TECHNICAL MEMORANDUM
GRAVITY STUDIES

SUBSURFACE STRUCTURE OF THE TRANSITION ZONE SUBAREA, MOJAVE WATER AGENCY, SAN BERNARDINO COUNTY, CALIFORNIA

Prepared for:

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Attachments on CD-ROM

Data Files, TRZNDEPF, TRZNELEF, and TRZNTOPF contain the basement depth and elevation and topographic X,Y,Z files in UTM (NAD27).

1. INTRODUCTION

URS Corporation (URS) and Dr. Shawn Biehler conducted a study to evaluate the results of hyperbolic density model construction using Complete Bouguer Anomaly data to refine basin depths and assess aquifer storage capacities. This Technical Memorandum presents a summary of 2 and 3-dimensional models based on hyperbolic density calculations for the depth to bedrock and a reassessment of the groundwater resources in the Transition Zone (TZ) Sub-area of the Mojave River Basin. The TZ Sub-area was identified as the evaluation study area based on water management plan priorities (e.g. proposed recharge projects) and available seismic study data and deep well logs. Recovered and previous gravity observations in the Mojave Water Agency (MWA) Transition Zone Sub-area, (URS, 2005) and existing United States Geological Survey (USGS) digital elevation data were used to calculate the basement depth and elevation models. The results are presented as contours of the basement depth and elevation. The contour maps were used to construct updated cross sections and provided the basis for comments on how the revised structure of the basins of the TZ compares with previous assessments (URS, 2003).

This memorandum documents the data collection, reduction, analysis and conclusions from this study. A CD-ROM containing the final basement models in digital form is included along with a copy of this memo, and figures.

2. SCOPE OF WORK

URS Corporation (URS), in accordance with the scope of work (URS, September 2005), constructed new 2- and 3-dimensional models of the depth to basement in the Transition Zone. Composite Basement Depth and Elevation Maps of the Transition Zone were produced in digital and analog form. The construction is based on over 1,800 gravity observations, regional and residual Bouguer anomaly maps, existing seismic data, and monitoring well boring logs from recently constructed MWA wells. The results are compared to a previous depth to basement model based on gravity studies presented in the Subsurface Surveys Inc. (SSI) report, *Inventory of Groundwater Stored in the Mojave River Basins*, dated May 1990, and estimates of the stored groundwater in the URS report, *Mojave River Transition Zone Recharge Project Phase I: Transition Zone Hydrogeology*, dated March 13, 2003.

3. BACKGROUND

During 1989–1990 Subsurface Surveys, Inc. (SSI) carried out gravity surveys of the Mojave River Basins for the Mojave Water Agency (MWA). Geophysical data were collected by SSI to supplement the gravity data set of the United States Geological Survey (USGS, 1960). In 1990, SSI produced a report, Inventory of Groundwater Stored in the Mojave River Basins, (SSI, 1990) which used Bouguer gravity anomaly data to estimate depth to bedrock and water level data to estimate groundwater storage volumes in basins throughout the MWA jurisdictional area.

URS Corporation (URS) presented a portion of the SSI bedrock depth interpretation in its Phase 1 report to MWA for the Transition Zone Groundwater Recharge Project (URS, 2003). During the Transition Zone project, URS conducted a deep seismic refraction survey directly north of the George Air Force Base, which established bedrock depth along the survey line. The new seismic profile provided an anchor point from which to reevaluate the SSI data. URS contacted SSI to obtain the raw gravity data for correlation with the new seismic data. Unfortunately, SSI could not locate the original data set.

In 2004 through 2005, URS recovered approximately 95% of the historical gravity data originally collected by SSI, from an old format data tape. The original SSI data was converted into a new format and screened for errors and corrupt sectors. Additionally, the SSI gravity data set was augmented with about 5,400 gravity stations from existing historical data sets that provide more coverage in the MWA service area. These data were presented in the URS report *Recovery of Subsurface Survey, Inc. Gravity Data and Incorporation of Other Historical Gravity Data Sets, Mojave Water Agency Area, San Bernardino County, California*, dated July 14, 2005.

A seismic survey conducted by URS as part of the TZ study and recent test hole drilling by MWA indicate a more accurate depth to bedrock map can be drawn, especially when applying new computer processing and modeling techniques. The newly recovered gravity data was used to re-evaluate and interpret the structure and groundwater resources of the TZ.

4. GEOLOGY

The TZ consists of complex fault and erosion controlled bedrock depressions that are partially filled with consolidated sedimentary materials, which in turn are covered with unconsolidated sediments. The Mojave River channel, has eroded into the older alluvial deposits, and has been partially backfilled with Mojave River fluvial deposits consisting of interbedded sand, gravel, boulders, silt, and clay (Figure 1).

