MONTANA BUREAU OF MINES AND GEOLOGY

OPEN-FILE REPORT 210

COMPLETE DATA COMPILATION THE LOWER MADISON VALLEY

ACCOMPANYING A REPRINT OF

ARSENIC CONTAMINATION OF AQUIFERS CAUSED BY IRRIGATION WITH DILUTED GEOTHERMAL WATER

By

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and

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INTRODUCTION

The purpose of this open-file report is too provide data that could not be included in the paper published by the American Water Resources Association in their "Headwaters Hydrology" volume. The principle items included in this report are: (1) a discussion of the geology; (2) a description of the drilling program and the well installation; (3) a table listing arsenic concentrations for all wells sampled during the study; and (4) and extended surface-water data table incorporating the results of the U. S. Geological Survey's sampling program on this portion of the Madison River. The accompanying article discusses the origin of the arsenic, briefly presents the results of the surface water sampling, and discusses the groundwater arsenic content in detail. Most readers will find reading the article first and then returning to the open-file report for additional details the most efficient procedure.

GEOLOGIC UNITS AND HYDROGEOLOGIC CONSIDERATIONS

The various geologic units that contain or control significant amounts of ground water are discussed below. To facilitate understanding by the reader, the units are presented from youngest to oldest. This is the sequence in which they are encountered when drilling a water well. Obviously, not all units are likely to be encountered in any one well. The reader interested in greater detail is referred to G. D. Robinson's U. S. Geological Survey Professional Paper 370, entitled "Geology of the Three Forks Quadrangle, Montana".

QUATERNARY DEPOSITS

The alluvial deposits of Quaternary age have been separated into younger and older alluvium by Robinson (1963), with the older alluvium exposed only outside of the Madison Valley floodplain. Test drilling just south of the Interstate on the eastern side of the valley floodplain suggests that the younger alluvium is is equivalent to the upper unit, a mixture of sands and rounded gravels with a thickness of 25 to 30 feet. This is underlain by sands with several pebbly zones. The lower unit is much better sorted and contains significantly less gravel. The sands are considerably finer, and "run" or "heave" into the well during drilling. The thickness of the this lower unit is about 50 feet at this location.

The presence of the lower alluvial unit may be of variable thickness and fairly erratic within the valley floodplain. Driller's logs for water wells at more centrally located sites sometimes indicate that clays, which are presumed to be of Tertiary age (Climbing Arrow Formation), are encountered at depths as shallow as 29 feet (Thorpe well log, NW1/4, sec. 29, T. 2 N., R. 2 E.). It may be a common drilling practice to drill to the depth at which fine grained deposits are encountered, when maximum well yields are sought from this aquifer. Thus, the depth of drilled wells (essentially all wells that are not driven sandpoints) that do not penetrate silts and clays may provide a rough approximation of the thickness of the alluvial aquifer.

Well yields from this unit are commonly limited by the well construction. A yield of 250 gallons per minute (gpm) was documented with about two feet of drawdown from a fully perforated, 22-foot deep, 5-inch diameter test well installed by Thomas, Dean and Hoskins in coarse gravels adjacent to the Jefferson River. The old City of Three Forks wells located on the western edge of the Madison floodplain (SW1/4, SE1/4, sec. 30, T. 2 N., R. 2 E.) were 125 and 150 feet deep and produced over 200 gpm from torch-cut slots in the steel casing. The driller's logs for these two wells have been interpreted to show 25 feet of the upper alluvial aquifer (mostly gravel) and up to 25 feet of the lower alluvial aquifer. These wells had to be abandoned in 1985 because of the high arsenic content of the water produced from them. It is believed that, because of ineffective seals, most of the water produced by these wells was actually coming from the alluvium, despite the fact that the inner pipe was only slotted within the Tertiary interval. Irrigation within the floodplain is based mainly upon water from the irrigation ditches. A secondary source for eastern benches (above the floodplain) has been the Tertiary aquifer. The authors have not attempted to locate alluvial irrigation wells to test and determine a reasonable range for the aquifer's hydraulic characteristics because such activity was outside of the basic scope of the study. It is estimated that transmissivities would normally be greater than 100,000 gallons per day per foot of drawdown (g/d*f), with storativities between 0.05 and 0.15.

TERTIARY FORMATIONS

Both of the units described below are thought to be derived predominently from the eolian, fluvial, and lacustrine deposits of Eocene and Oligocene volcanics (especially tuffs), intermixed with some detritus from older rocks (Robinson, 1963). The major distinction between these formations is based upon color and clay content.

Dunbar Creek Formation

This unit is exposed in the cliffs along both sides of the Madison Valley in much of the study area. It is a yellowish-white siltstone containing both sandstone and rare gravel beds. The cohesiveness of this unit is caused by both cementing agents (mainly calcite) and its clay content, although not all of the predominently thick beds are well indurated. It is distinguished from the lower alluvial unit when drilling by its greater resistance to drill bit penetration and rotation, and by the absence of "running sands". The basal 145 feet of this formation were encountered at the test well site. During drilling, a sand bed in the formation was sampled using the drillrig compressor; to accomplish this, water was mainly produced from depths of 100 to 105 feet, the distence that the drillbit had advanced beyond the end of the casing. The yield from this zone, one of the more productive sandstone beds encountered in well no. 4, was roughly 50-75 gpm. No caving or sloughing of the formation was noted as a result of this test, a distinct contrast to the behavior of the alluvium.

Climbing Arrow Formation

The contact between the Climbing Arrow formation and the Dunbar Creek formation is gradational (Robinson, 1963, p. 80). When driling, the contact can be defined by the depth of the first substantial occurance of olive-green mudstone. The color of the water being produced will change from milky-clear to muddy-gray with a slight greenish cast. The formation consists of montmorillonitic clay, tuffaceous siltstones, and coarse sandstones. Only the uppermost portion of this formation is exposed in the Madison Valley near Three Forks. Drilling results within the town of Three Forks have shown that the upper 150-200 feet of this unit is the most productive (Van Dyken well log for city well no. 3, drilled in 1945; Layne-Minnesota well log for city well no. 4, drilled in 1954-55). The well production is from the sandstone beds within the formation. With greater depth, the sand units become fewer, thinner, and apparently, less laterally extensive.

Test well no. 4 was completed in the first sandstone bed of this formation, which was 1.5 to 2.0 feet in thickness. During development, this sandstone layer was yielding about 150 gpm, as determined using a 5-gallon bucket and stopwatch.

PRE-TERTIARY ROCKS

Mississippian Age Rocks

The Madison Group limestones crop out just to the east of the Madison Valley and are well exposed near Logan. High capacity wells have been completed in the Madison Group near Logan. It is thought that the aquifer is recharged at Logan where the Gallatin River flows across the gravel covered Madison outcrop. One well sampled in this study is thought to be completed in this limestone aquifer.

Pre-Cambrian Age Rocks

Only one pre-Cambrian unit has been recognised in the study area. It is a pre-Belt quartzofeldspathic gneiss containing pods of amphibolite where exposed along the road just north of Cherry Creek, in the southeastern edge of the valley. There may be dolomitic marble layers present; however they were not noted during a brief inspection of the road cut. The major significance of this unit from a hydrogeologic perspective is that this crystalline rock unit provides a boundary condition for groundwater flow in the alluvium and the sedimentary rocks. Most crystalline rock units have low porosity and water moves mainly through interconnected fractures and joints. These openings are more common near the land surface. High capacity wells are extremely rare in such rocks. No wells sampled in this study are thought to encounter these rocks.

SURFACE WATER MONITORING

RATIONALE

Preliminary data indicated that the use of Madison River water for irrigation was the most likely source of the arsenic which has contaminated the groundwater in the alluvial aquifer (Sonderegger and Ohguchi, 1988). Quantification of the dissolved arsenic concentration in the river, above and below the major river stretch along which substantial irrigation occurs, was a major data collection goal within this study.

Most of the irrigators in the the valley utilize water taken from the Madison River. A monthly sampling program was instituted to provide information about the arsenic concentration in the river and a representative irrigation ditch. One sampling site was established at the upper end of the valley, at the Black's Ford fishin access, *.* miles below Beartrap Canyon. This is just above the first irrigation headgate and should represent the typical intake water before irrigation return flows have any impact upon the water chemistry. A second river sampling site was established just below Three Forks, 0.25 miles north of the northern access road which parallels Interstate Highway 90 (I-90). An irrigation ditch sampling site is located just south of I-90 on the east side of the valley.

These data will complement those collected by the U.S. Geological Survey and provide a longer period of record to assess the arsenic content of the irrigation water which is a significant factor in the recharge of the alluvial aquifer.

IMPLEMENTATION

Depth-integrated sampling techniques were used at all sites employing a DH-48 hand-held suspended-sediment sampler to collect the water samples. Use of a bridge crane was found to be impractical because of the traffic hazard. Cross-sectional wading was unsafe during peak discharge periods. Consequently, sites were selected on the convex side of a bend in the river and wading was employed to reach the deeper, main-channel portion of the river (commonly five feet deep at the lower site).

Samples were collected starting in August of 1987 for the upper station and the ditch, and in September for the lower station on the river. Sampling was continued through November, 1988. Results from this study are presented, along with the earlier U.S. Geological Survey results, in Table 1.

DISCUSSION

The results from this study alone are discussed in the accompanying article. However, utilization of the USGS data in conjunction with our sampling results permits the presentation of a longer term picture of the annual fluctuations in arsenic concentration in the Madison River. These data show :

1) The normal peak in river arsenic concentration occurs in March of April.

2) The runoff period (freshet) associated with snowmelt normally causes a 40 to 50 percent reduction in the rivers arsenic concentration.

Station 06042600 is a USGS sampling site approximately 0.3 miles south and on the opposite bank from the Bureau's downstream sampling site TFSWL. The data presented are not entirely compatible. The USGS determinations were performed on an unfiltered, acidified sample. The MBMG determinations were performed upon a filtered, acidified sample. However, during the initial stages we collected both types of samples and found that, even for turbid irrigation waters, there was essentially no difference in the arsenic content.

GROUNDWATER INVESTIGATION

INVENTORY

The inventory of existing wells was conducted by the junior author during the late summer and early fall of 1987. When residents could not be reached at home between 9 am and 8 pm, they were called to try to arrange a weekend meeting. Almost everyone in the valley was quite cooperative.

Information requested included depth of the well; when drilled, by whom, water levels (if known), and permission to sample the well was requested. We initially intended to minimize sampling in the high population density areas by only sampling about every third well where houses were clustered together. This policy was later modified for the north end of the valley in the high-arsenic zone.

Specific conductance was measured during the inventory stage to provide the sampling team with a cross check that they were at the proper well and to look for seasonal changes. No significant seasonal changes were noted.

SAMPLING

Well-water samples were initially collected during the period November 5-11, 1987 by the authors. When feasible, the samples were taken from outside hydrants prior to pressure tanks in the distribution system. However, because of the health-related aspects of the study, many "kitchen-sink" samples were collected at the request of the owner or occupant of the dwelling. Where treatment systems were installed, samples of both the treated and untreated water were commonly collected. Specific conductance and temperature were measured for all samples collected. To minimize the analytical costs, most of the samples were collected only for analysis of the dissolved-arsenic content in the water; hence, additional field parameters were not normally determined.

Review of the laboratory's analytical results showed unexpectedly high arsenic concentrations in wells completed in the Tertiary-age materials along the eastern edge of the valley on Buffalo Jump Road. Sampling in this area had been from roughly every third well in the intial stage because the Tertiary aquifer was not thought to be contaminated. This led to follow-up sampling in 1988 where essentially every household that would permit sampling was sampled.

SAMPLING RESULTS

The laboratory results for the the groundwater samples are presented in Appendix A, which is organized by owner or residents name to facilitate response to area resident inquiries. Addresses are provided to facilitate determining locations for those unfamiliar with the legal land description based upon township, range, and section. The date on which the sample was collected is included, as is the measured or reported depth of the well and whether the water was treated in any manner. The dissolved arsenic content is presented in micrograms per liter (ug/l). In dilute waters such as these, this is equivalent to parts per billion. The Montana Bureau of Mines laboratory number is included along with comments to help identify the sample and the sampling point.

Many of these analyses have been plotted in map format; the reader will find them depicted on Figure 2 of the accompanying article (Sonderegger and others, 1989).

DRILLING PROGRAM RESULTS

The location for the test drilling site (Figure 1 of the accompanying article) was chosen after the laboratory results from the fall (1987) well-sampling suite had been plotted on a base map. It was apparent that unexpectedly high arsenic concentrations were present in the water from wells along the eastern side of the valley. This phenomena was not restricted to wells deriving their water from the thin alluvial aquifer, but also included wells which clearly started in the older and less transmissive Tertiary aquifer. Consequently, a site was picked which was on the southeastern edge of the previously identified area, along and north of the Interstate Highway, and also was along the alluvial groundwater flow path (Sonderegger and Ohguchi, 1988) from the newly identified high arsenic occurrence on the east side of the valley. An agreement was drawn up with a cooperative landowner, Jeanette Smith Hepner, which permitted drilling as many wells as needed and as was feasible and which guaranteed continuing access to those wells for scientific purposes. The test-site location is along the south frontage road, 0.3 mile west of the the eastern valley side and about 200 feet west of the second irrigation ditch encountered as one crosses the valley from east to west. The legal description of this location is Township 2 North, Range 2 East, section 28, SE1/4, SE1/4, NE1/4, of the SW1/4. Appendix B contains more detailed information about the site location system used by the Bureau. The drilling logs for the test wells follow the narrative.

AUGER DRILLING PROGRAM

A Mobile B-50 auger drilling rig using 3.25-inch I.D. hollow-stem augers was used to install shallow monitoring wells at the research site. Drilling commenced on Monday, March 21, 1988 and was completed on Friday, March 25, 1988. In that time three monitoring wells were installed, using Timco internally-threaded monitoring pipe and screen. Each monitoring well had two feet of 0.010-inch slotted plastic screen installed just above the bottom cap. These wells were designed to measure water levels at different depths and to collect representative water samples from these depths. The fine screen slot size was necessary because of fine sand and silt as discussed below, but the short screen length and slot size prevented significant well development.

We attempted to install the deepest possible well first, with the intent of selecting the depths for additional wells from the lithologic information obtained from this first well. The hollow-stem auger bit required either a plug, basically a flat metal plate held in place by a snap ring, or the core barrel to be installed to prevent cuttings from coming up the interior open space of the hollow-stem auger during drilling. We started with the core barrel, but repeated plugging of the core barrel by large pebbles prevented its sucessful use. After installing the plug in the bit, we drilled to a total depth of 78 feet. There appeared to be a gravel-rich base to the unconsolidated sediments at a depth of 71 to 73 feet, based upon drill bit chatter and rig vibration, followed by a 2-foot transition to more indurated material which lifted the drill rig off of its rear leveling jacks.

We installed 80 feet of pipe, plus the 2.5-foot screen and bottom cap section, within the hollow-stem auger and attempted to use the well pipe to press the plug free by forcing the snap ring out of its groove. Even after raising the auger flight two feet and cutting the casing again to get optimal leverage, and later pressing the casing top with the drill head while supporting the raised auger flight with the rig sandline, did not free the bit plug. We were finally forced to remove the casing and knock the plug out with a weight attached to a rope. When the casing was put back into the well, only 45 feet would enter the hollow-stem auger. Fine sand and silt had flowed into the hollow portion of the auger and filled the bottom 31 feet. The casing was removed again, and the auger flight was rotated and raised until we were sure that the flight was free. Then, 40 feet of casing and screen were reinserted and the auger flight was rotated and raised. As each 5-foot auger section was removed from the flight, the casing was pressed down as far as possible with the drill head and the excess casing was cut off. In this manner, the auger flight was retrieved; however, the final well extended only 19.6 feet below land surface, with the center of the two-foot screen at at depth of 18.1 feet.

The second well was drilled to a depth of 43 feet and 40 feet of casing plus the 2.5 feet of screen and bottom cap were inserted in the hollow-stem auger. A short piece of casing from the first well had been threaded on to use to push the bit plug out, but again that was unsucessful. The casing was removed and the auger annulus filled with water from the adjacent irrigation ditch before knocking the plug out with the weight. The casing was reinstalled within the auger flight and the augers were removed. Clay was noted on the last few feet of the auger flight, but must not have been present in sufficient quantity to significantly effect the drilling characteristics. It is thought that this clay kept the fine sands and silts below from entering auger flight before the casing was installed. Completion included adding a short piece of female-threaded casing to permit use of the male-threaded well cap. The total cased depth of this well is 40.6 feet below land surface, with the center of the screen 1.5 feet higher.

