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GRAVITY GRADIOMETRY DIFFERENCE MEASUREMENT AS A TOOL FOR MONITORING PUMPING AND INJECTION; FORWARD MODELING RESULTS

Robert Creed
U.S. Department of Energy
850 Energy Dr. MS 1220
Idaho Falls, ID 83401-1563
creedrj@inel.gov

Andrew Edwards
Lockheed Martin Idaho Technologies Company
P.O. Box 1625
Idaho Falls, ID 83415-2202

ABSTRACT

Gravity gradiometry forward models have been developed at the Idaho National Engineering and Environmental laboratory (INEEL) that can characterize gravity gradient changes with the development of a cone of depression or injection mound in water table aquifers. Difference measurements at long time intervals reduce delayed drainage effects and eliminate the need for determining an initial density structure. Qualitative or semi-quantitative analysis of the gradient signal to determine changes in groundwater distribution with injection or pumping may be possible, particularly if the time varying nature of the signal is of interest. Gravity gradiometer instruments (such as the Gravity Gradient Survey System) have progressed to the point where the complete second order gravity gradient tensor can be measured with an instrument noise level of less than 1 Eotvos (0.1 microgals/meter). Modeling indicates direct gravity measurements for the injection mound perched aquifer case could produce similar signal to noise ratios. However gravity gradients provide 5 independent measurements and due to the common mode nature of the instruments are less susceptible to other effects (tide, latitude, elevation, etc.). The gradients also provide a sharper image of the edge of the anomaly. The systematic identification and removal of specific retention, rainfall and subsidence or uplift effects may be required to make gradiometry difference imaging practical for field use.

INTRODUCTION

The imaging of subsurface water movement is useful for characterizing the impact of development, disposal and remediation activities on aquifers. Monitoring wells provide information at specific points but interpretation is required to determine aquifer properties between wells. Various geophysical methods (especially electrical or electromagnetic methods) have been used to map groundwater and electrical tracer fate and transport with varying degrees of success. In the most successful methods, difference imaging is employed where an initial image is compared with subsequent images to determine changes over time (also called 4-D imaging). Difference imaging has the advantage that subtle changes tend to be imaged more clearly and direct inversion for initial conditions is not required.

To our knowledge, gravity gradiometry has not been considered as a difference imaging tool. The purpose of this paper is to show that difference gravity gradiometry can be an effective tool for imaging water table aquifer response to pumping or injection at scales appropriate for environmental applications. More detailed analysis or coinversion with other data would be required to explicitly relate gradient signals to water table geometries or other geohydrologic parameters of interest.

GRAVITY GRADIOMETRY

If gravity is defined as the gradient of the scalar geopotential T:

$$\vec{g} = -\vec{\nabla} T = -\vec{a}_x T_x - \vec{a}_y T_y - \vec{a}_z T_z \quad where \quad T_i = \frac{\partial T}{\partial i}$$

and the gravity gradients are given by the three directional derivatives of the gravity vector components:

$$\begin{vmatrix} T_{xx} & T_{xy} & T_{xz} \\ T_{yx} & T_{yy} & T_{yz} \\ T_{zx} & T_{zy} & T_{zz} \end{vmatrix} = \begin{vmatrix} \frac{\partial T_x}{\partial x} & \frac{\partial T_x}{\partial y} & \frac{\partial T_x}{\partial z} \\ \frac{\partial T_y}{\partial x} & \frac{\partial T_y}{\partial y} & \frac{\partial T_y}{\partial z} \\ \frac{\partial T_z}{\partial x} & \frac{\partial T_z}{\partial y} & \frac{\partial T_z}{\partial z} \end{vmatrix}$$

In an irrotational, curl free field the trace yields Laplace's Equation (a special case of Poisson's equation) and sums to zero:

$$T_{xx} + T_{yy} + T_{zz} = 0$$

Further, the matrix is symmetric and thus:

$$T_{xy} = T_{yx} \quad T_{xz} = T_{zx} \quad T_{yz} = T_{zy}$$

The model developed at the INEEL to calculate the gravity gradient anomalies produced at the surface by subterranean mass anomalies is based on a representation of the local vicinity as a three dimensional grid of point mass anomalies. The code is written in MATLAB. The basis is the universal law of gravitation. The individual gradients at a testpoint are calculated from the components of the gravity vector. The components of the gravity vector are calculated at two points separated by a small distance. The distance used can be varied in the model but for this case was 1 mm.

Use of larger distances may be justified if the aim is to accurately model the performance of a particular sensor. Increasing the separation distance can attenuate the signal in a sharply changing field. Also, if the gradients are not measured about a single point due to

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instrumentation design this can cause the loss of symmetry in the gradient tensor. (The element $T_{ij} \neq T_{ji}$).

The contributions from each of the point mass anomalies to the gradients at a testpoint are thus calculated and summed to give a gravity gradient anomaly at the testpoint. The plots shown here are produced from the results from a series of testpoints. The coordinate system used is x, y, and z. This is equivalent to a North, East and Down system. It has been observed that the gradients are very strongly correlated to the terrain features. By use of difference measuring techniques and reoccupation of the initial measurement points, terrain effects will be canceled or reduced.

GRAVITY GRADIOMETER SURVEY SYSTEM

There are a number of gravity gradiometers in various stages of development. Most are designed to measure one or two elements of the gravity gradient tensor with possible future extension to measuring more elements. There are examples which are capable of measuring only horizontal gradients T_{xy} and $(T_{xx}-T_{yy})/2$. There are also examples which are capable only of measuring vertical gradients such as T_{zz}, some of these could be extended in capability to measure T_{yz} and T_{xz}.

