CUMULATIVE HYDROLOGIC IMPACTS ON ROSEBUD CREEK FROM DEVELOPMENT NEAR COLSTRIP, MONTANA

BY
John Metesh
MONTANA BUREAU OF MINES AND GEOLOGY
Butte, Montana

Prepared in Cooperation
with
MONTANA DEPARTMENT OF STATE LANDS
Helena, Montana

MONTANA BUREAU OF MINES AND GEOLOGY
Open-file Report No. 273
1994

CONTENTS

FIGURES

TABLES

ABSTRACT

Cumulative Hydrologic Impacts on Rosebud Creek
from Development near Colstrip, Montana

Large-scale surface mining of coal began at Rosebud mine near Colstrip, Montana in 1924. A coal-fired electric power generating facility at Colstrip includes several ponds near the power generating plant and an effluent disposal (fly-ash) pond east of the facility. Alternative reclamation plans may be proposed in place of the usual method of post-mine regrading and revegetation. A municipal landfill was proposed as part of an alternative reclamation plan for the final pit of the Area E mine; the proposal was eventually withdrawn, but it did raise the question as to the practicality of such a plan. The cumulative effects of past, present, and future mining and mining related activities on ground water and surface water must be considered and weighed against the potential impact of a landfill.

The area of investigation includes the Rosebud mine (the Area E and D mines) in the Cow Creek and South Fork Cow Creek drainages and the Big Sky mine in the Miller Coulee drainage southwest of the Rosebud mine. Water levels and water quality in the Area E mine are recovering from past mining; conversely, active mining in Area D is already lowering ground-water levels. As mining continues, the generation of mine spoils in Area D will likely have an adverse impact on ground-water quality. The fly ash pond, located within the Cow Creek drainage, appears to have significantly impacted ground-water quality. Although a hydrologic barrier was constructed to minimize the impact, several monitoring wells outside the barrier have indicated both a rise in ground-water levels and degradation of ground-water quality directly attributable to the fly ash pond.

Based on ground-water flow rates and changes to TDS concentrations, the Area E mine is contributing 632 pounds per day of dissolved-solids to Cow Creek and Rosebud Creek; the Area D mine is contributing 283 pounds per day, the fly-ash pond is contributing 198 pounds per day, and the Big Sky mine is contributing 250 pounds per day. A landfill such as the one proposed in an alternate reclamation plan would contribute an estimated 17 to 140 pounds per day to Rosebud Creek.

INTRODUCTION

Large-scale surface coal mining at the Rosebud mine (Figure 1) began near Colstrip, Montana in 1924 by Northwestern Improvement Company and continued to 1958. Western Energy Company (WECO) began mining in Area E, adjacent to the Rosebud mine in 1973 and in Area D north and west of the Rosebud mine in 1986. Coal removal was completed by 1990 in Area E and is presently continuing in Area D. The Big Sky mine southwest of the Rosebud mine has a history similar to the Area D mine. Mining began in the 1920's and ended in the late 1950's; after several decades of inactivity, Peabody Coal Company began mining at the Area A mine in 1969 and continues at present in the Area B mine.

Coal strip mining in the area of Colstrip consists of removing the material overlying the coal bed (overburden) and placing it behind an advancing pit from which coal is removed. This produces a hummocky terrain referred to as spoils. The removal of the coal, which is an aquifer in the Colstrip area, often causes dramatic decreases in ground water levels. This drawdown of the ground water in the un-mined coal adjacent to the pit and the undisturbed beds beneath the coal results in an altered ground-water flow pattern and, ultimately, reduced recharge to area streams.

The spoils, which are initially unsaturated, become saturated as ground-water levels recover; it is important to note that the spoils are composed of material much different than that of the coal. As ground-water flow patterns return to pre-mining conditions, dissolved constituents leached from the spoils are re-mobilized in the ground-water system and may ultimately discharge to surface waters and other aquifers.

Reclamation of the spoils consists of regrading them to approximate pre-mining contours and re-vegetating the area with native grasses. Although reclamation of this type may slow the leaching of the spoils by infiltration, the leaching still occurs, and dissolved constituents can still be re-mobilized in the ground-water system.