The third well was a second attempt at the deep completion and proceeded more caution. Water was added to the flights annular space as each 5-foot section added. At 39 feet the flight was extracted, the plug was removed, and the flight reinstalled with a 2-foot split- spoon core barrel projecting slightly ahead of the bit. A sample from 39 to 41 feet was collected to evaluate the clay content noted on the outside of the auger from about this depth in the second well. The core contained just sand, although there was a smear of beige clay on the drive fitting at the mouth of the sampler. It is possible that we were just getting into clay-bound sand or a thin clay stringer when the split spoon was full and the bit rotation and penetration were stopped. The auger flight was removed to replace the bit plug and the hole was continued to a depth of 68.5 feet with water added to the annular space. The auger flight was rotated and lifted about 1 foot to provide room to press or knock the plug out. The intention was to install at least 60 feet of casing and screen below land surface in the fine "heaving" sands. To accomplish this, 70 feet of casing plus the screen and cap were inserted in the annular space and water added to "top off" both the augers and the casing. The bit plug was sucessfully pressed out, using the drill rig drive head. An unknown amount of sand flowed into the annular space between the casing and the hollow-stem auger; we immediately started removal of the auger flights, but the frictional drag of the sand caused us to lose 10 feet of casing depth during removal. The total depth of the third well is 55.4 feet below the land surface, with the two-foot screen centered at a depth of 53.9 feet.

ROTARY DRILLING PROGRAM

To obtain information about the water quality within the Tertiary formations, bids were requested for a 200 to 250 foot well, with the stipulation that it be drilled by forward rotary method using a casing hammer. This is a faster version of the old cable tool method. The casing is driven behind the bit, and cuttings blown out of the well using compressed air can be accurately ascribed to the interval that the bit has advanced ahead of the casing, unless the formation itself is extremely fluid. This latter condition is often logged by the drillers as "quicksand", "running sands", or "heaving sands".

Drilling started on Monday, June 27, 1988, and was completed on Wednesday, June 29th, except for surface casing recovery and cleanup work at the site. The well was drilled to a depth of 245 feet and was screened between the depths of 234.5 feet and 244.5 feet with 5-inch diameter, 0.020-inch slot size, stainless steel screen. The casing is 6-inch steel with a 0.25-inch wall thickness which weighs 17 pounds per linear foot. This is a standard grade of water-well casing. Formation top determinations are probably accurate to +/- one to two feet. Drilling started in the alluvial aquifer; the eroded top of the Dunbar Creek formation was encountered at a depth of 75 feet; the top of the Climbing Arrow formation was encountered at a depth of 220 feet.

A water sample was collected from the open interval 98 to 103 feet in the first sand unit of the Dunbar Creek formation after producing roughly 500 gallons of water from the formation. After installing the screen, the well was developed for one hour using the drill rig compressor and had a yield of about 150 gpm. Initially, a small amount of clay was produced along with fine sand and silt. Within two minutes all turbidness was gone from the water. The well continued to produce coarse silt in trace amounts for the first half hour and was virtually sand- and silt-free at the end of an hour. A water sample was collected 45 minutes after the development period started.

ACKNOWLEDGMENTS

We wish to thank the Montana Department of Natural Resources and Conservation through the Water Deveolpment Program for the majority of the funding necessary in undertaking this project. The residents of the lower were quite gracious and tolerant; their interest in the results of the study are appreciated. The cooperation of Dr. Edward King of the Gallatin County Health Department and of Dr. Abraham Horpestad of the state Water Quality Bureau was a great help in answering questions about the residents' concerns at public meetings.

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APPENDIX A

TABLE OF WELL AND ARSENIC DATA
FOR THE LOWER MADISON VALLEY
BETWEEN BEARTRAP AND THE MISSOURI RIVER

APPENDIX A. WELL AND ARSENIC DATA FOR THE LOWER MADISON VALLEY, BETWEEN BEARTRAP AND THE MISSOURI RIVER

NAME OF RESIDENT	ADDRESS	SAMPLE DATE	LOCATION	DEPTH	TREATED?	As ug/l	LAB NO.	COMMENTS
Allen, Tom	5353 Buffalo Jump Road	19-May-88	T1NR2E22CDCC	90	N	138	88Q0357	
Arbuckle, Merrill	1991 Frontage Road	14-Jun-84	T2NR2E29AD	22	N	150	84Q0367	
Aughney, Duane	535 Trident Road	05-Nov-87	T2NR2E20DDB	80	N	117	87Q1096	
Beartrap Campsite	Highway 84 @ Madison River	13-Jun-84	T3SR1E02BDC	?	N	26	84Q0359	
Bogonofsky, Frank	Box 1111, Three Forks	06-Nov-87	T2NR2E20CBDC	?	N	122	87Q1100	
Bokum, Richard	5157 Madison Road	20-May-88	T1NR2E20AC	?	N	35	88Q0362	Barn well
Bokum, Richard	5157 Madison Road	20-May-88	T1NR2E20AC	92	N	37	88Q0363	Main house well; kit. tap
Christiansen, Bill	2630 Madison Road	13-Jun-84	T1NR2E04DCCCC	44	N	88	84Q0365	
Christiansen, Bill	2630 Madison Road	09-Nov-87	T1NR2E04DCCCC	44	Y	105	87Q1076	After water softener & filter
Christiansen, Bill	2630 Madison Road	09-Nov-87	T1NR2E04DCCC	44	N	96	87Q1077	1984 Analysis: As = 88
Cleveland, Curtis	17550 Old Town Main Street	11-Nov-87	T2NR1E24DDA	47	Y	0.8	87Q1105	Purifier system
Cleveland, Curtis	17550 Old Town Main Street	11-Nov-87	T2NR1E24DDA	47	N	1.2	87Q1106	Stock & lawn
Climbing Arrow Ranch	c/o TBE Ranch	13-Jun-84	T1NR2E16CBD	?	N	69	84Q0364	Shallow dug well
Dale, Fred	Box 551, Three Forks	09-Nov-87	T2NR2E27CADD	60	N	16	87Q1085	Stock well in Zuelke's corral
Darlington, Gordon	8021 Madison Road	13-Jun-84	T1SR2E05AB	20	N	50	84Q0362	
Darlington, Gordon	8021 Madison Road	06-Nov-87	T1SR2E05AB	20	N	48	87Q1036	
Darlington, Steve	6623 Madison Road	13-Jun-84	T1NR2E29DAD	?	N	50	84Q0363	
Doak, June	4000 Buffalo Jump Road	10-Mar-88	T1NR2E15DD	102	N	63	88Q0121	
Doak, June	4000 Buffalo Jump Road	19-May-88	T1NR2E15DD	102	Y	0.9	88Q0356	Still sample (jug)
Ewan, J. R.	9920 Madison Road	13-Jun-84	T1SR2E17AAB	80	N	45	84Q0361	
Ewan, J. R.	9920 Madison Road	09-Nov-87	T1SR2E17AAB	30	N	52	87Q1080	
Ewan, J. R.	9920 Madison Road	09-Nov-87	T1SR2E17AAA	80	N	44	87Q1091	
Ewan, Lonny	11350 Buffalo Jump Road	20-May-88	T1SR2E22BCCB	?	N	20	88Q0364	
Fonk, Betty	6623 Madison Road	09-Nov-87	T1NR2E29DCA	?	N	53	87Q1079	1984 Analysis = 50 ug/l
Gillespie, John	1670 Carpenter Drive	09-Nov-87	T2NR2E21ACDB	25	N	61	87Q1083	
Gordon, Bob	13505 Buffalo Jump Road	05-Nov-87	T1SR2E29DDDB	33	N	25	87Q1046	
Hankin, Ernest	15520 Crowley Lane	09-Nov-87	T1NR2E21ABBA	32	N	54	87Q1075	
Hankin, Jay	15580 Crowley Lane	09-Nov-87	T1NR2E21ABBB	?	N	50	87Q1074	
Hargrove, David	3333 Frontage Road	05-Nov-87	T2NR2E27CBC	33	N	106	87Q1095	Located at lumber yard
Hargrove, David	3333 Frontage Road	20-May-88	T2NR2E27CBC	33	Y	11	88Q0366	Sears reverse-osmosis unit
Hargrove, David	3333 Frontage Road	16-Sep-88	T2NR2E27CBC	33	Y	1	88Q1333	Sears reverse-osmosis unit
Hart, Frank	1470 Trident Road	24-Mar-88	T2NR2E17DDCC	55	N	66	88Q0171	
Hartkopf, Joe	4333 Madison Road	09-Nov-87	T1NR2E16CBD	?	N	67	87Q1078	1984 Analysis: As = 69
Henry, Don	565 Madison Road	13-Jun-84	T2NR2E32AAAA	75	N	85	84Q0366	
Hepner, Jeanette Smith	16070 Madison Frontage Road	10-Nov-87	T2NR2E28CADD01	20	N	130	87Q1069	Sandpoint; ditch water As = 67
Hernandez, Amado	Box 2825, Norris	05-Nov-87	T2SR2E19BA	Shallow	N	32	87Q1041	
Hoffman, Chuck	Box 155, Three Forks	10-Nov-87	T2NR2E29DD	30	N	59	87Q1071	
Hotzel, James	290 Madison Road	10-Nov-87	T2NR2E28CBCC	40	N	92	87Q1070	Sandpoint, depth may be wrong
Jacobs, Allan	4470 Buffalo Jump Road	19-May-88	T1NR2E22ABB	78	N	98	88Q0355	
Jorgenson, Jack	7777 Buffalo Jump Road	10-Mar-88	T1SR2E04AACC	55	N	84	88Q0125	
Jorgenson, Jack	7777 Buffalo Jump Road	20-May-88	T1SR2E03DCC	400	N	61	88Q0367	Tertiary irrigation well
Kamerman, Brad	3995 Buffalo Jump Road	10-Mar-88	T1NR2E15DCBB	40	N	67	88Q0122	House Well
Kamerman, Brad	3995 Buffalo Jump Road	10-Mar-88	T1NR2E15DCBD	80	N	100	88Q0123	Dairy Well
Kieffer, Don	15393 Madison Road	05-Nov-87	T2SR2E05CCC	54	N	30	87Q1039	
Koenig, Martin	13999 Madison Road	05-Nov-87	T2SR2E05BDBD	60	N	39	87Q1050	
Ledebur, William	2655 Pyfer Road	06-Nov-87	T2NR2E20D	30	N	40	87Q1082	
Ledebur, William	2655 Pyfer Road	19-May-88	T2NR2E20DAC	30	N	52	88Q0354	
Love, Melvin	15140 Kilgore Lane	05-Nov-87	T1SR2E29AAC	61	N	27	87Q1045	

APPENDIX A. WELL AND ARSENIC DATA FOR THE LOWER MADISON VALLEY, BETWEEN BEARTRAP AND THE MISSOURI RIVER (CONTINUED)

NAME OF RESIDENT	ADDRESS	SAMPLE DATE	LOCATION	DEPTH	TREATED?	As ug/l	LAB NO.	COMMENTS
Martin, Ken	9919 Madison Road	06-Nov-87	T1SR2E08CDDC	100	N	48	8701037	Davis' live here now
Masters, Terry	5857 Buffalo Jump Road	06-Nov-87	T1NR2E27BCCB	48	N	112	8701042	
MBMG1	16070 Madison Frontage Road	14-Apr-88	T2NR2E28CADD02	19	N	43	8800230	Resampled 7/15/88
MBMG1	16070 Madison Frontage Road	15-Jul-88	T2NR2E28CADD02	19	N	71	8800832	
MBMG2	16070 Madison Frontage Road	14-Apr-88	T2NR2E28CADD03	43	N	68	8800229	Resampled 7/15/88
MBMG2	16070 Madison Frontage Road	15-Jul-88	T2NR2E28CADD03	43	N	58	8800833	
MBMG3	16070 Madison Frontage Road	14-Apr-88	T2NR2E28CADD04	56	N	29	8800228	Resampled 7/15/88
MBMG3	16070 Madison Frontage Road	15-Jul-88	T2NR2E28CADD04	56	N	22	8800834	
MBMG4	16070 Madison Frontage Road	29-Jun-88	T2NR2E28CADD05	109	N	25	8800699	Sampled while drilling
MBMG4	16070 Madison Frontage Road	29-Jun-88	T2NR2E28CADD05	245	N	95	8800700	Sampled after 1 hr. development
MBMG4	16070 Madison Frontage Road	16-Aug-88	T2NR2E28CADD05	245	N	76	8801247	Sampled after 2+hr.s pumping
McDonnell, Stephen Jr.	9050 Buffalo Jump Road	06-Nov-87	T1NR2E33DAB	?	N	68	8701043	
McDonnell, Stephen Jr.	9165 Buffalo Jump Road	06-Nov-87	T1SR2E10CAA	60	N	55	8701044	
Messing, Everett	31010 Francis Rd., Belgrade	20-May-88	T1SR2E16DDA	65	N	38	8800365	Near lower schoolhouse
Morgan, Gene(?)	Frontage Rd. E of Logan	16-Aug-88	T2NR2E35BBB	?	?	2.2	8801248	Sampled: lawn hose
Nerlin, Roger	40 Carpenter Lane	09-Nov-87	T2NR2E27DCA	33	N	4.1	8701087	Domestic well
Nerlin, Roger	40 Carpenter Lane	09-Nov-87	T2NR2E27DCA	29	N	3.7	8701088	Stock well
Olson, Edith	17444 Old Town Main Street	11-Nov-87	T2NR2E19CCB	20	N	3.7	8701101	
Potts, Mark & Kim	14045 Madison Road	13-Jun-84	T2SR2E05BAA	60	N	36	8400360	
Prescott, John & Ann	3080 Pyfer Road	06-Nov-87	T2NR2E20CABC	30	N	176	8701081	
Prescott, John & Ann	3080 Pyfer Road	04-Apr-88	T2NR2E20CABC	30	N	121	8800126	
Prescott, John & Ann	3080 Pyfer Road	19-May-88	T2NR2E20CABC	30	Y	0.3	8800352	Culligan reverse-osmosis unit
Prescott, John & Ann	3080 Pyfer Road	19-May-88	T2NR2E20CABC	30	N	148	8800353	
Prescott, John & Ann	3080 Pyfer Road	16-Sep-88	T2NR2E20CABC	30	Y	0.6	8801334	Culligan reverse-osmosis unit
Pyfer, Lloyd	3155 Pyfer Road	06-Nov-87	T2NR2E20CDAC	12	N	111	8701099	
Rae, Jack	2255 Madison Road	09-Nov-87	T1NR2E04CB	43	Y	62	8701073	"Conditioned" water from house
Rae, Jack	2255 Madison Road	20-May-88	T1NR2E04CB	21	N	88	8800360	Stock well
Rae, Jack	2255 Madison Road	20-May-88	T1NR2E04CB	8	N	91	8800361	Stock well
Randolph, Carol	14787 Madison Road	05-Nov-87	T2SR2E05CDA	63	N	27	8701038	
Richardson, Tom & Deirdre	4260 Buffalo Jump Road	10-Mar-88	T1NR2E22ABBB	58	N	119	8800119	House well
Richardson, Tom & Deirdre	4260 Buffalo Jump Road	10-Mar-88	T1NR2E22ABBB	58	Y	0.6	8800120	Distilled well water
Roadarmel, Jack	1150 Carpenter Lane	09-Nov-87	T2NR2E22CCC	60	N	72	8701084	
Robertson, Ellen	170 Old Town Road	09-Nov-87	T2NR2E19CCCB01	20	N	0.9	8701089	Sampled at corral
Robertson, Ellen	170 Old Town Road	09-Nov-87	T2NR2E19CCCB02	12	N	2.4	8701090	Flower Shop well
Schedel, Dean	360 Old Town Road	11-Nov-87	T2NR2E19CBCC	26	Y	1.2	8701103	Purifier on kitchen sink
Schedel, Dean	360 Old Town Road	11-Nov-87	T2NR2E19CBCC	26	N	1.6	8701104	Kitchen sink without purifier
Scollard, James	2375 Frontage Road	05-Nov-87	T2NR2E28CDAB	49	N	118	8701094	Swampy odor, black stain
Secora, Rick	15215 Madison Road	05-Nov-87	T2SR2E05CC	62	N	37	8701049	
Setzer, Randolph	16360 Madison Frontage Road	10-Nov-87	T2NR2E28CBD	50	N	123	8701068	Domestic & stock
Shaw, Carol	Box 915, Three Forks	05-Nov-87	T2NR2E29AD	37	N	73	8701092	House vacant, Shaw is owner
Shipton, Harold	11731 Buffalo Jump Road	06-Nov-87	T1SR2E21DBDB	180	N	44	8701047	
Shouse, Edith	17410 Old Town Main Street	11-Nov-87	T2NR2E19CCAB	SANDPOINT	N	2.6	8701102	
TBE Ranch	Box ???, Three Forks	15-Nov-83	T1NR2E06DAA	40	N	127	8301169	
Thorpe, Terry	3455 Pyfer Road	15-Nov-83	T2NR2E29BABD	27	Y	63	8301167	Iron removal filters
Thorpe, Terry	3455 Pyfer Road	06-Nov-87	T2NR2E29BABD	100	?	86	8701097	Well deepened
Tilden, Ruth	2325 Frontage Road	14-Jun-84	T2NR2E28BC	48	N	85	8400368	
Tilden, Ruth	2325 Frontage Road	05-Nov-87	T2NR2E28BC	48	N	119	8701093	Domestic & stock
Tinder, L. Marie	12060 Gallatin, Manhattan	10-Mar-88	T1NR2E22CABD	108	N	123	8800124	

APPENDIX A. WELL AND ARSENIC DATA FOR THE LOWER MADISON VALLEY, BETWEEN BEARTRAP AND THE MISSOURI RIVER (CONTINUED)

NAME OF RESIDENT	ADDRESS	SAMPLE DATE	LOCATION	DEPTH	TREATED?	As ug/l	LAB NO.	COMMENTS
Van Dyk, J. & J.	2545 Buffalo Jump Road	06-Nov-87	T1NR2E10DBB	45	N	120	87Q1048	
Wilcox, Ralph	4747 Buffalo Jump Road	19-May-88	T1NR2E22CA	73	N	130	88Q0358	
Wilkinson, Bob	3121 Pyfer Road	14-Jun-84	T2NR2E20CCAA	?	N	83	84Q0369	
Wilkinson, Bob	3121 Pyfer Road	06-Nov-87	T2NR2E20CCAA	?	N	105	87Q1098	
Williams, Chuck & Roberta	5545 Buffalo Jump Road	19-May-88	T1NR2E27BBD	145	Y	92	88Q0359	Kitchen tap (water softener)
Workman, Doc H.	Box 288, Norris	05-Nov-87	T2SR1E35DCD	29	N	47	87Q1040	Stock Well
Zuelke, John	101 Carpenter Lane	09-Nov-87	T2NR2E27DCB	56	N	18	87Q1086	Domestic, house & 2 trailers
Zuelke, Pat	565 Madison Road	10-Nov-87	T2NR2E32AAAA	75	N	90	87Q1072	As = 85 ug/l in 1984(Henry)

ARSENIC CONTAMINATION OF AQUIFERS CAUSED BY IRRIGATION WITH DILUTED GEOTHERMAL WATER

John L. Sonderegger, Brenda R. Sholes, Takeshi Ohguchi[1]

Abstract: The Madison River has its headwaters in Yellowstone National Park. River water leaving the Park typically contains 200 micrograms per liter (ug/l) dissolved arsenic. Downstream dilution normally reduces this to 40-80 ug/l in the lower valley (0-25 miles above the river mouth). Extensive use of the river water, via ditch systems, for irrigation of the valley bottom has been ongoing for the past 100 years. Sprinkler irrigation systems have become more popular over the last 20-30 years; sidehills and benches underlain by Tertiary-age sediments have also undergone irrigation.

