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EcoNomics

Wellfield Restoration Modeling
Crow Butte Resources Mine Units 2-5

Cameco Resources, Crow Butte Operations
Crawford, Nebraska

19 February 2009

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INTRODUCTION

This report summarizes results of wellfield restoration modeling conducted at Crow Butte Resources Mine Units 2-5. The purpose of the modeling was to assist Cameco with restoration planning by optimizing the restoration plan for each Mine Unit (MU). To accomplish this objective, a three-dimensional groundwater flow model of the Crow Butte permit area and surrounding region was developed for the purpose of optimizing restoration well locations, injection and extraction rates, and the overall restoration sequence for each Mine Unit.

GROUND WATER FLOW MODEL

Groundwater flow at the Crow Butte facility was simulated using MODFLOW2000[1], a three-dimensional groundwater flow model developed by the United States Geological Survey. The model domain covers an area of approximately 56 square miles and includes the entire current Crow Butte license area (Figure 1). The flow model grid consists of 374 rows, 313 columns, and 6 layers. The grid spacing varies from 25-feet in the vicinity of mine units to approximately 2000 feet in areas outside the current license boundary.

Boundary Conditions

The basal Chadron Sandstone, or mined interval, was divided into three layers (4, 5 and 6) to accommodate the roll-front geometry of the ore deposits and variable well construction (open/mined interval). The overlying alluvial sands, Brule Formation, and Chadron Formation clays are represented by shallow layers 1, 2 and 3, respectively.

Boundary conditions for the groundwater flow model were developed from pre-mining water level data collected as part of the original Crow Butte permit application, in conjunction with regional water level data compiled by the U.S. Geological Survey and University of Nebraska-Lincoln (Figure 2). These data indicate groundwater flows from recharge/outcrop areas south of the site in a north-northwest direction through the permit area. Groundwater in the shallow alluvial aquifer and Brule Sand aquifer discharges locally at the White River near Crawford. Groundwater in the basal Chadron Sandstone discharges at outcrop locations north of Crawford and in the White River valley northeast of the model area.

Groundwater flow is constrained by streamline (no flow) boundaries on the eastern and western model boundaries. Groundwater inflow from outcrop areas are specified as Constant Head boundaries along the southern model boundary. Groundwater discharge or outflow is simulated by Constant Head boundaries to the north of the license area.

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[1] Harbaugh, A. W., Banta, E. R., Hill, M. C., and McDonald, M. G. (2000). MODFLOW-2000, The U.S. Geological Survey Modular Groundwater Flow Model – User Guide to Modularization Concepts and the Ground-water Flow Process, U.S. Geological Survey Open File Report 00-92.

Aquifer Properties

Information concerning the aquifer properties of the basal Chadron Sandstone, including hydraulic conductivity, porosity, and storativity were obtained from four aquifer test reports prepared as part of the mine unit permit applications. Information concerning the porosity of the basal Chadron Sand, and the vertical hydraulic conductivity of the overlying Chadron Formation and underlying Pierre Shale were obtained from core testing data summarized in the aquifer test reports. In general, the basal Chadron Sandstone is fairly uniform, with hydraulic conductivity varying by less than a factor of four (from 7 to 27 ft/day) across the entire license area, with an average conductivity of approximately 9 ft/day. Porosity of the basal Chadron Sandstone varies from approximately 0.25 to 0.29. Groundwater recharge to the basal Chadron Sandstone is limited to leakage of groundwater from the overlying Chadron Formation clays and the underlying Pierre Shale of very low permeability.

Flow model calibration

Model calibration is the process whereby aquifer properties and boundary conditions are adjusted over a reasonable range of values in order to obtain a close match between modeled and observed conditions (water levels and flows). Flow model calibration is necessary for a model to produce reliable results and make predictions with a reasonable degree of confidence.

The groundwater flow model was calibrated to pre-mining conditions using water level data collected prior to the mining activities in January of 1983. Initial estimates of aquifer properties and boundary water levels were adjusted slightly as part of the model calibration process in order to achieve the best possible match between observed and simulated water levels. Adjustments were primarily confined to constant head elevations along the southern model boundary.

Results of the flow model calibration are provided in Table 1 and Figure 2. A contour map showing the calibrated water level elevation in the Basal Chadron Sand is provided in Figure 3.

WELLFIELD RESTORATION

The calibrated groundwater flow model was used to optimize restoration in MU2-MU5 given certain practical limitations on treatment rate, disposal capacity, and existing well injection and extraction rates. Restoration is planned to proceed in general accordance with permit conditions, to involve recovery of affected groundwater, treatment by Ion Exchange (IX) and Reverse Osmosis (RO), and injection of RO permeate into the wellfield.

Restoration Constraints

Wellfield restoration simulations were largely constrained by the Reverse Osmosis treatment rate, which limits the maximum injection rate available for restoration. Current sustainable RO treatment capacity is estimated to be 500-600 gpm with approximately 75% efficiency (25% bleed for disposal), with some additional decrease in treatment rate due to downtime for maintenance. Based on these estimates, a 400 gpm target RO treatment/injection rate was assumed for purposes of restoration simulations.

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Conceptual Restoration Objectives

Because of the close proximity of neighboring mine units at the Crow Butte facility, bleed rates of 2-5% (typically less than 20 gpm per restoration unit at 400 gpm treatment/injection rate) are considered optimal. This will ensure a sufficient area is treated, and should also ensure that neighboring mine units and wellfields are not negatively influenced by restoration activities.

Restoration Sequence

Restoration was simulated in the following sequence (for practical reasons and based on results of this modeling):

- Phase I – Resume restoration of MU2 (four months)
- Phase II – Resume restoration of MU3, complete restoration of MU2 and enter stabilization (2 months)
- Phase III – Complete restoration MU3, enter stabilization (6 months)
- Phase IV – Restoration of eastern half of MU4, enter stabilization (6 months)
- Phase V – Restoration of western half of MU4, enter stabilization (4 months)
- Phase VI – Restoration of eastern portion of MU5, enter stabilization (6 months)
- Phase VII – Restoration of western portion of MU5, enter stabilization (4 months)
- Phase VIII – Restoration of northern portion of MU5, enter stabilization (6 months)

RESTORATION SIMULATION AND OPTIMIZATION

Methodology

The objective of the wellfield restoration modeling is to find the optimal configuration of injection and extraction wells (number, location, and injection/extraction rate) that achieves maximum treatment in the shortest possible time. To accomplish this objective, the calibrated groundwater flow model was used to simulate groundwater flow, and the particle-tracking model MODPATH[2] was used to determine the area of the wellfield being treated (restored) over time. This process was facilitated by employing an automated well optimization procedure[3] that simulates a large number of possible well configurations and compares the number of particles captured by extraction wells as a means of determining which of the configurations offers the most efficient restoration. Results of the most

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[2] Pollack, D.W. (1994). A Users Guide for MODPATH/MODPATH-PLOT, Version 3; A particle-tracking post-processing package for MODFLOW, the U.S. Geological Survey finite-difference ground-water flow model, U.S. Geological Survey Open File Report 94-464.

[3] Environmental Simulations, Inc (2000). Users Guide for BRUTE FORCE version 2.1, a wellfield optimization program.

promising simulations were compared visually (e.g. by comparison of particle traces) and final modifications were made to ensure an optimal restoration scheme.

Phase I Simulations (MU2)

Phase I wellfield restoration will involve the restoration of MU2. The wellfield configuration that achieved the best overall restoration in the shortest time is illustrated in Figure 4. Optimized well locations and associated injection and extraction rates are provided in Table 2. The optimal configuration includes 18 injection wells and 13 extraction wells operating for four months. This scenario assumes injection of 360 gpm of treated water, with extraction of 365 gpm (1.4% bleed) for treatment.

The distribution of particle traces in Figure 4 demonstrates that more than 90% of the wellfield have been effectively treated over a 4 month simulation period, which corresponds to approximately 3.8 pore volumes treated. Results of this simulation, in conjunction with theoretical considerations, historical restoration data, and the most recent wellfield sampling information (August 2008), suggest that restoration of MU2 should be achieved by the end of the 4 month simulation period.

Phase II and III Simulations (MU3)

Phase II and III wellfield restoration will involve restoration of Mine Unit 3. The wellfield configuration that achieved the best overall restoration in the shortest time is illustrated in Figure 5. Optimized well locations and associated injection and extraction rates for Phase II and III are provided in Table 3. The optimal configuration for Phase II and III includes 21 injection wells and 7 extraction wells in MU3 operating for a total of eight months. This scenario assumes injection of 246 gpm of treated water, with extraction of 218 gpm from wells in MU3. Over-injection of treated water into MU3 is needed to address instability issues in MU1.

The distribution of particle traces in Figure 5 demonstrates that more than 90% of the wellfield have been effectively treated over the 8 month simulation period. This corresponds to approximately 4.4 pore volumes treated for MU3. Results of this simulation and theoretical considerations suggest that restoration of MU3 should be achieved by the end of the 8 month simulation period.

Phase IV Simulations (MU4, Eastern Half)

Phase IV wellfield restoration will involve the restoration of the eastern half of MU4. The wellfield configuration that achieved the best overall restoration in the shortest time is illustrated in Figure 6. Optimized well locations and associated injection and extraction rates for are provided in Table 4. The optimal configuration includes 41 injection wells and 22 extraction wells operating for 6 months. This scenario assumes injection of 396 gpm of treated water, with extraction of 402 gpm (1.5% bleed) for treatment.

The distribution of particle traces in Figure 6 demonstrates that more than 90% of the wellfield have been effectively treated over a 6 month simulation period, which corresponds to approximately 6.0 pore volumes treated. Results of this simulation and theoretical considerations suggest that restoration should be achieved by the end of the 8 month simulation period.

