FINAL REPORT

Gravity Acquisition and Depth to Basement Modeling of the Spokane Valley and Rathdrum Prairie Aquifer, Northeastern Washington and Northwestern Idaho

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SUMMARY

New and existing gravity measurements were combined and modeled to estimate the depth to basement in the Spokane Valley – Rathdrum Prairie (SVRP) aquifer system of Washington and Idaho. Existing data from earlier studies (Sprenke, 2006) were concentrated in the eastern Spokane Valley and southern Rathdrum Prairie and did not provide the necessary spatial coverage required in a regional geophysical model. To improve the spatial coverage of gravity measurements, nearly 1000 measurements were acquired during the summer of 2006: 499 in and around the Spokane Valley, Washington and 472 in and around the Rathdrum Prairie, Idaho.

New gravity measurements were made with a LaCoste-Romberg Model G gravimeter (with Aloid upgrade), and positioning was controlled by dual frequency Global Positioning System (GPS) receivers operating in Rapid Static mode. Repeatability of gravity measurements is estimated at 10 µGals and elevation control by GPS is 2.5 to 3.0 cm. The gravity stations were geospatially referenced to a GPS monument in the Liberty Lake Landfill in eastern Spokane Valley, and the positions of the new gravity stations are presented in geodetic coordinates with the elevations determined in ellipsoidal height. The GPS reference monument also served as the gravity base station for relative gravity measurements within the basin, and the relative gravity measurements were calibrated to an absolute National Geodetic Survey station (Spokane B) inside of the United States Post Office in Spokane, Washington.

The new data were combined with 1883 existing gravity measurements to compute a complete Bouguer anomaly for the SVRP basin and surrounding region. The high-quality results of the new survey, provided the calibration to bring all data sets into the same realization. Adjustment between surveys was carried out using linear regression of co-located stations.

Before depth modeling was performed, the effects of long wavelength contribution to the gravity and contributions from the heterogeneity of the rocks forming the basement to the basin were removed to provide a residual complete Bouguer anomaly. The development of the residual complete Bouguer anomaly followed a two step process. In the first, a second-order polynomial surface was fit to gravity station values measured on bedrock throughout the study region to remove negative density contrast associated with the northern Rocky Mountains. In the second step, the effect of local geological contributions to the gravity field (density heterogeneity) were eliminated by fitting a smooth spline function to gravity values from bedrock sites around the periphery of the basin.

The residual complete Bouguer anomaly was inverted for depth (Oldenburg, 1974) and produced a geologically reasonable model for the SVRP basin. Depths exceed 400 m in parts of the Rathdrum Prairie but do not exceed 200 m for the Spokane Valley.

INTRODUCTION

The purpose of this project was to supplement existing gravity measurements in the Spokane Valley – Rathdrum Prairie (SVRP) aquifer system of northeastern Washington and northwestern Idaho (Fig. 1) and to produce an improved depth model for the aquifer. New data acquisition focused on acquiring a regional network of gravity stations on bedrock exposures surrounding the basin and on measuring gravity values along several profiles across the basin where earlier data coverage was

insufficient or nonexistent. A combined data set, composed of existing and new gravity measurements, greatly improved the spatial coverage of the aquifer system and allowed calculation a more robust depth to basement model for the SVRP basin.

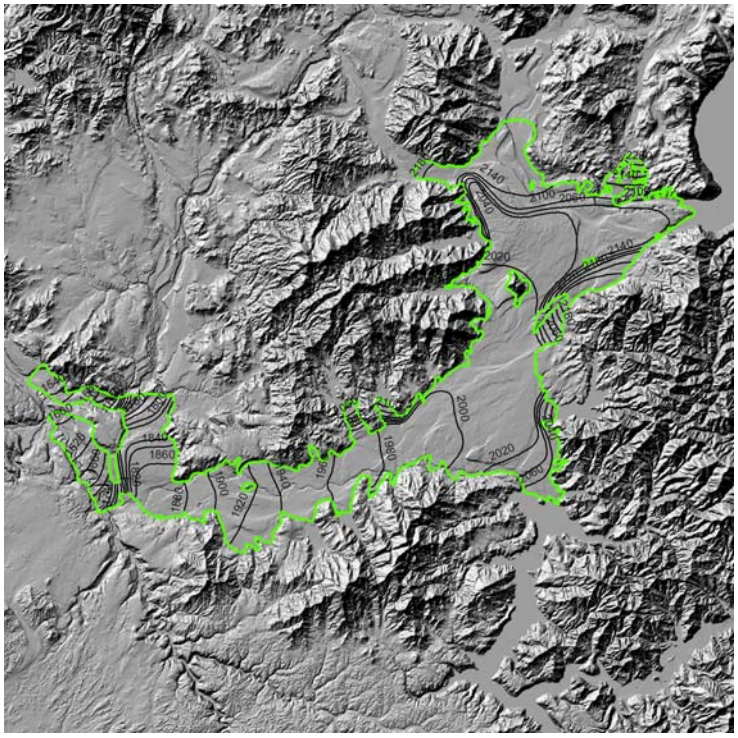


Figure 1. Digital elevation model of the Spokane Valley – Rathdrum Prairie showing the edge of the aquifer (green) and contours of water depth above sea level (feet).

The existing and new gravity data sets were combined and used to calculate a complete Bouguer anomaly for the region. Regional and local geologic contributions to the gravity anomaly were removed in the computation of a residual complete Bouguer anomaly for the SVRP basin. The residual complete Bouguer anomaly was inverted (Oldenburg, 1974) to produce a dept to basement model.

The project deliverables consist of three components: (1) 10 and 30 m digital elevation models (DEMs) and hillshade coverage of the study region; (2) GIS shape files of the gravity data, roads, geology, aquifer boundary, and well coverage, and; (3) multiple surfaces of the gravity and depth model for the basin. The surface-coverage for the basin consists of the complete Bouguer anomaly, primary and secondary regional trends associated with regional and local density variations not related to basin geometry, a residual complete Bouguer anomaly produced by subtracting the regional and local trends from the complete Bouguer anomaly, and a depth to basin model.

The results of this study are compiled in a ESRI GIS and supported by spreadsheets (see CD). All figures cited in the report are best viewed digitally in ESRI ArcMap of ESRI ArcScene, but we produce tiff images embedded in the text for convenience.