Arsenic concentrations of 80-130 ug/l were found in the alluvial aquifer during limited sampling in the mid-1980's. The current study is based upon sampling roughly 75% of the wells in the lower valley, combined with river sampling above and below the major irrigated zone. The major results are:

1. Both the alluvial and underlying Tertiary aquifers have been contaminated; statistically, the results are almost identical.
2. Substantial increases in surface-water dissolved-As content were found below the major irrigation area during freshet and most of the irrigation season.
3. Commercial reverse-osmosis units have been very effective at removing As (efficiencies > 99% are verified) and have resulted in one resident urine-arsenic level decrease of one order of magnitude within six months.

(KEY TERMS: arsenic; irrigation; groundwater contamination; natural source)

INTRODUCTION

The lower Madison Valley in southwestern Montana was shown to contain anomalously high arsenic concentrations within a thin, alluvial aquifer of Quaternary age; comparisons between the groundwater chemistry and the Madison River water chemistry from within Yellowstone Park and downstream showed that irrigation with this water, derived in part from the geothermal system within the Park, was the most probable cause for the elevated (up to 150 ug/l) arsenic concentrations in the groundwater (Sonderegger and Ohguchi, 1988). Arsenic is a particularly difficult contaminant to remove, either naturally or artificially, because it is present as an anion (a negatively-charged, dissolved species) and is not easily removed from water. During this investigation, we collected groundwater samples from the wells of all residents willing to participate in the study. Seventy to seventy-five families are currently living within or immediately adjacent to the valley bottom. The dominant land use is the production of hay and alfalfa, plus cattle pasture. Surface water samples were collected upstream at the highest irrigation diversion, downstream below the major irrigated area, and from the

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easternmost irrigation ditch at the mouth of the valley. Background concentrations of As in Quaternary aquifers are <5 ug/l, and generally <15 ug/l in Tertiary aquifers; samples collected from the Quaternary, alluvial aquifer within the valley contained as much as 150 ug/l, while an apparently shallow Tertiary-aquifer well had a maximum value of 176 ug/l arsenic. Both stills and reverse-osmosis equipment were installed for the purification of domestic drinking water during the course of the investigation, and the effectiveness of these units has been evaluated.

Geologic and Hydrologic Framework

The Madison Valley study area contains alluvial deposits on a relatively flat surface that were incised into Tertiary-age strata of the Bozeman Group except where, locally, older alluvial gravels have been "let down" by erosion of earlier benches (Robinson, 1963). Hydrogeologically, the veneer of gravels is insignificant, and the Tertiary strata constitute an eroded, less permeable, gently-dipping unit on top of which recent alluvial sands and gravels have been deposited. To the south, in the upstream direction, older pre-Cambrian and minor lower-Paleozoic rocks are exposed south of a major fault or fault zone.

It is often difficult to establish a lower boundary for the Quaternary alluvium, because the Tertiary formations along the Madison Valley contain layers of poorly consolidated sand, pebbly sand, and conglomerate interbedded with clay and claystones. We have used an operational definition by including older sand and gravel layers down to the first recognizable clay layer with the alluvial aquifer, as they are hydraulically interconnected. The alluvial aquifer ranges in thickness from at least 100 feet (30 meters) in the south to about 27 feet (8 meters) near the mouth of the valley in the north. The depth to the top of the water table ranges from 30 to 40 feet (9 to 12 m) in the south to generally about 5 feet (1 to 2 m) in the north. Figures 1a and 1b depict the generalized geologic framework and the approximate elevation of the top of the alluvial-aquifer water table, respectively. Notice that the 10-meter water-table contours do not compress with the thinning of the alluvial aquifer. This is thought to result from a substantially increased gravel-to-sand ratio within the aquifer and from the joining of three alluvial valleys and three rivers to form the Missouri River, on the northern edge of the study area. Once the rivers join, they cut through relatively impermeable bedrock; hence the mouth of the Madison Valley constitutes a groundwater discharge area.

An estimate of the thickness of the alluvial aquifer at the valley mouth was made using the available well logs and the assumption, for shallow wells without logs, that they were drilled to the base of the alluvial aquifer. The resulting data plot suggested a thin fill with incised distributaries or a meandering channel, but could not be contoured with sufficient confidence to present at this time. The proposed infilled channel was on the east side of the valley in the vicinity of the test-drilling site and is projected to the NNW. The area that it relates to is predominantly north of the Interstate Highway, I-90, and represents the area just north of the valley mouth above the top of the area shown on Figure 1.

The river is currently located near the west side of the valley. Consequently, most of the irrigation and irrigation ditches are located on the eastern side; generally four or five major ditches plus numerous laterals and return-flow ditches are present in the eastern alluvial portion of the valley. These ditches have been in place and functioning for more than 100 years in many cases. The easternmost ditch is located almost entirely upon a Tertiary formation above the alluvial aquifer that constitutes the valley floor. During the past 30 years, sprinkler irrigation has been added to the system. Some of the sprinklers have been employed in the valley bottom, but the major use has been to irrigate the more gently sloping portions of the valley sides. In almost all cases, the irrigation ditches carrying Madison River water are the supply source for these sprinkler systems.

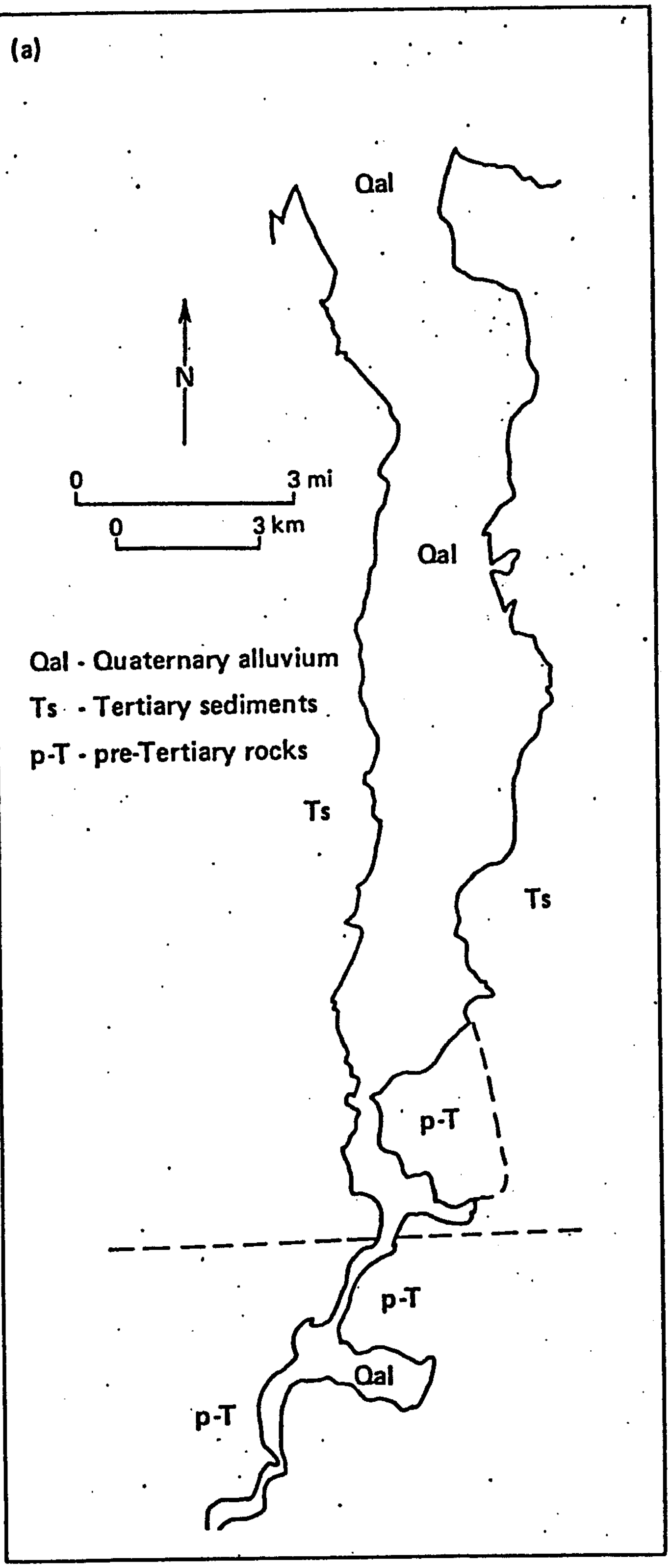

Figure 1a—Generalized geologic map of the study area. The dashed line represents the approximate location of the fault (down thrown to the north) which separates the more mountainous terrain to the south from the valley and hills to the north. Results presented are for dissolved arsenic concentrations in groundwater of the alluvial aquifer (Qal) and the Tertiary aquifer (Ts).

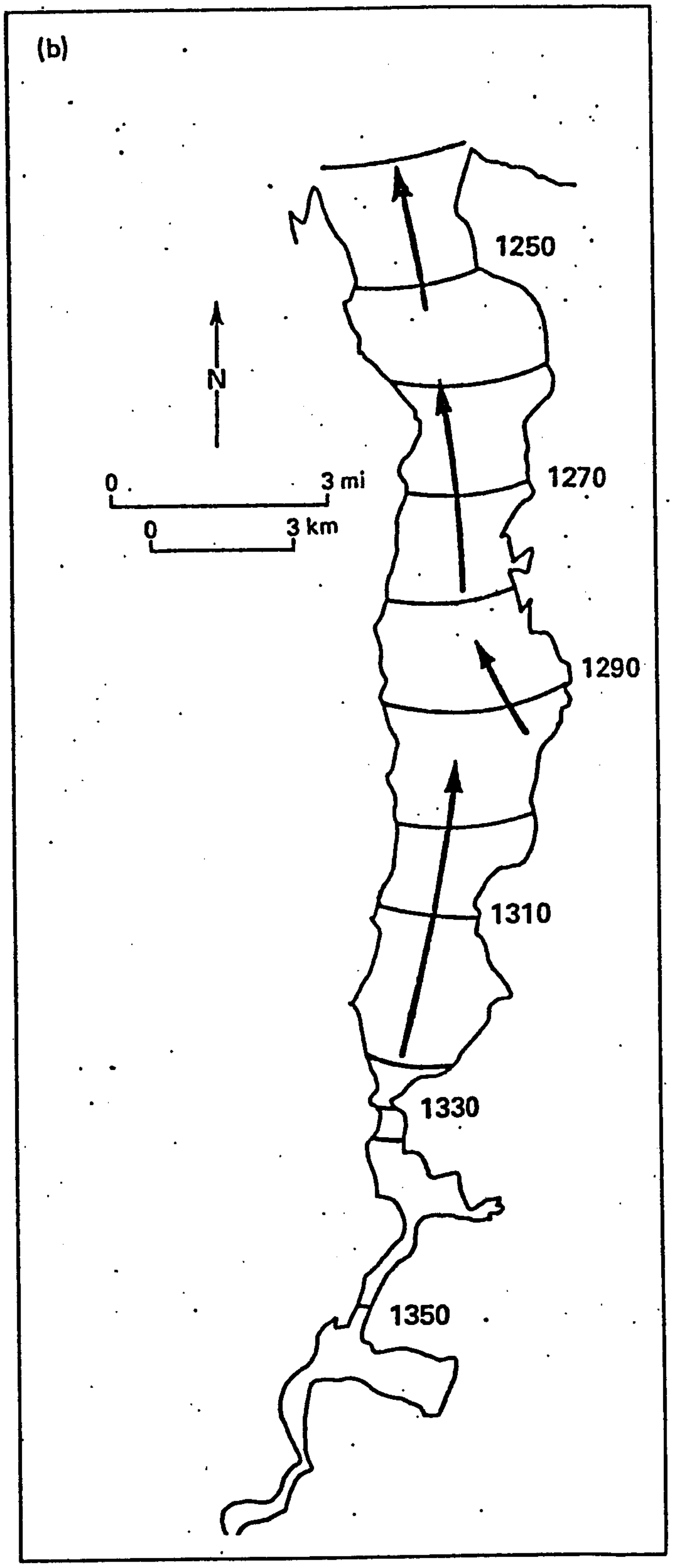

Figure 1b—Generalized elevation of the water table in meters. Data are from varying times and the figure is presented to show the general trend. In the vicinity of the 1240 meter contour there is no measurable head difference as a function of depth in piezometers ranging in depth from 19 to 56 feet (6 to 17 m).

PRESENTATION OF RESULTS

The results of the surface-water sampling are presented in Table 1 to show the range of values for the surface-water sites. It is clear that, during the freshet and most of the irrigation season, an impact upon the river, consisting of elevated arsenic concentrations at the downstream site can be shown. These increases are thought to result mainly from groundwater additions to the river water flux. Downstream concentrations during April through July were substantially higher than upstream concentrations. The August, 1988, concentrations may be nonrepresentative and reflect effects of the widespread forest fires occurring in the headwaters of the drainage.

Table 1. Surface Water Arsenic Concentrations (ug/l)

Date	Upstream	Downstream	Irrigation
18-Aug-87	61	NA	70
16-Sep-87	78	75	NA
21-Oct-87	80	66	72
19-Nov-87	78	79	65
17-Dec-87	77	80	74
18-Jan-88	73	78	70
19-Feb-88	75	76	69
20-Mar-88	72	81	69
14-Apr-88	49	74	59
18-May-88	41	72	58
18-Jun-88	54	66	72
15-Jul-88	71	94	86
16-Aug-88	95	100	81
16-Sep-88	77	78	77
16-Oct-88	58	60	62
16-Nov-88	62	57	61

Analytical results for over 100 groundwater samples are available elsewhere (Sonderegger and Sholes, 1989) in tabled form. These results may be more easily utilized when presented in map format. Figure 2 depicts the location of the sampling sites and lists the dissolved arsenic concentration. The numbers represent untreated water unless otherwise indicated. Where multiple samples were collected, as many of these values as possible are presented. What becomes immediately apparent is that the amount of arsenic present in the groundwater increases to the north, in the downstream direction. North of McDonnell Road, the average concentration is higher along the eastern side of the valley (Buffalo Jump Road) than it is along the western side or in the central area (Madison Road).

