EVALUATION OF EXISTING GRAVITY OBSERVATIONS IN THE RATHDRUM SPOKANE AQUIFER

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ABSTRACT

Since the 1960s, over a thousand gravity observations have been made on the Rathdrum-Spokane aquifer. No single source for the principal facts of these observations exists; federal compilations are particularly incomplete with respect to the aquifer. In fact, the most important sources for gravity data on the aquifer are graduate student theses at local universities. The aquifer itself is well covered by gravity stations with the exception of the western portion, which includes the City of Spokane. Over the northern half of the Rathdrum Prairie, the residual gravity anomaly is weak. In this area, the residual gravity cannot account even for the thickness of the known unsaturated gravel cover, much less for the unknown thickness of the underlying aquifer. In the southern Rathdrum Prairie and the Spokane Valley, the residual gravity anomaly seems more consistent with the expected geology of the aquifer but is nonetheless subject to considerable error. The major problem with the existing data distribution is the lack of observations on the outer periphery of the aquifer boundary, creating major problems for gravity interpretation, which depends critically on the lateral density contrast between the aquifer material and the neighboring bedrock. To adequately model the gravity field in terms of aquifer thickness, more observations are required. The existing gravity profiles throughout the aquifer area need to be extended into the surrounding hills and new profiles need to be established in the vicinity of Spokane.

EXECUTIVE SUMMARY

The Rathdrum-Spokane Aquifer (RSA) is a drinking water supply for approximately 500,000 people in Idaho and Washington States. A study is currently being conducted by Idaho, Washington and the U.S. Geological Survey to evaluate available water resources of the RSA. As part of this study, defining the basin will be beneficial in helpful for the hydrogeological conceptual model. The gravity method is applicable to investigations of a wide range of subsurface conditions. Gravity measurements indicate variations in the earth's gravitational field caused by lateral differences in the density in the subsurface soil or rock. The specific goals of this study are to evaluate the available gravity data for quality and distribution in relation to modeling the aquifer geometry of the RSA, and to define the problems in the gravity data sets and recommend additional work so that aquifer geometry can be determined.

Since the 1960s, over a thousand gravity observations have been made over the RSA and adjacent areas. No single source for the principal facts of these observations exists; the two predominant sources of gravity data are federal compilations and university graduate studies. Evaluation of these data sets with respect to the aquifer study indicates that the federal compilations are areal widespread but incomplete. The university studies, although more detailed, cover only portions of the RSA.

Analysis of the existing data shows that over the northern half of the Rathdrum Prairie, the residual gravity anomaly is weak. In this area, the gravity observations cannot account even for the thickness of the known unsaturated gravel cover, much less for the unknown thickness of the underlying aquifer. In the southern Rathdrum Prairie and the Spokane Valley, the existing observations seem more consistent with the conceptual geology of the aquifer but are nonetheless subject to considerable error. Few stations exist in Spokane area. The major problem with the existing data distribution is the lack of observations on the outer periphery of the aquifer boundary, creating significant problems for gravity interpretation, which depends critically on the lateral density contrast between the aquifer material and the neighboring bedrock. To adequately model the gravity field in terms of aquifer thickness, existing gravity profiles throughout the aquifer area need to be extended into the adjacent bedrock upland areas and new profiles need to be established in the vicinity of Spokane.

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Purpose

The purpose of this study is to evaluate the existing gravity data in northern Idaho and eastern Washington to determine what they reveal about the Spokane Valley-Rathdrum Prairie aquifer and to determine if additional gravity data would be of any value for further delineation of aquifer parameters.

Study Area

The study area for this report is the Rathdrum-Spokane Aquifer in northern Idaho and northeastern Washington. The boundary of the aquifer is defined by Kahle et al. (2005) and considered to be the same for this geophysical evaluation (Figure 1). In this report, it is presumed that, at the aquifer boundary, the saturated gravel is adjacent to and bounded by bedrock. A limited review of available geologic data indicates that this assumption is satisfactory along most of the boundary and is at least a reasonable approximation where the boundary is adjacent to the tributary valleys below which bedrock is thought to rise.

GEOLOGIC AND HYDROGEOLOGIC SETTING

Regional Geology

The geology of the RSA is largely comprised of four primary geologic units 1) Precambrian age rocks, 2) younger granitic intrusions, 3) basalt flows and 4) glacial flood deposits (Lewis, 2002). The Precambrian rocks are defined as the Priest River Metamorphic complex (PRMC) and the Belt Supergroup. The PRMC appear to be the oldest rocks of the area with age dates of approximately two billion years old. The PRMC is composed largely of gneiss (Lewis, 2002) a rock characterized by black and white bands made of alternating dark (biotite)and light (quartz and feldspars) colored minerals. This gneiss is commonly indicated as "granite" on driller's reports.

The Belt Supergroup is composed of a variety of very old sedimentary rocks that are over one billion years old. The Belt Supergroup sediments are estimated to be tens of thousands of feet thick and are believed to have been deposited in a narrow ocean basin. The pressure of the overlying sediments has caused the rocks to metamorphose with time. Belt rocks are sometimes referred to as "shale" on driller's reports. The Belt rocks were deformed into folds, faults and fractures about 70 to 80 million years ago.

The granitic intrusions pushed up into the overlying rock from about 70 to 50 million years ago. A large granitic intrusion (batholith) pushed up underneath the PRMC and the Belt Supergroup sediments forming the Kaniksu Batholith. It is believed that the large granitic intrusion pushed the belt rocks upward and to the east off of the PRMC. The contact between the two is called the Purcell Trench and is oriented north-south underneath the Rathdrum Prairie. The result is predominantly gneissic rocks to the west of the Rathdrum Prairie and the Belt rocks to the east.

Flood basalt originating from the northeast Oregon-Idaho area flowed predominantly north and west creating the Columbia Plateau during the Miocene about 14 to 17 million years ago. The flood basalt flowed as far north as the Spokane and Coeur d'Alene areas. The basalt is believed to have damned the surface water flowing near the Spokane area creating a lake environment possibly as far north as what is now Lake Pend Oreille. The sediments are believed at time to be covered by subsequent basalt flows with additional damming and deposition of fine grained sediments (Latah Formation). Significant portions of the sediment and basalt may have been removed from general erosional processes and subsequent glaciation and the flood events described below.

North Idaho was covered by glaciers during at least two ice ages that flowed south from Canada (Breckenridge, 1989), with the latest glaciation occurring approximately 10,000 to 15,000 years ago. Lobes of ice flowing from north to south blocked the Clark Fork River near Clark Fork Idaho causing significant quantities of water to pool behind the ice dam forming Lake Missoula. Occasionally the ice dam would fail causing very large flood events to occur. The flood waters would carry large boulders, gravel and sand down stream depositing them within what is now the Rathdrum Prairie.

Regional Hydrogeology

The Rathdrum Spokane Aquifer (RSA) is a largely unconfined aquifer, and covers an area from Lake Pend Oreille and the city of Spirit Lake to the cities of Coeur d'Alene and Spokane and north into the Hillyard trough. The RSA is composed of coarse sand and gravel with cobbles and boulders from the glacial flood events described above. Recharge to the aquifer is in the form of runoff from upland area, leakage from surrounding lake and rivers along with precipitation. Groundwater flows regionally from north-northeast to south-southwest.

The hydraulic conductivity of the sediments is generally very high with municipal water wells capable of drawing significant quantities of water with limited drawdown. Areas around the margin of the RPA may contain some to significant quantities of silt. The silt is most likely due to a depositional environment with low water velocities occurring along the edges of the flood path or backwater environments. The bedrock topography is largely unknown. Water wells in the area have generally shallow completions due to the high permeability and wells completed to bedrock are relatively uncommon.

GRAVITY METHOD

The gravity method relies on measuring very small variations of the earth's gravitational field using an instrument called a gravimeter. The unit of gravity measurements is the gal ($1\ cm/s^2$). Because the variations in the measured gravity is so small the milligal is usually used and is approximately equal to one millionth of the earth's gravity. Gravity measurements are influenced by a number of different factors that include the distance from the earth's center, shape of the earth, and local variations in terrain. If these effects are removed from the gravity measurement then the resultant observation is termed the Bouguer anomaly. The Bouguer anomaly is dependent on bulk densities and geometries of the subsurface material in the vicinity and region of the station. The Bouguer anomaly values at different geographic locations can then be compared and the geologic framework can be inferred.

Typically a regional gravity trend is present caused by deep changes in the earth's structure or lithology. The regional trend is generally broad scale with an increase or decrease of the gravity field over many hundreds or thousands of kilometers. The regional trend is not a flat plane but an undulating surface that will gradually change over a large area. If the target of the survey is a relatively small local anomaly a few kilometers in depth and width then the regional trend is best defined by obtaining gravity measurements as close to the anomaly as possible without influence from that anomaly. By removing the regional trend specific to the study area, a better definition of the local anomaly is possible. If the regional trend is removed from the Bouguer anomaly then the resultant gravity anomaly, due only to the target of interest, is termed the residual gravity anomaly.

If quantitative depths and thicknesses of the target are necessary, then the residual gravity anomaly needs to be modeled. The geological input to the modeling process is in the form of the densities and geometry of the subsurface materials present. These parameters are then adjusted until a satisfactory match is obtained between the gravity anomaly predicted by the model and the residual gravity anomaly actually measured. If the densities or geometry of the subsurface materials are poorly known, then uncertainties will be introduced into the model results.

Gravity interpretation is inherently ambiguous; that is, many geological models can be fit to the same data. The uniqueness problem can be overcome only if sufficient constraint can be placed on the unknown variables in the subsurface geological model. Thus it is critical for successful gravity modeling that the geological conceptual model of the target be sound. On the other hand, the gravity method is a powerful method for testing geological conceptual models. If a geological conceptual model of a target is inconsistent with the observed gravity field, then that particular model is physically impossible and in need of revision.

EXISTING GRAVITY OBSERVATIONS

Gravity Stations

Several thousand gravity observations have been made in and around the RSA (Figure 2). The sources of these data are described in the next section. Very detailed observations are available for the Spokane Valley and the southern Rathdrum Prairie. Less detail is available in the northern half of the Rathdrum prairie. Only sparse observations are available in the City of Spokane, the Hillyard trough or in the westernmost Spokane River Valley portions of the aquifer. The greater region surrounding the aquifer is covered reasonably well by stations with the important exception that few stations exist within a kilometer or so of the aquifer boundary. The Fivemile Prairie, for example, has no stations. Nor do most of the "islands" of bedrock extending to the surface within the aquifer boundaries. Most of the detailed gravity profiles within the aquifer have been obtained along roads that do not extend into the surrounding upland areas (Figures 3, 4, 5). Thus most road profiles do not terminate on bedrock making gravity modeling problematic since the density contrast between the basin sediment and the surrounding bedrock is unknown

Sources and Quality of Gravity Data

Several previously published gravity studies have included portions of the RSA. Some of these included new gravity observations; others involved compilation and reprocessing of existing data.

Bonini (1963) performed the first regional gravity survey that included the RSA. The survey correlated the Idaho batholith with negative Bouguer anomalies and basalt terrain with relative gravity highs. In northern Idaho he identified a modest variation in the Bouguer anomaly that generally followed a north-south trend. Bonini's stations in the RSA were generally spaced on a township grid over the study area. Additional regional stations in Idaho and Washington were subsequently added by the U.S. Geological Survey (USGS) and Defense Mapping Agency on an approximate square mile grid and many are shown on the complete Bouguer Anomaly map of Idaho (Bankey et al., 1985). Standard drift, latitude, free-air, Bouguer, and terrain reductions were made to the data. The principle facts of these observations can be found in a number of published compilations that are described below.