GRAVITY OBSERVATIONS (2006)

The primary gravity survey was carried out over six weeks in mid-May through June, 2006 and supplemented by additional work needed to provide better spatial coverage in select areas during August, 2006. The gravity data collected during this project are presented in Table 1. The gravity survey focused on profiles across the basin that were supplemented by measurements in bedrock sites along the basin margin (Fig. 2). The basin-margin measurements were used to provide control on the regional gravity trends not associated with the basin fill. Gravity profiles are composed of a series of stations with a

nominal spacing of 300 m stretching across the basin floor and are anchored on each end by measurements in bedrock or are tied to existing gravity profiles.

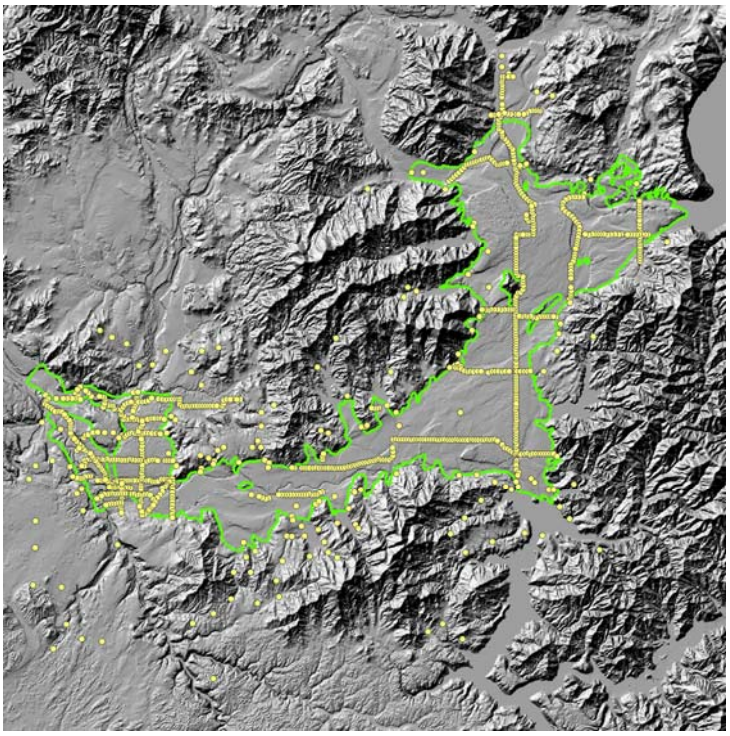


Figure 2. Terrain map of he SVRP showing the distribution of gravity stations measured in this project.

The location of the new survey stations was predicated on existing gravity coverage. The map of gravity measurements that existed before this work (Fig. 3) illustrates several areas of inadequate or nonexistent data coverage, particularly in the western part of Spokane Valley, the northern Rathdrum Prairie, and along north-south and east-west profiles in the Rathdrum Prairie and eastern Spokane Valley, respectively. In the Spokane Valley, we focused much of our effort in developing a grid of profiles in the west part of the basin (Fig. 2). Here we collected north-south and east-west profiles, all of which were anchored in bedrock exposures. The concentrated effort in the western part of the basin was supplemented by expanding existing data coverage in the eastern part of the valley via east-west trending profiles. The east-west profile in the eastern Spokane Valley (Fig. 2) stretches from bedrock east across the Idaho-Washington border and continues east through Post Falls and Coeur d'Alene to bedrock. In the Rathdrum Prairie, a long north-south profile was extended from bedrock exposures south of the Spokane River in western Coeur d'Alene north along the valley axis to Clagstone and beyond to the Priest River, north of the aquifer boundary (Fig. 2). East-west profiles were completed across the basin south of Round Mountain and in the northern reaches of the Rathdrum Prairie near and north of Spirit Lake. Several north-south and east-west profiles were completed in the northeastern Rathdrum Prairie between Athol and the village of Lakeview on Lake Pend Oreille. The combined datasets (Table 2) provides good coverage of the SVRP basin (Fig. 4).

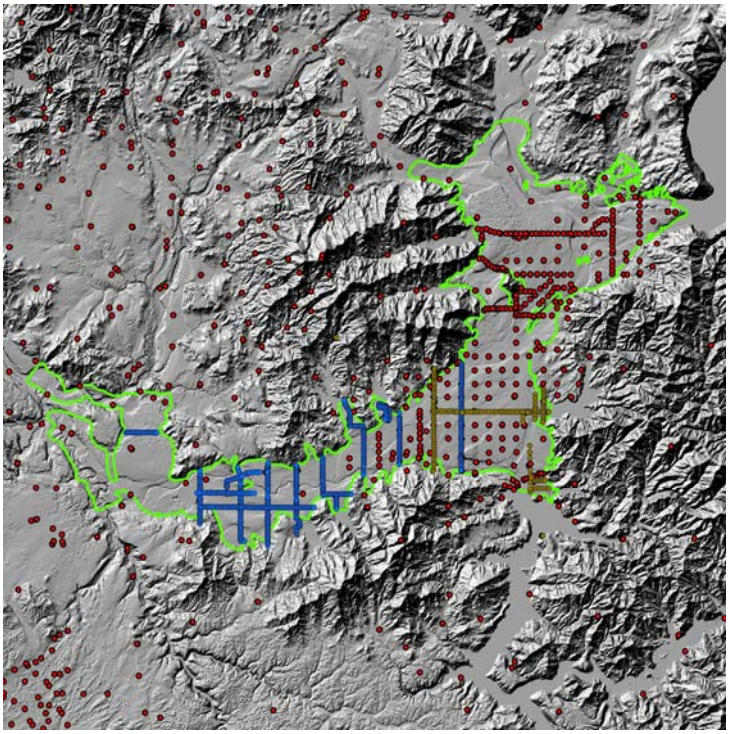


Figure 3. Terrain map of the SVRP showing the distribution of gravity data prior to this project. Red, data from the Pan American Center for Earth Science; Blue, data from Purvis (1969), and: Brown, data from Adema (1999).

