

THE URANIUM-BEARING FOX HILLS AND LARAMIE AQUIFERS,
CHEYENNE BASIN, COLORADO: STRUCTURE, DEPOSITIONAL
SYSTEMS AND GROUNDWATER

An Interim Report

Part II

GROUNDWATER

by

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INTRODUCTION/OBJECTIVES

The recognition of low-grade roll-front uranium deposits in the Cheyenne Basin and their future development in several areas has prompted this study. The primary concerns have to do with the effects, if any, of in situ recovery of uranium on aquifer water quality and quantity. In this report we have compiled all available information on groundwater in the study area with respect to yields as well as water quality. Comparisons of water quality in aquifers formed by differing depositional processes are summarized. Finally, these baseline data are used to evaluate the pilot project near Grover (section 24, T10N, R62W) with respect to restoration of the uranium host aquifer. The suitability of these groundwaters for irrigation, domestic, or livestock use is summarized.

METHODOLOGY AND DATA SOURCES

Published and unpublished reports with groundwater data have been compiled. These include Babcock, Bjorklund, and Klister (1956); Schneider and Hershey (1961); Weist (1964); Hershey and Schneider (1964); Weist and Brennan (1965); Reade (1976, 1978); Kirkham (1979); Wacinski (1979); Hillier and Schneider (1979); and Kirkham, O'Leary, and Warner (unpublished manuscript). In addition, reports by Wyoming Mineral Corporation (1976, 1978, 1979), available from the Colorado Department of Health, have given baseline, monitor, and restoration data as well as field pump test data with respect to in situ mining at Grover and Keota. The aquifer parameters have been tabulated and the chemical data plotted on stiff and trilinear (Piper) diagrams. Water samples were collected at the Grover site in June, 1979, for analyses to allow us to evaluate the impact of the pilot plant operation and the restoration of aquifer quality to baseline levels.

GROUNDWATER AQUIFERS

The original intent of this study was to focus only on the Upper Cretaceous aquifers; however, it has become apparent that the base of the Oligocene White River Group comes in contact with these aquifers as progressive truncation occurs from west to east across the Cheyenne Basin (Fig. 3, pt. 1). Data from three aquifer groups, thus, have been compiled. These include, in ascending order: 1) The Fox Hills Formation, 2) the Laramie Formation, and 3) the White River Group (Fig. 4, Pt. 1). Each has numerous aquifers as seen on geophysical logs, however, potentiometric and water quality data are generally only identified as to the formational source. The exceptions to aquifer identification come from the uranium exploration sites where sampling is confined to a screened interval within the formation.

