Spatial Examination of Backfill Aquifer Water Quality, Powder River Basin, Wyoming Using GIS[1]

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Abstract. Backfill water quality is a critical issue in reclamation of large strip mines. With large expanses of land being mined and reclaimed, it is important to evaluate if the water quality in the backfill aquifer will be suitable to support the post mining land use. The concentration of dissolved constituents is expected to increase in the backfill aquifer since additional fresh mineral surfaces are exposed for chemical reaction in the backfill and oxidizing conditions prevail after initial placement of the backfill. Because only limited data were available prior to issuance of the initial permits in the Powder River Basin of Wyoming in the 1970's and 1980's, many predictions of backfill aquifer water quality were based on lab tests and literature research.

However, after approximately 25 years of mining, water quality data for the backfill aquifer are available. Currently in the Basin, 95 monitoring wells are completed in the backfill aquifer and have sufficient re-saturation to allow sampling. The mean depth of the backfill monitor wells is 32.9 meters (108 feet) with the well locations distributed across the mining areas in the Basin. Approximately 2,000 water samples were collected from those backfill monitor wells with most of the samples collected between 1986 and 2002. The mean total dissolved solids (TDS) of the backfill aquifer samples are 3,920 mg/l and the water type is calcium sulfate. Of the 2,000 samples, 75 percent fall below the Wyoming livestock standard of 5,000 mg/l with 25 percent above that standard.

Examination of the data using a Geographic Information System (GIS) indicated that elevated TDS concentrations might be related to recharge. The relation of the TDS concentrations to the well's proximity to two recharge features, clinker deposits and stream channels were examined. GIS analysis revealed that wells within 610 meters (2,000 feet) of the clinker deposits had a 17 percent higher mean TDS and wells within 152 meters (500 feet) of stream channels had a 20 percent higher mean TDS concentration. When the mean TDS concentration was calculated for wells that were proximate to both the clinker deposits and the stream channels locations, the mean TDS concentration increased by 55 percent.

Additional Key Words: surface mining, TDS, monitoring wells

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Introduction

The water quality in the backfilled materials placed in the pits of large strip mines is an issue of environmental concern and regulation in Wyoming. With strip mines covering large areas, the backfill material will need to function as an aquifer and to restore the essential hydrologic functions to the aquifer system. By 2004, about 504 square kilometers (110 square miles) of land in Wyoming has been affected by surface coal mining. Approximately 56 percent of that disturbance has occurred since the 1970's in the eastern part of the Powder River Basin (PRB), which is the focus of this paper (Figure 1).

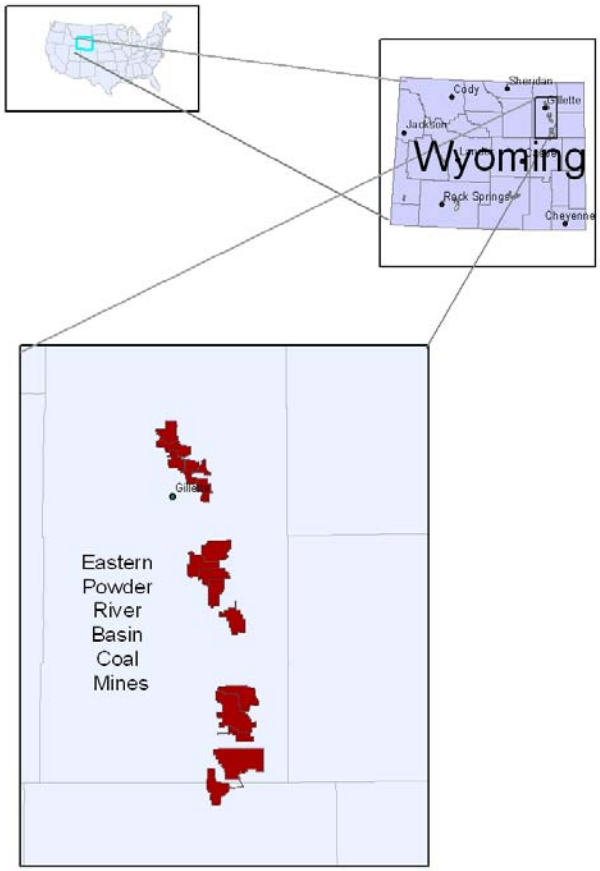

Figure 1. -- Location of coal strip mines in the eastern Powder River Basin, Wyoming.

The backfill materials used to fill the pits have been physically disturbed and chemically oxidized. This increase in exposed mineral surfaces and difference in oxidation state often causes an increase in total dissolved solids (TDS) and other constituents in groundwater. Assessing the post-mining water quality in the backfill aquifer is a critical determination for the regulatory agency. A Graphical Information System (GIS) is used as a tool to assist the agency with meeting the regulatory obligations. A GIS was applied to examine the distribution of backfill aquifer water quality data and to examine possible factors affecting the quality.

Initial research by Van Voast (1974), Van Voast and Hedges (1975), McWhorter, et al. (1975), Rahn (1976), Van Voast, et al. (1976), Arnold and Dollhopf (1977), Dollhopf, et al. (1977, 1981), Davis, et. al. (1978), Moran, et al. (1978), Van Voast and Thompson (1982), Groenewold, et al. (1983) and Martin, et al. (1988) indicated that the first groundwater to enter a backfill aquifer would dissolve a high percentage of the available salts. After the initial research, most of which was based on lab tests or limited data, evaluations continued of data from sites where backfill was starting to saturate. In an update to the original research at the Colstrip and Decker Mines, Wheaton and Reiten (1996) found that mineralization in the backfill aquifers has increased by 50 to 200 percent, but some sites experienced a decrease in the mineralization that was attributed to flushing of the initial salt load. Erbes (2000) reported TDS in the backfill aquifer at the Rosebud Mine in Montana to range from 1,200 to 5,500 mg/l after 20 to 25 years of monitoring.

In the western US, the primary water quality concerns associated with the backfill aquifer and surface coal mining is the elevation of TDS with sodium, calcium, magnesium and sulfate being the major ionic constituents (Office of Technology Assessment, 1985). These constituents were found to comprise most of the TDS concentration in two wells at the West Decker mine where the TDS ranged from 4,100 to 5,700 mg/l and were likewise dominate in a larger number of wells where the average TDS concentration was 2,500 mg/l (Reiten and Wheaton, 1993). Moran, et al. (1978) recognized that the general geochemical processes that drive the increase in dissolved constituents in the backfill aquifer are the oxidation of mineral matter and organic matter, reaction of carbon dioxide and water to form carbonic acid, dissolutions of calcite and dolomite, precipitation and dissolution of gypsum, cation exchange and sulfate reduction. Clark (1995) identified an increase of about 1,600 mg/l in TDS as water flowed into the backfill aquifer at the Decker Mine from the coal aquifer and suggested the increase was probably a result of de-dolomitization. Davis (1978) found that chemical equilibrium was reached very quickly. The differing trends in individual wells appear to reflect proximity to features such as: outcrops and unmined coal. Changes in mining activities may also contribute to the variability (Hoy, et al., 2003).

