THESIS

ESTIMATION OF UNCONFINED AQUIFER HYDRAULIC PROPERTIES USING GRAVITY AND DRAWDOWN DATA

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ABSTRACT

ESTIMATION OF UNCONFINED AQUIFER HYDRAULIC PROPERTIES USING GRAVITY AND DRAWDOWN DATA

An unconfined aquifer test using temporal gravity measurements was conducted in shallow alluvium near Fort Collins, Colorado on September 26-27, 2009. Drawdown was recorded in four monitoring wells at distances of 6.34, 15.4, 30.7, and 60.2 m from the pumping well. Continuous gravity measurements were recorded with a Scintrex ® CG-5 gravimeter near the closest well, at 6.3 m, over several multi-hour intervals during the 27 hour pumping test. Type-curve matching of the drawdown data performed assuming Neuman's solution yields transmissivity *T*, specific yield *Sy*, and elastic component of storativity *S* estimates of 0.018 m^2s^{-1}, 0.041, and 0.0093. The gravitational response to dewatering was modeled assuming drawdown cone geometries described by the Neuman drawdown solution using combinations of *T*, *Sy*, and *S*. The best fitting gravity model based on minimization of the root mean square error between the modeled and observed gravity change during drawdown resulted from the parameters *T*=0.0033 m^2s^{-1}, *Sy*=0.45, and *S* =0.0052. Conservative precision estimates in the gravity data widen these estimates to *T*=0.002-0.006 m^2s^{-1}, *Sy*=0.25-0.65, and *S* =0-0.2. Drawdown conforming to the Neuman solution was forward modeled using combinations of *T*, *Sy*, and *S*. Minimization of the root mean square misfit between these forward models and observed drawdown in the monitoring wells results in T=0.0080 m^2s^{-1}, Sy=0.26, and S=0.000004. Discrepancy between type-curve matching results, gravity analysis results, and drawdown modeling is attributed to heterogeneity and anisotropy within the aquifer, and a relatively large amount drawdown compared to initial saturated thickness, conditions which fail the Neuman solution assumptions. In this aquifer test, gravity was most sensitive to transmissivity, less sensitive to specific yield, and insensitive to the specific storage-saturated thickness quotient. Simultaneous deployment of multiple gravity stations during similar tests should better constrain gravity analysis aquifer property estimates of transmissivity and specific yield.

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CHAPTER 1

MOTIVATION FOR GRAVITY METHOD USE

Many of the principal aquifers in the U.S. consist of unconsolidated and semiconsolidated sand and gravel, largely under unconfined conditions. These include the High Plains aquifer, the Central Valley aquifer system in California, the Mississippi River Valley alluvial aquifer, the Basin and Range basin-fill aquifers, and others across the country. These aquifers account for about 80 percent of ground water withdrawals in the US [*Maupin and Barber*, 2005]. Approximately 82,600 Mgal/d of water was withdrawn from groundwater sources in 2005, with about two thirds of that used for irrigation [*Kenny et al*., 2009]. The majority of water supplied for irrigation comes from unconsolidated and semiconsolidated sand and gravel aquifers [*Maupin and Barber*, 2005]. The high demand for the water these aquifers provide motivates an understanding and characterization of the aquifer properties, enabling more thoughtful management of the resources. Tools which provide a means of ascertaining aquifer properties such as transmissivity, inelastic, and elastic storage can play an important role in ground water management.

Unconfined aquifers are often characterized by analysis of water level changes in a well as a response to pumping of water from or into the aquifer. The drawdown data is then compared to type-curves, defined by various assumptions about the aquifer and test conditions. While methods such as these are deemed to be reliable ways to determine aquifer properties [*Moench*, 1994], they require installation of monitoring wells for data collection. Installing a large number of monitoring wells is expensive and often impractical, but may be required to adequately characterize heterogeneous, anisotropic aquifers.

A potential alternative to a dense well network is the use of portable gravimeters to measure temporal changes in apparent gravity during an aquifer test. The gravity method has been shown to be effective in monitoring subsurface water movement and storage changes [e.g. *Pool and Eychaner*, 1995; *Howle et al*., 2003; *Gehman et al*., 2009]. An extension of the technique to estimate aquifer properties and a test of the method via comparison with drawdown data is required to fully assess the suitability of gravimetric methods as a proxy for measuring drawdown data in monitoring wells for aquifer tests. This work utilizes an expression for the gravitational response due to drawdown in an unconfined aquifer [*Damiata and Lee*, 2006] to analyze gravity data collected during an aquifer test in an unconfined alluvial aquifer in Fort Collins, Colorado. Results of the gravity analysis are compared to standard drawdown analyses, revealing limitations and potential for temporal microgravity use in aquifer testing.

CHAPTER 2

METHODS AND ANALYSIS

1. Introduction

1.1. Background

Groundwater resources are becoming increasingly valuable as human populations dependent on this resource continue to increase. Management of groundwater resources is greatly improved with a thorough understanding of local and regional hydrogeological systems. This includes an understanding of groundwater volume, location, and aquifer properties that influence movement and withdrawal. This information is typically obtained by drilling wells into an aquifer and conducting aquifer tests. Drawdown in these wells permits estimation of aquifer parameters such as transmissivity, storage, and specific yield. The data set is limited to the area in which wells are drilled, and its spatial resolution is only commensurate with the density of well placements. The cost and logistics of drilling many wells makes collecting a dense data set impractical. An easier, cost-effective method of ascertaining aquifer properties is needed.

The use of time-lapse microgravity measurements offers a promising alternative to dense well placement for determination of multi-azimuth aquifer parameters. Modern portable gravimeters, such as the Scintrex ® CG-5, with potential precision of only a few μGal, have the capability of monitoring changes in subsurface water storage associated with changes in water table elevation of 10 cm [*Gehman et al*., 2009]. Time-dependent changes in drawdown during aquifer tests permit estimation of aquifer parameters from monitoring well observations. By relating water table changes to gravity changes, these same aquifer parameters can, in principle, be estimated from gravity measurements.

Estimates of specific yield have been made in several studies by coupling gravity change with measured water table change [e.g. *Pool and Eychaner*, 1995; *Howle et al*., 2003; *Gehman et al*., 2009]. Extending these analyses to include estimation of other aquifer parameters, specifically transmissivity and storativity, without the necessity of monitoring well data, would greatly add to the value of the method. *Damiata and Lee* [2006] have taken this step by evaluating the theoretical gravitational response expected due to drawdown during pumping of unconfined aquifers. The goal of this paper is to use aquifer test data to compare aquifer parameter results obtained by using the *Damiata and Lee* [2006] gravity response algorithm with parameter estimates obtained using traditional drawdown analysis.

1.2. Previous Studies

Pool and Eychaner [1995] in central Arizona and *Pool and Schmidt* [1997] in southern Arizona investigated the utility of time-lapse gravity measurements for monitoring storage changes in unconfined aquifers in arid environments. They collected temporal gravity measurements in several experiments during periods of groundwater storage change due to periodic natural recharge. Specific yield values were estimated, assuming a Bouguer slab model, using drawdown from observation wells and temporal gravity changes measured at those wells. *Pool and Eychaner* [1995] observed increases in gravity as much as 158 μGal associated with a water table rise of as much as 19 m.

Initial water table depths varied from 1 to 20 m at different wells. Specific yield estimates ranged from 0.16 to 0.21. *Pool and Schmidt* [1997] observed gravity increase by as much as 90 μGal with water level in wells rising by as much as 10 m. Initial water table depths ranged from 3 to 70 m. Specific yield estimates were 0.15 to 0.34 for stream-channel deposits and 0.07 to 0.18 for the Fort Lowell Formation, which typically consists of interbedded layers of clay, silt, sand, gravel, and boulders [*Pool and Schmidt*, 1997]. This compares favorably with previous studies, which estimated local stream alluvium specific yield to be 0.25 to 0.29 [*Montgomery*, 1971] and about 0.15 for the Fort Lowell Formation [*Davidson*, 1973].

Howle et al. [2003] employed a similar method to determine specific yield in an Antelope Valley, California groundwater system. This study took place during injection, with gravity measurements and monitoring well water levels simultaneously recorded to observe changes due to groundwater mound growth. Initial water table depth averaged 100 m below surface. Rising water levels are assumed to have caused observed increases in gravity as much as 66 μGal. Specific yield was calculated to be 0.13 for an alluvial aquifer near an observation well, which is within the range of values estimated in previous studies [*Durbin*, 1978]. To simulate the contribution of the injection mound to gravity, a two-dimensional gravity model was developed. The effect of the water mound on gravity change in this experiment was determined to be negligible. Still, the authors recommend gravity stations used in similar experiments be placed far enough from the groundwater mound to minimize the irregular gravity effects caused by the groundwater mound.

A different approach was used by *Gehman et al*. [2009] to estimate storage change and specific yield in an unconfined aquifer at a managed groundwater site near Crook, Colorado using temporal gravity surveys. At the site, water is pumped from the alluvial aquifer of the South Platte River during winter months to recharge ponds, forming groundwater mounds which dissipate by subsurface flow to supplement river flow during peak irrigation months. The authors used a three-dimensional inverse method to model gravity changes observed between pumping and post-pumping periods. Temporal changes in gravity were attributed to pumping, dissipation of groundwater mounds, and infiltration. Inversion of the gravity data provided an estimate of the total change in storage in the vicinity of the recharge ponds and spatial distribution of storage change within the aquifer due to dissipation and infiltration, independently from any aquifer parameter assumptions. Water level changes predicted from the gravity data agree with measured changes to within 0.45 m, on average. Coupling the change in water volume per unit area derived from the inversion program with water table measurements collected at observation wells allowed calculation of specific yield, 0.21, within the range estimated by aquifer tests conducted at the site.

Temporal gravity surveys have also been used to monitor water movement through unconfined aquifers. As part of an ongoing effort to monitor an enhanced oil recovery subsurface waterflood project in Prudhoe Bay, Alaska, *Hare et al*. [2008] modeled microgravity measurements recorded during several periods of the waterflood process. The gas cap is at a depth of 2.5 km, but reservoir thickness (>100 m), porosity (>20%), and density change (up to 120 kg/m^3) permit substantial gravity signals at the surface. Inversion of the gravity data allowed estimation of waterflood spatial expansion, the results of which indicate greater structural control on expansion than expected.

Davis et al. [2008] successfully used time-lapse microgravity measurements to monitor injection of water into an abandoned underground coal mine in Leyden, Colorado. 3D inversion of the gravity data produced density contrast models and imaged zones of water distribution in the 300 m deep mine. Dual method inversion produced higher resolution imaging of the mine, distinguishing different rubble zones and mined rooms. Rubble porosity was estimated to be 35% from inversion results, in agreement with geomechanical analyses.

In a theoretical study, *Damiata and Lee* [2006] showed that temporal changes in water table depth due to dewatering during aquifer tests can be sufficient in near-surface, unconfined aquifers to produce gravity signals great enough to be detected with modern portable gravimeters. They derived an expression for the gravitational effect of drawdown cone expansion, described by *Neuman* [1972], based on the attraction of solids of revolution about the pumping well. The expression assumes a homogenous, isotropic aquifer, and that gravity-driven pore drainage is instantaneous. Simulations performed using this expression for typical hydrologic properties and pumping conditions, assuming negligible aquifer compaction, indicated the potential for temporal gravity change on the order of tens of μGal after only one day of pumping from an aquifer with an initial water table depth of 10 meters. Such changes are within the detectable range of portable gravimeters, suggesting the utility of using these instruments for shallow, unconfined aquifer test analysis.

Blainey et al. [2007] extended the work of *Damiata and Lee* [2006] to examine how gravity-derived aquifer parameters compare to parameters obtained from drawdown analysis. They used aquifer parameters consistent with those used by *Damiata and Lee* [2006], simulating drawdown after seven days of pumping at nine radial distances from the pumping well using a *Moench* [1996] drawdown model with instantaneous pore drainage. The gravity response was modeled using superposition of semi-infinite cylinders, as described by *Telford et al*. [1990]. Uncertainty estimates were added to the simulated gravity and drawdown values to obtain synthetic pumping test data. An optimization function describing variance between synthetic measurements and simulated drawdown and gravity was minimized for 100 realizations. The authors found greater bias and parameter uncertainty in the gravity data analysis than the drawdown data analysis. The authors concluded that the gravity measurements alone were not enough to determine aquifer parameters in this case. However, the impact of using gravity measurements from multiple times in the analysis was not discussed. Time and radial distance have a nonlinear relationship in the *Neuman* [1972] drawdown solution, presenting the possibility that aquifer parameter analysis results may be influenced by the choice of either time or location as the control variable.

1.3. Purpose

In this paper, I expand on the work of *Damiata and Lee* [2006] and *Blainey et al.* [2007] to assess the use of temporal microgravity measurements to estimate transmissivity, specific yield, and storativity in shallow, unconfined aquifers. Gravity and drawdown data were collected during pumping of a water table aquifer, allowing for comparison of aquifer parameters estimated using gravity analysis to parameters estimated using drawdown analysis. The parameters estimated are transmissivity *T*, specific yield *Sy*, and the elastic component of storativity – the specific storage and aquifer thickness quotient - for convenience referred to here as storativity *S*. Assumptions made about the aquifer response to pumping - i.e., that changes in water table elevation are described by the *Neuman* [1972] drawdown solution - are consistent between the two analysis techniques.

2. Methods

2.1. Site Description

The aquifer test was conducted at the Colorado State University Horticulture Field Research Center, a 65 acre facility that is mainly used for turfgrass, ornamental trees and shrubs, organic crop, and specialty crop research projects. It is located east of the Colorado Front Range, the eastern escarpment of the Rocky Mountains, approximately seven kilometers northeast of downtown Fort Collins, CO (Figure 1). The site is in the catchment of the Cache la Poudre River, which is the largest tributary of the South Platte River.

A generalized cross section of the study area is shown in Figure 2. The aquifer lies within the Pleistocene Broadway Alluvium [*USGS*, 1979], which has been locally exposed by erosion resulting from southward migration of the Cache la Poudre River during the Holocene [*Lindsey et al*., 2005]. The Broadway Alluvium consists of poorly sorted sand, arkosic gravel, and minor amounts of clay, derived mainly from erosion of Cretaceous and Cenozoic clastic rocks exposed along the Front Range, 14 km to the west [*Hershey and Schneider*, 1964]. Sorted gravels contain clasts of cobble and pebble size with lenses of silt, sand, and clay, and are interleaved with a very poorly sorted mixture of gravel, sand, and silt [*Lindsey et al*., 2005]. The alluvium may be as thick as 15 m, but averages approximately 10 m thick in the study area and is underlain by the Pierre Shale.

At the CSU Horticulture Research Center the Broadway Alluvium is overlain by up to 1 m thick soil identified in regional soil surveys as Nunn clay loam [*Moreland*, 1980]. This is consistent with site samples taken from the upper 30 cm of topsoil at the pumping site. The Nunn clay loam is described as deep, well drained, and formed in alluvium. The upper 25 cm of soil have hydraulic conductivity values of 1.4×10^{-6} to 1.4×10^{-5} ms^{-1} [*Moreland*, 1980]. Soil deeper than 25 cm has hydraulic conductivity values ranging from 4.2×10^{-7} to 1.4×10^{-6} ms^{-1}.

2.2. Data Collection

2.2.1. Gravity Data Collection

Gravity data were collected with a Scintrex ® CG-5 portable gravimeter with GPS positioning for recording time and location[1]. The gravimeter was placed on a tripod stand with adjustable legs for leveling. One leg of the tripod was locked in position during the survey to maintain a constant gravimeter height. The tripod was placed on a metal plate positioned on the ground at each gravity station to prevent the tripod legs from sinking into soil. Barometric pressure (used for gravity data corrections discussed in section 2.4) was recorded at a weather station on the Colorado State University Campus

[1]Gravity data is archived with CSU Department of Geosciences

in Fort Collins, located 8.5 km to the west. A wind block was used to minimize wind-induced gravimeter tilt.

The CG-5 automatically corrects for instrument drift (measured to be 0.475 mGal/day in this experiment), instrument tilt, and Earth tides [*Gettings et al.*, 2008; *Scintrex*, 2009]. The seismic filter built into the instrument was used to minimize accelerations associated with seismicity [*Goodkind*, 1986; *Scintrex*, 2009].

2.2.2. Hydrologic Data Collection

Depth to water was 4.0 m and initial saturated thickness was approximately 5.7 m (Figure 2). The pumping well diameter is 0.5 m. Four monitoring wells are installed along a radial azimuth west of the pumping well. Well 1 is at a radial distance of 6.34 m from the pumping well and has an inside diameter of 0.16 m. Wells 2, 3, and 4 are 15.4, 30.7, and 61.2 m from the pumping well, respectively, with 0.05 m inside diameters. The pumping and monitoring wells are all fully penetrating and screened along the entire saturated zone. Water levels in monitoring wells 1 and 2 were measured and logged with pressure transducers/loggers. Water level was measured periodically in the pumping well and wells 3 and 4 with a water level tape. The capacity of the pump used in this experiment is approximately 0.03 to 0.04 m^3s^{-1}. Water extracted during the aquifer test was piped ~230 m from the pumping well and discharged on the ground, where a totalizer measured discharge (Figure 3).

2.3. Survey Design

2.3.1. Gravity Survey

Multiple factors contributed to the choice of location of gravity stations during the aquifer test. It was necessary that sites be near enough to the pumping well such that drawdown was large enough to produce changes in gravity that exceed expected sensitivity, noise level, and uncertainty. Conversely, irregular drawdown geometry proximal to the pumping well complicates interpretation of gravity changes at stations near the pumping well [*Howle et al.*, 2003]. Finally, to make a direct comparison of aquifer properties estimated with the gravity method and from the type-curve analysis of drawdown, it is desirable to place gravity stations at the same locations as the monitoring wells. Modeling prior to the aquifer test indicated drawdown would be great enough for a measurable change in gravity only at the nearest monitoring wells, within several meters of the pumping well. Consequently, the two monitoring wells closest to the pumping well were chosen to be the primary gravity stations, where continuous gravity measurements would be taken. However, drawdown at well 2 during the early part of the aquifer test was less than anticipated, so gravity data were only collected at the closest monitoring well (well 1) during most of the test. Attempts were made to periodically collect gravity data at the two most distal wells (wells 3 and 4), but tares incurred while moving the gravimeter exceeded the signal at the sites. Tares are shifts in the magnitude of measured gravity which may occur if the gravimeter spring is subjected to shock.