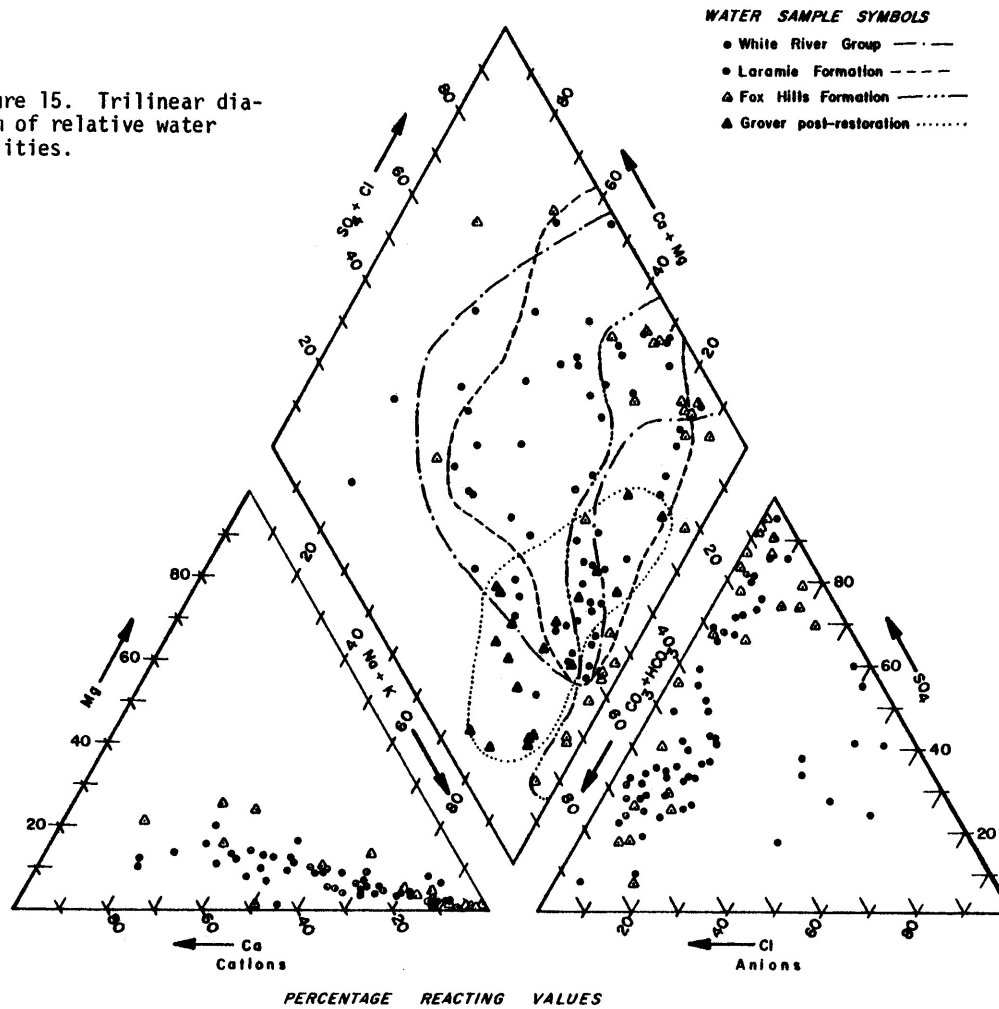
Aquifer Potentiometric Surfaces

Maps are currently being constructed for each of the three aquifer groups and will be included in the final project report. Reade (1975) constructed a potentiometric map for the Laramie Formation, based on water level measurements collected in 1962. The regional groundwater flow is to the southeast in the study area as seen from Reade's map. In the area immediately northwest of the Grover uranium deposit the gradient in the Laramie Formation is 28.5 feet per mile but to the southeast decreases to approximately 14 feet per mile.

Aquifer Water Quality

Trilinear plots of water quality from the three aquifer groups are on Figure 15. Waters from the White River Group and Laramie Formation are

Figure 15. Trilinear diagram of relative water qualities.



essentially identical. Both can be characterized as sodium-calcium bicarbonate-sulfate waters. Their similarities may be due to mixing. Water from the Fox Hills Formation, however, is a sodium bicarbonate type that locally has a significant sulfate component. Evaluation of areal water quality variation in addition to defining areas where mixing of White River Group groundwater with that of the other two groups are future objectives of this research. In summary, the groundwater of the two formations which are fluvial in origin (as far as the aquifers are concerned) are typified as sodium-calcium bicarbonate-sulfate waters while the deltaic aquifer unit has sodium bicarbonate groundwater.

The principal uses of groundwater in the study area are agricultural and domestic. Much of the water exceeds domestic or agricultural standards of the U. S. Public Health Service. This is due to excessive total dissolved solids, sulfate, iron, selenium, and/or manganese (Kirkham et al., unpublished); however, the water locally is an important asset to future developments.

Aquifer Yield Characteristics

Bedrock aquifers in the southern part of the Cheyenne Basin are only sparsely developed. As a result, data on their characteristics are limited (Table 1) with no known information concerning the aquifers of the Fox Hills Formation. The upper Laramie Formation supplies two wells for the town of Grover with yields of 35 and 55 gpm (Weist et al., 1965), and it appears that the Cretaceous aquifers have adequate yields for domestic use.

Table 1. Bedrock Aquifer Characteristics in the Southern Cheyenne Basin.

