ADDENDUM MP-G:

NICHOLS RANCH NUMERICAL GROUNDWATER MODELING

January 2010

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Acronyms and Abbreviations

gpd	gallons per day
gpm	gallons per minute
ID	inner (inside) diameter
ISR	In-Situ Recovery
UZF	unsaturated zone flow
WDEQ	Wyoming Department of Environmental Quality
WY	Wyoming

MPG.1 NICHOLS SITE NUMERICAL GROUND-WATER MODELING

The primary modeling approach used a version of the MODFLOW model to evaluate ground-water flow and drawdown resulting from the planned mining operations. The MODFLOW model was developed by the USGS in 1988 and has been updated and revised several times. MODFLOW-96 (Harbaugh and McDonald, 1996) was used for modeling of the ground-water system at the Nichols Project. The names MODFLOW and MODFLOW-96 are used interchangeably in the remainder of the addendum.

MPG.1.1 Nichols Project Modeling

MODFLOW-96 was used to model the ground-water flow prior to, during and after operation of the wellfield(s). A model grid was developed to cover the proposed mine area with a relatively fine grid (50 foot by 50 foot cells) and extending the modeled area with increased cell size to encompass approximately 5,050 square miles. Injection and production wells were included as well stresses within the fine grid area.

MPG.1.1.1 Model Configuration

The five layer model utilized a confined aquifer type for all five layers, with a series of general head boundaries on the perimeter of the model grid. The initial potentiometric head in each of the five layers was approximated as a uniform gradient across the model grid areas. This surface was developed using the typical gradient of 0.0033 feet/feet and the general gradient is from southeast to northwest. Because the aquifer is confined, no structural information is necessary to define the ground-water system.

On the periphery of the model grid, selected cells were designated as general head boundary cells to stabilize the potentiometric surface. The head in each of the 79 designated general head boundary cells for each layer was set at the initial model head and the cell conductance was set at a relatively high level to provide a generally stable regional potentiometric surface.

MPG.1.1.1.1 Model Grid

The model grid consists of 164 rows by 104 columns and is rotated approximately 35 degrees counterclockwise from the orthogonal directions. The smallest cell dimension is 50 feet by 50 feet, and the largest cell dimension is 73,895 feet by 73,895 feet as shown in Figure MPG.1-1.

The model grid extends beyond the limits of the Wasatch aquifer on the west and southeast sides of the grid and some of the model cells are inactive. Figure MPG.1-2 presents the cells that are inactive, and also shows the initial potentiometric surface used in the modeling.

MPG.1.1.1.2 Aquifer Properties

The primary aquifer properties information used in the model included transmissivity, storage coefficient and vertical conductance. The transmissivity and storage coefficient were distinct for each of the five layers primarily as a function of the typical layer thickness. Three distinct ore zones are identified in layers three, four and five. These ore-bearing intervals are hereafter described as upper, middle and lower ore zones. The transmissivity of layers one, two and four was set at 10.0 ft^2/day (75 gal/day/ft). The transmissivity of layers three and five was set at 8.4

ft^2/day (63 gal/day/ft). The storage coefficient for layer one was set at 6E-05 and the storage coefficient for layer two was set at 5E-05. The storage coefficient of layers three and five was set at 2E-05 and the storage coefficient of layer four was set at 3E-05. These values of storage coefficient were adjusted from the composite storage coefficient for the A sand to reflect the individual sand thicknesses.

The vertical conductance between layers is specified by the term VCONT which is the vertical hydraulic conductivity divided by the thickness between the layers and has units of day^{-1}. Because vertical continuity is profoundly reduced by even a thin layer of low permeability material, the effective values of VCONT primarily reflect the presence of shale and siltstone layers within the sequence of ore bearing sands and sandstones. VCONT was set at 1E-08 day^{-1} for the interface between layers one and two and at 2E-08 day^{-1} for the remaining layer interfaces.

MPG.1.1.1.3 Wellfield Configuration

The proposed mining sequence includes two distinct wellfields with an anticipated mining period of 1½ years for each wellfield. Each wellfield consists of a combination of staggered production and injection wells arranged generally in a line drive layout for the sinuous ore body. Number of wells and well locations is preliminary and may be adjusted with further delineation of the ore bodies. Several model runs were conducted to evaluate horizontal flare, general wellfield operation, and excursion control and retrieval. Model runs and wellfield configuration for the horizontal flare evaluation are described in a following section. For the purposes of presentation, both wellfields are shown with a bounding line for the upper, middle, and lower ore zones in Figures MPG.1-3, MPG.1-4, and MPG.1-5, respectively. The middle ore zone represents the largest ore body within the project area for both wellfield #1 and wellfield #2.

MPG.1.1.1.4 Operational Parameters

The anticipated production rates from the wellfield #1 wells range from 15.8 to 15.9 gpm. A total of 221 production wells were included in the full wellfield #1 operation with 62 wells in the upper ore zone, 115 wells in the middle ore zone, and 44 wells in the lower ore zone. Total production rate was 3,507 gpm. Injection well operational rates ranged from 5.5 to 28.2 gpm with a total of 266 injection wells, with 81 wells in the upper ore zone, 128 wells in the middle ore zone, and 57 wells in the lower ore zone. Excess production or bleed rate was set at 1% of total production with a resulting injection rate of 3,472 gpm.

The anticipated production rate from the wellfield #2 wells is 21.3 gpm. A total of 164 production wells were included in the full wellfield #2 operation with 25 wells in the upper ore zone, 99 wells in the middle ore zone, and 40 wells in the lower ore zone. Total production rate was 3,500 gpm. Injection well operational rates ranged from 9.5 to 39.9 gpm with a total of 183 injection wells, with 28 wells in the upper ore zone, 111 wells in the middle ore zone, and 44 wells in the lower ore zone. Excess production or bleed rate was set at 1% of total production with a resulting injection rate of 3,465 gpm.

MPG.1.1.1.5 Stress Periods

Numerous stress periods were included to allow comparison of predicted aquifer response to the wellfield operations at several times during the simulation period. A transient simulation also requires very small computational time steps after each significant change in aquifer stresses including startup or shutdown of well operation. This is necessary to prevent a failure to converge in the model computation. The initial stress period and time steps were set at a very small value (0.0001 day with 5 time steps) to produce a model output result that essentially reflects initial head conditions. The stress period lengths were then gradually increased until there was a significant change in model stresses, at which the sequence reverted to a short stress period followed by gradually increasing stress period lengths. A total of 11 stress periods were used in a total simulation period of six years which included 1.5 years of operation of each wellfield followed by a three year period of post-mining recovery.

MPG.1.1.2 Model Results

The MODFLOW model produces output in terms of predicted drawdown or predicted head at selected times within the simulation. The drawdown or water-level rise is calculated as the difference between head at a selected time and the initial head for the aquifer at the start of the simulation. Both results are useful in the interpretation of aquifer response to the mining and are used to evaluate the modeling predictions.