One of the questions, that this study hoped to resolve, was whether the aquifer materials could be the source of the arsenic in the alluvial-aquifer system. A test-drilling site was located just south of I-90 at the mouth of the valley; this site overlies the high-As plume coming from the east side of the valley as it moves northwest under the more developed area north of highway. Samples from the first and fourth test wells were collected at various depths and used to test whether the aquifer materials could be the arsenic source. The aquifer samples were not far above what would be considered average rock values for total arsenic. Shales average about 6 parts per million (ppm or ug/g), while granites and sandstones contain less arsenic. These aquifer samples contain two to three times the amount of arsenic that would be predicted based upon such average values. This is not sufficiently high to be considered a major source, when the groundwater contains 10 to 100 times the normal arsenic content. Instead, it almost certainly results in part from sorption and possibly precipitation reactions which have removed some of the dissolved arsenic, and in part from the fact that a portion of the sediments being studied were derived from intermediate-to-acidic volcanic rocks which tend to be enriched in arsenic.

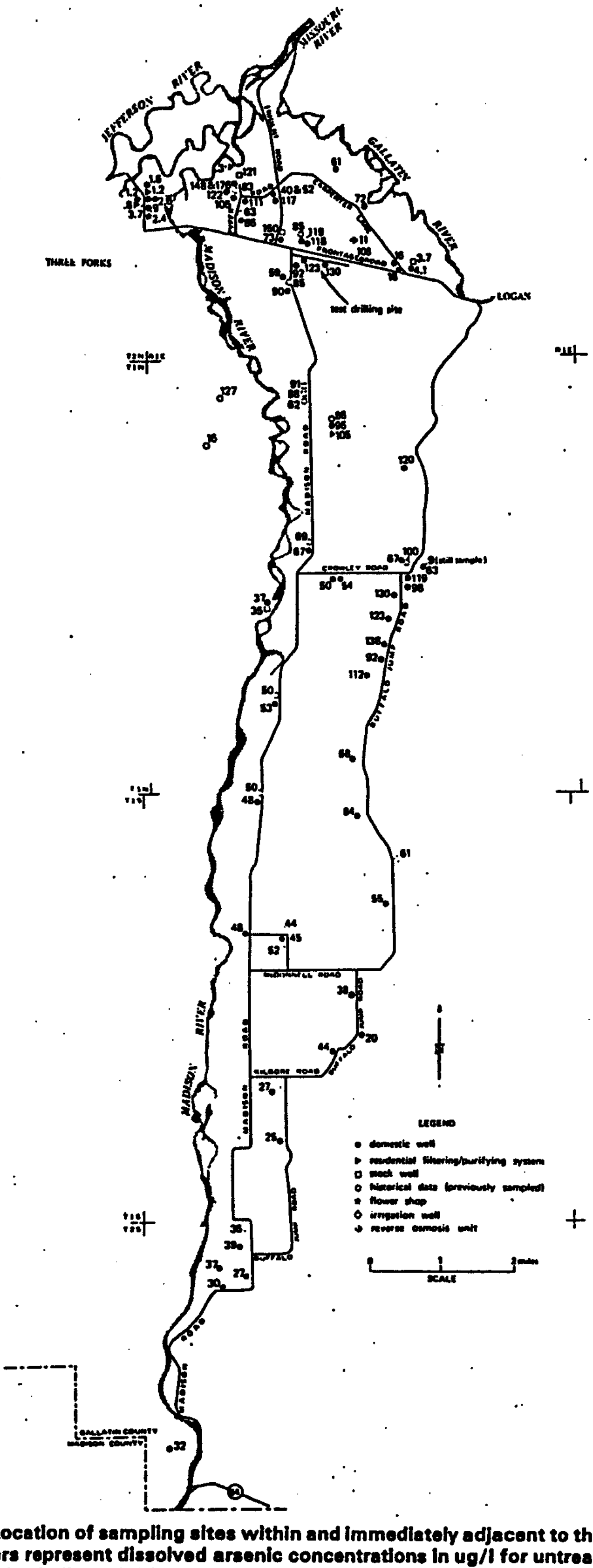

Figure 2—Location of sampling sites within and immediately adjacent to the valley floor. The numbers represent dissolved arsenic concentrations in ug/l for untreated water unless otherwise indicated. The Bureau's test wells are located by the * symbol.

Table 2 contains the results of several leaching experiments. The first column shows the footage interval from which the sample was collected. The second column represents a whole-rock arsenic content, resulting from a complete digestion of the sample. The next three columns represent the amount of arsenic released by leaching a small amount of sample in a large amount of neutral, acidic, or basic water. The amount of arsenic released by leaching ranges from about 10 to 25 percent of the total amount determined by the complete digestion in the whole-rock analysis. The last column represents the adaptation of a soils study approach to create a "worst case" situation. The samples when collected were somewhat "soupy" and had to be oven dried and crushed. This process retained the arsenic dissolved in the water and caused many newly fractured surfaces to be formed during crushing. A weighed amount of sample was put in a small beaker and distilled water was added until the sample was saturated. After 24 hours the sample was filtered under vacuum and the water drawn off was analyzed. Only the deepest samples produced water containing significantly greater arsenic than the groundwater samples from roughly the same depth. The two water samples collected from the 235 to 245 foot depth contained 76 and 95 ug/l As (test well no. 4), compared with the soil paste extract values of 191 and 244 ug/l. The cause of these elevated arsenic concentrations in the leachate is not fully understood. It does suggest that a kinetically-rapid sorption or precipitation mechanism (a calcium-arsenate phase?) may be occurring within this portion of the aquifer.

Table 2. Madison Valley Leaching Experiment Results

Sample Depth (feet)	Digestion (ug/g)	Water Leach (ug/g)	Acid Leach (ug/g)	Base Leach (ug/g)	Soil Paste (ug/l)
20-22	4.4	1.10	.40	.81	22
29-33	3.7	.96	.34	.66	25
50	3.1	.83	.26	.51	42
70	2.6	.68	.20	.35	94
78	5.6	.97	.48	.58	61
145-147	4.4	.64	.35	.35	87
194	6.0	1.40	.49	.62	88
235-240	7.2	.62	.72	.86	191
240-245	4.6	.41	.48	.60	244

DISCUSSION OF RESULTS

Well logs filed by the well drillers were used to separate those wells completed in the Tertiary clays and sands from those completed in the Quaternary alluvium. Any such separation will include some error as descriptions will vary from driller to driller before the added complexity of mixing drill-rig types (cable tool and forward rotary are the two main types used in the valley) is considered. Additionally, not all wells had logs recorded. One of the hypotheses that we tried to further evaluate with this study was whether the arsenic concentrations increased in a downstream direction in a manner consistent with irrigation usage. After separating the wells as to aquifer, a statistical program (STATGRAPHICS) was used to calculate correlation coefficients between the distance downstream from the upper surface water sampling site near the first irrigation headgate and the arsenic content of the water from both of the aquifers. The assumption implicit in this approach is that irrigation impacts could be approximated by a linear function; this assumption proved to be invalid, but provided an initial analysis approach which, we believe, has furthered our understanding of the system.

The correlation coefficients between the variables were quite low, +0.681 for th alluvial aquifer and +0.554 for the Tertiary aquifer. Surprisingly, when all well samples were lumped together, the correlation coefficient was only slightly reduced (+0.643) from that of the alluvial aquifer alone. The largest standard deviation was calculated for the

Tertiary samples. This was not solely the result of the smaller sample size, but also flected the greater variability in the data. This variability is attributed to the greater riety of irrigation impact upon this aquifer.

Much of the outcrop of the Tertiary aquifer is not irrigated, which was the reason that we did not expect to see the aquifer significantly impacted. However, the main irrigation ditch on the east side of the valley is located roughly twenty to thirty feet (6 to 9 m) above the elevation of the alluvial contact. This location was undoubtedly chosen to reduce ditch losses by placing the ditch within the more clay-rich sediments of this unit. Still, leakage of river water through the ditch bottom must occur. Because the ditch, road, and houses along Buffalo Jump Road are all collinear, it is logical to assume that some correlation exists. The strongest impact would be expected to be found among the shallow wells close to the irrigation ditch. This concept is verified to some degree as shown by inspection of the results for wells located along this road. Wells deeper than 100 feet tend to have lower arsenic concentrations, but the pattern is neither clear nor internally consistent along Buffalo Jump Road.

Additional features which may complicate the picture include the fact that ditch irrigation is still the major irrigation method in the valley bottom, while sprinkler irrigation is the only feasible method of irrigating the steeper terrain associated with the Tertiary outcrop area. Sprinkler irrigation causes higher evaporation losses than ditch irrigation; hence, the infiltrating river water used for irrigation has a greater arsenic-enrichment factor. Ditch irrigation has been utilized for the past century, while sprinkler irrigation use started approximately 30 years ago.

Irrigation of the Tertiary bench on the western side of the valley has been more limited, and, with the exception of Bokum property, the minor amount of land irrigated has mainly utilized groundwater or non-Madison River surface water. Earlier studies by the Bureau (Sonderegger, 1983, ms) showed that the Tertiary formations south of Three Forks ntained water with "acceptable" arsenic content (normally <15 ug/l). Consequently, the rsenic concentrations from the two wells on the Bokum property (35 and 37 ug/l) probably reflect an irrigation impact also.

Distinguishing between aquifers for some of the wells was accomplished using the major-ion chemistry. Figure 3 is a Piper plot depicting the relative concentrations of the dominant cations and anions. These analyses are from wells with good lithologic descriptions, and include our deep test well. The Tertiary-aquifer samples from outside the area of irrigation impact are characteristically very high in sodium and low in calcium and magnesium whereas the alluvial-aquifer samples generally have combined alkaline earths (Ca and Mg for the purposes of this plot) as the dominant cations. The arrow shows the shift in major-ion chemistry attributed to the use of river water for irrigation on the Tertiary outcrop. The cause of this shift is interpreted to be the depletion of sodium on the ion-exchange sites of the clays contained within this aquifer and re-equilibration of the clays with the chemistry of the irrigation water.

An alternate, physical explanation for these chemistries exists. If the wells which pass through the alluvium have significantly disturbed and/or more permeable materials adjacent to the casing throughout the (Tertiary) unit, water from the alluvial aquifer can move down this zone and enter the well. If the well starts in the Tertiary formation, but is adjacent to the valley alluvium, any coarse and permeable layer which extends to the alluvial fill may provide a pathway for the movement of some groundwater from the alluvial aquifer to either the annular zone or directly to the open zone of the well. As the distance of the well from the edge of the valley increases, the amount of the alluvial groundwater component should decrease.

Every effort was made to prevent the first situation described above from occurring with our deep test well. Eight-inch surface casing was driven through the alluvial aquifer nd stopped in a 20-foot thick (6-m) clay layer. Six-inch casing was driven inside the urface casing and bentonite was added to the annular space between the two strings of casing, as it was being driven the last 30 feet (9 m) to insure a good vertical seal. Thus, we believe that vertical contamination was not a factor causing the water chemistry shown on Figure 3 for the 240-foot well.

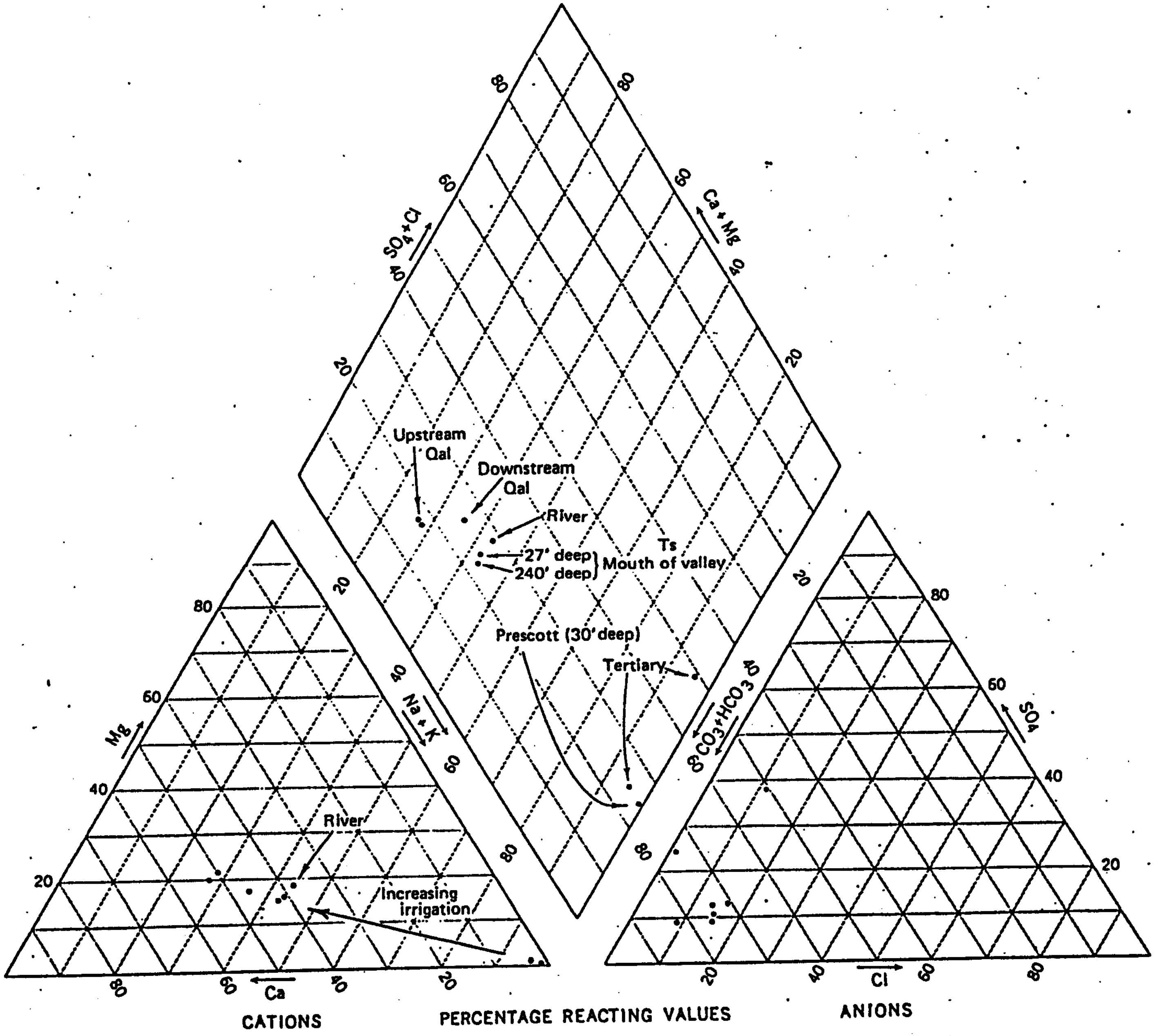

Figure 3—Piper plot depicting the normal range of chemical composition for groundwaters in the alluvial and Tertiary aquifers. The surface water chemistry sampled upstream at the first irrigation headgate is presented for comparison. The arrow depicts the presumed mixing effects of irrigation water recharge upon the Tertiary aquifer.

The Prescott well contained the highest dissolved-arsenic concentration determined in is study. The well is located on the northern edge of the study area where the three river lleys merge. Because of its shallow depth (30 ft), the well was originally thought to have been completed and developed within the alluvial aquifer. However, a complete analysis of water from this well shows an unmistakable Tertiary chemistry (99.5 % Na+K). The records for this well were very poor, consisting of only a groundwater appropriation form. However, this well's water chemistry suggests that it may have been a common drilling practice to drive casing through the alluvial aquifer and complete wells in the first sand below a clay layer.

It can be postulated that the flushing action of recharge from irrigating with river water has not yet caused any significant replacement of sodium on exchange sites, and that the sample from this location represents the leading edge of the impact from such irrigation. If this is valid, the groundwater flow rate in the Tertiary-aquifer system can be estimated to be between 500 and 2,000 feet per year, if the source of the arsenic enriched water is the result of sprinkler irrigation of the Tertiary outcrop area. This groundwater velocity is roughly one order of magnitude greater than would normally be expected for Tertiary basin-fill materials, and, if valid, must represent the larger hydraulic-conductivity values of the sandstone members. The high apparent velocity, plus results from the 245 foot-deep test well, suggest that vertical movement into the Tertiary aquifer is dominated by secondary porosity associated with features such as joints.

Health Related Aspects

Stills and reverse-osmosis purifiers have been put into use at residences in the study area during the period of the investigation. Both types of purifying system can produce ter with 99 % removal of arsenic when properly maintained. One of the residents with a ghly impacted well had a 24-hour urine test conducted to see if she had elevated arsenic in her body (this is the same type of test that is routinely given to workers at hazardous waste sites where arsenic is a health concern; concentrations greater than 100 ug/l require withdrawing the worker from the site). Upon learning that her test results were 220 ug/l, the family installed a reverse-osmosis unit. The average of three untreated samples from their well was 147 ug/l; the average of two treated samples collected four months apart was 0.45 ug/l. A repeat 24-hour urine test of this resident six months later showed that her concentration had been reduced to 25 ug/l. Both the family and the physician are pleased with these results.