<u>AQUIFER</u>	<u>SPECIFIC CAPACITY</u>	<u>STORAGE COEFFICIENT</u>	<u>FIELD COEFFICIENTS OF</u>	
			<u>TRANSMISSIBILITY</u>	<u>PERMEABILITY</u>
White River Group	0.35 ¹ 2-2.57 ³	1.57-3.18 ³ ($\times 10^{-3}$)	350 ¹	4 ¹
Laramie FM	0.48-2.40 ¹	NA	662 ² to 1,000 ¹	3-6 ¹ 1.5 Darcy ²
Fox Hills FM	NA	NA	NA	NA

NA- Not available

Sources

¹Weist et al., 1965

²WMC

³Marvin, Crist, and Borchert, 1972

URANIUM-BEARING AQUIFERS

The occurrence of uranium roll-front deposits in Fox Hills and Laramie aquifers has been known for several years (Reade, 1976; 1978; Kirkham, 1979; Kirkham et al., unpublished). This study is focused on the deposit near Grover (sec. 24, T10N, R62W). This deposit has been the site of an in situ recovery pilot plant operated by Wyoming Mineral Corporation (WMC) of Lakewood, Colorado.

The aquifers of interest within the test site area are sandstone units of the lower Laramie Formation designated by Wyoming Mineral Corporation from upper to lower as: Porter Creek, Grover, and "Fox Hills" (Fig. 16). The term Fox Hills is more properly the formation underlying the Laramie.

The Porter Creek consists of 2 to 3 beds of sandstone totaling about 40 feet in thickness. The Grover is about 50 feet thick. The two units are separated by 40 to 60 feet of siltstone and mudstone. According to test conducted by WMC the aquifers are artesian but are not hydraulically connected. The regional geology indicates the beds dip to the north at low angle (Reade, 1976). The sandstones are of similar mineralogy and maturity. Both are salt and pepper colored, well sorted, friable, fine to medium grained arkosic sandstones composed of angular to subrounded grains of quartz, chert, orthoclase, microcline, plagioclase, and small amounts of either pyrite or magnetite. The Porter Creek is marked by goethite-stained grain coats and a higher porosity. Its feldspars, particularly plagioclase, are partially altered to kaolinite, smectite, and sericite. The Grover contains chlorite that is an alteration product of detrital ferromagnesian minerals.