MPG.1.1.2.1 Wellfield #1

The configuration for wellfield #1 is a combination of wells in the upper, middle and lower ore zones as shown in Figures MPG.1-3, MPG.1-4 and MPG.1-5. Because the generally sinuous ore bodies are in the same area, there may be up to three wells completed in a single planar cell. The modeled potentiometric surface for all layers prior to the start of mining is presented Figure MPG.1-2. The mining operation of the production and injection wells is expected to continue for 18 months, after which mining of wellfield #2 begins. Figure MPG.1-6 presents the predicted drawdown contours for layer four of wellfield #1 after one year of operation, with the production from this layer is over one-half of the total wellfield production. Hence, the propagation of drawdown for this layer represents the maximum ground-water impact for the three-layer wellfield operation after one year. Figure MPG.1-7 presents the predicted water-level elevation contours for layer four of wellfield #1 after one year of operation. The operation of the wellfield at a bleed rate of 1% of the planned 3,500 gpm production rate (1,821 gpm expected production from layer four) has resulted in development of a significant cone of depression around the operating wellfield. The area of gradient reversal in layer four extends approximately 3,000 feet to the northwest of wellfield #1.

Figure MPG.1-8 presents the predicted potentiometric surface for the upper (layer three) ore zone at the end of mining for wellfield #1. On the northwest side of the wellfield, the zone of gradient reversal extends more than 1,000 feet beyond the wellfield, and the potentiometric surface is generally convergent to the operating wellfield. Figure MPG.1-9 presents the predicted potentiometric surface for the lower (layer five) ore zone at the end of mining for wellfield #1. Like the upper and middle ore zones, there is a significant area of gradient reversal on the northwest side of the wellfield that is similar in extent to that of the middle ore zone reversal.

MPG.1.1.2.2 Wellfield #2

Wellfield #2 also consists of injection and production wells in the upper, middle and lower ore zones as shown in Figures MPG.1-3, MPG.1-4 and MPG.1-5. The operation of wellfield #2 will begin after mining is completed in wellfield #1. In wellfield #2 the expected middle zone production constitutes 2,113 gpm of the total three layer wellfield production rate of 3,500 gpm. Figure MPG.1-10 presents the predicted potentiometric surface after 18 months of operation in wellfield #2. The area of gradient reversal to the northwest of the wellfield extends more than 4,000 feet from the wellfield.

Figure MPG.1-11 presents the predicted potentiometric surface for the upper (layer three) ore zone at the end of mining for wellfield #2. On the northwest side of the wellfield, there is a substantial area of gradient reversal. Figure MPG.1-12 presents the predicted potentiometric surface for the lower (layer five) ore zone at the end of mining for wellfield #2. Like the upper and middle ore zones, there is a significant area of gradient reversal on the northwest side of the wellfield.

MPG.1.1.2.3 End of Mining

The end of mining water level changes are reflected in Figures MPG.1-10, MPG.1-11 and MPH.1-12 as described in the previous section. The planned Nichols area ISR project includes two adjacent wellfields operated in sequence for a period of 18 months per wellfield. The area of the wellfields is similar, but wellfield #1 has a larger number of operating wells. The majority of the production is in the middle ore zone (layer four) for both wellfields, but is a larger fraction of the total production for wellfield #2. Hence, the largest cone of depression for the mining operation occurs in the middle ore zone at the end of 18 months of operation of wellfield #2 (see Figure MPG.1-10).

MPG.1.1.2.4 Extent of Drawdown

The drawdown in the middle ore zone at the end of mining is presented in Figure MPG.1-13. The middle ore zone represents more than one-half of the total wellfield production, and when the proportioning of the aquifer storage to the ore sand thickness is considered, this ore zone represents the maximum drawdown impact on the aquifer. The extent of the drawdown is very similar to that produced by the analytical modeling with a five foot drawdown contour extending approximately 4.9 to 5.1 miles from the central mining area. The drawdown cone for the MODFLOW modeling is slightly elongated in the north/south direction to correspond with the general wellfield orientation, while the results from the analytical modeling are generally symmetrical. For the purposes of evaluating regional ground-water impacts of mining, the results of the two models are very similar and both are representative of predicted ground-water response.

MPG.1.2 Horizontal Flare Evaluation

Horizontal flare around the operating well field was evaluated by modeling transport of a generic solute that was introduced into the injection wells. The MODFLOW results for a selected ore zone within wellfield #1 were used as a basis for simulating flare of the lixiviant in the operating wellfield. The MT3DMS model is an update of the MT3D (Zheng, 1992) contaminant transport model.

MPG.1.2.1 MT3DMS Modeling

The MT3DMS model is a convection-dispersion equation (CDE) based model that utilizes ground-water flow output from the MODFLOW model to simulate solute transport. This is accomplished using a routine in MODFLOW that produces a transfer file that includes cell by cell flow terms. This transfer file is then read by MT3DMS, and the solute transport processes are "superimposed" on the ground-water flow. The MT3DMS has features for solute adsorption, retardation, transformation, degradation, etc., but for this application, the solute was assumed to be conservatively transported and these features were not used.

In order to evaluate the flare, a generic solute was used with an elevated concentration of the lixiviant injectate. The ratio of lixiviant concentration to background concentration was 5, and the background concentration was set at 1.0 for simplicity. The lixiviant concentration was set at 5.0, and the increase in concentration in the area surrounding injection wells was used as the indicator of flare. Because the solute was generic and the magnitude of concentration changes is used to quantify flare, the units of concentration do not affect the evaluation.

MPG.1.2.1.1 Transport Model Configuration

The model grid, dimensions, and layout are the same as those established in the MODFLOW-96 modeling.

MPG.1.2.1.2 Wellfield Configuration

The wellfield utilized in the MODFLOW-96/MT3DMS modeling was limited to the middle ore zone of wellfield #1, This subset of wellfield #1 included 115 production wells operating at a rate of 15.84 gpm, and 128 injection wells operating at a rate averaging 14.1 gpm. There was a 1% bleed in the well field operation with a resulting net extraction stress of approximately 18 gpm. The wells included in the horizontal flare modeling are shown along with the approximate area of the identified ore body (light green shading) in Figure MPG.1-15.

MPG.1.2.1.3 Stress Periods

Because MT3DMS and MODFLOW are coupled through a transfer file, the stress periods for MT3DMS are the same as those used in MODFLOW. A modeling period of 120 days was used in the interpretation of horizontal flare. This modeling period was selected as being sufficient to allow establishment of pseudo steady-state solution flow paths and gradients within the operating wellfield, while being a short enough period that the increased gradient reversal with longer operation will not appreciably change or reduce the flare zone.

MPG.1.2.1.4 MT3DMS Inputs

For confined aquifers, there is no thickness defined in the inputs for the MODFLOW modeling. For the MT3DMS model, the thickness of the upper two layers was estimated at 15 feet for each layer, and the thickness of the lower three layers was set at 10 feet for each layer. The effective porosity of the ore zone was estimated at 10%. The dispersivity was set at 10 feet, but it is not considered a critical factor because ISR mining is primarily a pseudo steady-state convection dominated process. The diffusion coefficient was set at zero. As discussed previously, the background generic solute concentration was set at one, with a lixiviant injectate concentration of five.