TZ formations were grouped into three hydrogeologic units: 1) non-waterbearing units composed of bedrock and consolidated sediments, 2) the Regional aquifer composed of Older Alluvium, and 3) the Floodplain aquifer composed of Mojave River fluvial deposits. Non-water bearing units that underlie the Regional aquifer form the effective base of the groundwater system. The Regional aquifer is generally located between exposed bedrock outcrops and underlies the Floodplain aquifer.

5. GRAVITY INVERSION

Based on the gravity observations in the TZ, a regional gravity field was determined and complete Bouguer anomalies developed for the TZ that were inverted into depths for construction of a basement elevation map (Figure 2). The depth to basement in the TZ was estimated using a gravity inversion method. The following section describes the inversion of the gravity data to develop a basement elevation map.

Sedimentary basins are generally associated with low gravity values due to lower density of the sedimentary infill. The densities of sedimentary rocks and the basement often vary with location location because of the effects of stratigraphic layering, facies variations, diagenesis, tectonic history, cementations and compaction from geostatic pressure. Thus, variable density contrasts rather than constant density contrasts are considered in the interpretation subsurface structures. By assuming density contrasts in the sub-surface, it is possible to estimate the depth of the basement.

The modeled depth of the basin is affected by the density contrast between basin deposits and basement rocks, which in turn depends on the assumed value for the average bedrock density. The analysis is based on the assumptions that there are no major density reversals with depth, the basement density is assumed constant across the area of study and the primary seismic control and basement outcrops are accurate. Also the extrapolation of the density-depth function from two sites to the entire TZ is assumed to be valid.

Gravity values from irregularly distributed observation stations were converted to a regular grid using a method of weighted least squares (LSFSGA). In areas where the size of the grid cell dimensions greatly exceeds the spacing of the original gravity stations artifacts and aliasing can occur producing false anomalies. Aliasing occurs where areas of minimal data are biased by being attributed equal weighting as areas with higher data density. The construction of a gravity data grid prior to contouring eliminates most of the bias associated with the unequal distribution of gravity data points.

To invert the complete Bouguer anomalies into depths, the regional gravity field was determined, followed by the production of a Complete Bouguer Anomaly Map (Figure 2). From this set of grid values, a series of regional and residual Bouguer anomalies using various separation widths were computed using a program REGRES (Biehler, 1988) based on a modified Griffin technique (Dobrin and Savit, 1988). The Residual Anomaly (**RESA**) is defined as the difference between the Least Squares Fit Complete Bouguer Anomaly (**LSFCBA**) and the Regional Anomaly (**REGA**) at a given grid point for a specific separation width.

A program, using a modified Litinsky algorithm, that applies a hyperbolic depth versus density function, was applied to the residual Bouguer anomalies to compute digital basement depth models (Litinsky, 1989; Biehler, 1990, 1999, 2001). The gravity basement depth models were combined with the geology to produce a composite basement depth map (Figure 4). To convert the basement depth model to a basement elevation model, the digital elevation data was averaged on a 500 meter (1640 foot) grid (Figure 5). The basement depth grid was then subtracted from the elevation grid and the results are contoured to produce a Composite Basement Elevation Map (Figure 6).

The data for contouring the basin thickness, basement elevation and topographic maps are supplied in digital form as files **TRZNDEPF.XYZ, TRZNTOPF.XYZ**, and **TRZNELEF.XYZ** on CD. The grid spacing for these files is 500 meters (1,640 feet). The results are most accurate for depths between 1,500 feet and 3,000 feet. This is due to the insensitivity of the residual gravity to minor fluctuations in basement depths and to the spacing of the original field data.

The accuracy of the depth to basement calculation is related to the accuracy of the residual anomaly, the surface density contrast, and the proximity of the depth control points. Depth control points, such as well logs or seismic survey data, located closer to the maximum thickness of sediments in a given cell, improves the overall inversion. Based on measured densities of sediments and bedrock types in the Mojave Desert (SSI, 1990), an average surface density contrast of 0.45 g/cm^3 was selected (Figure 3). Primary density-depth control was provided by one seismic refraction profile near the center of the TZ (Figure 4) and a deep well (08N/06W-12B1) located in the Astley Bedrock Basin (Figure 9). Rock outcrops provided points of zero depth to basement.