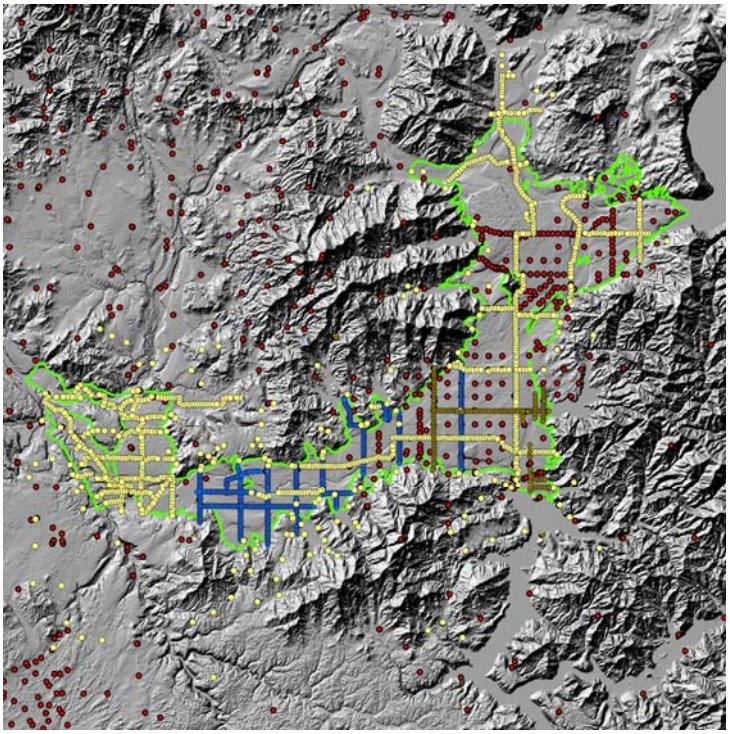


Figure 4. Terrain map of the SVRP showing the distribution of all gravity data used in this project.

Positioning for the gravity survey was supplied by differential Global Positioning System (GPS) measurement. Dual frequency Leica 530 receivers were deployed in Rapid Static mode and positions determined by post-processing of baselines between a base station and rover (receiver at gravity station). The base station (Fig. 5) was established on a GPS monument within the confines of the abandoned Liberty Lake Landfill. Access to and the precise location of the base-station monument was provided by James McLefresh of Spokane County. The base station consisted of a tripod mounted Leica AT504 chokering antenna set over the monument recording at 5 second epochs for the duration of the survey. The roving GPS receiver (Fig. 6) used a Leica AT502 antenna mounted on a constant length pole with a bulls-eye level. Each gravity station was measured with at least 120 epochs (5 second intervals). GPS data were post-processed using the Leica software SKI-Pro each evening. Ambiguity resolution was attained on all solutions and computed baselines between the rover and base station and the average positional uncertainty was 0.0045 ± 0.004 m (1 sigma). Formal uncertainties typically are a poor estimate of accuracy, which is better represented by repeatability. For baselines of less than 100 km the repeatability of station positions are 3.0 cm or better (Featherstone et al., 1998).

Figure 5. GPS base station at the abandoned Liberty Lake landfill.

Figure 6. GPS rover used to located gravity stations.

Gravity measurements were made using a LaCoste-Romberg G meter (Fig. 7) with electronic leveling and digital measurement averaging (Aloid upgrade). Continuous observation of the gravity field was made over periods of 2 to 3 minutes at each station with two measurement being recorded per second and averaged for the entire measurement duration. The LaCoste-Romberg meter (G1069) has a

measurement repeatability determined by LaCoste-Romberg of 10 µGal. The electronic averaging capability of the meter allowed accurate measurement even in areas where ground vibrations produced by high traffic volume would have made reading with a conventional meter difficult if not impossible.

Figure 7. LaCoste-Romberg G meter with Aloid upgrade (meter G1069) used in gravity acquisition.

The typical configuration for a measurement of a gravity station is shown in Figure 8. The gravity measurements were made from a truck and acquisition rates varied during the survey. Measurements

Figure 8. Typical measurement configuration showing gravimeter and GPS positioning.

were made during two 8 hour shifts per day. Typically, up to 40 stations per day were accomplished but rates decreased substantially in populated areas and when regional stations were measured.

COMBINED DATA SET

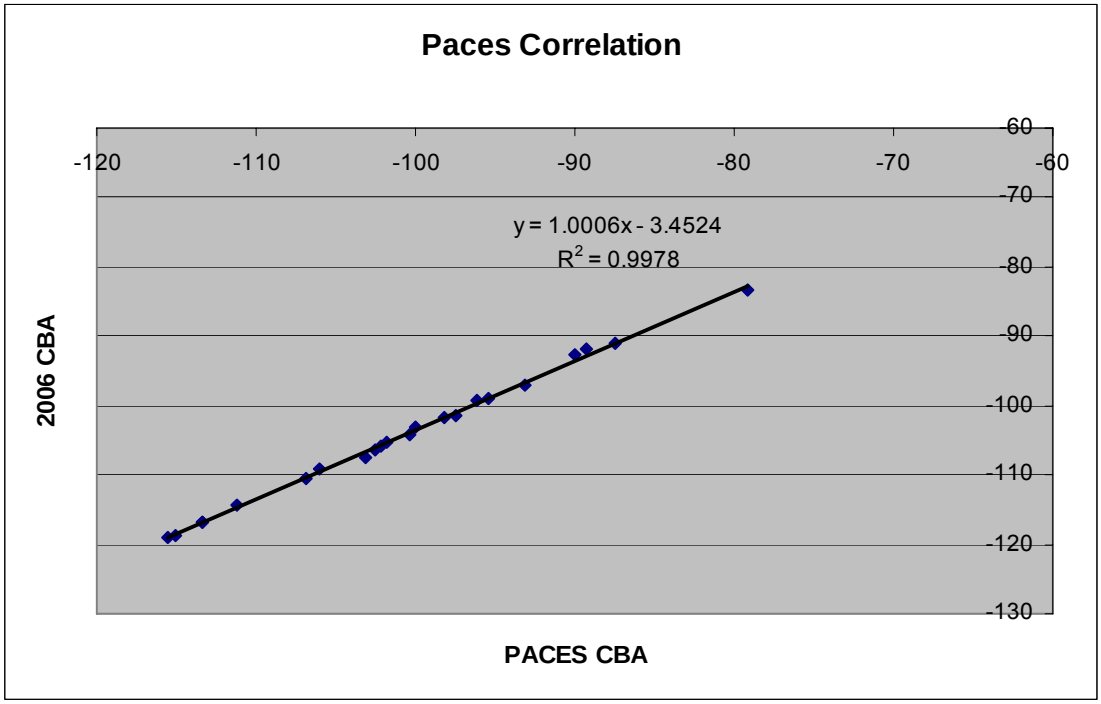
The relative gravity measurements of the 2006 survey were calibrated to absolution values by occupation of a National Geodetic Survey (NGS) absolute gravity reference site. The NGS site Spokane B, located in the U.S. Post Office in downtown Spokane, was used for calibration.