A municipal landfill was proposed as part of an alternative reclamation plan for the final pit of the Area E mine; the proposal was eventually withdrawn, but did raise the question as to the practicality of such a plan. The Administrative Rules of Montana (ARM) defines "cumulative hydrologic impacts" as "the expected total qualitative and quantitative, direct and indirect effects of mining and reclamation operations on the hydrologic balance." As described in the ARM, the area to be considered in an impact assessment includes the mine area and permit area within which the proposed operation is to take place.

The focus of this assessment is to estimate the cumulative impacts to water-quality in Rosebud Creek from mining and mining related activities. Since the impact of other activities such as agriculture must be excluded from the estimate, it is necessary to identify and evaluate individual sources within the assessment area. Once this is accomplished, the cumulative impact can be estimated in terms of loading, and a comparison made of predevelopment and post-development loading on Rosebud Creek. The potential impact of new activities, such as a proposed landfill can then be estimated. This assessment of impacts to Rosebud Creek includes the Cow Creek drainage, Miller Coulee, and Lee Coulee. The Cow Creek drainage includes the Area E mine, a portion of the Area D mine, and an effluent holding pond or fly-ash pond, constructed in 1983. Located in a tributary drainage to Cow Creek east of the Area E mine, this pond receives a fly-ash slurry pumped from the mine-mouth, coal-fired power-generating plant at Colstrip via a pipeline (Figure 2). Peabody's Area A mine is located at the head of Miller Coulee and the Area B mine is located in Lee Coulee to the west (Figure 1).

Several factors must be known or estimated in order to quantify the impacts, expressed as loading, of mining on the hydrologic balance. For the purposes of this assessment, loading is the **additional** volume of dissolved-solids with respect to time that is released from the source area to Rosebud Creek. The factors required in estimating loading at any one time include the concentration of dissolved constituents and the rate of flow through the affected aquifer(s).

PREVIOUS INVESTIGATIONS

The effects of mining on ground water and related surface water quantity and quality have been extensively monitored since the 1970's by WECO which collects data pertaining to mining activities, the Montana Power Company (MPC) which collects data pertaining to the fly-ash pond; and the Montana Bureau of Mines and Geology (MBMG) which has collected data pertaining to mining and reclamation activities since the 1970's. WECO, MPC, and the U.S. Geological Survey (USGS) have collected long-term, surface-water-flow and -quality data. Hydrologic investigations that pertain, in part, to the assessment area were conducted by Van Voast and others (1977), Van Voast and others (1978), Ferreira (1985), Van Voast and Reiten (1988), Davis (1984), and Olsen and others (1991).

The Montana Department of State Lands / Office of Surface Mining (MDSL/OSM) produced a comprehensive Environmental Impact Study (EIS) in 1983. In this study, estimates were made as to the future impacts of the Rosebud mine, however, in several areas such as the Area D mine and the fly-ash pond, data were limited or not available. A comparison of current information with the 1983 study indicated that some impacts were underestimated whereas others were overestimated. Additional water-level and water-quality data collected since the 1983 study enables an updated estimate of current impacts and future impacts.