Purves (1969) performed an extensive gravity survey of the Spokane Valley and southern Rathdrum Prairie. Over 743 gravity measurements were taken on 16 profiles over the aquifer in Idaho and Washington (Figure 3). All standard corrections, including terrain, were made, and measurements were tied to the extended gravity control network of North America established by Wollard and Behrendt (1961). Horizontal positions were provided in tenths of a mile. Vertical positions were obtained using an altimeter. The altimeter's readings were checked against local benchmarks at numerous times during each day. Elevation drift due to barometric pressure change was controlled by allowing no more than a 0.3% elevation disparity in measured elevations between local benchmarks. The horizontal positions were originally measured with a car's odometer; stations were normally spaced every 1/10 of a mile (170 m). These locations were plotted on a topographic map based on detailed descriptions of the starting points for each line. There is no reason to suspect inconsistent levels of precision in the data, which are thought to be good to +/- 0.03 milligals. The principal facts are tabulated in the appendices of Purves (1969). A copy of Purves's original field notes is on file in the Idaho Geological Survey library in Moscow, Idaho.

As shown in Figure 5, a gravity survey of the northern half of the Rathdrum Prairie was performed by the U.S. Geological Survey, in cooperation with the Idaho Department of Water Administration in 1969 and published by Hammond (1974). The purpose was to study the quantity of water being recharged to the aquifer by Lake Pend Oreille. Although claims are commonly made to the contrary, Hammond (1974) did not model or interpret his gravity data. Only the general observation was made that “the very steep regional gravity gradient occurring in this general area makes interpretation of the gravity data difficult.” Nonetheless, the gravity observations were made to USGS standards and there is little reason to question their quality. The principal facts are tabulated in later USGS compilations.

In 1997, the Idaho Geological Survey performed 146 gravity measurements along three main transects in the Rathdrum Prairie, as well as at the mouths of Hayden Lake and Coeur d’Alene Lake (Figure 4). Gravity measurements were made with a high quality Lacoste & Romberg Model G gravity meter. A standard base plate was used. At least two measurements were made at each station, with the requirement that they agree to within 0.01 milligal. Measurements were made at a base station at least three times per day in order to monitor instrument drift. All gravity measurements are thought to be precise to at least 0.01 milligal before correction. Coordinates and elevations for each gravity station were obtained using the differential Global Positioning System (GPS) technique. With the techniques exercised, horizontal and vertical accuracy is better than ±2 cm. Under normal circumstances, a 2 cm vertical variation should result in no more than a 0.01 milligal gravity variation. Measurements were made on level road surfaces, with the GPS receiver and gravity meter at equal elevations. The principal facts are tabulated in the appendix of Adema (1999).

For his thesis at the University of Idaho, Adema (1999) modeled the gravity data along a number of roads crossing the southern Rathdrum Prairie portion of the RSA, using available data, as described above, from Washington State University and the Idaho Geological Survey. Despite the fact that Purves (1969) performed the standard gravity reductions to his data, Adema worked directly from Purves’s original data to ensure that identical corrections were applied to all of the incorporated observations. Gravity readings, elevations, times, locations, temperatures, base readings, and meter constants were provided. Subsequent analysis shows that the Purves’s (1969) terrain corrections, which were performed by hand, and Adema’s (1999) terrain corrections, which were obtained using digital elevation models, agree within 0.03 milligal, well within the estimated precision (0.14 milligal) of Purves’s data.

A number of regional compilations of gravity data exist. In 1976, in a study of possible uranium mineralization in the region around Spokane, Washington, Cady and Meyer (1976a) compiled the principal facts for 2,077 gravity stations. These principal facts were used to construct a Bouguer gravity anomaly map of the Okanogan, Sandpoint, Ritzville, and Spokane 1° x 2° quadrangles (Cady and Meyer, 1976b). The principal facts for the stations were obtained from a variety of sources, including previous USGS open-file reports and the Department of Defense Gravity Library. Data from investigations by

Hammond (1975) were included; data from Purves (1969) was not. The Cady and Meyer (1 976a) principal facts were compiled in digital form as Hittelman and others (1994), a CD-ROM collection of significant gravity data sets. Today, the principal facts for these same data are available online as the PACES data set (United States Gravity Data Repository at the University of Texas at El Paso).

Several other local gravity investigations have been performed in the aquifer area. Steffy (1983) reported on a gravity experiment in the Little Spokane River Valley and Kahle (2005) shows a short “microgravity” profile at the north end of the Hillyard trough. Because the principal facts of these surveys are not published, these observations are not included in this report.

BULK DENSITY MEASUREMENTS

Geological units

The geological units in the study area fall into four categories based on the basis of bulk density. These are the unsaturated basin fill sediments above the water table, the saturated basin fill sediments below the water table, the crystalline country rock generally surrounding the aquifer, and the basalt flows that occur irregularly in the study area.

Crystalline Country Rock

Measured densities of the Belt and Cretaceous rocks which form the country rock range from 2.64 — 2.80 grams per cubic centimeter (g/cm^3), with an average of 2.67 g/cm^3 (Purves, 1969; Harrison and others, 1972). This value is at least reasonable for most of the intrusive and metamorphic complex rocks surrounding and underlying the prairie and is consistent with regional density maps of the Rocky Mountains.

Columbia River Basalt

Where Columbia River basalt flows surround and possibly underlie the aquifer, the rock density is probably higher than the Belt and Cretaceous rocks, near 3.1 g/cm^3. However, flows are commonly interbedded with sediments with densities much less. Because of this the densities of the Columbia River Basalt fall into a very broad range from 2.78 g/cm^3 for vesicular samples to 3.21 g/cm^3 for massive samples.

Unsaturated Basin-Fill Sediment

The unsaturated basin-fill sediment that overlies the aquifer includes Pleistocene glacial flood deposits and Tertiary Latah sediments. To estimate the density of these sediments, a short gravity profile across Greenacres Ditch north of Post falls was analyzed using the density profile technique (Nettleton, 1940). This method provides the bulk density of the near surface material from changes in gravity readings and corresponding changes in elevation. An important assumption is that the surface topography is independent of subsurface geology—a condition that would seem to be reasonable in this case. Adema's (1999) gravity data along this profile--collected with a modern instrument with GPS elevation control—results in an unsaturated density estimate of 1.67 +/- 0.2 g/cm^3 (Figure 6).

This result is very consistent with other published data on the sediment density. As reported in Purves (1969), the Washington State Highway Department measured 1.66 g/cm^3 (range 1.60-1.78) for unsaturated glacial material in the Spokane Valley. Balko and Stone (2003) measured the bulk density of glacial sediment samples from boreholes in Minnesota, South Dakota, and Iowa. They found dry densities of 1.77 +/- 0.25 g/cm^3 for sorted glacial sands and silts. Unsaturated Latah sediments have similarly low density. Non-indurated dry samples showed densities of 1.09 to 1.57 g/cm^3 in the Washington State Highway Dept survey. Hosterman (1960) found dry Latah clays to have a density of 1.62 g/cm^3.

Saturated Basin-Fill Sediments

Below the water table, sediments have somewhat higher bulk densities because the pore spaces are full of water. Assuming a generally quartz and feldspar composition of the clasts, the Greenacres Ditch density profile result suggests a saturated density of 2.03 +/- 0.2 g/cm^3. This is consistent with wet sample densities of 1.68 to 1.87 g/cm^3 in valley gravels and the 2.13 g/cm^3 measurement in wet Latah clays.measured by the Washington State Highway Department. Indurated Latah sediments have been measured as high as 2.43 g/cm^3. Newcomb and others (1953) suggest seismic velocities of saturated glacial gravels to range from 5000 feet per second (ft/s) to 7,400 ft/s—which converts to a density of 1.76 +/- 0.25 gm/cm^3 using the standard Nafe-Drake conversion curve. Presumed Latah sediments in the seismic survey ranged from 7,500 ft/s to 12,800 ft/s—equivalent to a density of 2.20 +/- 0.2. Wet glacial gravels are estimated to range from 1.96 to 2.44 g/cm^3 if possible cementation of the gravels is considered (Adema, 1999).

Density Contrasts

Based on the above, except perhaps in very local areas, no consistent density contrast is expected between Latah sediments and glacial sediments. The gravity method is therefore not an appropriate tool to discriminate these units. On the other hand, the water table itself should result in a density increase of about 0.36 +/- 0.2 g/cm^3 regardless of the sediment present. Thus the water table itself is a reasonable gravity target as is the aquifer itself and the unsaturated material above the water table.

For this report, the density contrast between the country rock and unsaturated aquifer cover is estimated at 1.00 +/- 0.2 g/cm^3. The density contrast between the saturated aquifer gravel and the country rock is estimated to be 0.64 +/- 0.2 g/cm^3. The density contrast between the saturated and unsaturated valley sediments is 0.36+/-0.2 g/cm^3. The one standard deviation uncertainties in these density contrasts are 20% and 32% and 54% respectively. This uncertainty will carry through in any interpretation of aquifer thickness using the gravity data without further geologic control.

ANALYSIS OF GRAVITY DATA

Merging the Surveys

The final gravity values plotted on many gravity maps is technically the Bouguer anomaly—the difference between the gravity observed and the theoretical gravity field at that location based on the geodetic shape of the Earth. The gravity observations in and around the RSA were made at different times using different geodetic datums; some care is required to combine the results into single map. Adema (1999) tied his observations into those compiled by the USGS (Cady and Meyer, 1976a) by comparing observed gravity at mutually occupied locations. His final Bouguer anomaly values are thus consistent with that data set (and the PACES data set).

For the present study, the Purves (1999) Bouguer anomaly values were compared to the Adema data set, and a correction factor of 888.80 +/- 0.03 milligal was determined. This factor needs to be subtracted from the Bouguer anomaly values listed in Purves's original thesis appendix to put his results on the same datum as Adema (1999) and the USGS compilations. The error in this conversion is small compared to the 0.14 milligal precision of the Purves data set.

Bouguer Anomaly

The Bouguer anomaly of the greater study area is shown in Figure 7. A regional trend that affects the gravity because of broad changes in regional geology is apparent. For example, the thickening of the continental crust beneath the northern Rocky Mountains, east of the study area, causes a regional decrease in the Bouguer anomaly of 0.8 to 1.9 milligals per kilometer (km) eastward. This gradient levels out markedly toward the western side of the map area. Pronounced gravity highs occur above extensive Columbia River basalt flows on the eastern side of the map area. The extent of these flows beneath the RSA is unknown, as is the thickness of interbeds that may or may not exist between flows at depth.

As might be expected, the low-density basin fill beneath the southern Rathdrum Prairie produces a pronounced gravity low on this map. However, because of low station density in the hills immediately surrounding the prairie, the boundary of the aquifer is poorly defined on the gravity map. In the northern half of the Rathdrum Prairie, the regional trend is also perturbed by the basin fill, but not as much as in the southern prairie. Due to sparse station coverage in the western portions of the aquifer at Spokane, the Bouguer anomaly gravity contours show little correlation with the aquifer.

