Time-lapse gravity monitoring: A systematic 4D approach with application to aquifer storage and recovery

Kristofer Davis¹, Yaoguo Li¹, and Michael Batzle²

ABSTRACT

We studied time-lapse gravity surveys applied to the monitoring of an artificial aquifer storage and recovery (ASR) system in Leyden, Colorado. An abandoned underground coal mine has been developed into a subsurface water reservoir. Water from surface sources is injected into the artificial aquifer during winter for retrieval and use in summer. As a key component in the geophysical monitoring of the artificial ASR system, three microgravity surveys were conducted over the course of ten months during the initial water-injection stage. The time-lapse microgravity surveys successfully detected the distribution of injected water as well as its general movement. Quantitative interpretation based on 3D inversions produced hydrologically meaningful density-contrast models and imaged major zones of water distribution. The site formed an ideal natural laboratory for investigating various aspects of time-lapse gravity methodology. Through this application, we have studied systematically all steps of the method, including survey design, data acquisition, processing, and quantitative interpretation.

INTRODUCTION

The Colorado Front Range has a history of repeated drought conditions, and therefore the issue of water storage and retrieval is an increasing concern in the region. Figure 1 shows the conflict between the need and supply of water in the western United States (U. S. Department of Interior, 2007). Large amounts of excess water are present during the winter months; yet during summer, increased consumption of water for the rapidly growing population strains the water supply. Surface reservoirs use valuable land needed for development or the preservation of open space and can have an annual pan evaporation loss of 1.5 m of water (GROW, 2002). In addition, this method of storage is not always viable economically for the local community because the cost of construction and maintenance of such reservoirs can reach tens of millions of dollars.

The aquifer storage recovery (ASR) process (Pyne, 1995) provides an alternative and affordable management approach to the water supply needs in this region because it utilizes an underground reservoir, and surface space is not required. Traditionally, ASR systems use natural aquifers; but the same technology can be applied to artificial aquifers such as man-made subsurface voids. Instead of further straining naturally occurring aquifers, the city of Arvada, Colorado, has turned to an abandoned underground room and pillar coal mine, the Leyden mine, as a solution for water storage. This alternative solution is advantageous because abandoned underground coal mines have a large storage capacity, and their subsurface conditions are better known.

Filling coal mines with water has been done locally in Colorado Springs, Colorado, for subsidence prevention, as well as nationally for other ASR projects such as those in the Appalachian coal belt (Topper et al., 2004) where coal mines are abundant. As in any storage-recovery process, however, there are many uncertainties. In particular, water distribution in the subsurface is unknown. Although local observations from wells provide valuable localized information, monitoring using geophysical methods is necessary to provide large-scale characterization.

One possible means of monitoring water distribution in the mine is through the time-lapse gravity method. This approach has demonstrated several successful applications such as monitoring urban tunnel advancement (Butler, 1991); geothermal reservoir change (Allis and Hunt, 1986); water injection into petroleum reservoirs (Ferguson et al., 2007); and more relevant to our problem, characterizing natural aquifers (Pool and Schmidt, 1997). However, the site condition and areal extent make the Leyden mine a rather unique case for time-lapse gravity surveys. The mine also provides the unusual opportunity to study the method in a natural laboratory setting.

To determine the feasibility of the method, over a ten-month period we acquired three separate relative gravity surveys that observed...
the injection of water during the first ASR process. The use of relative gravity significantly decreases the cost of monitoring the ASR process compared with absolute gravity. Modern relative gravimeters have the requisite accuracy to detect the signal from water injection while allowing the process to be economical. From the gravity surveys, we observed stable anomalies over the period of time; and the data are consistent with the known geology and projected water distribution.