The Gravity Gradiometer Survey System (GGSS) is currently the only full tensor gravity gradiometer system known to the authors which is operational on a moving base (Jekeli, C., 1988 and Gleason, D. M., 1995). Water table aquifer response to pumping or injection could be detected by a system like the GGSS. The instruments on the GGSS would have a noise level of 0.9 Eotvos for a dwell time of 300 seconds. By reoccupying the same site after a significant period of time the two sets of gradient data can be subtracted to determine gradient changes with time.

GRAVITY GRADIENTS IN WATER TABLE AQUIFERS

We have forward modeled the gravity gradients resulting from simple pumping scenarios and cones of depression in water table aquifers. Discontinued injection and infiltration activities have lead to the development of a perched water body beneath the Test Reactor Area (TRA) at the INEEL. Using contoured perched water elevation maps, we have modeled the difference gradient signal for water level decreases over time. We have determined the gradient signal from the decay in perched water volume. A similar signal with opposite sign would be obtained for T_{zz} in the case of injection mound build-up.

Gravity Gradient Difference Measurements Resulting from Pumping

Rather than use complex analytical or numerical methods to determine water table surfaces, we have used an example from Davis and DeWiest (1966, eqn. 7.9). In this example hydraulic conductivity is 500×10^{-4} cm/sec, discharge is 300 gal/min, and a steady condition of flow is reached at 2,000 feet from the pumping well. The assumed porosity is 20%. These conditions are consistent with a coarse sand or gravel aquifer where specific retention and delayed drainage effects would probably be insignificant (Heath, 1984). Because we are using a difference image, there is no need to explicitly account for the density of the aquifer matrix. As long as the density of the matrix is not expected to change, this is a reasonable approach.

Drawdown as a function of distance is shown in Figure 1 for pumping rates of 300 and 450 gal/min. The computed gravity gradient difference signal (gravity gradient before pumping minus gravity gradient after pumping) for an initial water table 11 meters below land surface (bls) and 300 gal/min is shown in Figure 2.

Figure 2 illustrates two important points about the gradiometry technique. First, notice that T_{zz} is the dominant signal. Second, at the plus or minus 1 Eotvos level (the lowest gradient detectable by the GGSS) T_{zz} is not measurable until a water level drop of approximately 2 meters has occurred. This amount of drawdown occurs at a distance of 17 meters from the hypothetical well. This scale of investigation is not unreasonable for environmental restoration characterization activities and would probably be sufficient to qualitatively estimate the effects of pumping on the water table surface and flow directions in the area away from the well. This information could be useful for identifying and characterizing heterogeneities and anisotropy affecting flow near wells in water table aquifers.

We contend that gradiometer surveys over time would give important qualitative information on flow anisotropy and water table surface configurations with various pump and treat or development strategies. Although we have not considered subsidence or other topographic effects from pumping, it should not be difficult to account for these effects either by maintaining measurement elevations or by numerical methods whereby the gradient change due to elevation difference is subtracted from the measurement. Density changes due to compaction with subsidence are more difficult to account for, but would likely be small with respect to gradient changes with pumping. Another significant effect results from rainfall. Care would have to be taken to ensure that the moisture content of the soil was reasonably consistent or otherwise accounted for at the times of the measurements.

Gravity Gradient Difference Measurements of Perched Water from Injection

Monitoring wells at the TRA indicate that perched aquifer water levels have decreased over time (Arnett, et al., 1996). The top of the perched aquifer decreased from approximately 80 feet bls to 100 feet bls over 5 years. Figures 3 and 4 from Arnett et al. (1996) are water elevation contour maps of the perched water surface interpolated from monitoring well data from March 1991 and April 1996 respectively. The land surface elevation is approximately 4,930 feet at TRA which is located on a low relief alluvial surface. The bottom of the perched aquifer is assumed to be at an elevation of 4,750 feet.

The perched aquifer is in porous fractured basalt above a relatively impermeable and flat lying sedimentary interbed composed of silts, sands and clays. We have used a porosity of 15% (R. Arnett, pers. Comm.) for the basalt. As with the pumping case, the difference method does not require explicit input for aquifer matrix density.

Figures 5 and 6 are difference gradiometry images for the T_{zz} gravity gradient that show what the signal would be if a gradiometer image before injection was subtracted from a March 1991 image (Figure 5) and later subtracted from an April 1996 image (Figure 6). In a very simple sense, the positive values (in Eotvos) reflect increases in gradient due to mass increases (water addition) nearest to the surface. The negative values correspond to aquifer edges where T_{zz} is decreasing most rapidly due to a combination of mass decrease and minimum anomaly elevation change. The zero contour corresponds to a relatively constant gradient of the perched water surface where T_{zz} has not changed. The reader is referred to Butler (1995) for a more complete discussion on the relationship between T_{zz} and mass.

In order to assess the utility of the difference gradiometry technique for mapping perched aquifer distribution over time, we constructed a difference image by subtracting the values on Figure 5 from those on Figure 6. The results are shown on Figure 7. One way to interpret Figure 7 is that the positive values are proportional to the increase in gradient (and water levels) over time while the negative values reflect decrease in mass or water levels over time. Thus the difference image indicates an overall decline in perched water elevation with some lateral spreading to the northeast and northwest with possible recharge from the Big Lost River increasing water levels to the east. Because our forward modeling relies on interpreted contour maps, our interpretation of an interpretation should not be taken as a rigorous assessment of TRA perched water evolution. In an actual field application injection related uplift or loading could affect the gradiometry measurements but these effects are likely to be small.