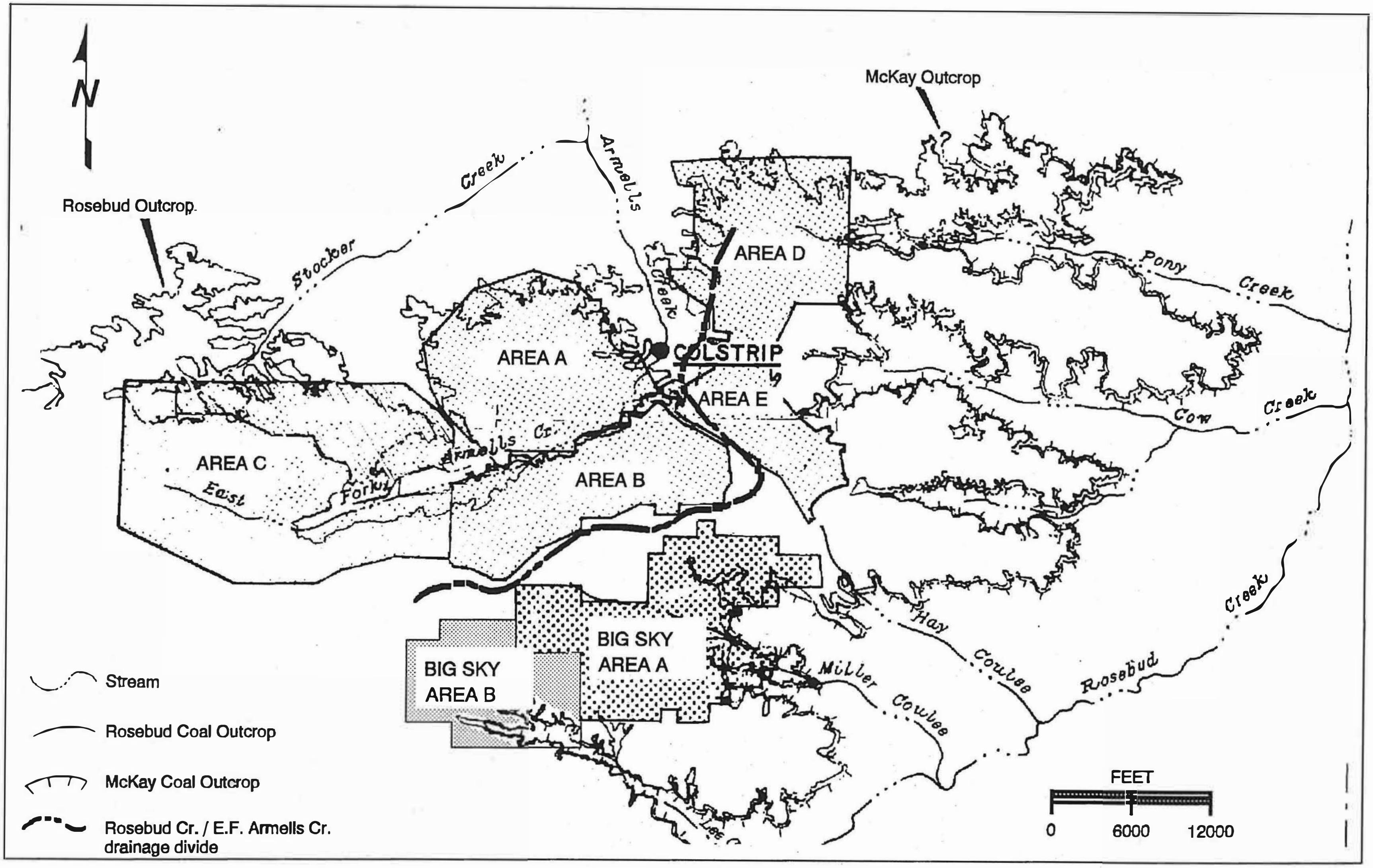


Figure 1. The Rosebud mine and Big Sky mine permit areas.