The new gravity measurements were terrain corrected (Cogbill, 1990) and the complete Bouguer anomaly computed using standardized methods and constants outlined by the Standards/Format Working Group of the North American Gravity Database Committee (Hinze et al., 2003). Actual computation was performed using the Holom and Oldow (in press) spreadsheet. A copy of the spreadsheet is provided in the supporting material (see CD).

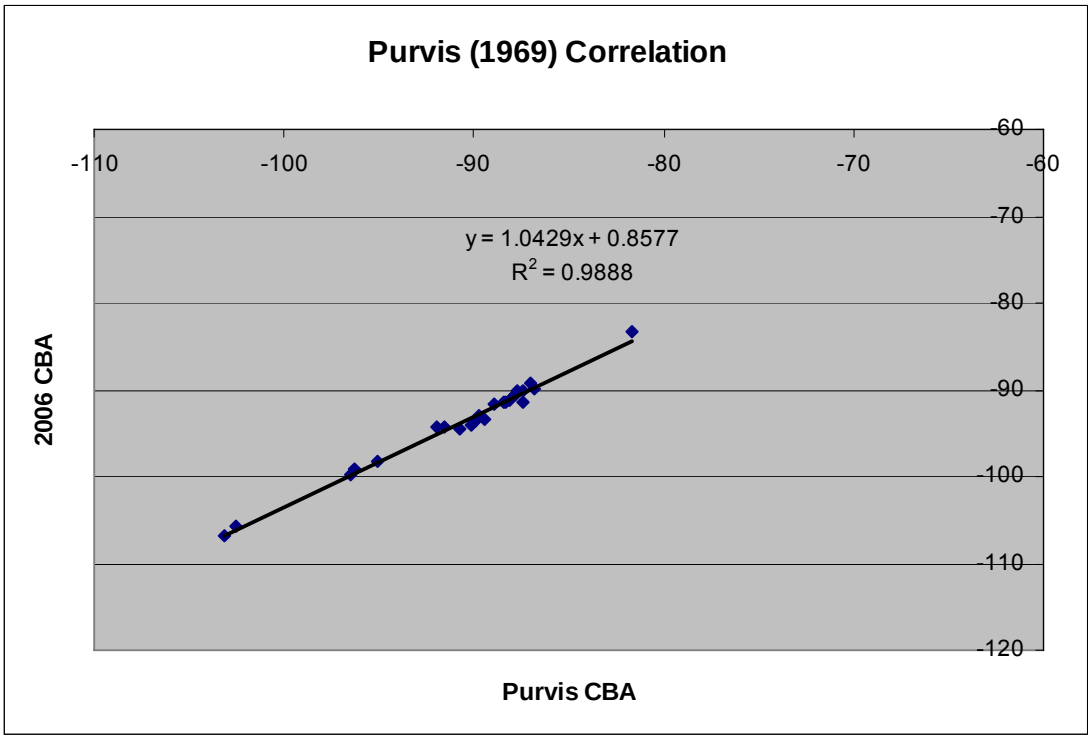
Published gravity studies from earlier studies provide a significant proportion of the coverage over the aquifer (Purvis, 1969; Adema, 1999; Sprenke, 2006), and the complete Bouguer anomalies for each survey were incorporated with the new gravity observations to produce a combined data set. The computation of the complete Bouguer anomaly for the older surveys, however, do not conform to the new computational standards using ellipsoidal heights (Hinze et al., 2003). As a result, the older values could not be directly combined with the results of our 2006 survey. Further complicating the situation, many of the older survey datasets do not include principal facts, which precluded our ability to recompute the complete Bouguer using new standardized methods.

As a consequence, the complete Bouguer anomalies for each of the surveys were adjusted and brought into conformity with the high-quality 2006 dataset through a linear regression between co-located sites in the 2006 gravity survey and the older surveys. The linear regression of values from co-located stations produced excellent fits. The correlation coefficient for the PACES data was 0.9978 (Fig. 9A) , for the Purvis (1969) data was 0.9888 (Fig. 9B), and was 0.9848 for the Adema (1999) data (Fig. 9C).

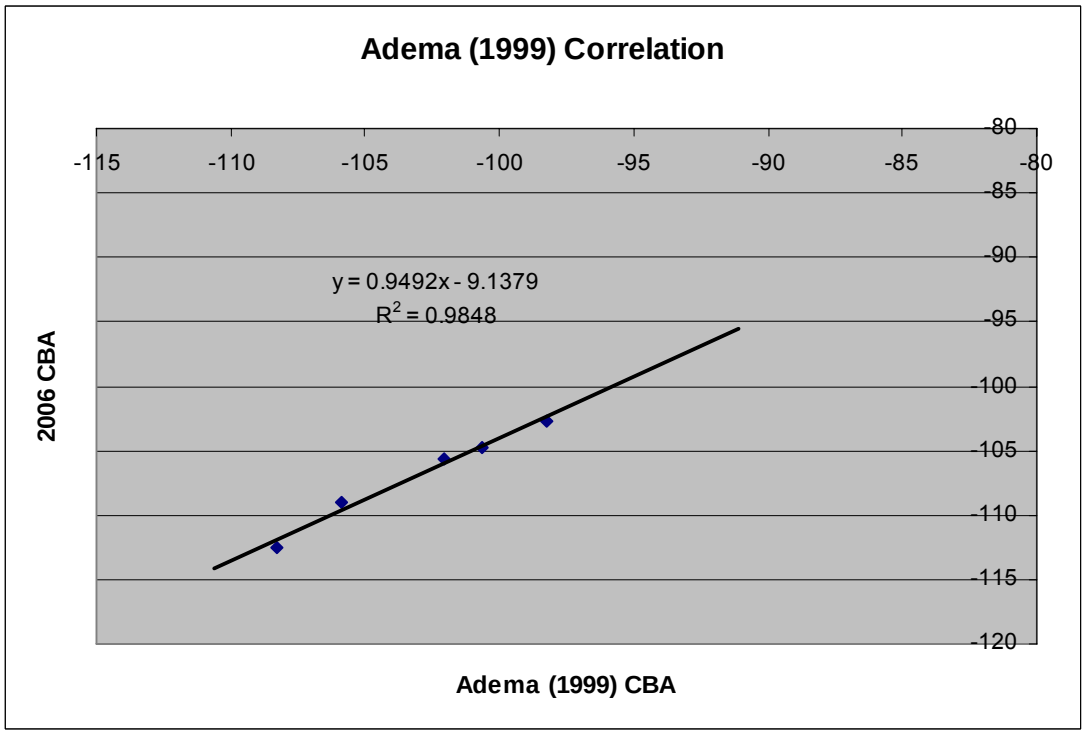
Figure 9. Linear regressions between the complete Bouguer anomalies (CBA) of previous gravity surveys and the 2006 complete Bouguer anomaly computed for this study. A, PACES versus 2006 survey; B, Purvis versus 2006 survey, and C, Adema versus 2006 survey.