**BACKGROUND**

The Leyden mine, located in the city of Arvada, Colorado, was an active dual-seam underground coal mine until its closure in 1958. Subsequently, the mine was used as a natural gas storage facility for the Public Service Company of Colorado (PSC). The natural gas storage project was suspended after forty years. The Oil and Gas Commission of Colorado accepted a closure and remediation plan whereby the gas would be removed through displacement with water. The City of Arvada retained rights to the area as a water storage facility and began using the site as a subsurface reservoir in 2003. There was a two-year period of purified water injection, which was to be followed by storage/recovery cycles to maintain water quality.

The mine workings span an area of approximately 4.3 square kilometers at 300 m below the surface in the Laramie Formation (a fluvial, shaley sand). About 30 m below the base of the mine is the top of the Fox Hills sandstone, containing a natural confined aquifer underlain by the Pierre Shale. Overall, permeability of the Laramie formation is low, and it acts as a cap to the mine. Figure 2 is a vertically exaggerated, simplified geologic cross section of the mine. The overall dip of the area is less than five degrees, dipping southwest. An injection well was placed in the southwest to force the residual stored gas to the shallower, northeast portion of the mine for withdrawal.

The two coal seams were mined by using a room-and-pillar method that left large void spaces within the mine workings. These voids have become the primary storage space for water. Unfortunately, abandoned coal mines rarely maintain their structural integrity; and various degrees of collapse can occur, as illustrated in Figure 3. This collapse, called stoping, is the result of roof material falling into the mine workings, leading to rubble zones of an unknown height. If the mine is large enough or close enough to the surface, subsidence can be measured at ground level. Otherwise, the stoping reaches some height before equilibrium is reached (Dunrud, 1998). Stoping will occur only within a few months to years following mining (Colorado Geological Survey, 1986; Amuedo and Ivey, 1997).

Rubble zones in the mine can create more permeable zones through which water can flow. Therefore, injected water can flood the voids to a considerable height and volume above the original roof of the mine. The water also can infiltrate these zones before the mine voids are filled. However, when rock collapses from the rubble zones, it will expand (Dunrud, 1998). The Lower Laramie Formation rock will expand in volume by approximately 20% (Sherman, 2003). This expansion could cut off the mine workings and not allow for maximum storage. The extent and precise nature of these rubble zones are unknown and constitute the largest variability in factors that control movement and distribution of water.

An independent study by Sherman (2003) showed that the maximum subsidence at Leyden would be less than 25 cm. Within this study, it was shown that no actual subsidence was observed on the surface. Using strain analysis, Sherman (2003) also calculated the rubble zone height to be no more than 35 m. Using the method described in Dunrud (1998), the rubble zones at the Leyden mine should be no higher than 45 m from the coal seams. We calculated that the expected rubble zone porosity is approximately 35%.

Other methods to quantify the maximum rubble zone height also have been used, and they result in approximately the same heights (Bell, 1975; Ackenheil and Dougherty, 1970). Based on this information and specific study of the area, we are confident that there is no elevation change as a result of subsidence at Leyden. For that reason, we elected not to monitor the surface elevation. We remark, however, that elevation monitoring should be considered essential, in general, in 4D gravity surveys.

To effectively use the Leyden mine for water storage and recovery, details of water distribution are critical. Knowledge regarding the locations of
rubble zones also is crucial for the placement of recovery wells to achieve optimal water retrieval. Any information about leakage out of the mined area also is desired; because the recovery efficiency, defined here as the percentage of injected water that can be recovered, is significant in any storage-recovery problem. We chose time-lapse gravity as one of the geophysical methods for monitoring the ASR process after forward modeling predicted a substantial gravity anomaly from injected water.

**TIME-LAPSE GRAVITY SURVEY**

**Survey design**

Based on knowledge that the mine workings are at a depth of 300 m, we chose a 300-m station spacing for the microgravity survey, as the theory of survey design would suggest (e.g., Elkins and Hammer, 1938; Reid, 1980; Murray and Tracey, 2001). The terrain, lateral extent of the mine workings (16 km²), and cost consideration all have influences in survey design. The original goal was to attempt to monitor the entire mine at an even grid; thus 90 stations were planned. However, because of time constraints, terrain, and inclement weather, only 56 stations were occupied consistently throughout all three surveys (Figure 4).