Projections for the Future

The groundwater samples show that the arsenic-concentration problem has become worse in portions of the Tertiary aquifer than in the alluvial aquifer. The data from the test drilling site indicate that the arsenic concentration within the various Tertiary-aquifer sand units is variable. The amount and percentage of irrigation related recharge to these units will obviously vary somewhat. When that variable is coupled with variations in hydraulic conductivity, head differentials, and flow-path distances, it becomes virtually impossible to make quantitative predictions; however qualitative predictions can be made. If all irrigation were to cease, it would take a minimum of 15 to 30 years to see a substantial improvement in the groundwater arsenic concentrations. We are probably not seeing maximum values in any of the wells. An indication of the rate of change in arsenic ncentration caused by sprinkler irrigation can be estimated using a commercial well-water alysis provided with sale documents for a house on Buffalo Jump Road. The house is sited on Tertiary strata and the 90-foot (27 m) deep well is solely within the Tertiary. In a little less than 10 years, the arsenic concentration has increased from 24 to 138 ug/l. These data suggest that continued degradation of the Tertiary aquifer will probably continue until a steady-state system, both hydraulic and chemical, is established in response to irrigation impacts. The geochemical control will probably be calcium concentration in the water; because the waters commonly have "mixed" geochemical signatures with calcium concentrations in the 50 to 100 mg/l range, groundwater concentrations of As are not expected to exceed 200 ug/l. However, continued degradation of water quality in the less severely impacted Tertiary sands should occur, with higher arsenic concentrations than found in the alluvial aquifer as the probable final condition.

ACKNOWLEDGMENTS

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HEADWATERS HYDROLOGY
JUNE AMERICAN WATER RESOURCES ASSOCIATION 1989

ARSENIC CONTAMINATION OF AQUIFERS CAUSED BY IRRIGATION WITH DILUTED GEOTHERMAL WATER

John L. Sonderegger, Brenda R. Sholes, Takeshi Ohguchi[1]

Abstract: The Madison River has its headwaters in Yellowstone National Park. River water leaving the Park typically contains 200 micrograms per liter (ug/l) dissolved arsenic. Downstream dilution normally reduces this to 40-80 ug/l in the lower valley (0-25 miles above the river mouth). Extensive use of the river water, via ditch systems, for irrigation of the valley bottom has been ongoing for the past 100 years. Sprinkler irrigation systems have become more popular over the last 20-30 years; sidehills and benches underlain by Tertiary-age sediments have also undergone irrigation.

Arsenic concentrations of 80-130 ug/l were found in the alluvial aquifer during limited sampling in the mid-1980's. The current study is based upon sampling roughly 75% of the wells in the lower valley, combined with river sampling above and below the major irrigated zone. The major results are:

1. Both the alluvial and underlying Tertiary aquifers have been contaminated; statistically, the results are almost identical.
2. Substantial increases in surface-water dissolved-As content were found below the major irrigation area during freshet and most of the irrigation season.
3. Commercial reverse-osmosis units have been very effective at removing As (efficiencies > 99% are verified) and have resulted in one resident urine-arsenic level decrease of one order of magnitude within six months.

(KEY TERMS: arsenic; irrigation; groundwater contamination; natural source)

INTRODUCTION

The lower Madison Valley in southwestern Montana was shown to contain anomalously high arsenic concentrations within a thin, alluvial aquifer of Quaternary age; comparisons between the groundwater chemistry and the Madison River water chemistry from within Yellowstone Park and downstream showed that irrigation with this water, derived in part from the geothermal system within the Park, was the most probable cause for the elevated (up to 150 ug/l) arsenic concentrations in the groundwater (Sonderegger and Ohguchi, 1988). Arsenic is a particularly difficult contaminant to remove, either naturally or artificially, because it is present as an anion (a negatively-charged, dissolved species) and is not easily removed from water. During this investigation, we collected groundwater samples from the wells of all residents willing to participate in the study. Seventy to seventy-five families are currently living within or immediately adjacent to the valley bottom. The dominant land use is the production of hay and alfalfa, plus cattle pasture. Surface water samples were collected upstream at

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the highest irrigation diversion, downstream below the major irrigated area, and from the easternmost irrigation ditch at the mouth of the valley. Background concentrations of As in Quaternary aquifers are <5 ug/l, and generally <15 ug/l in Tertiary aquifers; samples collected from the Quaternary, alluvial aquifer within the valley contained as much as 150 ug/l, while an apparently shallow Tertiary-aquifer well had a maximum value of 176 ug/l arsenic. Both stills and reverse-osmosis equipment were installed for the purification of domestic drinking water during the course of the investigation, and the effectiveness of these units has been evaluated.

Geologic and Hydrologic Framework

The Madison Valley study area contains alluvial deposits on a relatively flat surface that were incised into Tertiary-age strata of the Bozeman Group except where, locally, older alluvial gravels have been "let down" by erosion of earlier benches (Robinson, 1963). Hydrogeologically, the veneer of gravels is insignificant, and the Tertiary strata constitute an eroded, less permeable, gently-dipping unit on top of which recent alluvial sands and gravels have been deposited. To the south, in the upstream direction, older pre-Cambrian and minor lower-Paleozoic rocks are exposed south of a major fault or fault zone.

It is often difficult to establish a lower boundary for the Quaternary alluvium, because the Tertiary formations along the Madison Valley contain layers of poorly consolidated sand, pebbly sand, and conglomerate interbedded with clay and claystones. We have used an operational definition by including older sand and gravel layers down to the first recognizable clay layer with the alluvial aquifer, as they are hydraulically interconnected. The alluvial aquifer ranges in thickness from at least 100 feet (30 meters) in the south to about 27 feet (8 meters) near the mouth of the valley in the north. The depth to the top of the water table ranges from 30 to 40 feet (9 to 12 m) in the south to generally about 5 feet (1 to 2 m) in the north. Figures 1a and 1b depict the generalized geologic framework and the approximate elevation of the top of the alluvial-aquifer water table, respectively. Notice that the 10-meter water-table contours do not compress with the thinning of the alluvial aquifer. This is thought to result from a substantially increased gravel-to-sand ratio within the aquifer and from the joining of three alluvial valleys and three rivers to form the Missouri River, on the northern edge of the study area. Once the rivers join, they cut through relatively impermeable bedrock; hence the mouth of the Madison Valley constitutes a groundwater discharge area.

An estimate of the thickness of the alluvial aquifer at the valley mouth was made using the available well logs and the assumption, for shallow wells without logs, that they were drilled to the base of the alluvial aquifer. The resulting data plot suggested a thin fill with incised distributaries or a meandering channel, but could not be contoured with sufficient confidence to present at this time. The proposed infilled channel was on the east side of the valley in the vicinity of the test-drilling site and is projected to the NNW. The area that it relates to is predominantly north of the Interstate Highway, I-90, and represents the area just north of the valley mouth above the top of the area shown on Figure 1.

The river is currently located near the west side of the valley. Consequently, most of the irrigation and irrigation ditches are located on the eastern side; generally four or five major ditches plus numerous laterals and return-flow ditches are present in the eastern alluvial portion of the valley. These ditches have been in place and functioning for more than 100 years in many cases. The easternmost ditch is located almost entirely upon a Tertiary formation above the alluvial aquifer that constitutes the valley floor. During the past 30 years, sprinkler irrigation has been added to the system. Some of the sprinklers have been employed in the valley bottom, but the major use has been to irrigate the more gently sloping portions of the valley sides. In almost all cases, the irrigation ditches carrying Madison River water are the supply source for these sprinkler systems.

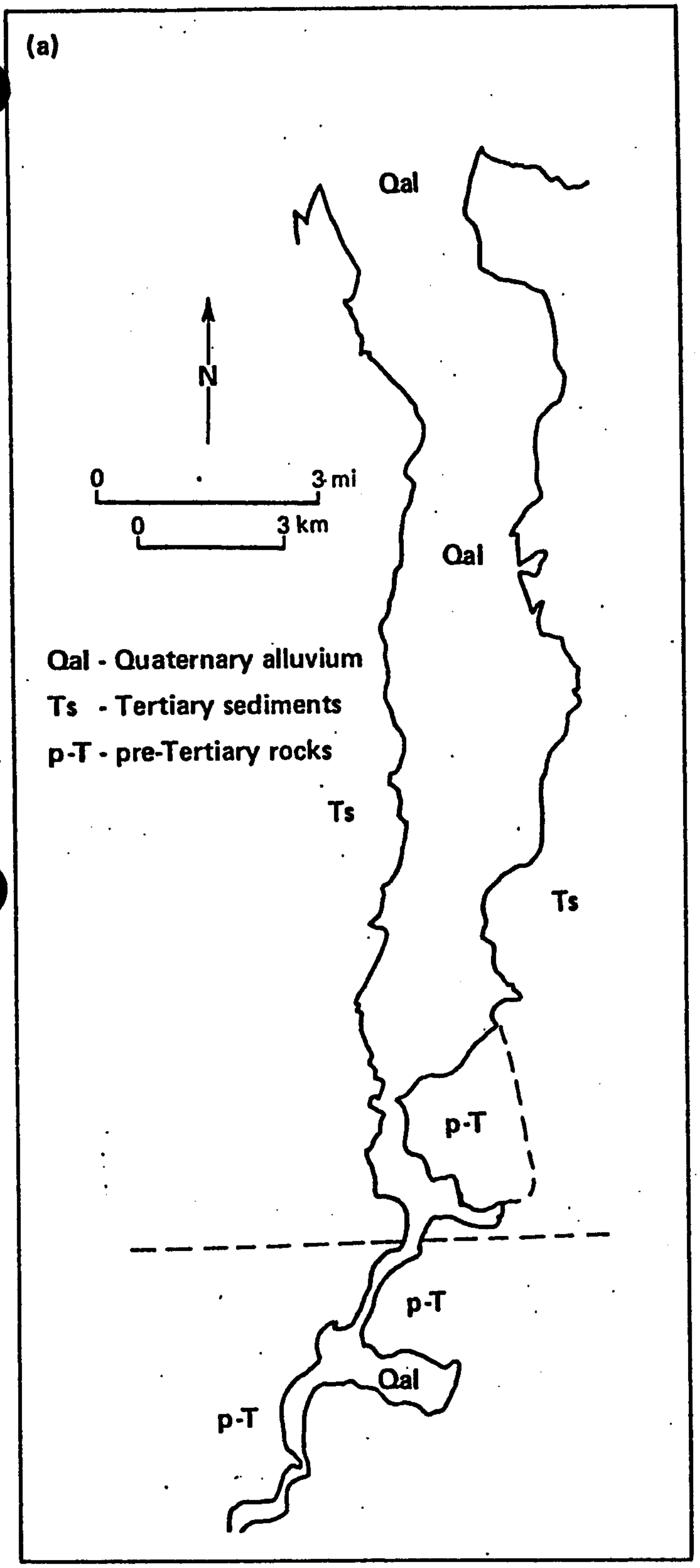

Figure 1a—Generalized geologic map of the study area. The dashed line represents the approximate location of the fault (down thrown to the north) which separates the more mountainous terrain to the south from the valley and hills to the north. Results presented are for dissolved arsenic concentrations in groundwater of the alluvial aquifer (Qal) and the Tertiary aquifer (Ts).

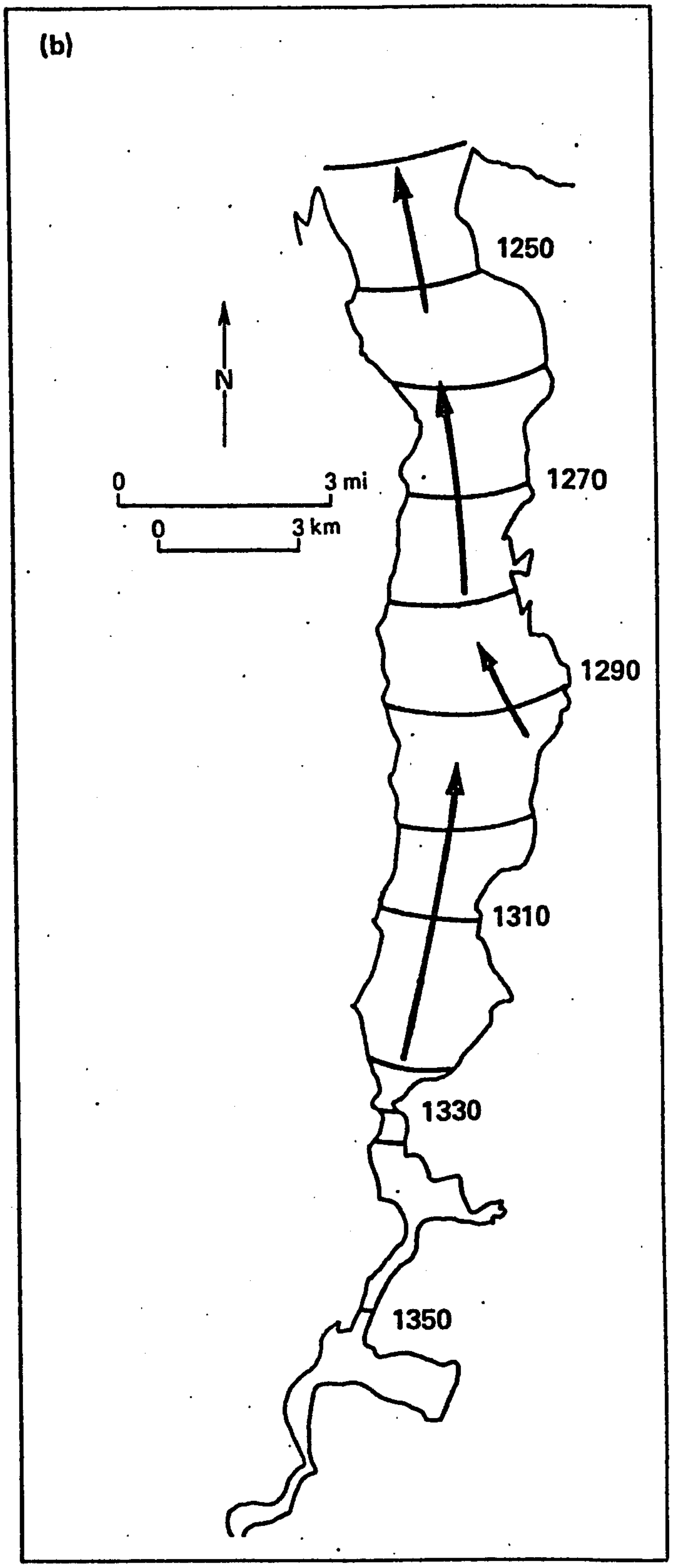

Figure 1b—Generalized elevation of the water table in meters. Data are from varying times and the figure is presented to show the general trend. In the vicinity of the 1240 meter contour there is no measurable head difference as a function of depth in piezometers ranging in depth from 19 to 56 feet (6 to 17 m).

PRESENTATION OF RESULTS

The results of the surface-water sampling are presented in Table 1 to show the range of values for the surface-water sites. It is clear that, during the freshet and most of the irrigation season, an impact upon the river, consisting of elevated arsenic concentrations at the downstream site can be shown. These increases are thought to result mainly from groundwater additions to the river water flux. Downstream concentrations during April through July were substantially higher than upstream concentrations. The August, 1988, concentrations may be nonrepresentative and reflect effects of the widespread forest fires occurring in the headwaters of the drainage.

Table 1. Surface Water Arsenic Concentrations (ug/l)

Date	Upstream	Downstream	Irrigation
18-Aug-87	61	NA	70
16-Sep-87	78	75	NA
21-Oct-87	80	66	72
19-Nov-87	78	79	65
17-Dec-87	77	80	74
18-Jan-88	73	78	70
19-Feb-88	75	76	69
20-Mar-88	72	81	69
14-Apr-88	49	74	59
18-May-88	41	72	58
18-Jun-88	54	66	72
15-Jul-88	71	94	86
16-Aug-88	95	100	81
16-Sep-88	77	78	77
16-Oct-88	58	60	62
16-Nov-88	62	57	61

Analytical results for over 100 groundwater samples are available elsewhere (Sonderegger and Sholes, 1989) in tabled form. These results may be more easily utilized when presented in map format. Figure 2 depicts the location of the sampling sites and lists the dissolved arsenic concentration. The numbers represent untreated water unless otherwise indicated. Where multiple samples were collected, as many of these values as possible are presented. What becomes immediately apparent is that the amount of arsenic present in the groundwater increases to the north, in the downstream direction. North of McDonnell Road, the average concentration is higher along the eastern side of the valley (Buffalo Jump Road) than it is along the western side or in the central area (Madison Road).