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Phase V Simulations (MU4, Western Half)

Phase V wellfield restoration will involve the restoration of the western half of MU4. The wellfield configuration that achieved the best overall restoration in the shortest time is illustrated in Figure 7. Optimized well locations and associated injection and extraction rates for are provided in Table 5. The optimal configuration includes 24 injection wells and 18 extraction wells operating for 4 months. This scenario assumes injection of 392 gpm of treated water, with extraction of 400 gpm (2% bleed) for treatment.

The distribution of particle traces in Figure 7 demonstrates that more than 90% of the wellfield have been effectively treated over a 4 month simulation period, which corresponds to approximately 4.8 pore volumes treated. Results of this simulation and theoretical considerations suggest that restoration should be achieved by the end of the 4 month simulation period.

Phase VI Simulations (MU5, Eastern Portion)

Due to the large size of MU5 (roughly three times the pore volume size of MU2) it was deemed most efficient to break the restoration of MU5 into three pieces – the eastern portion, western portion, and northern portion – in three separate phases.

Phase VI wellfield restoration will involve the restoration of the eastern portion of MU5. The wellfield configuration that achieved the best overall restoration in the shortest time is illustrated in Figure 8. Optimized well locations and associated injection and extraction rates for are provided in Table 6. The optimal configuration includes 25 injection wells and 13 extraction wells operating for 6 months. This scenario assumes injection of 267 gpm of treated water, with extraction of 272 gpm (1.8% bleed) for treatment.

The distribution of particle traces in Figure 8 demonstrates that more than 90% of the wellfield have been effectively treated over a 6 month simulation period, which corresponds to approximately 4.9 pore volumes treated. Results of this simulation and theoretical considerations suggest restoration should be achieved by the end of the 6 month simulation period.

Phase VII Simulations (MU5, Western Portion)

Phase VII wellfield restoration will involve the restoration of the western portion of MU5. The wellfield configuration that achieved the best overall restoration in the shortest time is illustrated in Figure 9. Optimized well locations and associated injection and extraction rates for are provided in Table 7. The optimal configuration includes 23 injection wells and 17 extraction wells operating for 4 months. This scenario assumes injection of 345 gpm of treated water, with extraction of 351 gpm (1.7% bleed) for treatment.

The distribution of particle traces in Figure 9 demonstrates that more than 90% of the wellfield have been effectively treated over a 4 month simulation period, which corresponds to approximately 4.3 pore volumes treated. Results of this simulation and theoretical considerations suggest restoration should be achieved by the end of the 4 month simulation period.

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Phase VIII Simulations (MU5, Northern Portion)

Phase VIII wellfield restoration will involve the restoration of the northern portion of MU5. The wellfield configuration that achieved the best overall restoration in the shortest time is illustrated in Figure 10. Optimized well locations and associated injection and extraction rates are provided in Table 8. The optimal configuration includes 48 injection wells and 19 extraction wells operating for 6 months. This scenario assumes injection of 353 gpm of treated water, with extraction of 360 gpm (1.9% bleed) for treatment.

The distribution of particle traces in Figure 10 demonstrates that more than 90% of the wellfield have been effectively treated over a 6 month simulation period, which corresponds to approximately 6.5 pore volumes treated. Results of this simulation and theoretical considerations suggest restoration should be achieved by the end of the 6 month simulation period.

Table 1. Flow Model Calibration Statistics, Modeled Vs. Observed Water Levels, January 1983

Name	X	Y	Layer	Observed	Computed	Weight	Group	Residual
well1	1099888	488363.3	4	3756.2	3757.36773	1	1	-1.167727
well2	1096019	493553.4	4	3755.6	3753.98576	1	1	1.614241
well3	1100428	499469.1	6	3752.9	3750.94347	1	1	1.956526
well4	1090531	503450	4	3746.6	3744.82302	1	1	1.776979
well5	1091852	504863.8	4	3746.3	3743.23794	1	1	3.062056
well6	1093359	509812.1	4	3732	3732.69845	1	1	-0.69845
well7	1083525	515355.7	4	3715.2	3717.37891	1	1	-2.178913
well7	1083521	515355.7	6	3715.2	3717.37645	1	1	-2.176447
well7	1083518	515355.7	5	3715.2	3717.37482	1	1	-2.174819
well6	1093359	509812.1	6	3732	3732.69845	1	1	-0.69845
well6	1093359	509812.1	5	3732	3732.69845	1	1	-0.69845
well5	1091852	504863.8	6	3746.3	3743.23794	1	1	3.062056
well5	1091852	504863.8	5	3746.3	3743.23794	1	1	3.062056
well4	1090531	503450	6	3746.6	3744.82302	1	1	1.776979
well4	1090531	503450	5	3746.6	3744.82302	1	1	1.776979
well3	1100501	499469.1	4	3752.9	3750.96849	1	1	1.931508
well3	1100428	499469.1	5	3752.9	3750.94347	1	1	1.956526
well2	1096019	493553.4	6	3755.6	3753.98576	1	1	1.614241
well2	1096019	493553.4	5	3755.6	3753.98576	1	1	1.614241
well1	1099888	488363.3	6	3756.2	3757.36773	1	1	-1.167727
well1	1099888	488363.3	5	3756.2	3757.36773	1	1	-1.167727
Residual Mean						0.622651		
Res. Std. Dev.						1.805186		
Sum of Squares						76.57423		
Abs. Res. Mean						1.777767		
Min. Residual						-2.17891		
Max. Residual						3.062056		
Range in Target Values						41		
Std. Dev./Range						0.044029		

Table 2. Phase I Restoration Simulation Results

MU2 Wells and Rates

Well ID	Well Type	Easting (ft)	Northing (ft)	Rate (gpm)	Duration (days)	Comments
P124i	Injection	1099057	495729	22.2	120	
I155	Injection	1099062	496210	25.0	120	
I133	Injection	1098676	496467	10.0	120	
I142	Injection	1098834	496518	20.0	120	
I131	Injection	1098640	496297	21.0	120	
I153	Injection	1098971	496332	24.0	120	
I143	Injection	1098959	496586	13.0	120	
I169	Injection	1099623	495621	6.0	120	
I170	Injection	1099036	496042	10.0	120	
I177	Injection	1099597	495465	10.0	120	
I184	Injection	1099104	495958	27.0	120	
I197	Injection	1099307	495809	27.0	120	
I198	Injection	1099615	495771	27.0	120	
I202	Injection	1099161	495632	18.0	120	
I206	Injection	1099389	495534	28.0	120	
P117i	Injection	1099101	495816	22.2	120	
P85i	Injection	1098804	496254	22.2	120	
I138	Injection	1099557	495900	27.0	120	
P97	Extraction	1099530	495590	-29.0	120	
P119	Extraction	1099337	495680	-36.0	120	
P83	Extraction	1098832	496385	-30.0	120	
P121	Extraction	1099453	495737	-24.0	120	
P110	Extraction	1099253	495922	-32.0	120	
P112	Extraction	1099435	495999	-11.0	120	
P210	Extraction	1099487	495932	-30.0	120	
P105	Extraction	1099265	496046	-26.0	120	
P98	Extraction	1099152	496158	-30.0	120	
P92	Extraction	1099130	496330	-31.0	120	
P91	Extraction	1099083	496442	-27.0	120	
P88	Extraction	1098939	496417	-29.0	120	
P84	Extraction	1098725	496391	-30.0	120	

Table 3. Phase II and III Restoration Simulation Results

MU3 Wells and Rates

Well ID	Well Type	Easting (ft)	Northing (ft)	Rate (gpm)	Period of Operation (days)	Comments
I270	Injection	1098153	496464	10.0	180	
I271	Injection	1098228	496330	10.0	180	
I299	Injection	1098102	496155	26.0	180	
I318	Injection	1098107	495971	5.0	180	
P254i	Injection	1098129	495776	10.0	180	
I366	Injection	1098285	495496	10.0	180	
I367	Injection	1098166	495501	10.0	180	
I361	Injection	1098047	495549	7.0	180	
I360	Injection	1097923	495594	5.2	180	
I350	Injection	1097797	495640	10.0	180	
I347	Injection	1097603	495592	10.0	180	MU4 Well
I339	Injection	1097419	495636	10.0	180	MU7 Well
I340	Injection	1097432	495780	10.0	180	
I337	Injection	1097401	495855	10.0	180	
I333	Injection	1097401	495988	10.0	180	
I332	Injection	1097469	496036	10.0	180	
I309	Injection	1097429	496205	5.0	180	
I336	Injection	1097549	496264	14.0	180	
I284	Injection	1097648	496425	6.0	180	
I281	Injection	1097777	496360	10.0	180	
I275	Injection	1098027	496492	8.0	180	
P222	Extraction	1098056	496314	-29.0	180	
P228	Extraction	1097831	496239	-45.0	180	
P232	Extraction	1097736	496058	-35.0	180	
P235	Extraction	1097924	496044	-23.0	180	
I343P	Extraction	1097626	495812	-30.0	180	
P259	Extraction	1097904	495809	-36.0	180	
I355P	Extraction	1098114	495699	-20.0	180	