These stations covered the area over the southern portion of the lower coal seam (B) into which the water was injected. Each station was marked with a 12-inch steel bar so that both the exact location and elevation of a gravity station could be repeated accurately throughout all surveys, as well as in future surveys. The data were repeated at an elevation consistent with each respective rebar throughout all surveys to minimize the data error caused by variation in vertical position of the gravimeter. The steel bar also enabled us to re-locate the stations with a metal detector throughout the year, regardless of weather conditions.

We remark that an often-mentioned design for time-lapse gravity surveys is to pour a concrete platform at each station. We found that this is not necessary; and on the contrary, such a platform actually might be noisier in high-resolution microgravity surveys because it transmits ground and wind vibration to the gravimeter. We found that it is better to place the gravimeter on soft but stable soil. In addition to regular stations, we also placed four stations far from the area of mine workings. We used these stations as reference points to tie together the multiple relative gravity surveys and for quality-control purposes. Forward modeling helps place the reference stations properly so that the expected changes at the reference stations are less than instrument error. The locations of gravity stations occupied in the surveys are shown by white dots in different maps that will be discussed later (e.g., Figure 4).

**Data acquisition and processing**

Three microgravity surveys were conducted. The first two surveys were performed with a Scintrex CG-3 relative gravimeter. These surveys were taken in April and October 2004. The CG-3 has a published accuracy to within ±10 μGal.

Measurements were recorded for 60 s, and an average reading was obtained. To improve accuracy, two readings were taken at each station. The third survey was acquired with a Scintrex CG-5 relative gravimeter. This survey was taken in February 2005. The CG-5 has a published accuracy of ±5 μGal. Measurements also were recorded for 60 s with two readings per station, as with the CG-3. Each pair of readings from each survey was averaged to obtain one reading per station for difference mapping and inversion purposes.

Both gravimeters had an automatic tide correction, seismic correction, and auto rejection of outliers. In addition, base stations were repeated every two to three hours for improved accuracy of the tidal and drift correction. As a part of quality control, we also repeated approximately 15% of the stations during each survey.

Of the four reference stations located away from the coal seams, one was lost because of construction at the site. Of the remaining three, we used one as a reference station at which the gravity value is assumed to be constant over time. The gravity differences of the other reference stations are less than instrument error. The average gravity readings from each survey was averaged to obtain one reading per station for difference mapping and inversion purposes.

![Figure 2: A vertically exaggerated, simplified geologic cross section of the Leyden coal mine in the Lower Laramie Formation. The coal seams are located approximately 300 m below the surface. Water is being injected into the deeper part of the mine to help remove residual natural gas by pushing it to the shallower seam, where it can be extracted.](image)

![Figure 3: Illustration of types of collapse above mine workings and the formation of rubble zones (modified from Dunrud, 1998).](image)
er two background stations were examined for quality-control purposes. During the surveys, the remote background stations varied less than 5 μGal in time-lapse signal, which is within the accuracy of the gravimeter. Three data sets were processed accordingly. The importance of multiple background stations is twofold. Without the aid of absolute gravimetry, the unexpected loss of a sole background station renders the time-lapse surveys useless. Quality assurance also is achieved with comparison of the multiple stations, in case one is influenced by the injected mass or other unforeseen circumstances.

Background or reference stations play an important role in time-lapse relative gravity survey. These stations should have no influence from the targets being monitored. In the absence of absolute gravity stations, background stations serve as anchors to difference multiple data sets. Furthermore, the zero-anomaly requirement at background stations allows one to remove any unknown spatially common-mode changes that affect the data sets, such as atmospheric loading and regional aquifer variation, whose gravitational effect changes temporally but remains constant spatially within the survey. In this application, numerical modeling during the survey design stage ensured the zero-anomaly requirement of these stations. We lost one during the course of the survey, and the remaining three ensured the accurate processing of the data sets.