A gravity base station was established for periodic reoccupation in order to improve on the instrument drift and Earth tide corrections automatically applied by the CG-5 (Figure 3). Ideally, the base station should be located a sufficient distance from the pumping well and discharge point to prevent changes in gravity at the base station due to dewatering or recharge. Accordingly, the base station chosen for this experiment was ~430 m from the pumping well and ~215 m from the effluent discharge point. The base station was located on a large concrete slab for stability. Following each gravimeter relocation, the instrument was allowed to sit for at least three minutes prior to recording, allowing transient effects from movement to dissipate [*Gettings et al.*, 2008].

The gravimeter was set to record gravity for 60 second intervals, weighting and rejecting measurements during each interval according to the instrument filter. This resulted in a single gravity measurement for each of the intervals. Three of these measurements were recorded at each base station occupation, with the instrument leveled between measurements. At well 1, the gravimeter continuously recorded gravity for up to several hours, recording discrete measurements for each 60 second interval.

2.3.2. Hydrogeology Survey

To ensure collection of late time drawdown data, pumping continued 27 hours, until drawdown in the monitoring wells approached steady-state. Pressure transducers and data loggers in wells 1 and 2 were set to record once every minute. Depth to water was measured periodically in wells 3 and 4 with a water level tape. Discharge totalizer readings were taken periodically then used to calculate an average pump discharge rate.

Drawdown data analysis was done with Environmental Simulation, Inc. AquiferWin32 ® software [*Rumbaugh and Rumbaugh*, 2009]. The software provides a means of matching drawdown data to type-curves manually or through inverse modeling using a damped least squares fit [*Marquardt*, 1963]. To allow direct comparison to the results achieved with the gravity analysis method of *Damiata and Lee* [2006], the curve fitting solution used is the *Neuman* [1972] unconfined aquifer drawdown solution, which assumes isotropic and homogeneous conditions in the aquifer. Type curves are generated for drawdown data matching for the parameter β, which is a relationship between radial distance from the monitoring well to the pumping well and initial saturated thickness of the aquifer:

$$\beta = \frac{r^2}{b^2} \tag{1}$$

where r is radial distance from the monitoring well to pumping well and b is initial saturated thickness of the aquifer.

Early time drawdown data is also analyzed via type-curve matching for wells 1 and 2 using the *Neuman* [1974] drawdown solution, which allows for anisotropic conditions ($Kv \neq Kh$) and provides a check on the assumption of isotropy in the aquifer.

2.4. Gravity Data Reductions

Traditional corrections to gravity data, including a latitude correction, a Bouguer correction, a free air correction, and a terrain correction [*Telford et al*., 1990] are not applied in temporal gravity surveys because these corrections all are dependent on station location, and temporal gravity surveys are concerned with gravity changes through time at the same location. A correction for instrument height changes between readings was also not required because the instrument was maintained at a fixed height above the baseplate (Section 2.2.1). Atmospheric effects, on the other hand, may be significant, with corrections ranging from -0.3 to -0.43 μGal/mbar [*Niebauer*, 1988; *Merriam*, 1992; *van Dam and Francis*, 1998]. *Van Dam and Francis* [1998] found the admittance due to local air pressure to be -0.356 μGal/mbar in the vicinity of Boulder, Colorado, located 70 km from the study area. This value was used to correct for atmospheric pressure changes in this experiment. Barometric pressure, measured at Colorado State University, varied over a range of approximately 8 mbar during the aquifer test (Figure 4). Gravity corrections vary from -1.2 to 1 μGal over the pumping duration. These pressure corrections were applied to all gravity data prior to aquifer parameter estimation.

Two tares are evident in the data, one at approximately 20,000 s and one at approximately 70,000 s (Figure 5). The tares occurred when the gravimeter was moved to take a base station measurement. Rough estimates of the tare magnitudes were made by assuming the data must lie on a smooth, continuous curve. The tare at 20,000 s was estimated to be 30 μGal and the tare at 70,000 s was about 40 μGal. Calculated tare values were used to correct the gravity data by subtracting the tare magnitudes from the affected gravity data (Figure 6). The magnitudes of the tares were refined in the modeling process and were applied to base station gravity prior to drift corrections (Section 3.3).

At each base station occupation, three gravity measurements were recorded and later corrected for barometric pressure changes and tares. These three measurements were then averaged and assigned to the time of the last of the three measurements. A piecewise linear curve was constructed to connect the averaged gravity measurements (Figure 7). The curve trends were removed from the monitoring well gravity data, thus correcting for tares and base station drift (Figure 8).

3. Results

3.1. Measured Drawdown and Gravity Change

Pumping rates were averaged between totalizer readings during the pumping duration of 27 hours and 4 minutes (Figure 9). Average pumping rate for the entire test was calculated to be 0.0335 m^3s^{-1} and was used for all modeling. Initial static water level was 4.0 m below ground surface. Drawdown data for wells 1 and 2 are shown in Figure

10. After ~660 s since onset of pumping, power to the pump was lost for approximately 240 s, during which time water levels rose. The drawdown data were edited by removing data from the time the pump was non-operational, and until drawdown levels reached those prior to pump stoppage. This required deletion of 420 s of data, or seven data points, since drawdown was recorded each minute. Additionally, elapsed time measurement values following this period were reduced by 420 s. The resulting drawdown data from wells 1 and 2 used for analysis with the type-curve matching software are plotted with dashed lines (Figure 10) and the edited drawdown for the entire duration of the test is shown in Figure 11.

Five data clusters can be identified in the gravity data (Figure 8), each representing an interval of stationary gravity data collection at well 1. Interval 1 is a short duration collection interval with measurement scatter of approximately 4 μGal. Interval 2 is approximately 5,000 s of recording time, with gravity measurements increasing about 15 μGal over the interval. Interval 3, the next cluster, is about 5,000 s in duration. Here gravity decreases approximately 15 μGal. Interval 4 covers about 40,000 s of recording. Gravity continues to drop during this interval, by about 10 μGal. Interval 5 has a varying trend across the approximately 10,000 s interval, with a gravity drop of about 35 μGal over the first half of the interval. The rest of interval 5 sees a rise in gravity of approximately 15 μGal.

3.2. Aquifer Parameter Estimation Using Drawdown Data

For each monitoring well, type-curve matching was initially done manually to generate an approximate solution assuming an isotropic aquifer, per the *Neuman* [1972] drawdown solution. The approximate solution was then refined through inverse modeling, as described in Section 2.3.2 (Figure 12 and Table 1). In general, each of the models provides a very good fit to drawdown, with a residual mean less than 0.0001 m in all cases. Some small differences between drawdown and modeled drawdown exist. For well 1, the measured and calculated curves show the most deviation from each other during times 0 to 5,000 s. Also, the calculated drawdown curve has a greater slope than the measured drawdown curve at the later times. For well 2, the misfit between observed and modeled drawdown, like the solution for well 1, is greatest in early times. Slightly greater drawdown is predicted for late times with the calculated curve than the measured data, just as in well 1. Well 3 drawdown was measured with a level tape and so the data set is much less dense than those recorded for wells 1 and 2. Residuals are small, averaging -0.000090 m, with most calculated values falling within the observed data range of uncertainty. The exception is the earliest data point, where calculated drawdown is greater than measured drawdown. In well 4, residual values are small, with most calculated drawdown values within the range of measurement uncertainty, similar to well 3. Despite the apparently good fit of the models to the drawdown, all models except that from well 2 predict greater storativity values than specific yield values (Table 1). This is contrary to the expected relationship between these components of storage in unconfined aquifers, where *Sy* is usually several orders of magnitude greater than *S* [*Fetter*, 2001].

Models were also generated for well 1 and 2 early time (0 to 600 s) drawdown data using the *Neuman* [1974] drawdown solution, without the assumption of an isotropic aquifer (Figure 13). Only the early time data was used because this provides better estimate of storativity values than late time [*Chen et al.*, 2003]. Data from these times were not recorded for wells 3 and 4. The type-curve analyses allowing for anisotropy result in transmissivity values slightly lower than the values obtained from isotropic models (Table 2). Storativity estimates are an order of magnitude lower, and specific yield values are an order of magnitude higher. Importantly, specific yield values are an order of magnitude greater than storativity values, consistent with the relationship between these parameters in unconfined aquifers [*Fetter*, 2001]. K_v/K_h estimates indicate greater horizontal hydraulic conductivity than vertical hydraulic conductivity in both wells.

3.3. Aquifer Parameter Estimation Using Gravity Data

An expression for gravity changes due to dewatering of pore spaces according to the *Neuman* [1972] unconfined aquifer drawdown solution was derived by *Damiata and Lee* [2006]. The *Neuman* [1972] drawdown solution assumes the aquifer is homogeneous, isotropic, that the pumping well is fully penetrating, and that pump discharge is constant. Additionally, water is assumed to be released from the aquifer by compaction of the aquifer material, expansion of the water, and gravity drainage at the free surface. This solution assumes instantaneous drainage of pore spaces above the saturated zone, with no impact on the saturated zone from water in the vadose zone. *Damiata and Lee* [2006] further constrain the aquifer characteristics in the model by assuming the aquifer is relatively incompressible, so no subsidence occurs which may impact gravity.

The *Damiata and Lee* [2006] algorithm was used to model gravity changes expected for the aquifer test performed here. By varying values of transmissivity (5 x 10^{-5} to 0.1 m^2s^{-1}), storativity (10^{-5} to 1), and specific yield (0.05 to 1), 4200 realizations were constructed for modeling gravity change. These values span the ranges of realistic values and beyond, permitting identification of the absolute minima and parameter determination to two decimal places. Pumping rate and static water table depth were held fixed at 0.0335 m^3s^{-1} and 4.0 m (Section 3.1). Gravitational response was modeled for each realization for the times gravity data were collected, allowing direct comparison of modeled and measured gravity changes. The *Damiata and Lee* [2006] gravity response algorithm predicts a decrease in gravity with time due to drawdown. The only intervals of the gravity data that show this behavior are intervals 3, 4, and the first half of 5. Additionally, the change in gravity with time should approach zero as the aquifer system approaches steady-state. The only intervals with this pattern are intervals 3 and 4 (Figure 8). Accordingly, only the data collected during these two intervals were used to compare with the gravity models to estimate transmissivity, storativity, and specific yield.

A residual static shift was included as an unknown parameter in the modeling to refine the initial estimate made for the tare between intervals 3 and 4 and to account for the offset between relative gravity (measured) and zero gravity change at time zero. Initial static shifts were calculated as the difference between the data interval's mean modeled gravity and the mean observed gravity (Section 2.4). This produced a rough fit of the model to the data for both observation intervals. A residual static shift correction for each interval was then made by adding and subtracting 1 μGal to the initial static shift, with trial corrections spanning the data collection interval's range of deviation between measured gravity and its mean. This total static shift (initial plus residual) was added to each data point in the respective interval for every gravity model produced with the *Damiata and Lee* [2006] gravity response algorithm. The procedure can be summarized as:

$$g_i^{m\prime}(t) = g_i^m(t) + [g^{obs}(t)] - [g_i^m(t)] + SC_f \qquad (2)$$

where $g_i^{m\prime}$ is the shifted model gravity, g_i^m is the original model gravity, $[g^{obs}(t)] - [g_i^m(t)]$ is the initial static shift estimate, SC_f is the residual static shift, *i* represents the realization, and *f* represents the correction.

Observed gravity and shifted model gravity were compared for each model by calculating the root mean square error between the two data sets:

$$RMSE_i = \sqrt{\frac{1}{n}\sum_{t=1}^{n}(g_{i,t}^{m\prime} - g_t^{obs})^2} \tag{3}$$

where $g_i^{m\prime}$ is the shifted model gravity, g_t^{obs} is the observed gravity, *i* represents the realization, *t* represents data times, and *n* represents the number of data points.

SC_f was varied iteratively until the RMS misfit between the model and data was minimized. Thus, the minimum RMSE for each realization identifies the correct total static shift for that realization. The minimum RMSE for all realizations identifies the realization with aquifer properties that best fit gravity change observed in both intervals during the aquifer test. The best fitting model resulted in a minimum RMSE value of 2.36 μGal, a transmissivity of 0.0033 m^2s^{-1}, storativity of 0.0052, and specific yield of 0.45 (Figure 14). The data required a static shift correction of -32.1 μGal between intervals 3 and 4.

Following estimation of the best fitting aquifer parameters using the gravity models, the parameters were systematically varied in an effort to determine the uncertainty of the parameters. Transmissivity, storativity, and specific yield were each, in turn, varied while maintaining constant values equal to those obtained from the best fitting model for the other parameters (Figures 15-17). Assuming a conservative estimate of uncertainty of 7.6 μGal (Section 5.1), parameter estimate ranges are *T*=0.0022 - 0.006

m^2s^{-1}, S=0 – 0.19, and Sy=0.27 – 0.63. These ranges are significantly reduced using an uncertainty estimate of 3 μGal: T=0.003 - 0.004 m^2s^{-1}, S=0 – 0.03, and Sy=0.39 – 0.48.

In order to understand the model sensitivity to parameters in combination, the model objective function was plotted holding only a single parameter fixed at the value obtained from the best fitting model (Figures 18-20). For low values of transmissivity (< 0.001 m^2s^{-1}) and most values of storativity (< 0.1) the gravity data constrains specific yield from 0.05 to 0.22 (Figures 18- 19). For higher values of transmissivity (> 0.003 m^2s^{-1}) the model is insensitive to specific yield and constrains transmissivity to within half an order of magnitude (Figure 18). The model shows very little sensitivity to storativity, robustly constraining specific yield between 0.27 and 0.64 for all values of storativity less than 0.1 (Figure 20). Three RMSE lows are observed: T=0.0008 m^2s^{-1} and Sy=0.15, T=0.003 m^2s^{-1} and Sy=0.4, and T=0.01 m^2s^{-1} and Sy=1.

For comparison with typical sandy gravel aquifers, RMSE objective functions were also made for transmissivity versus storativity, using specific yield values of 0.20 and 0.35, the lower and upper expected bounds for sandy gravel [*Fetter*, 2001] (Figures 21-22). In each case the gravity data is insensitive to storativity less than 0.1 and transmissivity is constrained to half an order of magnitude. For Sy=0.2, the low RMSE occurs for T=0.001 m^2s^{-1} and S=0.001. For Sy=0.35, the low RMSE occurs for T=0.003 m^2s^{-1} and S=0.05.

3.4. Forward Modeled Drawdown

Because of the discrepancy between aquifer parameters estimated using gravity analysis and drawdown type-curve fitting, a forward model of drawdown was constructed to simultaneously fit drawdown in each of the four monitoring wells. Drawdown, as described by the *Neuman* [1972] drawdown solution, was modeled, varying transmissivity (5 x 10^{-5} to 0.1 m^2s^{-1}), storativity (5 x 10^{-8} to 5 x 10^{-2}), and specific yield (0.05 to 1). Approximately 1500 such realizations were compared to late time drawdown in the four observation wells. Storativity required a lower bound to find the minima than was required in the gravity analysis. Late time data were used in an attempt to closely model the shape of the drawdown cone near the end of the aquifer test. For wells 1 and 2, in which drawdown was recorded each minute, data from elapsed times 50,940 to 96,960 s were used. In wells 3 and 4, data collected at the following times were used: 65,940 s; 71,040 s; 81,840 s; 87,840 s; and 94,140 s. Root mean square error was calculated for each model based on the following formula, which applies equal weight to drawdown data from each of the four wells:

$$RMSE = \frac{1}{4}\sum_{w=1}^{4}\sqrt{\sum_{t=1}^{n}\frac{(Observed\ drawdown_{w,t} - Modeled\ drawdown_{w,t})^2}{n}} \quad (4)$$

where *w* is the observation well, *t* is each data point time, and *n* is the number of data points at the respective well.

Minimization of forward modeled drawdown RMS misfit resulted in parameter estimations differing from both the gravity analysis and type-curve matching. The best fitting model had a RMSE of 0.0448 m, a transmissivity of 0.0080 m^2s^{-1}, specific yield of 0.26, and storativity of 0.000004.

The parameters describing the model with the lowest RMSE were used to create a synthetic gravity model based on the modeled drawdown cone geometry at time 66,241 s, the end of the period of gravity data collection during interval 4 (Section 3.3). The radial drawdown profile created using the *Neuman* [1972] drawdown solution was rotated around the pumping well 360° to create a three dimensional model of the drawdown cone. This assumes drawdown to be symmetrical around the pumping well, consistent with a homogeneous and isotropic aquifer. A 1 m by 1 m grid of the drawdown cone was created using the Multiquadratic Radial Basis Function in Surfer ® [*Golden Software, Inc*., 2002]. This grid was used with the *Parker* [1973] algorithm to model the gravity changes. Density contrast was estimated assuming that model-predicted specific yield (0.26) represented total porosity, that pore spaces above the water table were completely drained, and the density of water ρ_w is 1000 kg/m^3. Using the relationship $\Delta\rho=\rho_w*Sy$ leads to a density contrast $\Delta\rho$ of 260 kg/m^3.

The predicted gravity response at 66,241 s using these parameters with the *Parker* [1973] algorithm is shown in Figure 23 for radial distances up to 60 m from the pumping well. The gravity response predicted by the *Parker* [1973] algorithm at the pumping well (0 m) for this time is approximately 40 μGal. The predicted gravity response is greater than 10 μGal at distances up to approximately 15 m. The curve in Figure 23 shows that the gravity response predicted by the *Parker* [1973] algorithm at well 1 (6.34 m) is approximately 16 μGal less (absolute difference) than the gravity response predicted using the aquifer parameters estimated from the best fitting gravity model for the same time and location, which is outside the conservative measurement uncertainty estimate of 7.6 μGal.

4. Comparison of Type-Curve and Gravity Results

Drawdown predicted from the best fitting gravity model in well 1 is approximately 3 m at the end of pumping, compared to approximately 1.7 m of observed drawdown (Figure 24). The gravity solution predicts higher than observed drawdown at well 1 after 11,500 s of pumping and lower than observed drawdown prior to this time. Drawdown predicted from the best fitting gravity model approaches 1.5 m in well 2 at the end of pumping, compared to observed drawdown of just over 1 m. Drawdown predicted from the gravity model is greater than observed drawdown after about 1,260 s of pumping in this well and lower than observed drawdown prior to this time. For well 3, drawdown predicted from the gravity model is approximately equal to observed drawdown at the end of pumping, but observed drawdown is greater than predicted drawdown until approximately 87,840 s after pumping began. Also, drawdown predicted from the gravity model has a more positive slope at the end of pumping than observed drawdown in well 3. Observed drawdown is greater than drawdown predicted from the best fitting gravity model for all pumping times in well 4.