MPG.1.2.2 Model Results

The development of the drawdown around the operating wellfield area with the 120 day simulation period results in gradient reversal to the wellfield. Figure MPG.1-14 presents the predicted potentiometric surface for the horizontal flare wellfield operation. There is a zone of gradient reversal extending around the ore body after 120 days of operation.

The MT3DMS simulation utilized the ground-water flow predictions from MODFLOW-96 to simulate the transport of the generic solute from the injection wells to the production wells. The results of this simulation are presented in Figure MPG.1-15 as concentrations centered around the operating injection wells. The contour interval is 0.5 units, and the outer contour is 1.5 times the natural background concentration of the aquifer. This is interpreted as a concentration change representing the extent of the lixiviant flare. In the model cells containing an active injection well, the concentration approaches the injectate concentration of five.

MPG.1.2.2.1 Flare Evaluation

As shown in Figure MPG.1-14, the lixiviant does flare beyond the boundary of the ore body. This horizontal flare is quantified as the ratio of the area contacted by the injectate to the area of the ore body under wellfield pattern. The area contacted by the injectate is represented by the contour line where there is a 0.5 unit concentration increase over the background concentration of 1.0. The ratio of the area within the 1.5 concentration contour to the area of the ore body within the well pattern is 1.19 and this is considered the horizontal flare factor. This flare factor is within the expected range of horizontal flare. There will also be a degree of vertical flare, and the composite flare factor of 1.45 includes both vertical and horizontal flare.

MPG.1.3 Excursion Control and Retrieval

The potential for excursion was considered in a MODFLOW-96 modeling scenario by adjusting modeling parameters to produce a temporary and local imbalance in wellfield operation. The imbalance involves either insufficient production rate or excess injection rate for a local area such that the local bleed rate is zero or actually negative representing more injection than production. Limiting this condition to a local area of a few wells is considered appropriate because a wider scale imbalance with insufficient bleed is unlikely given continuous monitoring of production and injection rates.

Simulation of retrieval of an excursion is essentially a reversal of the process that created the excursion. Increasing the effective bleed rate for a local area will increase the local drawdown and cause an expansion of the area of gradient reversal. Within this zone of gradient reversal, ground water will be flowing to the production wells and any ground water that has been impacted by mining fluids will be retrieved.

MPG.1.3.1 MODFLOW Modeling Changes

The MODFLOW-96 modeling configuration described in Section MPG.1.1.1 was used for the simulation of excursion and retrieval. The model included operation of wellfield #1 with adjustment of production rates from two wells in the middle ore zone to create a local imbalance resulting in excursion, followed by overproduction to affect retrieval. In the simulations, the rate adjustments were preceded by a period of normal wellfield operation.

The wellfield operation simulation included a 60 day period of normal operation with a 1% bleed rate followed by a period of local imbalance. In order to simulate a local imbalance, the extraction rate for two middle ore zone production wells in the south-central portion of the wellfield was reduced by 5.2 gpm/well for a 60 day period. This was followed by a 60 day stress period in which the extraction rate for the two designated wells was increased by 5.2 gpm/well. This is a significant change in the well production rate for the two wells, but only resulted in a wellfield bleed rate range of 0.7 to 1.3% of total wellfield production. The rates and operation for all other wells was unchanged from the previous simulations.

MPG.1.3.2 60 Day Excursion and Retrieval Simulation

The results of a MODFLOW-96 simulation of 60 days of normal wellfield operation are presented in Figure MPG.1-16. The cone of depression around the wellfield is expanding, and on the potentiometric surface is generally convergent to the wellfield. At the end of the initial 60 day period, the production rates were reduced for two wells within the area indicated in Figure MPG.1-17. At the end of 60 days with this local imbalance, there is a significant zone where gradient reversal has been lost on the west side of wellfield #1. This area where there is a potential excursion is over 800 feet wide and extends a distance of more than 1,200 feet from the wellfield (see Figure MPG.1-17). The reduction of production rates for this simulation has resulted in significant gradient away from the wellfield and significant potential for excursion. Based on the surface presented in Figure MPG.1-17, the potential excursion of mining fluids would be spread over a width that is much larger than the planned spacing for monitoring ring wells. Figure MPG.1-18 presents the potentiometric surface after an additional 60 day stress period with increased well production rates to offset the period of excursion. A strong gradient reversal has been regained and extends over 1,000 feet to the west of the wellfield. This indicates that retrieval will be effective, and could occur at moderate rates under strong gradients.

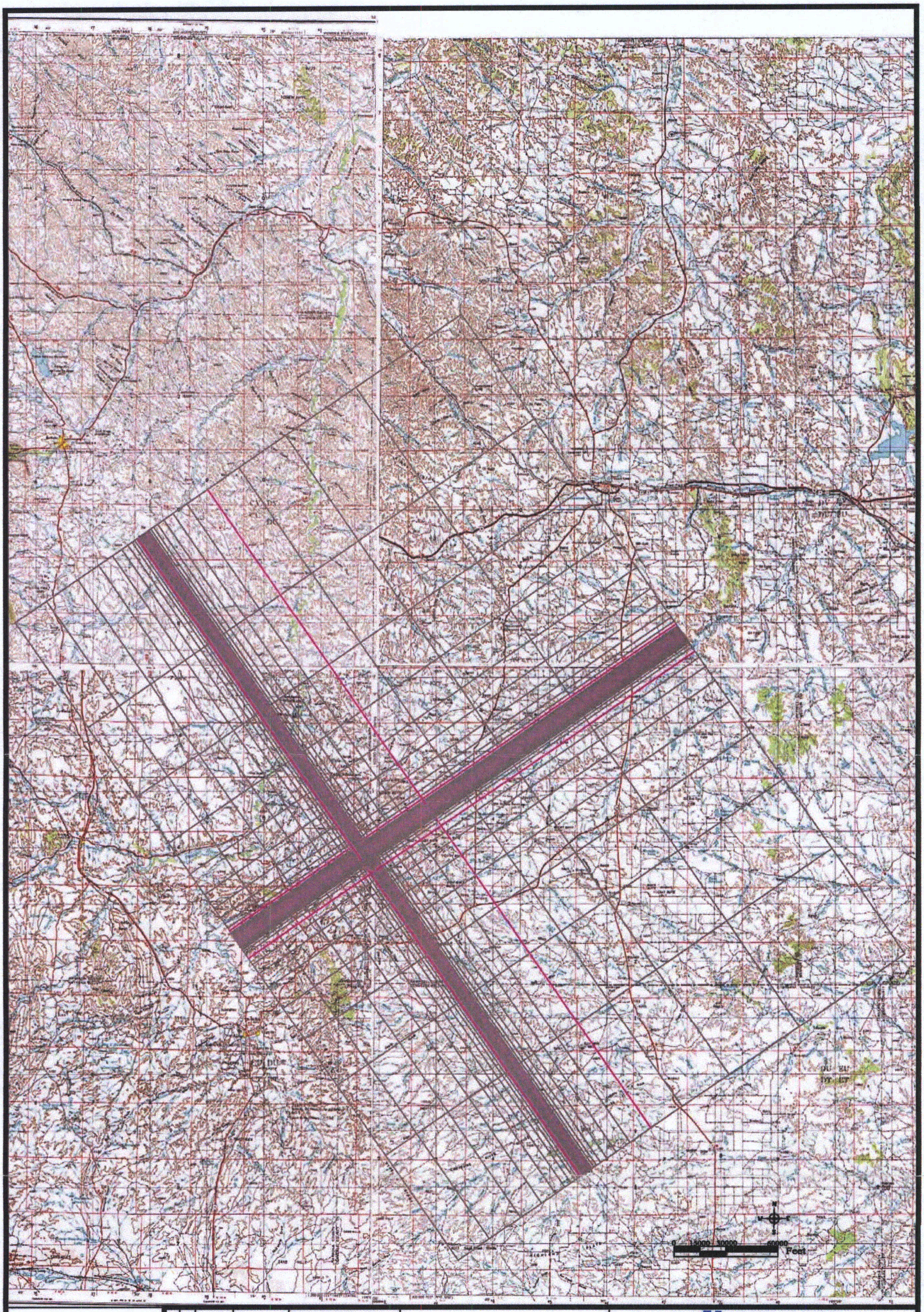
MPG.1.3.3 Discussion of Excursion Simulation

