PROJECTED IMPACTS OF MINING ON ALLUVIAL AQUIFERS AT COLSTRIP, SOUTHEASTERN MONTANA (1)

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Abstract.--Western Energy Company has developed a computer program to estimate cumulative hydrologic impacts related to mining at Colstrip. Predicted increases in total dissolved solids for the Rosebud Mine, Big Sky Mine, Montana Power Company's Colstrip Generating Units 1-4, and associated facilities were routed, using Darcy's law, through bedrock aquifers to alluvial aquifers and summed over time.

INTRODUCTION

Western Energy Company, at the Rosebud Mine at Colstrip, mines 10-12 million tons per year of sub-bituminous coal for export to midwestern customers and for use at four mine mouth power plants. The mine is located at Colstrip, Montana approximately 35 miles south of Forsyth and 125 miles east of Billings. Peabody Coal Company's Big Sky Mine is approximately five miles south of Colstrip (Figure 1). The Colstrip area receives 15-16 in. of precipitation per year and is drained by ephemeral or intermittent streams. At the Rosebud Mine, overburden material consisting of sandstone, siltstone and shale overlying the Rosebud Coal is stripped by means of 60 and 75 cubic yard draglines and coal is mined with 15 cubic yard coal shovels. Regrading is done by dozers with the help of graders for final smoothing. Sub-soil and topsoil are laid down by scrapers and the regraded and topsoiled surface is then seeded using standard farming techniques.

The Rosebud coal seam is approximately 24 ft. thick near Colstrip and is separated from the underlying McKay coal seam (about 8 ft. thick) by 10 to 100 ft. of interburden material consisting of shale, siltstone and lesser amounts of sandstone (Figure 2). The McKay coal seam is not mined at the Rosebud Mine because of ash, sulfur content, and BTU values. The Northern Pacific Railroad mined coal in Area E and Pit 6 for its locomotives from 1924 until 1958 when diesel supplanted coal. Western Energy Company started mining in Pit 6 in 1967 and has since expanded into Areas A, B, C, D and E. Pit 6 and Area E have been mined out and have been or are currently being reclaimed.

Federal and State regulations require that each mine permit include a Cumulative Hydrologic Impact Assessment (CHIA). Much of the effort in a CHIA is directed toward alluvial aquifers. Most impact analyses to date (whether state, federal of industry efforts) have been qualitative determinations, whereas both state and federal regulators have been increasingly asking for quantitative determinations.

In an effort to provide quantitative estimates of potential impacts, Western Energy Company developed a computer program based on work published by R. A. Rohlf (1982) to estimate increases in dissolved solids for alluvial aquifers which might result from mining. That program predicted impacts of present and future mining based on average water quality loading and estimated mining rates for an entire watershed or basin. Rohlf (1982) presented predicted TDS and sulfate loading for two basins in Kentucky.

In an attempt to provide better estimates using actual mine plans, overburden data, premine water quality data, and postmine spoils water quality collected at the Rosebud Mine, the algorithm as originally published (Rohlf, 1982) was modified based in part on research by the Montana Bureau of Mines and Geology. Premine overburden data and postmine spoils water quality data are used to predict postmine water quality for areas to be mined. Predicted increases in total dissolved solids are then routed using Darcy's law through the bedrock aquifers to alluvial aquifers and summed over time. Output consists of plots of predicted postmine TDS vs time. The computer program described in this paper was written in Basic, but the procedure just described could easily be done for a specific mine using a spreadsheet. Western Energy Company's program provides versatility in that it can be used in a variety of situations, but it is