A


Purvis (1969) Correlation
-110
-100
-90
-80
-70
-60
60
-70
-80
-90
-100
-110
-120
y = 1.0429x + 0.8577
R2 = 0.9888
2006 CBA
Purvis CBA

B


Adema (1999) Correlation
-115
-110
-105
-100
-95
-90
-85
-80
-80
-85
-90
-95
-100
-105
-110
-115
-120
y = 0.9492x - 9.1379
R2 = 0.9848
2006 CBA
Adema (1999) CBA

C

DATA REDUCTION

The complete Bouguer anomaly for the study region (Fig. 10) shows a strong trend from low values on the east to higher values on the west. This regional trend obscures the gravitational signature of the aquifer, due in large part to broad variations in geological structure and lithology across the study area.

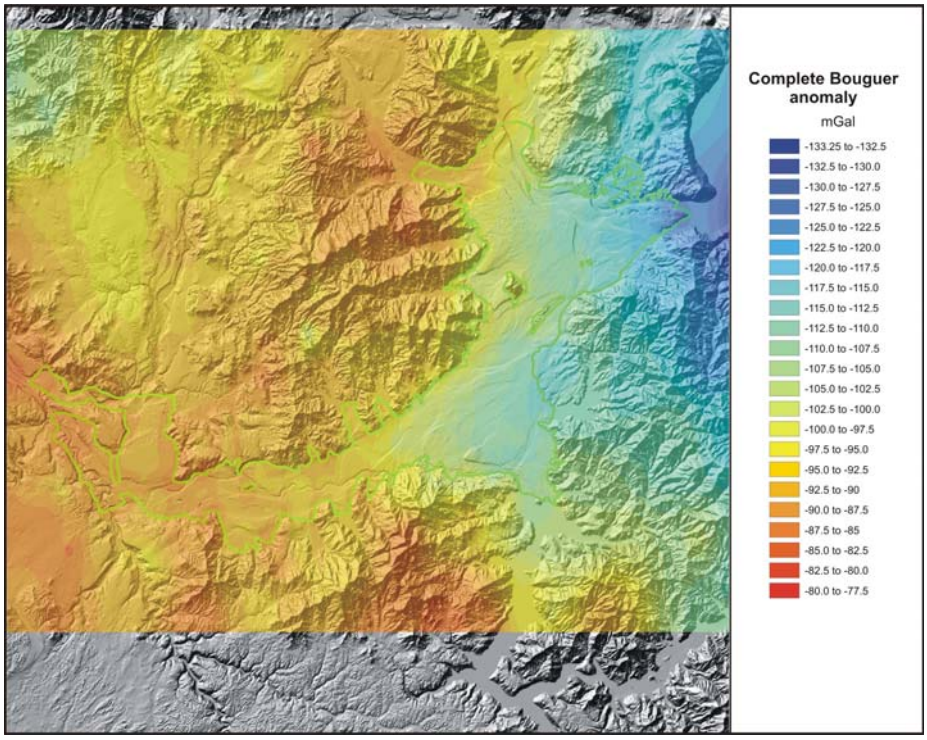


Figure 10. Complete Bouguer anomaly for the SRVP. Yellow and orange are positive values and green to blue are negative values.

In order to interpret these gravity data in terms of basin geometry, the gravitational effects of all extraneous geological features must be removed. These extraneous features constitute the regional gravity trend. By removal of the regional gravity trend from the complete Bouguer anomaly, a residual complete Bouguer anomaly is computed that can be interpreted directly in terms of basin geometry.

For this study, we removed the regional trend in two steps. First, we eliminate the gravity effect of regional-scale geological features, such as the northern Rocky Mountains, by fitting a smooth polynomial to the gravity measurements known to be on bedrock across the region. In the second step, we eliminated the effect of more local geological features by fitting a smooth spline surface to selected gravity stations near the boundaries of the basin where the saturated gravels of the aquifer thin to zero.

The primary regional trend, due largely to the isostatic compensation of the northern Rocky Mountains, is represented by a 2nd order polynomial fit of all the stations located on bedrock in the region (Fig. 11). Removal of this trend from the complete Bouguer anomaly, however, does not remove the effects of local geologic heterogeneity such as basalt flows, igneous intrusives, major faults, and water table variations within the basin (Fig. 12).

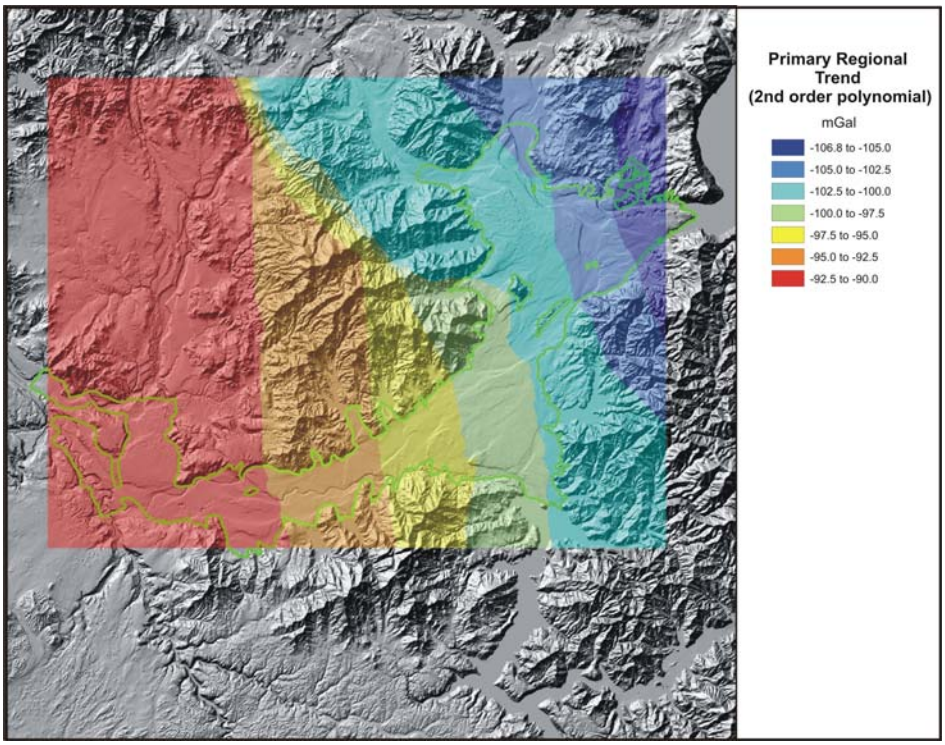


Figure 11. Second-order polynomial surface of the Complete Bouguer anomaly used as primary regional trend.