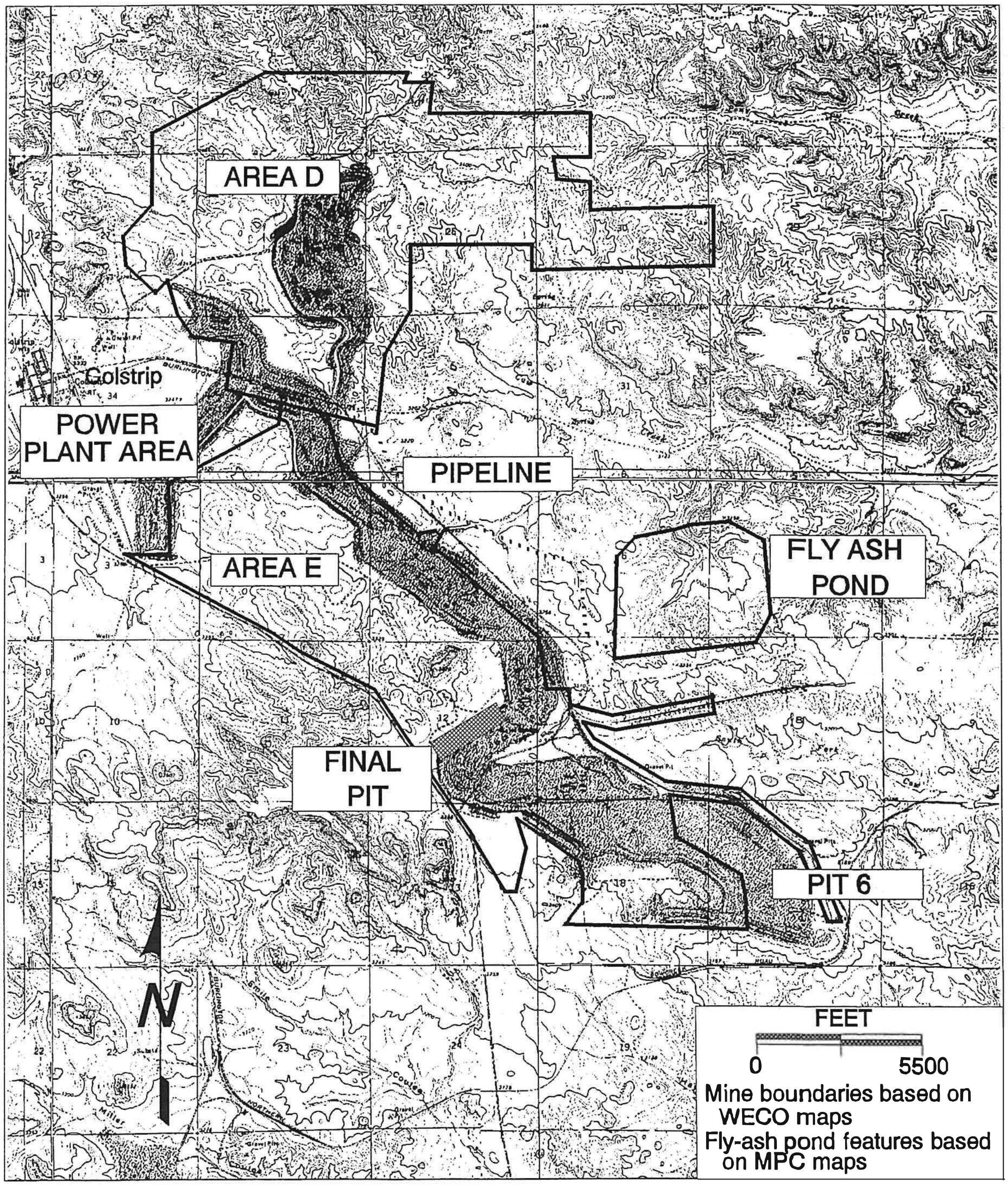
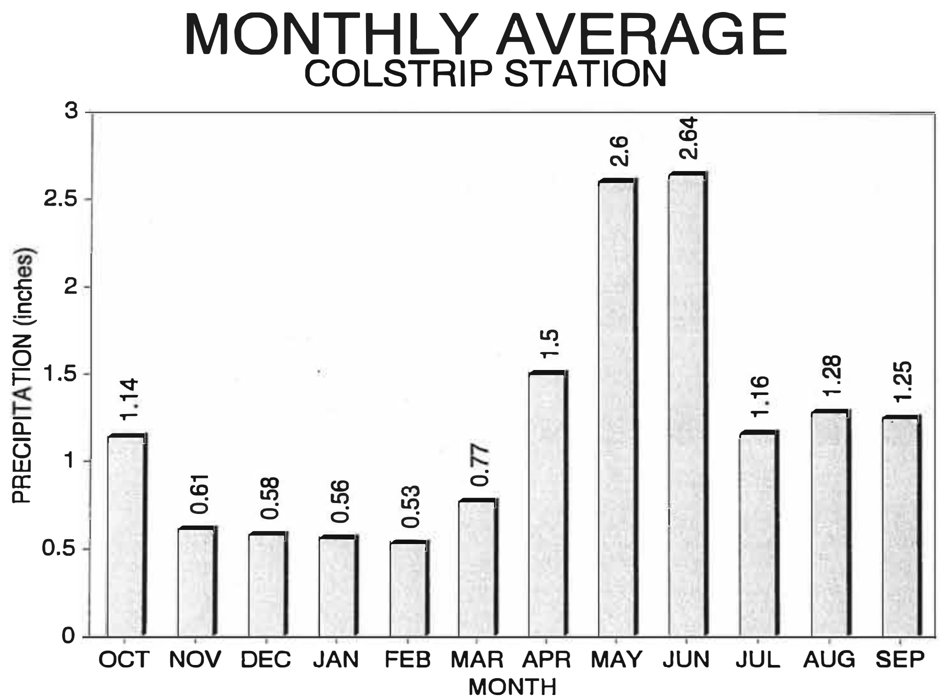