Figure 8 shows the difference gravity anomaly corresponding to the difference gradient image in Figure 7. In theory the the difference gravity signal will be as easy to detect as the difference gradiometry signal. Although the difference gravity signal appears to be robust (at the 5 microgal level of accuracy), micro gravity surveys are labor intensive and require many tedious corrections that hinder reproducibility and the difference imaging approach. Also less definition is provided with the gravity data. In a smaller survey it may be possible to make gravity measurements at the required level of accuracy, but an area of the size of TRA would require that multiple base stations be set up to provide for drift and tare corrections. Maintaining survey quality becomes exponentially more difficult with increase in survey area size.

CONCLUSIONS

Forward modeling has shown the gravity gradient anomalies due to a theoretical cone of depression caused by pumping from a hypothetical water table aquifer. The gradient anomalies are detectable for the case we considered (a coarse grained productive aquifer 11 meters bls) at a scale appropriate for environmental characterization. With further work, the incorporation of other site specific data, and the use of all elements of the gradient tensor it may be possible approach a true inversion of the signal.

In a more realistic case, actual data from a perched aquifer (caused by injection) was used to successfully show how gravity gradiometry could be used to monitor the effects of injection with time. We compared to the gravity difference signal with the gradient difference and showed that while in theory similar signal to noise ratios are obtained, gravity gradiometry has distinct advantages over gravity measurements due to the common mode nature of the gradiometer instrument. Tedious corrections for tides, drift, tares, elevation, and latitude need to be routinely applied to gravity meter results but do not apply to gravity gradiometers which also provide better anomaly definition

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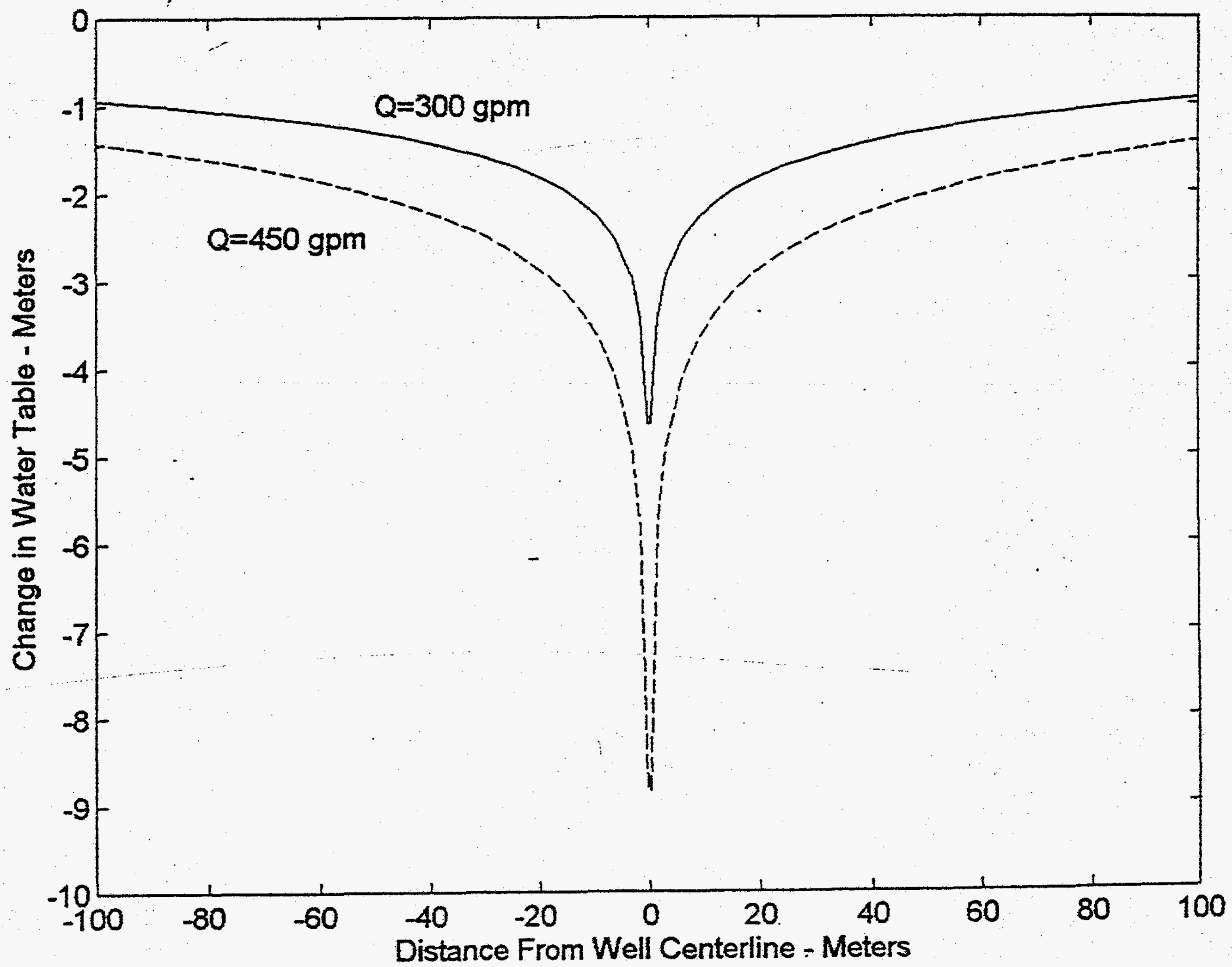

Figure 1. Hypothetical shapes of water table aquifer cones of depression for 300 gpm and 450 gpm. In calculating the gradient for Figure 2 the 300 gpm curve was used with an initial water depth of 11 meters. Calculated from Davis and DeWeist (1966, eqn. 7.9).