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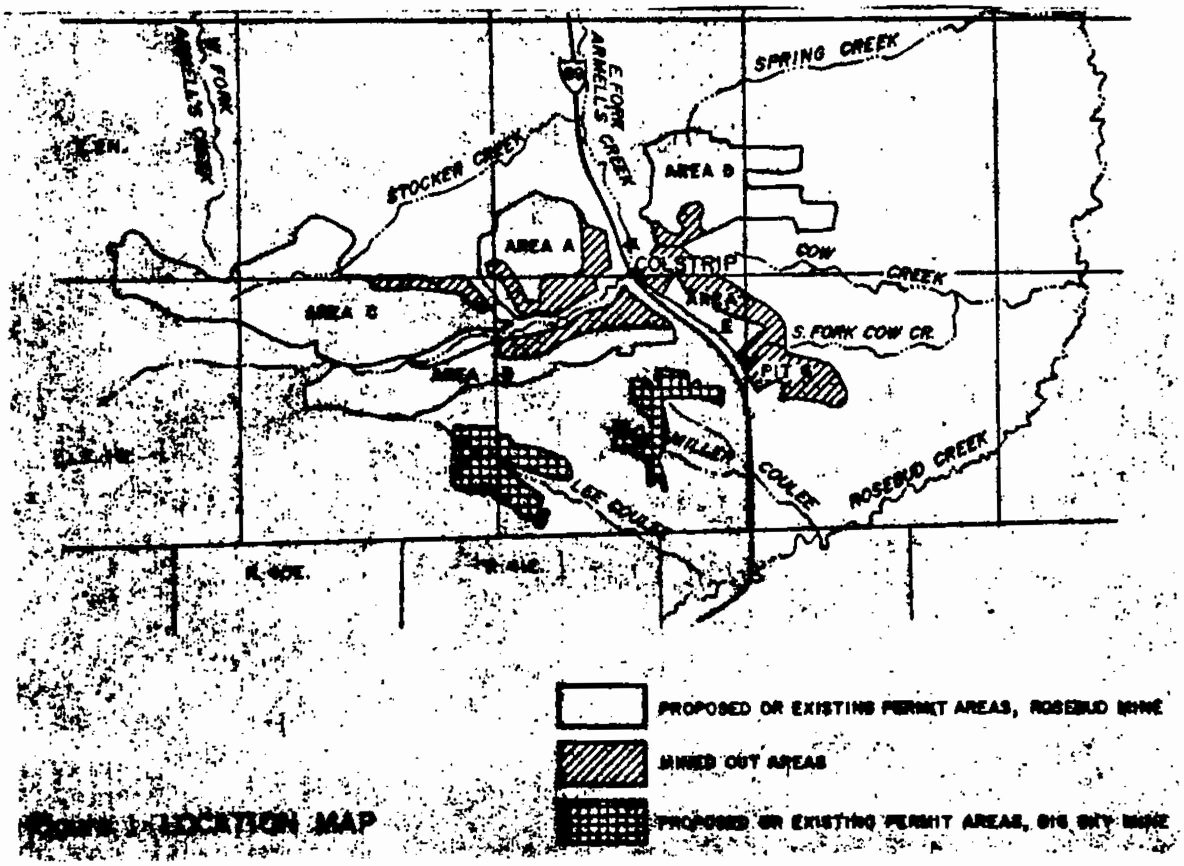

Figure 1. LOCATION MAP

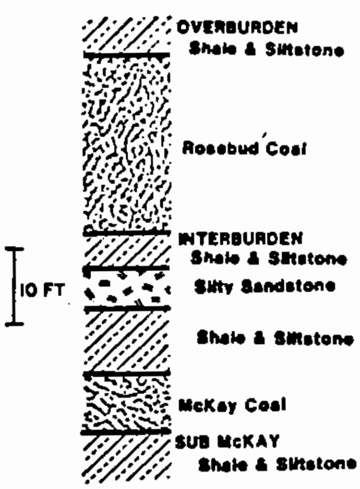

Figure 2. GENERALIZED LITHOLOGY

somewhat cumbersome for a situation such as Colstrip because each watershed requires a separate run with two data files for each run. A spreadsheet would have to be set up for each specific situation but the entire Colstrip area could be built into a single program.

Western Energy Company's program was used in preparation of the CHIA for their Area B Expansion Permit Application (Western Energy Company, 1986). Results are discussed on pages 175-180 of that permit and input data and output from the program are included in Appendix F of that application. This paper discusses the methodology behind the program and briefly describes the results of the Area B CHIA which includes predicted impacts of mining at the Rosebud and Big Sky Mines as well as estimated impacts of Colstrip Generating Units 1-4 and associated facilities.

UNIT RESPONSE THEORY

A well known example of unit response modeling is the theory of unit hydrographs (Sherman, 1932). The unit hydrograph represents the runoff from a basin that would result from one inch of rainfall occurring uniformly over the entire basin during a specified time period. Physical characteristics of the basin such as slope and storage are reflected in the runoff hydrograph (Figure 3). In a like manner, each unit of coal mining activity can be assumed to result in a water quality unit response function which shows the change in total dissolved solids (TDS) or other conservative constituent loading

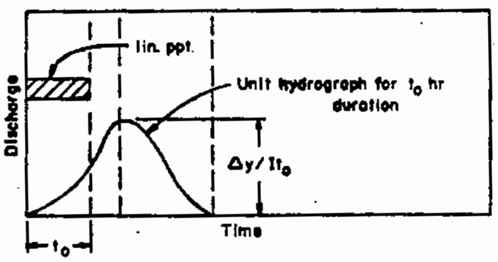

FIG. 3-Derivation of a unit hydrograph (CHOW, 1964)

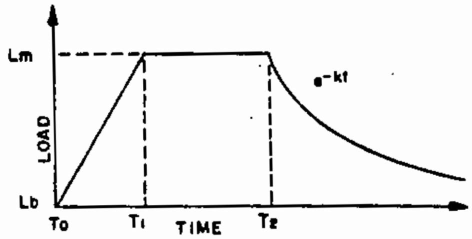

Figure 4 - Unit response function (Rohlf, 1982)

caused by coal extraction and accompanying overburden disturbance. Rohlf (1982) based his model on the unit response function shown in Figure 4 and represented by the following equations:

$$U(t) = \frac{Lm \cdot t}{T1}, \text{ for } t \leq T1$$

$$U(t) = Lm, \text{ for } T1 < t \leq T2$$

$$U(t) = Lm \cdot e^{-k(t-T2)}, \text{ for } t > T2$$

where Lm is the maximum loading in mass per unit time, k is an empirical decay coefficient (which, for this study, is based on data published by Van Voast, 1978), T1 and T2 are time parameters, t is time, and U is the unit response loading function (mass of constituent per unit time per unit of coal). Rohlf's model then integrated the unit response functions over time to produce a water quality constituent load, L(t) related to the rate of mining.