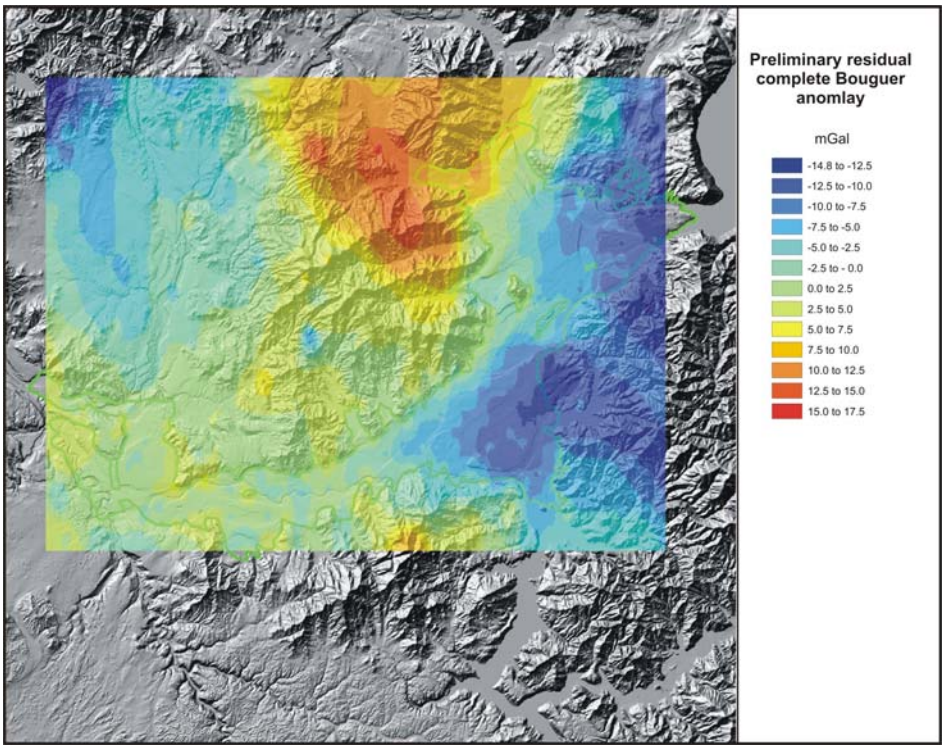


Figure 12. Preliminary residual Complete Bouguer anomaly after removal of regional trend.

To remove the impact of these local perturbations of the gravity field, a secondary regional trend (Fig. 13) was estimated by considering only gravity observations made directly over the outer boundary of

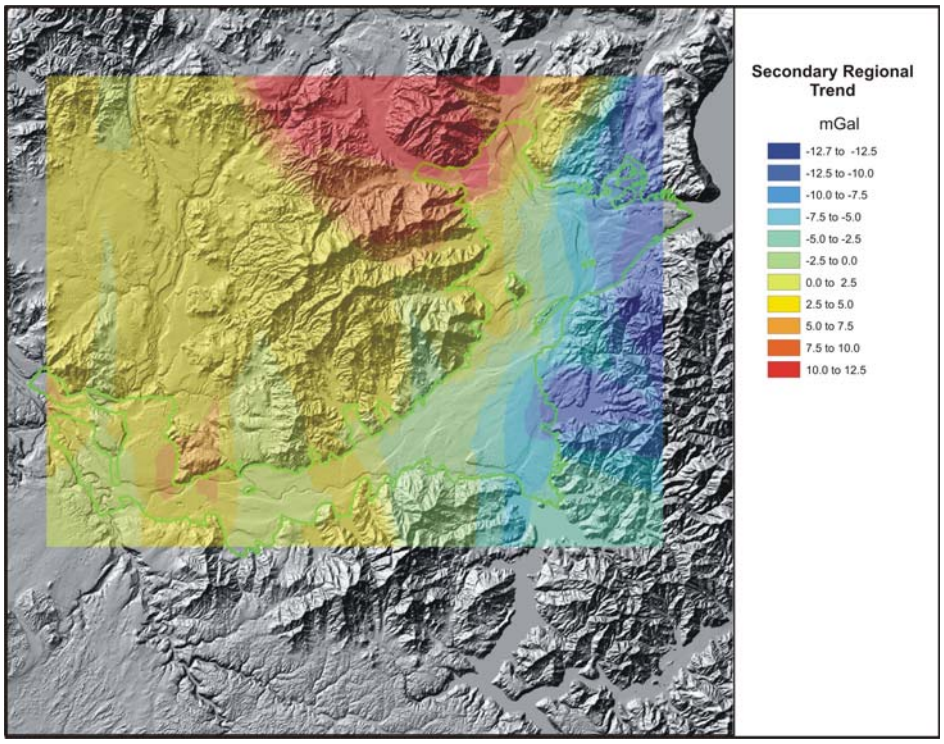


Figure 13. Secondary residual determined by bicubic spline interpolation of zero values along basin margin.

the saturated basin fill. These points were identified by analysis of the slope of the exposed valley walls and the generally known thickness of the unsaturated basin cover. At these points, the gravity effect of the saturated basin fill should approach zero. Any remaining gravity attraction at these locations must then be due to local geological features surrounding and enclosing the saturated aquifer. The secondary regional trend was estimated by fitting a bicubic spline to the gravity observations at these points. It is important to note that the gravity effect of the generally smooth variations in the regional water table are also removed as part of this secondary regional trend. However, these vadose zone thickness variations are restored in the final step of the modeling process.