Data

There are 95 wells completed in the backfill aquifer in mined areas of the eastern Powder River Basin, Wyoming (GAGMO, 2002). GIS was used as a tool to examine the dataset for both management and environmental analysis purposes. First, GIS was used as a data exploration tool to examine the time periods over which the wells were installed, the well depth, and the distribution of the monitor wells within the northern, middle and southern groups of mines. The data exploration was completed before any analysis of the data, in order to better define the type of data set being examined.

Time Period of Well Installation

The number of wells completed in the backfill aquifer has increased with time as the coal mines expanded and as reclamation occurred. Table 1 summarizes the number of wells completed by approximately 5-year intervals.

Table 1. -- Number of backfill aquifer monitor wells by year of completion, eastern Powder River Basin, Wyoming [data source: GAGMO, 2002].

Years	Number of backfill aquifer monitor wells
1980 and before	9
1981 - 1985	31
1986 - 1990	18
1991 - 1995	22
1995 - 2001	15
TOTAL	**95**

By 1980, there were nine backfill aquifer monitor wells in the PRB distributed between the Wyodak Mine where mining had been underway since 1922**,** and two newer mines in the middle

Figure 2. -- Backfill monitor wells and the periods of installation, eastern Powder River Basin, Wyoming.

part of the PRB where small amounts of backfill were beginning to saturate (Figure 2). In the period from 1981 to 1985, the greatest number of wells was installed as more mines were permitted and saturated backfill became more common. Additional wells were added in the period from 1995 to 2001, with the installations focused on mines that were permitted later or on those that were in areas with drier hydrologic conditions. Between 1991 and 1995 only 18 new backfill wells were completed and none of those were in the middle part of the PRB mines. That was most likely because a number of wells were installed between 1981 and 1990 in the middle mine area.

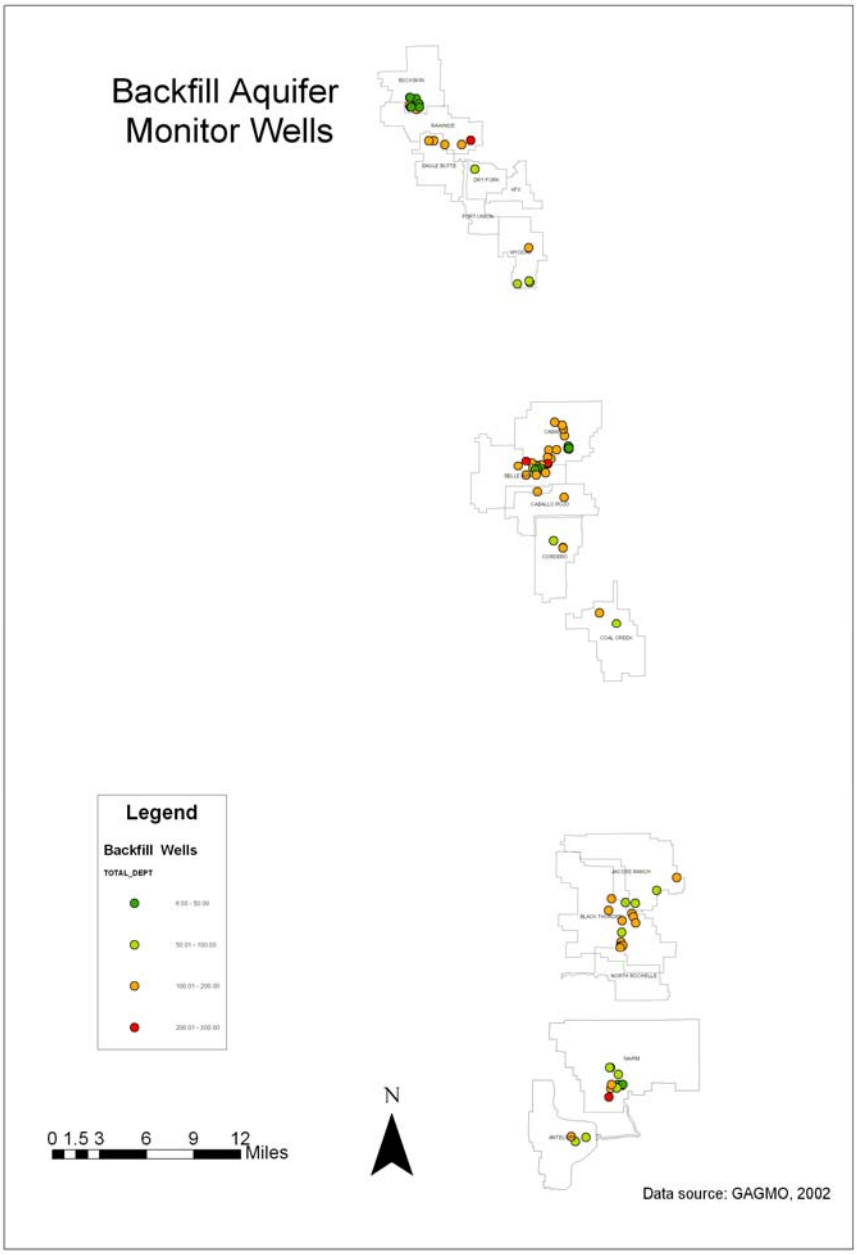

Figure 3. -- Distribution of total well depths for backfill monitor wells, eastern Powder River Basin, Wyoming.

Total Depth of Monitor Wells

The total depth drilled of the backfill monitor wells varied from 1.8 meters (6 feet) to 82.9 meters (272 feet) with a mean depth of 32.9 meters (108 feet) and a standard deviation around that mean of 20.1 meters (66 feet). One of the reasons for the variability of the depth of the backfill wells is because some wells monitor reclaimed alluvial backfill

areas while other wells monitor the deeper backfill material. Additionally, as mining progresses from the east to the west, the coal dips increase. Thus results in thicker backfill materials, and as a consequence, deeper backfill monitor wells. Examination of Figure 3 indicates that variable depths of backfill monitor wells are distributed through all three mining areas and within individual mines.