Figure 2. Mine, power plant, and fly-ash pond features near Colstrip, Montana.

PHYSIOGRAPHY

Climate in the Colstrip area is semi-arid; mean annual precipitation through the period 1948 to 1990 was 14.69 inches. Much of the precipitation occurs during the late spring and early summer months (Figure 3). Precipitation during April, May, and June is approximately 46 percent of the annual total.

Streamflow in the smaller tributaries to Rosebud Creek, such as Cow Creek and South Fork Cow Creek, is intermittent; flow occurs only in response to runoff from snowmelt and large precipitation events. The intermittent and ephemeral nature of these streams makes it necessary to estimate the loading to Rosebud Creek using the ground-water flow rate. Several discharges from the Big Sky Area A mine have been directed toward Miller Coulee; as this was a stream similar in nature to Cow Creek, much of the flow in upper reaches of this drainage results from mine discharge. Lee Coulee, below the Big Sky Area B mine, is intermittent and ephemeral in the lower reaches. Streamflow in Rosebud Creek is also intermittent and is strongly influenced by snowmelt and storm runoff; flow is greatest during the late spring and early summer (Figure 4). Stream discharge for both the reach near Colstrip and at the mouth has declined throughout the period of record (1975-1990) except for 1978 and 1979, which are marked by much higher flows. The apparent decline in flow corresponds to a general trend of decreased precipitation for the same period (Figure 3).