In addition to the differences in drawdown history, the gravity and type-curve analyses provide disparate estimates of the study area aquifer parameters. Transmissivity estimated from gravimetric observations (0.0033 m^2s^{-1}) is nearly an order of magnitude lower than the transmissivity estimated from type-curve analysis (0.0176 m^2s^{-1}), but both estimates are within reported ranges of unconsolidated sediment transmissivity values [*Schwartz and Zhang*, 2003]. Storativity estimates, conversely, are an order of magnitude higher via type-curve analysis than gravity analysis. Storativity in an aquifer with a saturated thickness of ~10 m is generally less than 0.003 [*Schwartz and Zhang*, 2003]. Specific yield had the largest disparity between estimation methods. Type-curve analysis indicated near zero specific yield, while gravity analysis requires specific yield (0.45) greater than typically observed in sandy gravel aquifers such as the one present at the study site [*Schwartz and Zhang*, 2003].

5. Uncertainty Analysis

5.1. Gravity Data

Sources of uncertainty include instrument precision, Earth tide corrections, atmospheric pressure, and instrument height. The precision of the gravimeter itself is reported as ±3 μGal [*Scintrex*, 2009]. Earth tide corrections made by the gravimeter are also reportedly correct to within 3 μGal. While corrections were made to compensate for local air pressure changes on the scale of 10^{-5} bar, far field pressure changes can also impact gravity. *Merriam* [1992] found that gravity is affected by local air pressure changes in a 50 km radius, reporting these far field affects to be on the order of 1 μGal. The weather station used for barometric pressure monitoring is ~8.5 km southwest from the test site, meaning that relevant pressure changes occurring beyond this radius may not have been properly corrected for. Additionally, the correction factor used to compensate for barometric pressure changes was derived from data collected near Boulder. There may be a discrepancy between the proper admittance values at each locale.

Some other uncertainties in the gravity measurements are not so easily quantifiable, but may have had some impact. Base station drift was assumed to be linear between base station gravity measurement times. Any nonlinear gravity effects, then, would be improperly corrected for. Another source of potential uncertainty is due to aquifer compaction, which was assumed to be negligible. Studies conducted elsewhere suggest that several millimeters of subsidence are possible, depending on initial saturated thickness, water table depth, total drawdown, and aquifer properties [*Romagnoli et al*., 2003]. However, given the conditions at the test site, including the thinness of the aquifer and small amount of drawdown, minimal subsidence is expected. Any subsidence would cause an increase in measured gravity. Finally, gravimeter height variations between station occupations might vary slightly. Gravimeter height differences in this test are estimated to be a maximum of 2 mm. Given a free-air correction of 0.3086 μGal/mm, the uncertainty due to height variations is approximately ±0.6 μGal.

Given all factors discussed above, a conservative, high-end estimate of total, quantifiable uncertainty in the gravity measurements is ±7.6 μGal.

5.2. Hydrologic Data

The Level TROLL ® pressure transducers used in this study have a reported accuracy of 0.05% full scale at 15 °C [*In-Situ Inc*., 2007]. Full scale in well 1 was set to monitor a range of 0 to 21 m. The transducer in well 2 was set to a range of 0 to 11 m. The accuracies of the two instruments at these settings are ±0.010 m and ±0.0055 m, respectively. The measuring tape used to manually measure water level in wells 3 and 4 was marked with 1 mm graduations. A conservative estimate of accuracy of the water levels measured during this test is ±1 cm.

Drawdown measurements are assumed to be affected solely by dewatering produced by the pump. Although efforts were made to minimize recharge due to infiltration of discharged water by locating the discharge at a large distance (~230 m) from the monitoring wells, it is possible that some recharge may have occurred that could impact well water levels. Irrigation or pumping on adjacent farmland also could impact water table levels at the test site. The only other pump known to be near the test site is approximately 500 m north of the site. It is not known if the pump was active during the test. A pivot irrigation system was operating on the land to the north of the field site, 25 to 600 m away, during several hours of the test.

6. Discussion

Encouraging results of the pumping test analyses were not without several unanticipated problems which required correction to, or disuse of, portions of the gravity data. Gravity measured at well 1 (Figures 5 and 8) is an example and has some unexpected trends in two of the data collection intervals. Gravity increases approximately 15 μGal during the first 10,000 s after the onset of pumping (Interval 2), then, after approximately 80,000 s (Interval 5), gravity decreases at a faster rate than the previous interval, followed by a rapid increase. The cause of these patterns is unknown and drift corrections do not remove the trends. A potential source for the gravity increases could be groundwater infiltration (recharge). However, drawdown data from well 1 does not indicate any such event, indicating that any recharge that occurred must have followed heterogeneous flow patterns. Aquifer compaction would also contribute to an increase in gravity. Assuming a free air gravity gradient of approximately 3 μGal/m [*Telford et al*., 1990], the ground below the gravimeter would need to subside 5 cm during interval 2 to contribute a 15 μGal increase in gravity. Greater subsidence would be required to account for the increase in gravity in interval 5. Subsidence of this magnitude is unlikely with the amount of drawdown observed and would have been visually noticeable. Since the causes of the increase in gravity in intervals 2 and 5 are unknown, those intervals were not used in the analysis.

Another surprising aspect of the gravity data collected at well 1 is the apparent tares in the data at ~20,000 and 70,000 s (Figure 5). Tares with magnitudes of tens of μgals are observed due to moving the gravimeter between the well site and base station, despite careful movement of the gravimeter. This is unusual for the CG-5, which is reported to be able to withstand a 20 G shock with less than a 5 μGal tare [*Scintrex*, 2009]. The expected resistance to tares was not observed in this test, prompting suspicion of the gravimeter's reliability. However, repeated gravity measurements conducted at absolute gravity stations on the CSU campus (including relocation of the meter between stations) indicated the gravimeter was functioning correctly, without the occurrence of tares. Thus, the cause of the tares is uncertain, but they were compensated for as described earlier (Section 2.4), allowing for inclusion of this data in the analysis.

Finally, anomalous data is observed in the intervals used for analysis, both at the beginning and end of interval 3 (high and low gravity clusters), and at the end of the interval 4 (rapid gravity decrease) (Figure 14). Removal of these data and recalculation of gravity model RMSE resulted in negligible change to the RMSE value, demonstrating that the model is relatively insensitive to these outlier data points. This is likely due to the small amount of anomalous data relative to the complete data set. The anomalous data in interval 3 lie outside the main cluster of gravity values recorded for the interval, but can be interpreted as in line with the trend of the data. Accordingly, data in these intervals were used for gravity analysis.

Despite the data issues, gravity modeling produced a range of estimates for transmissivity consistent with the expected aquifer materials. In fact, RMSE plotted as a function of transmissivity (Figure 15) indicates a fairly narrow range of permissible transmissivity values. As discussed earlier, gravity measurements are conservatively estimated to have a precision of 7.6 μGal. With this uncertainty, permissible transmissivity ranges between 0.002 and 0.006 m^2s^{-1}. This corresponds to hydraulic conductivity values of approximately 17 and 51 m/day for an aquifer with initial saturated thickness of ~6 m. This is consistent with poorly sorted, fine sand to coarse gravel [*Schwartz and Zhang*, 2003], which comprises much of the Broadway Alluvium [*Lindsey et al*., 2005]. Storativity, on the other hand, is poorly constrained (Figure 16), ranging from 0 to 0.2 when using a conservative estimate of uncertainty. This more than spans the range of expected unconfined aquifer storage coefficients, which is 0.0001 to 0.01 for an unconfined aquifer with a saturated thickness of 10 m [*Schwartz and Zhang*, 2003]. Therefore, the gravity model does not constrain storativity to within realistic values. Similarly, conservative uncertainty constraints place specific yield between 0.275 and 0.65, ranging well above 0.35, the approximate maximum specific yield of sandy gravel [*Fetter*, 2001]. However, the gravity model does place constraints on storativity and specific yield such that specific yield is greater than storativity. This is the expected relationship in an unconfined aquifer, where inelastic storage is greater than elastic storage.

The examination of parameters in pairs also shows the robustness with which transmissivity is estimated with the gravity analysis. For the best fitting gravity model, at values of transmissivity below 0.0003 m^2s^{-1}, specific yield is constrained to within ~ ±0.05 for a fixed storativity of 0.0052 (Figure 18) and is constrained to within ~ ±0.15 over a wide range of storativity for a fixed transmissivity of 0.0033 m^2s^{-1} (Figure 20). At higher transmissivity values, the objective function reflects a much stronger, sub-linear, relationship between specific yield and the log of transmissivity. For unrealistically higher values of specific yield (> 0.5), RMSE becomes less dependent on specific yield and is mainly determined by transmissivity. Transmissivity is constrained to a narrow band of about half an order of magnitude given the measurement uncertainty of 7.6 μGal

(Figure 18). There is a strong dependence on transmissivity and insensitivity of gravity to storativity (Figure 19). The insensitivity of gravity to storativity is also revealed in the plot of specific yield versus storativity (Figure 20). The low RMSE range is marked by a broad, low RMSE gradient, also reflecting a relatively low sensitivity of gravity to specific yield. The objective functions show that gravity, in this aquifer test, does not appear to be independently sensitive to a single parameter, but rather to the combined transmissivity – specific yield relationship.

For comparison to typical gravelly sand aquifers, analysis of the relationship of storativity and transmissivity was done using values of specific yield consistent with the maximum and minimum values for gravelly sand. Conservative uncertainty of 7.6 μGal constrains transmissivity to within an order of magnitude for Sy=0.2 (Figure 21). A similar pattern emerges using the upper expected bound on specific yield, 0.35 [*Fetter*, 2001] (Figure 22). In both cases the gravity data is insensitive to storativity, while transmissivity is fairly well constrained. Transmissivity, when Sy=0.35, is constrained to within half an order of magnitude. Better constraint on transmissivity using higher specific yield is likely due to the a priori assumption being closer to 0.45, the value estimated by the best fitting gravity model. Considering the range of expected specific yields for the aquifer material, 0.2 – 0.35 [*Fetter*, 2001], and a conservative precision estimate of 7.6 μGal for the gravimeter, transmissivity is constrained to one order of magnitude (0.00045 to 0.0045 m^2s^{-1}). This suggests gravity measurements, for this test, are most robust for transmissivity estimation.

These parameter range estimates should be more tightly constrained by reducing the uncertainty in the gravity data collection and using multiple gravity stations. This potential was explored by using the ranges of aquifer parameter values determined assuming a gravity data uncertainty of 3 μGal (lower dashed line in Figures 15-17) to model the expected gravity response at well 2 (Figure 25). After approximately 30,000 s, the range between the minimum and maximum expected gravity response at well 2 is greater than the gravimeter precision, 3 μGal. So, a gravimeter recording gravity at well 2 should provide data that would complement the parameter estimates based on well 1 gravity observations if gravity is measured beyond 30,000 s at well 2. The range between the minimum and maximum expected gravity response at well 2 is not greater than 7.6 μGal until after approximately 50,000 s. This shows that, while gravimeters located at greater radial distances might further constrain the parameter estimates given sufficient drawdown, greater distances between the pump and gravimeter require longer observation times. Also, the amount of additional observation time needed is reduced with higher precision gravimetry.

Curve matching of drawdown data for individual wells resulted in much lower misfit for each well (all lower than data uncertainty) than fitting drawdown in all wells with a single drawdown solution via forward modeling. Transmissivity values obtained from type-curve fitting for each well were in close agreement, with well 4 only slightly greater than the other wells (Table 1). The average transmissivity from the four wells corresponds to a hydraulic conductivity value of approximately 156 m/day, which is consistent with values expected for well sorted, coarse gravel [*Schwartz and Zhang*, 2003]. Storativity values determined from curve matching span four orders of magnitude and three are above the expected maximum for an unconfined aquifer, 0.001 [*Schwartz and Zhang*, 2003] . Specific yield values vary across three orders of magnitude, with all the estimates well below expected minimum for a sandy gravel aquifer, 0.2 [*Fetter*, 2001]. Type-curve fitting methods have been reported to underestimate long-term specific yield characteristics of the aquifer [*Nwankwor et al*., 1984], possibly due to delayed pore drainage or aquifer heterogeneities [*Moench*, 1994]. This may account for the very low values of specific yield determined by type-curve matching. Overestimation of horizontal hydraulic conductivity can lead to underestimation of specific yield, as these parameters are highly correlated [*Chen et al*., 2003]. The specific yield estimates made by curve matching are likely underestimated, since the values are much lower than expected specific yield for the aquifer material. So, if the transmissivity - specific yield relationship described by *Chen et al.* [2003] is valid, the transmissivity values are likely overestimates of the actual aquifer properties.

Moench [1994] found that analyzing drawdown data from several wells together provides a much better estimate of specific yield than analyzing individual well drawdown. This type of analysis was done here by using the *Neuman* [1972] drawdown solution forward model discussed earlier. The specific yield determined in that analysis was 0.26, which falls within the range of expected values for a sandy gravel aquifer [*Fetter*, 2001]. Additionally, the data used in that analysis is all late time data, which has higher sensitivity to specific yield [*Chen et al.*, 2003]. Transmissivity was estimated in that analysis to be 0.0080 m^2s^{-1}, lower than the values determined by analyzing individual wells. The relative difference in transmissivity and specific yield values obtained using forward modeling vs. individual type-curve matching is consistent with the relationship expressed by *Chen et al*. [2003]. Specific yield estimates obtained from type-curve matching are unrealistically low, so the transmissivity estimates should be overestimates.

Forward modeling of drawdown estimates specific yield to be higher than individual well analysis, which is accompanied by a lower estimate of transmissivity. The aquifer parameters determined by analyzing all the wells at once are, perhaps, a better estimate of the aquifer properties than individual well drawdown curve matching, consistent with *Moench's* [1994] results.

There are some discrepancies between the aquifer parameters estimated using each of the three analysis methods. This may be due to departure from assumed aquifer and test conditions, for which there is some evidence and knowledge. The best fitting *Neuman* [1972] drawdown model for drawdown in all four of the monitoring wells has an RMSE value of about 0.05 m, well above the measurement precision range of 0.005 to 0.010 m. This suggests that drawdown in the four wells did not adhere to the *Neuman* [1972] drawdown solution, at least for the late time data used in the analysis. In fact, misfit exists between modeled drawdown and drawdown in each of the monitoring wells. Additionally, in all wells, forward modeling predicts a higher drawdown rate at the end of the analyzed interval than observed. This would not be expected if the hydrogeology and test conditions were aligned with *Neuman's* [1972] assumptions.

Real world aquifers can vary significantly from the conditions set out in *Neuman's* [1972] solution and the fluvial nature of the test aquifer is consistent with lateral and vertical variations in aquifer properties. Silt and sand lenses similar to those observed elsewhere in the Broadway Alluvium could certainly account for such variations. Heterogeneity in the aquifer is suggested by the discrepancy between parameters determined from gravity and drawdown analysis. Drawdown in each well reflects local properties, while gravity measurements are affected by aquifer storage changes over a broader area. The gravity change indicates greater storage change than that expressed by drawdown data from the four monitoring wells, by comparison of drawdown predicted from the gravity analysis parameters versus the observed drawdown (Figure 24). Similarly, using parameters derived from the forward modeled drawdown analysis, drawdown in well 1 (Figure 26) is predicted to be about half the drawdown predicted by gravity analysis. The gravity signal suggests that relatively large storage changes occurred during the test away from the monitoring wells.

There is also evidence of anisotropy within the drawdown analysis done on early time data. The curve fitting process used for this early time data did not impose the restriction that horizontal and vertical hydraulic conductivity be the same, with resulting horizontal hydraulic conductivity estimates several times greater than vertical hydraulic conductivity at wells 1 and 2. Additionally, since drawdown is much more sensitive to storativity during the first minute than at later times [*Chen et al*., 2003], this early time drawdown analysis should yield a more realistic storativity value (Table 2), for which other analysis methods provided unrealistic and poorly constrained results.

In addition to hydrogeologic conditions, there are pumping test conditions which may have been present and unaccounted for in the modeling. Recharge would affect drawdown, but is not observed in the drawdown data. However, it cannot be ruled out. The expected maximum drawdown radius (defined as ≥ 0.0001 m of drawdown) predicted using the *Neuman* [1972] drawdown solution and the parameters obtained from gravity analysis does not extend to 200 m (Figure 30). Using the average parameters determined by type-curve fitting, the drawdown cone radius surpasses 700 m, greater than the distance to the gravity base station. Estimating the infiltration geometry from the pump discharge to be the inverse of the drawdown cone suggests the possibility of recharge influence on both drawdown and the base station gravity. If the individual well drawdown analyses correctly estimated the aquifer parameters, pump discharge may have affected drawdown, monitoring well gravity, and base station gravity as early as 10,000 s after pumping began. The magnitude of recharge, estimated with the *Neuman* [1972] drawdown solution for time 96,960 s, is approximately 1 m at well 1 and 0.5 m at well 4. Recharge of this magnitude should be evident in drawdown, but was not observed. Likewise, significant delayed yield was not observed in the drawdown data, so likely had minimal impact on drawdown and gravity measurements. It does have the potential to lower the gravity signal. A similar effect would result from significant aquifer compaction, which was assumed to be negligible.

Two aspects of the pumping test are known to not meet *Neuman's* [1972] assumptions. Drawdown at well 1 reached 1.67 m by the end of pumping, which is arguably significant compared to the initial saturated thickness, 4.73 m. Secondly, the pumping rate was averaged over the pumping interval to conform to analysis requirements, but was actually variable during the test (Figure 9). The magnitude of these conditions on the analyses is unknown.

Despite these issues, gravity results are similar to results from drawdown analysis done on the four wells. The estimate discrepancies may be minimized by using a different drawdown solution. Drawdown modeling used in this analysis was necessarily limited to conform to the *Neuman* [1972] drawdown solution for comparison with the gravity analysis, which was also based on the *Neuman* [1972] drawdown solution. Numerous other drawdown analysis methods are available, many of which allow for anisotropy, heterogeneities, variable pumping rate, and other considerations which potentially affected the results of this analysis.