One of the questions, that this study hoped to resolve, was whether the aquifer materials could be the source of the arsenic in the alluvial-aquifer system. A test-drilling site was located just south of I-90 at the mouth of the valley; this site overlies the high-As plume coming from the east side of the valley as it moves northwest under the more developed area north of highway. Samples from the first and fourth test wells were collected at various depths and used to test whether the aquifer materials could be the arsenic source. The aquifer samples were not far above what would be considered average rock values for total arsenic. Shales average about 6 parts per million (ppm or ug/g), while granites and sandstones contain less arsenic. These aquifer samples contain two to three times the amount of arsenic that would be predicted based upon such average values. This is not sufficiently high to be considered a major source, when the groundwater contains 10 to 100 times the normal arsenic content. Instead, it almost certainly results in part from sorption and possibly precipitation reactions which have removed some of the dissolved arsenic, and in

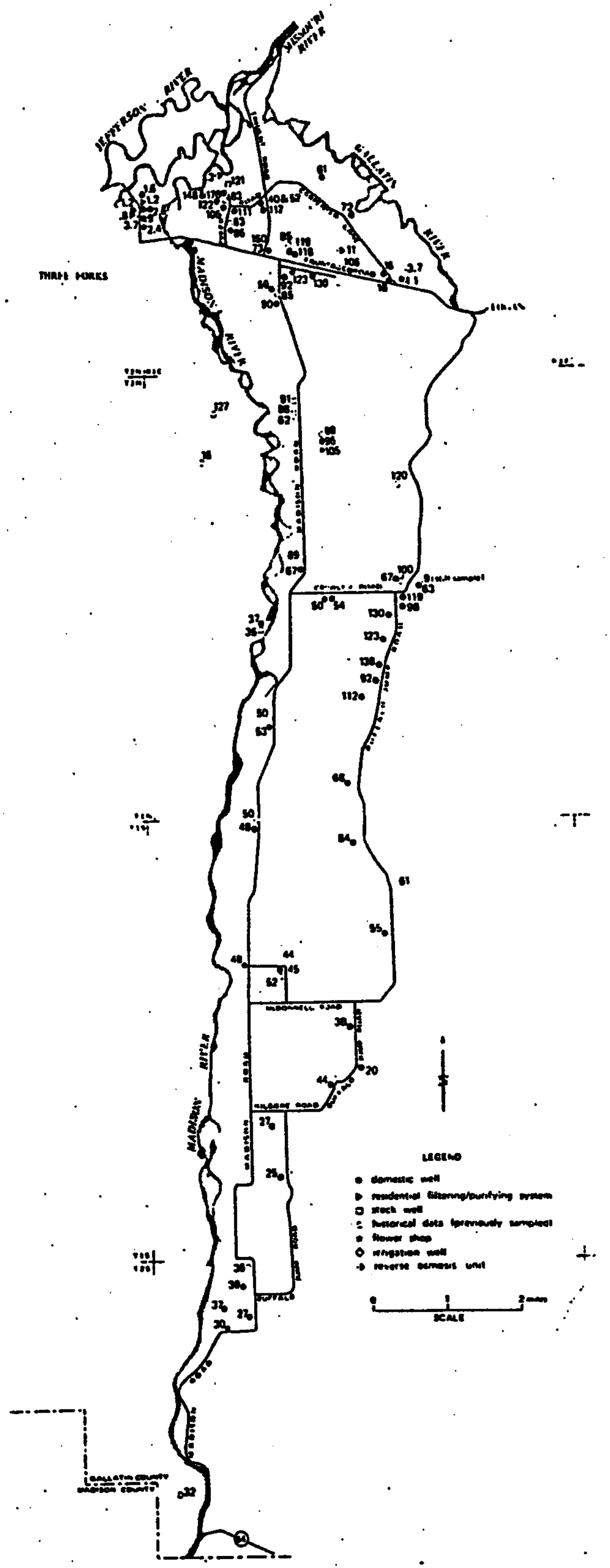

Figure 2—Location of sampling sites within and immediately adjacent to the valley floor. The numbers represent dissolved arsenic concentrations in ug/l for untreated water unless otherwise indicated. The Bureau's test wells are located by the * symbol.

part from the fact that a portion of the sediments being studied were derived from intermediate-to-acidic volcanic rocks which tend to be enriched in arsenic.

Table 2 contains the results of several leaching experiments. The first column shows the footage interval from which the sample was collected. The second column represents a whole-rock arsenic content, resulting from a complete digestion of the sample. The next three columns represent the amount of arsenic released by leaching a small amount of sample in a large amount of neutral, acidic, or basic water. The amount of arsenic released by leaching ranges from about 10 to 25 percent of the total amount determined by the complete digestion in the whole-rock analysis. The last column represents the adaptation of a soils study approach to create a "worst case" situation. The samples when collected were somewhat "soupy" and had to be oven dried and crushed. This process retained the arsenic dissolved in the water and caused many newly fractured surfaces to be formed during crushing. A weighed amount of sample was put in a small beaker and distilled water was added until the sample was saturated. After 24 hours the sample was filtered under vacuum and the water drawn off was analyzed. Only the deepest samples produced water containing significantly greater arsenic than the groundwater samples from roughly the same depth. The two water samples collected from the 235 to 245 foot depth contained 76 and 95 ug/l As (test well no. 4), compared with the soil paste extract values of 191 and 244 ug/l. The cause of these elevated arsenic concentrations in the leachate is not fully understood. It does suggest that a kinetically-rapid sorption or precipitation mechanism (a calcium-arsenate phase?) may be occurring within this portion of the aquifer.

Table 2. Madison Valley Leaching Experiment Results

Sample Depth (feet)	Digestion (ug/g)	Water Leach (ug/g)	Acid Leach (ug/g)	Base Leach (ug/g)	Soil Paste (ug/l)
20-22	4.4	1.10	.40	.81	22
29-33	3.7	.96	.34	.66	25
50	3.1	.83	.26	.51	42
70	2.6	.68	.20	.35	94
78	5.6	.97	.48	.58	61
145-147	4.4	.64	.35	.35	87
194	6.0	1.40	.49	.62	88
235-240	7.2	.62	.72	.86	191
240-245	4.6	.41	.48	.60	244

DISCUSSION OF RESULTS

Well logs filed by the well drillers were used to separate those wells completed in the Tertiary clays and sands from those completed in the Quaternary alluvium. Any such separation will include some error as descriptions will vary from driller to driller before the added complexity of mixing drill-rig types (cable tool and forward rotary are the two main types used in the valley) is considered. Additionally, not all wells had logs recorded. One of the hypotheses that we tried to further evaluate with this study was whether the arsenic concentrations increased in a downstream direction in a manner consistent with irrigation usage. After separating the wells as to aquifer, a statistical program (STATGRAPHICS) was used to calculate correlation coefficients between the distance downstream from the upper surface water sampling site near the first irrigation headgate and the arsenic content of the water from both of the aquifers. The assumption implicit in this approach is that irrigation impacts could be approximated by a linear function; this assumption proved to be invalid, but provided an initial analysis approach which, we believe, has furthered our understanding of the system.

The correlation coefficients between the variables were quite low, +0.681 for the alluvial aquifer and +0.554 for the Tertiary aquifer. Surprisingly, when all well samples were lumped together, the correlation coefficient was only slightly reduced (+0.643) from that of the alluvial aquifer alone. The largest standard deviation was calculated for the Tertiary samples. This was not solely the result of the smaller sample size, but also reflected the greater variability in the data. This variability is attributed to the greater variety of irrigation impact upon this aquifer.

Much of the outcrop of the Tertiary aquifer is not irrigated, which was the reason that we did not expect to see the aquifer significantly impacted. However, the main irrigation ditch on the east side of the valley is located roughly twenty to thirty feet (6 to 9 m) above the elevation of the alluvial contact. This location was undoubtedly chosen to reduce ditch losses by placing the ditch within the more clay-rich sediments of this unit. Still, leakage of river water through the ditch bottom must occur. Because the ditch, road, and houses along Buffalo Jump Road are all collinear, it is logical to assume that some correlation exists. The strongest impact would be expected to be found among the shallow wells close to the irrigation ditch. This concept is verified to some degree as shown by inspection of the results for wells located along this road. Wells deeper than 100 feet tend to have lower arsenic concentrations, but the pattern is neither clear nor internally consistent along Buffalo Jump Road.

Additional features which may complicate the picture include the fact that ditch irrigation is still the major irrigation method in the valley bottom, while sprinkler irrigation is the only feasible method of irrigating the steeper terrain associated with the Tertiary outcrop area. Sprinkler irrigation causes higher evaporation losses than ditch irrigation; hence, the infiltrating river water used for irrigation has a greater arsenic-enrichment factor. Ditch irrigation has been utilized for the past century, while sprinkler irrigation use started approximately 30 years ago.

Irrigation of the Tertiary bench on the western side of the valley has been more limited, and, with the exception of Bokum property, the minor amount of land irrigated has mainly utilized groundwater or non-Madison River surface water. Earlier studies by the Bureau (Sonderegger, 1983, ms) showed that the Tertiary formations south of Three Forks contained water with "acceptable" arsenic content (normally <15 ug/l). Consequently, the arsenic concentrations from the two wells on the Bokum property (35 and 37 ug/l) probably reflect an irrigation impact also.

Distinguishing between aquifers for some of the wells was accomplished using the major-ion chemistry. Figure 3 is a Piper plot depicting the relative concentrations of the dominant cations and anions. These analyses are from wells with good lithologic descriptions, and include our deep test well. The Tertiary-aquifer samples from outside the area of irrigation impact are characteristically very high in sodium and low in calcium and magnesium whereas the alluvial-aquifer samples generally have combined alkaline earths (Ca and Mg for the purposes of this plot) as the dominant cations. The arrow shows the shift in major-ion chemistry attributed to the use of river water for irrigation on the Tertiary outcrop. The cause of this shift is interpreted to be the depletion of sodium on the ion-exchange sites of the clays contained within this aquifer and re-equilibration of the clays with the chemistry of the irrigation water.

An alternate, physical explanation for these chemistries exists. If the wells which pass through the alluvium have significantly disturbed and/or more permeable materials adjacent to the casing throughout the (Tertiary) unit, water from the alluvial aquifer can move down this zone and enter the well. If the well starts in the Tertiary formation, but is adjacent to the valley alluvium, any coarse and permeable layer which extends to the alluvial fill may provide a pathway for the movement of some groundwater from the alluvial aquifer to either the annular zone or directly to the open zone of the well. As the distance of the well from the edge of the valley increases, the amount of the alluvial groundwater component should decrease.

Every effort was made to prevent the first situation described above from occurring with our deep test well. Eight-inch surface casing was driven through the alluvial aquifer and stopped in a 20-foot thick (6-m) clay layer. Six-inch casing was driven inside the surface casing and bentonite was added to the annular space between the two strings of casing, as it was being driven the last 30 feet (9 m) to insure a good vertical seal. Thus,

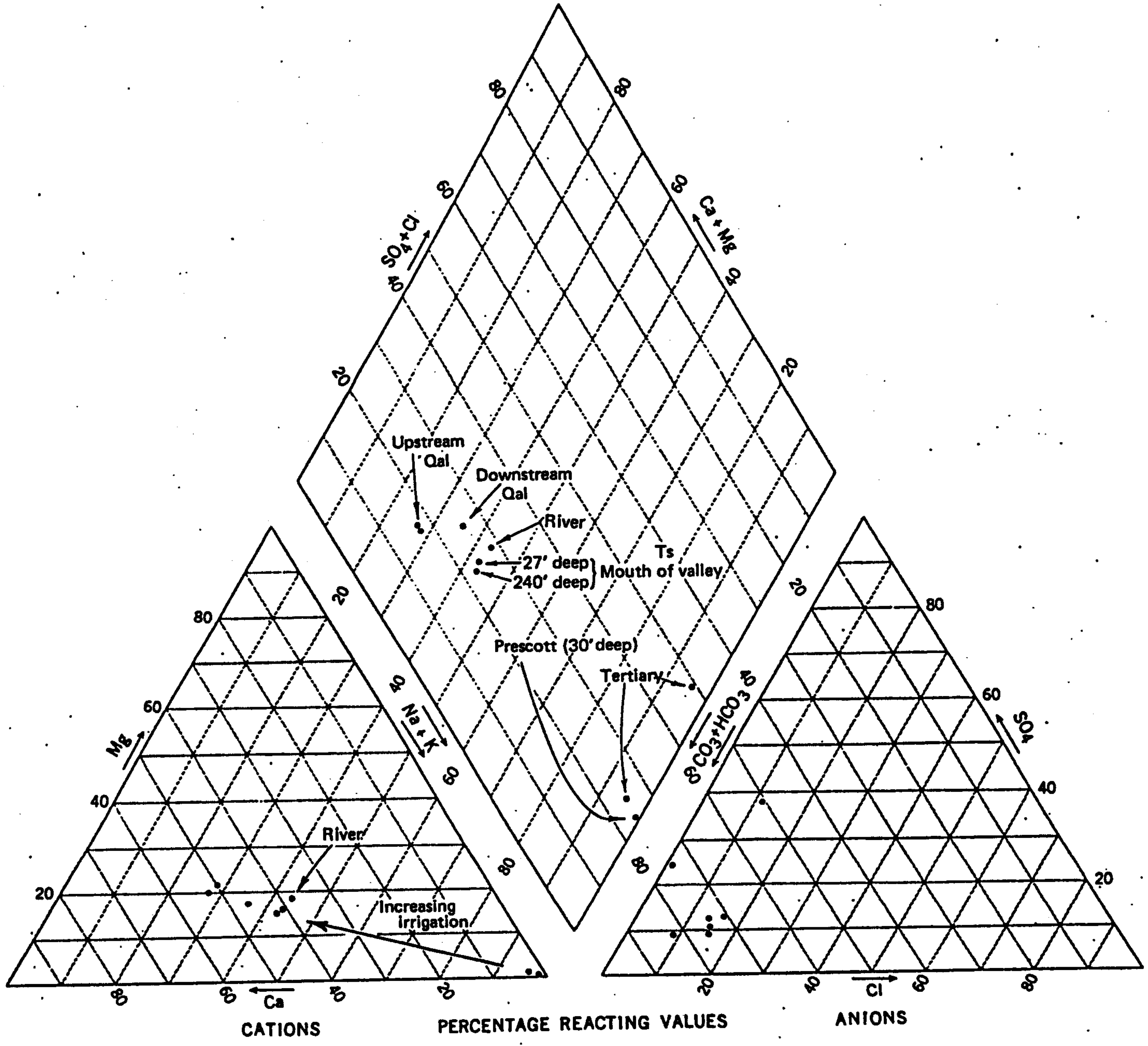

Figure 3—Piper plot depicting the normal range of chemical composition for groundwaters in the alluvial and Tertiary aquifers. The surface water chemistry sampled upstream at the first irrigation headgate is presented for comparison. The arrow depicts the presumed mixing effects of irrigation water recharge upon the Tertiary aquifer.

we believe that vertical contamination was not a factor causing the water chemistry shown on Figure 3 for the 240-foot well.

The Prescott well contained the highest dissolved-arsenic concentration determined in this study. The well is located on the northern edge of the study area where the three river valleys merge. Because of its shallow depth (30 ft), the well was originally thought to have been completed and developed within the alluvial aquifer. However, a complete analysis of water from this well shows an unmistakable Tertiary chemistry (99.5 % Na+K). The records for this well were very poor, consisting of only a groundwater appropriation form. However, this well's water chemistry suggests that it may have been a common drilling practice to drive casing through the alluvial aquifer and complete wells in the first sand below a clay layer.

It can be postulated that the flushing action of recharge from irrigating with river water has not yet caused any significant replacement of sodium on exchange sites, and that the sample from this location represents the leading edge of the impact from such irrigation. If this is valid, the groundwater flow rate in the Tertiary-aquifer system can be estimated to be between 500 and 2,000 feet per year, if the source of the arsenic enriched water is the result of sprinkler irrigation of the Tertiary outcrop area. This groundwater velocity is roughly one order of magnitude greater than would normally be expected for Tertiary basin-fill materials, and, if valid, must represent the larger hydraulic-conductivity values of the sandstone members. The high apparent velocity, plus results from the 245 foot-deep test well, suggest that vertical movement into the Tertiary aquifer is dominated by secondary porosity associated with features such as joints.

Health Related Aspects

Stills and reverse-osmosis purifiers have been put into use at residences in the study area during the period of the investigation. Both types of purifying system can produce water with 99 % removal of arsenic when properly maintained. One of the residents with a highly impacted well had a 24-hour urine test conducted to see if she had elevated arsenic in her body (this is the same type of test that is routinely given to workers at hazardous waste sites where arsenic is a health concern; concentrations greater than 100 ug/l require withdrawing the worker from the site). Upon learning that her test results were 220 ug/l, the family installed a reverse-osmosis unit. The average of three untreated samples from their well was 147 ug/l; the average of two treated samples collected four months apart was 0.45 ug/l. A repeat 24-hour urine test of this resident six months later showed that her concentration had been reduced to 25 ug/l. Both the family and the physician are pleased with these results.

