test in Antelope Valley (figure 3), Howle and others (2003) used gravity to measure a rate of aquifer-storage change that was equivalent to only 42 percent of the injection rate; it was hypothesized that the unmeasured volume was caused by the mound of water extending significantly beyond the gravity network (figure 4). This edge problem was not corrected. The areal extent of the gravity network is not rectangular, but approximately trapezoidal, and the gravity anomaly is not in the center of the network. However, if it is estimated that X is about 220 ± 20 m, Y is about 440 ± 20 m, and Z is about 88 ± 5 m; then C is about 1.37 ± 0.04. With this correction, there is still only about 57 percent of the injected water accounted for.

DISCUSSION

Several examples may be useful to demonstrate the calculation of the uncertainty of the aquifer-storage change. Results from one case in Antelope Valley, California; and two cases in the Lower Canada del Oro subbasin, Arizona are discussed. In each of these cases, the uncertainty of the aquifer-storage change was not reported.

Antelope Valley, November 1996 to April 1997

In Antelope Valley, California, an average change in gravity of about 33 μGal was monitored at 20 sites to estimate an aquifer-storage increase of about 4.9 x 10^5 m^3 between November 1996 and April 1997 (Howle and others, 2003) (figures 1 through 4). This storage increase was monitored during an injection, storage, and recovery test; and after correcting for the edge problem, the rate of increase determined from gravity measurements was only 57 percent of the rate of injection. Absolute gravity was not measured, instead it was assumed that a nearby crystalline bedrock promontory was a stable gravity reference (figure 2). L&R gravimeter D79 was used to do the relative gravity surveys (Metzger and others, 2002), and the calibration of the relative gravimeter was apparently not checked.

The uncertainty of the average change in gravity ($\delta\mu_{\Delta g}$) can be estimated by calculating the error from assumptions (δa), the measurement error (δm), and the sampling error (δs). Because gravity was assumed to be stable at the reference station, δa is assumed to be 5.5 μGal. The probability of a significant calibration shift within 5 months should be small, but the effect of a 0.1 % calibration shift can be calculated from the reported relative gravity values, and the result is an error in the average change of gravity of about 4.8 μGal. Relative measurements tied the reference station to one station within the study area, to which all the other sites were tied; therefore, equation 14 can be used to calculate the relative measurement error. The reported values of $\sigma_{s\alpha}$ and $\sigma_{s\omega}$ are 5.3 μGal and 7.4 μGal; and each of the gravity surveys consisted of two loops, so $n_{s\alpha}$ and $n_{s\omega}$ are both 3. Taking the reported average repeatability of the relative measurements, $\sigma_{r\alpha}$ is 4.2 μGal and $\sigma_{r\omega}$ is 3.4 μGal; and $n_{r\alpha}$ and $n_{r\omega}$ are both 19. Therefore, δm_r is about 5.4 μGal – assuming there was no calibration shift – or about 7.2 μGal – assuming the possibility of a 0.1 % calibration shift. In calculating the sampling error, many of the 20 sites were clustered near the center of the injection mound (figure 4), so they should not all be used; instead, breaking the area into six elements and randomly selecting one site from each gives a δs of about 6.6 μGal. Therefore, $\delta\mu_{\Delta g}$ is about 10 μGal if the possibility of a calibration shift is ignored, or about 11 μGal if the possibility of a calibration shift is included.

Vertical deformation was apparently insignificant during the 5 month period. Land subsidence has exceeded 2 m in the study area since the 1920s (Ikehara and Phillips, 1994), and interferometric synthetic aperture radar (InSAR) measurements showed that land subsidence continued between 1993 and 1995 (Galloway and others, 1998). However, Howle and others (2003) monitored vertical deformation at 15 of the 20 stations with GPS surveys during the injection test, and interestingly, the average vertical deformation was only 0.02 cm over the five month period. The uncertainty of the average vertical deformation was not assessed. In general, the best attainable uncertainty of the average vertical deformation using GPS measurements is perhaps 0.3 to 0.5 cm (R. Bennett, oral commun., 2005), and the vertical gravity gradient is about -3 μGal/cm, so it is assumed that $\delta\mu_{\gamma\cdot\Delta h}$ is at least 1 μGal.