The residual gravity over the aquifer basin (Fig. 14) was found by subtracting the primary and secondary regional trends from the complete Bouguer anomaly. This residual complete Bouguer anomaly is interpreted to be due solely to changes in thickness of the saturated aquifer. Over almost all of the basin, the residual anomaly is negative and approaches zero at the basin boundaries, consistent with the interpretation that the residual anomaly represents the signature of relatively low density aquifer gravels. At some locations, notably along the western reaches of the Spokane River and in the Chilco Channel east of Round Mountain, the residual anomaly is locally positive. These localities are complex geomorphically with substantial relief between basin fill and bedrock and rapid lateral variations in bedrock composition. With the existing data density (no better than 300 m), short-wavelength features are beyond the resolution of the gravity field and cannot be modeled more realistically without a more detailed investigation of local surface and subsurface geology. Nevertheless, most of the remaining aquifer area appears to be interpretable in terms of a simple geological conceptual model.

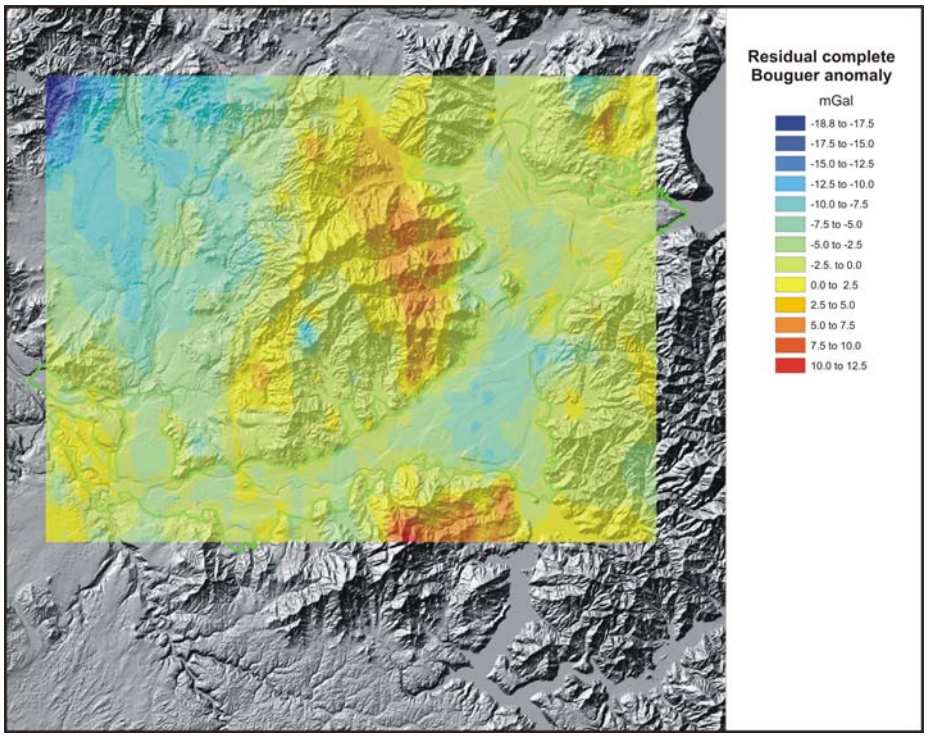


Figure 14. Residual complete Bouguer anomaly of the SVRP basin calculated by subtracting primary and secondary trends from the complete Bouguer anomaly.

DEPTH MODELING

Conceptually, the simplest geological model of the aquifer basin consists of a valley cut into pre-Tertiary bedrock and filled with sediment, unsaturated above the water table and saturated below. On a regional basis, good estimates exist for the unsaturated gravel thickness and for the densities of unsaturated gravel, saturated gravel, and bedrock. Given these values, the depth to basement and thickness of the saturated aquifer can be computed from the residual gravity.

Many wells have been drilled to the water table throughout the study area, and the U.S. Geological Survey has completed a synoptic water level measurement. For each gravity station within the aquifer, the thickness of the unsaturated aquifer cover was computed by subtracting the interpolated water table elevation from the elevation of the gravity station.

A review of probable rock and sediment bulk densities in the aquifer area is given by Sprenke (2006) and will not be repeated here. Based on measurements of geological materials in the area, the density contrast between the saturated aquifer gravel and the country rock is estimated to be 0.64 ± 0.2 g/cm^3. The one standard deviation uncertainty in this density contrast is 32%. This uncertainty would carry through in any interpretation of aquifer thickness using the gravity data without further geologic control. To better constrain this density contrast, two controls on the saturated aquifer thickness in the deeper parts of the basin were considered. Near the state line, Newcomb and others (1953) found the deepest first-arrival seismic refractor to lie below a 114 m thickness of saturated aquifer. The minimum residual gravity anomaly (Fig. 14) near the state line is -2.97 mGal. Using the simple Bouguer slab formula, this predicts a density contrast of 0.62 g/cm^3, in excellent agreement with the value above. On the other hand, in the Hillyard Trough along Magnesium Road, Newcomb and others (1953) detected a basement seismic refractor some 213 m below the water table. The minimum residual gravity at this location is -4.26 mGal, which results in a density contrast of 0.48 g/cm^3 between the saturated basin fill and the surrounding country rock. This density contrast is in the lower part of the predicted range (0.64 ± 0.2 g/cm^3). In our gravity modeling, we accordingly used a density contrast of 0.64 g/cm^3 in the Spokane Valley and Rathdrum Prairie, but a lower value of 0.48 g/cm^3 in the City of Spokane west of Park Road.

For the gravity modeling, the Parker-Oldenburg algorithm was used, and the algorithm is based on two-dimensional Fourier Transforms (Oldenburg, 1974; Sprenke and Kanasewich,1982). In this three-

dimensional modeling scheme, the aquifer thickness at depth is represented by a series of rectangular prisms of constant density. The gravitational field is calculated and compared to the field observations. An adjustment is made to the height of the prisms and the new gravitational field is computed and is again compared to the field observations. The interactive process is repeated until the resultant difference between the observed and calculated gravity fields has reached zero or an acceptable level of error. Because this process is computationally intensive, the fast Fourier Transform is used to make the calculations efficiently. The result is reasonably unique, given that the geological conceptual model and relative densities are correct. The final depth to bedrock was found by summing the gravitationally determined saturated aquifer thickness and the known vadose zone thickness.

RESULTS

The primary result of this project is the estimated depth to basement at each gravity station. The depths are tabulated (Table 3) and used to compute depth to basement below the ground surface (Fig. 15). For this map, values were interpolated to a 100 x 100 m grid from a source consisting of 65,536 points on a grid (Table 4) with spacings of 330 m and 272 m in the east and north directions, respectively. Over most of the aquifer, the results are geologically reasonable.