In addition, variation of time-lapse gravity among multiple background stations serves as a tool for data quality control and assurance. By utilizing multiple background stations that meet the zero-anomaly requirement, we can obtain reliable difference maps without tying the survey to a local absolute gravity station. If such stations are not available, or one is not certain that the gravity field will remain constant at reference stations, the use of one absolute station at any relative station will measure the difference over the course of multiple surveys. This difference can then be used to reference multiple data sets to calculate appropriate time-lapse difference.

As with all gravity surveys using a relative gravimeter, instrument drift and tidal influence must be quantified and removed from the data. It is common practice to also process terrain, free air, Bouguer, latitude, elevation, and isostatic corrections (e.g., Reynolds, 1997). However, with the use of permanent station locations, the exact spatial position for each station is repeated during each individual survey. Other than instrument drift and tides, the remaining corrections are static over time and naturally removed when two data sets are subtracted from each other. Therefore, one needs to apply only the drift and tidal corrections to the individual surveys to create difference maps that capture the change of gravity over time resulting from subsurface mass change. We also performed a statistical analysis and removed one outlier from the eastern portion of the survey. This data point does not affect any of the quantitative analysis because we focus on the southwest portion of the mine near the injection well.

The processing of normal gravity surveys does not include environmental effects, which can vary in time. Environmental effects have two main components: atmospheric loading and aquifer fluctuation. Effects from atmospheric loading in Colorado are on the order of 4 μGal (van Dam and Wahr, 1987), but they can fluctuate more at lower elevations. A standard approach to atmospheric loading is to multiply −0.42 μGal/mbar to the pressure difference between the surveys (e.g., Niebauer, 1988; Merriam, 1992; van Dam and Wahr, 1998). This effect is on a regional scale and can be considered common-mode noise because it influences all measurements, including the background values. For large surveys, when there could be lateral variations, it might have to be taken into account.

Day-to-day fluctuations are within instrument noise but are also accounted for by referencing the data to the previous day’s data utilizing base stations. Aquifer fluctuation caused by recharge, or lack thereof, and other effects might not be on the regional scale. Understanding the withdrawal of water between surveys also is important in quantifying the influence from an aquifer (unless this is what one is monitoring). The influence might vary within the survey, and more information would be required to take these effects into account. In the case of Leyden, the aquifer contained in the Fox Hills is confined, and the piezometric surface is above the confining layer. Thus, the aquifer would not have changed elevation.

The effects of environmental loading can be significant, but specific monitoring and processing might not be necessary. One exception is the presence of unconfined aquifers that are not the desired target. Fluctuations over a multiday gravity survey also are common-mode noise because of the requirement to repeat base stations. Most variations resulting from atmospheric loading within a single day are within instrument error, but they are taken into account by repeating base stations for instrumental drift and tide corrections.

Three difference maps were generated from the data sets. The differences between the first and second, the second and third, and the first and third surveys are shown in Figures 5, 6, and 7, respectively. Standard deviations were calculated from reference and the approximately 15% repeated stations for the three generated difference maps. The repeated stations allowed for a quantitative estimate of the errors associated with just reoccupying stations. The calculated errors for each difference map were 10.5, 12.6, and 22.7 μGal, respectively. Although an active local sand quarry is located near the water-injection well, the modeled influence of this was less than the calculated errors (<1 μGal), as was the modeled influence of the precipitation between the surveys (2 μGal).
Changes in the vadose zone above the mine workings are expected to be much smaller than those resulting from precipitation, and they are included in the modeling. The influence of these errors are well below the observed anomalies. Repeatability of human operation seemed to be the largest error factor. Figure 5 indicates the change in gravity resulting from water distribution between April and October 2004. A broad anomaly, observed at many stations, is present near the injection well. It is important also to note the large amplitude (−150 μGal) associated with this anomaly.