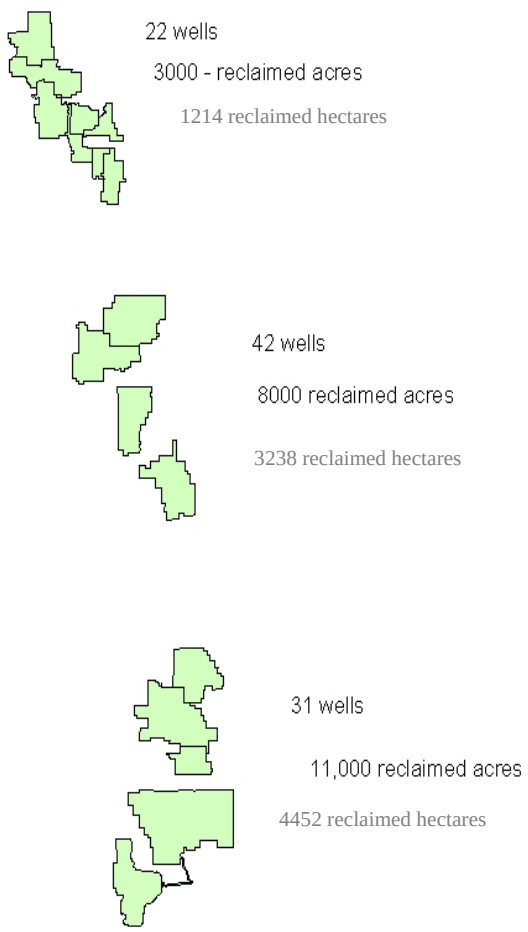

Figure 4. – Number of backfill monitor wells by northern, middle and southern groups of coal mines, eastern Powder River Basin, Wyoming. [Data source, GAGMO 2002]

Distribution of Monitoring Wells by Groups of Mines

When the number of wells in each mining area is examined (Figure 4), it can be seen that the wells are distributed throughout the three mining areas – northern, middle and southern. There are 22 wells within the northern group of mines, 42 wells within the middle group of mines and 31 wells within the southern group of mines. The regulatory agency examines information such as that contained in Figure 4, along with the number of backfill aquifer monitor wells at individual mines to assure both sufficient environmental protection and equitable treatment of mines.

Analysis of Water Quality in the Backfill Aquifer

After determining that the data were distributed throughout the three areas of mining, analysis of selected water quality constituents was examined. Major ions and TDS concentrations from data collected between 1986 and 2002 were evaluated. Larger concentrations of TDS were evaluated in more detail using GIS plots to explore possible relationships to clinker outcrops and stream channels.

General Statistical Summary and Water Type of Backfill Aquifer

The data were statistically summarized for the northern, middle and southern mines, and for all mines together. For each of the constituents examined, the following measures were calculated; mean, median, standard deviation, minimum, maximum, number of samples (count) and 90 percent confidence level. Table 2 summarizes the statistical results for the data from all the mines. The anions are dominated by sulfate, which has a mean concentration of 2,082 mg/l. The cations are dominated by sodium, calcium and magnesium.

Table 2. -- Summary of the major ions for the backfill monitor wells, eastern Powder River Basin, Wyoming from 1986 to 2002.

	All Mines							
Constituent	Na	K	Ca	Mg	Cl	HCO3	SO4	TDS
	in mg/l							
Statistical summary data								
Mean	413	26	343	282	52	842	2,082	3,920
Median	**353**	**25**	**393**	**197**	**24**	**868**	**1,847**	**3,514**
Standard Deviation	290	17	211	399	70	342	2,169	3,264
Minimum	39	1	1	0	1	7	0	1
Maximum	3,000	380	957	3,060	706	2,991	17,170	25,812
Count	2,082	2,083	2,078	2,080	2,081	2,081	2,083	2,074
Confidence Level (90.0%)	10	1	8	14	3	12	78	118

There are several observations that can be made by examining the statistical summaries in Table 2. First, there are a significant number of samples in this data compilation, with over 2,000 samples for each constituent. That number of samples results in a relatively robust data set. With 95 wells in the sample set, there is an average of about 21 samples per well. Second, when the two measures of centrality, the mean and the median, are compared, the median is smaller for six of the eight constituents, with calcium and bicarbonate being the exception. Such a relation is indicative of log-normally distributed populations as are often observed in groundwater quality data. The mean, which is derived by dividing the sum of the samples by the number of samples, is subject to greater influence of a few high or low samples than the median, which is the middle number of the observations.

Of particular concern are the concentrations of sulfate and TDS. The general use of the water in the area is for livestock watering and Wyoming's groundwater livestock use standards are 3000 mg/l for sulfate and 5,000 mg/l for TDS. The data summary (Table 2) indicates that both the mean and the median for these two constituents lie below the associated standard. It should be noted that there is significant variance within the data, and at some individual sites those standards may be exceeded. The TDS values ranged from 1 mg/l (most likely a reporting error) to 25,812. The wide range of values and large standard deviation indicated a large variability in the data set. This fits with the conceptualization of the groundwater system in the backfill aquifer, since the data included samples from the initial saturations to samples collected after 20 years of geochemical reactions.

A histogram of the TDS concentrations for all the samples (Figure 5) shows that while most of the samples are in the lower concentrations of the distribution, the distribution does have a long tail extending into the high concentration range. About 75 percent of the concentrations are below the Wyoming livestock use standard of 5,000 mg/l, whereas about 25 percent exceed it (Figure 5).