This experiment demonstrated that time-lapse gravity collected at one station may complement data obtained from multiple monitoring well analyses. Also, the potential benefit of occupying multiple stations was illustrated. To fully realize the capability of using gravity measurements for aquifer parameter analysis, multiple gravity stations, along multiple azimuths must be used. Additionally, the gravity analysis process must be capable of evaluating anisotropic, heterogeneous aquifers. An inversion process that considers multi-azimuth gravity data as well as drawdown data would be a powerful tool for evaluating aquifer properties.

7. Conclusion

Time-lapse gravity measurements have been useful for monitoring unconfined aquifer storage change and, coupled with well level data, estimating specific yield. The aquifer test conducted here provided a comparison of aquifer parameters estimated using a traditional type-curve fitting approach, gravity change analysis, and forward modeled drawdown comparison. The estimates varied between the three methods. Gravity analysis yielded estimates of T=0.0033 m^2s^{-1}, S=0.0052, and Sy=0.45. Type-curve matching resulted parameter estimates which varied slightly between wells, with average estimates being T=0.018 m^2s^{-1}, S=0.041, and Sy=0.0093. Forward modeling of drawdown defined by the *Neuman* [1972] drawdown solution simultaneously compared to drawdown in all four monitoring wells resulted in parameter estimates of T=0.0080 m^2s^{-1}, S=0.000004, and Sy=0.26. The variations in parameter estimates obtained with these analyses are attributed to heterogeneities and anisotropy within the aquifer. In this aquifer test the best fitting gravity model showed greater sensitivity to transmissivity than specific yield or storativity. Objective functions showed a strong relationship between transmissivity and specific yield. Transmissivity is robustly constrained when greater than ~0.003 m^2s^{-1}, to within half an order of magnitude. When transmissivity is less than ~0.001, specific yield is constrained to within ~0.1 to 0.2. The modeling is insensitive to storativity values less than 0.1. Uncertainty in the gravity data is conservatively estimated to be ≤ 7.6 μGal. Uncertainty in the drawdown data is estimated to be ±1 cm.

Transmissivity estimates from all three analysis methods spanned less than one order of magnitude, which is less range than normally expressed for any type of unconsolidated sediment aquifer [*Fetter*, 2001]. Additionally, the estimated transmissivity values are all realistic estimates for a sandy gravel aquifer. This suggests that any of these analysis techniques can provide a good estimate of transmissivity. This was not the case for the storage parameters, specific yield and storativity. Individual well type-curve matching provided unrealistic values of these parameters - storativity estimates were greater than specific yield, an unacceptable relationship for an unconfined aquifer. Both forward modeled drawdown analysis (comparing drawdown in all wells simultaneously) and gravity analysis provided storativity estimates that were both realistic and less than estimated specific yield. Forward modeling of drawdown and gravity analysis both estimated similar, reasonable values of specific yield, considering uncertainty in the gravity analysis. The ability of these two analysis methods to estimate reasonable aquifer parameters, despite evidence of heterogeneities in the aquifer, likely lies in the fact that both methods consider spatially distributed drawdown.

CHAPTER 3

RECOMMENDATIONS

Field gravimetry techniques used in this experiment were largely consistent with the recommended procedures in the body of literature, but this experiment required some different approaches. Additionally, some of the methods employed would benefit from revision. Drawdown data collection and pumping test design also show room for improvement. Perhaps the greatest boon to this aquifer property analysis method, though, would come from improved techniques in data analysis.

Environmental factors, like in many field experiments, played a role in the gravimetry techniques used here. Initial efforts at the site (prior to the aquifer test) to obtain quality gravity data were unsuccessful due to ground subsidence below the gravimeter tripod base. This resulted in an inability to maintain a near-zero tilt on the gravimeter. Commonly, the tripod is pressed into the ground, helping to reduce subsidence. To maintain constant gravimeter height, though, one leg of the tripod was fixed and placed at the same location at each gravity station. This negated the need to measure gravimeter height for each measurement. To prevent ground subsidence, a metal base plate was positioned below the tripod for each gravity station occupation. One base plate was used and transported between gravity stations. Placement of test-durationpermanent base plates at each gravity station would help prevent slight elevation differences between station occupations. Testing must be done to insure the base plates do not transmit high levels of noise to the gravimeter.

High winds also complicated efforts to maintain a level gravimeter. Attempts to use an umbrella to block the wind were unsuccessful. A four-walled wood structure, approximately two feet tall, was used as a wind block. A large piece of corrugated sheet metal was then placed on the outside wall of the windward side of the wooden structure to further block the wind. Concrete blocks were leaned against the sheet metal to help prevent vibration between the sheet metal and the wood housing. This setup illustrates an example of the equipment that may be required in windy areas to obtain quality gravity measurements, although a tent covering the gravimeter should suffice.

An unusual method employed in this experiment, but which is important in the technique, is long term, stationary gravity data collection. Gravity data were collected with a periodicity of about one minute for several hours at a station. Due to potential uncompensated drift in the data due to spring relaxation, it is imperative that the gravimeter be calibrated against a gravity base station with consistent gravity. This is generally done with periodic reoccupation of the base station with each gravimeter. Movement of the gravimeter in this experiment resulted in significant tares in the gravity data, forcing assumptions about tare effects in data analysis.

Alternatively, a gravimeter could be placed at the gravity base station to continuously record gravity during the experiment. Other gravimeters would be used to collect drawdown data and calibrated against the base station gravimeter. This would negate the need for using the software Earth tide correction, removing 3 μGal of uncertainty in the data. However, this would require very careful determination of the base station gravimeter drift so as not to introduce uncompensated drift in all the gravity data. This method would also allow for multi-position, multi-azimuth gravity data collection without the burden of frequent base station reoccupations, potentially reducing manpower requirements.

The use of multiple gravimeters for aquifer data collection would also be beneficial. As discussed in Chapter 2, multiple radii gravity data has the potential to better constrain aquifer parameters than a single station gravity data. Using multiple gravimeters would help minimize gravimeter movement and also allow gravimeter placement at multiple radii and/or azimuths for any desired time interval. Careful determination of pumping duration and gravimeter locations should be made to help ensure adequate gravity signal is measured with each gravimeter.

The equipment used for the pumping test and water level monitoring was typical of that used for similar tests. Drawdown data in two of the monitoring wells in this experiment were collected with a level tape. Better quality, and higher quantity, data would have been collected in these wells with pressure transducers, such as those used in the other wells. It is important that the transducer measurement scales be set such that sufficient range exists to capture drawdown data, but that uncertainty is minimized. Also, some control on pumping rate would minimize fluctuations like the ones seen in this experiment. It is also important to locate pump discharge sufficiently far from the pumping well and gravity base station to prevent influent water from affecting gravity and drawdown data. This may be difficult to ensure. Preliminary gravity model testing indicated that the discharge point used in this experiment was located appropriately.

Drawdown data analyzed after the test do not positively indicate that recharge infiltration occurred, but it cannot be ruled out.

Another way to deal with limitations on equipment design and layout would be to improve the analysis techniques. An inversion process that allows variability in pumping rate, multiple points of aquifer pumping and infiltration, and aquifer heterogeneities and anisotropy is an important next step. A joint inversion scheme that considers multipoint gravity and drawdown data, allowing for realistic geological and equipment conditions, would open the door to fully realizing the potential for using these tools to evaluate aquifer properties.

Table 1.

Well	Radial Distance (m)	T (m^2s^1)	S	Sy	Damping Factor	Residual Mean
1	6.34	0.0173	0.0021	0.000052	0.01	< 0.01
2	15.35	0.0172	0.000026	0.019	0.001	< 0.01
3	30.7	0.0173	0.049	0.018	0.01	< 0.01
4	60.15	0.0186	0.11	0.00047	0.01	< 0.01
Average	--	0.0176	0.041	0.0093	--	--

Table 2.

Well	T (m2s-1)	S	Sy	K_v/K_h	Damping Factor	Residual Mean (m)
1	0.00807	0.0090	0.042	0.115	0.01	< 0.01
2	0.01205	0.0086	0.039	0.067	0.001	< 0.01

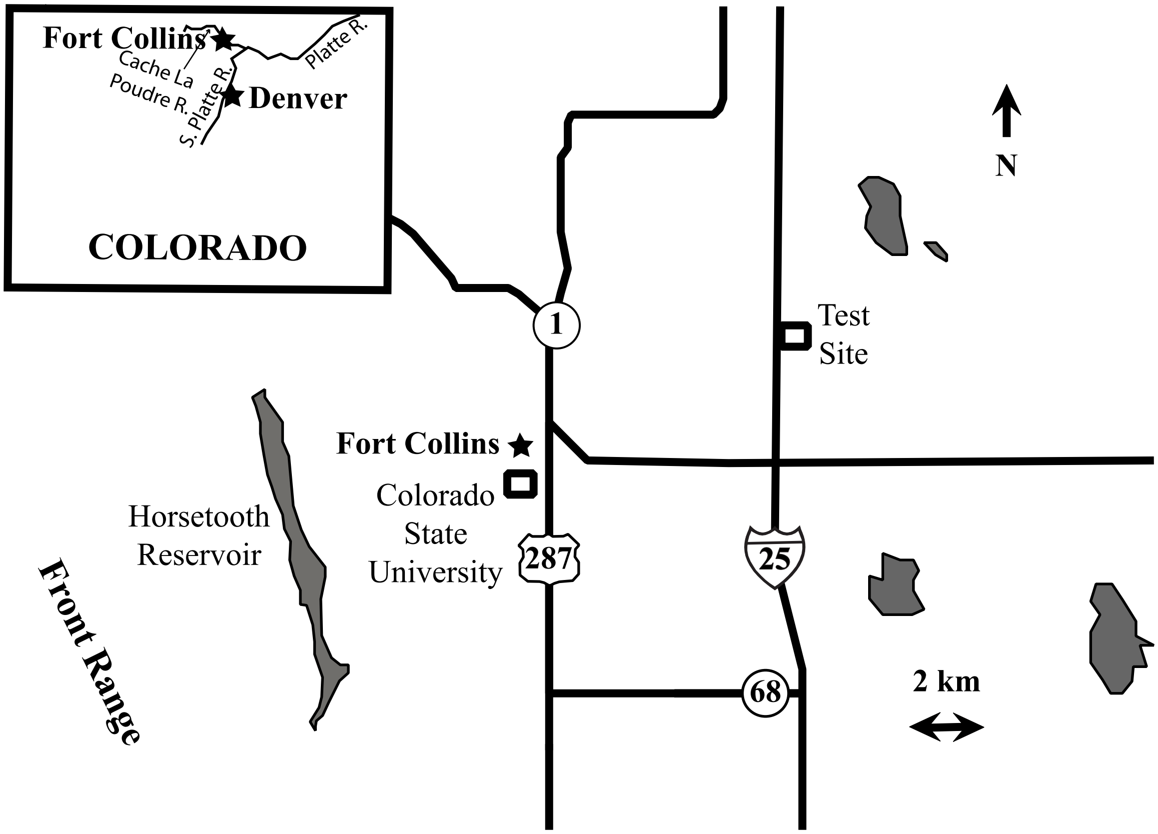

Fort Collins
Cache La Poudre R.
Platte R.
S. Platte R.
Denver
COLORADO
N
1
Test Site
Fort Collins
Colorado State University
Horsetooth Reservoir
Front Range
287
25
68
2 km

Figure 1.

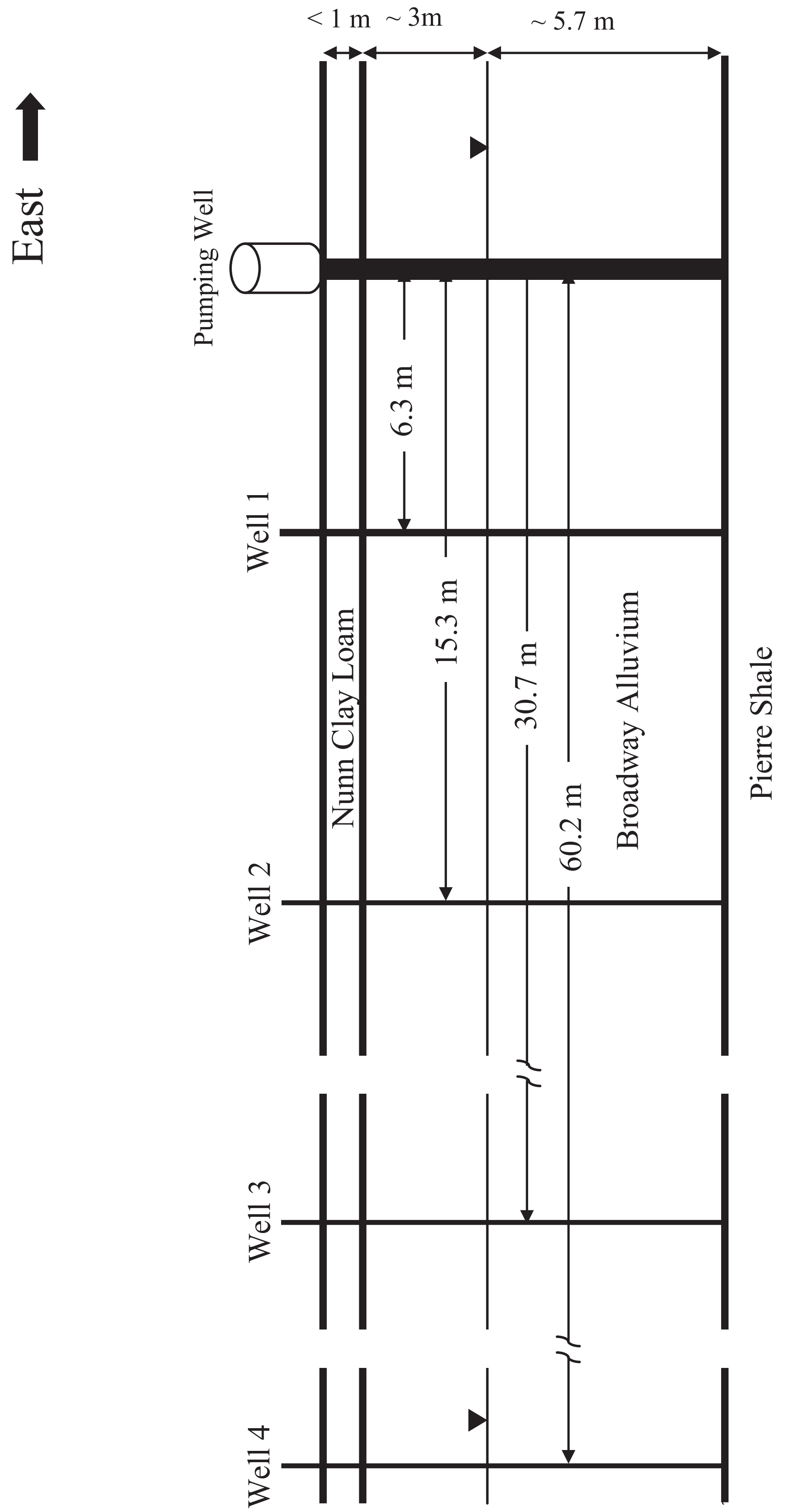

East
Pumping Well
< 1 m
~ 3m
~ 5.7 m
6.3 m
15.3 m
30.7 m
60.2 m
Well 1
Well 2
Well 3
Well 4
Nunn Clay Loam
Broadway Alluvium
Pierre Shale

Figure 2.

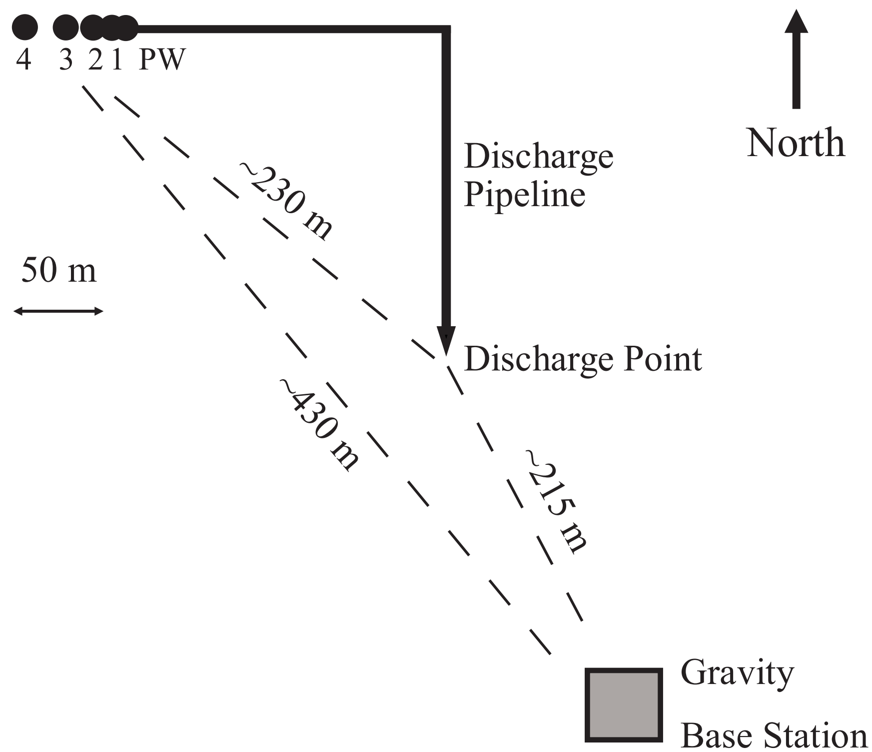

4
3
2
1
PW
North
Discharge
Pipeline
~230 m
50 m
Discharge Point
~430 m
~215 m
Gravity
Base Station

Figure 3.