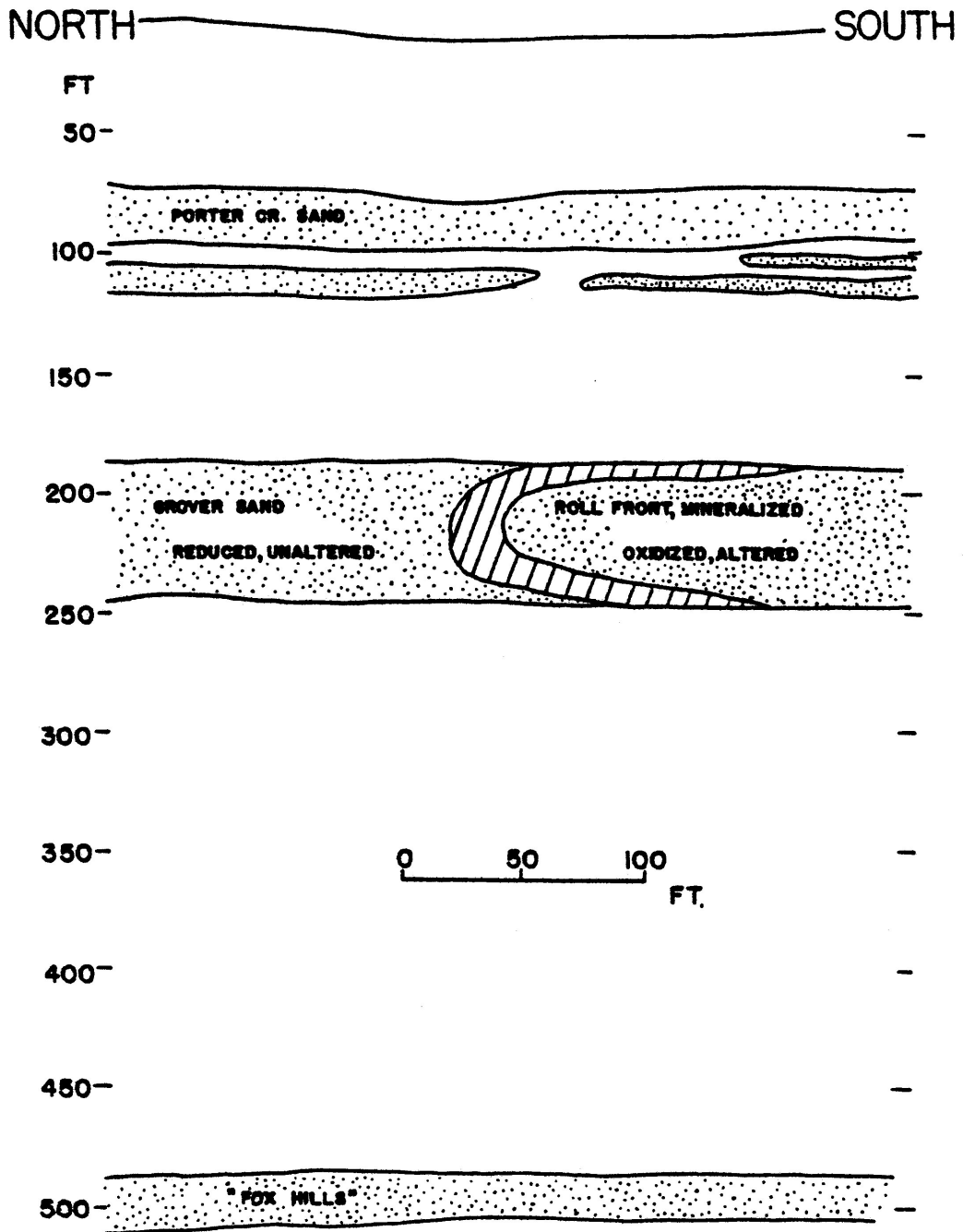


Figure 16. Cross section of Porter Creek, Grover and "Fox Hills" sands, Grover Test Site, Cheyenne Basin, Colorado.

The Grover is a laminated to thinly bedded sandstone containing clay lenses and intraclasts, organic partings with plant debris, coal laminae up to 1 cm in thickness, and black layers up to 20 cm in which the sand is saturated with an asphaltic substance often mineralized by radioactive material. Some of the sandstone shows small scale high angle crossbeds. Calcite replacement of the sandstone was noted in one sample and a layer of calcareous mud showing cone-in-cone structures was found. Overall, the sandstone has little calcite. This is reflected in the low calcium content of the water contained in the Grover Sand.

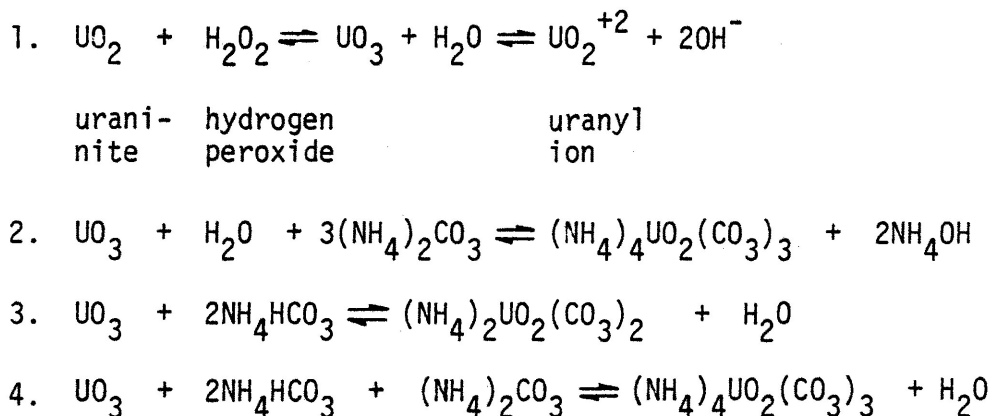
URANIUM DEPOSITS

The Grover Sandstone is the host for uranium mineralization. The mineralizing fluids appear to have moved to the northeast, creating roll-front type deposits which were the target of the solution mining test (Reade, 1976). It is conceivable that the fluids responsible for the Grover deposit moved easterly through the White River Group paleochannels and uranium was deposited where these (Fig. 5) cut into the Laramie Formation.