Table 4. Phase IV Restoration Simulation Results

MU4 (East Half) Wells and Rates

Well ID	Well Type	Easting (ft)	Northing (ft)	Rate (gpm)	Period of Operation (days)	Comments
I505	Injection	1099875	495614	9.0	180	
I509	Injection	1099972	495412	35.1	180	
P423I	Injection	1099481	495117	13.3	180	
I591	Injection	1100059	494611	10.4	180	
I594	Injection	1099888	494831	13.3	180	
I596	Injection	1100163	494911	13.3	180	
P376I	Injection	1099211	495569	6.7	180	
P378I	Injection	1099096	495609	6.7	180	
P390I	Injection	1100150	495295	6.7	180	
P403I	Injection	1100667	494642	6.7	180	
P411I	Injection	1100250	494575	6.7	180	
P464I	Injection	1100491	495091	15.6	180	
P469I	Injection	1100733	494490	6.7	180	
I506	Injection	1099975	495539	6.7	180	
I512	Injection	1099655	495408	20.0	180	
I514	Injection	1099256	495451	10.0	180	
I517	Injection	1099327	495420	6.7	180	
I522	Injection	1099025	495607	6.7	180	
I527	Injection	1099397	495129	6.7	180	
I529	Injection	1099201	495338	6.7	180	
I533	Injection	1099838	495178	18.2	180	
I535	Injection	1100326	495145	13.0	180	
I538P	Injection	1100287	494953	15.0	180	
I555	Injection	1100241	495290	6.7	180	
I562	Injection	1100627	494991	5.0	180	
I568	Injection	1100570	494731	18.0	180	
I569	Injection	1100658	494705	6.7	180	
I570	Injection	1100739	494585	6.7	180	
I572	Injection	1100614	494504	6.7	180	
I575	Injection	1100790	494309	6.7	180	
I577	Injection	1100607	494341	6.7	180	
I584	Injection	1100395	494384	6.7	180	
I586	Injection	1100408	494667	15.0	180	
I592	Injection	1100003	494670	6.7	180	
I600	Injection	1099758	495151	7.8	180	
I603	Injection	1099862	494967	5.0	180	
I604	Injection	1099803	494839	6.7	180	
I605	Injection	1099747	494901	6.7	180	
I607	Injection	1099626	494978	6.7	180	
I608	Injection	1099621	495118	5.0	180	
I611	Injection	1099525	495047	6.7	180	

MU4 (East Half) Wells and Rates

Well ID	Well Type	Easting (ft)	Northing (ft)	Rate (gpm)	Period of Operation (days)	Comments
P375	Extraction	1099321	495492	-13.0	180	
P377	Extraction	1099193	495515	-20.8	180	
P398	Extraction	1100579	495021	-23.0	180	
P396	Extraction	1100300	495196	-15.6	180	
P397	Extraction	1100103	495311	-24.0	180	
P372	Extraction	1099684	495583	-20.8	180	
P387	Extraction	1099264	495295	-13.0	180	
P392	Extraction	1100461	494525	-15.0	180	
P404	Extraction	1100581	494584	-22.0	180	
P407	Extraction	1100703	494444	-26.0	180	
P412	Extraction	1100311	494677	-26.0	180	
P413	Extraction	1100169	494634	-15.0	180	
P420	Extraction	1099887	494918	-5.0	180	
P421	Extraction	1099701	494967	-28.0	180	
P422	Extraction	1099595	495046	-15.6	180	
P426	Extraction	1099768	495334	-13.0	180	
P380	Extraction	1099462	495260	-25.0	180	
I504P	Extraction	1099843	495565	-20.0	180	
I539P	Extraction	1100418	494840	-10.4	180	
I598P	Extraction	1100031	494962	-10.4	180	
I599P	Extraction	1099927	495087	-22.0	180	
I544P	Extraction	1100113	494817	-18.5	180	

Table 5. Phase V Restoration Simulation Results

MU4 (West Half) Wells and Rates

Well ID	Well Type	Easting (ft)	Northing (ft)	Rate (gpm)	Period of Operation (days)	Comments
I612	Injection	1097753	495600	27.0	120	
I616	Injection	1098214	495400	28.0	120	
I665	Injection	1098210	495230	20.0	120	
I631	Injection	1098226	495074	12.9	120	
I644	Injection	1098362	495129	10.4	120	
I650	Injection	1097855	495570	12.9	120	
I651	Injection	1098759	494930	10.4	120	
I550	Injection	1098680	494972	12.9	120	
I658	Injection	1097709	495452	8.0	120	
I549	Injection	1097772	495327	12.9	120	
I654	Injection	1097864	495269	12.9	120	
I628	Injection	1097876	495136	11.0	120	
I672A	Injection	1097891	494970	10.4	120	
I671A	Injection	1098030	494955	12.9	120	
I668	Injection	1098085	494777	15.6	120	
I664	Injection	1098157	494691	12.9	120	
I663	Injection	1098247	494736	22.5	120	
I660	Injection	1098325	494812	22.5	120	
I620	Injection	1098350	494935	18.0	120	
I618	Injection	1098663	494914	18.0	120	
I621	Injection	1098476	495225	24.0	120	
I656	Injection	1098176	494810	12.0	120	
P430	Injection	1098928	494833	22.5	120	
P429	Injection	1097954	495551	22.0	120	
P431	Extraction	1098148	495421	-15.6	120	
P437	Extraction	1097886	495477	-31.0	120	
P446	Extraction	1098119	495169	-33.0	120	
P454	Extraction	1098247	494809	-14.5	120	
P461	Extraction	1098903	494784	-30.0	120	
I617P	Extraction	1098853	494714	-11.0	120	
I635P	Extraction	1098592	495213	-10.0	120	
I636P	Extraction	1098338	495214	-18.2	120	
I634P	Extraction	1098524	495334	-37.0	120	
P458	Extraction	1098433	495359	-27.0	120	
I624P	Extraction	1098356	495428	-29.0	120	
P463	Extraction	1098010	495101	-28.0	120	
P462	Extraction	1098253	495438	-36.0	120	
P445	Extraction	1098055	495492	-13.0	120	
I613P	Extraction	1097690	495636	-7.0	120	
I653P	Extraction	1098241	494941	-12.0	120	
P393	Extraction	1097954	495551	-32.0	120	
P394	Extraction	1098597	495058	-15.6	120	

Table 6. Phase VI Restoration Results

MU5 (Eastern Portion) Wells and Rates

Well ID	Well Type	Easting (ft)	Northing (ft)	Rate (gpm)	Period of Operation (days)	Comments
I1175	Injection	1098120	498240	9.0	180	
I1186	Injection	1097949	497813	14.0	180	
I1202	Injection	1097966	498182	13.0	180	
I676	Injection	1098514	496924	2.0	180	
P683I	Injection	1098553	497688	20.0	180	
I719	Injection	1097839	497636	10.0	180	
I727	Injection	1098782	497322	10.0	180	
I728	Injection	1098755	497094	5.0	180	
I761	Injection	1098162	497194	36.0	180	
I775	Injection	1098184	497811	20.0	180	
P790I	Injection	1098400	497354	10.0	180	
I802	Injection	1098223	496835	6.7	180	
P814I	Injection	1098119	497929	20.0	180	
P718I	Injection	1098852	497060	5.0	180	
I723	Injection	1098896	496843	5.0	180	
I730	Injection	1098468	496575	3.6	180	
I744	Injection	1098900	496628	5.0	180	
P706I	Injection	1098949	496955	15.0	180	
I742	Injection	1098623	497368	21.0	180	
P748I	Injection	1098076	497421	10.0	180	
P749I	Injection	1098168	498097	5.0	180	
I754	Injection	1098353	497091	10.0	180	
I774	Injection	1098446	496804	2.0	180	
P846I	Injection	1098013	497711	10.0	180	
P690	Extraction	1098119	497773	-31.0	180	
P691	Extraction	1097891	497717	-5.0	180	
P745	Extraction	1098838	496743	-10.0	180	
P767	Extraction	1098311	497996	-20.0	180	
P770	Extraction	1098514	496765	-3.0	180	
P773	Extraction	1098365	496668	-6.0	180	
I860P	Extraction	1097981	497553	-26.0	180	
I1168P	Extraction	1097950	497971	-35.0	180	
I1173P	Extraction	1098006	498329	-10.0	180	
I721P	Extraction	1098506	497484	-25.0	180	
795P	Extraction	1098278	497461	-20.0	180	
712P	Extraction	1098567	497194	-34.0	180	
I736P	Extraction	1098473	497126	-11.0	180	
P741	Extraction	1098692	496980	-36.0	180	

Table 7. Phase VII Restoration Simulation Results

MU5 (Western Portion) Wells and Rates

Well ID	Well Type	Easting (ft)	Northing (ft)	Rate (gpm)	Period of Operation (days)	Comments
I698	Injection	1096783	497374	18.2	120	
P1002I	Injection	1096412	497685	15.6	120	
1003I	Injection	1095916	497102	15.6	120	
I1010	Injection	1095983	497385	18.2	120	
I1011	Injection	1096178	497367	15.6	120	
I1012	Injection	1096379	497436	10.0	120	
I1021	Injection	1096282	497283	15.6	120	
P1028I	Injection	1096252	497338	5.0	120	
I1040	Injection	1096283	497025	15.6	120	
I1046	Injection	1096276	497545	10.0	120	
P1050I	Injection	1096548	497209	18.5	120	
P1055I	Injection	1096545	496957	20.8	120	
P1062I	Injection	1096374	497365	7.0	120	
P1064I	Injection	1096765	497212	15.0	120	
P1076I	Injection	1096774	496829	10.4	120	
I1078	Injection	1096968	497164	9.0	120	
I1080	Injection	1097170	497065	22.0	120	
I1088	Injection	1096975	496790	10.0	120	
P1094I	Injection	1096433	497016	21.8	120	
I1103	Injection	1097030	496644	27.0	120	
I1130	Injection	1097299	496584	9.0	120	
I1136	Injection	1097218	496495	15.6	120	
I1142	Injection	1097502	496674	19.2	120	
P699	Extraction	1096379	497517	-10.4	120	
P998	Extraction	1096843	497086	-18.2	120	
P1013	Extraction	1096543	497083	-39.0	120	
P1016	Extraction	1096529	497493	-6.2	120	
P1020	Extraction	1096109	497326	-16.0	120	
I1038P	Extraction	1096116	497137	-20.8	120	
P1044	Extraction	1096116	497412	-16.0	120	
I1049P	Extraction	1096357	497155	-20.8	120	
I1053P	Extraction	1096727	497023	-26.0	120	
I1066P	Extraction	1096910	497284	-2.0	120	
P1085	Extraction	1096992	496958	-40.0	120	
P1094	Extraction	1097063	496837	-38.3	120	
I1097P	Extraction	1097212	496825	-16.0	120	
P1073	Extraction	1096878	497020	-22.0	120	
P1104P	Extraction	1097214	496668	-27.0	120	
P1116	Extraction	1097678	496536	-21.8	120	
P1137	Extraction	1097352	496814	-10.0	120	