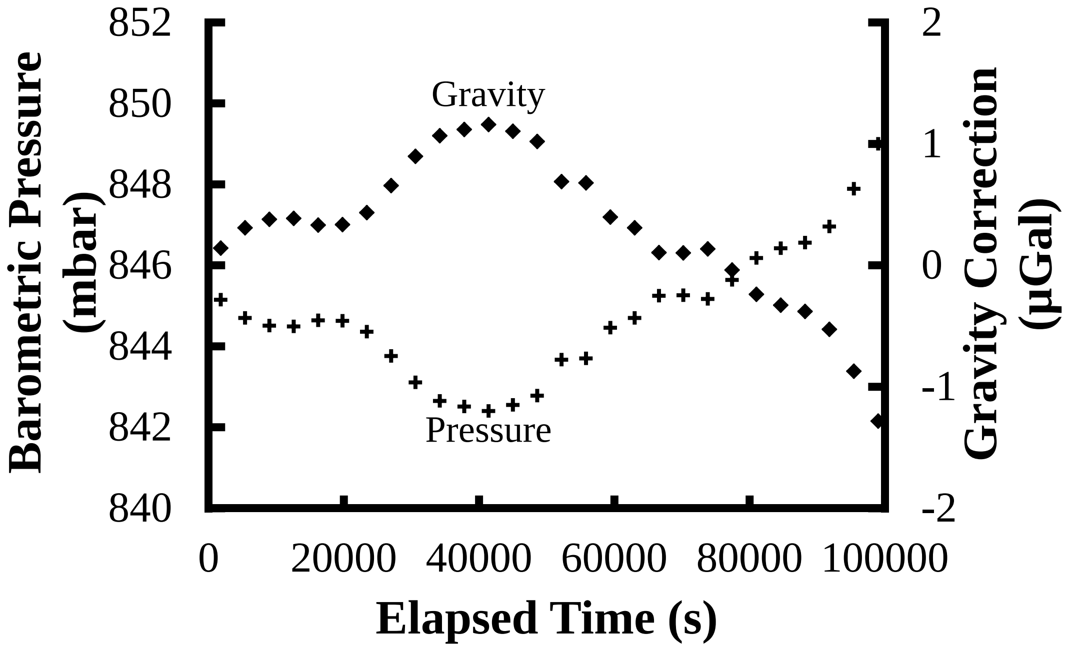
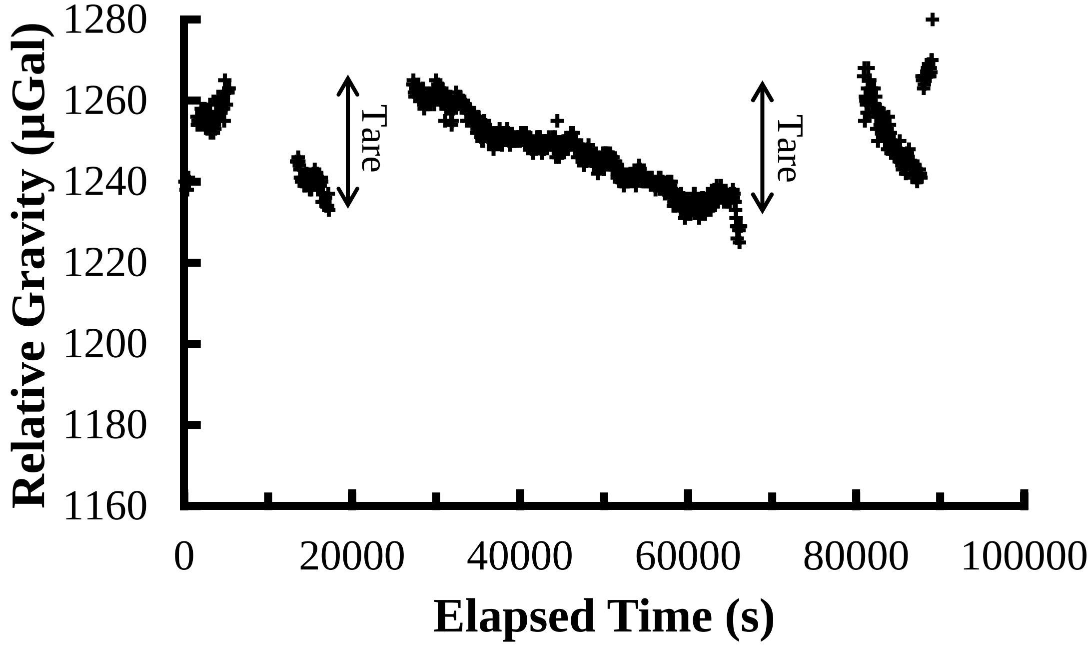

Barometric Pressure (mbar)
Gravity Correction (μGal)
Elapsed Time (s)
Gravity
Pressure
852
850
848
846
844
842
840
2
1
0
-1
-2
0
20000
40000
60000
80000
100000

Figure 4.



Relative Gravity (µGal)
1280
1260
1240
1220
1200
1180
1160
0
20000
40000
60000
80000
100000
Elapsed Time (s)
Tare
Tare

Figure 5.

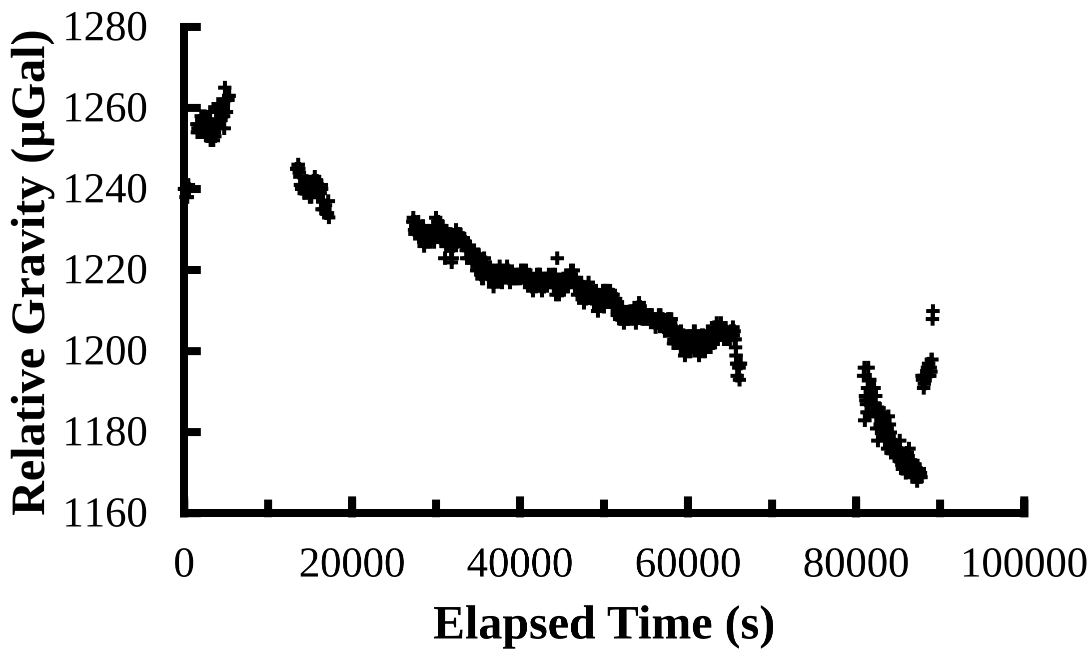

1280
1260
1240
1220
1200
1180
1160
Relative Gravity (µGal)
0
20000
40000
60000
80000
100000
Elapsed Time (s)

Figure 6.

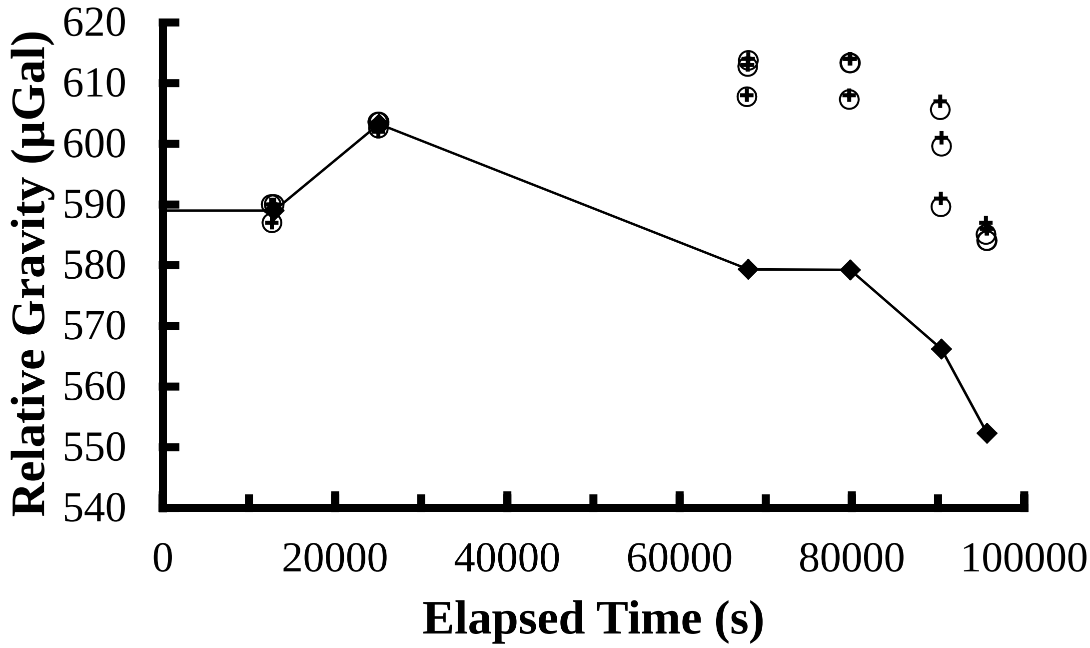
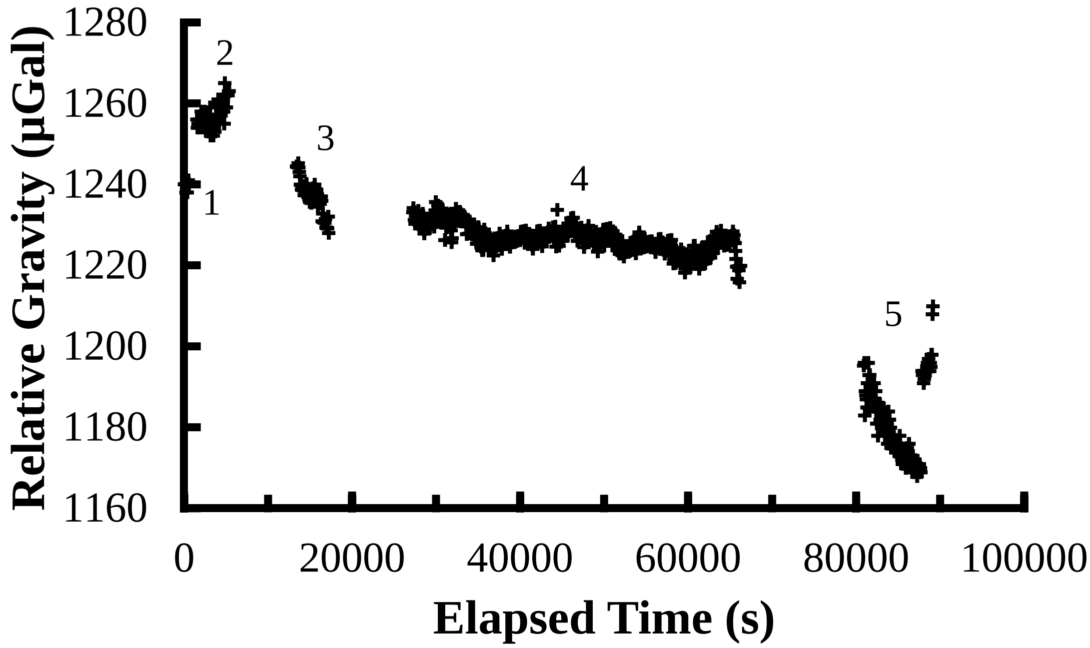

Relative Gravity (µGal)
620
610
600
590
580
570
560
550
540
0
20000
40000
60000
80000
100000
Elapsed Time (s)

Figure 7.



Relative Gravity (µGal)
1280
1260
1240
1220
1200
1180
1160
0
20000
40000
60000
80000
100000
Elapsed Time (s)
1
2
3
4
5

Figure 8.

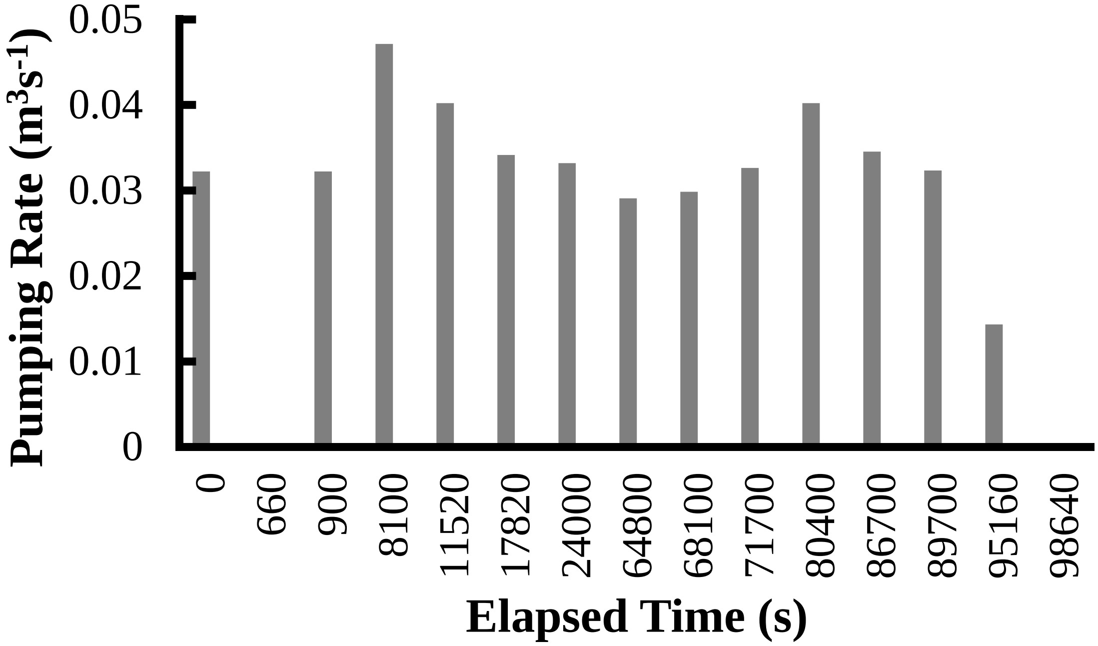

Pumping Rate (m3s-1)
0.05
0.04
0.03
0.02
0.01
0
0
660
900
8100
11520
17820
24000
64800
68100
71700
80400
86700
89700
95160
98640
Elapsed Time (s)

Figure 9.

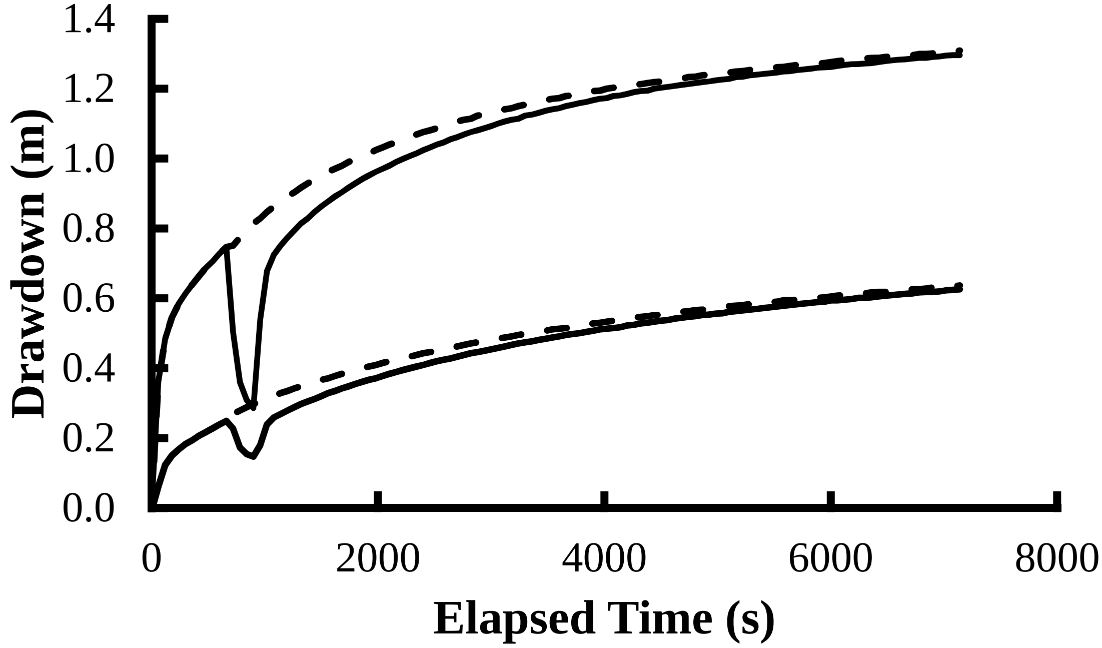
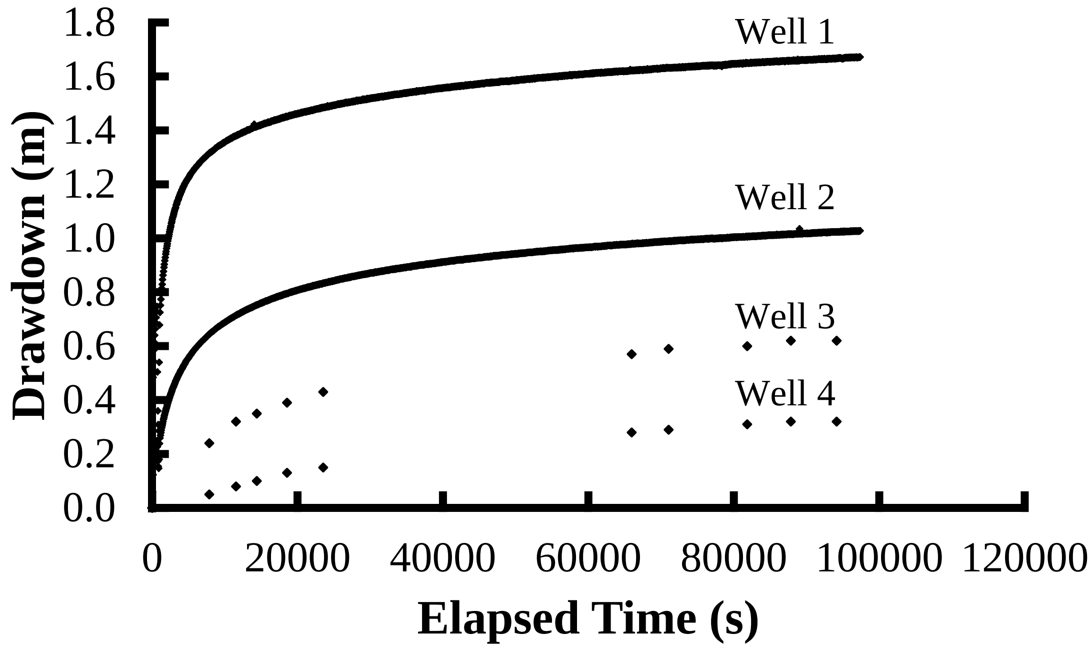
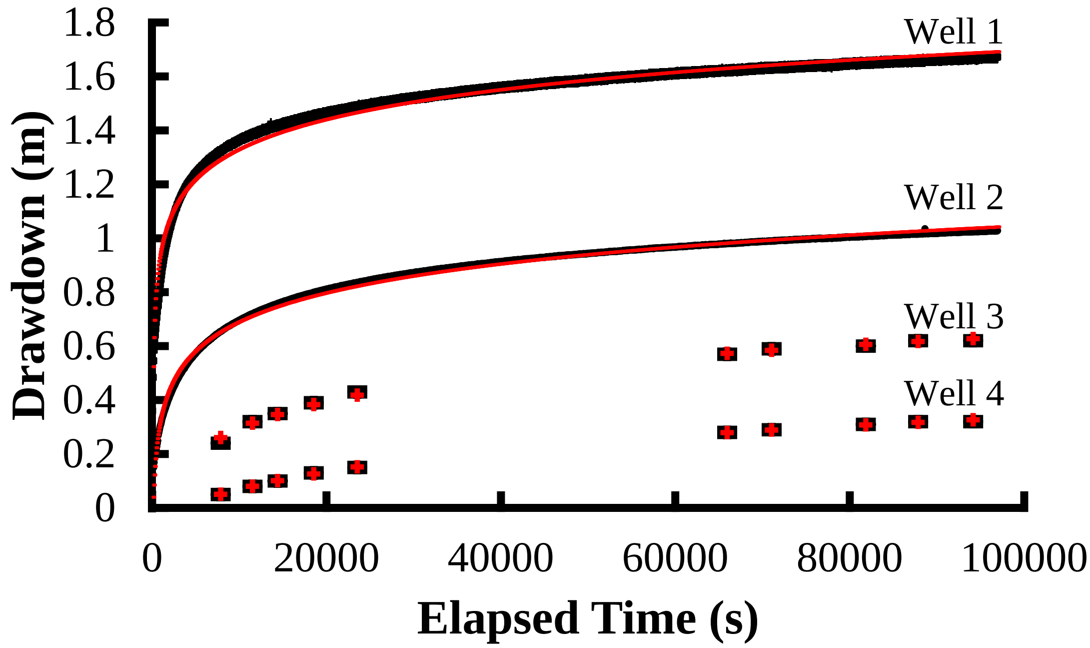