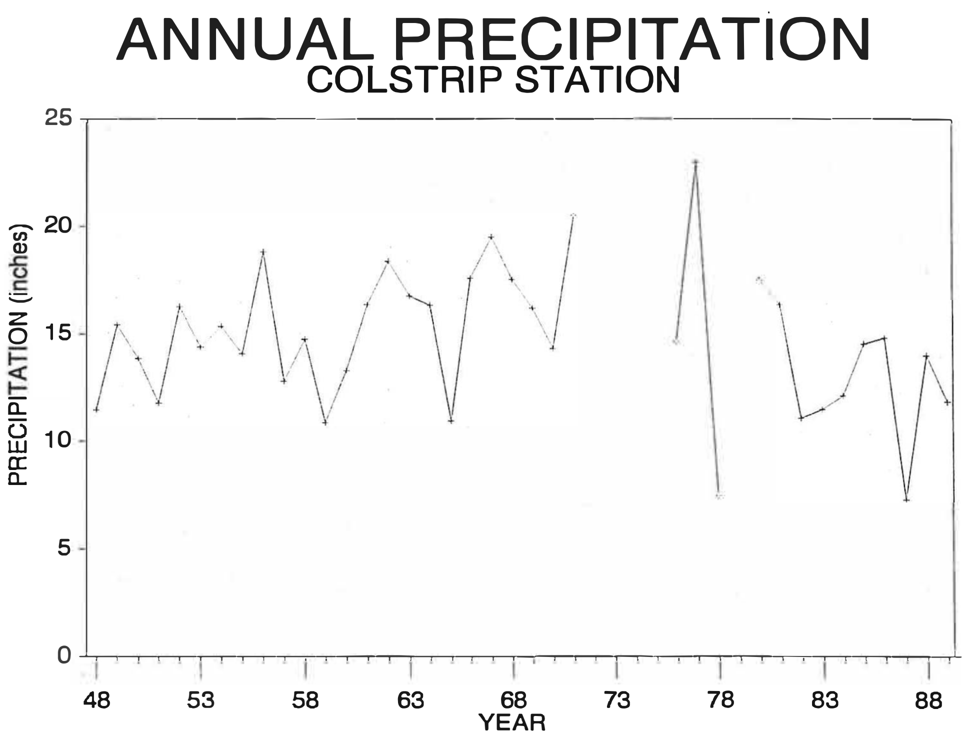
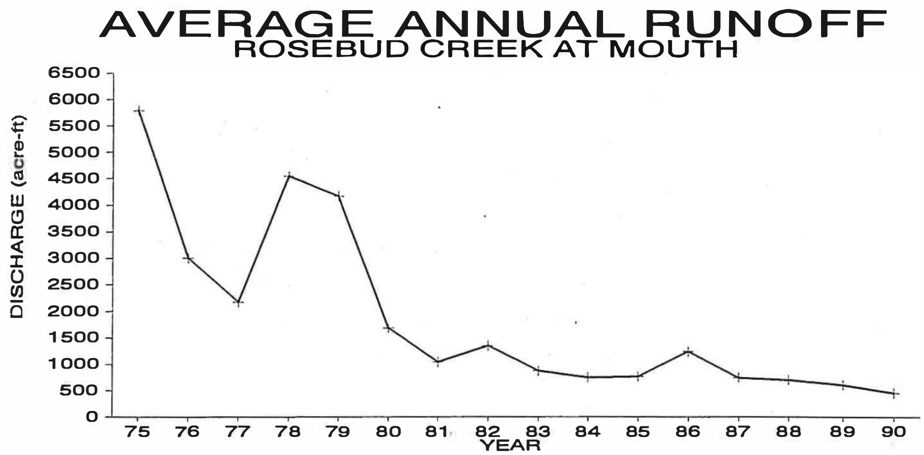
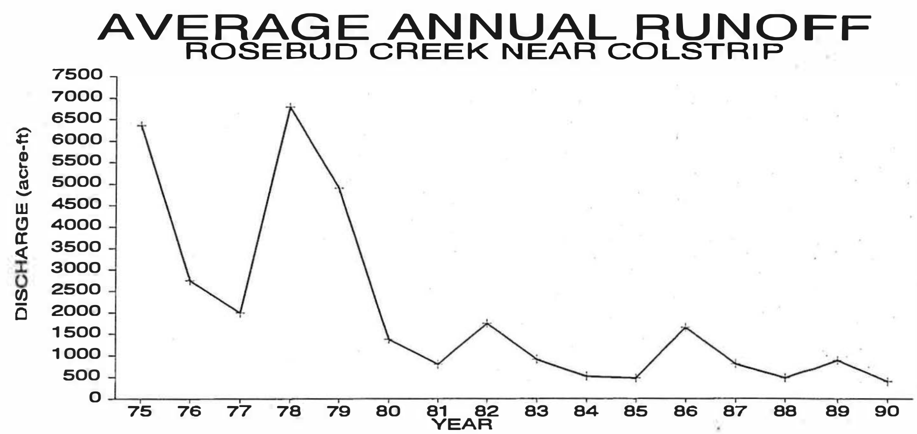


Figure 3 Precipitation data for the Colstrip station from 1948 to 1990 (data source: USGS, 1990).