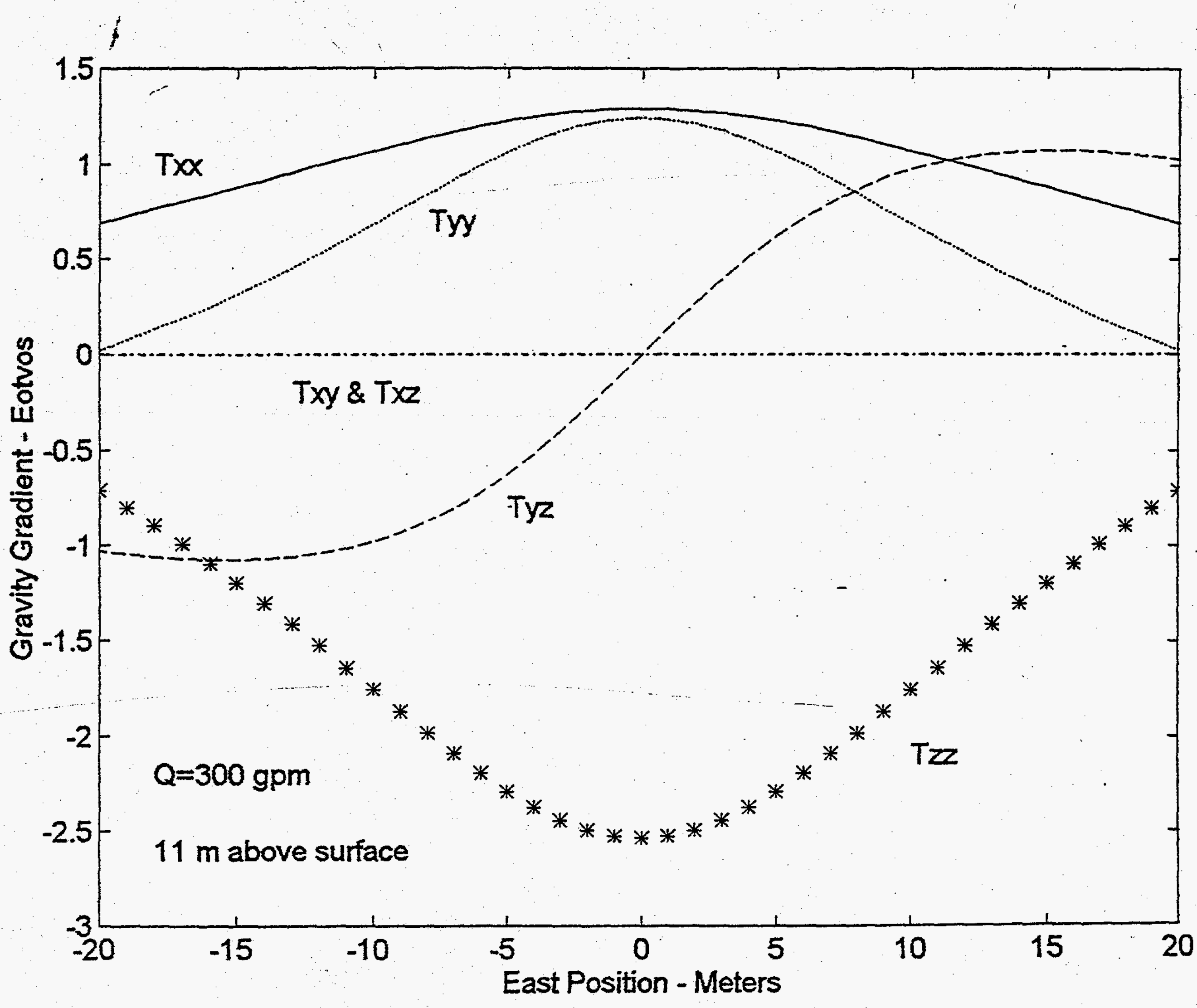

Figure 2. Gravity gradient for the 300 gpm case with an initial water depth of 11 meters, bulk density of 2 g/cm^3 and porosity of 20%. The gradients attenuate roughly as the third power of the distance from the center of the mass anomaly. T_{zz} is the dominant signal. The detection limit of the GGSS is 1 Eotvos. In this model the water table surface could be characterized to a distance of 16 meters from the well.