Removal of Regional Trend

Bouguer anomaly maps always include the effects of density contrasts of no relevance to the target of interest. The regional trend due to deep-seated crustal effects is generally removed by mathematical techniques based on the premise that regional trends will be more uniform than the local anomaly over the target. Conventional methods to do this include polynomial surface fitting, high-pass filtering, and other digital smoothing techniques.

Adema (1999) dealt with this problem in the limited area of the southern Rathdrum prairie by simply modeling the regional trend as a plane dipping 1.1 milligal/ km eastward. This had the disadvantage of creating a somewhat arbitrary value for zero residual gravity on some of his cross-sections and an unknown uncertainty in his thickness calculations. Furthermore, inspection of the Bouguer anomaly (Figure 7) shows that although a dipping plane might be a reasonable fit for the limited area on the Idaho side of the aquifer, it is inappropriate for the Washington side where the regional gravity flattens out considerably and thus has a substantially different regional trend. Furthermore, this method does not take into account any variability in the known bedrock geology immediately surrounding the aquifer boundary.

Evaluation of station distribution (Figure 2) in the study area suggests that the removal of the regional trend is problematic. The best approach for regional trend removal is to include gravity measurements that are 1) just outside the aquifer boundary where the gravity effect of the basin itself approaches zero and are 2) distributed around the periphery. If enough stations just outside the periphery of the aquifer are incorporated the regional trend specific to the study area can be interpolated between these stations.

However, virtually all the stations that exist in the vicinity of the aquifer are within the aquifer boundaries. That is, there are generally few stations on the upland bedrock areas immediately surrounding the aquifer and are poorly distributed. This is not surprising because the Rathdrum Prairie is very flat and accessible whereas the surrounding mountains are steep and inaccessible. Thus, most gravity observations are on the flat roads within the aquifer boundary.

The need for additional gravity data along the periphery is illustrated by inspection of the Bouguer gravity anomaly map (Figure 7). The interpolated gravity contours many kilometers from the aquifer appear to be influenced by the aquifer itself despite the fact that the gravity effect of the aquifer certainly does not extend more than perhaps a kilometer outward from the aquifer boundary. New stations close to the aquifer but not within the boundaries are necessary to better delineate the aquifer effect within the regional gravity field.

A simple model of an idealized cross-section through the aquifer boundary is shown in Figure 8. In this model, the valley walls dip about 15 degrees basinward, a slope typical of the hills surrounding the RSA aquifer. In this case the true aquifer boundary will be several hundred meters—depending on the cover thickness-- basinward of the topographic edge of the prairie. Thus the saturated aquifer gravel unit can be expected to pinchout basinward of the unsaturated cover. The theoretical gravity anomalies due to entire basin fill and to the saturated aquifer gravel are also shown.

It is apparent from Figure 8 that in order to actually measure the zero level of the anomaly due to the entire basin fill, it is necessary to have stations some hundreds of meters outside the prairie boundary. Lacking such observations, distant stations must be used to provide estimates of the zero level of the residual anomaly due to the basin fill materials. Then the effect of the unsaturated cover can be removed using water well data.

The effect on the gravity field of density contrasts originating outside the RSA boundaries in Idaho and Washington was estimated in a conventional manner by fitting a smooth surface with mathematical minimum curvature to the interpolated Bouguer anomaly at a distance of about one kilometer outside the aquifer boundaries. This regional trend (Figure 9) compensates at least in part for any variability in the density and geometry of the large rock units surrounding the aquifer boundary. The residual gravity is reduced to zero on the aquifer boundary regardless of the geological material locally surrounding the aquifer. The major disadvantage of this method is that very few actual measurements exist close to but outside the aquifer boundaries. Thus the regional trend estimate depends a great deal on stations distant from the aquifer that may have significantly different local densities then bedrock immediately surrounding the study area.

The regional trend (Figure 9) seems reasonable. The gradient in the Idaho portion is consistent with that estimated by Adema (1999) and the contours on the Washington side seem consistent with the regional stations. Most importantly, the regional trend does not appear to be creating anomalies where none might otherwise exist within the aquifer boundary. Several apparent deviations in the regional surface do appear because of the presence of islands of bedrock within the aquifer such as Round Mountain and the Pines Road Knoll, which are not well sampled by gravity stations.

Residual Gravity

The residual gravity anomaly (Figure 10) over the RSA represents the difference between the Bouguer anomaly and the regional background gravity effects. The residual gravity should only be responsive to the thickness and density of the basin-fill materials. Because of the relatively low density of these sediments compared to the surrounding bedrock, the residual gravity is expected to be negative throughout the aquifer. Inspection of Figure 10 shows that, with the exception of a few small areas of poor station coverage, this is the case over most of the aquifer. However, the strength of the negative anomaly is surprisingly low in the northern half of the Rathdrum Prairie where it is known from water wells that relatively thick deposits of unsaturated gravels exist.

Modeling the Residual Gravity

The simplest geological conceptual model of the RSA aquifer 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 unsatuated gravel thickness and for the densities of unsaturated gravels, saturated gravels, and bedrock. Given these values, the thickness of the lower aquifer can be computed.

Many wells have been drilled to the water table throughout the study area. A synoptic water level measurement was completed by the U.S. Geological Survey and is described in Cambell, 2005. For each gravity station within the aquifer, the thickness of the unsaturated aquifer cover was computed by subtracting the interpolated water elevation from the elevation of the gravity station. Because of the smoothness of the water table surface and the surface elevations within the study area, a reduction for the gravity effect of the unsaturated cover at each station was calculated using the simple Bouguer slab formula.

To compute the aquifer thickness, the Parker-Oldenburg algorithm which is based on two-dimensional Fourier Transforms, was used (Oldenburg, 1974; Sprenke and Kanasewich,1982). In this three-dimensional modeling scheme, the bedrock mass at depth is represented by a series of rectanglular 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 interative 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 unique, given that the geological conceptual model and relative densities are correct.

The computed thickness of the saturated aquifer is shown in Figure 11. Values are computed on a 250,000 point grid with spacings of 165 m and 136 m in the east and north directions respectively. In the southern Rathdrum Prairie of Idaho, the results appear geologically reasonable. The maximum saturated aquifer thickness is as much as 400 m

(+/- 125 m). In the northern half of the Rathdrum Prairie, the results are not presented because the aquifer thickness computed to a negative value. Because in most of these areas, saturated aquifer gravels are known to exist, either the geophysical results are in error or the geological conceptual model is wrong.

If the discrepancy in the northern half of the Rathdrum Prairie is geological, the most likely explanation is the presence of massive basalt filling the basin beneath the aquifer. If this were the case, the gravity response of such higher density material would annihilate the lower density signal from the aquifer. In most of northern half of the Rathdrum Prairie, hundreds of meters of massive basalt would have to underlie the aquifer to cancel out the gravity effect of the relatively low density sediment that comprises the aquifer and its unsaturated cover.

The only direct evidence of massive basalt beneath the plains around Athol is the driller's log of the San Francisco Ranch well, which is located at the SE NE Sec. 24 T.53 R4W (Figure 12). Under some 400 feet of gravelly units, "basalt" (black) is indicated from 409 ft to 434 ft and below that, continuous "clays" (black, brown, blue, and gray) are indicated to a total depth of 570 ft. In such a hole drilled by cable tool, the so-called clays may actually indicate the presence of soft, weathered basalt (Personal Communication, Dr. John Bush). The well was drilled in 1969 and subsequently abandoned. The only water found was in the basalt unit from 430-434 feet, which produced less than 20 gpm.

No evidence of basalt is apparent in surrounding wells other than a questionable encounter in a 1941 oil exploration hole that was drilled several miles northeast of Round Mountain in the Ramsey Channel (Figure 12). In this cable tool well, bedrock was encountered at 280 feet and was shown on the driller's log as "Bedrock, granite [Basalt?]". This oil well went to a total depth of some 742 feet and it is not at all clear from the driller's log whether the well penetrated a basalt section with interbeds or simply Belt rock.

If the discrepancy in the gravity results is geophysical, the most likely cause is the regional trend used to determine the residual gravity anomaly. This regional trend estimate relies strongly on stations distant from the aquifer which are generally spaced six miles or more apart. Furthermore, because the terrain of northern Idaho is very rugged, these regional stations themselves are likely located along Idaho roads, which tend to follow the valleys, not the ridges. The valleys are commonly floored by sediment rather than bedrock. Thus the regional stations might contain a bias toward low gravity values. This bias in the background estimate could then result in the low intensity of the residual gravity over the northern Rathdrum Prairie. The uncertainty in the gravity modeling process using the existing data set to estimate the regional trend is shown in Figure 13. This uncertainty estimate was determined by using different assumptions for the regional trend estimate ranging over the whole gamut of possibilities--from using only distant stations to using only local stations.

DISCUSSION

Uncertainties

With regard to existing gravity observations, the RSA can be divided into three areas. The City of Spokane area to the west, the Spokane Valley and southern Rathdrum Prairie area in the center, and the northern half of the Rathdrum Prairie in the northeast. In the southern Rathdrum prairie and the Spokane Valley, the data coverage is sufficient to delineate the general features of the subsurface, with the critical exception that the outer periphery of the aquifer is poorly sampled. This lack of data leads to some doubt as to how to quantitatively remove the background to isolate the anomaly due to the saturated aquifer from other sources. However, because the unsaturated cover is relatively thin in this area, the error due to the lack of peripheral stations is much lower than in the rest of the RSA (Figure 13). Nonetheless, significant errors up to 50 or 100 meters in aquifer thickness remain, as a result of poor station coverage in the mountains on the periphery of the aquifer.

In the City of Spokane area east of Park Road, only a few gravity stations exist in the PACES and National Geophysical Data Center listings. Purves (1969) performed only a single profile across the Hillyard Trough along Magnesium Road. He observed a relative negative anomaly of about 2.5 milligal along this profile but the profile does not extend far enough in either direction to reliably measure a reference level. Because of the lack of peripheral stations, the Hillyard trough gravity model shows considerable uncertainty (Figure 13). The remainder of the western portion of the aquifer has too few stations to do any type of gravity analysis.

As might be expected, the area with the greatest uncertainty in making any use of the existing gravity data to resolve depth to bedrock is in the northern half of the Rathdrum Prairie. Here, the unsaturated layer is relatively thick, local stations are sparse on the outer periphery of the aquifer, and regional stations are possibly biased. Here also, the geological conceptual model might be inadequate as is indicated by the possible occurrence of thick basalt in at least one deep well. The extreme northern areas of the Rathdrum Prairie, such as the Hoodoo and Spirit valleys, are not sufficiently sampled by gravity stations to interpret at present.

Sources of Error

The various source of error for computing the RSA thickness using the gravity method are illustrated in Figure 14.

The major source of error is the lack of stations in the peripheral areas of the aquifer that leads to considerable difficulty in separating the gravity effect of the aquifer from background effects. This potential error, although most serious in the northern half of the Rathdrum Prairie, is significant throughout the area of the aquifer. This error can be reduced by additional gravity measurements on bedrock outside of but close to the aquifer boundaries.

The second major source of error is with uncertainties in the bulk densities of the geological materials present in the basin. The uncertainty in bulk density contrast between the saturated gravels and the surrounding bedrock alone is 33%. Any aquifer thickness estimate, regardless of the quality and spacing of the existing and future gravity stations, will carry this amount of uncertainty. The only way to decrease the error in bulk density contrast is some borehole control so that the gravity results can be calibrated directly to local density contrasts.