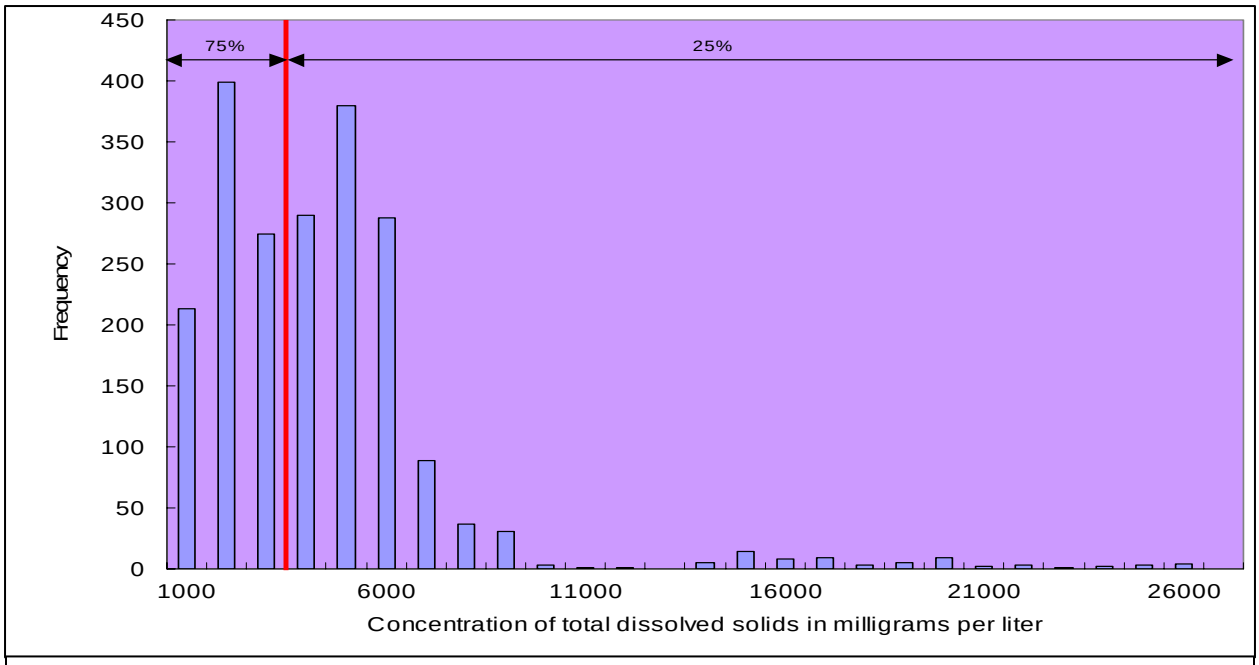

Figure 5. -- Histogram of total dissolved solids concentrations for the backfill aquifer, 1986 to 2002, eastern Powder River Basin, Wyoming.

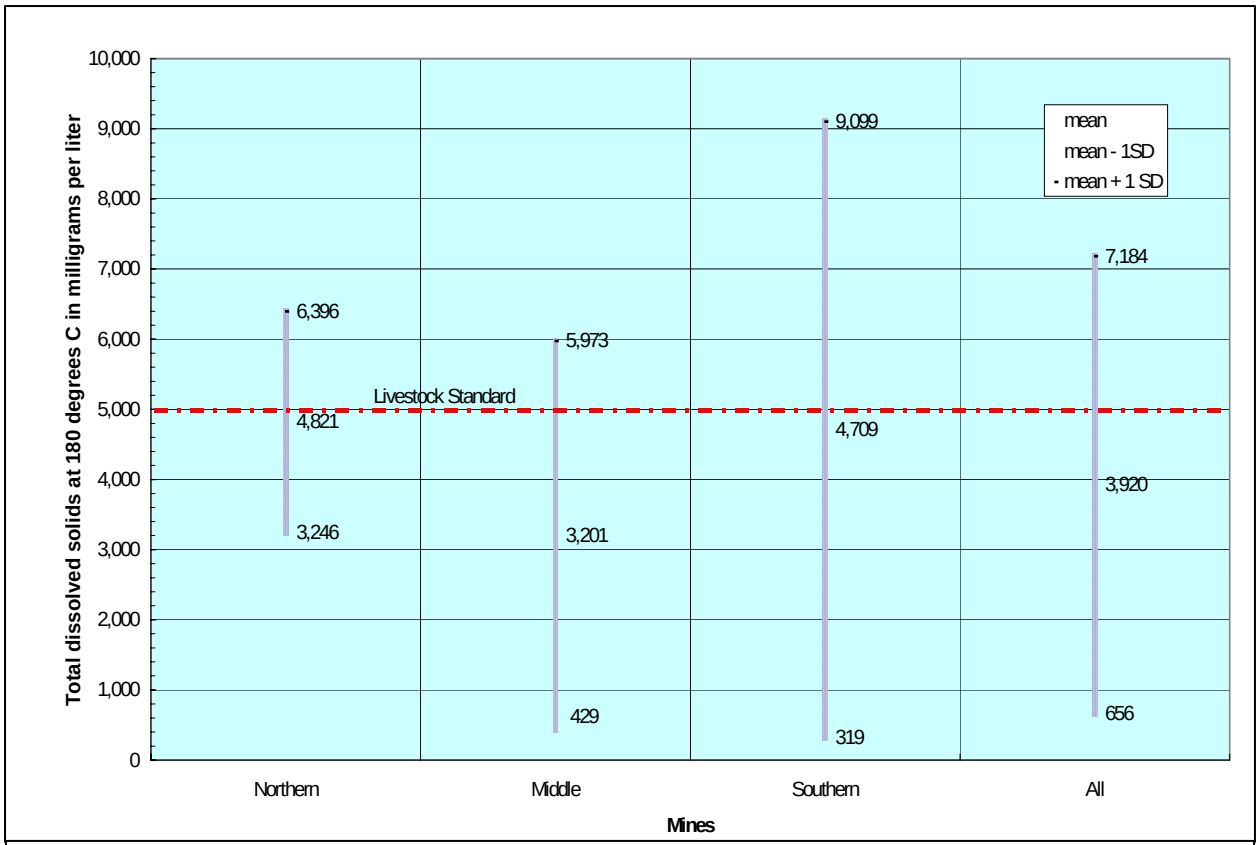

Figure 6. -- Mean total dissolved solids with plus and minus one standard deviation, backfill water quality, 1986 to 2002, eastern Powder River Basin, Wyoming.

The TDS mean values, and mean values plus or minus one standard deviation for the backfill aquifer were compared to the livestock use standard for Wyoming groundwater for all three mining areas and for all mines together (Figure 6). The southern set of mines had the highest mean TDS concentrations with a mean value of 4,709 mg/l and the largest variance. The middle group of mines had the lowest mean concentration with a value of 3,201 mg/l. The northern set of mines had the lowest standard deviation.

The water type for each of the groups of mines – northern, middle and southern – as well as all the mines for the backfill aquifer samples was determined by converting the median concentration from milligram per liter to milliequivalents per liter and plotting the result in a Stiff diagram (Figure 7).