1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Drawdown (m)
0
2000
4000
6000
8000
Elapsed Time (s)

Figure 10.



1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Drawdown (m)
Well 1
Well 2
Well 3
Well 4
0
20000
40000
60000
80000
100000
120000
Elapsed Time (s)

Figure 11.



1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Drawdown (m)
Well 1
Well 2
Well 3
Well 4
0
20000
40000
60000
80000
100000
Elapsed Time (s)

Figure 12.

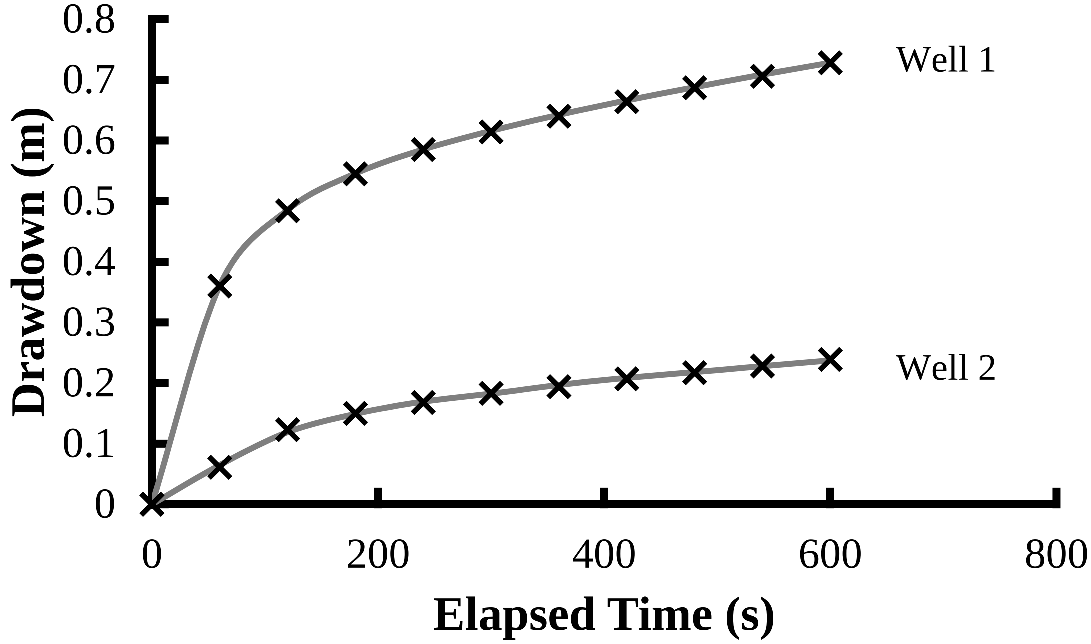

0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Drawdown (m)
Well 1
Well 2
0
200
400
600
800
Elapsed Time (s)

Figure 13.

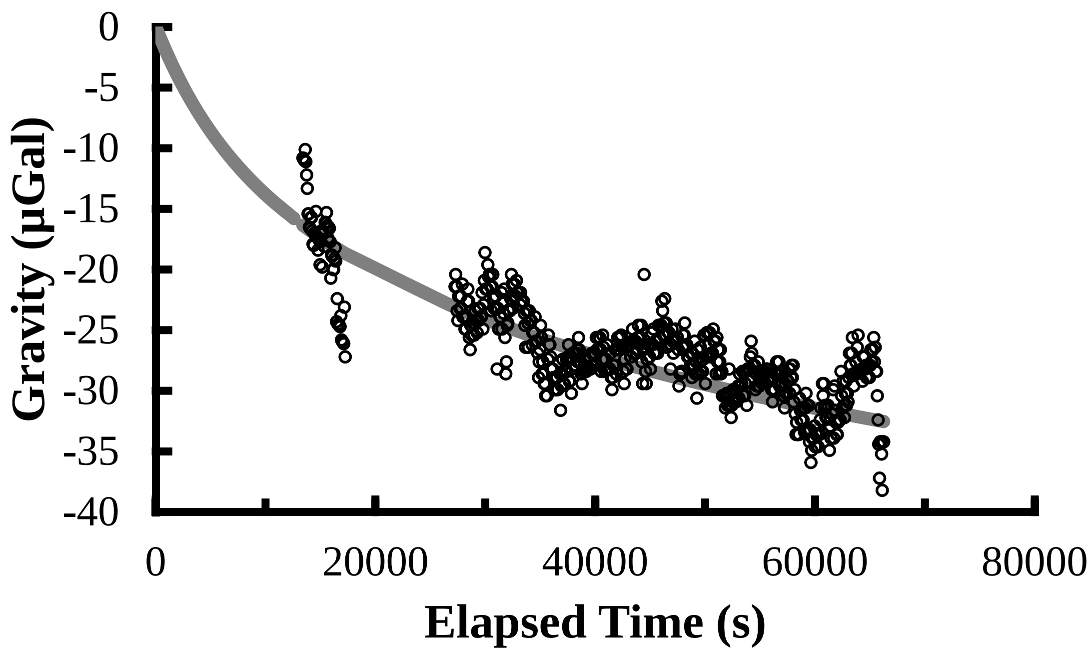
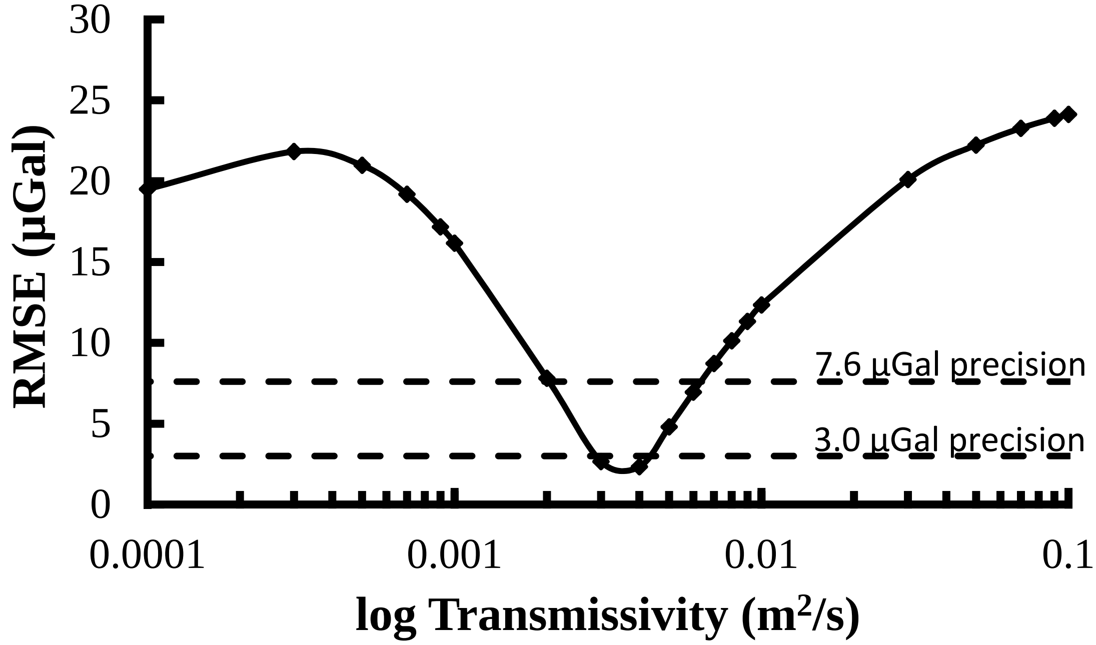
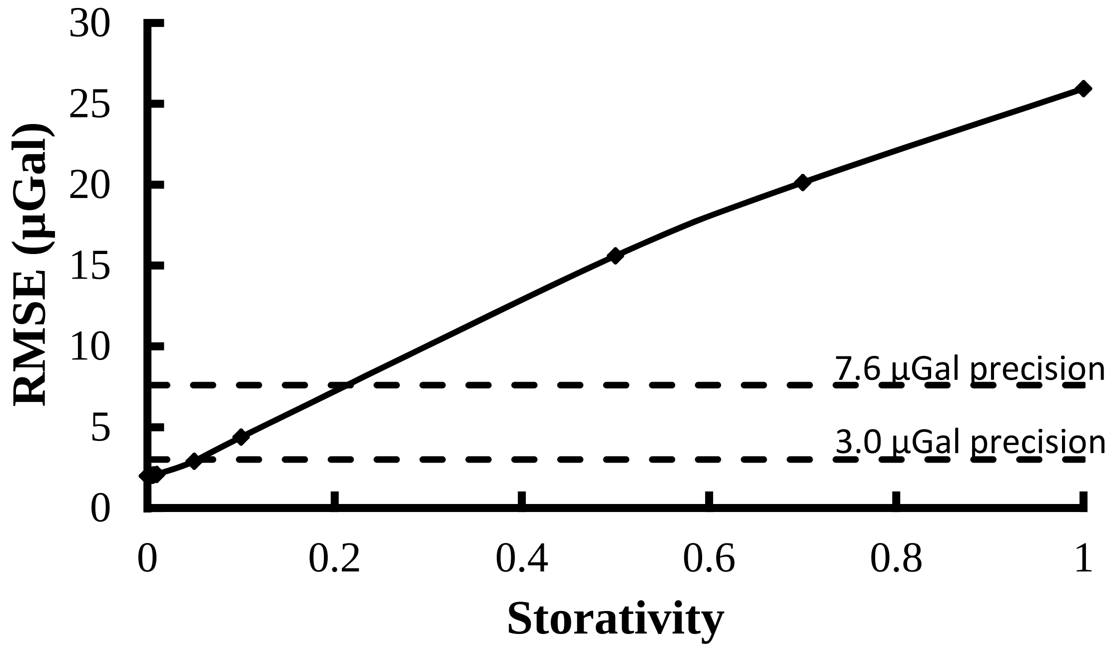

0
-5
-10
-15
-20
-25
-30
-35
-40
Gravity (μGal)
0
20000
40000
60000
80000
Elapsed Time (s)

Figure 14.



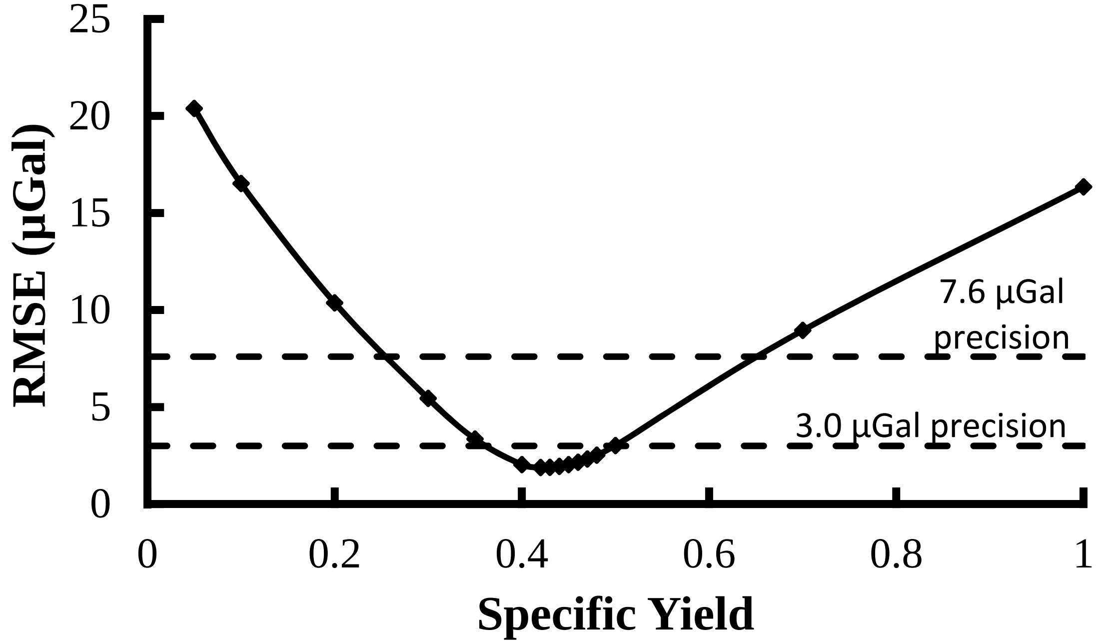
30
25
20
15
10
5
0
RMSE (µGal)
7.6 µGal precision
3.0 µGal precision
0.0001
0.001
0.01
0.1
log Transmissivity (m²/s)

Figure 15.



30
25
20
15
10
5
0
RMSE (µGal)
7.6 µGal precision
3.0 µGal precision
0
0.2
0.4
0.6
0.8
1
Storativity

Figure 16.



25
20
15
10
5
0
RMSE (µGal)
7.6 µGal precision
3.0 µGal precision
0
0.2
0.4
0.6
0.8
1
Specific Yield

Figure 17.

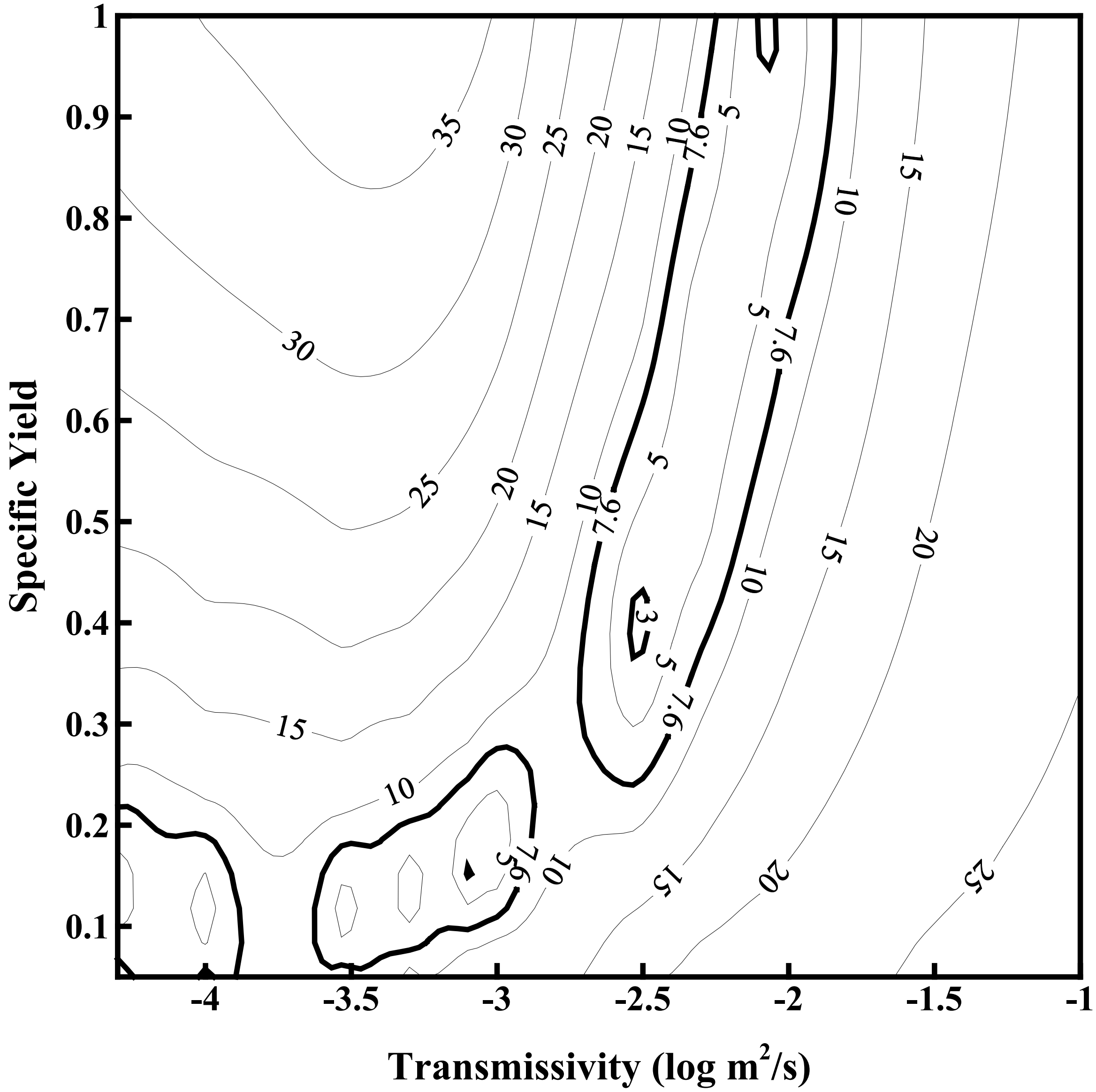

Specific Yield
Transmissivity (log m^2/s)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-4
-3.5
-3
-2.5
-2
-1.5
-1
35
30
25
20
15
10
7.6
5
3

Figure 18.