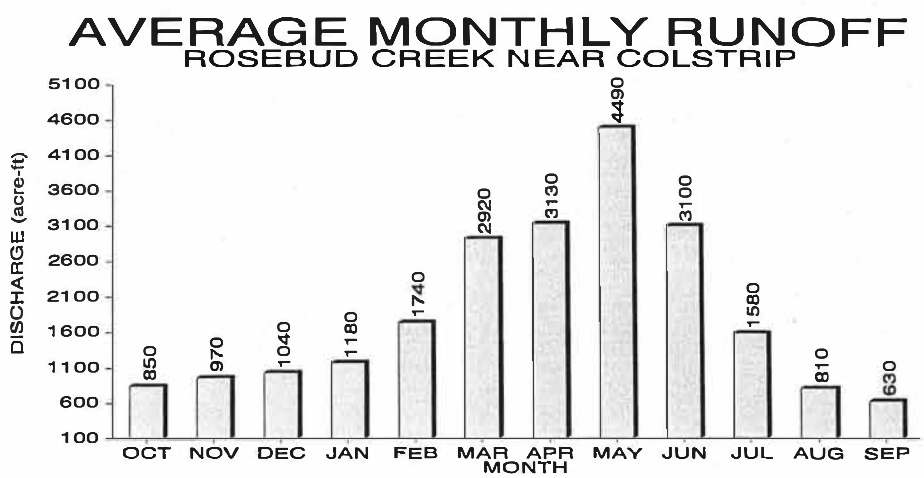


Figure 4 Stream discharge for Rosebud Creek near Colstrip and for Rosebud creek at its mouth near Rosebud for the period 1975 - 1990 (data source: USGS, 1990).

GEOLOGY

STRATIGRAPHY

The Tongue River Member of the Paleocene Fort Union Formation is exposed throughout the assessment area. On a regional scale, the Tongue River Member is predominantly yellow to cream-colored sandstone and sandy shale, black to gray carbonaceous shale, and coal. Red clinker is found throughout the region where coal beds have burned along the outcrop. The individual units of the Tongue River Member within the assessment area are most often described in local terms such as Rosebud coal overburden, Rosebud coal bed, the Rosebud coal - McKay coal interburden, and the SubMcKay. Ground water in each of these units and in the alluvial material within valley bottoms has been described in previous investigations as having been impacted to at least some degree by mining and related activities. An estimate of the saturated thickness of each unit is required to calculate the ground-water flow rate; the lithologic information is valuable in understanding the chemistry of the ground water and provides insight as to pre-mining water quality. The descriptions presented here are based on lithologic logs for monitoring wells installed by WECO, MPC, and MBMG in the assessment area.

The uppermost unit within the assessment area is the Rosebud overburden. This unit is composed of brown to gray, very fine to medium sandstone, black shale, gray claystone, and red to buff-colored clinker. Clinker, or porcelanite, is fused or baked by the burning of the underlying coal bed along outcrops and, in some cases, for a considerable distance back from the crop line. Within the assessment area, the thickness of the Rosebud overburden ranges from 60 to 120 feet. It is this material that becomes spoils in the mined areas; the overburden is stripped off and placed behind the pit to replace the mined-out coal. Depending on the method of placement, a rubble layer may form at the base of the spoils dumps; this becomes important when the spoils are saturated.

The Rosebud coal bed is the target for mining in the Colstrip area. This subbituminous coal bed ranges from 24.5 to 28 feet thick within the assessment area.

The Rosebud-McKay interburden is composed of gray- to buff-colored shale, siltstone, and claystone. This unit lies below the Rosebud coal bed and above the McKay coal bed. The thickness ranges from 3 to 30 feet within the assessment area and averages 10 feet thick.

The McKay coal bed has not been mined at the Rosebud mine and is exposed only along outcrops. It has been mined with the Rosebud coal in the Big Sky Area A mine, but will not be mined at the Big Sky Area B mine. Both beds crop out at the heads of Miller Coulee and Lee Coulee. The thickness of the Rosebud coal ranges from 8 to 15 feet throughout the area.

The term "SubMcKay" refers to beds that underlie the McKay coal bed. Available sources of information of the lithology and thickness of the SubMcKay were limited to logs of wells completed at depths within 100 feet below the base of the McKay bed. The SubMckay beds are gray sandstone and claystone, and gray to black carbonaceous shale. Coal stringers have been encountered at depths of 30 to 50 feet below the base of McKay coal bed.

STRUCTURE

The assessment area is located on the northeast limb of a broad, northwest-trending syncline (Dobbin, 1929). Locally, there is a northeast-trending anticline and a northwest trending syncline (Balster 1973). Overall, the structural gradient dips to the southeast at an angle of less than one-half degree, but is interrupted by gentle folds trending northeast-southwest. Dips on limbs of the folds are less than one-half degree toward the northwest or southeast. The general southeast dip of the beds and the variations in land surface combine to create a southeast flowing ground-water system diverted locally toward water courses eroded into the beds.