Additional sources of error are small in comparison. The rather coarse survey precision of 0.14 milligal for the older data such as that of Purves (1969) seems large compared to the precision of 0.02 milligal for modern data such as that of Adema (1999). However, this improvement in precision makes less than a six meter difference in any final aquifer thickness calculations. Larger errors arise from uncertainties in contouring between stations and profiles (+/- 20 m) and interpolation of water table elevations (+/- 8 m) from existing wells.

RECOMMENDATIONS

The existing RSA gravity data set has limitations that make meaningful interpretation in terms of depth to bedrock difficult to impossible at the present time. The aquifer isopach map presented in this study (Figure 11) should be used with caution in any ground water flow model at the present time and must consider the uncertainties associated with the gravity evaluation (Figures 13 and 14). Below are suggestions to improve the data set and its eventual interpretation.

1. Verify and expand the gravity data in the northern half of the Rathdrum Prairie. Because of inconsistencies with the geological models of the area and/or with regional gravity measurements, the gravity observations of Hammond (1974) in this area need to be replicated and additional stations are needed to fill in holes. A recent report on the Ramsey Channel by Baldwin and Owsley (2005) provides four hydrogeological sections across the western, Ramsey and Chilco Channels. Gravity profiles run along these profiles should be sufficient to verify the Hammond (1974) gravity data as well as to improve these newer hydrogeological interpretations. At the same time it would be worthwhile to fill in holes in the gravity coverage in the extreme northern Rathdrum Prairie, especially the Hoodoo and Spirit valleys. In all cases, it is essential that gravity measurements be made not only over the aquifer but at least a kilometer beyond the boundary up into the surrounding mountains onto bedrock to ensure adequate characterization of the regional trend in the area.

2. Look for evidence of massive basalt in subsurface of the northern half of the Rathdrum Prairie. If the geological model in this area is inadequate, the gravity model

cannot be sufficiently constrained to yield a unique result and any aquifer thickness estimates are meaningless. Thick massive basalt units beneath the aquifer will have deleterious effects on any attempts to make quantitative aquifer thickness estimates. The geological model, where it is unclear, can of course be improved by better geological analysis and new geophysical surveys. Aeromagnetic data, for example, probably exists for much of the RSA. These data need to be compiled and interpreted to see if indications of massive basalt beneath the aquifer are present. If aeromagnetic coverage is inadequate, ground magnetic measurements can be made. Basalt is generally extremely magnetic and should have a distinctive signature on magnetic data.

3. Verify and extend the gravity data in all areas of the aquifer. The old data of Purvis (1969), though not collected with modern technology, is probably adequate. However, a few of his profiles should be repeated to make sure. All existing gravity profiles need to be extended across the RSA boundary into the surrounding hills onto bedrock sites. The major weakness of the existing gravity profiles is that the lines do not extend at least one kilometer beyond the aquifer boundary. Without these data, the background gravity has to be estimated from potentially biased distant stations—a procedure that can result in serious misinterpretation. New gravity observations should be made to extend all the profiles of Purves (1969) and Adema (1999) and Hammond (1974) to a distance of at least a kilometer outside the aquifer boundary. Care must be taken to tie into their outermost stations. All new and existing observations should be processed using the standard modern geodetic datum.

4. Extend the profile of Purves (1969) across the Hillyard Trough along Magnesium Road considerably. To the east, the profile should be continued until the stations are clearly onto a crystalline rock surface. To the west, the profile should be extended across the Fivemile Prairie and across the Spokane River and several kilometers beyond that. In this manner the relation of the gravity results to the rock types present can be established.

5. Establish new gravity profiles across the western part of the aquifer. The largest hole in the gravity stations is in the City of Spokane west of Park St. Only the single profile of Purves across the Hillyard Trough and a few isolated stations exist. If any understanding on the distribution of basalt and its affect on the aquifer in this area is to be obtained, perhaps six new gravity profiles of the city and its surroundings needs to be accomplished. For consistency with existing profiles, station spacings of about 300 meters would be adequate. It is imperative that the profiles extend to well outside the perimeter of the aquifer, preferably to pre-Tertiary bedrock sites where such sites exist.

6. Undertake a thorough geological review and study of the extent of the Columbia River Basalt Group in the subsurface of Spokane and the Spokane Valley. Without a good handle on the basalt stratigraphy and probable flow elevations, interpretation of gravity data in the Spokane area will prove difficult.

7. If future geophysical results continue to suggest the presence of massive basalt, consider deepening an existing water well in the northern half of the Rathdrum prairie to

verify its existence beneath the aquifer in that area and to determine its hydrogeological significance.

8. Drill monitoring wells to bedrock in the Spokane Valley and Rathdrum Prairie. Without borehole calibration, any aquifer thickness estimate, regardless of the quality and spacing of the gravity survey on which it is based, will carry some uncertainty.

REFERENCES

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

Balco, G. and Stone, J.O., 2003. Measuring the density of rock, sand, till, etc. UW Cosmogenic Nuclide Laboratory, methods and procedures. http: //depts.washington. edu/cosmolab/chem.

Baldwin, J., and Owsley, D., 2005, The Ramsey Channel of the Rathdrum Prairie Aquifer, Idaho Department of Environmental Quality, 20 p.

Bankey, V., Webring, M., Mabey, D. R., Kleinkopf, M. D., Bennett, E. H., Complete Bouguer gravity anomaly map of Idaho: U.S. Geological Survey miscellaneous field studies map, MF-1773.

Bonini, W. E., 1963, Gravity anomalies in Idaho: Idaho Bureau of Mines and Geology, Pamphlet 132, 39p.

Cady, J. W., and Meyer, R. R., 1 976a, Principal facts for gravity stations in the Okanogan, Sandpoint, Ritzville, and Spokane 10 x 20 quadrangles, northeastern Washington and northern Idaho: U.S. Geol. Survey Open-File Report 76-290, 57 p.

Cady, J.W., and Meyer, R. R., 1 976b, Bouguer gravity anomaly map of the Okanogan, Sandpoint, Ritzville, and Spokane 10 by 20 quadrangles, northeastern Washington and northern Idaho: U.S. Geological Survey Geophysical Investigation Map GP-9 14.

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

Hammond, R. E., 1974, Ground-water occurrence and movement in the Athol area and the northern Rathdrum Prairie, northern Idaho: Idaho Department of Water Administration, Water Information Bulletin no. 35, 18 p.

Harrison, J. E., Kleinkopf, M. D., and Obradovich, J. D., 1972, Tectonic events at the intersection between the Hope fault and the Purcell Trench, northern Idaho: U.S. Geological Survey Professional Paper 719, 24p.

Hittelman, A., Dater, D., Buhman, R., and Racey, 5., 1994, Gravity CD-ROM — 1994 Editions and User's Manual. Revised, 1996. U. S. Department of Commerce, National Geophysical Data Center, Boulder, Colorado.

Hosterman, J. W., 1960, Investigations of some clay deposits in parts of Washington and Idaho: U. S. Geological Survey Bulletin 1091, 146 p.

Kahle, S.C., Caldwell, R.R., and Bartolino, J.R., 2005, Compilation of geologic and hydrologic information for the Spokane Valley-Rathdrum Prairie Aquifer, Bonner and Kootenai Counties, Idaho and Spokane County, Washington: U.S. Geological Survey Scientific Investigations Report 2005-5227, 64 p

Nettleton, L.L., 1940. Geophysical Prospecting for Oil. McGraw-Hill, New York, 444 pp.

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, 39(4), 526-536.

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

Steffy, D.A., 1983, Gravity survey of the Little Spokane River valley, Washington [abs.]: Eos, Transactions, American Geophysical Union, v. 64, no. 9, p. 88.

Wollard, G. P., and Behrendt, J. C., 1961, An evaluation of the gravity control network in North America: Geophysics, v. 50, p. 866-88 1.

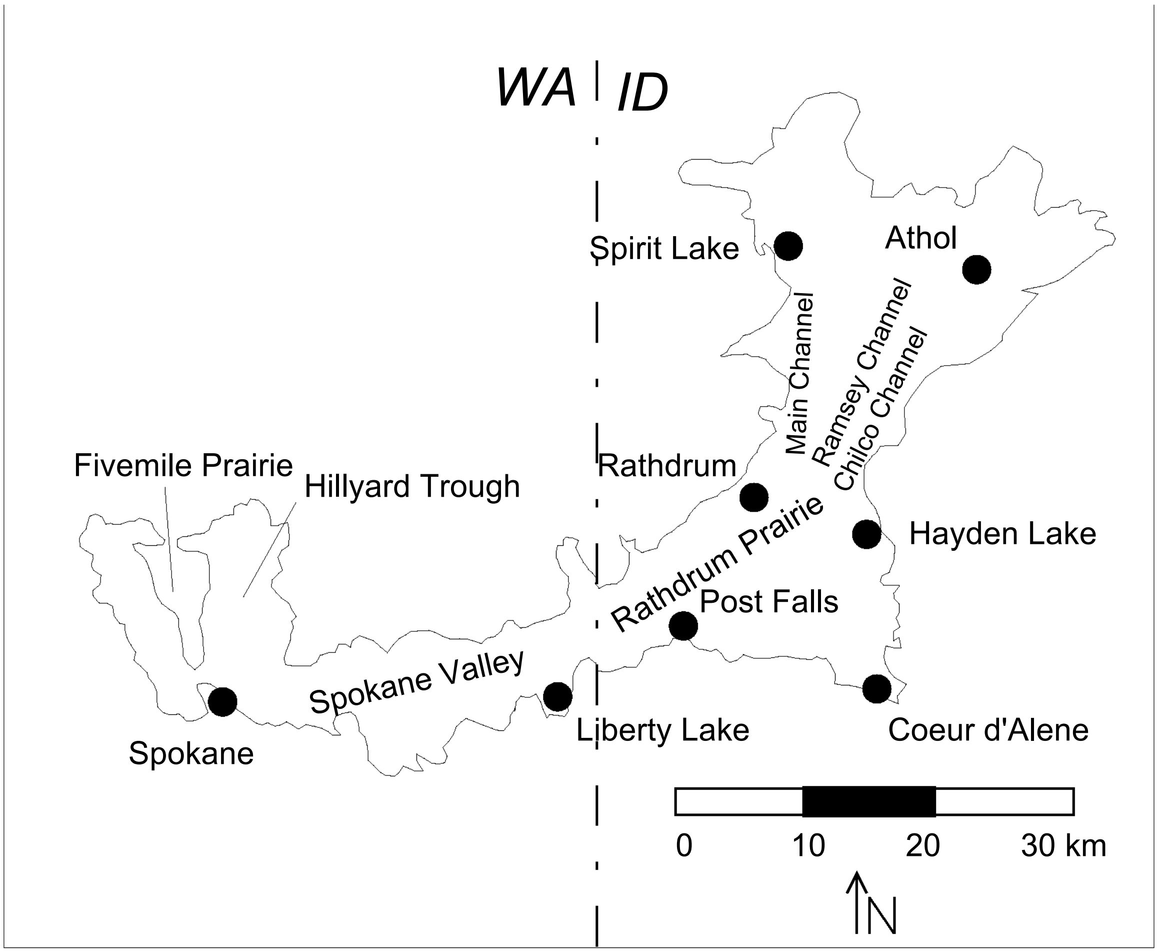

Figure 1. The Rathdrum Prairie Aquifer and the geographical locations mentioned in this report. The boundary shown is that of Kahle et al., 2005.