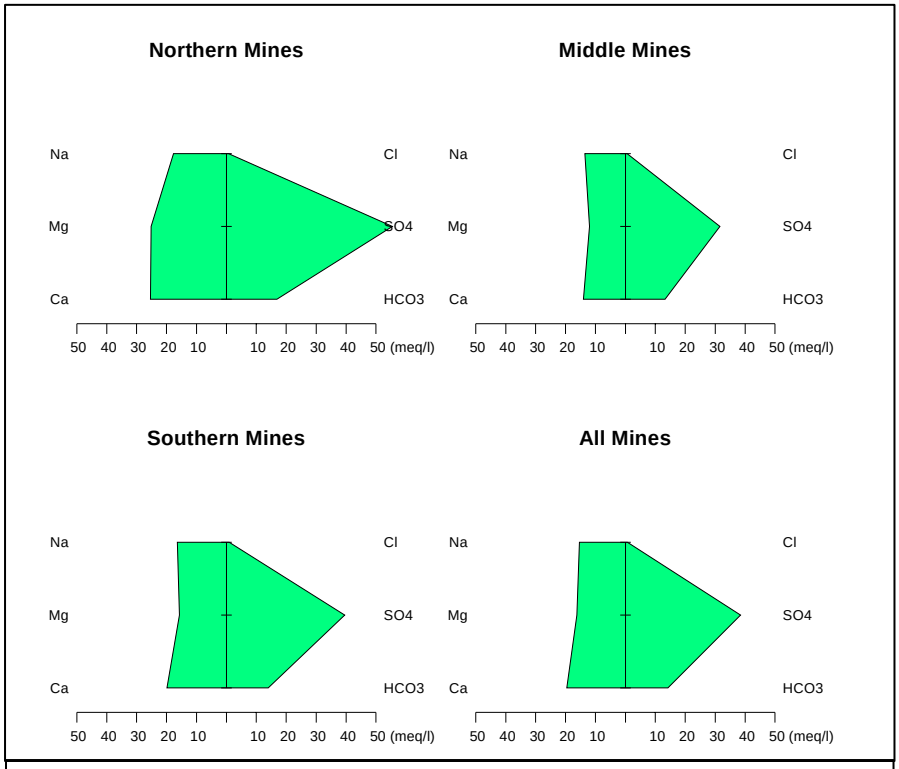

Figure 7. -- Stiff diagrams for the northern, middle, southern and all mines of the median total dissolved solids concentration of the backfill aquifer between 1986 to 2002, eastern Powder River Basin, Wyoming.

The shapes of Stiff diagrams are representative of different water types. The shapes of all four Stiff diagrams are quite similar, indicating that all three groups of mines and the data set as a whole have a similar type of water. The Stiff diagrams all indicate a sulfate type of water, with the anions of calcium, sodium and magnesium present in similar concentrations with some variance between mining areas (Figure 7). The northern mines generally show a high concentration of all the ions, but the water type is still comparable to the other areas. This similar water type may be a result of similar backfill

materials, comparable mining processes, and a common geochemical evolution of water in the backfill aquifer.

Spatial Distribution of Total Dissolved Solids Concentrations in the Backfill Aquifer

TDS concentrations were examined spatially using GIS. The TDS concentrations were compared to the livestock standards for Wyoming and were related to the proximity to the physical features, the clinker deposits and the locations of stream channels.

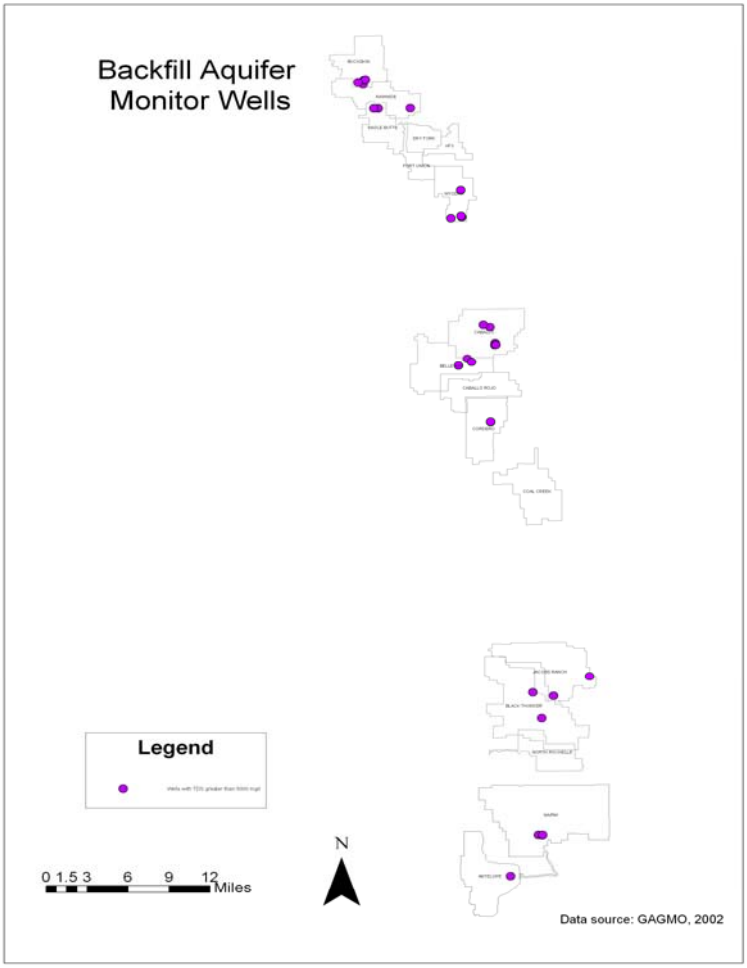

Figure 8. -- Backfill aquifer monitor wells with at least one sample exceeding the 5,000 mg/l concentration for total dissolved solids between 1986 and 2002, eastern Powder River Basin, Wyoming.

First, 2,074 TDS values were pulled into GIS coverages and plotted to examine where high and low concentrations were present. The data were divided into categories based on the groundwater quality use standards for Wyoming. Twenty-six samples were at or below 500 mg/l, (the TDS groundwater standard in Wyoming for domestic use). Detailed examination of these data revealed that 24 of the 26 samples were collected from one well with the other two samples from two different wells. Two of the wells are close together and the third well is distant from the two wells. The

Wyoming groundwater agricultural use standard for TDS is 2,000 mg/l. Six hundred and twelve samples had TDS concentrations at or below the agricultural standard and were distributed spatially throughout the mines. The Wyoming groundwater livestock use standard for TDS is 5,000 mg/l and was met by 1,556 samples in the data set, which was distributed throughout the mines. However, 518 samples exceeded the livestock standard and those values are likewise distributed throughout the mines, indicating that there is not a single area of concentration of high TDS values (Figure 8). The values exceeding the livestock standard were reported from a total of 27 wells or about 28 percent of the total number of wells, while 72 percent of the wells always had samples below the livestock standard (Figure 8).