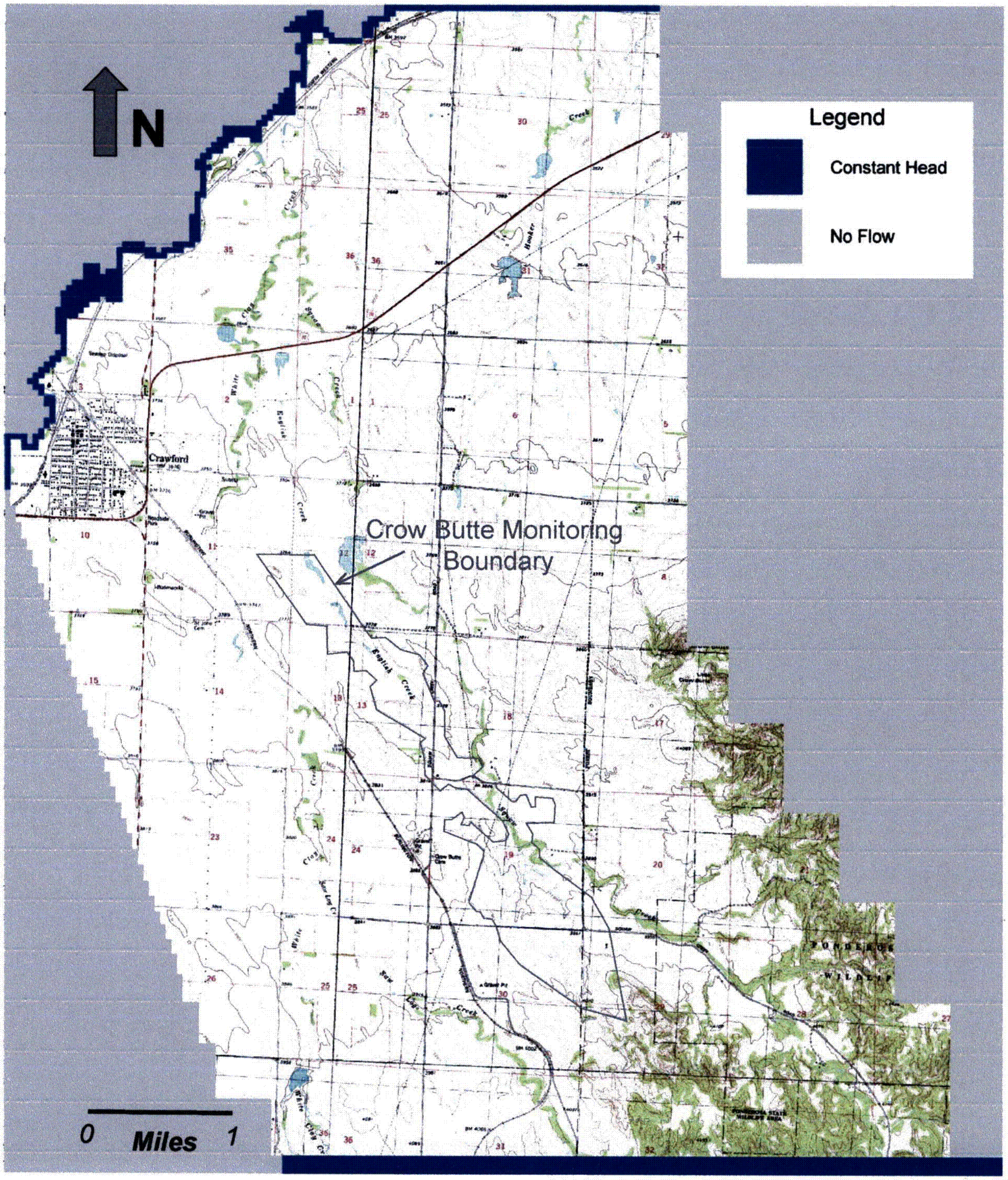
Table 8. Phase VIII Restoration Simulation Results

MU5 (Northern Portion) Wells and Rates

Well ID	Well Type	Easting (ft)	Northing (ft)	Rate (gpm)	Period of Operation (days)	Comments
I1147	Injection	1098585	497933	15.6	180	
P1189I	Injection	1096834	499022	10.4	180	
P1253I	Injection	1097402	498676	5.2	180	
P821I	Injection	1099452	497805	5.0	180	
I852	Injection	1097797	498442	10.0	180	
P873I	Injection	1099790	497393	17.8	180	
I913	Injection	1099510	497490	6.2	180	
I933	Injection	1099090	497768	5.0	180	
I954	Injection	1098946	497632	13.0	180	
I962	Injection	1099011	497765	7.8	180	
I1245	Injection	1097064	498443	1.0	180	
I796	Injection	1098738	498284	5.0	180	
I797	Injection	1096930	498461	4.2	180	
I1218	Injection	1096835	498636	6.0	180	
P1213I	Injection	1096756	498629	6.0	180	
I1191	Injection	1096681	498626	6.0	180	
P1181I	Injection	1098399	498119	3.0	180	
P1196I	Injection	1096572	498748	6.0	180	
I1190	Injection	1096612	498908	2.0	180	
I1223	Injection	1096774	498989	4.2	180	
P1208I	Injection	1096856	498875	6.0	180	
P1247I	Injection	1096872	498718	6.0	180	
I1224	Injection	1097224	498614	2.0	180	
P1144I	Injection	1098779	498002	18.2	180	
I1139	Injection	1098876	497897	8.9	180	
I817	Injection	1099516	497985	10.0	180	
P843I	Injection	1099769	498052	8.9	180	
I858	Injection	1099747	498136	5.2	180	
I863	Injection	1097573	498567	5.0	180	
I877	Injection	1099511	498141	5.0	180	
P884I	Injection	1099798	497881	8.0	180	
P889I	Injection	1099691	497935	8.9	180	
P874I	Injection	1099730	497754	5.2	180	
I898	Injection	1099635	497427	5.0	180	
I899	Injection	1099656	497621	7.8	180	
I905	Injection	1099514	497627	8.9	180	
P804I	Injection	1099546	498202	5.0	180	
I806	Injection	1099548	497705	4.0	180	
I909	Injection	1099171	497640	13.0	180	
I917	Injection	1099121	497381	10.0	180	
P930I	Injection	1089898	497568	10.0	180	
I941	Injection	1099035	497506	7.8	180	

MU5 (Northern Portion) Wells and Rates

Well ID	Well Type	Easting (ft)	Northing (ft)	Rate (gpm)	Period of Operation (days)	Comments
I946	Injection	1099222	497827	5.0	180	
I1112	Injection	1098861	497758	15.0	180	
P1149I	Injection	1098751	497701	15.0	180	
I1197	Injection	1097349	498734	1.0	180	
P1203I	Injection	1097533	498723	5.0	180	
I1255	Injection	1097162	498519	4.2	180	
P1254	Extraction	1097522	498629	-26.0	180	
P1259	Extraction	1096726	498822	-21.0	180	
P686	Extraction	1099633	498063	-20.0	180	
I688P	Extraction	1099623	497557	-18.2	180	
P690	Extraction	1097144	498627	-5.0	180	
I693P	Extraction	1097633	498524	-14.0	180	
P695	Extraction	1096786	498753	-20.0	180	
I787P	Extraction	1099596	497869	-18.0	180	
P1155	Extraction	1098709	497853	-33.8	180	
P947	Extraction	1099317	497801	-13.0	180	
I904P	Extraction	1099617	497684	-20.0	180	
I919P	Extraction	1099101	497639	-34.8	180	
I931P	Extraction	1099111	497508	-22.0	180	
P940	Extraction	1099270	498108	-18.2	180	
P962	Extraction	1099011	497764	-31.2	180	
I1127P	Extraction	1098634	498183	-15.6	180	
I1158P	Extraction	1098470	498070	-12.0	180	
P1209	Extraction	1097001	498496	-7.8	180	
P1222	Extraction	1097249	498423	-10.0	180	