Figure 6 shows the change between October 2004 and February 2005. Smaller spatial and amplitude anomalies are present where the broad initial anomaly was located. In addition, other smaller anomalies are present where little to no change was observed between the first and second surveys. Figure 7 reflects the total change in gravity over the mine between April 2004 and February 2005. There are two major anomalies, one in the southern portion of the survey and one in the northern portion. Moreover, all stations observed positive gravity change. These changes in the gravity field correspond well with the expected lateral water distribution based on the mine workings and changes over time that were produced by water injection.

**INTERPRETATION**

We now examine the time-lapse gravity anomaly and its spatial relation to the known mine workings. Overlaying the observed gravity anomaly and the known mine workings (Figure 8), we can interpret whether the water is staying laterally within the workings. We then can forward model the response of water in the known mine workings and examine the residuals to understand more about water movement in the subsurface. These semiquantitative techniques will aid in an overall interpretation of water movement.
quantitative information, we must reconstruct the 3D distribution density change through 3D inversion with constraints. We use the known mine workings as a reference model and the depth range and expected density contrast as basic constraints. We find the expected volume of the southern portion of the mine simply by calculating from the spatial extent of the mine workings and known thickness.

It might be appealing to calculate the excess mass (Grant and West, 1965) from time-lapse gravity data. However, the calculation assumes a sufficiently large data area to capture the entire anomaly from peak through zero amplitude. In many realistic scenarios, this assumption cannot be met. Consequently, the resulting calculation of excess mass is a gross underestimate of the true mass; such is the case in this study.

Instead, we perform 3D inversion to quantify the lateral location of the rubble zones and obtain a more quantitative image of the subsurface. We do know how much water was injected into the ASR process, but the survey area lacks the lateral coverage of the mine workings to use this data to full potential. If the time-lapse gravity over the entire extent of the mine workings were observed, one could use the volume of injected mass as a constraint to the inversion or simply as a check to account for all of the water.

Semiquantitative analysis

Although we ultimately prefer the approach of quantitative analysis via modeling and inversion, we can obtain valuable information from direct inspection of the gravity difference maps. Overlaying the total gravity difference (Figure 7) and the known mine workings (Figure 8), we can see that the shape of the anomaly corresponds well to the shape of the southern portion of the mine. This indicates that the time-lapse microgravity surveys have successfully detected and mapped the water injected into the mine workings. Furthermore, combined with the constant hydraulic head observed in the injection well after the first phase ended, this correspondence strongly suggests there is no leakage occurring, and the injected water is distributed entirely in the mine workings.

The broadest positive anomaly occurs near the injection well, reflecting the increased water mass in the vicinity. A rubble zone might be present just northwest of the injector; as a well-defined anomaly is present in the first difference map (Figure 5), and it expands outward in the second difference map (Figure 6). This anomaly leads us to believe that this rubble zone was filled to a large extent with water during the early stages of injection. The total amplitude of the change in gravity over this zone is about 250 μGal.

In addition to this rubble zone, another zone to the north has begun to fill. These two zones are within the same coal seam (B) and appear to be filling at about the same rate, because they have similar anomaly magnitudes. The zone near the injection well continues to fill as water is being pushed through the lower (B) seam to the upper (A) seam in the eastern portion of the survey. The difference between the second and third gravity surveys shows an anomaly that has the same characteristics as the one (discussed above) in the eastern portion of the survey. Unfortunately, data coverage is sparse and does not capture the anomaly as it does near the injection well. A 130 μGal anomaly is observed, but we might not be observing the entire anomaly or highest amplitude because it could extend north beyond the survey and possibly be larger than the interpreted southern rubble zone.

Two other anomalies spanning multiple stations are present above the two mined rooms near the water-injection well. It is interpreted that the collapsed zone in the north and the remaining mine workings are filled through conduits of water smaller than the resolving power of the survey.

To the east, moderate change has occurred with anomaly magnitudes close to the first difference map, which suggests that coal seam A is filling by these small conduits of water flowing from what is believed to be a single shaft that connects the two coal seams.