Overburden data, collected on a 1000 ft. grid, have been correlated with spoils water quality at the Rosebud Mine. Rather than use average values of TDS loading for the entire mine and relate the unit response function to mining rate as in Rohlf's model, the computer program developed during this study calculates the response for each cell of a flow net based on predicted postmine TDS values derived from kriged overburden electrical conductivities. The unit response loading function, U(t), then becomes the constituent per unit time for a cell. Mining and resaturation of the spoils is assumed to take place during time T0 to T1 and T1 to T2 is the time for the first pore volume of water to flow through the spoils in a cell (Figure 4).

The flow net was drawn using Rosebud coal and spoils water levels adjusted to estimated postmine conditions. A simplified representation is shown in Figure 5. Contour plots of transmissivity and TDS were prepared for the Rosebud coal and overburden to facilitate estimation of these parameters for each element in the flow net. These values were used to calculate the premine mass transport of dissolved solids through each cell in a flow path. The maximum postmine increase in mass transport through each element (or maximum loading, Lm) is calculated as the difference between predicted postmine dissolved solids mass transport values (based on the predicted postmine TDS as shown on Figure 6 and discussed later) and premine dissolved solids transport. From this difference the unit response function is determined for each element according to the equations above.

The study area was divided into seven watersheds or drainage basins: East Fork Armells Creek, Stocker Creek, West Fork Armells Creek, Cow Creek, South Fork Cow Creek, Lee Coulee, and Miller Coulee (Figure 5). Response functions are routed using Darcy's law along bedrock flow paths to the alluvial aquifer associated with the stream draining the watershed and then downstream through the alluvium. Response functions, corrected for flow time, are summed for all bedrock elements to be mined in the watershed above the point along the stream (usually an alluvial cross section) under consideration according the following equation:

$$L(t) = \sum_{d1}^{d2} U(t)$$

where L(t) is the dissolved solids load in mass per unit time and d1 and d2 are the distances upstream to the lowest and highest points affected by mining. The TDS concentration at any time can then be calculated from:

$$C(t) = (Lb + L(t)) / Qb$$

where C(t) is the TDS concentration (mass per unit volume), Lb is the premine transport of dissolved solids (mass per unit time), and Q is the groundwater flow (volume per unit time). For elements of the flow net not mined, the postmine TDS was assumed to be unchanged and was set equal to the premine TDS. Output from the program consists of line printer plots of predicted postmine alluvial water quality (TDS) vs time. For this study impacts were predicted out to 1000 years beyond the end of mining.