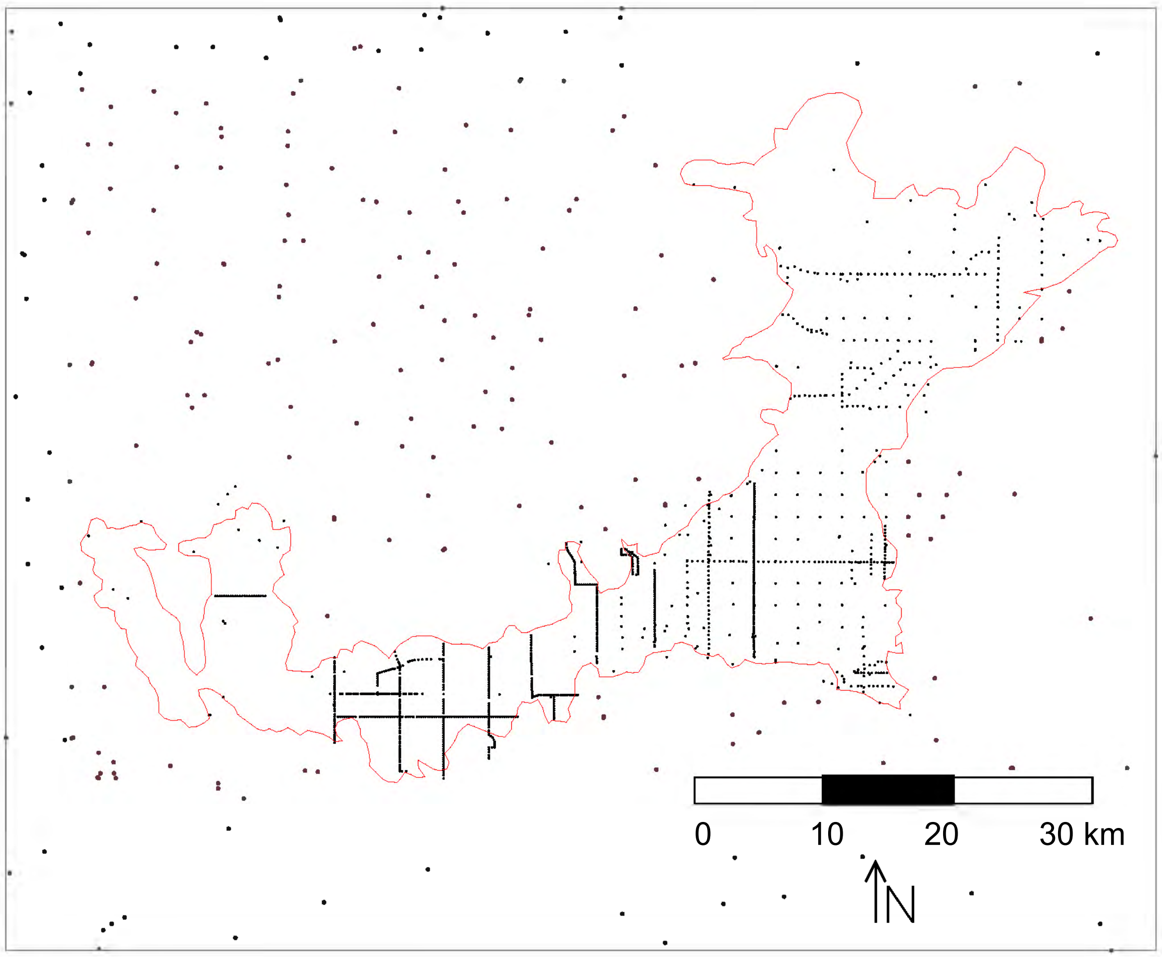

Figure 2. The gravity stations used in this study.

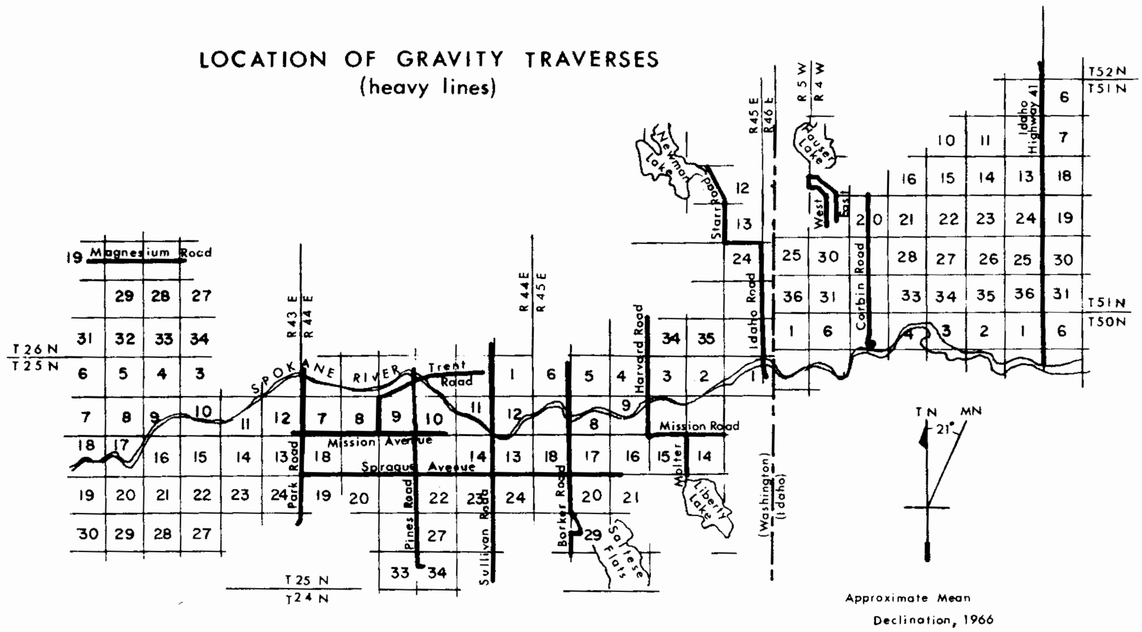

Figure 3. Gravity traverses of Washington State University (Purves, 1969)

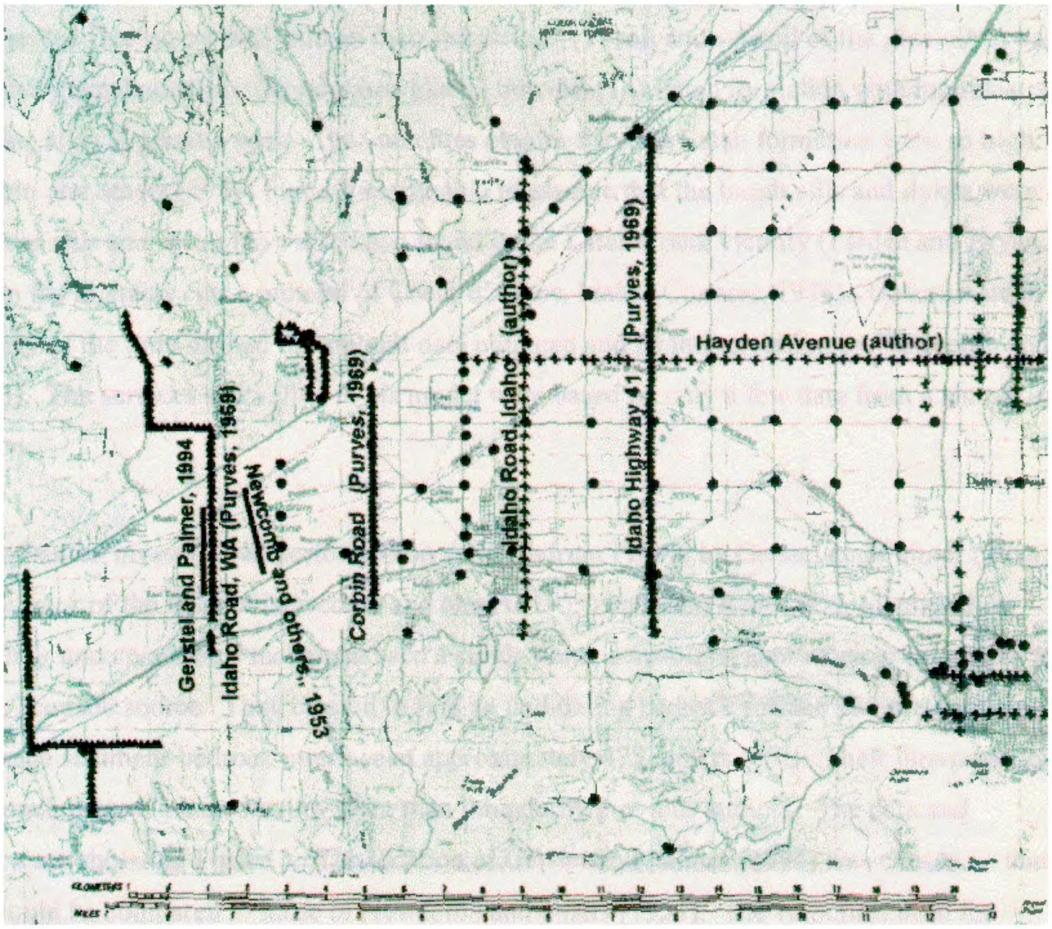

Figure 4. Gravity traverses of Idaho Geological Survey (Adema, 1999)

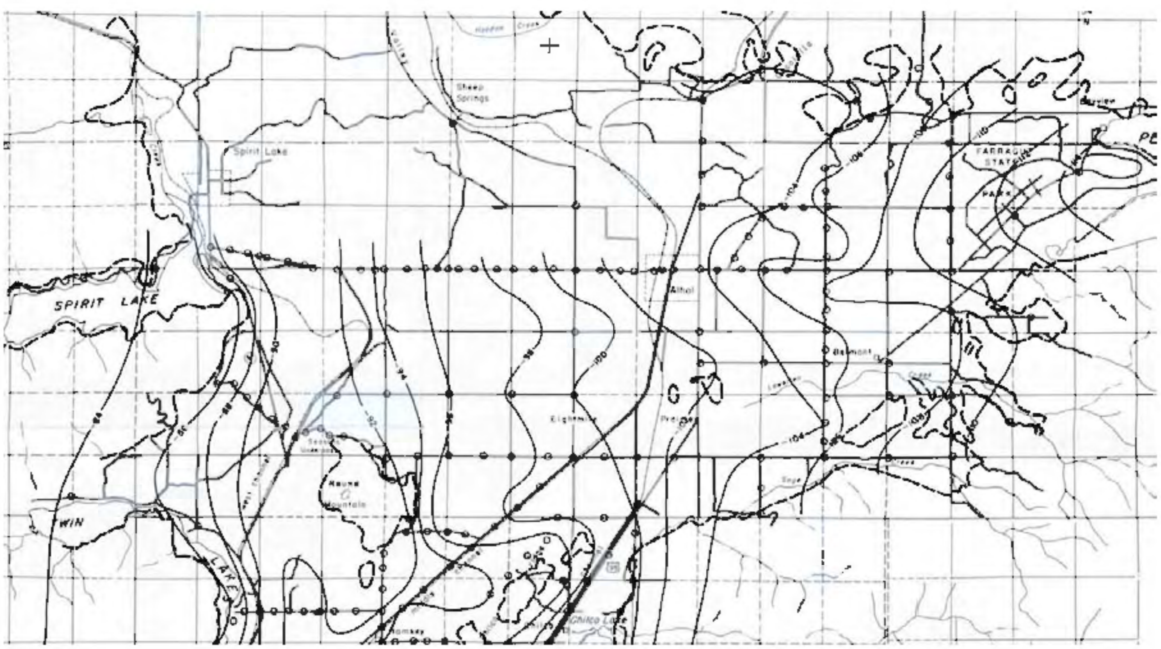

Figure 5. Gravity stations of Hammond (1974) in the northern Rathdrum Prairie.