Projections for the Future

The groundwater samples show that the arsenic-concentration problem has become worse in portions of the Tertiary aquifer than in the alluvial aquifer. The data from the test drilling site indicate that the arsenic concentration within the various Tertiary-aquifer sand units is variable. The amount and percentage of irrigation related recharge to these units will obviously vary somewhat. When that variable is coupled with variations in hydraulic conductivity, head differentials, and flow-path distances, it becomes virtually impossible to make quantitative predictions; however qualitative predictions can be made. If all irrigation were to cease, it would take a minimum of 15 to 30 years to see a substantial improvement in the groundwater arsenic concentrations. We are probably not seeing maximum values in any of the wells. An indication of the rate of change in arsenic concentration caused by sprinkler irrigation can be estimated using a commercial well-water analysis provided with sale documents for a house on Buffalo Jump Road. The house is sited on Tertiary strata and the 90-foot (27 m) deep well is solely within the Tertiary. In a little less than 10 years, the arsenic concentration has increased from 24 to 138 ug/l. These data suggest that continued degradation of the Tertiary aquifer will probably continue until a steady-state system, both hydraulic and chemical, is established in response to irrigation impacts. The geochemical control will probably be calcium concentration in the water; because the waters commonly have "mixed" geochemical signatures with calcium concentrations in the 50 to 100 mg/l range, groundwater concentrations of As are not expected to exceed 200 ug/l. However, continued degradation of water quality in the less severely impacted Tertiary sands should occur, with higher arsenic concentrations than found in the alluvial aquifer as the probable final condition.

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ADDENDUM

MONTANA BUREAU OF MINES AND GEOLOGY

OPEN-FILE REPORT 210

by

JOHN L. SONDEREGGER

September 25, 1989

ADDENDUM

Fifteen additional samples were collected during May of 1989 for complete analysis to aid in characterizing the major element chemistry of the aquifers in the study area. The 29 complete analyses used for data interpretation are presented in Table 1.

Figure 1 depicts all of the analyses. Diamonds represent samples collected from wells believed to be completed in the Tertiary aquifer. In several cases the well construction details are not known, however, the well was sampled for a complete analysis because of the arsenic concentration in the water. Circles represent wells thought to be completed in the alluvial aquifer. The two X symbols represent ditch samples and the square boxes are river water samples.

Figure 2 shows only the surface-water data. There is no significant change in either the major-element ion ratios or the total dissolved solids when comparing analyses from above and below the major irrigated area during non-irrigation periods (analyses 88Q1465 and 88Q1466 in Table 1). However, the irrigation ditch sample (88Q1467) shows an approximate doubling of the Ca, Mg, K, and HCO_3 content of the water in the Rey Creek ditch at the interstate highway (I-90). This sample is the X furthest from the river-water squares on this figure. The other X represents a return-ditch sample collected in August.

A fair amount of uniformity is demonstrated by the plot of the analyses from the alluvial aquifer (Figure 3). The two obvious outliers in the anion and combined plots have elevated percentages of sulfate and chloride. These two samples are from a sandpoint (Hepner) and a 50-foot well (Setzer); both came from houses located on the Madison Frontage Road (east of the main road down the valley and just south of the I-90). The higher sulfate content is typical of the Tertiary wells on the northern end of the valley where the cumulative effects of irrigation might be expected to be most pronounced. Consequently, the different water quality (and higher arsenic concentrations) noted at this location may represent discharge or leakage from the Tertiary aquifer into the alluvial aquifer in areas immediately to the south.

Figure 4 depicts the character of the Tertiary-well samples. The water analyses show a bimodal character for the anion distributions. The scattered, high sulfate, diamonds represent the northern, valley-margin wells discussed previously. The cations show the same trend of 30 to 60 % sodium plus potassium (plus two high Na samples) at a relatively constant calcium to magnesium ratio.

The results of these additional samples do not change the conclusions drawn in the earlier report. The additional data suggest more annual variability in the arsenic content than previously documented, particularly from sandpoint wells such as Hepners'; however, the data do not warrant any alterations of the interpretations.

Table 2 is a revised listing of all of the arsenic data collected within the lower Madison Valley. It supercedes Appendix A in Open-File Report 210.

TABLE 1. Complete chemical analyses used for analysis in this Addendum to Open-File Report 210.

NAME	LOCATION	DATE	AQUIFER	LAB NO.	pH field	SC field	Ca	Mg	Na	K	Fe	Mn	SiO2	HCO3	Cl	SO4	NO3 as N	.F	B
						UMho/cM	<-------------------------					Milligrams/liter						------------>	<---
Christiansen, Bill	1N2E04DCCC	13-JUN-84	Q	84Q0365	*	677	73.1	16.3	62.0	6.3	1.310	0.340	39.3	358.0	35.9	47.0	0.02	2.0	34
Darlington, Steve	1N2E29DAD	13-JUN-84	Q?	84Q0363	*	475	50.1	13.8	32.0	5.2	0.012	0.001	39.3	254.0	16.6	25.1	0.41	1.7	1
Doak, June	1N2E15DD	05-MAY-89	T	89Q0567	7.34	1004	89.7	21.2	84.4	21.0	0.014	0.001	60.8	334.0	29.3	193.0	0.56	1.3	54
Ewan, J.R.	1S2E17AAA	13-JUN-84	Q	84Q0361	*	417	45.0	11.6	27.3	5.0	<.002	<.001	39.4	223.0	13.7	21.0	0.40	1.6	1
Hart, Frank	2N2E17DDCC	04-MAY-89	T?	89Q0555	7.84	444	34.9	7.6	44.6	6.2	0.110	0.016	35.8	198.1	25.8	21.3	0.01	2.6	4
Hepner, Jeanette	2N2E28CADD	04-MAY-89	Q	89Q0556	7.44	819	68.1	19.5	60.8	7.0	0.780	0.150	27.9	304.0	34.8	80.8	0.51	2.5	4
Jorgenson, Jack	1S2E04AACC	05-MAY-89	T	89Q0570	7.46	782	73.1	22.7	50.2	12.6	<.002	<.001	57.2	370.0	33.0	53.9	0.66	1.6	5
Koenig, Martin	2S2E05BDBD	09-MAY-89	Q	89Q0572	7.76	382	44.3	11.3	23.7	4.3	0.003	<.001	31.1	210.8	14.8	19.4	0.61	1.4	17
Ledebur, William	2N2E20D	02-MAY-89	Q	89Q0548	7.63	421	44.6	10.5	34.1	4.3	0.110	0.060	30.6	224.5	20.1	17.4	0.71	2.0	47
MBMG	2N2E28CADD05	29-JUN-88	T	88Q0700	*	474	51.1	11.4	48.5	13.1	0.110	0.076	67.4	269.4	29.1	25.7	0.02	2.3	27
Mills, Ken	1S2E22BCCB	05-MAY-89	T	89Q0568	7.48	1141	130.0	31.7	54.9	18.5	<.002	<.001	55.6	290.8	43.4	216.0	21.5	0.9	22
Potts, Mark & Kim	2S2E05BAA	13-JUN-84	Q	84Q0360	*	375	42.2	9.8	23.2	4.1	0.004	<.001	32.1	200.0	12.4	18.0	0.35	1.5	1
Prescott, John	2N2E20CABC	11-MAR-88	T?	88Q0126	*	640	0.5	0.1	147.0	3.0	0.009	0.004	37.0	286.9	33.0	32.8	0.06	2.0	2
Prescott, John	2N2E20CABC	03-MAY-89	T?	89Q0550	7.59	563	32.6	10.2	74.6	10.1	0.002	0.006	36.5	270.4	27.3	25.9	0.22	2.4	43
Pyfer, Lloyd	2N2E20CDAC	03-MAY-89	Q	89Q0551	7.32	570	56.1	12.4	47.4	6.2	0.008	0.026	35.8	274.3	28.8	26.8	0.72	2.5	43
Setzer, Randolph	2N2E28CBD?	04-MAY-89	Q?	89Q0554	7.56	925	71.9	14.6	89.2	5.9	0.630	1.130	38.9	372.0	47.8	64.8	0.02	2.7	7
Shipton, Harold	1S2E21DBDB	09-MAY-89	T	89Q0571	7.63	540	59.0	26.4	27.0	5.2	<.002	<.001	50.7	284.9	32.0	24.9	2.50	1.4	1
TBE Ranch	1N2E07AACB	09-NOV-83	T	83Q1139	*	691	15.5	2.1	121.0	10.7	0.092	0.013	35.8	133.7	64.9	103.0	3.32	1.2	5
TBE Ranch	1N2E06DAA	15-NOV-83	Q	83Q1169	*	757	65.8	16.5	79.6	7.3	0.011	0.012	57.1	309.0	37.2	84.8	2.21	1.8	5
TFS4	1N2E16CAA	18-AUG-87		87Q0727	7.95	365	54.5	15.3	28.3	5.3	<.002	<.001	35.3	257.7	18.3	26.4	0.58	1.4	1
TFSWL	2N2E30BABA	16-OCT-88		88Q1466	8.42	314	26.1	7.4	33.9	4.9	0.028	0.004	35.7	144.0	20.9	17.3	0.02	2.6	2
TFSWU	2S2E19DBD	17-AUG-87		87Q0724	>8	225	21.5	6.3	24.9	4.8	0.005	0.001	33.8	99.1	14.6	14.0	0.05	2.0	22
TFSWU	2S2E19BDB	16-OCT-88		88Q1465	8.45	318	25.3	7.5	31.8	4.4	0.020	0.003	35.0	139.6	18.8	20.1	0.02	2.1	2
TFS-6	2N2E28DDAA	16-OCT-88		88Q1467	8.10	567	54.7	16.0	45.1	8.2	0.011	0.003	39.9	295.2	21.2	30.3	0.51	1.8	3
Thorpe, Terry	2N2E29BABD	15-NOV-83	Q?	83Q1167	*	753	70.8	14.7	77.9	7.0	0.220	0.015	42.4	368.0	39.8	41.7	0.19	3.1	4
Thorpe, Terry	2N2E29BABD	03-MAY-89	T	89Q0549	7.70	573	57.5	12.5	48.0	6.7	0.440	0.370	39.8	268.4	39.6	29.9	0.04	2.5	5
Tinder, L. Marie	1N2E22CABD	05-MAY-89	T	89Q0569	7.54	668	46.5	13.0	74.6	11.3	<.002	<.001	49.6	334.0	18.6	40.4	0.90	2.2	3
van Dyk, J & J	1N2E10DBB	04-MAY-89	T	89Q0557	7.52	1181	95.7	24.8	108.0	23.0	0.190	0.039	55.9	330.0	58.4	239.0	0.01	1.6	6
Wilkinson, Bob	2N2E20CCAA	02-MAY-89	Q	89Q0547	7.37	548	58.5	11.3	48.2	4.5	0.032	0.340	36.5	279.1	30.8	25.7	0.49	2.4	3

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     Li     Mo     Pb  P-tot    Sr     Zn  P-orth  As
                        as P                as P
-----------Micrograms/liter--------------------->

:2   240    <20     *    300   250     <3  <100    88
.1   170    <20     *   <100   170     21  <100    50
.6   100     50   <40   <100   600      6   100    60
:2   140    <20     *    300   160     11  <100    45
:2   180    <20   <40    100   160     <3  <100    70
:2   210    <20   <40    100   640     <3   100  11.6
:2   130     34   <40   <100   530     20  <100    70
:2   100    <20   <40    100   140     20   100    41
:2   170    <20   <40    200   170     16  <110    38
:2   230    <20     *   <100   280     10  <100    95 TEST WELL
:2    60    100   <40   <100   870     19  <100    21
 6   110     20     *    400   130     29  <100    36
 8   280    <20     *    100     2     <3   100   121
 5   220     20    80    200 ******    47  <100   159
<2   210     20   <40    200   180    160  <100   120
<2   240    <20   <40    100   260      5  <100   123
 3   130    <20   <40    200   360     30   100    45
<2    64    <20   <40      *   200     <3     *    16
10   190     30   <40      *   380    170     *   127
 4   170    <20     *   <100   180     <3  <100    34 IRRIG. DITCH
 8   180    <20     *    100    97     <3  <100    60
 3   150     60     *   <100    81      7  <100    61 CO3=10.7 mg/l
 6   160    <20     *   <100    93     <3   200    58 CO3=1.2 mg/l; Al=50 ug/l
<2   170    <20     *   <100   220     <3   100    62 IRRIG. DITCH
 7   310    <20   <40      *   260      4     *    63
<2   220    <20   <40   <100   280     <3  <100    84
 5   160     27   <40   <100   240    687  <100   116
<2   190     30   <40    100   640     <3   200   120
 8   210     20   <40    200   170     16  <100   102
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TABLE 2. Well and Arsenic Data for the Lower Madison Valley, between Beartrap and the Missouri River.

NAME OF RESIDENT	ADDRESS	SAMPLE DATE	LOCATION	DEPTH	TREATED?	As ug/l	LAB NO.	COMMENTS
Allen, Tom	5353 Buffalo Jump Road	19-May-88	T1NR2E22CDCC	90	N	138	8800357	
Arbuckle, Merrill	1991 Frontage Road	14-Jun-84	T2NR2E29AD	22	N	150	8400367	
Aughney, Duane	535 Trident Road	05-Nov-87	T2NR2E20DDB	80	N	117	8701096	
Beartrap Campsite	Highway 84 @ Madison River	13-Jun-84	T3SR1E02BDC	?	N	26	8400359	
Bogonofsky, Frank	Box 1111, Three Forks	06-Nov-87	T2NR2E20CBDC	?	N	122	8701100	
Bokum, Richard	5157 Madison Road	20-May-88	T1NR2E20AC	?	N	35	8800362	Barn well
Bokum, Richard	5157 Madison Road	20-May-88	T1NR2E20AC	92	N	37	8800363	Main house well; kit. tap
Christiansen, Bill	2630 Madison Road	13-Jun-84	T1NR2E04DCCCC	44	N	88	8400365	
Christiansen, Bill	2630 Madison Road	09-Nov-87	T1NR2E04DCCCC	44	Y	105	8701076	After water softener & filter
Christiansen, Bill	2630 Madison Road	09-Nov-87	T1NR2E04DCCC	44	N	96	8701077	1984 Analysis: As = 88
Cleveland, Curtis	17550 Old Town Main Street	11-Nov-87	T2NR1E24DDA	47	Y	0.8	8701105	Purifier system for domestic water
Cleveland, Curtis	17550 Old Town Main Street	11-Nov-87	T2NR1E24DDA	47	N	1.2	8701106	Stock & lawn
Climbing Arrow Ranch	c/o TBE Ranch	13-Jun-84	T1NR2E16CBD	?	N	69	8400364	Shallow dug well
Dale, Fred	Box 551, Three Forks	09-Nov-87	T2NR2E27CADD	60	N	16	8701085	Stock well in Zuelke's corral
Darlington, Gordon	8021 Madison Road	13-Jun-84	T1SR2E05AB	20	N	50	8400362	
Darlington, Gordon	8021 Madison Road	06-Nov-87	T1SR2E05AB	20	N	48	8701036	
Darlington, Steve	6623 Madison Road	13-Jun-84	T1NR2E29DAD	?	N	50	8400363	
Doak, June	4000 Buffalo Jump Road	10-Mar-88	T1NR2E15DD	102	N	63	8800121	
Doak, June	4000 Buffalo Jump Road	19-May-88	T1NR2E15DD	102	Y	0.9	8800356	Still sample
Doak, June	4000 Buffalo Jump Road	05-May-89	T1NR2E15DD	102	N	60	8900567	
Ewan, J. R.	9920 Madison Road	13-Jun-84	T1SR2E17AAB	80	N	45	8400361	
Ewan, J. R.	9920 Madison Road	09-Nov-87	T1SR2E17AAB	30	N	52	8701080	
Ewan, J. R.	9920 Madison Road	09-Nov-87	T1SR2E17AAA	80	N	44	8701091	
Ewan, Lonny	11350 Buffalo Jump Road	20-May-88	T1SR2E22BCCB	?	N	20	8800364	
[illegible]k, Betty	6623 Madison Road	09-Nov-87	T1NR2E29DCA	?	N	53	8701079	1984 Analysis = 50 ug/l
Gillespie, John	1670 Carpenter Drive	09-Nov-87	T2NR2E21ACDB	25	N	61	8701083	
Gordon, Bob	13505 Buffalo Jump Road	05-Nov-87	T1SR2E29DDDB	33	N	25	8701046	
Hankin, Ernest	15520 Crowley Lane	09-Nov-87	T1NR2E21ABBA	32	N	54	8701075	
Hankin, Jay	15580 Crowley Lane	09-Nov-87	T1NR2E21ABBB	?	N	50	8701074	
Hargrove, David	3333 Frontage Road	05-Nov-87	T2NR2E27CBC	33	N	106	8701095	Located at lumber yard
Hargrove, David	3333 Frontage Road	20-May-88	T2NR2E27CBC	33	Y	11	8800366	Sears reverse-osmosis unit
Hargrove, David	3333 Frontage Road	16-Sep-88	T2NR2E27CBC	33	Y	1	8801333	Sears reverse-osmosis unit
Hart, Frank	1470 Trident Road	24-Mar-88	T2NR2E17DDCC	55	N	66	8800171	
Hart, Frank	1470 Trident Road	01-May-89	T2NR2E17DDCC	55	N	70	8900555	
Hartkopf, Joe	4333 Madison Road	09-Nov-87	T1NR2E16CBD	?	N	67	8701078	1984 Analysis: As = 69
Henry, Don	565 Madison Road	13-Jun-84	T2NR2E32AAAA	75	N	85	8400366	
Hepner, Jeanette Smith	16070 Madison Frontage Road	10-Nov-87	T2NR2E28CADD01	20	N	130	8701069	Sandpoint; ditch water As = 67 ug/l
Hepner, Jeanette Smith	16070 Madison Frontage Road	04-May-89	T2NR2E28CADD01	20	N	11.6	8900556	Sandpoint; ditch water As = 67 ug/l
Hernandez, Amado	Box 2825, Norris	05-Nov-87	T2SR2E19BA	Shallow	N	32	8701041	
Hoffman, Chuck	Box 155, Three Forks	10-Nov-87	T2NR2E29DD	30	N	59	8701071	
Hotzel, James	290 Madison Road	10-Nov-87	T2NR2E28CBCC	40	N	92	8701070	Sandpoint, depth may be wrong
Jacobs, Allan	4470 Buffalo Jump Road	19-May-88	T1NR2E22ABB	78	N	98	8800355	
Jorgenson, Jack	7777 Buffalo Jump Road	10-Mar-88	T1SR2E04AACC	55	N	84	8800125	
Jorgenson, Jack	7777 Buffalo Jump Road	05-May-89	T1SR2E04AACC	55	N	70	8900570	
Jorgenson, Jack	7777 Buffalo Jump Road	20-May-88	T1SR2E03DCC	400	N	61	8800367	Tertiary irrigation well
Kamerman, Brad	3995 Buffalo Jump Road	10-Mar-88	T1NR2E15DCBB	40	N	67	8800122	House Well
Kamerman, Brad	3995 Buffalo Jump Road	10-Mar-88	T1NR2E15DCBD	80	N	100	8800123	Dairy Well
Kieffer, Don	15393 Madison Road	05-Nov-87	T2SR2E05CCC	54	N	30	8701039	
Koenig, Martin	13999 Madison Road	05-Nov-87	T2SR2E05BDBD	60	N	39	8701050	
[illegible]enig, Martin	13999 Madison Road	09-May-89	T2SR2E05BDBD	60	N	41	8900572	
[illegible]debur, William	2655 Pyfer Road	06-Nov-87	T2NR2E20D	30	N	40	8701092	
Ledebur, William	2655 Pyfer Road	19-May-88	T2NR2E20DAC	30	N	52	8800354	
Ledebur, William	2655 Pyfer Road	02-May-89	T2NR2E20DAC	30	N	38	8900548	