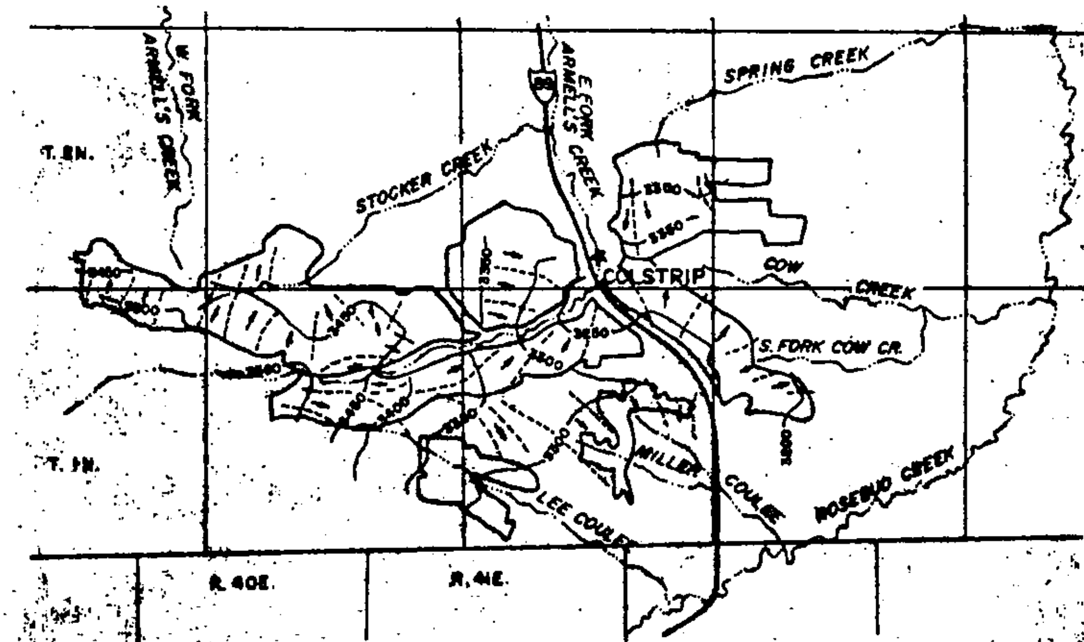

Figure 5 Generalized Flow Net

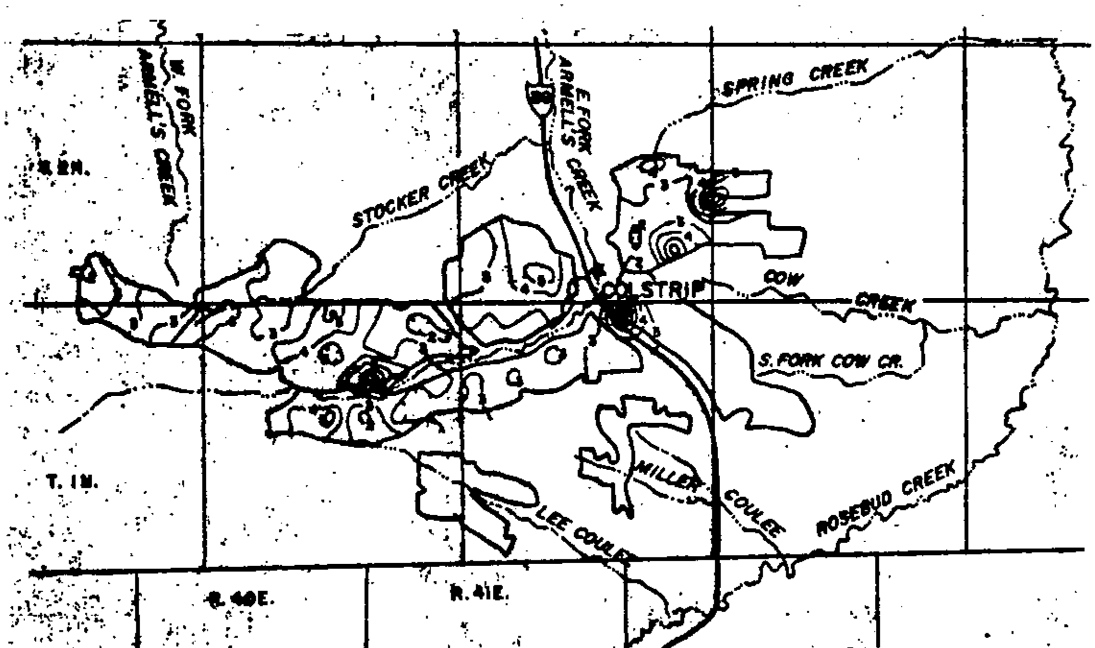

Figure 6 Predicted Postmine TDS

ROSEBUD MINE DATA BASE

Most of the data used in this study were gathered as part of baseline and ongoing monitoring programs conducted at the Rosebud Mine and is included in Western Energy Company's Resource Data Volumes on file with the Department of State Lands in Helena and with Western Energy Company in Billings and Colstrip. Information for the Big Sky Mine was derived from publications or from personal communications with Peabody Coal Company hydrologists (Koffler, 1986, and Wheaton, 1986). Information for Colstrip Generating Units 1-4 and associated facilities (including the ash ponds) was derived in part from discussions with Montana Power Company personnel (Chaffee, 1986) or consultants working for them (Hydrometrics, 1986), and in part represents estimates made by Western Energy Company.

The data base utilized in this study includes 476 overburden analyses covering 22,000 acres and water quality and water level data from about 70 wells completed in the Rosebud coal, 50 wells in spoils, 50 wells in overburden, and 140 wells in alluvium. Overburden electrical conductivities (E.C.) from paste extracts were averaged for each hole and analyzed using statistical methods, including kriging, contained in a geostatistics package developed by H. P. Knudsen (1978). Average premine overburden E.C. values and drill hole coordinates were entered on Western Energy Company's main-frame computer. Multidirectional variograms (plots of sample variance vs distance) were generated and since the data exhibited little anisotropy, the omnidirectional variogram was fitted with a validated spherical model. Vertical variability was not considered as the overburden E.C. data were averaged vertically for the entire depth of each hole. The variogram model was used to krig overburden E.C. values for 300 ft. blocks. A subroutine written into the kriging program converted kriged E.C. values to TDS values according to a linear regression equation relating overburden E.C. to spoils TDS (Figure 7).

As previously mentioned, TDS values and transmissivities were contoured to facilitate estimation of these parameters for each cell within the flow net. Because of the relatively sparse density and poor distribution of data in some areas and limited access to Western Energy Company's computer, it was felt that kriging these data would not enhance the accuracy of the estimations enough to justify the effort.