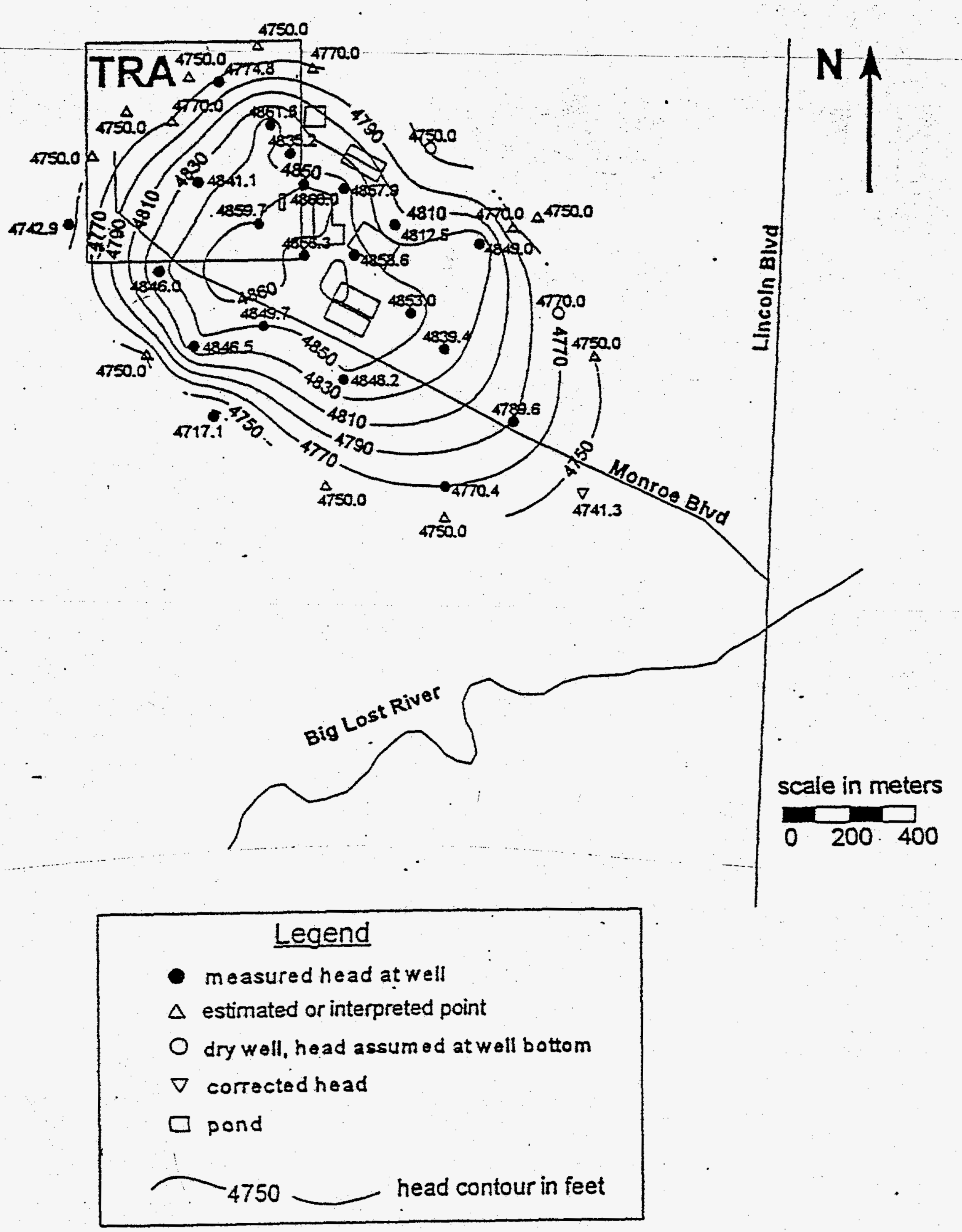

Figure 3. Elevation contour map of the TRA perched water system, March 1991 (Arnett et al., 1996).

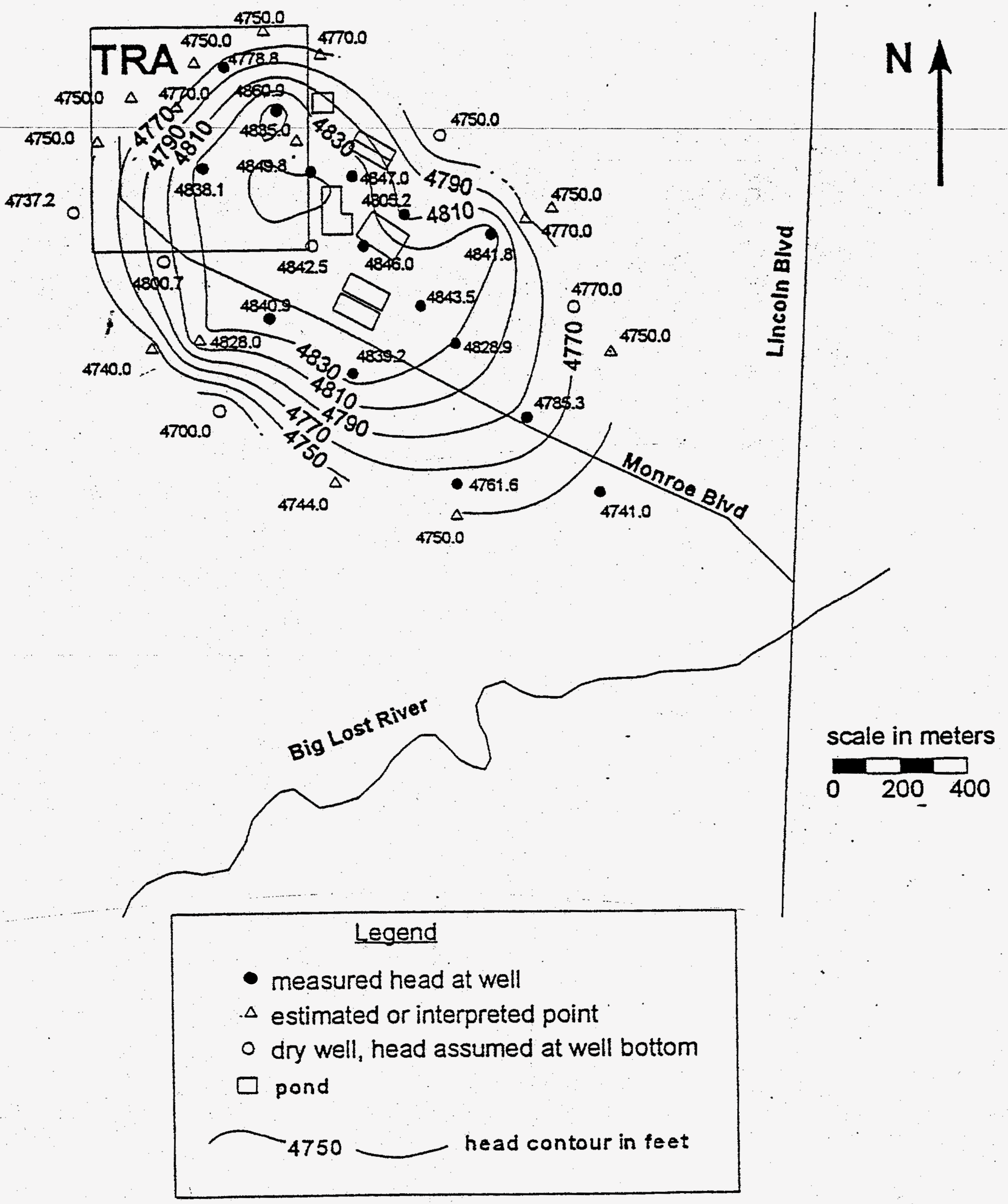

Figure 4. Elevation contour map of the TRA perched water system, April 1996 (Arnett et al., 1996).