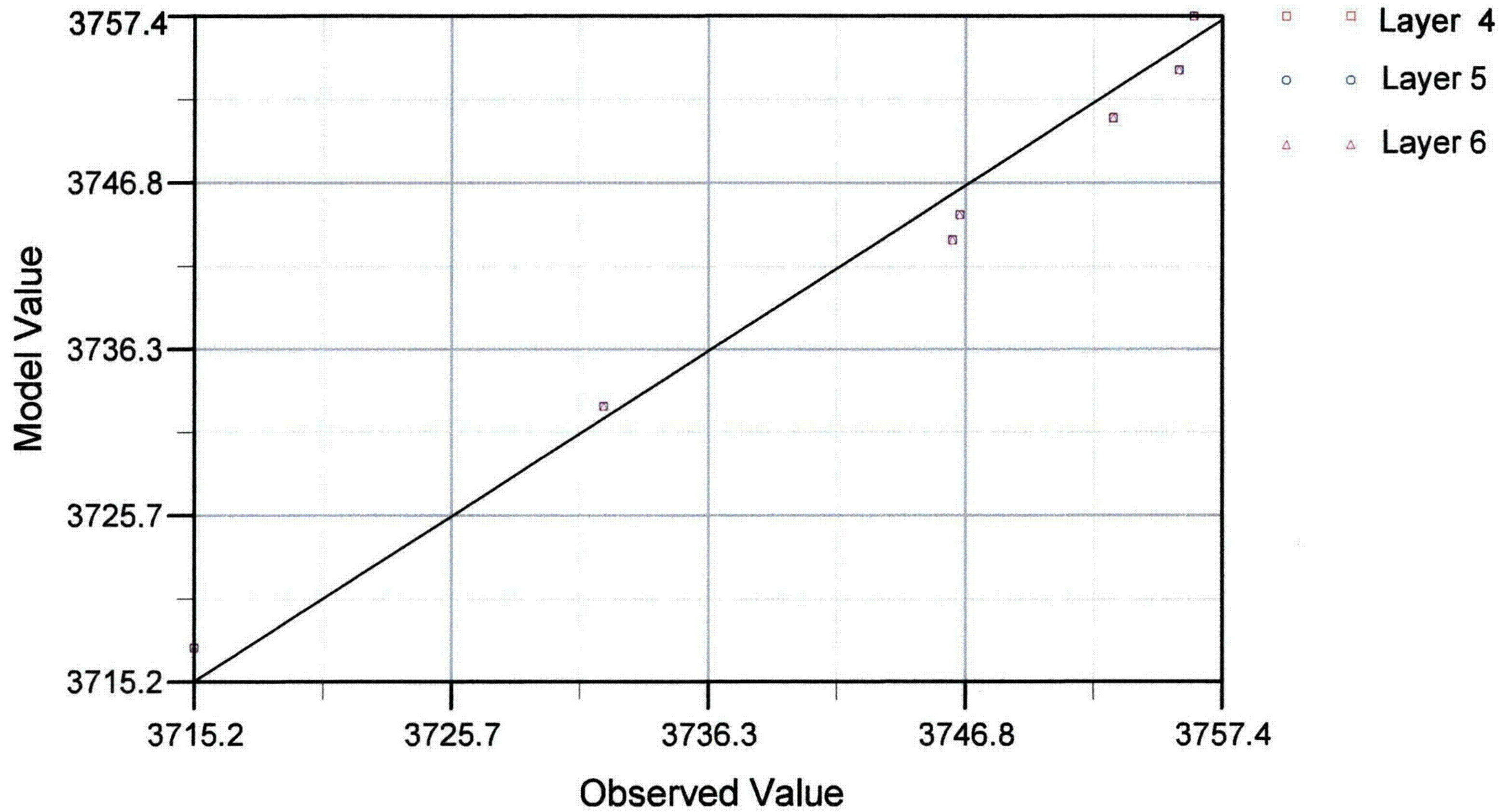
Crow Butte Resources
Wellfield Restoration Modeling

WorleyParsons
resources & energy

MODFLOW-2000 Model Domain and Boundary Conditions

Drawn By:	Edited By:	Date:
BL	BL	11/8/08

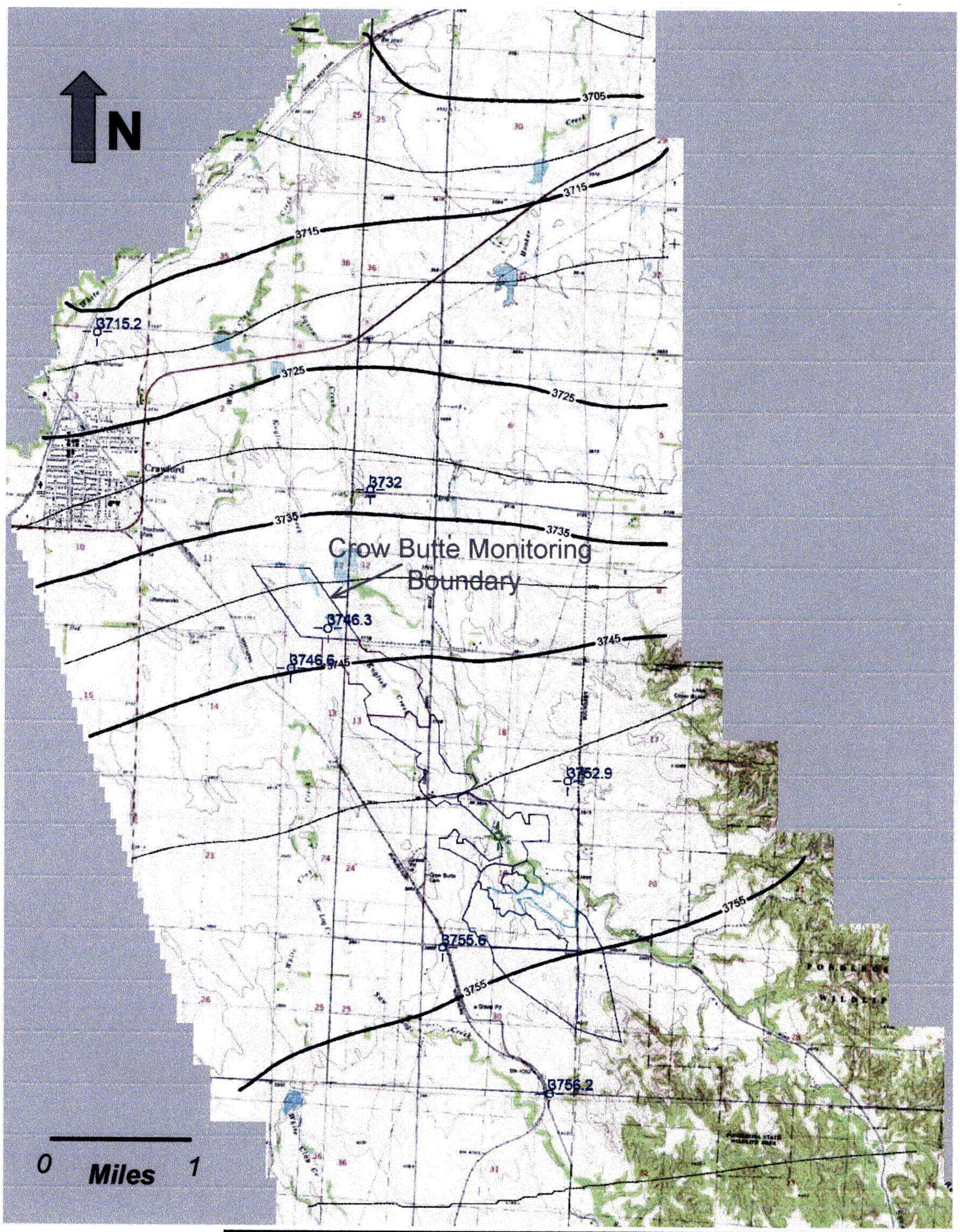
Approved By:	
MG	**Figure 1**



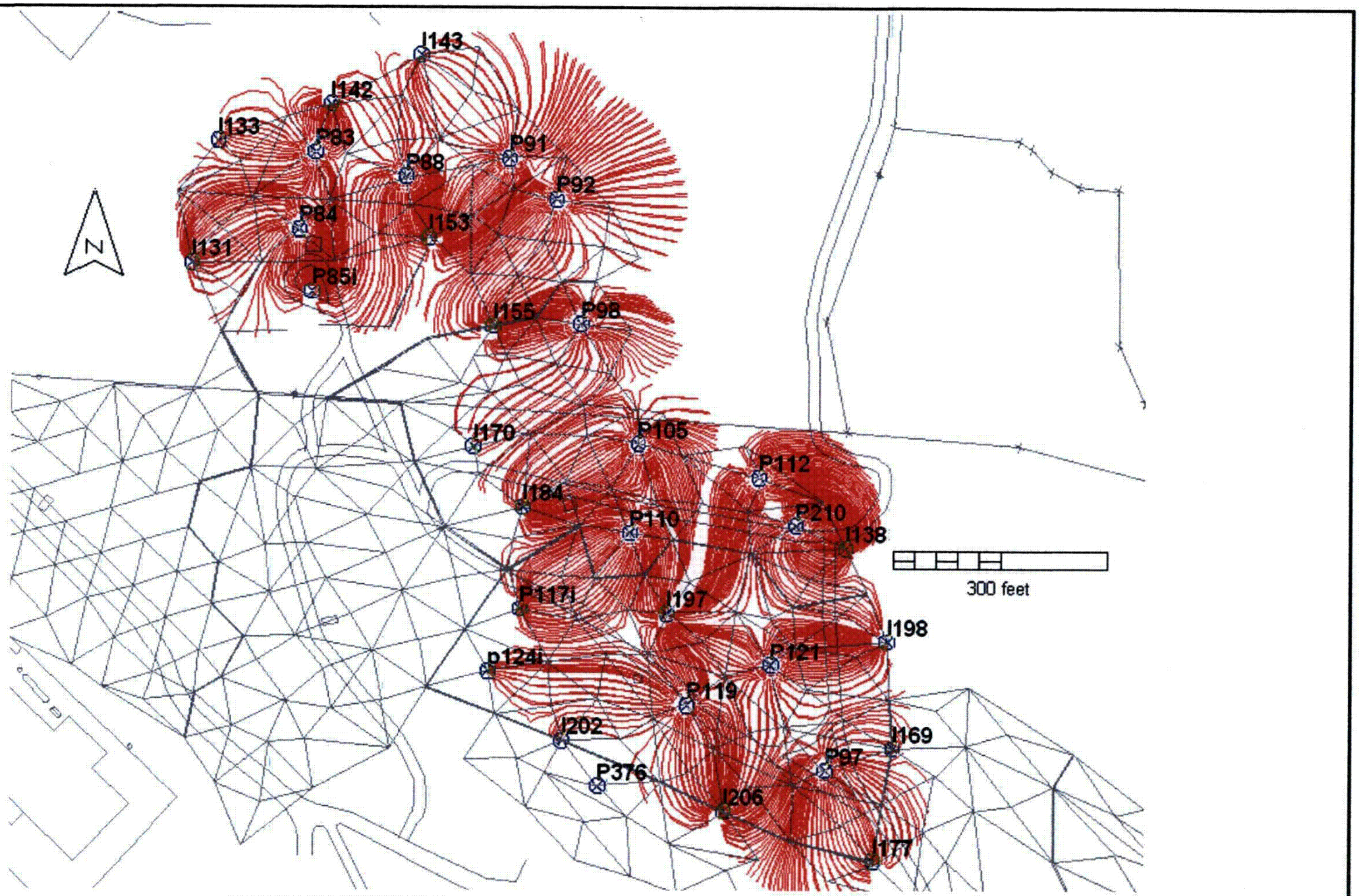
Crow Butte Resources **Wellfield Restoration Modeling**	**WorleyParsons** resources & energy