Water quality samples have been collected from over 125 alluvial wells in the Colstrip area. Naturally occurring TDS levels range from 1206 to 4815 mg/l for East Fork Armells Creek alluvium, 1929 to 4852 mg/l for West Fork Armells Creek alluvium, and 1543 to 6434 mg/l for Stocker Creek alluvium. Lithologic logs of monitoring wells and drill holes completed in alluvium were used to construct cross sections for each of the streams draining the study area. Thirteen cross sections were prepared for the alluvium of East Fork Armells Creek, five for Stocker Creek, eight for West Fork Armells Creek, two for Cow Creek and three for South Fork Cow Creek. Data published by Dollhopf, et al (1981) as well as information from Peabody Coal Company (Koffler, 1986 and Wheaton, 1986) were used for Lee and Miller Coulees. Locations were assigned to each cross-section based on the distance up-gradient (or up-stream since alluvial groundwater gradients parallel stream courses) along the axis of the alluvium

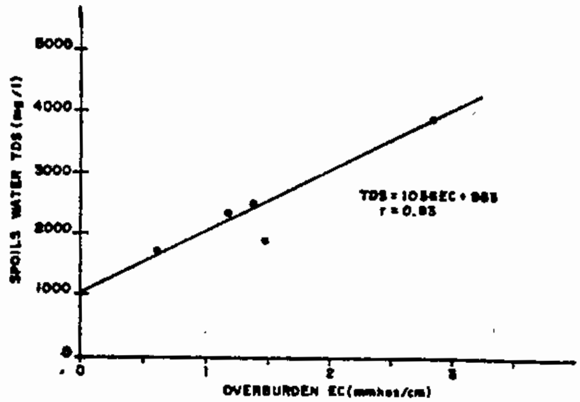

FIG. 7 SPOILS WATER QUALITY-vs-OVERBURDEN EC (Wells within 500' of overburden sites)

with the lowermost cross-section designated as mile 0.

Computer input data for alluvial aquifers include groundwater gradient, average premine TDS, mile designation, and the number of wells in each cross-section; and the permeability and cross-sectional flow area for each well. The lowest cross-section in each of the basins considered in this study was several miles below mining. Computer data input parameters had to be estimated for the lowest cross-sections along Cow Creek, South Fork Cow Creek, Lee Coulee and Miller Coulee.

Groundwater divides near Colstrip generally correspond to surface water divides, and groundwater flow is toward the alluvium which underlies stream channels or toward outcrop areas. The flow net was created by drawing hypothetical flow lines at right angles to potentiometric surface contours so that the area was divided approximately into squares. By definition, flow does not cross flow lines, so they can be considered to be flow path boundaries. The series of cells between flowlines or boundaries that a molecule of water would flow through as it moves down-gradient represent a flow path. Input data to the computer program for the bedrock aquifers includes the number of cells in each flow path and the mile point along the axis of the alluvial aquifer where the bedrock flow path discharges to the alluvium; the width and length of each cell; the Rosebud coal transmissivity, gradient and premine TDS; overburden transmissivity, gradient and premine TDS; and the predicted postmine TDS. For flow net cells which will not be mined, the postmine TDS was set equal to the premine TDS.

In its present form, the program routes dissolved solids along a single alluvial flow path; so for this analysis, tributaries were handled by setting the alluvial flow time from the point where the bedrock flow enters the tributary alluvium to the confluence of the tributary and the main stem equal to zero. This will not introduce appreciable error because alluvial flow times are short relative to the length of the analysis. For some areas which have been or will be mined, it is known that no direct connection exists with the alluvial aquifer associated with the ephemeral stream draining the area. It is assumed that groundwater discharges to the surface in these areas and then evaporates creating a slight salt buildup which is flushed away each spring during runoff. Areas where the degree of alluvial connection was unknown were assumed to impact alluvium, even though in some cases a direct connection is extremely unlikely.

Potential impacts of the lined ponds associated with the Colstrip Generating Units 1-4 (Sec. 34, T.2N., R.41E.) were factored into the analysis by assuming that 1,000,000 gallons of water per year (less than 2 gpm) might enter the alluvial groundwater system from that source. Montana Power Company's two ash ponds in Sec. 29, T.2N., R.41E. and in Sec. 5 and 6, T.1N., R.42E. were simulated by setting the post-disturbance TDS for the bedrock cells under the ponds equal to 15,000 mg/l (the approximate TDS of water in the ponds), although no monitoring wells indicate TDS levels near this concentration.

IMPACT EVALUATION

Line printer plots of calculated postmine alluvial aquifer groundwater TDS vs time were generated by the computer program for 21 alluvial cross-sections plus 5 additional points on Cow Creek, South Fork Cow Creek, Miller Coulee and Lee Coulee. Only the lowermost cross-sections were replotted for inclusion in this paper as Figures 8-14. Locations and changes in TDS corresponding to all 26 TDS vs time plots are tabulated in Table 1 starting with the lowermost cross-sections for each drainage. In most cases predicted impacts to alluvial groundwater quality for the drainages under consideration are small because the estimated flow rates through Rosebud coal, overburden and spoils are very small in comparison to flow rates through the alluvium. Predicted increases in TDS for alluvial groundwater quality at the lowest cross-section in each drainage are 31% for East Fork Armells Creek, 10% for Stocker Creek, 3% for West Fork Armells Creek, 6% for Cow Creek, 0% for South Fork Cow Creek, 181% for Lee Coulee, and 64% for Miller Coulee.