The excursion and retrieval simulations indicate that potential excursion conditions will be produced under local but rather severe wellfield imbalances. The confined aquifer conditions contribute to relatively rapid changes in gradients and gradient reversal with imbalance or overproduction. The width of the zone over which gradient reversal is lost is also relatively wide at over 800 feet. Mining fluids that are migrating away from the active wellfield will be spread over a width that is approaching the width of the area where gradient reversal is lost, and there will be additional flare as the impacted ground water moves away from the wellfield. This indicates that the anticipated monitoring ring well spacing of 500 feet will be sufficient to detect potential excursions.

MPG.2 REFERENCES

Harbaugh, A.W., and M.G. McDonald, 1996, User's Documentation for MODFLOW-96, an update to the U.S. Geological Survey Modular Finite-Difference Ground-Water Flow Model, U.S. Geological Survey Open-File Report 96-485, Reston Virginia.

Zheng, C., 1992, MT3D, A Modular Three-Dimensional Transport Model, Version 1.5, Documentation and User's Guide, S.S. Papadopulos & Associates, Inc.



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Nichols Project Area
Modflow Model Grid

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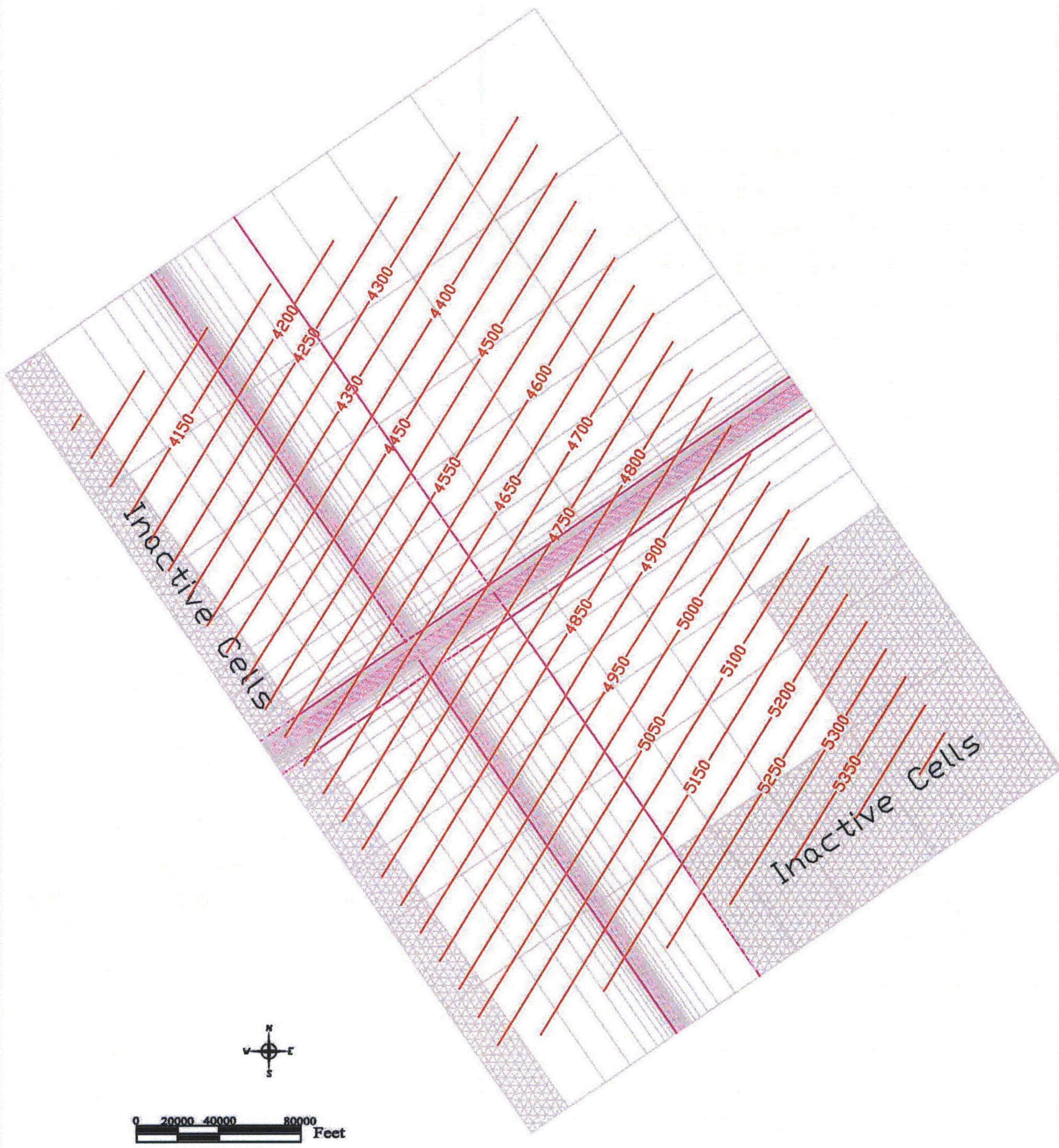
Figure MPG.1-1. Nichols Project Area Modflow Model Grid



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General Potentiometric Surface and Active Model Cells