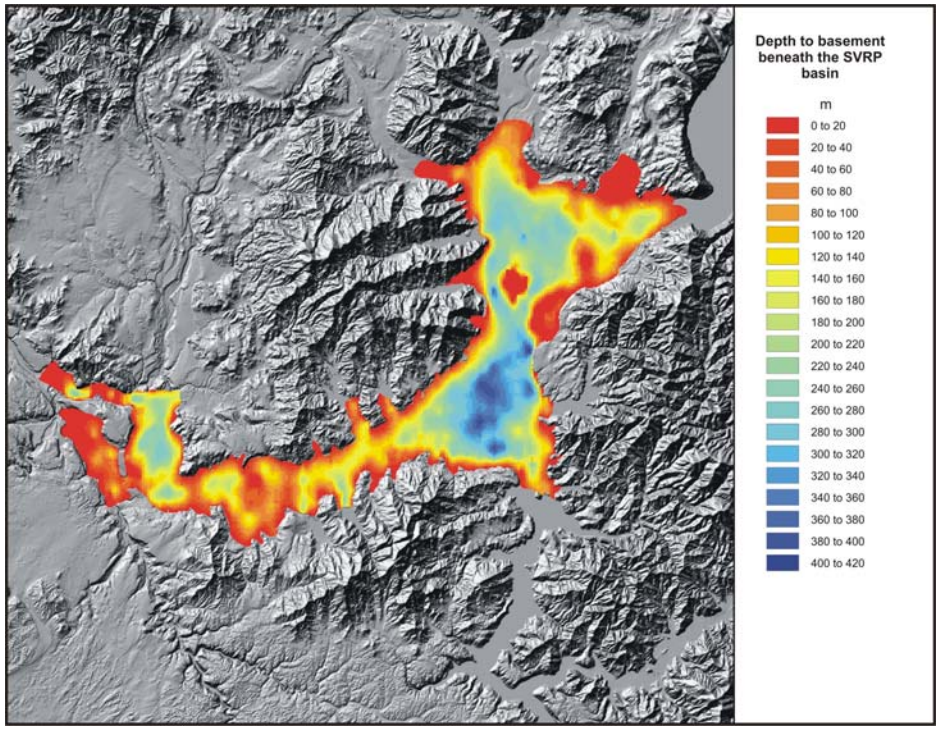


Figure 15. Terrain map showing depth to basement beneath the Spokane Valley – Rathdrum Prairie basin.

The maximum basin fill thickness locally exceeds 400 m in the Rathdrum Prairie. In general, the basement elevations decrease from near Lake Pend Oreille south toward Coeur d'Alene. The deep depression in the basement surface in the southern half of the Rathdrum Prairie may be the consequence of erosion as Missoula Flood waters emerged from the narrow channels on the sides of Round Mountain or may represent a glacial trough similar that below Lake Pend Oreille where glacial sediments extend to well below sea level.

To the west into the Spokane Valley, the basement depth decreases to depths ranging from 40 to 200 m. A central trough of up to 200 m deep follows the axis of the valley and locally extend into prominent valleys that emerge from the bounding highlands on the north and south. In the central reaches of the Spokane Valley, basin depth decreases to less than 150 m and in may areas may be less than 80 m. The basement high appears to be incised by a narrow channel that, from east to west, swings

south and then back to the north. The continuity of the inferred channel axis cannot be documented at the resolution of the gravity measurement spacing, but may represent a river canyon buried beneath Missoula flood deposits. Farther west, the basin deep extends north along the eastern side of the Five Mile Prairie mesa and then swings west into the Little Spokane River drainage. The depth to basement beneath the western-most part of Spokane Valley appears to be relatively shallow, but details of the basement geometry cannot be adequately resolved with existing data density.

REFERENCES

Adema, G.W., 1999. Bedrock depth and morphology of the Rathdrum Prairie, Idaho: MS Thesis, University of Idaho, Moscow, Idaho.

Cogbill, A. H., 1990, Gravity terrain corrections calculated using digital elevation models: Geophysics, v.55, n. 1, p. 102-106.

Featherstone, W.E., Detith, M.C., and Kirby, J.F., 1998, Strategies for the accurate determination of orthometric heights from GSP: Survey Review, v. 34, p. 278-296.

Hinze, W., Aiken, C., Brozena, J., Coakley, B., Dater, D., Flanagan, G., Forsberg, R., Hildenbrand, T., Keller, G.R., Kellogg, J., Kucks, R., Li, X., Mainville, A., Morin, R., Pilkington, M., Plouff, D., Ravat, D., Roman, D., Urrutia-Fucugauchi, J., Véronneau, M., Webring, M., and Winester, D., 2003, New standards for reducing gravity observations: The Revised North American Gravity Database http://paces.geo.utep.edu/research/gravmag/PDF/Final%20NAGDB%20Report%20091403.pdf

Holom, D.L., and Oldow, J.S., Gravity reduction spreadsheet to calculate the Bouguer anomaly using standardized methods and constants: Geological Society of America Geopshere, in press.

Newcomb, R. C. and others, 1953, Seismic cross sections across the Spokane River Valley and the Hillyard Trough, Idaho and Washington: USGS Open File Report, 16 p.

Oldenburg, D. W., 1974. The inversion and interpretation of gravity anomalies. Geophysics, v. 39, p. 526-536.

PACES: Pan-American Center for Earth Sciences: http://paces.geo.utep.edu/

Purves, W. J., 1969, The stratigraphic control of groundwater through the Spokane Valley: Washington State University Master of Science thesis, 213 p.

Sprenke, K.F., 2006, Evaluation of existing gravity observations in the Rathdrum- Spokane aquifer. Final Report: Contract # CON00693: Technical Assistance For Spokane-Rathdrum Hydrologic Modeling And Studies Project, Idaho Department Of Water Resources.

Sprenke, K.F. and E.R. Kanasewich, 1982. Gravity modeling and isostasy in western Canada. Journal of the Canadian Society of Exploration Geophysicists, v. 18, p. 49-57.

FIGURES AND TABLES

All Figures derived from ESRI_ArcMap files presented in CD-ROM
Tables 1 through 4 are included in CD-ROM

Table 1. Gravity Datasheet, 2006 Survey
Table 2. Combined Gravity Datasheet
Table 3. Gravity Modeling Results
Table 4. Depth to Basement Grid