Significant increases in TDS were predicted for East Fork Armells Creek alluvial groundwater immediately below Colstrip. The estimated flow rate for alluvial groundwater at the NE 1/4, Sec. 4, T.1N., R.41E. is about 63 gpm. At 1.6 and 2.2 mi. downstream (SW 1/4, Sec. 27, T.2N., R.41E. and NE 1/4, Sec. 28, T.2N., R.41E.) the alluvial groundwater flow is reduced to 23 and 13 gpm respectively accompanied by increased surface flow in East Fork Armells Creek which is a perennial stream below Colstrip and ephemeral or intermittent above. Because of the reduced flow in the alluvium and the resulting lack of dilution of estimated lateral inflows to these locations

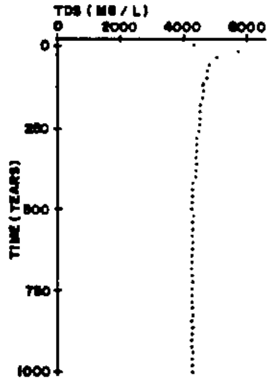

FIG. 8 - EAST FORK, ARMELLS CR. NW1/4 Sec.21 T.2N. R.41E.

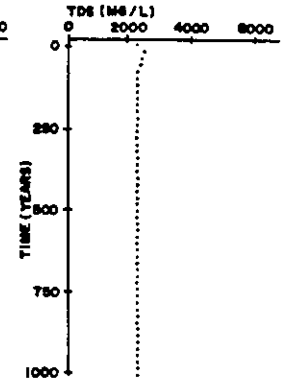

FIG. 9 - STOCKER CR. NE1/4 Sec.17 T.2N. R.41E.

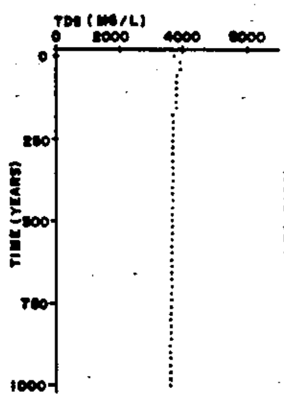

FIG. 10 - WEST FORK, ARMELLS CR. NE1/4 Sec.13 T.2N. R.41E.

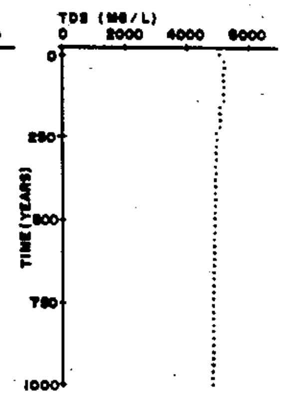

FIG. 11 - COW CREEK NW1/4 Sec.4 T.1N. R.42E.

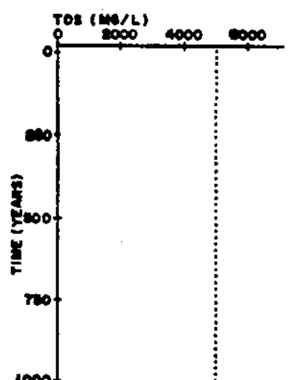

FIG. 12 - SOUTH FORK, COW CREEK SE1/4 Sec.4 T.1N. R.42E.

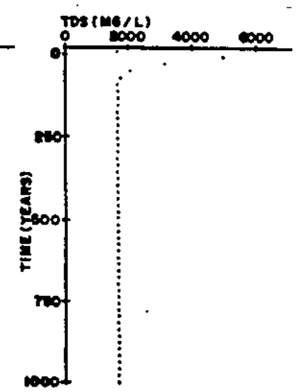

FIG. 13 - LEE COULEE NW1/4 Sec.8 T.1S. R.42E.

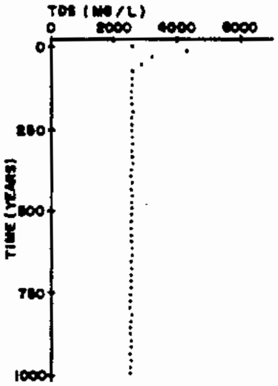

FIG. 14-MILLER COULEE NE 1/4 Sec. 3 T. 1S. R.42E.