The backfill wells were further analyzed in relation to two features that may have significant hydrologic impacts, clinker deposits and stream channels. Both clinker and stream channels have been identified as areas of focused recharge. Clinker deposits (Figure 9) are identified as an important recharge source for the shallow hydrologic system in the PRB (Heffern et al., 1996, Bartos and Ogle, 2002). Clinker deposits associated with the Wyodak Anderson coal seam are located along the eastern edge of the mine permit areas. Burning of coal deposits in the past created extreme heat and produced the pyrometamorphic clinker rocks from the clays and sandstones, which overlaid the coal. The clinker is highly fractured and permeable. It readily accepts precipitation and generally recharges the coal. It is estimated that the influence of the clinker on recharge to the backfill aquifer might be dominant for approximately 610 meters (2000 feet). The clinker GIS coverage was imported, a buffer of 610 meters was created around the outcrop of the clinker. Then all the backfill wells lying within the buffered area were clipped from the backfill well coverage. Thirty-six wells, or 38 percent of the wells were within the buffered area (Figure 9).

From those 36 wells, 820 samples were collected. The mean TDS concentration for the wells within 610 meters of the clinker was 4,597 mg/l, with the minimum of 296 mg/l and a maximum of 25,320 mg/l. The difference between the mean of the overall data and this sub-set of data that lies within 610 meters of the clinker outcrop is that the buffered data has a mean TDS concentration that is 677 mg/l higher than the overall data set.

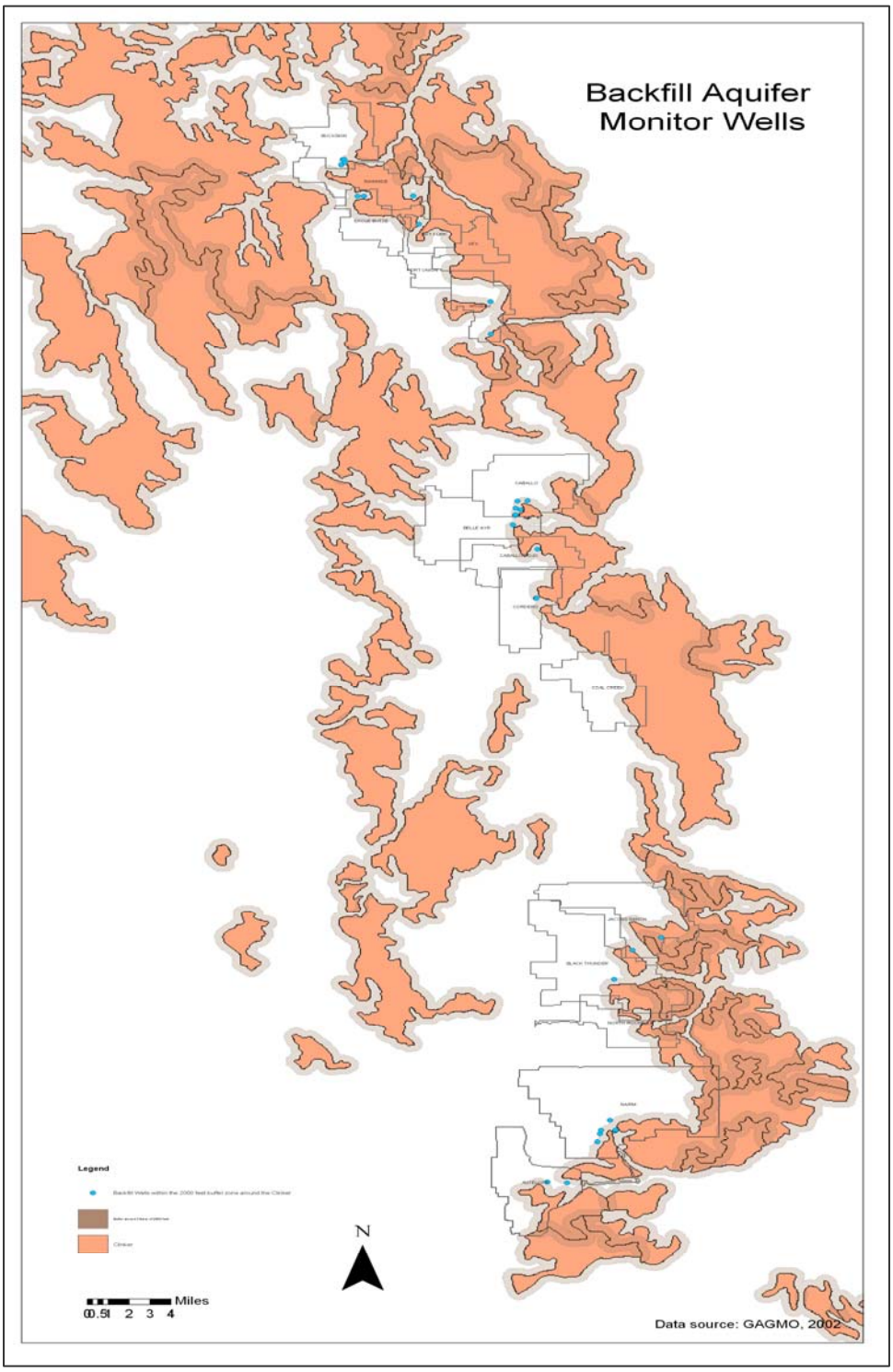

Figure 9. -- Backfill monitor wells that are within 610 meters (2,000 feet) of clinker deposits, eastern Powder River Basin, Wyoming.

Stream channels, even those of ephemeral streams, are recognized as areas of recharge within the PRB. It is estimated that the influence of the stream channels might extend up to 152 meters (500 feet) away from the stream channels. Forty wells, or 42 percent of the backfill monitor wells are within 152 meters of the drainages (Figure 10). From these 40 wells, 1,006 samples have been collected. The mean TDS concentration for these wells proximate to the drainages is 4,738 mg/l and the values range from 632 mg/l to 25, 320 mg/l. The mean TDS value of the samples from these wells is 818 mg/l higher than the mean for all the backfill samples.

In the next step of the GIS analysis, wells were selected that were both within 152 meters of a drainage and within 610 meters of the clinker outcrop. The areas of the clinker buffer and the stream channels buffer were intersected and then only backfill monitor wells within that area were clipped for the coverage containing all the backfill wells. Eleven wells, or 12% of the wells fell in that area. A total of 384 samples had been collected from these 11 wells (Figure 11). The mean TDS concentration for the 11 wells was 6,063 and the values ranged from 632 mg/l to 25,320 mg/l. The mean TDS is 2,143 mg/l higher than the mean of all the samples.