Flow Model Calibration Results
Observed vs. Modeled Water Levels, January 1983

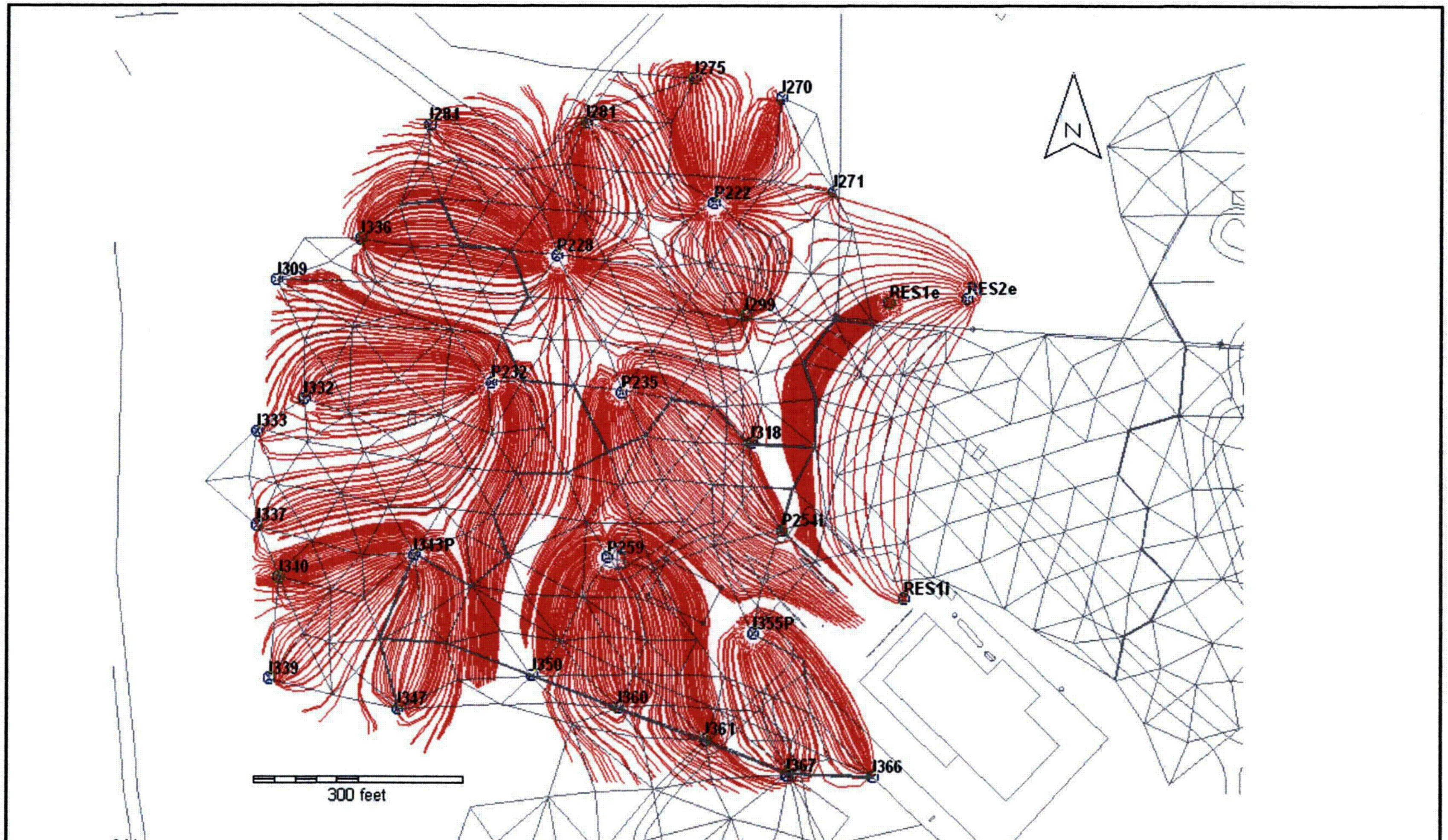
DRAWN BY:	EDITED BY:	DATE:
BL	BL	11/8/2008
APPROVED: MG		**Figure 2**



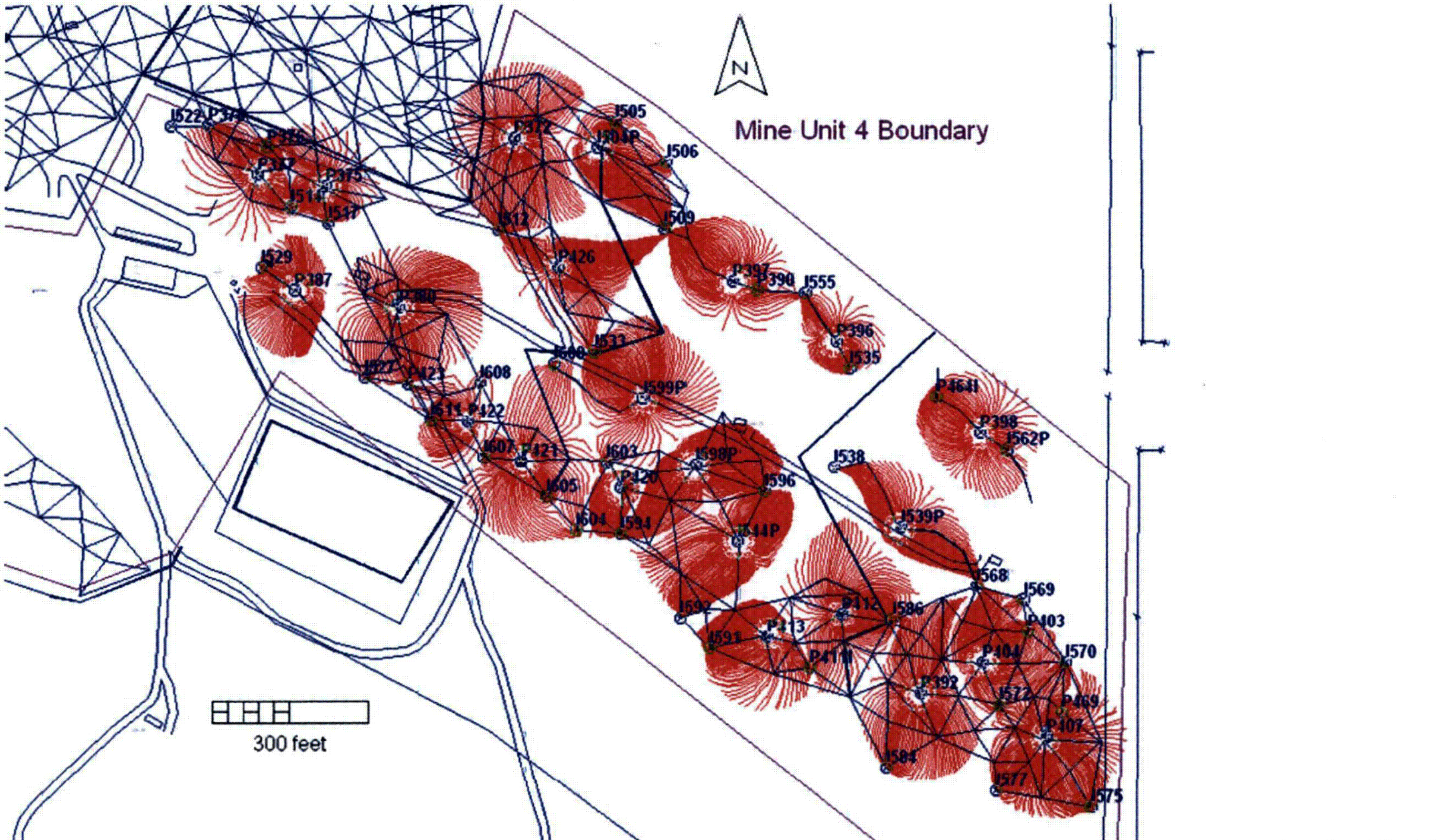
Crow Butte Resources Wellfield Restoration Modeling	WorleyParsons resources & energy		
Calibrated Groundwater Elevation (ft-MSL) **Basal Chadron Sandstone** **January 1983**	Drawn By: BL	Edited By: BL	Date: 11/8/08
	Approved By: MG	Figure 3	



Crow Butte Resources Wellfield Restoration Modeling	WorleyParsons resources & energy		
Phase I Restoration Results – MU2 Optimized Wellfield Configuration and Four Month Particle Traces (Treatment Area)	DRAWN BY: BL	EDITED BY: BL	DATE: 1/20/09
	APPROVED: MG		**Figure 4**