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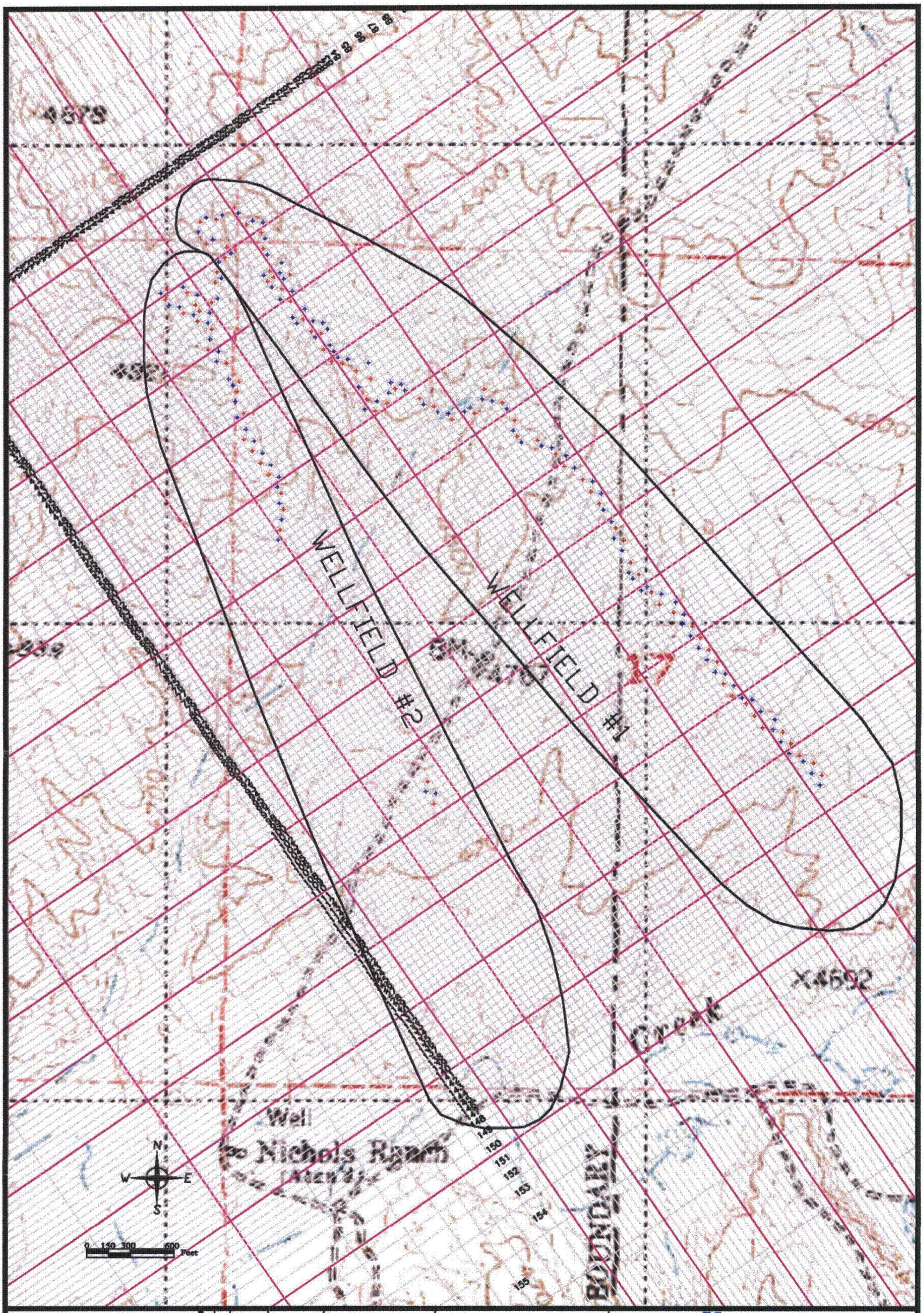
Figure MPG.1-2. General Potentiometric Surface and Active Model Cells



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Injection Well
Extraction Well

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Nichols Upper Ore Zone Model Configuration

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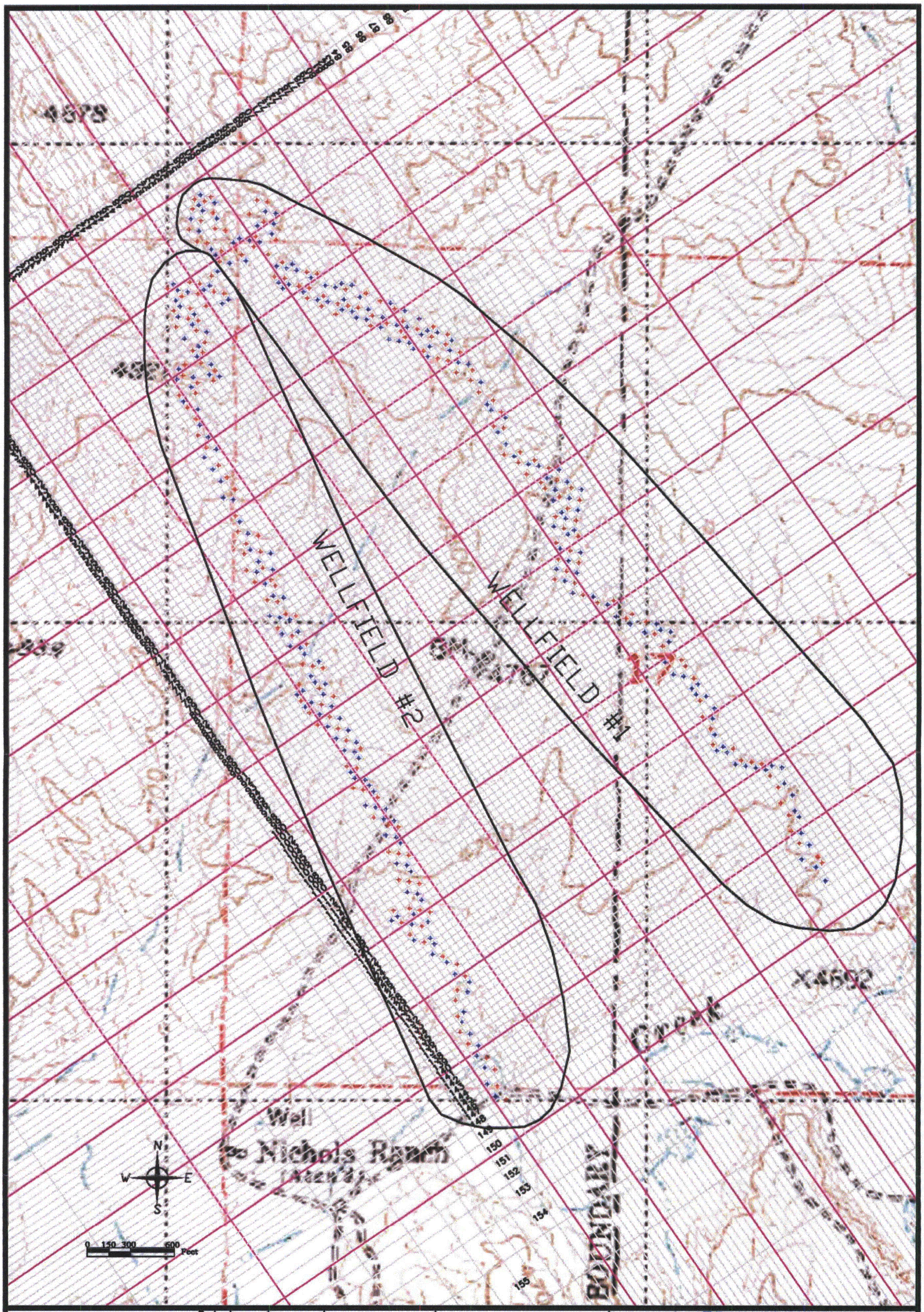
Figure MPG.1-3. Nichols Upper Ore Zone Model Configuration