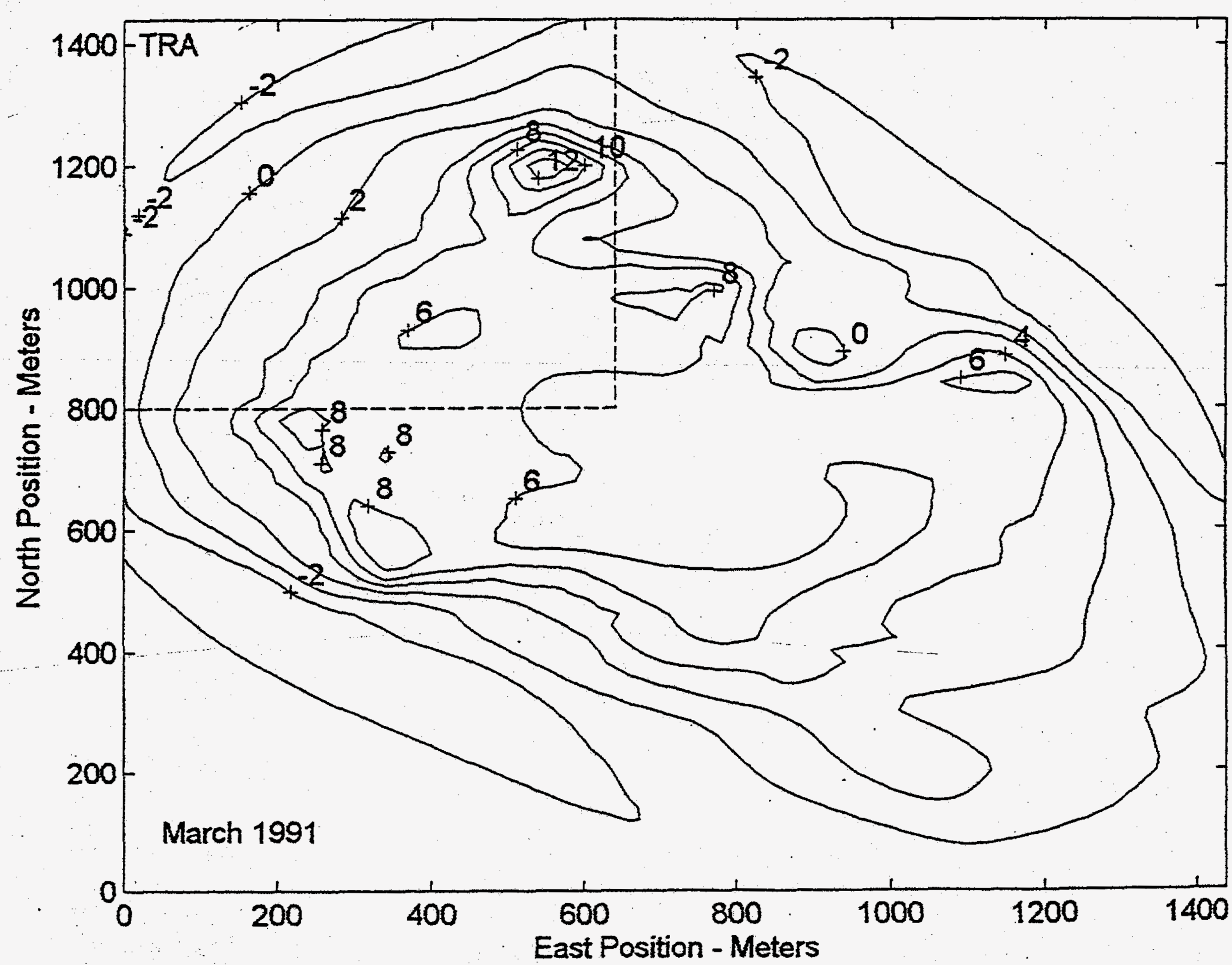

Figure 5. Modeled difference T_{zz} gradient signal for the perched water configuration shown in Figure 3 assuming a porosity of 15%. This image is equivalent to subtracting an initial pre-injection image from an image generated with the March 1991 data.