Non-aquifer mass flux is probably insignificant. The study area is outside the urbanized areas of Lancaster and Quartz Hill (figure 2) and there is no known mining, so the mass flux from human activity is assumed to be small. The only known possible geologic process that may cause significant mass flux in the study area is sedimentation. Amargosa Creek (figures 2 and 3) is ephemeral and generally flows only after periods of intense rain, but there was no mention of any runoff during the 5 month period of the test (Howle and others, 2003). Therefore, it is assumed that any mass flux from geological processes was small, and the density of the mass is estimated to be about 1000 ± 5 kg/m^3.

The areal extent of the gravity network (figure 4) and the correction factor need to be estimated, because they were not reported by Howle and others (2003). The area is estimated to be about 3.9 ± 0.4 x 10^5 m^2, and the correction factor has been estimated to be about 1.37 ± 0.04 (page 19).

The aquifer-storage change and its uncertainty can now be estimated. Correcting for the edge problem and using equation 9 to calculate the uncertainty of the aquifer-storage change results in an aquifer-storage increase of about 7 ± 3 x 10^5 m^3.

Lower Cañada del Oro Subbasin, July 1997 to October 1998

In the Lower Cañada del Oro subbasin, Arizona, an average change in gravity of about 5 μGal was monitored at 20 sites to estimate an aquifer-storage loss of about 1.4 x 10^7 m^3 between July 1997 and October 1998 (Pool, 1999). It was assumed that gravity at two reference stations on crystalline bedrock was stable, and that vertical deformation was insignificant based upon GPS measurements of a few of the stations. L&R gravimeter D127 was used for all of the relative gravity measurements.

The uncertainty of the assumption that gravity on bedrock is constant was estimated to be about 5.5 μGal (Schmerge, 2006), but because 2 reference stations were used, the error may be somewhat smaller than this. If the change in gravity at the 2 reference stations is correlated, then the estimated uncertainty of 5.5 μGal is reasonable. However, if gravity is changing independently at the 2 sights, then the uncertainty can be estimated not as the standard deviation, but the standard error, which for two reference stations is about 3.9 μGal. Without a time series of the change in gravity at these two sites, it is not possible to determine if the change is correlated.

The uncertainty of the relative measurements depends on the possibility of a calibration shift and how the network was tied together. A calibration shift of 0.1 percent has been estimated to cause an error of about 5 μGal (page 12). The network ties were not thoroughly described by Pool (1999), so the uncertainty of the relative measurements is not simple to estimate; however, it is apparent from the description that there was some bias in the measurements, that the repeatability was generally better than about 4 μGal, and that about 2 loops were generally completed for each survey. Therefore, about 3 to 5 μGal of uncertainty from the network ties seems like a reasonable estimate.

The sampling error (δs) can be calculated using all twenty stations in the network because they are well distributed. The standard deviation of the change in gravity is about 6.8 μGal, so the sampling error for 20 stations is about 1.5 μGal.

The uncertainty of the average change in gravity ($\delta\mu_{\Delta g}$) can now be estimated from equation 10. For a δa of about 3.9 to 5.5 μGal, a δm of about 3 to 7 μGal, and a δs of about 1.5, $\delta\mu_{\Delta g}$ is about 5 to 9 μGal. The average change in gravity was only 5 μGal, so it is apparent that the measured change in gravity was not significant.

Vertical deformation during the time period was assumed to be insignificant based on GPS measurements from two stations. The uncertainty of this assumption was not assessed, but Schmerge (2006) concluded that an average deformation of about 1 cm was a reasonable possibility, and therefore estimated the uncertainty of $\delta\mu_{\gamma\cdot\Delta h}$ to be about 3 μGal.

The measured average change in gravity of 5 μGal was assumed totally caused by a mass flux, because the average change in gravity caused by vertical deformation was assumed to be zero. Using an uncertainty of 5 to 9 μGal for $\delta\mu_{\Delta g}$, and an uncertainty of 3 μGal for $\delta\mu_{\gamma\cdot\Delta h}$, the uncertainty of the average change in gravity caused by a mass flux is about 6 to 10 μGal. The estimated change in gravity caused by a mass flux is smaller than the range of the uncertainty, so regardless of the uncertainty of the density, area, and edge problem, the aquifer-storage change is smaller than the uncertainty. It is therefore necessary to conclude that the aquifer-storage change estimated by Pool (1999) is not significant.