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Nichols Middle Ore Zone Model Configuration

Figure MPG.1-4. Nichols Middle Ore Zone Model Configuration

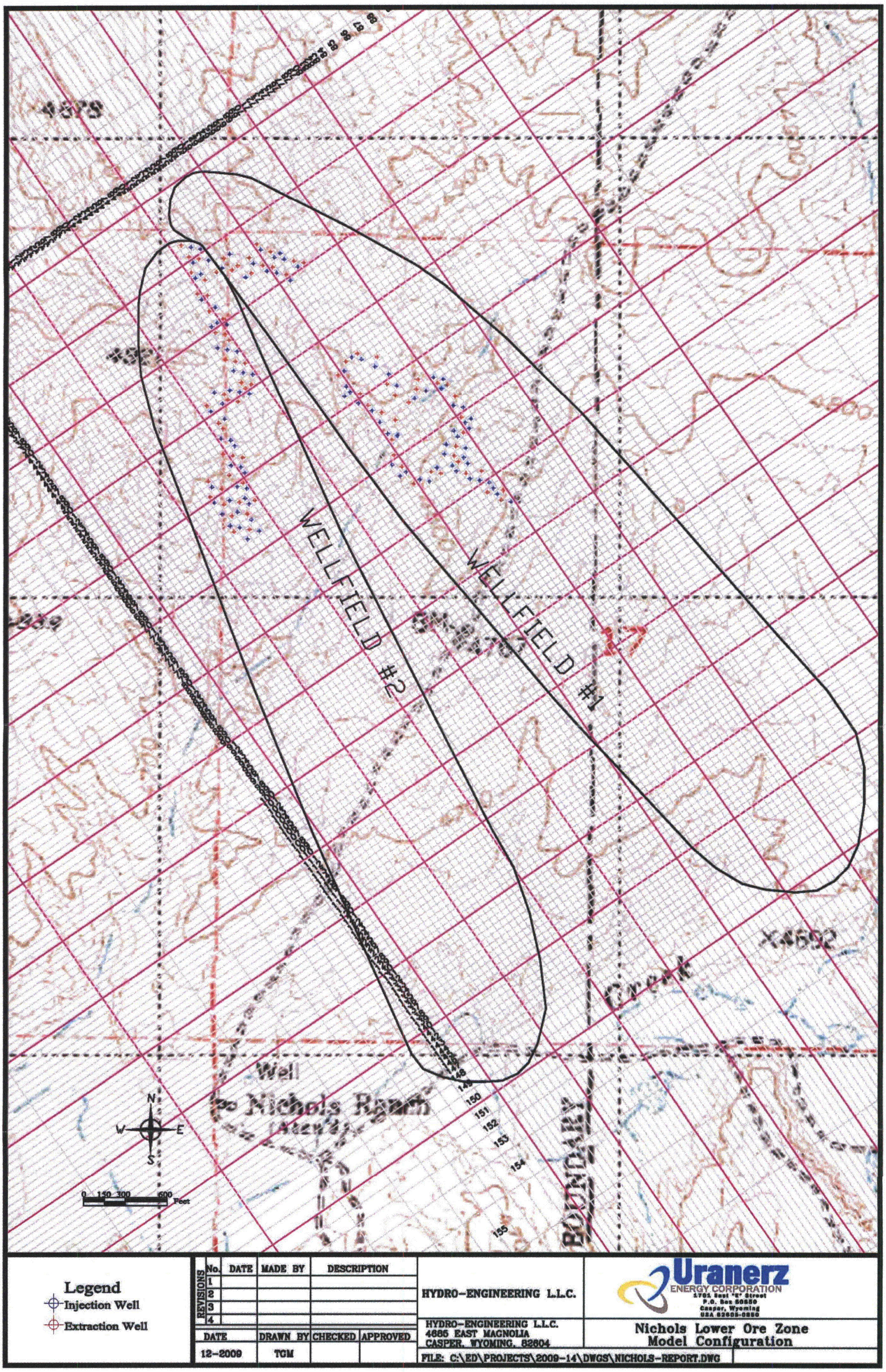

Figure MPG.1-5. Nichols Lower Ore Zone Model Configuration