STREAM	LOCATION	PREMINE TDS (mg/l)	CALCULATED PEAK POSTMINE TDS (mg/l)
East Fork Armells Cr.	NW1/4 S21 T2N R41E	4318	5669
	NE1/4 S28 T2N R41E	2943	7636
	SW1/4 S27 T2N R41E	4081	6749
	NE1/4 S 4 T1N R41E	2190	2924
	NE1/4 S 7 T1N R41E	1492	1793
	SE1/4 S11 T1N R40E	2008	2733
	NW1/4 S15 T1N R40E	1004	1499
	NW1/4 S15 T1N R40E	3570	3674
Stocker Cr.	NE1/4 S17 T2N R41E	2320	2538
	NE1/4 S19 T2N R41E	2032	2291
	SW1/4 S24 T2N R40E	1852	2096
	NW1/4 S26 T2N R40E	3436	3819
West Fork Armells Cr.	NE1/4 S13 T2N R39E	3741	3864
	SE1/4 S24 T2N R39E	4403	5716
Cow Creek	NW1/4 S 4 T1N R43E	4990	5278
	SW1/4 S 6 T1N R43E	4180	4629
	SW1/4 S 1 T1N R42E	2340	2431
	SE1/4 S32 T2N R42E	2660	2754
So. Fork Cow Creek	NW1/4 S 4 T1N R43E	4990	4990
	SW1/4 S 6 T1N R43E	4180	4180
	SW1/4 S 1 T1N R42E	2340	2340
	SW1/4 S 9 T1N R42E	3170	3170
	SE1/4 S 7 T1N R42E	3120	3214
Lee Coulee	NW1/4 S 8 T1S R42E	1765	4955
Miller Coulee	NE1/4 S 3 T1S R42E	2636	4321
	SW1/4 S30 T1N R42E	2636	3061

Table 1. Summary of predicted impacts

from tributary alluvium, relatively large increases in TDS are predicted. Estimated TDS inputs from Areas A and D, power plant facilities, and the ash pond in Sec. 29, T.2N., R.41E. combine to produce an estimated 2.5 fold increase in TDS for alluvial groundwater at the NE 1/4, Sec. 28, T.2N., R.41E. Considerable data has been gathered for the purpose of tracking impacts of mining on East Fork Armells Creek alluvium, but Western Energy Company has little data on the existence, extent and aquifer properties of the alluvium in tributaries to East Fork Armells Creek downstream from Colstrip. Therefore, as a conservative estimate, a direct connection between the potential sources of TDS loading and East Fork Armells Creek alluvium was assumed. In addition, leakage (if any) from surge pond which stores water for the plants and town as well as the several hundred thousand gallons per day of relatively low TDS (about 1200 mg/l) water from the sewage treatment plant was not accounted for in this analysis because it is not known how much actually enters the groundwater system. A small amount of water from either the surge pond or the sewage treatment plant entering the alluvial groundwater system would result in a significant reduction in predicted impacts downstream. For example, 5 gpm of water from the sewage treatment plant (1-2% of the effluent) infiltrating into the alluvial groundwater system would reduce the impacts at the NE 1/4, Sec. 28, T.2N., R.41E. by 10 per cent. Groundwater quality data for alluvial wells at the SW 1/4, Sec. 27, T.2N., R.41E. suggest a significant contribution to alluvial groundwater flow from sewage treatment plant effluent.

To meet regulatory requirements for a CHIA, cumulative impacts of mining at the Rosebud Mine and the Big Sky Mine had to be addressed. Predicted impacts to Lee Coulee and Miller Coulee are significant for the first 20 years after mining. Predicted increases in TDS concentrations (4,200 mg/l for Lee Coulee and 1,700 mg/l for Miller Coulee) in alluvial groundwater near Rosebud Creek are thought to be higher than what could be reasonably expected because of assumptions made to overcome data gaps. Although Peabody Coal Company personnel were very helpful during this study and most of the needed information for the Big Sky Mine is available in mine permit applications, little information is available on lower Lee or Miller Coulees and Western Energy Company does not have direct access to Peabody Coal Company's mine plans or data. Mine blocks assumed for the input data were large which tends to compress the time period over which impacts are calculated to occur and increases the peak change in TDS. Because little information was available concerning cross-sections or aquifer properties for Lee and Miller Coulees, input parameters had to be estimated from data reported by Dollhopf, et al (1981) and Peabody Coal Company (Koffler, 1986 and Wheaton, 1986). Western Energy Company did not have access to actual potentiometric surface maps for the Big Sky Mine area, so the potentiometric surface was approximated using data published by Dollhopf, et al (1981) and Van Voast (1977). Owing to time constraints and uncertainties about the flow system and extent of alluvium, the flow net was drawn assuming as a worst case that all mining at the Big Sky Mine would occur simultaneously and would contribute groundwater flow to either Lee of Miller Coulee. As a result of these assumptions, the flow patterns do not fit the potentiometric contours precisely, and the impacts of areas which probably do not contribute to alluvium of Lee Coulee or Miller Coulee were included. An error analysis along with the results of experimental runs during program development with varying cell sizes suggest that the ideal cell size for a simulation of this large an area is about 1500 by 1500 ft., whereas cell sizes for the Big Sky Mine were about 3000 by 3000 ft. For the reasons mentioned above, the predicted maximum postmine TDS loading for Lee and Miller Coulees is thought to be greatly exaggerated.