The uranium was transported downdip by the infiltrating surface water as the uranyl ion (UO_2^{+2}) until the groundwater became more reduced through interactions with reducing materials in the sandstone. The uranium was then reduced to the less soluble U^{+4} state and precipitated in the crescent shaped roll-front ore bodies (Figure 16). Since the organic materials in the sandstone are associated with mineralization, organic complexes may have had a role in precipitation and even transport of the uranium.

TEST SITES

Two leach fields were used at the Grover Test Site. Well Field I (WFI) consisted of three five-spot patterns and Well Field II (WFII) contained two five-spot patterns (Fig. 17). Solutions of ammonium bicarbonate-hydrogen peroxide, calcium bicarbonate-hydrogen peroxide, or sodium bicarbonate-hydrogen peroxide were used to oxidize and complex the uranium. In each five-spot pattern the solution was pumped under pressure into four corner injection wells and then pumped out of the central production or recovery well. The pregnant leach solution was then processed to remove the uranium. The solution was then regenerated with fresh chemicals, its pH adjusted, and reinjected into the ore zones. Some likely reactions between the leach solution and uranium are as follows:



Well Field I began operation in June of 1977 and terminated in September, 1977. Well Field II began in October of 1977 and terminated in May of 1978. A clean water restoration cycle was then begun in which contaminated water from the leach field was circulated through a series of reverse osmosis units and then reinjected into the field. Injection and production wells were changed to maximize the area swept by the clean water.

After equilibrium conditions were established, a chemical treatment of CaCl_2 was initiated to remove ions sorbed into clays in the leach field. This was followed by clean water sweeps.

Horizontal migration of leach fluids was monitored by the Grover Monitor Wells (GM, Fig. 17) which encircled the leach fields. These wells were screened in only the Grover Sandstone. Vertical migrations were monitored by the Porter Creek Monitor Wells (PM), which were screened in the sandstone unit overlying the Grover. The "Fox Hills" Monitor Wells (FM) were screened in the sandstone unit underlying the Grover. Weekly analyses of waters from the monitor wells were made to check for excursions of the leach fluids. Net production excess was maintained in the leach fields to produce a hydraulic gradient which would cause waters to move toward the leach field. This is reflected in a maximum drawdown in the Grover Monitor Wells of about 17 feet.

Using water heights in the GM wells a series of potentiometric maps of the Grover aquifer were prepared in this study. The results indicate a gradient which averaged 26.9 feet per mile southward. WMC had pump tests made in the Grover Sandstone. One test (April 7, 1976) indicated a transmissivity of 662 g.p.d./ft and a permeability of 1.5 Darcy (Wyoming Mineral Corporation, 1976). Using a 26.9 feet per mile gradient and a saturated thickness of 50 feet, the Darcy or bulk velocity would be 3.2 feet per year. From thin section, bulk density, and sieve analyses the porosity of the Grover Sandstone was found to range from 30 to 40 percent with a mean for 7 samples of 35.9 percent. This would give a seepage velocity of 19.4 feet per year. The permeability of the Grover

Sandstone in the leach field area was found by WMC to be anisotropic. The axis of major transmissivity is northwest to southeast (Wyoming Mineral Corporation, 1978a & b). It is possible that reductions in porosity due to mineralization at the roll front could be responsible for this anisotropism.

WATER QUALITY

After completion of the restoration activity production and injection wells were sealed. On June 18th, 1978 seven of the leach field wells were sampled by WMC, Colorado Department of Health, U.S. Geological Survey, and Colorado State University. Analysis of the water samples are shown on Table 2. The wells were sampled after 2 and 6 well bore volumes had been pumped. These are denoted by the letters A and B, respectively (Table 2). Little difference was found between samples taken when the different water volumes were pumped. The radium-226 and gross alpha samples were unfiltered, and others were all filtered. Two conductivities are shown on Table 2 for each sample. The upper number represents measurements made in the field at the time of sampling while the lower one was measured in the laboratory. Skyline Labs., Wheatridge, Colorado, did all analyses except the radium 226 and gross alpha which were done by the Department of Radiology and Radiation Biology, Colorado State University. Both radium 226 and gross alpha measured at Colorado State University showed values higher than those analyzed by WMC and the Colorado Department of Health. The lower values are the result of their samples being filtered and a 1 to 14 day waiting period before the gross alpha samples are conducted. It should be noted that gross alpha values are inconsistent with uranium values, reflecting analytical problems.