To test further the interpretation that there is a rubble zone in the southern part of the mine, we forward modeled the response of this portion of the mine assuming that the void space was 3 m in height and 300 m in depth. Such a model assumes that there are no rubble zones and that the void space was filled with water. We then examined the difference between the observed field data and the modeled data without rubble zones in the southern region.

Figure 9 shows the 3D model, modeled response, observed data, and difference between the model and observed data. There are noticeably high amplitudes in which the main anomaly is present. The increased anomaly amplitude can come only from the presence of excess mass in re-

Figure 9. (a) Model response of the southern part of the mine workings. The response is simulated if the mine was filled with water (density contrast of 1.0 g/cm³) and no rubble zones were present. (c) Model used. (b) Observed data. (d) Difference between the observed and modeled. The positive anomaly in the residual suggests that water infiltrated above the mine workings, most likely into rubble zones near the injection well. Color bars are consistent for all data and range from −80 through 220 μGal.
regions shallower than the original mine workings. This excess mass can be attributed to water infiltrating the low permeable geologic layer above the mine through rubble zones. This modeling confirms our earlier conjecture of rubble zones. This is supported further by quantitative analysis through 3D inversion.

### 3D inversion

We inverted the time-lapse anomaly data (the observed total difference in the southern portion of the mine, as shown in Figure 9a) using two algorithms. Both algorithms reconstruct a distribution of density contrast as a function of position in a 3D volume using the formalism of Tikhonov regularization, and they fit the observed data within the data errors. However, the first algorithm (Li and Oldenburg, 1998) assumes that the density contrast can vary continuously between lower and upper bounds, whereas the second is a binary inversion (Krahenbuhl and Li, 2006) that assumes a prescribed density contrast and constructs a 3D region with the assumed density contrast within the volume.

For this analysis, we focus on time-lapse gravity data over the southern portion of the coal mine. The spatial extent of gravity coverage was very limited; therefore as the entire time-lapse gravity anomaly is not captured by the data, the entire anomaly source will not be captured by the inversion. The model region for inversion was designed to extend 60 m above the mine surface, twice the calculated maximum extent of the rubble zone (Sherman, 2003); and the 3D model based on coal mine workings was used as a reference model. The model region was discretized into 75 × 75 × 5-m cells.

Most applications do not have enough information to incorporate a nonzero reference model, so first we inverted the data using both algorithms with no constraints other than bounding the continuous variable density contrast between 0.0 and 1.0 g/cm$^3$ (Figure 10) and using the calculated rubble zone porosity of 35% (translating to 0.35 g/cm$^3$ in density-contrast change over time) as the maximum for the binary solution. By using these two methods of inversion, we also gain a high confidence in the final quantitative interpretation.

Figure 11 illustrates the inversion result using the continuous variable inversion with a lower and upper bound of 0.0 and 1.0 g/cm$^3$, respectively, as well as the mine workings incorporated as a reference model with a density contrast of 0.35 g/cm$^3$. This figure displays a volume-rendered image of the inversion result. All cells shown have a density contrast above 0.12 g/cm$^3$. The inversion shows laterally where the rubble zones are located and has an average density contrast of 0.30 g/cm$^3$ within the zones, close to the calculated value of the rubble-zone porosity. The majority of rubble zones also should be higher in porosity and might be higher in permeability than the surrounding collapsed mine workings.

Although the results do not give absolute information about the depth extent or thickness of the rubble zone, they do confirm that multiple rubble zones are present in the large anomaly area; whereas the quantitative interpretation had only one major rubble zone and gives a lateral extent. The results show a large area north of the rubble zones where no density change has occurred. The conduits of water flowing into the remaining mine workings are smaller than the resolution of survey, as confirmed by the inversion.