Since there are significant variations in the composition and density of the sediments and the basement rock across the TZ, the depth inversion results for areas that are more distant from the depth to basement control points, are less accurate. By only using a single depth control point such as the seismic line, the gravity inversion resulted in a maximum depth of the Astley Bedrock Basin of approximately 1,200 feet shallower than indicated by the lithologic log of deep well 08N/06W-12B1 (Figures 9 and 13). Erroneous depth to basement interpretations will result if the density of the basement rock is assumed to be similar throughout the TZ. The density of the basement in the TZ can range from 2.56 gm/cc for metamorphosed sediments, to 2.78 gm/cc for basic volcanic rocks (SSI, 1990).

The accuracy of locating the lateral extent of the basin margins, will improve the calculated groundwater resources of the TZ Basins. In particular, a more reliable estimate of the groundwater resources on the TZ basins is possible if depth control points were located within the western areas of the TZ Basins.

6. RESULTS OF GRAVITY DATA INVERSION

The results of the gravity inversion are presented in the Composite Basement Depth Map (Figure 6). The map indicates a maximum thickness of over 5,000 feet in the central portion of the George Bedrock Basin (Figure 4). This basin extends beyond the southern boundary of the TZ. The Astley Bedrock Basin has an estimated maximum depth in excess of 5,000 feet. A saddle point is observed at a depth of about 1,000 feet between the George Bedrock Basin and the Astley Bedrock Basin. The Helendale Fault is clearly indicated by a very steep linear gradient in the basement depth contours as well as the steep gravity gradient (Figure 6).

The Composite Basement Elevation Map (Figure 6) is similar to the basement depth map (Figure 4). The elevations of the base of the George and Astley Bedrock Basins are more than 2,000 feet below sea level. This indicates that these basins are consistent with a tectonic origin are probably tectonic and not erosional (Figures 11 and 13). The edge of the Bryman Basin can be seen along the eastern edge of the map separated from the seismic line by a basement ridge (Figure 7). In comparison with the regional depth to basement contours on Figure 6, greater topographic definition and an increase in the accuracy of the basement depth is possible within a radius of approximately 4 miles of a control point, shown on Figure 7.

Cross sections of the TZ sedimentary basins were drafted along the same section lines presented on Plate 1, of URS' Phase I Report (URS, 2003). Cross-Sections, A1-A1', B1-B1', C1-C1' and D1-D1', are based on re-calculated basement elevations shown on Figure 9.

The cross sections, Figures 10 to 13 and contour map Figure 14, illustrate the following basement structures and groundwater levels in the TZ:

- A fault in the Ore Grande Canyon area is indicated by the steep eastern edge of the George Bedrock Basin (Figures 10 and 13).
- Prominent basement highs are shown near Bryman and Silver Lakes (Figures 10 and 13).

- The western edge of George Bedrock Basin is near the Fremont Wash. Saturated sediments do not appear to be located west of the Fremont Wash. (Figures 11, 12 and 13).
- The Astley Bedrock Basin extends below sea-level and is most probably a structural basin bounded by faults, including the Leuman and Blake Ranch Faults (Figures 13 and 14).
- Based on USGS Well ID 08/06W-12B1, the elevation of the base of the Astley Bedrock Basin may be more than 2,400 feet below mean sea level (Figure 13). This would indicate a sedimentary thickness of approximately 5,000 feet for the deepest part of the Astley Bedrock Basin (Figure 13).

6.1 Basin Structure Comparison

The basin inversion model results in a structure map that is generally similar to that presented in the SSI report. The primary differences between the SSI report (1990) and this gravity inversion derived structure of the TZ Sub-Basins, are in the interpretation of the depth of the TZ Basins. The current memo indicates that the George Bedrock Basin could be up to 5,500 feet deep, whereas the SSI report indicate a maximum depth for the George Bedrock Basin of possibly 3,500 feet. The SSI report (1990) indicates the Astley Bedrock Basin may be more than 4,000 feet deep. This memo indicates the maximum depth of the Astley Bedrock Basin may be 5,000 feet (Figure 13).

The URS 2006 presentation of depth to basement contours are shown superimposed on the earlier depth of bedrock presented by SSI in the 1990 report. (Figure 14). The lateral extent of the Astley Bedrock Basin, as defined by the basement contours, appears to be more extensive for the SSI Report (1990) compared with this memo. The opposite is true of the George Bedrock Basin, where the SSI report indicates the eastern limit of the George Bedrock Basin located approximately 2 miles east of this report's boundary of the George Bedrock Basin. (Figure14).

7. GROUNDWATER STORAGE

This section discusses the methods used, and results of the earlier estimates of the volume of groundwater stored in the TZ (SSI, 1990, URS 2003), and compares them with the data presented in this memo.