Table 2. Grover Test Site Well Data of June 18, 1979

Constituent	WELL-PG2A*	PG2B	G5A	G5B	G6A	G6B	G7A	G7B	G11A	G11B	G19A	G19B	G20A	G20B	Ave.
Radium 226 (pc/l)	4.96 ^{+0.95}	NA	145 ^{+6.82}	NA	166 ^{+7.35}	NA	6.90 ^{+1.10}	NA	2.02 ^{+0.685}	NA	375 ^{+17.4}	NA	24.3 ^{+2.00}	NA	103
Gross Alpha (pc/l)	17.3	NA	1370.	NA	920.	NA	142	NA	17.3	NA	5620.	NA	1300	NA	1341
Conductivity (mhos/cm)	620/534	620/512	280/250	285/252	300/264	330/269	245/226	260/210	600/543	580/484	190/196	225/193	260/232	260/209	361
TDS (mg/l dry)	330	285	145	185.	180	140	165	145	265	220	70	130	55	140	175
pH (standard units)	7.7	7.7	7.2	7.7	8.4	7.8	8.7	8.2	7.2	7.3	6.5	6.5	8.7	7.2	8.2
Alkalinity (total as CaCO ₃ , mg/l)	100	96	52	58	68	66	54	38	135	115	30	30	46	38	66
NH ₃ -N (mg/l)	7.5	8.0	2.8	2.0	11.0	0.5	1.8	1.5	0.3	0.2	0.4	0.1	1.2	0.1	2.7
NO ₃ -N (mg/l)	15	17	18	19	6.0	14	1.1	0.5	7.9	6.3	0.2	0.3	0.7	0.2	8.1
Uranium (mg/l)	0.44	0.38	0.32	0.28	.24	0.24	0.12	0.16	0.022	0.018	0.055	0.048	0.065	0.055	0.17
Calcium (mg/l)	12.8	12.2	10.9	13.2	11.3	11.6	15.7	13.6	38.7	34.8	4.54	4.19	10.5	5.7	14.3
Mg (mg/l)	2.64	2.57	1.17	1.33	0.76	0.92	0.36	0.46	8.1	7.8	0.45	0.45	0.1	0.21	2.0
Na (mg/l)	91	90	47	43	51	51	36	37	81	73	43	44	46	45	55.6
K (mg/l)	6.2	5.9	2.1	2.0	2.2	2.8	1.8	1.5	8.7	8.6	1.7	1.4	5.5	2.5	3.78
HCO ₃ (mg/l)	120	115	64	70	80	80	52	46	165	145	36	36	30	46	77.5
CO ₃ (mg/l)	<2	<2	<2	<2	2.0	<2	6.0	<2	<2	<2	<2	<2	12	<2	--
SO ₄ (mg/l)	46	28	12	<2	<2	26	4	8	32	38	40	100	24	20	26.3
Cl (mg/l)	30	28	7	5	8	7	13	7	40	26	6	7	12	9	14.6
F (mg/l)	0.44	0.4	0.25	0.2	0.2	0.2	0.23	0.2	0.8	1.0	0.15	0.12	0.16	0.16	0.32
SiO ₂ (mg/l)	9.4	7.3	5.5	4.6	5.6	4.7	3.7	3.7	13	14	9.3	10.0	9.3	8.3	7.7
Mo (mg/l)	0.14	0.12	0.07	0.064	0.035	0.066	0.038	0.043	0.025	0.032	0.13	0.1	0.21	0.09	0.08
Fe (mg/l)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.1	0.5	0.3	<0.1	0.1	0.1
Se (mg/l)	<.02	<0.02	0.15	0.25	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	--
V (mg/l)	0.033	0.042	0.044	0.044	0.028	0.022	0.008	0.010	0.006	0.030	0.030	0.063	0.025	0.038	.03
TDS (mg/l wet)	342	315	161	161	161	199	136	120	396	354	142	141	152	144	210
Boron (mg/l)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.15	0.20	--

*A denotes sample taken after two bore volumes pumped *B denotes sample taken after six bore volumes pumped
 NA- not analyzed

Total Dissolved Solids (TDS) were measured in the lab and a comparison was made with the lab analyses by calculating wet TDS. The wet TDS average adjusted to a dry comparative value gives a value of 171 mg/l which compares closely with the actual dry average of 175 mg/l, however, the ion balance shows a consistent cation excess or anion deficiency. The good agreement between A and B samples indicates the relative analysis precision.