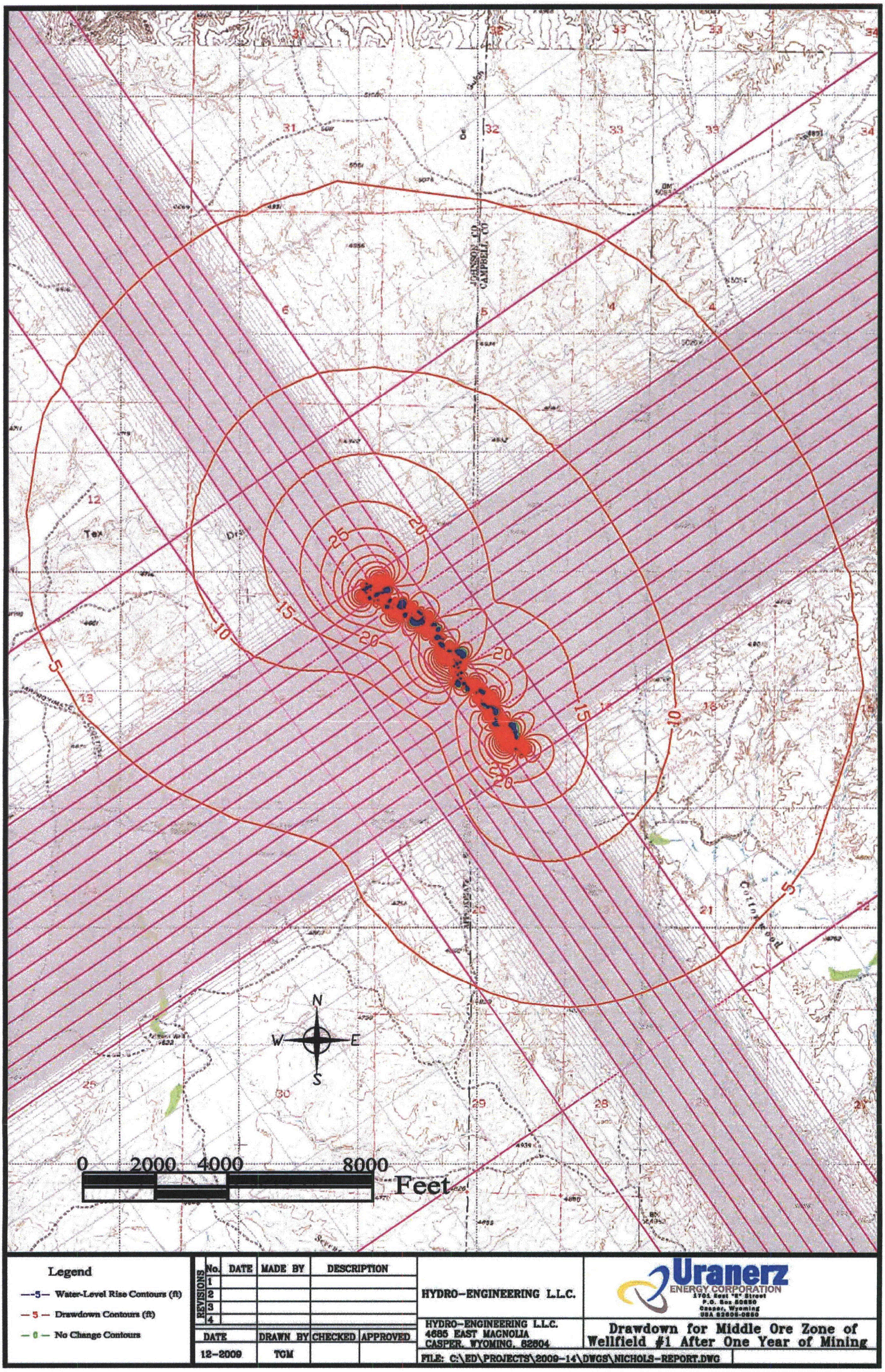

Figure MPG.1-6. Drawdown for Middle Ore Zone of Wellfield #1 After One Year of Mining

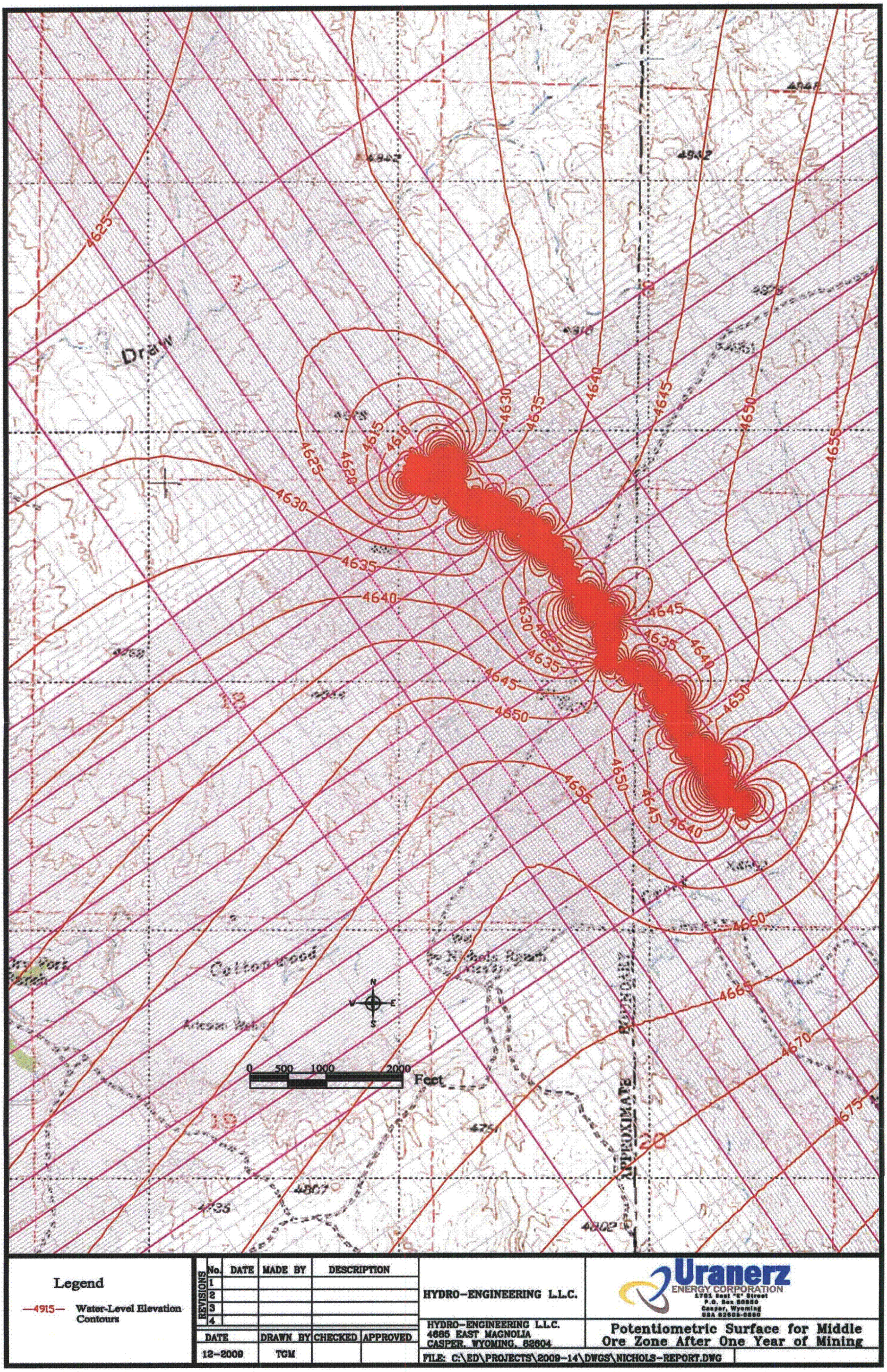

Figure MPG.1-7. Potentiometric Surface for Middle Ore Zone After One Year of Mining