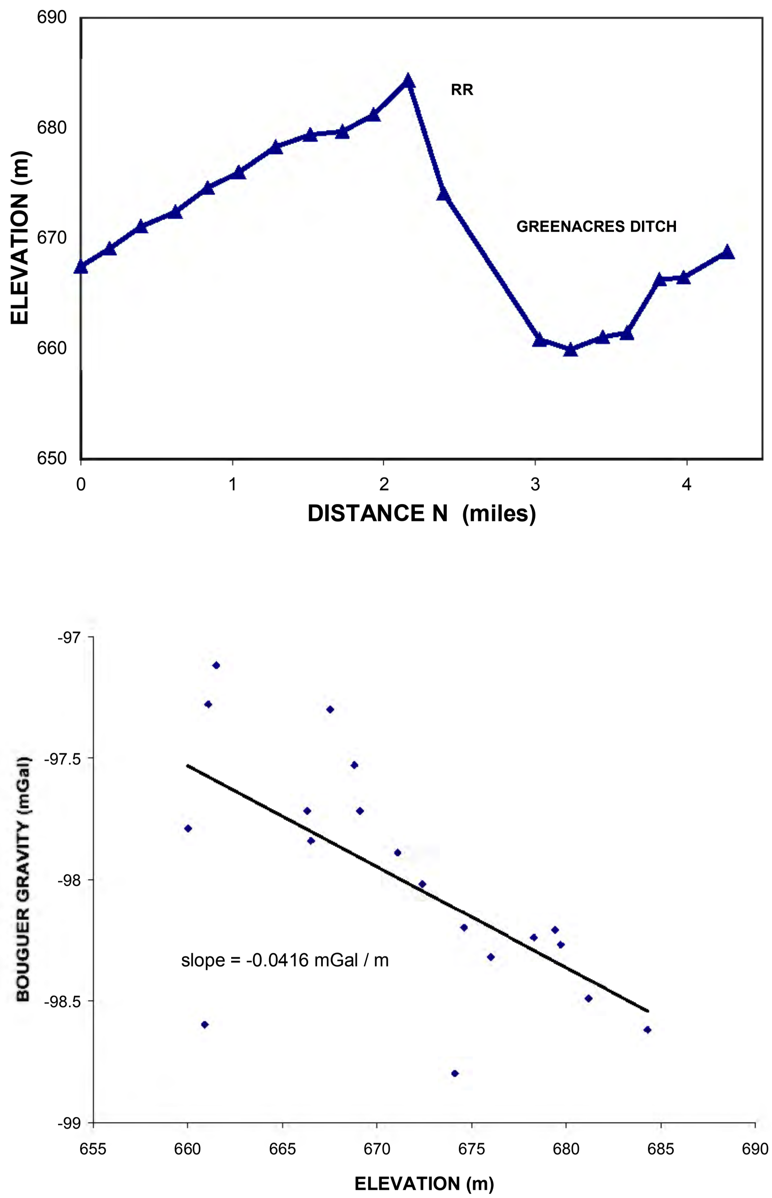

Figure 6. Density profile over the Greenacres Ditch north of Post Falls. The triangles in upper graph indicate gravity stations. The slope of the lower graph provides an estimate of near surface bulk density (see text).

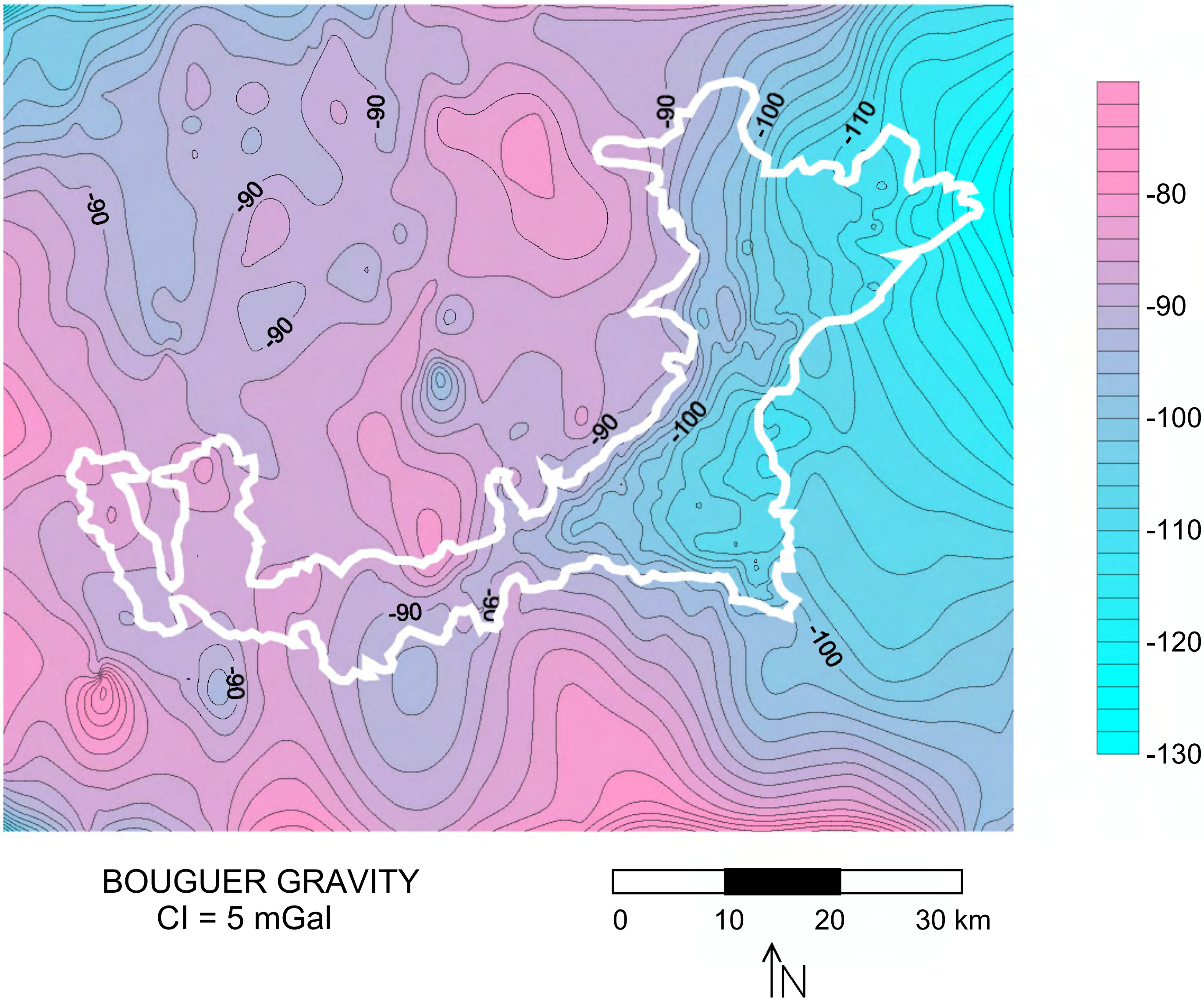

Figure 7. Bouguer gravity in the aquifer region.

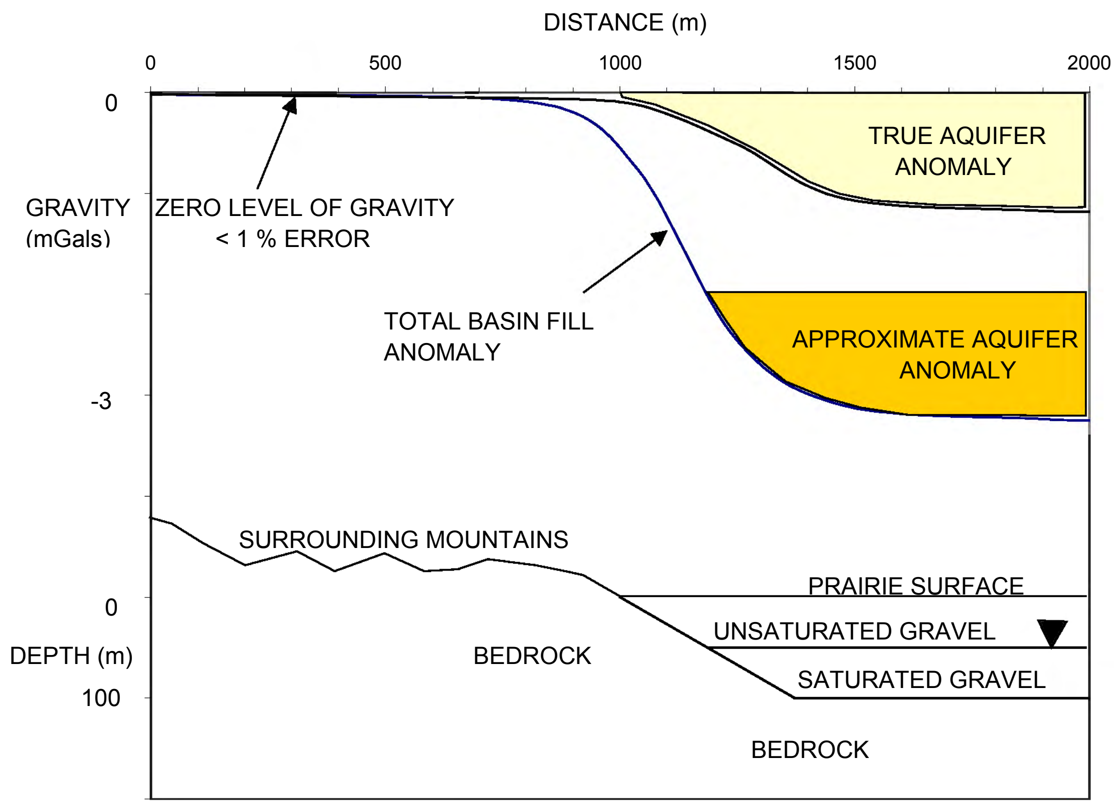

Figure 8. Geology section and the gravity response over a typical aquifer boundary. The gravity effect of the aquifer extends to about one kilometer outside the aquifer boundary.