Total impacts to Rosebud Creek were estimated by summing the maximum increase in mass transport of dissolved solids for Miller Coulee, Lee Coulee, South Fork Cow Creek and Cow Creek (total alluvial aquifer mass transport = 5.1 x 10^8 mg/day) and comparing that figure to the average mass transport for Rosebud Creek near Colstrip (USGS station 0695250, mass transport = 1.2 x 10^11 mg/day). Maximum impacts for all four streams were assumed to reach Rosebud Creek simultaneously and, because Western Energy Company has no information on groundwater flow rates or water quality for Rosebud Creek alluvium, the entire change in mass transport predicted by the model was assumed to impact surface water quality. Under these assumptions the predicted change in total dissolved solids for the average annual flow of Rosebud Creek would be an increase of about 0.4 % from 950 to 954 mg/l.

Analyses of the impacts of mining were evaluated for specific locations which are thought to be sensitive in Western Energy Company's Area C Amendment Application (Western Energy Company, 1984) and their Area D Permit Application (Western Energy Company, 1986). Input data for those analyses were updated and included in this analysis where appropriate (Western Energy Company, 1986). Exceptions were analyses of impacts for springs along West Fork Armells Creek in the NE 1/4, Sec. 1, T.1N., R.39E. (Western Energy Company, 1984) and a spring in the SW 1/4, Sec. 19, T.2N., R.42E. on Pony Creek (Western Energy Company, 1986). Alluvium Associated with these ephemeral streams is not continuous below the springs so impacts which might be felt at the springs will not affect alluvial groundwater quality downstream where alluvium is again present.

SUMMARY AND CONCLUSIONS

A computer program to calculate cumulative hydrologic impacts was developed by Western Energy Company and used to estimate impacts of mining and related activities near Colstrip on alluvial aquifer water quality. The estimates described in this paper were originally done for permit applications for the Rosebud Mine. Predicted impacts are generally small because of dilution resulting from the fact that calculated groundwater flow rates for spoils are very small relative to groundwater flow rates for alluvium. The most significant impacts are predicted for areas which have significant data inadequacies for the purposes of this type of analysis. Predicted maximum postmine alluvial groundwater TDS levels for these areas, where worst case assumptions were made, range from 4321 to 7636 mg/l as compared with maximum TDS levels of 4815 to 6434 mg/l for alluvial groundwater quality in areas unaffected by mining. Because these predicted extremes are unlikely to be reached, postmine alluvial groundwater is expected to be within the range of natural groundwater quality for the Colstrip area.

The same type of analysis was worked out by hand and added to Western Energy Company's Area B, Sec. 7, 8, 17 and 18 permit in 1982 (Western Energy Company, 1981). In 1983 the Department of State Lands who regulates surface mining in Montana had a similar analysis done by a consulting firm (Systems Technology, 1983) for Area E. This type of mass transport analysis where dissolved solids or any other conservative constituent is routed through a system defined by a flow net is easy to visual, has been accepted by the state and can be set up easily for most situations using a spread sheet. Such a program would be site specific, but could provide a graphic representation of water quality changes occurring as water moves through a system disturbed by mining.

REFERENCES CITED

Chaffee, J. T. 1986. Personal communication.

Dollhopf, D. J., J. D. Goering, C. J. Levine, S. A. Young and E. L. Ayers. 1981. Crop characteristics on subirrigated alluvial valley systems. Research Report 178, Montana State University, Bozeman, Montana.

Knudsen, H. P., and Y. C. Kim. 1978. A short course on geostatistical ore reserve estimation. University of Arizona, Tucson, Arizona.

Hydrometrics. 1986. Personal communication with D. C. Parker and D. Rogness.

Koffler, M. 1986. Personal communication.

Rohlf, R. A. 1982. Unit response water quality modelling for cumulative impact assessment. Proceedings of the 1982 Symposium on Surface Mining Hydrology, Sedimentology and Reclamation (Lexington, Kentucky, December 5-10, 1982), pp. 609-616.

Sherman, L. K. 1932. Streamflow from rainfall by the unit-graph method. Engineering News Record, vol. 108, pp. 501-505, April 7, 1932.

Systems Technology Inc. 1983. Potential water use effects of estimated spoils related increases in total dissolved solids of the Rosebud Mine Area. DSL Open File Report.

Van Voast, W. A., R. B. Hedges, J. J. McDermott. 1977. Hydrogeologic conditions and projections related to mining near Colstrip, Southeastern Montana. Montana Bureau of Mines and Geology Bulletin 102.

Van Voast, W. A., R. B. Hedges, J. J. McDermott. 1978. Strip coal mining and mined land reclamation in the hydrogeologic system, Southeastern Montana. Project Completion Report.

Western Energy Company. 1981. Western Energy Company's application for amendment to surface mining permit No. 80003, Area B, Sections 7,8,17,18, T.1N., R.40E., Mining expansion.

Western Energy Company. 1984. Western Energy Company's application for amendment to surface mining permit 82003C-A001.

Western Energy Company. 1986. Western Energy Company's application for surface mining permit. Area D West, SMP 86003-D.

Western Energy Company. 1986. Western Energy Company's amendment to surface mining permit 84003B-R1, Area B.

Wheaton, J. R. 1986. Personal communication.