The binary inversion method (Krahenbuhl and Li, 2006) differs from the continuous variable method in that cells within the model can take on only one of two values: zero, which represents no change in the subsurface during water injection; or one, which represents a change in mass distribution. The binary method should be suited ide-
density over time. Thus, the resolving capability of the data set is evaluated better based on what one can achieve in these inversions. One can assess the resolution capability through the use of nonlinear model resolution matrix. The columns of the resolution matrix are the point spread functions (PSF) (Parker, 1994), and they quantify how an impulse anomaly in the true density model would spread out in the recovered density distribution. Each column of the resolution matrix can be generated numerically by inverting the data from an impulse model, using the same inverse operator as for the time-lapse data set (Kirkendall et al., 2007). For this study, we use an impulse model that has a single cell of 1.0 g/cm³ located at the center of the recovered anomaly in Figure 11 and cells with zero density elsewhere.

Figure 12. Model created by the binary inversion using the mine workings as a reference model. The cells have a density contrast of 0.35 g/cm³.

Figure 13 shows the PSF resulting from the continuous variable inversion. Although the function is spread out more in depth, the lateral extent is confined to a total width of 225 m in the northing and easting directions. Thus, the resolution width of time-lapse data with estimated errors is about 225 m at the depth of mine workings. This width is much smaller than the width of each high-density zone recovered from time-lapse data or the zero-density gap between the high-density zones. We can state confidently, therefore, that features shown in the inverted density model are well resolved.

CONCLUSION

We carried out a time-lapse gravity survey over an artificial aquifer storage and recovery site and investigated the practical aspects necessary to obtain quality data. The outcome proves that time-lapse gravity is an effective tool to monitor aquifer storage recovery systems. Results show that the observed gravity anomalies directly detect water distribution within the underground coal mine. Furthermore, the data contain sufficient information to image the distribution of water and detect the presence and location of rubble zones. Qualitatively, one might interpret a major anomaly to be a single large rubble zone, but quantitative analyses using two inversion techniques model the same area as multiple rubble zones above different mined rooms. Away from the mine workings there are also rubble zones that hold, but do not cause leakage of water.

Recent advancements in relative gravity instrumentation allow for a more cost-effective approach and open the avenue for wider application of monitoring technology based on time-lapse gravity. The 300-m depth of the mine workings, serving as the artificial storage in this study, lies between the deep end of groundwater problems and shallow end of petroleum applications. Consequently, the approach taken here potentially can be extended to both areas of applications. We have discussed in detail the necessary steps to obtain successful time-lapse gravity results. For the method to work, reference stations must be placed where there is no signal from the mass injection, but there can be common-mode noise. Of particular importance is the placement of multiple background stations, careful evaluation of environmental effects, and quantitative analyses through 3D inversions.

The use of inversion to determine density-change distributions is necessary to extract the maximum amount of information from time-lapse data. Recovered density change could be translated into hydrogeologic parameters, and a hydrologic model could be developed. One valuable aspect of time-lapse gravity is the observation of changes in density. Water flow could be monitored, and estimates of connectivity and connected porosity could be obtained.

In this case, the inversion results indicate that the rubble zones have an average porosity of 35%, which is consistent with the estimate derived from the geomechanical analysis of collapses forming the rubble zones. Thus, the geophysical model obtained in this study seems to provide quantitative information that could be useful for further hydrologic modeling, if so desired. This aspect is a potential direction for future research because the estimated mass change and associated porosity offer a direct connection between geophysical data and hydrologic parameters.

ACKNOWLEDGMENTS

We thank Mark Floyd and the City of Arvada, Colorado, for their interest in and support for the project. We thank Bob Raynolds of the
Denver Museum of Nature and Science for helpful in-depth discussions. We thank Tim Niebauer, Micro-g LaCoste, Bill Male, and Scintrex for the use of CG-3 and CG-5 gravimeters. We thank Paul Schwering, Matt Gardine, and Andy Kass who helped with field work. We also thank Rich Krahenbuhl for his contribution with the binary inversion. Funding for the project was provided in part by a grant from the City of Arvada. Additional funding was provided by the Gravity and Magnetics Research Consortium (GMRC) sponsored by Anadarko, BGP, Chevron, and ConocoPhillips.

REFERENCES