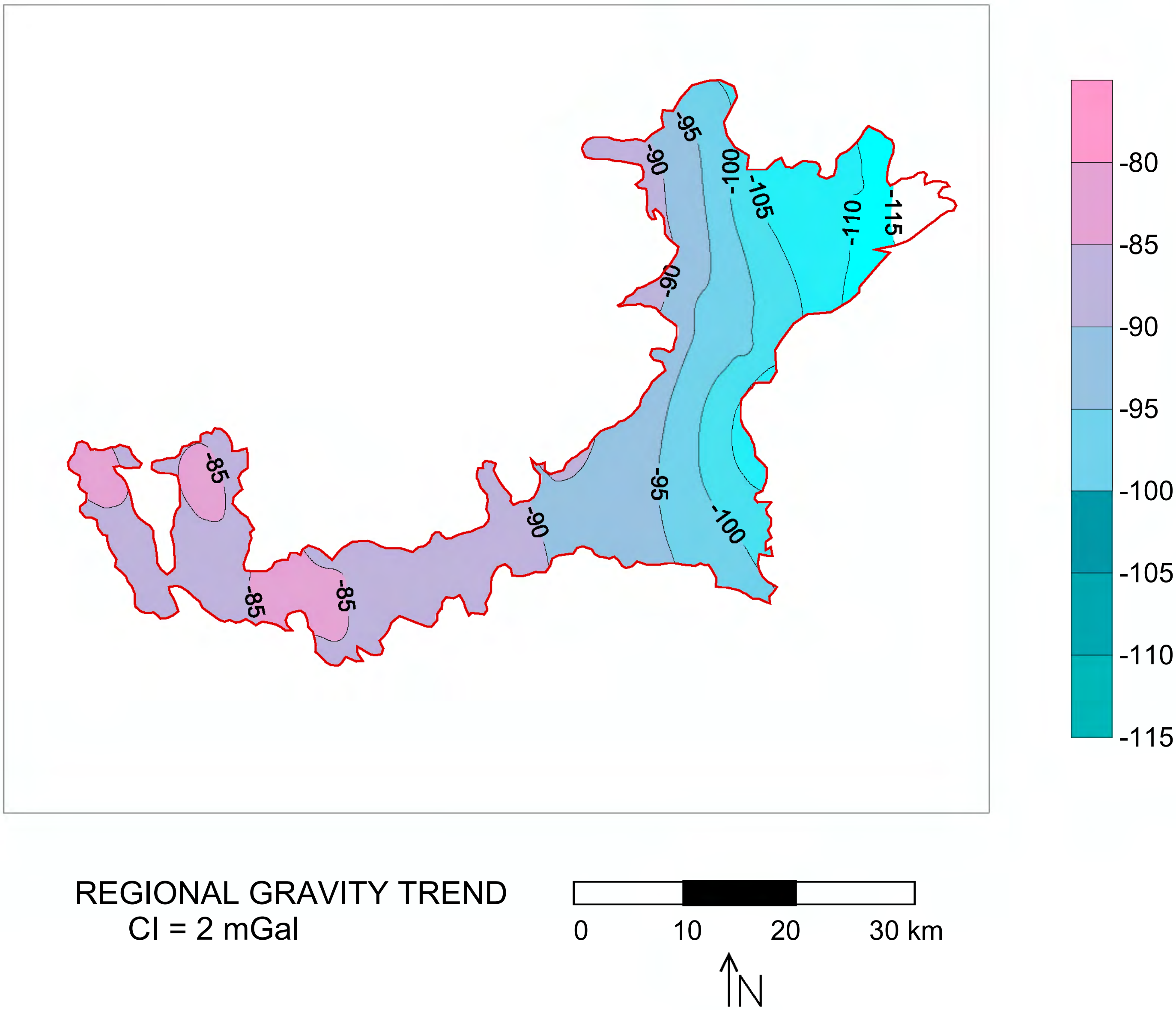

Figure 9. The background regional trend over the aquifer as estimated using distant stations.

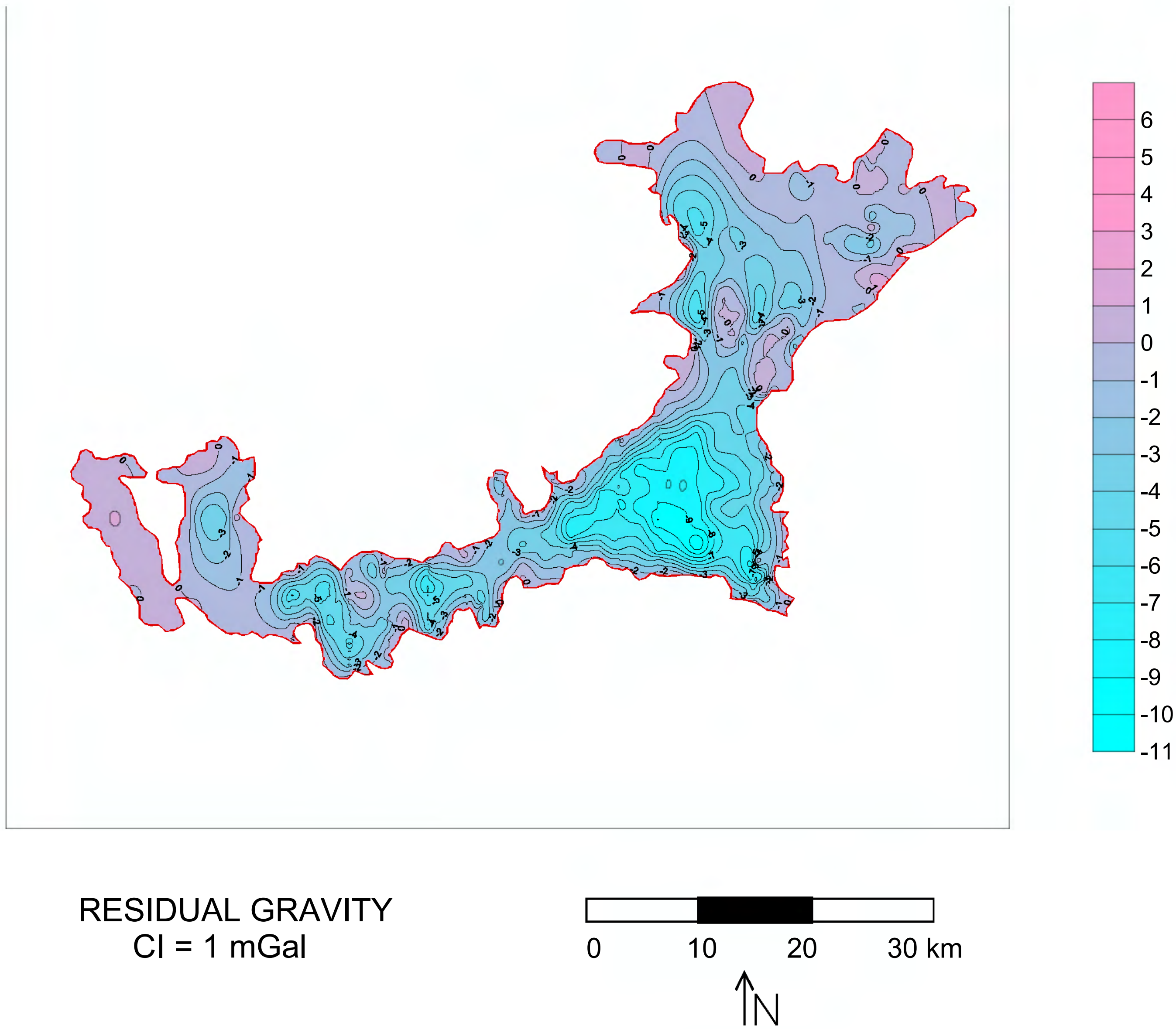

Figure 10. The residual gravity representing the original Bouguer gravity with the effects of the regional trend removed.

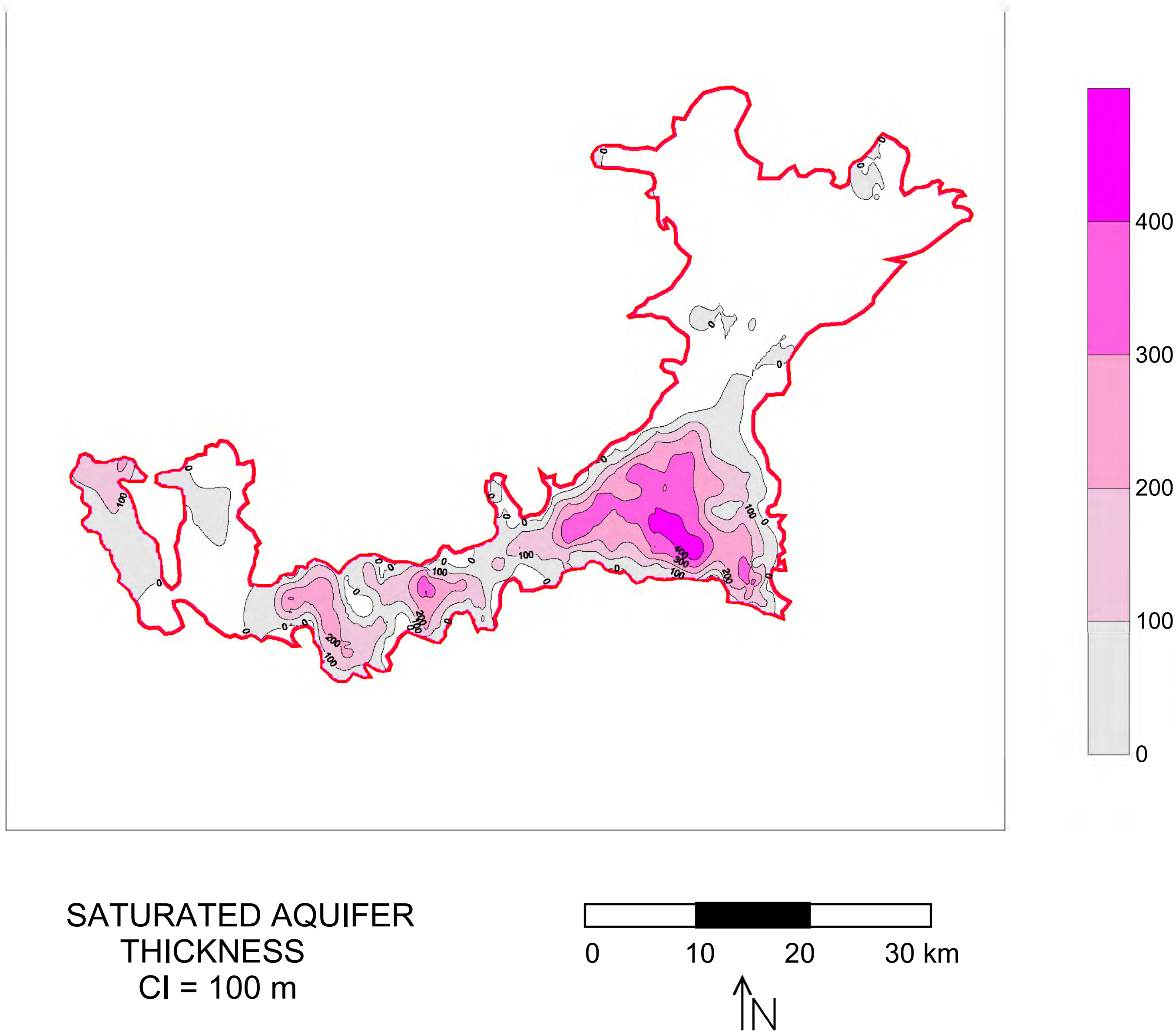

Figure 11. Isopach of the aquifer based on residual gravity.