Crow Butte Resources Wellfield Restoration Modeling	WorleyParsons resources & energy	
Phase II and III Restoration Results – MU3 Optimized Wellfield Configuration and Eight Month Particle Traces (Treatment Area)	DRAWN BY: BL	EDITED BY: BL	DATE: 1/20/09
	APPROVED: MG	**Figure 5**



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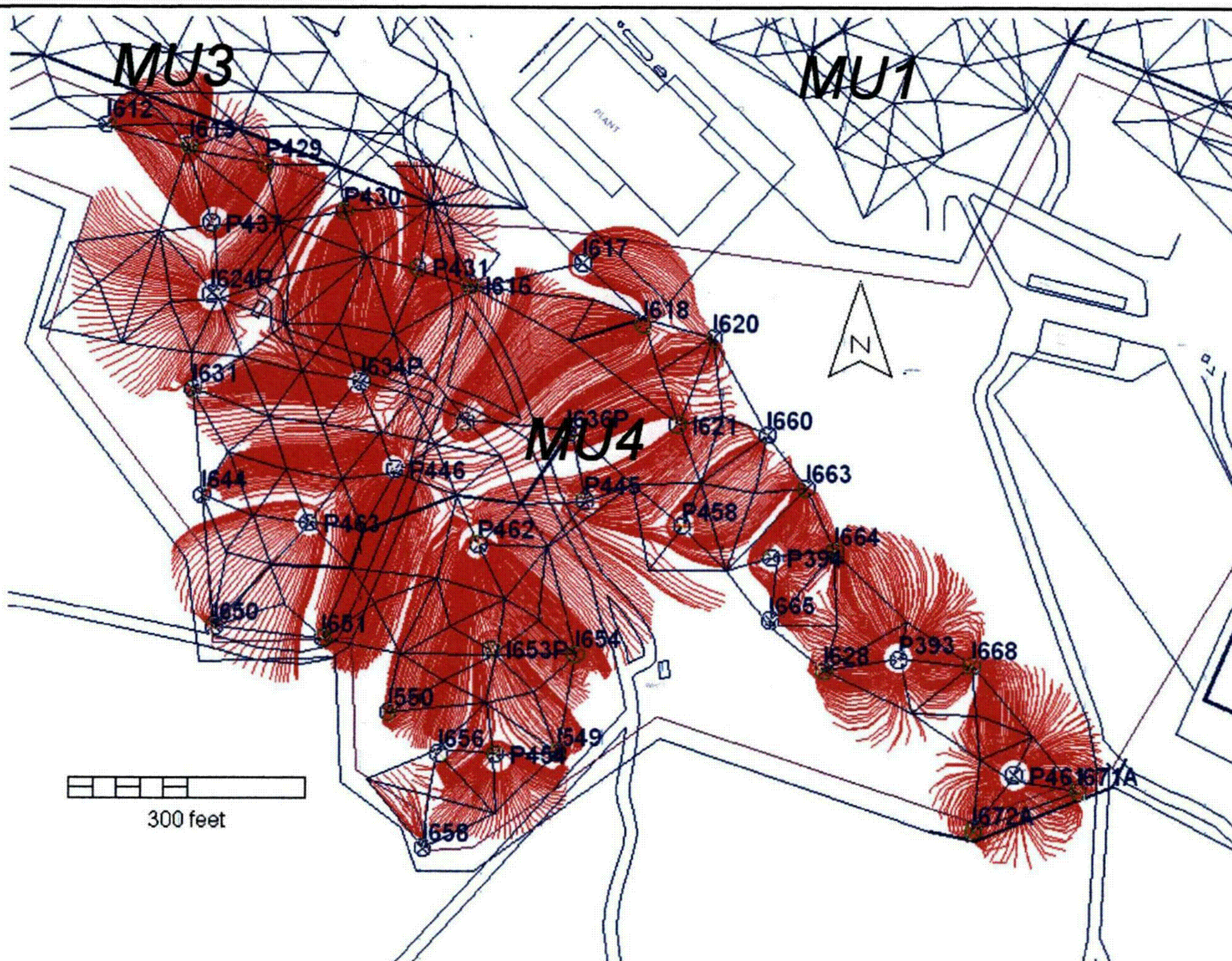
Phase IV Restoration Results – East Half MU4
Optimized Wellfield Configuration and Six Month Particle Traces
(Treatment Area)

DRAWN BY:	EDITED BY:	DATE:
BL	BL	1/20/09
APPROVED: MG		**Figure 6**



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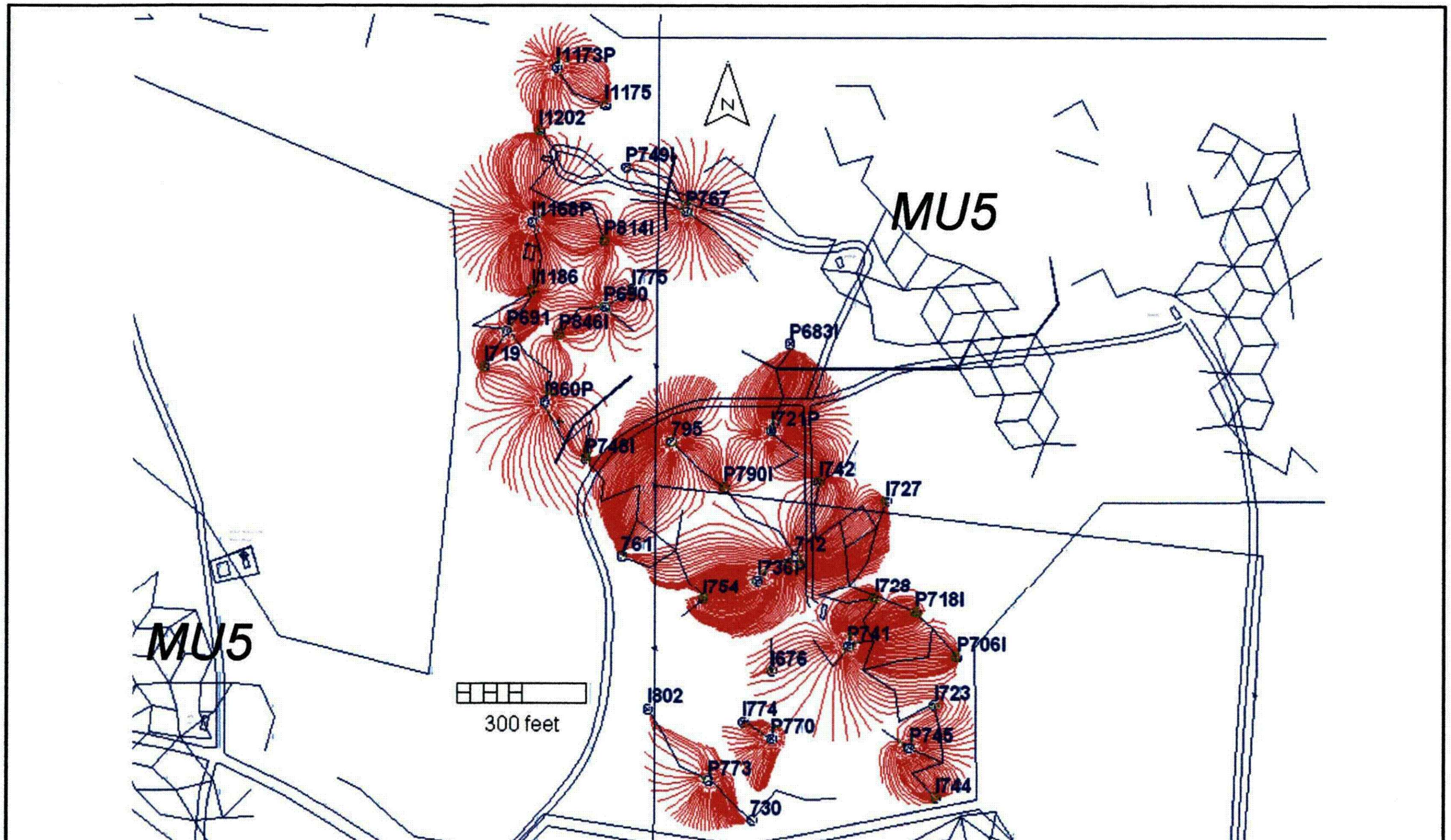
Phase V Restoration Results – West Half MU4
Optimized Wellfield Configuration and Four Month Particle Traces
(Treatment Area)