Lower Cañada del Oro subbasin, October 1998 to October 2002

In the Lower Cañada del Oro subbasin, Schmerge (2003) estimated an aquifer-storage loss of about 1.3 x 10^8 m^3 between October 1998 and October 2002. The network consisted of 63 stations. Gravity was assumed to be constant at a reference station in the Tortolita Mountains (figure 6). Relative gravimeter D127 was used to collect all the gravity data, the calibration was not checked, and the repeatability of the measurements was ≤ 5 μGal. The change in gravity of the measurements ranged from + 4 to – 141 μGal. Vertical deformation was assumed to be insignificant based upon GPS surveys of a few sites. The size of the study area is about 1.4 x 10^8 m^2. The study area was divided into cells of size 10^4 m^2 and geostatistics was used to interpolate changes in gravity between measured stations. The change in gravity of each cell was then summed to estimate the total aquifer-storage change. The average change in gravity of the estimated cells was about 39 μGal.

The uncertainty of the average change in gravity ($\delta\mu_{\Delta g}$) can be estimated by calculating the error from assumptions (δa), the measurement error (δm), and the sampling error (δs). Because gravity at the reference station was assumed stable, δa was estimated to be 5.5 μGal (Schmerge, 2006). Because the calibration of D127 was not checked, for a network of stations with a range of 28 mGal and a reference station with the lowest value of gravity in the network, the effect of a 0.1 % calibration shift is estimated to be 14 μGal (Schmerge, 2003) (table 2). A description of how the network was tied together was not provided and the error was not estimated, so the error is estimated to be about 5 μGal. Combining the error from a calibration shift and the network ties gives an uncertainty of the relative measurements of about 15 μGal. The sampling error has been estimated to be about 11 μGal (page 16). Combining δa, δm, and δs gives an uncertainty of the average change in gravity of about 19 μGal.

The uncertainties of the change in gravity caused by vertical deformation and the density were estimated to be about 3 μGal and about 5 kg / m^3 respectively (Schmerge, 2006). The area was reported to two significant figures by Schmerge (2003), so δA is estimated to be about 0.1 x 10^8 m^2.

The correction factor has not been considered for this case. The approximation of placing all the concentration of the mass at its center is not suitable for a study area like the Lower Cañada del Oro subbasin (figure 6), where the depth to the gravity anomaly – between 0 and 100 m – is much smaller than the lateral extent of the anomaly. Therefore, for cases like this, an alternative strategy needs to be considered to adequately correct the edge problem.

Therefore, if the edge problem is ignored, the aquifer-storage change and its uncertainty is estimated to be about 1.3 ± 0.6 x 10^8 m^3.

CONCLUSIONS

After an analysis of the sources of error and their propagation, it is apparent that the method of using temporal changes in gravity to estimate aquifer-storage changes has not always provided significant results. However, it is also apparent that the results have sometimes been significant. The uncertainty of the aquifer-storage change estimated from a temporal change in gravity can be considered in 5 parts: (1) the average change of gravity, (2) the average change of gravity caused by vertical deformation, (3) the density of the mass, (4) the size of the study area, and (5) the edge problem. The average change in gravity was the largest source of error for each of the three cases reviewed. In the two cases that yielded significant results the average change in gravity was greater than 10 μGal, while in the case that yielded an insignificant result, the average change in gravity was less than 10 μGal. There are multiple things that can be done to minimize the uncertainty in the average change in gravity, including: regularly check the calibration of L&R gravimeters, reduce the sampling error, and measure absolute gravity at the reference stations. Vertical deformation may also be a significant source of error, especially if permanent land subsidence is occurring while it is not being measured. Seasonal deformation of several centimeters may also cause a significant error unless deformation and gravity are measured simultaneously. The uncertainty of the density has been insignificant, but may be a significant problem in some settings. The area and edge problem should be taken into account by measuring over as large an area as possible, and using a correction factor to compensate for the missing part of the gravity anomaly. Finally, an alternative strategy to solving the edge problem may prove to be beneficial for a large study area such as the lower Cañada del Oro subbasin,

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