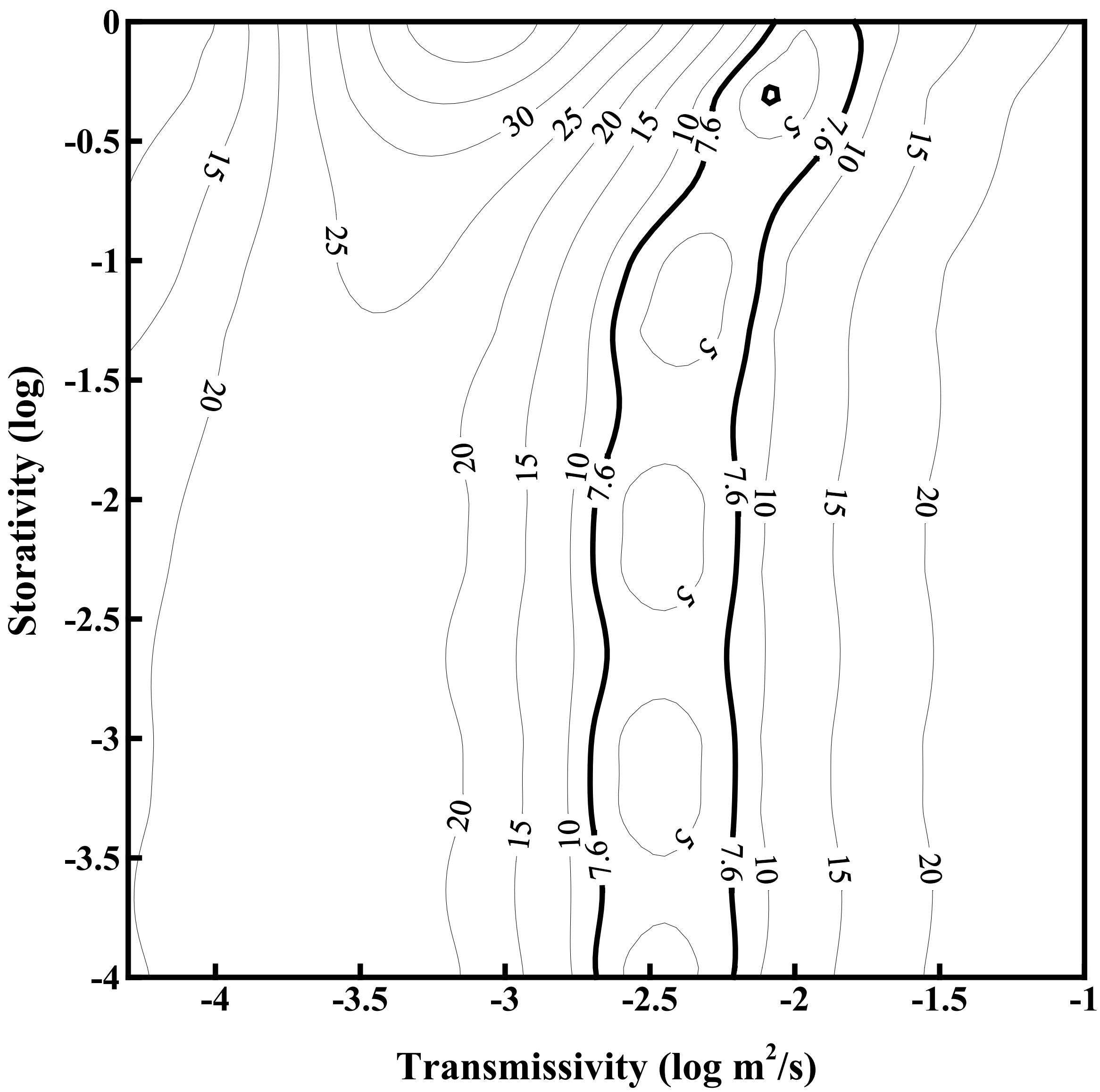
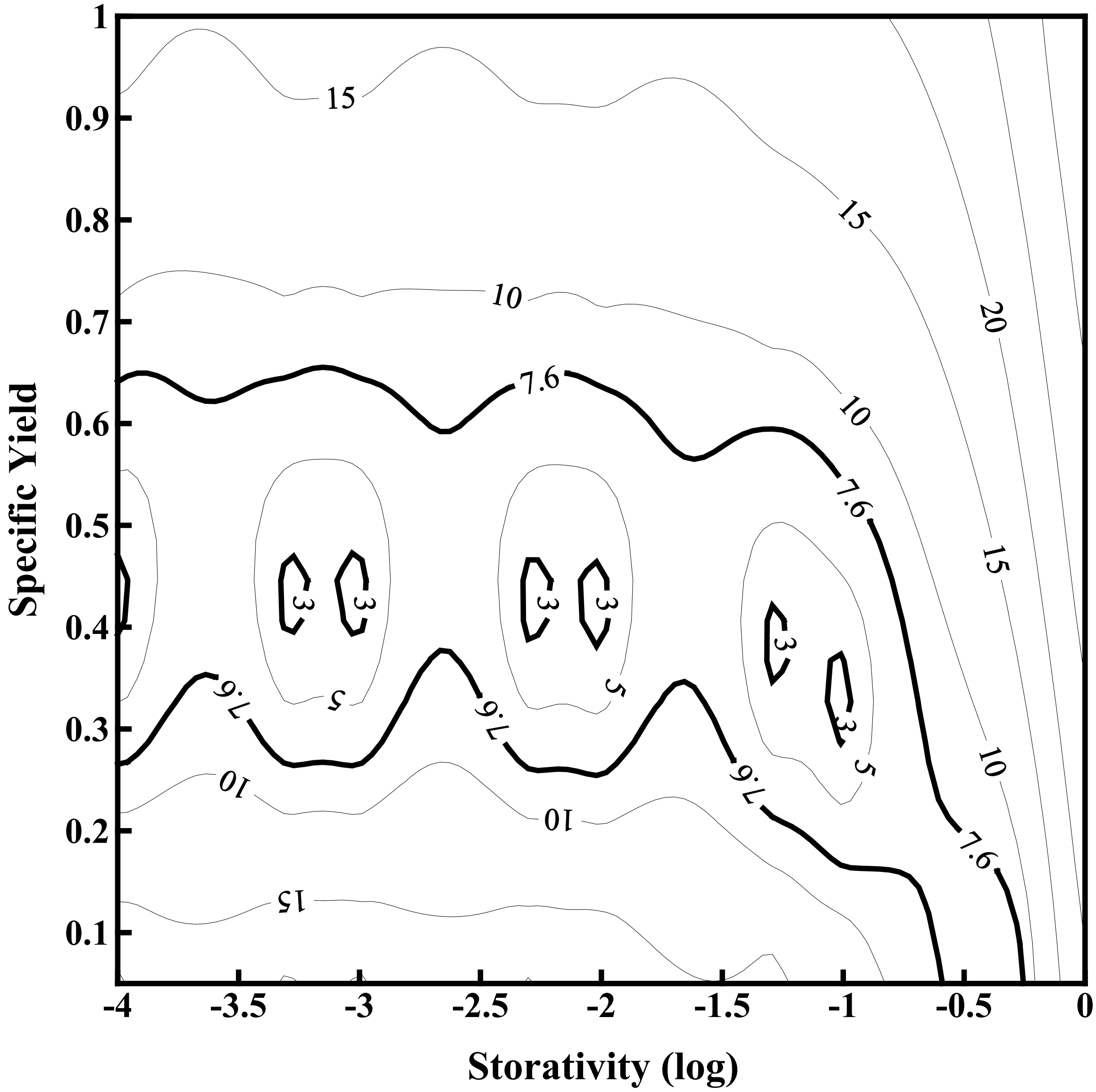

Storativity (log)
Transmissivity (log m²/s)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4
-3.5
-3
-2.5
-2
-1.5
-1
30
25
20
15
10
7.6
5

Figure 19.



Specific Yield
Storativity (log)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-4
-3.5
-3
-2.5
-2
-1.5
-1
-0.5
0
15
10
7.6
5
3
20

Figure 20.

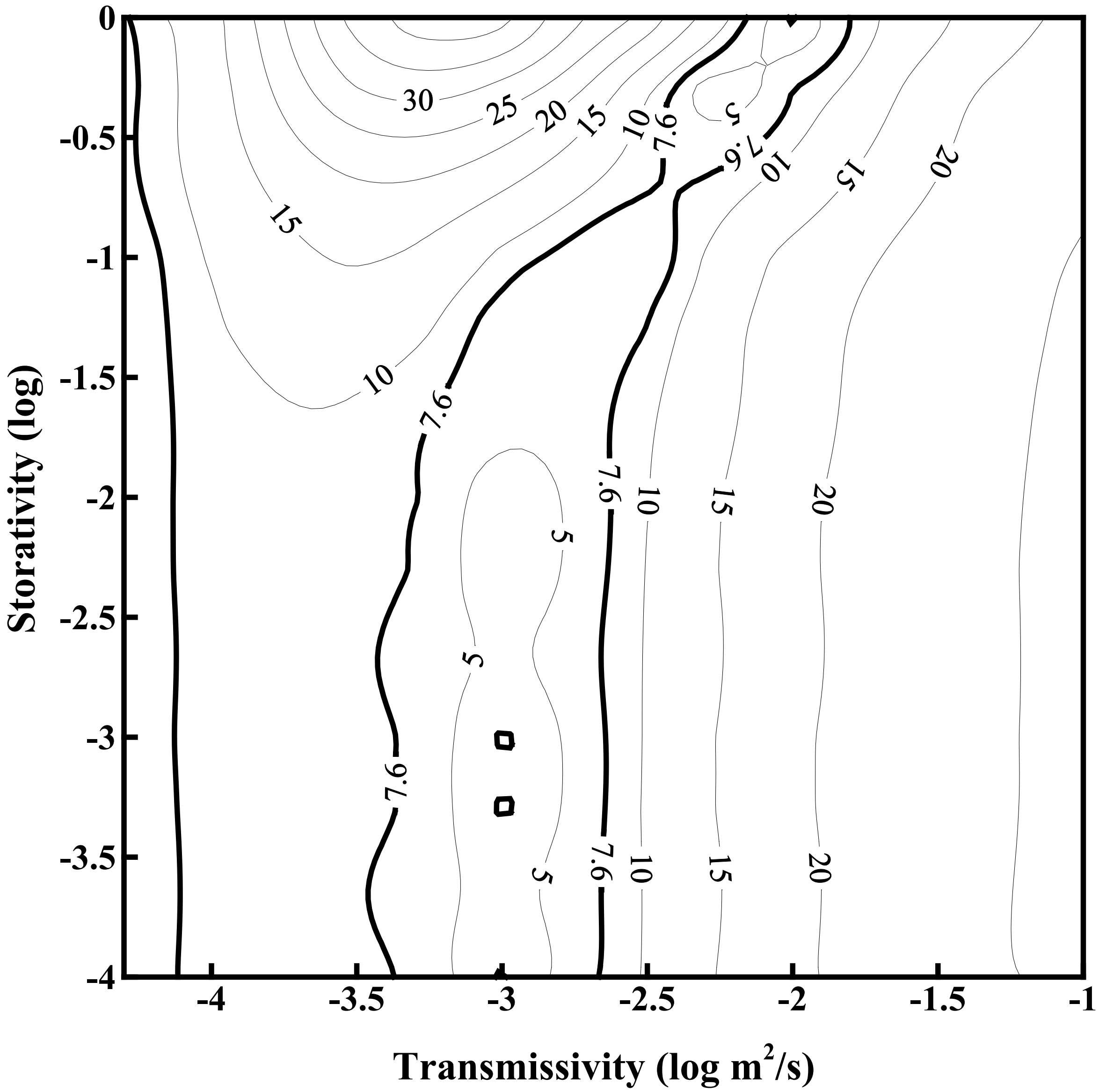
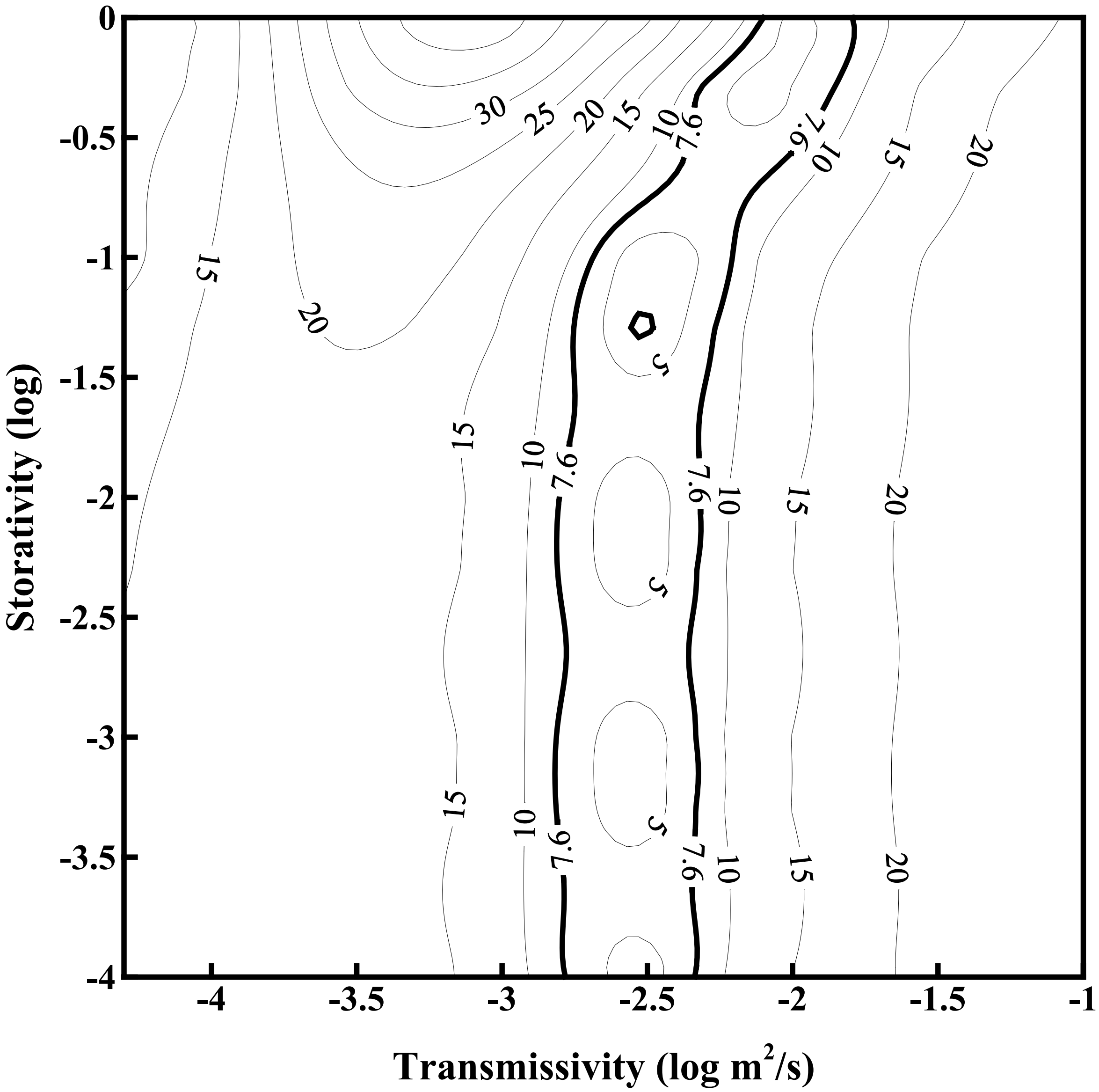

Storativity (log)
Transmissivity (log m²/s)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4
-3.5
-3
-2.5
-2
-1.5
-1
30
25
20
15
10
7.6
5

Figure 21.



0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
Storativity (log)
-4
-3.5
-3
-2.5
-2
-1.5
-1
Transmissivity (log m2/s)
30
25
20
15
10
7.6
5

Figure 22.