In analyzing the effects of solution mining on the groundwater, the distinction must be made between water contained in mineralized (roll front) sands and those waters in relatively unmineralized sands. The Grover, Porter Creek, and "Fox Hills" monitor wells are usually located in relatively unmineralized sands and represent more normal ground water. The characteristics of these waters are graphically represented in Figure 18. The shapes of the diagrams characterize the water while their size indicates the total ionic content or relative amounts of total dissolved solids (TDS). The levels of radium 226 make the Grover Monitor Well waters unsuitable for domestic or livestock use (Table 3) (Water Quality Control Commission, 1979). Because of limited data the possible uses of the Porter Creek water cannot be ascertained. The "Fox Hills" has a radium 226 value acceptable for domestic use but the ammonia value of 0.6 mg/l is greater than the allowable standard of 0.5. Its sodium absorption ratio (SAR) of 17.3 is large enough to restrict its use in some irrigation applications.

The averages of constituents found in each aquifer and the effects of mining on ground water quality are listed in Table 3. Table 4 shows the immediate effect of solution mining on the groundwater before any

Table 3. A comparison of Groundwaters with Colorado and EPA Standards

Constituents	Grover ¹	Porter ² Creek	Fox Hills ³	Well Field ⁴ I (baseline)	Well Field ⁵ I and II Post leach	Colorado Domestic Water	Colorado & EPA Agricultural Std.	EPA Livestock Std.
Radium 226 pc/l	23.6	--	0.85	7.2	103.	5	-	5
Gross Alpha pc/l	67.3		18	122	1341	-	-	-
Conductance mhos/cm	488	473	672	--	361	-	-	-
TDS (wet)	647	--	332	295	210	-	2000-5000	3000
Alkalinity mg/l	168	191	235	--	66	-	-	-
NH ₃ -N mg/l	3.4	--	0.6	0.25	2.7	0.5	-	-
NO ₃ -N mg/l	--	--	--	1.4	8.1	10	100	-
Uranium mg/l	0.04	0.13	0.035	0.086	0.17	-	-	-
Calcium mg/l	5.5	20.4	3.3	9.1	14.3	-	-	-
Magnesium mg/l	1.8	--	0.48	1.1	2.0	-	-	-
Sodium ng/l	81	68.7	126	85.2	55.6	-	-	-
Potassium mg/l	26	--	2.6	--	3.78	-	-	-
Bicarbonate mg/l	257	150	300	220	77.5	-	-	-
Carbonate mg/l	22	--	16	--	12 (max)	-	-	-
Sulfate mg/l	40.6	43	7.0	38.3	26.3	-	-	-
Chloride mg/l	7.3	8.3	9.4	7.0	14.6	250	-	-
Fluoride mg/l	0.73	--	0.78	0.7	0.32	1.4-2.4	1	2
Silica mg/l	10.8	--	9.0	--	7.7	-	-	-
Molybdenum mg/l	--	--	--	0.02	0.08	-	0.01-0.05	-
Iron mg/l	0.6	--	0.068	0.7	0.5 (max)	0.3	5	-
Selenium mg/l	--	--	--	0.01	0.25 (max)	0.01	0.02	0.05
Vanadium mg/l	--	--	--	0.03	0.03	-	0.1	-
Boron mg/l	--	--	0.178	0.1	0.2 (max)	-	0.75	-
Hardness	24.7	63	16	--	--	-	-	-
Sodium Adsorption Ratio (SAR)	7.68	4.19	17.3	7.12	3.64	-	-	-
Ph	7.38	6.04	7.4	8.45	8.2	-	-	-

1, 2, 3, data averaged from weekly analytical reports filed by WMC with Colorado Dept. of Health

4-from Groundwater Status Report of WMC filed with Colorado Dept. of Health

5-Averages of analyses made by Skyline Labs for this study

TABLE 4. Effects of Mining on Groundwater Before Restoration
(Data from WMC Groundwater Restoration Status Report, Aug 22, 1978)