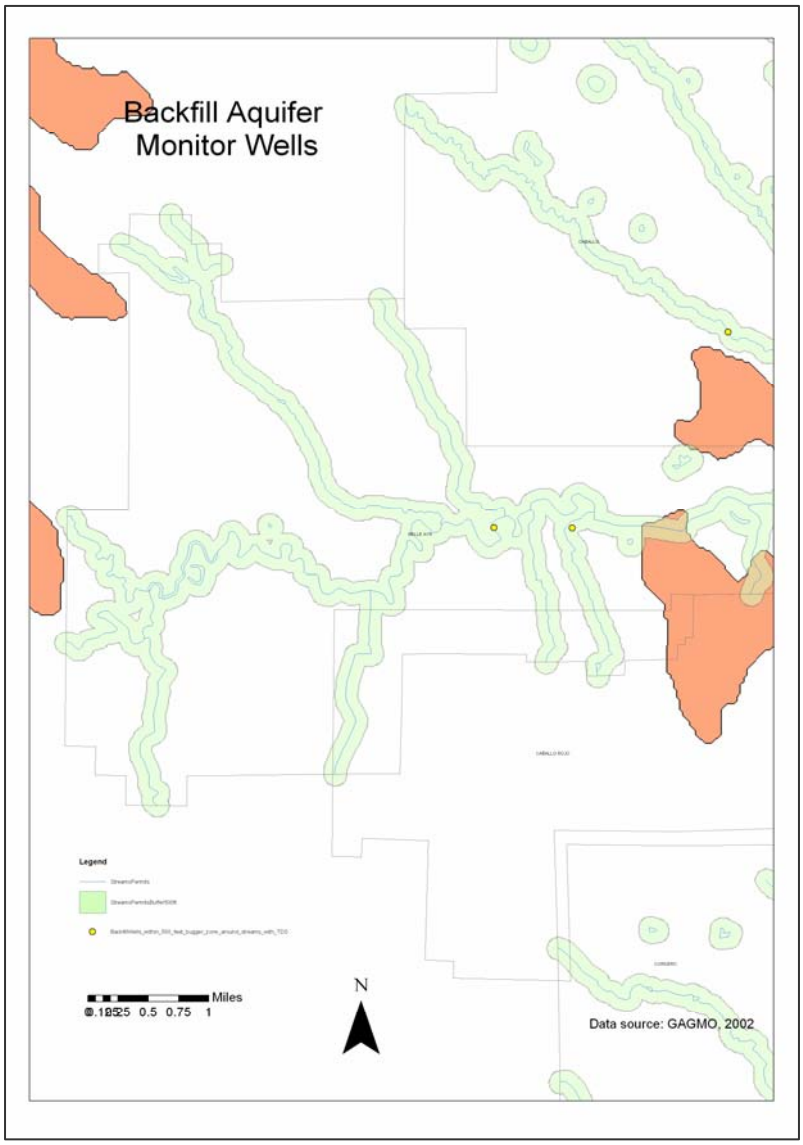

Figure 10. -- Example of backfill monitor wells within 152 meters (500 feet) of streams, 1986 to 2002, eastern Powder River Basin, Wyoming.

The mean TDS concentrations are compared for 1.) all the backfill wells, 2.) the wells close to the clinker deposits, 3.) the wells close to the stream channels, and 4.) the wells close to both the clinker and stream channels (Figure 12), an increase in TDS is observed in the wells associated with the physical features of clinker and stream channels. Proximity to the clinker results in a 17 percent increase in mean TDS concentration in samples from backfill monitor wells, and proximity to stream channels results in a 21 percent increase in TDS. When wells that are proximate to both clinker deposits and stream channels are examined, a 55 percent increase in mean TDS concentrations is observed. Based on the data available, it appears that proximity to either clinker deposits or stream channels or both features results in an increased mean TDS