7.1 Subsurface Surveys, Inc. Groundwater Storage Calculations (May, 1990)

Subsurface Surveys, Inc. (SSI, 1990), identified 19 sub-basins in the Mojave River region. Three of those sub-basins are located in the TZ. The George Bedrock Basin, located around Adelanto, the Astley Bedrock Basin, located northeast of Shadow Mountains, and the small Bryman Sub-Basin, located between the Mojave River and Silver Mountain.

SSI computed the depth to bedrock based on approximately 3,800 gravity data points located throughout the region occupied by the Mojave River Basins. The groundwater stored in the Sub-Basins was calculated by constructing an isopach map of the saturated thickness of the sediments and calculating the difference between the depth to bedrock, and the depth to the water table. A one-mile grid was placed over the isopach map and the volume of each cell added to calculate the total saturated volume. The SSI separated the groundwater resources into depth intervals for each of the Mojave River Sub-basins. The groundwater stored in the first depth interval of 0 to 1,000 feet below ground surface (bgs) for the TZ Sub-basins. The resource calculations and results presented in the SSI report cannot be compared with the URS results, since the extraction of groundwater until the depth to groundwater is 1,000 bgs is impractical and not “exploitable” as suggested. (SSI, 1990).

7.2 Groundwater Storage Calculations, URS, 2003.

URS (2003) provided an estimate for the volume of groundwater stored in the Regional and Floodplain aquifers within the TZ boundary by calculating the volume of water between the base of each aquifer and the 1998 groundwater elevations. The TZ areas underlain by aquifers were divided into grids. Each grid cell was assigned a top and bottom elevation for the aquifers. The difference between the elevations multiplied by the area of the cell provided the volume of saturated sediments within each grid cell. Summing the volumes for all cells provided an estimate of the total volume of saturated sediments in each aquifer.

The total volumes of each aquifer were multiplied by an average specific yield to provide an estimate of the groundwater in storage. For the Floodplain and Regional aquifers, specific yield values of 20 percent and 10 percent were used, respectively (URS, 2003).

Based on the above method of estimation, the Regional and Floodplain aquifers within the TZ contain approximately 7.3 million acre-feet of groundwater. The estimated available groundwater in the TZ for use, assuming water levels were drawn down 100 feet from the 1998 groundwater level, is 1.4 million acre-feet.

7.3 Estimated Groundwater Storage, URS, 2006

Since the uppermost 100 feet of saturated aquifer is the predominant source of exploitable groundwater, any change in the lateral extent of the groundwater basins could alter the estimate of available groundwater stored in the TZ. The groundwater storage calculations in the Phase I Report (URS, 2003) extended beyond the boundaries of the TZ into the adjacent areas north and south of the TZ. Based on the lateral extent of the western boundaries of the sedimentary basins shown on the cross-sections, Figures 10 to 13, and contour map Figure 14, this study refines the boundaries to a slightly smaller area. This is indicated in the northern portion of the TZ area where saturated sediments in the Astley Basin are limited to the area north of the extension of the Blake Ranch Fault.

The accuracy of determining the lateral extent of the TZ Basins depends on assigning the appropriate density contrast between the sediments and the basement. Since the basement density varies significantly, local depth control points are required to produce reliable gravity data inversions. Since depth control points are only available for two areas of the TZ, the accuracy of the depth inversion of the gravity data likely decreases with distance from these control points.

8. SUMMARY

Utilization of gravity data to construct hyperbolic density models to determine the depth of a basin provides an effective means of determining the groundwater resources and the relationship between surface topography, the shape, and the lateral extremities of sedimentary basins.

The accuracy of the calculation of the depth of the sediments within the TZ basins by the inversion of gravity data is based on the application of a valid density-depth function. Extrapolations utilizing gravity data, seismic reflection data and a well log indicate that the density of the basement rocks beneath the northern and central areas of the TZ varies substantially. Within the TZ, in the areas with available depth control data, the inversion of the gravity data was effective in refining the local basin geometry as illustrated by depth calculations in the northern portion of the TZ (Astley Basin). However, due to the variable bedrock densities in the TZ, the accuracy of the depth inversion of the gravity data likely decreases with distance from these control points. Additional depth control points, particularly for the western extremities of the TZ, such as well log information or seismic refraction data, would substantially improve the accuracy of the calculated depth of the basins, the lateral extent, and estimates of the groundwater resources.

The Alto Subarea and George Basin appear to be candidate areas for model development. If well logs and seismic data are available for these areas, hyperbolic density functions can be applied to the available gravity data, to produce revised depth to basement maps. Updated contour maps and cross sections could facilitate a more accurate assessment of the storage and structure of groundwater basins in these areas.

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