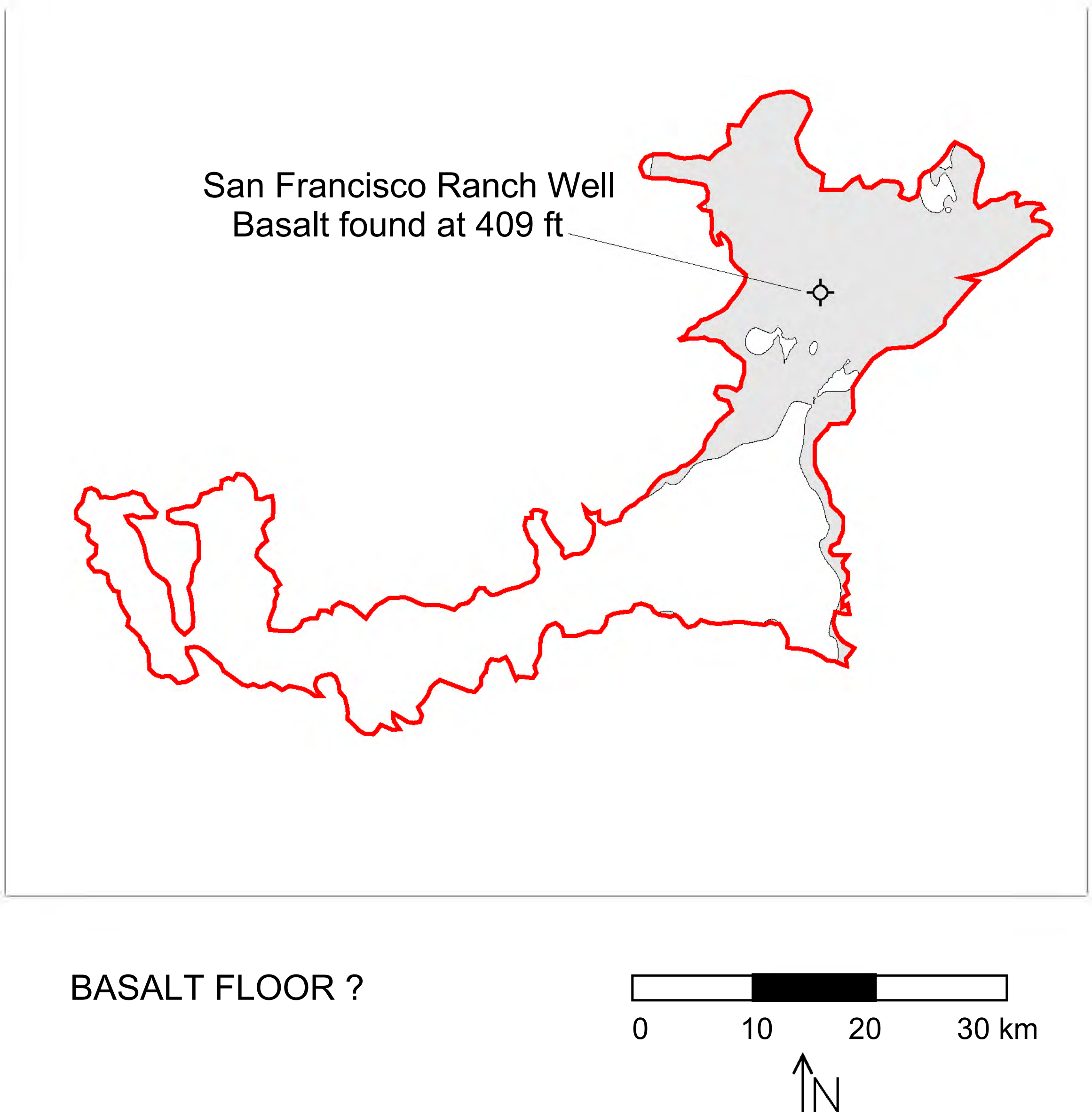

Figure 12. Areas of the aquifer possibly underlain by massive basalt flows.

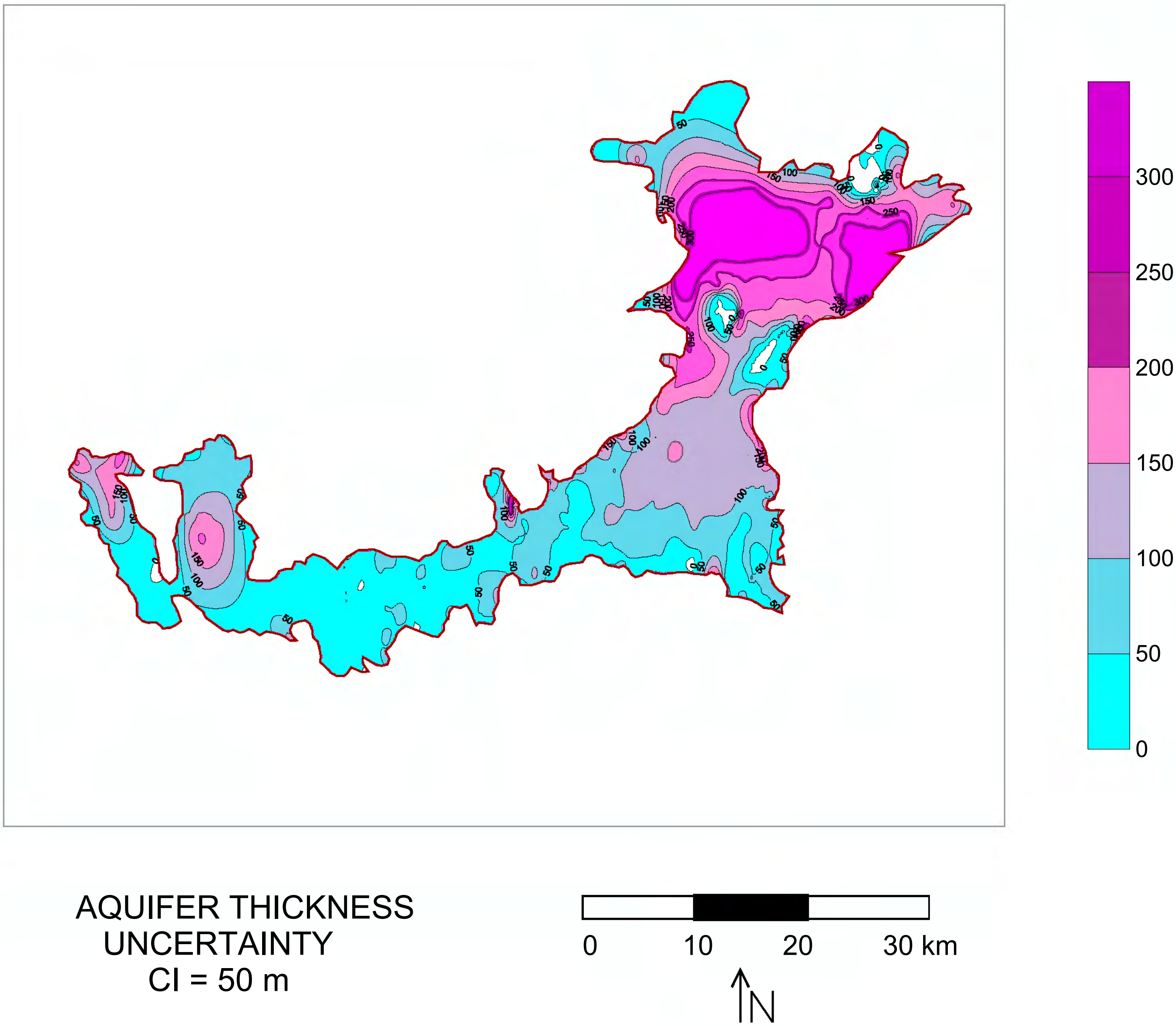

Figure 13. The uncertainty in aquifer thickness due to lack of gravity stations on the periphery of the aquifer boundary.

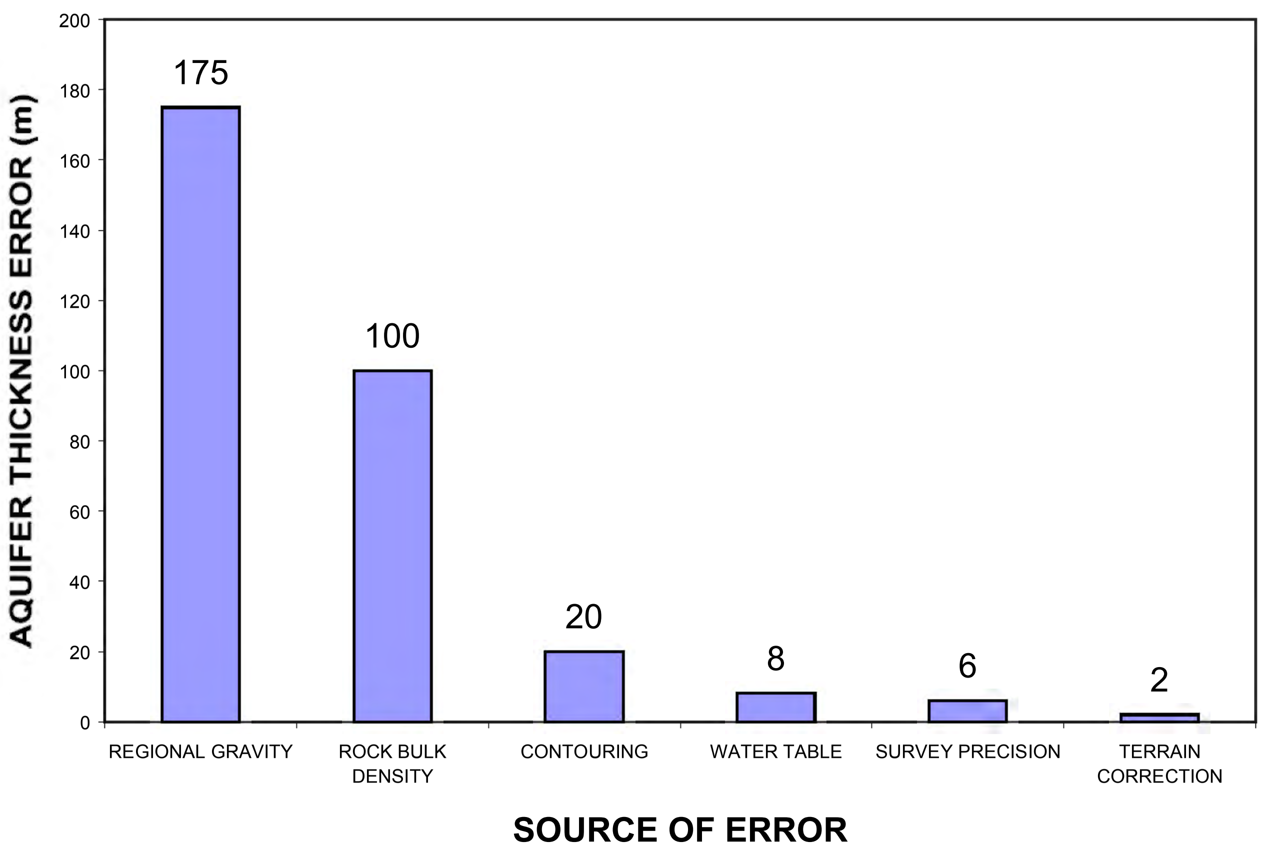

Figure 14. Sources of error in gravity interpretation of the SVRP aquifer.