DRAWN BY:	EDITED BY:	DATE:
BL	BL	1/20/09
APPROVED: MG		**Figure 7**



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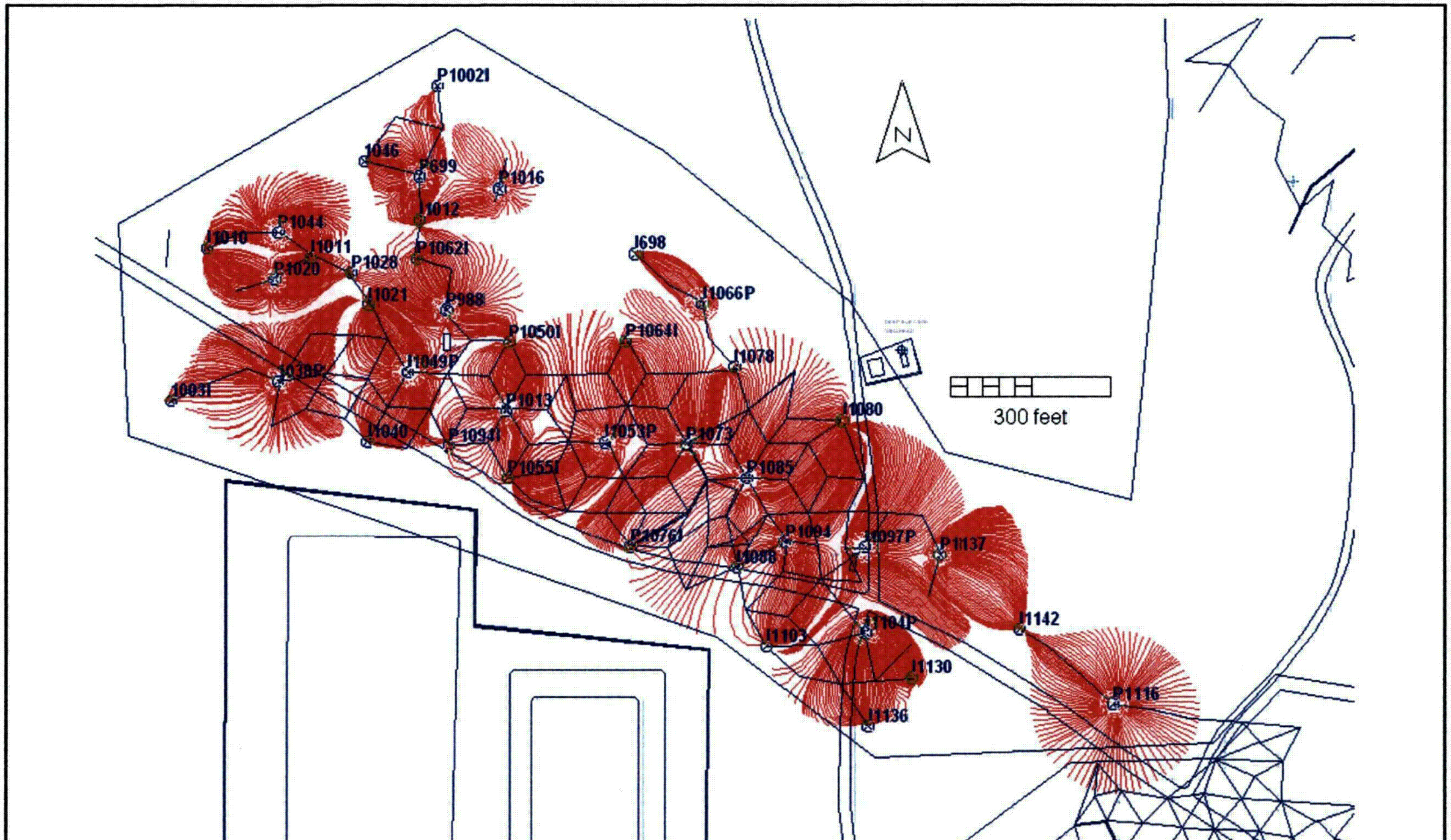
Phase VI Restoration Results – Eastern Portion of MU5
Optimized Wellfield Configuration and Six Month Particle Traces
(Treatment Area)

DRAWN BY:	EDITED BY:	DATE:
BL	BL	1/20/09
APPROVED: MG		**Figure 8**



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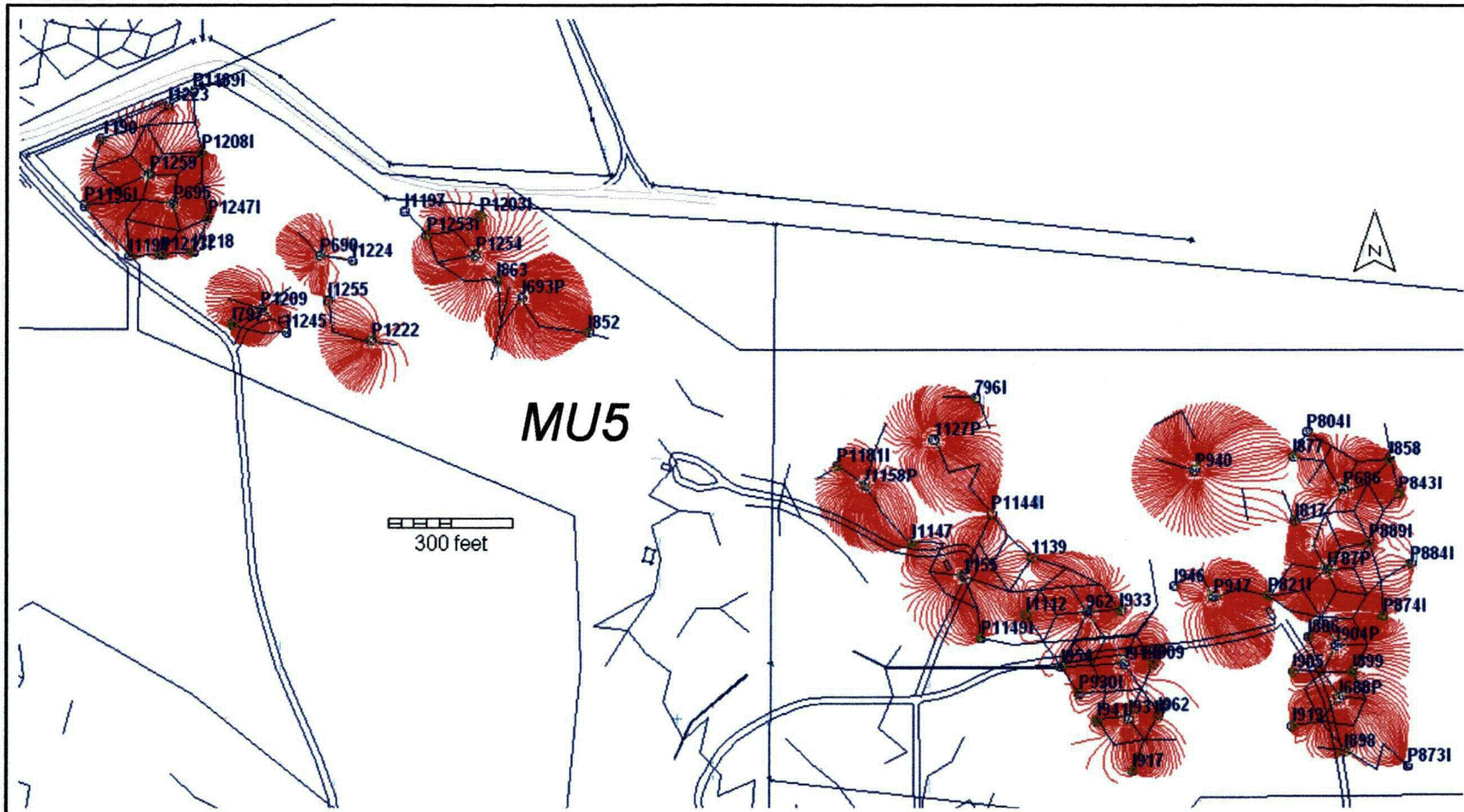
Phase VII Restoration Results – Western Portion of MU5
Optimized Wellfield Configuration and Four Month Particle Traces
(Treatment Area)

DRAWN BY:	EDITED BY:	DATE:
BL	BL	1/20/09
APPROVED: MG		**Figure 9**



MU5

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Phase VIII Restoration Results – Northern Portion of MU5
Optimized Wellfield Configuration and Six Month Particle Traces
(Treatment Area)

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BL	BL	1/20/09
APPROVED: MG		**Figure 10**

CROW BUTTE RESOURCES RESTORATION SCHEDULE

			Schedule (2009–2023, Q1–Q4)
MINE UNIT 2		**524 days**	
IX Treatment/Reinjection	100 GPM	90 days	
RO Treatment	408 GPM	184 days	6 PV
Recirculation	100 GPM	250 days	2 PV
MINE UNIT 3		**877 days**	
IX Treatment/Reinjection	100 GPM	331 days	3 PV
RO Treatment	204 GPM	325 days	6 PV
Recirculation	100 GPM	221 days	2 PV
MINE UNIT 4		**1353 days**	
IX Treatment/Reinjection	100 GPM	602 days	3 PV
RO Treatment	408 GPM	295 days	6 PV
Recirculation	100 GPM	402 days	2 PV
MINE UNIT 5		**2015 days**	
IX Treatment/Reinjection	100 GPM	920 days	3 PV
RO Treatment	408 GPM	451 days	6 PV
Recirculation	100 GPM	613 days	2 PV
MINE UNIT 6		**2232 days**	
IX Treatment/Reinjection	100 GPM	1035 days	3 PV
RO Treatment	408 GPM	507 days	6 PV
Recirculation	100 GPM	690 days	2 PV
MINE UNIT 7		**2592 days**	
IX Treatment/Reinjection	100 GPM	1356 days	3 PV
RO Treatment	816 GPM	332 days	6 PV
Recirculation	100 GPM	904 days	2 PV
MINE UNIT 8		**1705 days**	
IX Treatment/Reinjection	200 GPM	935 days	3 PV
RO Treatment	816 GPM	458 days	6 PV
Recirculation	400 GPM	312 days	2 PV
MINE UNIT 9		**1704 days**	
IX Treatment/Reinjection	200 GPM	790 days	3 PV
RO Treatment	816 GPM	387 days	6 PV
Recirculation	200 GPM	527 days	2 PV
MINE UNIT 10		**1943 days**	
IX Treatment/Reinjection	400 GPM	734 days	3 PV
RO Treatment	816 GPM	720 days	6 PV
Recirculation	400 GPM	489 days	2 PV
MINE UNIT 11		**1518 days**	
IX Treatment/Reinjection	400 GPM	574 days	3 PV
RO Treatment	816 GPM	562 days	6 PV
Recirculation	400 GPM	382 days	2 PV