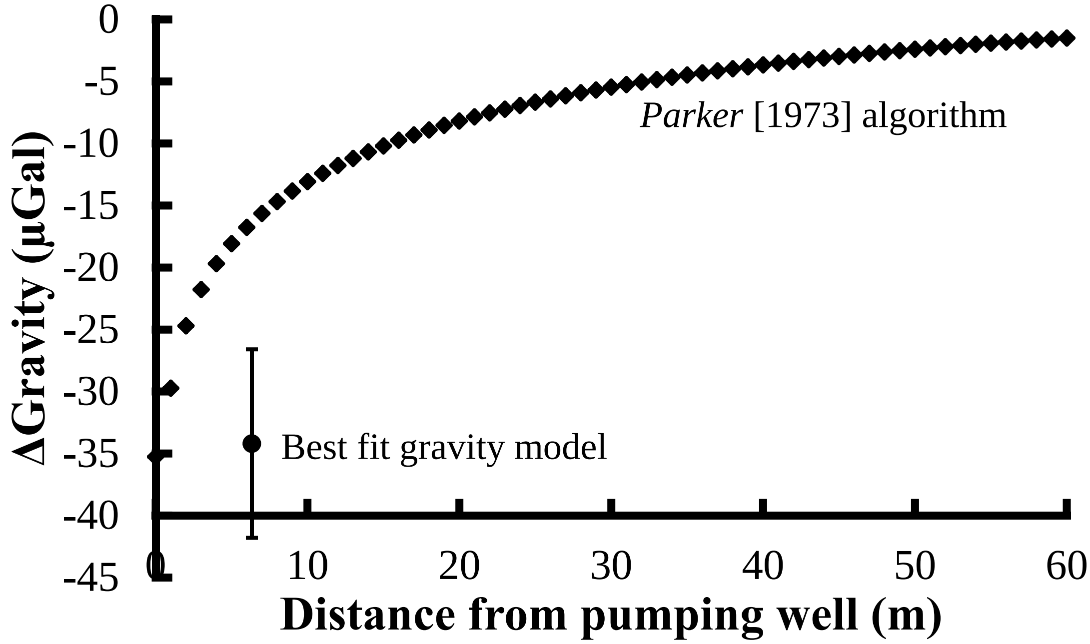
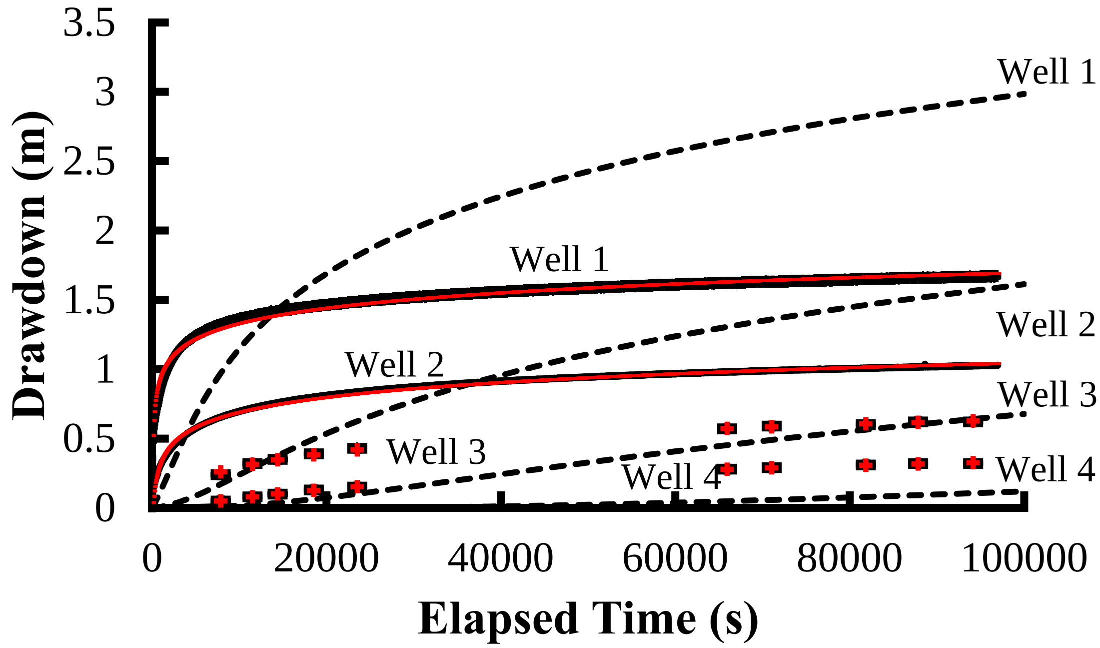

0
-5
-10
-15
-20
-25
-30
-35
-40
-45
ΔGravity (μGal)
Parker [1973] algorithm
Best fit gravity model
0
10
20
30
40
50
60
Distance from pumping well (m)

Figure 23.



3.5
3
2.5
2
1.5
1
0.5
0
Drawdown (m)
0
20000
40000
60000
80000
100000
Elapsed Time (s)
Well 1
Well 1
Well 2
Well 2
Well 3
Well 3
Well 4
Well 4

Figure 24.

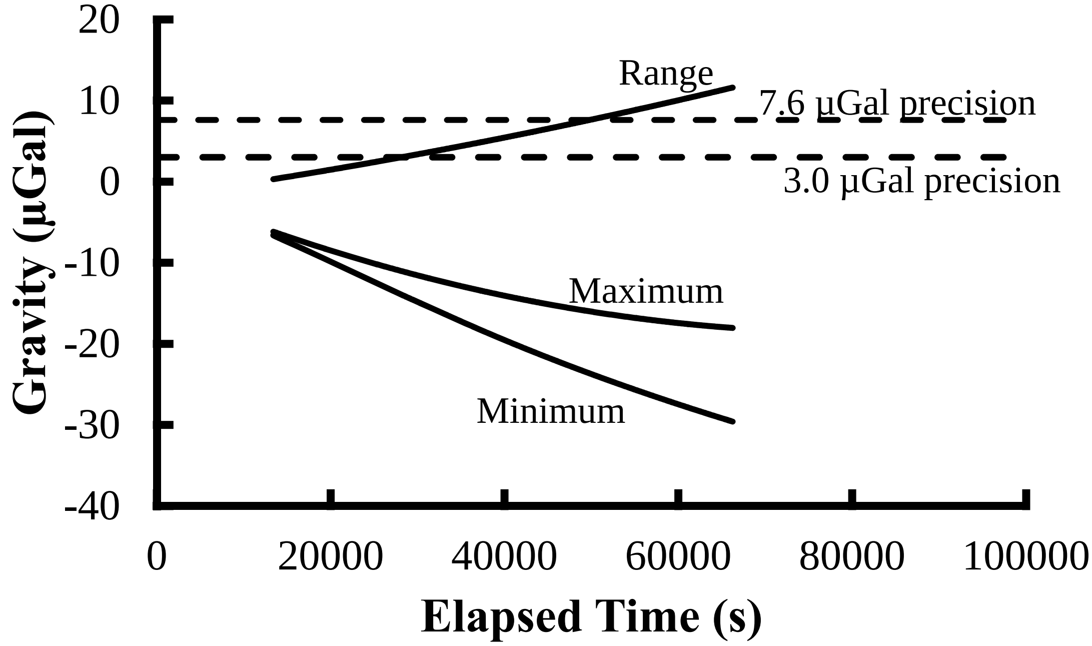

20
10
0
-10
-20
-30
-40
Gravity (µGal)
0
20000
40000
60000
80000
100000
Elapsed Time (s)
Range
7.6 µGal precision
3.0 µGal precision
Maximum
Minimum

Figure 25.

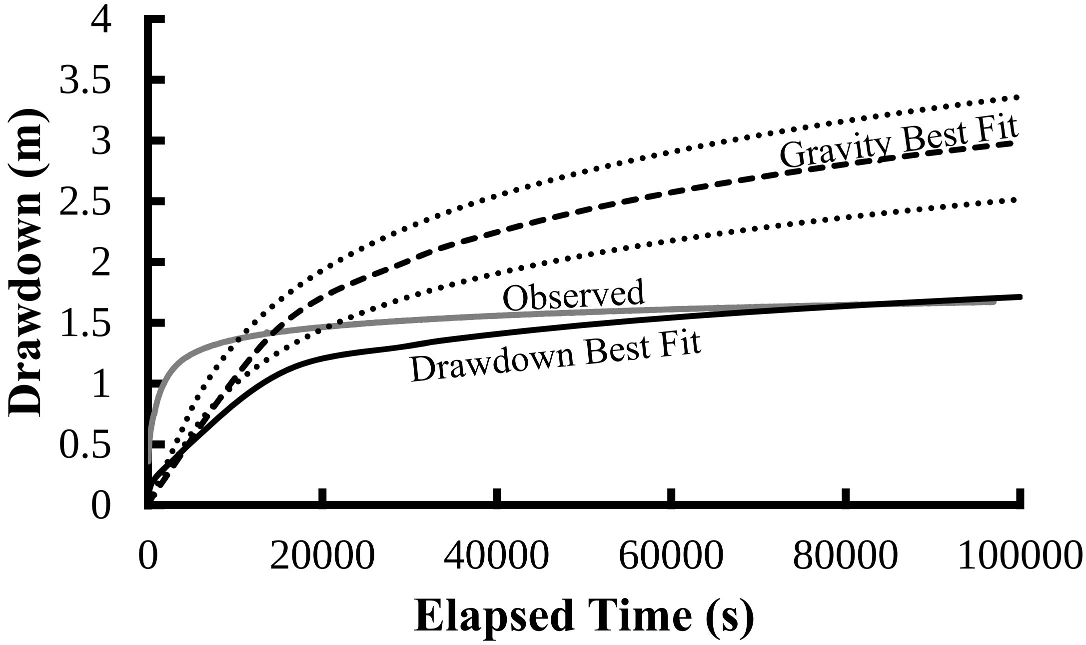
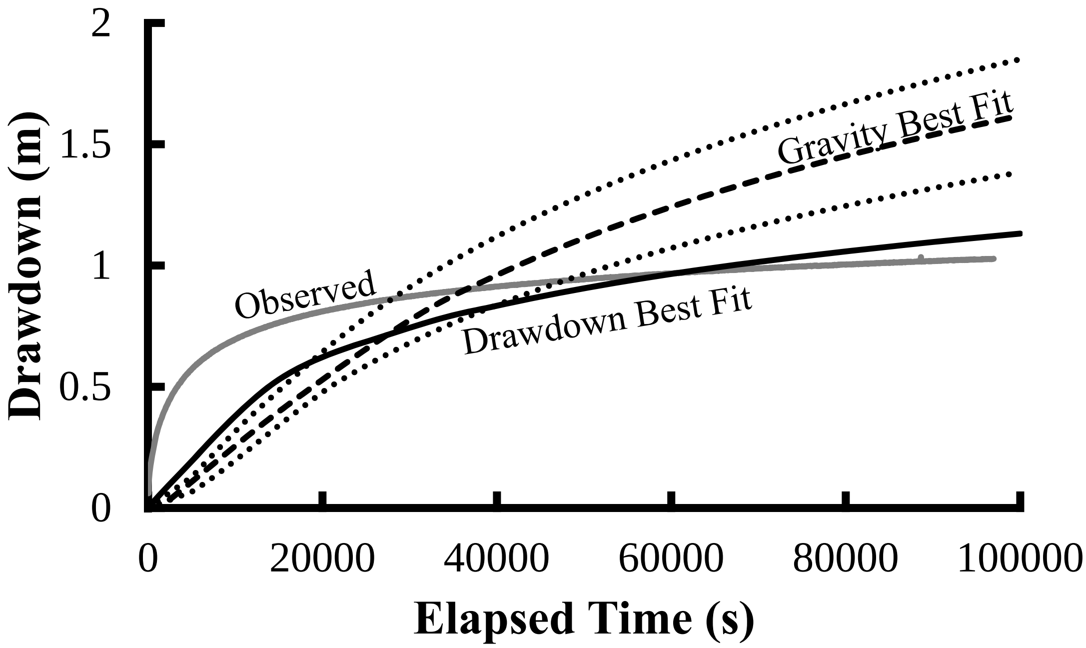

4
3.5
3
2.5
2
1.5
1
0.5
0
Drawdown (m)
Gravity Best Fit
Observed
Drawdown Best Fit
0
20000
40000
60000
80000
100000
Elapsed Time (s)

Figure 26.



2
1.5
1
0.5
0
Drawdown (m)
0
20000
40000
60000
80000
100000
Elapsed Time (s)
Observed
Gravity Best Fit
Drawdown Best Fit

Figure 27.

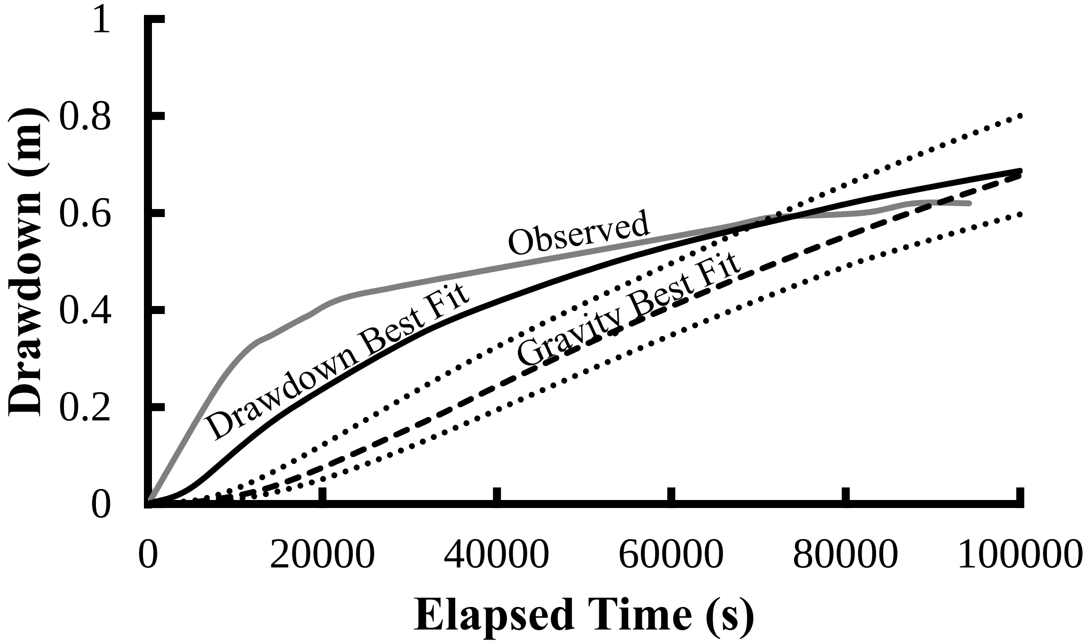

1
0.8
0.6
0.4
0.2
0
Drawdown (m)
0
20000
40000
60000
80000
100000
Elapsed Time (s)
Observed
Drawdown Best Fit
Gravity Best Fit

Figure 28.

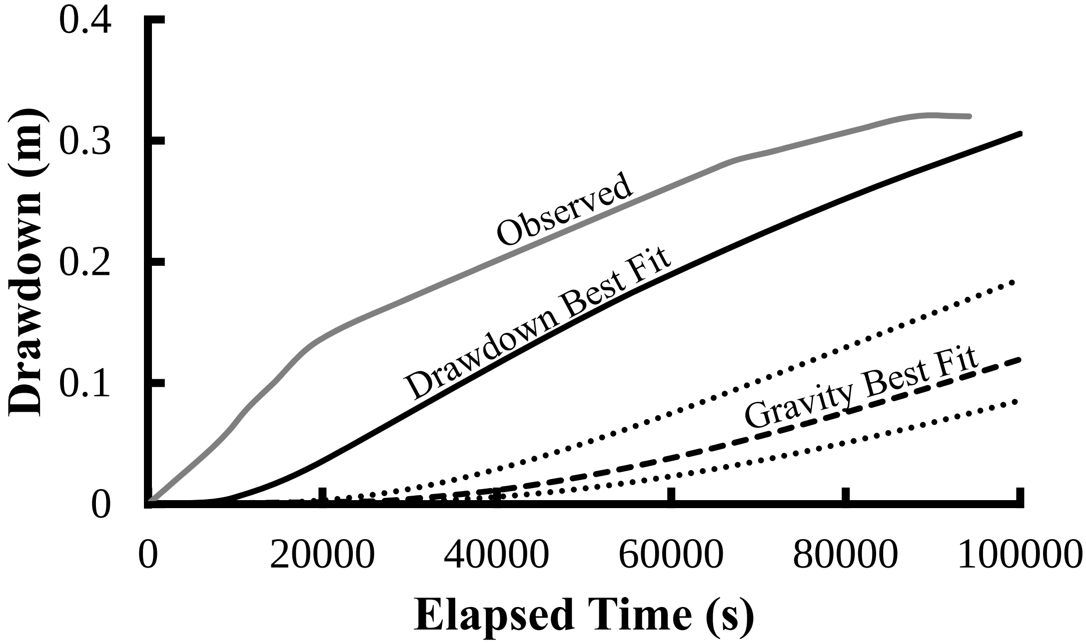
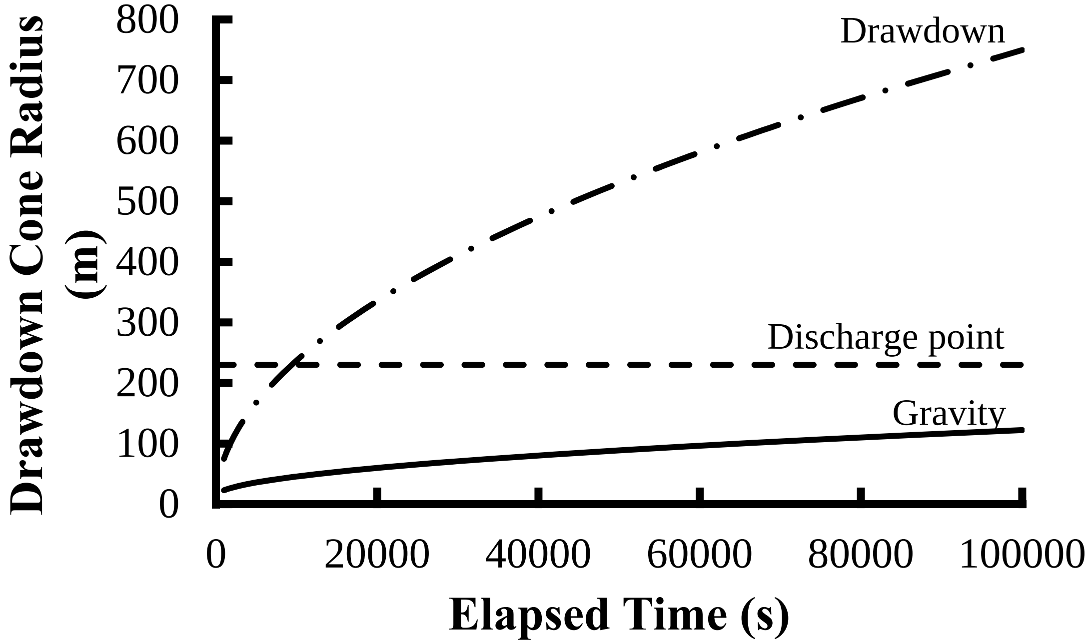

Drawdown (m)
0.4
0.3
0.2
0.1
0
Observed
Drawdown Best Fit
Gravity Best Fit
0
20000
40000
60000
80000
100000
Elapsed Time (s)

Figure 29.



Drawdown Cone Radius (m)
800
700
600
500
400
300
200
100
0
Drawdown
Discharge point
Gravity
0
20000
40000
60000
80000
100000
Elapsed Time (s)

Figure 30.

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