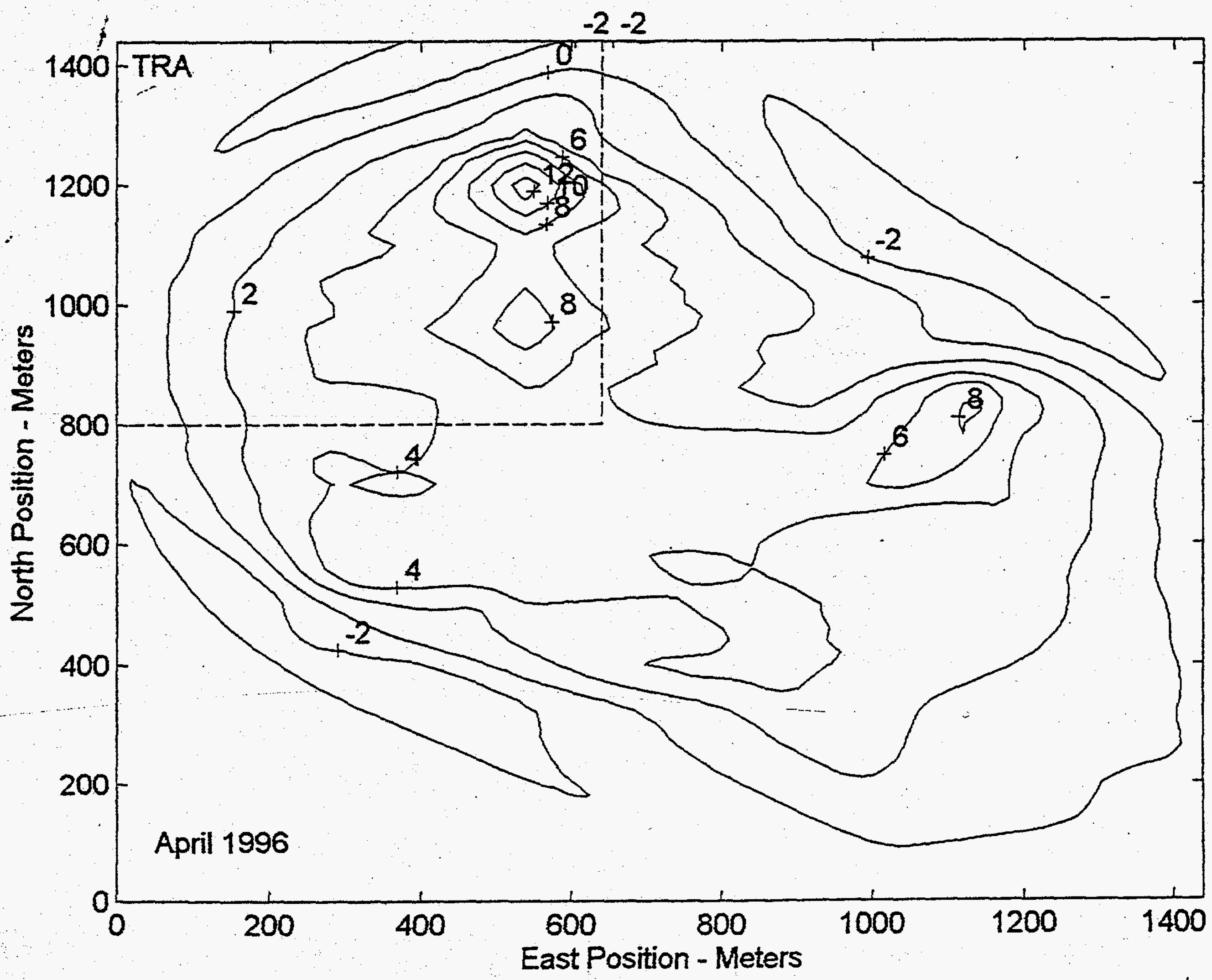

Figure 6. Modeled difference T_{zz} gradient signal for the perched water configuration shown in Figure 4 assuming a porosity of 15%. This image is equivalent to subtracting an initial pre-injection image from an image generated with the April 1996 data.