<u>Constituent</u> (PPM)	<u>WF-1 Baseline</u> (Pre-mining)	<u>Post-Mining Analysis</u>	
		<u>WF-1</u>	<u>WF-2</u>
Calcium	9.1	75.8	190.0
Magnesium	1.1	22.4	32.95
Sodium	85.2	237.5	268.5
Bicarbonate	220.1	1158	1088.5
Sulfate	38.3	311	404.5
Chloride	7.0	75.5	93.0
Nitrate	1.4	5.2	3.0
Fluoride	0.7	0.1	0.1
TDS	295	728	1392
pH	8.45	8.07	7.45
Arsenic	0.01	0.01	0.01
Barium	0.03	0.16	0.15
Cadmium	0.002	0.004	0.006
Chromium	0.003	0.005	0.066
Copper	0.06	0.08	0.036
Iron	0.7	1.25	0.03
Lead	0.02	0.03	0.023
Manganese	0.02	0.16	0.64
Mercury	0.0002	0.000	0.00
Molybdenum	0.02	0.31	0.10
Nickel	0.2	0.02	0.2
Selenium	0.01	8.9	0.095
Silver	0.003	0.002	--
Zinc	0.04	0.06	0.035
Boron	0.10	0.16	0.235
Vanadium	0.03	0.3	1.87
Uranium	0.25	12.48	11.65
Ra226 (pc/l)	13.4	259.8 [±] 3.9	1069 [±] 9.5
Ammonia	0.086	1248	11.05

restoration (Wyoming Mineral Corporation, 1978a). Before restoration, all major anions and cations increased as well as the leach target, uranium. Increases also occurred with barium, chromium, copper, iron, manganese, molybdenum, nickel, selenium, vanadium, ammonia, and radium 226. The pH and fluoride decreased. Changes in the ammonia, bicarbonate, and pH were probably caused by direct additions of the chemical leach solution. Increases in the other constituents must be attributed to the mobilizing effects of the leach solution.

The goal of restoration was to reduce total dissolved solids to within 10% of baseline and return the water quality to all possible uses the water could be put to prior to mining (Wyoming Mineral Corporation, 1978b). In order to establish a baseline of water quality, the three production wells of Well Field I were sampled before mining was initiated (see column 4 of Table 3). This baseline indicates the values of iron and radium 226 preclude the use of these waters for domestic use. The selenium value is the limit set for domestic use. The low TDS and SAR makes the water suitable for irrigation but the molybdenum (0.02mg/l) content limits its use for irrigation in certain applications. The radium 226 value (13.4 pc/l) precludes its use for livestock. In conclusion, it is seen that natural waters drawn from the mineralized sands are suitable only for restricted agricultural use.

CONCLUSIONS

From these data it is apparent that uranium-bearing aquifers yield prior to mining water unsuitable for domestic or agricultural use in the area of the orebodies. Post-restoration water analyses indicate that Wyoming Mineral Corporation has complied with state requirements

in restoring the aquifer water to within 10 percent of its original Total Dissolved Solids content; however, the post-restoration water near the orebodies does have increased ammonia, uranium, calcium, chloride, molybdenum, gross alpha, and radium 226. Ground water depletion does not occur with the in situ process due to reinjection of formational water during the mining and restoration processes.

Recommendations

1. State limits for acceptable post-restoration molybdenum should be established.

2. Pre-mining baseline water quality data should be from more than three wells. The variability of waters obtained from different parts of the aquifer make averaging of baseline data inappropriate. Individual wells, predesigned by the regulatory agencies, should each have a baseline for restoration guidelines.

3. Monitor wells for detecting leach solution excursion should be closer to the production field. At Grover the nearest Monitor well was 230 feet downgradient from the production field. At the estimated seepage velocity of 19.4 feet per year it would take almost eleven years for any contaminated water to reach to monitor well. It is recognized that hydraulic gradients during mining will create solution velocities well in excess of seepage velocity, and early recognition of casing failures and the resulting excursion of leachate into other aquifers is critical (Kirkham, 1979).

4. Gross alpha analyses are anomalously high in the monitor wells even after restoration. Sampling and analytical procedures should be evaluated, and some acceptable standard adopted.

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