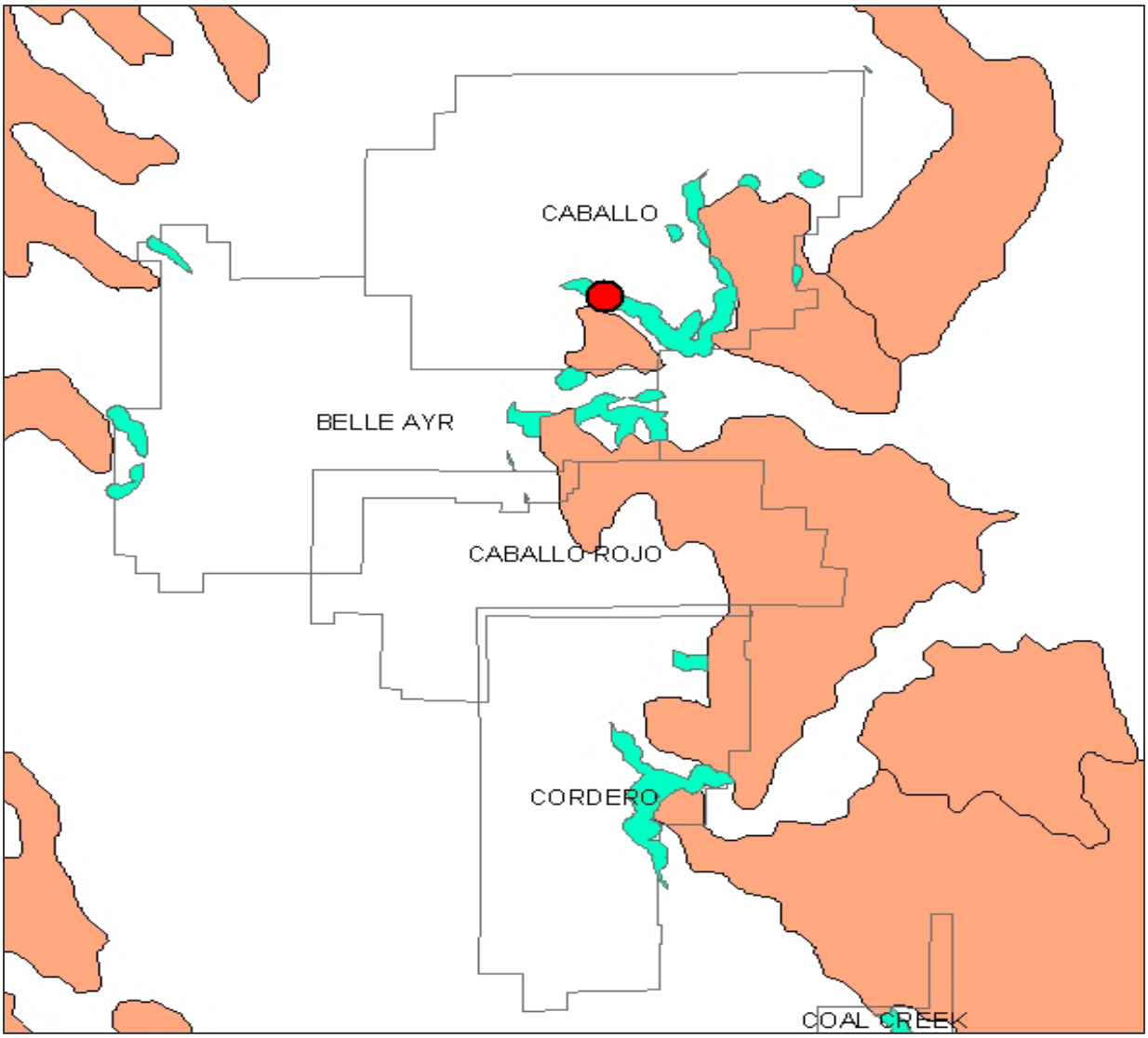

Figure 11. -- Example of a well (red dot) that falls within the intersected area of the clinker and stream buffers (blue area), eastern Powder River Basin, Wyoming.

concentration.

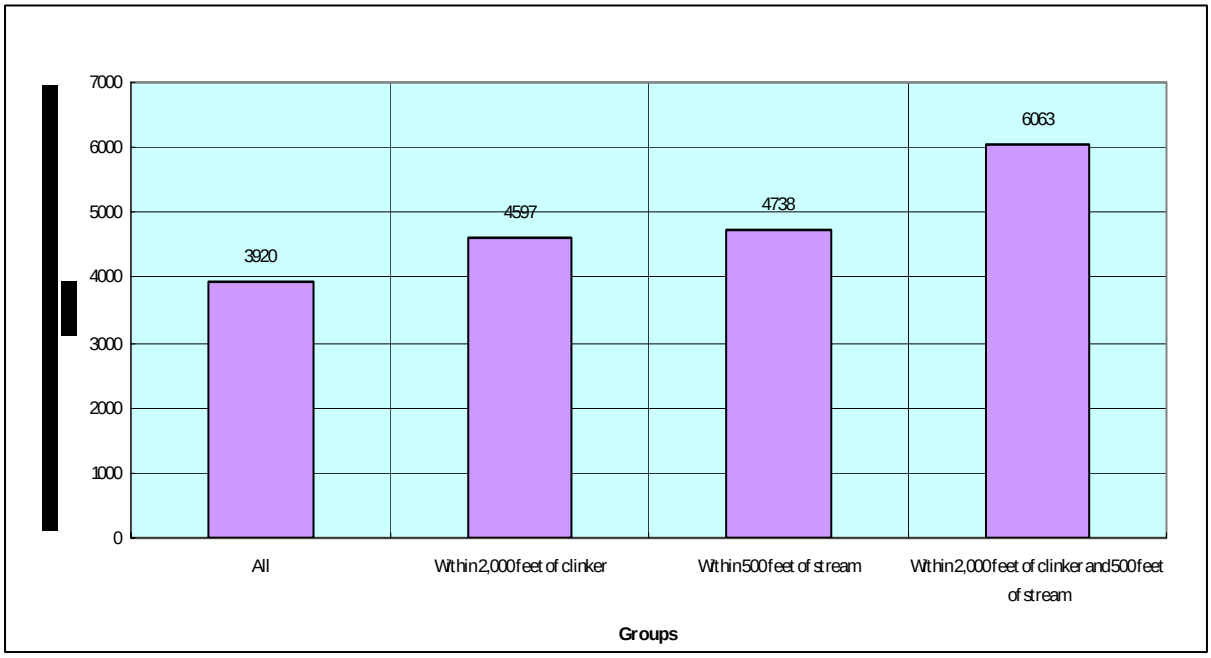

Figure 12. -- Mean total dissolved solids concentrations for all wells, wells proximate to clinker, to streams and to both clinker and streams, eastern Powder River Basin, Wyoming.

Conclusions

GIS and statistical analysis was combined to examine over 2,000 samples of water quality from 95 wells completed in the backfill aquifer in the eastern Powder River Basin of Wyoming. The first step was to use GIS as an exploration tool to determine if there were any biases in the data set based on spatial distribution, depth of well completion or clustering of high concentrations. GIS analysis showed that the data are distributed throughout the mining area with 22 wells in the northern group of mines, 42 in the middle group of mines and 31 in the southern group of mines. The mean well depth was 32.9 meters with well depth varying throughout the mining area. GIS analysis showed that 26 samples had TDS concentrations at or below 500 mg/l, 612 samples had TDS concentrations below 2,000 mg/l, and 1,556 samples had TDS concentrations at or below 5,000 mg/l. TDS concentrations exceeded 5,000 mg/l in 518 samples. No clustering of the data was observed. GIS analysis was used to select wells that had a

sample that exceeded the Wyoming livestock use standard for TDS. The higher TDS values were also distributed throughout the mining areas.

Statistical summaries, water type analysis and histogram examination were used to describe the backfill aquifer water quality. The mean TDS concentration of all samples was 3,920 mg/l. Sulfate was the major component of that TDS concentration. Both the mean and median concentrations of TDS and sulfate were below the Wyoming groundwater livestock use standards. Likewise, mean TDS concentrations for the three groups of mines were either near or below the Wyoming groundwater livestock use standard. The water type in the backfill aquifer was sulfate with about equal amounts of calcium, sodium and magnesium. The water type was consistent for the northern, middle and southern groups of mines and for the data set of all mines. The middle group of mines did have more sodium relative to the calcium than the other two areas. Seventy-five percent of the samples were below the Wyoming groundwater livestock use standard and 25 percent exceeded the standard.

TDS concentrations were examined in relation to the sampling points proximity to clinker deposits and stream channels locations. Both clinker deposits and stream channels locations are identified as recharge areas. GIS analysis was used to select all wells within 610 meters (2,000 feet) of clinker deposits. The mean TDS of the wells proximate to the clinker deposits was 17 percent higher than the overall data set. GIS analysis was used to select all wells within 152 meters (500 feet) of stream channels. The wells proximate to the stream channels had a mean TDS concentration 20 percent high than the overall data set. When GIS was used to select wells that were proximate to both the clinker deposits and the stream channels, the mean TDS concentrations was 6,063 mg/l, which is a 55 percent increase from the overall data set. It appears that proximity to clinker deposits and stream channels is associated with elevated TDS concentrations.

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