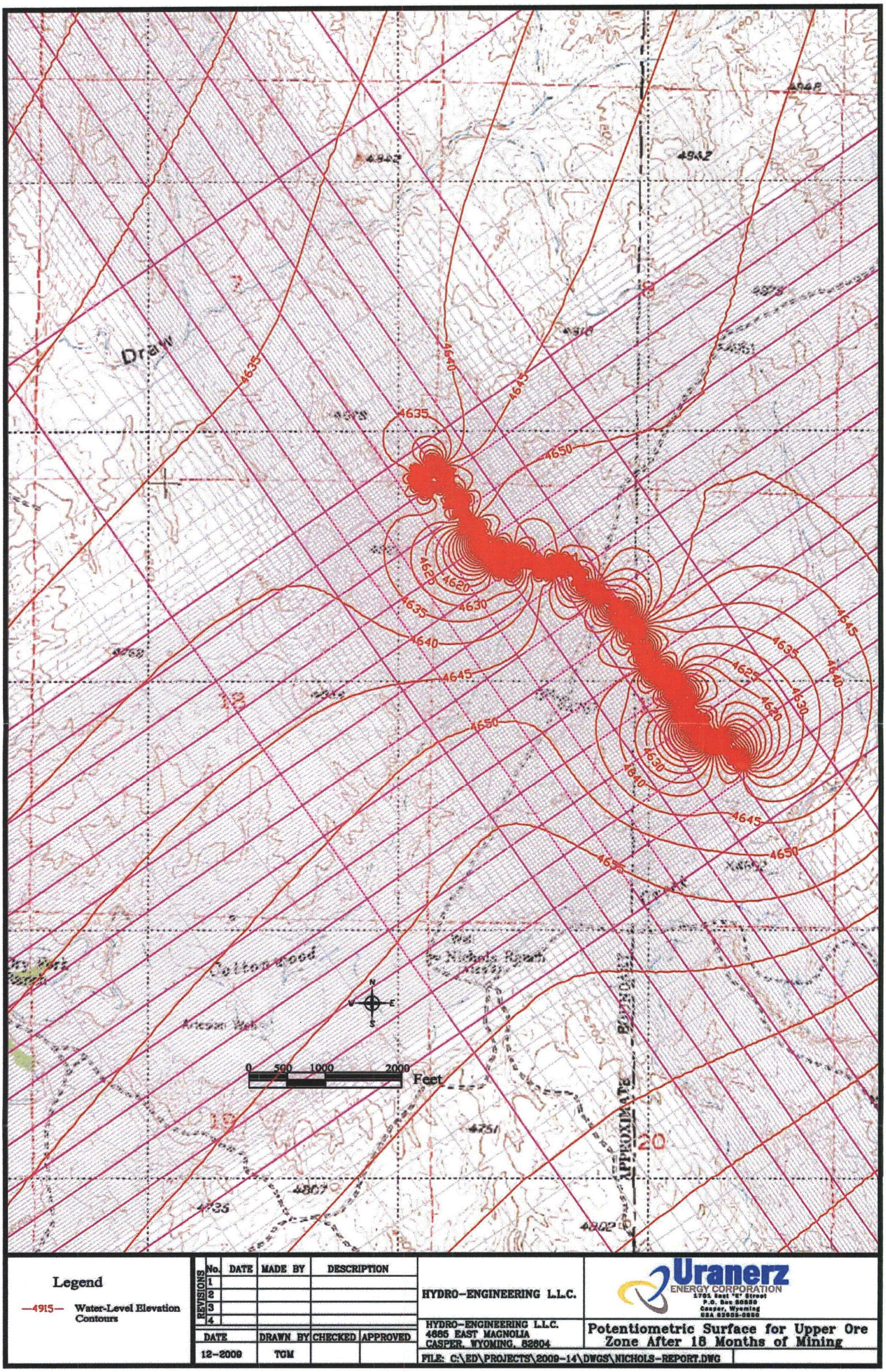

Figure MPG.1-8. Potentiometric Surface for Upper Ore Zone After 18 Months of Mining

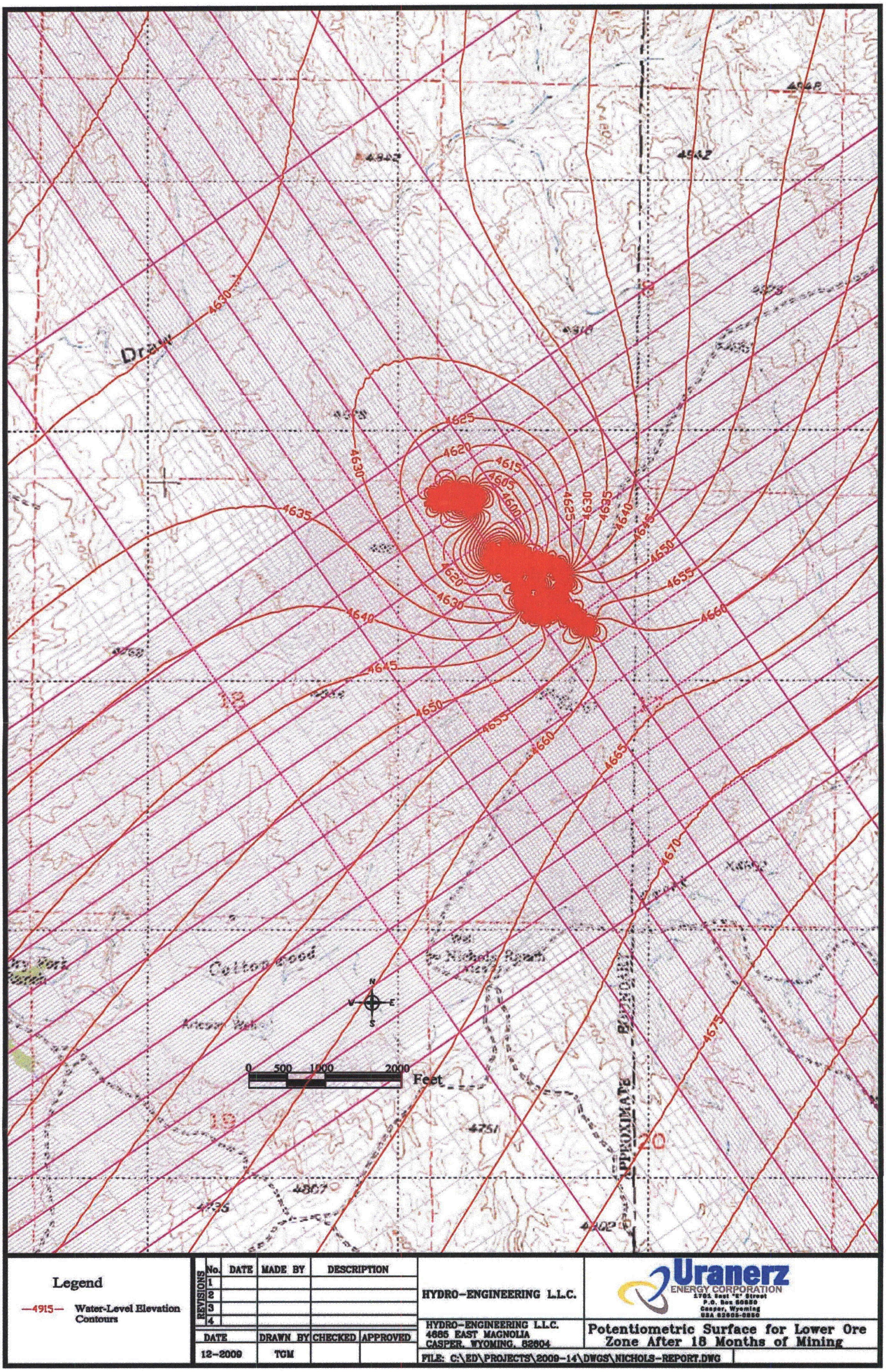

Figure MPG.1-9. Potentiometric Surface for Lower Ore Zone After 18 Months of Mining