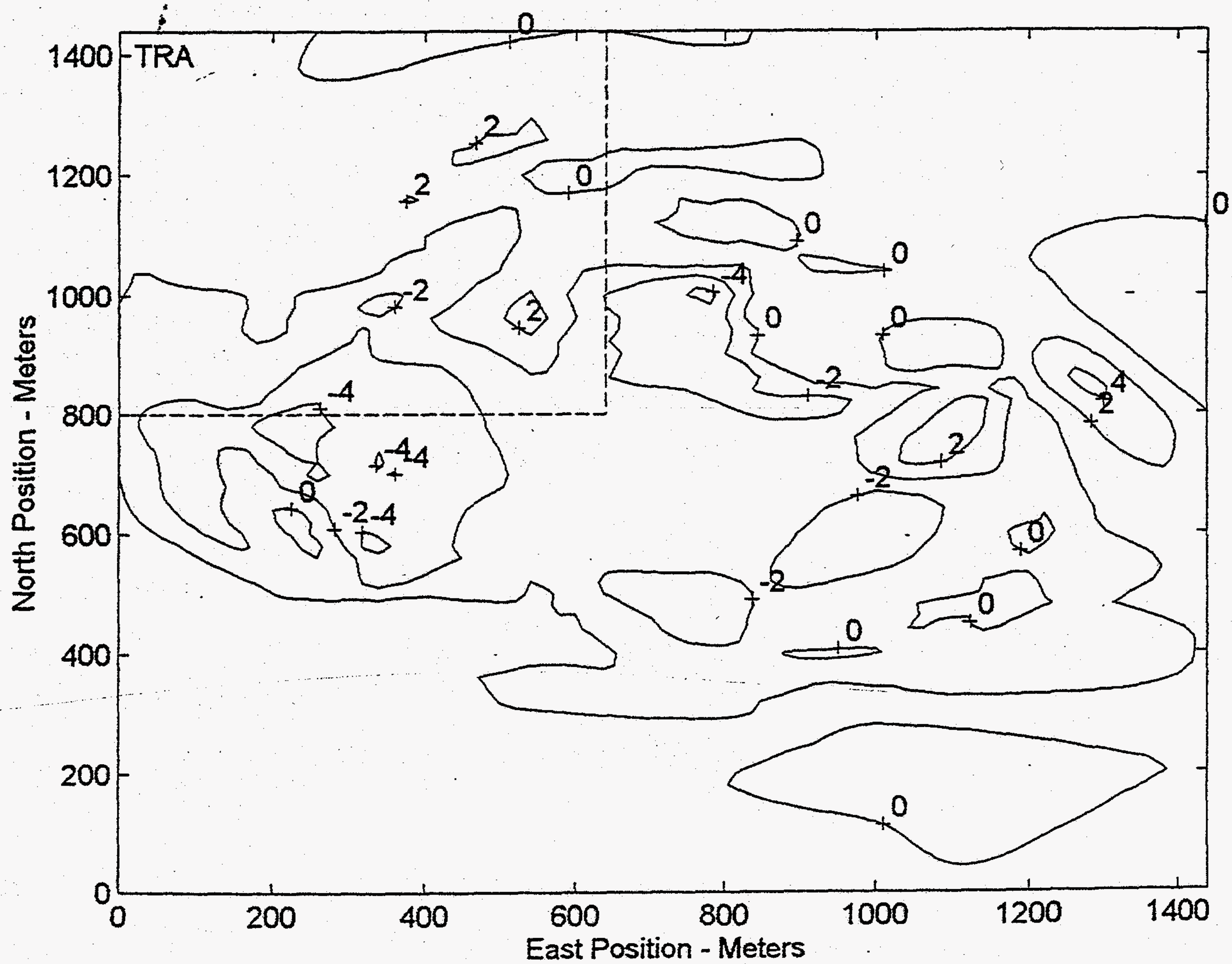

Figure 7. Difference T_{zz} gradient image made by subtracting the values on Figure 5 from those on Figure 6. This is equivalent to the difference signal expected for gradient measurements made over a spreading and declining perched water body.

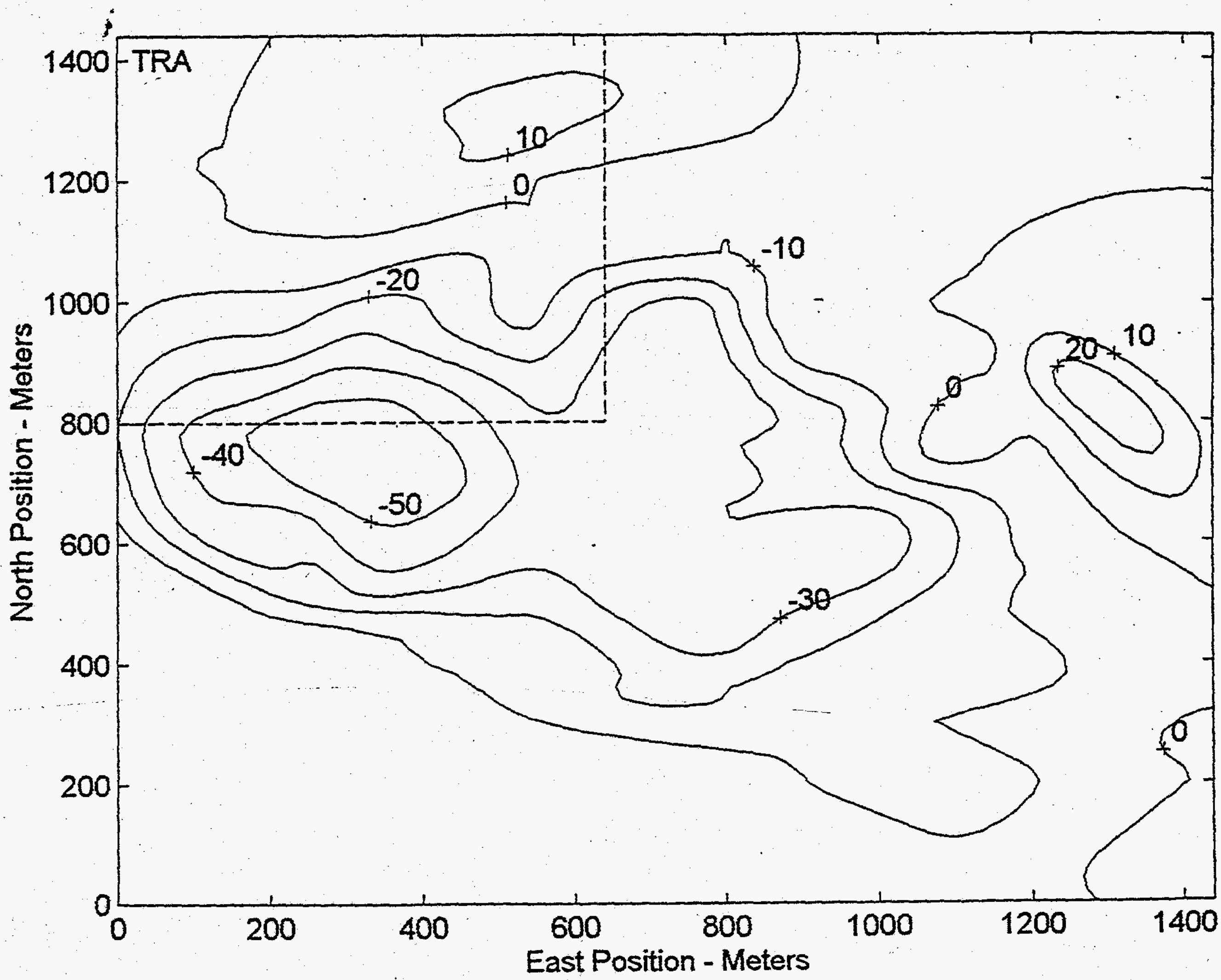

Figure 8. Modeled difference gravity image corresponding to Figure 7. The edges of the anomaly are not as distinct.