Table 2 continued, p. 2

Love, Melvin	15140 Kilgore Lane	05-Nov-87	T1SR2E29AAC	61	N	27	8701045	
Martin, Ken	9919 Madison Road	06-Nov-87	T1SR2E08CDDC	100	N	48	8701037	Davis' live here now (July, 1988).
Masters, Terry	5857 Buffalo Jump Road	06-Nov-87	T1NR2E27BCCB	48	N	112	8701042	
MBMG1	16070 Madison Frontage Road	14-Apr-88	T2NR2E28CADD02	19	N	43	8800230	Resampled 7/15/88
MBMG1	16070 Madison Frontage Road	15-Jul-88	T2NR2E28CADD02	19	N	71	8800832	
MBMG2	16070 Madison Frontage Road	14-Apr-88	T2NR2E28CADD03	43	N	68	8800229	Resampled 7/15/88
MBMG2	16070 Madison Frontage Road	15-Jul-88	T2NR2E28CADD03	43	N	58	8800833	
MBMG3	16070 Madison Frontage Road	14-Apr-88	T2NR2E28CADD04	56	N	29	8800228	Resampled 7/15/88
MBMG3	16070 Madison Frontage Road	15-Jul-88	T2NR2E28CADD04	56	N	22	8800834	
MBMG4	16070 Madison Frontage Road	29-Jun-88	T2NR2E28CADD05	109	N	25	8800699	Sampled while drilling
MBMG4	16070 Madison Frontage Road	29-Jun-88	T2NR2E28CADD05	245	N	95	8800700	Sampled after 1 hr. development
MBMG4	16070 Madison Frontage Road	16-Aug-88	T2NR2E28CADD05	245	N	76	8801247	Sampled after 2+hr.s pumping
McDonnell, Stephen Jr.	9050 Buffalo Jump Road	06-Nov-87	T1NR2E33DAB	?	N	68	8701043	
McDonnell, Stephen Jr.	9165 Buffalo Jump Road	06-Nov-87	T1SR2E10CAA	60	N	55	8701044	
Messing, Everett	31010 Francis Rd., Belgrade	20-May-88	T1SR2E16DDA	65	N	38	8800365	Near lower schoolhouse
Mills, Ken	11350 Buffalo Jump Road	05-May-89	T1SR2E22BCCB	?	N	21	8900568	see Lonny Ewan
Morgan, Gene(?)	Frontage Rd. E of Logan	16-Aug-88	T2NR2E35BBB	?	?	2.2	8801248	Sampled lawn hose
Nerlin, Roger	40 Carpenter Lane	09-Nov-87	T2NR2E27DCA	33	N	4.1	8701087	Domestic well
Nerlin, Roger	40 Carpenter Lane	09-Nov-87	T2NR2E27DCA	29	N	3.7	8701088	Stock well
Olson, Edith	17444 Old Town Main Street	11-Nov-87	T2NR2E19CCB	20	N	3.7	8701101	
Potts, Mark & Kim	14045 Madison Road	13-Jun-84	T2SR2E05BAA	60	N	36	8400360	
Prescott, John & Ann	3080 Pyfer Road	06-Nov-87	T2NR2E20CABC	30	N	176	8701081	
Prescott, John & Ann	3080 Pyfer Road	04-Apr-88	T2NR2E20CABC	30	N	121	8800126	
Prescott, John & Ann	3080 Pyfer Road	19-May-88	T2NR2E20CABC	30	Y	0.3	8800352	Culligan reverse-osmosis unit
Prescott, John & Ann	3080 Pyfer Road	19-May-88	T2NR2E20CABC	30	N	148	8800353	
Prescott, John & Ann	3080 Pyfer Road	16-Sep-88	T2NR2E20CABC	30	Y	0.6	8801334	Culligan reverse-osmosis unit
Prescott, John & Ann	3080 Pyfer Road	03-May-89	T2NR2E20CABC	30	N	159	8900550	
Pyfer, Lloyd	3155 Pyfer Road	06-Nov-87	T2NR2E20CDAC	12	N	111	8701099	
Pyfer, Lloyd	3155 Pyfer Road	04-May-89	T2NR2E20CDAC	12	N	120	8900551	
Rae, Jack	2255 Madison Road	09-Nov-87	T1NR2E04CB	43	Y	62	8701073	"Conditioned" water from house well
Rae, Jack	2255 Madison Road	20-May-88	T1NR2E04CB	21	N	88	8800360	Stock well
Rae, Jack	2255 Madison Road	20-May-88	T1NR2E04CB	8	N	91	8800361	Stock well
Randolph, Carol	14787 Madison Road	05-Nov-87	T2SR2E05CDA	63	N	27	8701038	
Richardson, Tom & Deirdre	4260 Buffalo Jump Road	10-Mar-88	T1NR2E22ABBB	58	N	119	8800119	House well
Richardson, Tom & Deirdre	4260 Buffalo Jump Road	10-Mar-88	T1NR2E22ABBB	58	Y	0.6	8800120	Distilled well water
Roadarmel, Jack	1150 Carpenter Lane	09-Nov-87	T2NR2E22CCC	60	N	72	8701084	
Robertson, Ellen	170 Old Town Road	09-Nov-87	T2NR2E19CCCB01	20	N	0.9	8701089	Sampled at corral
Robertson, Ellen	170 Old Town Road	09-Nov-87	T2NR2E19CCCB02	12	N	2.4	8701090	Flower Shop well
Schedel, Dean	360 Old Town Road	11-Nov-87	T2NR2E19CBCC	26	Y	1.2	8701103	Purifier on kitchen sink
Schedel, Dean	360 Old Town Road	11-Nov-87	T2NR2E19CBCC	26	N	1.6	8701104	Kitchen sink without purifier
Scollard, James	2375 Frontage Road	05-Nov-87	T2NR2E28CDAB	49	N	118	8701094	Swampy odor, black stain
Secora, Rick	15215 Madison Road	05-Nov-87	T2SR2E05CC	62	N	37	8701049	
Setzer, Randolph	16360 Madison Frontage Road	10-Nov-87	T2NR2E28CBD	50	N	123	8701068	Domestic & stock
Setzer, Randolph	16360 Madison Frontage Road	04-May-89	T2NR2E28CBD	50	N	123	8900554	
Shaw, Carol	Box 915, Three Forks	05-Nov-87	T2NR2E29AD	37	N	73	8701092	House vacant, Shaw is owner
Shipton, Harold	11731 Buffalo Jump Road	06-Nov-87	T1SR2E21DBDB	180	N	44	8701047	
Shipton, Harold	11731 Buffalo Jump Road	09-May-89	T1SR2E21DBDB	180	N	45	8900571	
Shouse, Edith	17410 Old Town Main Street	11-Nov-87	T2NR2E19CCAB	SANDPOINT	N	2.6	8701102	
TBE Ranch	Box ???, Three Forks	15-Nov-83	T1NR2E06DAA	40	N	127	8301169	
Thorpe, Terry	3455 Pyfer Road	15-Nov-83	T2NR2E29BABD	27	Y	63	8301167	Iron removal filters
Thorpe, Terry	3455 Pyfer Road	06-Nov-87	T2NR2E29BABD	100	?	86	8701097	Well deepened
Thorpe, Terry	3455 Pyfer Road	03-May-89	T2NR2E29BABD	100	?	84	8900549	Well deepened
Tilden, Ruth	2325 Frontage Road	14-Jun-84	T2NR2E28BC	48	N	85	8400368	
Tilden, Ruth	2325 Frontage Road	05-Nov-87	T2NR2E28BC	48	N	119	8701093	Domestic & stock

Table 2 continued, p. 3

[illegible]er, L. Marie	12060 Gallatin, Manhattan	10-Mar-88	T1NR2E22CABD	108		N	123	8800124	
Tinder, L. Marie	12060 Gallatin, Manhattan	05-May-89	T1NR2E22CABD	108		N	116	8900569	
Van Dyk, J. & J.	2545 Buffalo Jump Road	06-Nov-87	T1NR2E10DBB	45		N	120	8701048	
Van Dyk, J. & J.	2545 Buffalo Jump Road	04-May-89	T1NR2E10DBB	45		N	120	8900557	
Wilcox, Ralph	4747 Buffalo Jump Road	19-May-88	T1NR2E22CA	73		N	130	8800358	
Wilkinson, Bob	3121 Pyfer Road	14-Jun-84	T2NR2E20CCAA		?	N	83	8400369	
Wilkinson, Bob	3121 Pyfer Road	06-Nov-87	T2NR2E20CCAA		?	N	105	8701098	
Wilkinson, Bob	3121 Pyfer Road	02-May-89	T2NR2E20CCAA		?	N	102	8900547	
Williams, Chuck & Roberta	5545 Buffalo Jump Road	19-May-88	T1NR2E27BBD	145		Y	92	8800359	Passed through water softner.
Workman, Doc H.	Box 288, Norris	05-Nov-87	T2SR1E35DCD	29		N	47	8701040	Stock Well
Zuelke, John	101 Carpenter Lane	09-Nov-87	T2NR2E27DCB	56		N	18	8701086	Domestic, house & 2 trailers
Zuelke, Pat	565 Madison Road	10-Nov-87	T2NR2E32AAAA	75		N	90	8701072	As = 85 ug/l in 1984(Henry)

Date of current printout is September 24, 1989.

HC—GRAM

HydroChemical Graphic Representation Analysis Methods

Version: HC-GRAM 1.42

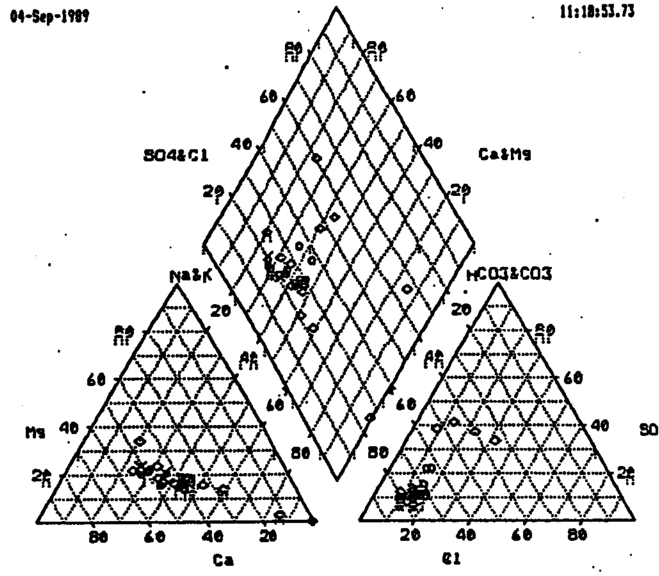

Figure 1 — Piper plot of the Madison valley analyses.

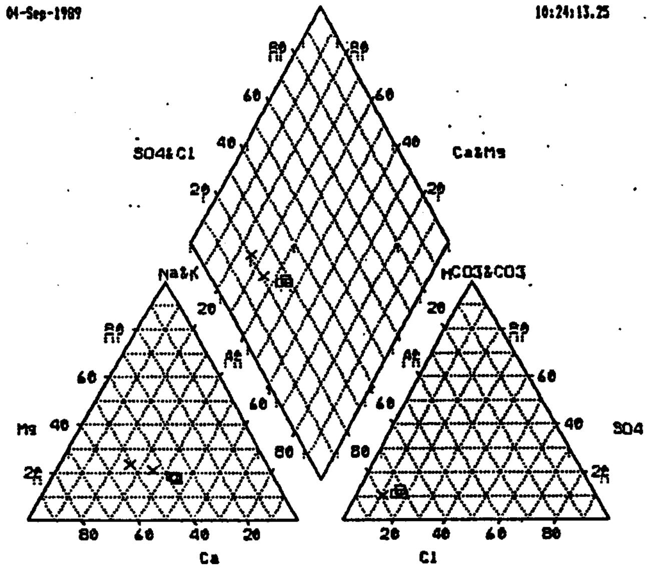

Figure 2 — Surface-water analyses, Madison valley.

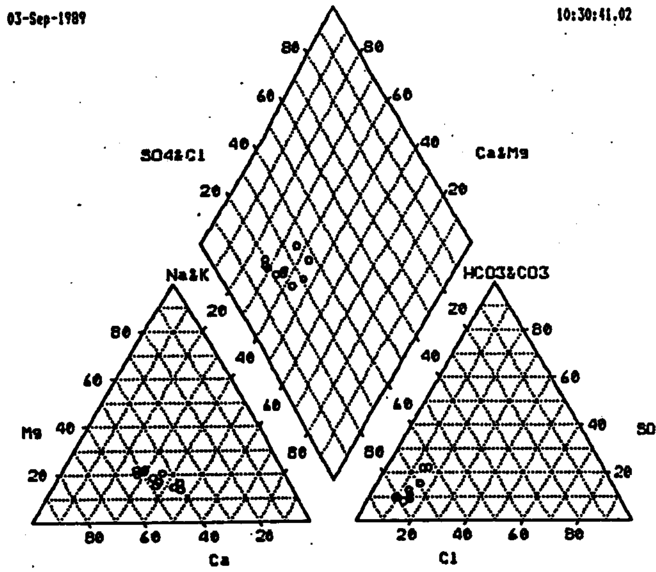

Figure 3 — Quaternary, alluvial aquifer analyses.

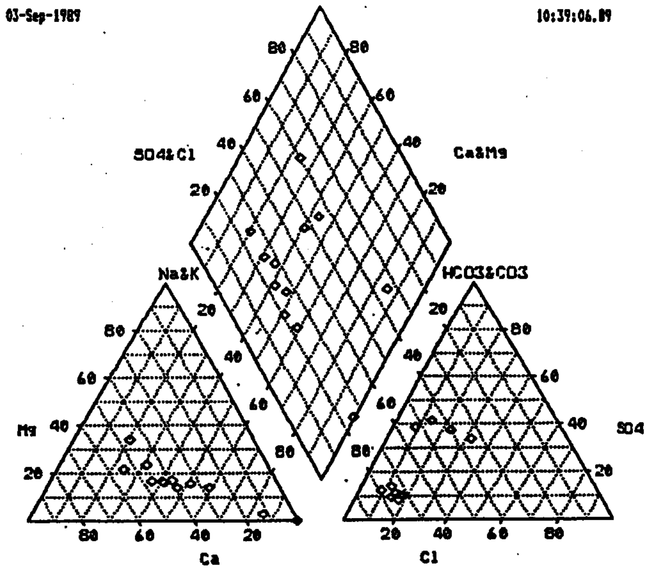

Figure 4 — Tertiary aquifer analyses, Madison valley.