HYDROGEOLOGY

GROUND-WATER TERMINOLOGY

The uppermost surface below which geologic materials are saturated under hydrostatic pressure is termed the water table. Water is stored within spaces between grains or in fractures in the geologic material; the ratio of volume of pore space to total volume, expressed as a percentage, is known as porosity. All geologic materials are porous to some degree. Their ability to transmit water under field conditions is termed hydraulic conductivity and depends on the size of the pore spaces and the degree of their interconnection. Hydraulic conductivity, as used in this report, is defined as the flow of water in feet per day through a cross-sectional area of geologic material 1 foot thick and 1 foot wide under a hydraulic gradient of 1 foot per foot.

GROUND-WATER FLOW - COW CREEK DRAINAGE

Most Rosebud spoils water east of Colstrip is in the Cow Creek and South Fork Cow Creek drainages (Figure 5) and discharges ultimately to Rosebud Creek (Figure 1). Ground-water flow patterns in the Rosebud coal/spoils aquifer tend to be diverse owing to the proximity of the discharge areas (Figure 5). Lateral recharge from the west and north is combined with a lesser amount of vertical recharge and discharges to Cow Creek, South Fork Cow Creek, and the associated alluvium. A well-developed ground-water divide exists between the Rosebud Creek and East Fork Armells Creek drainages. The position of this divide is important in determining whether the electrical generating facility at Colstrip (Figure 2) should be included in the assessment; since it is within the East Fork Armells Creek drainage, impacts to ground water and surface water are not likely to occur in the Rosebud Creek drainage. A second ground-water divide occurs near the Cow Creek - South Fork Cow Creek drainage divide. This divide is of little consequence since both drainages are included in the assessment.

In order to estimate the rate of ground-water flow, the hydraulic conductivity which can be estimated or determined from aquifer tests, the cross-sectional area (aquifer thickness x width), and the hydraulic gradient, determined from monitoring well data, must be known. Aquifer tests have been conducted by previous investigators on 37 wells in Rosebud spoils, Rosebud coal, and McKay coal within the assessment area. Hydraulic conductivity values for wells in the Colstrip area were compiled from several reports by MBMG and WECO.

The reported results indicate a broad range of hydraulic conductivity for the Rosebud coal/spoils aquifer (0.01 to <170 gpd/ft^2), but highly similar mean hydraulic conductivities (13.3 to 7.1 gpd/ft^2). The similarity of the spoils aquifer to the mined coal has been described in several previous investigations such as those by Van Voast and Reiten (1988) and Van Voast and others (1978).

Ground water also occurs in the alluvial material in valley bottoms. The location and relationship of the alluvial aquifer to the other aquifers provides additional means to estimate the local impacts of mining and related activities. Van Voast and others (1978) calculated a hydraulic conductivity of 1200 gpd/ft^2 for East Fork Armells Creek alluvium, and Olsen and others (1991) estimated a hydraulic conductivity of 900 gpd/ft^2 for alluvium in the Cow Creek drainage.

The McKay coal aquifer has a hydraulic conductivity similar to that of the Rosebud coal spoils; the mean reported value is 13.8 gpd/ft^2.

The upper portions of the SubMcKay consists predominantly of alternating layers of sandstone and siltstone of varying thicknesses. Based on this lithology, and with no aquifer test data available, a conservative value of 0.22 gpd/ft^2 was assumed for the hydraulic conductivity of the upper SubMcKay.

Using a hydraulic conductivity value of 10 gpd/ft^2, a saturated thickness of 20 feet and hydraulic gradient values of 0.012, 0.009, and .007 ft/ft for the southern, mid, and northern portions respectively, ground-water discharge through the mined areas in the Cow Creek drainage is approximately 7670 ft^3/day. In reference to Figure 2, approximately 5300 ft^3/day flows through the Area E mine and approximately 2370 ft^3/day flows through the Area D mine.

An assessment of the hydrologic impacts of mining and related activities must also include the potential effects of the fly-ash pond east of the Rosebud mine (Figure 6). The fly-ash pond was constructed in a tributary drainage to the Cow Creek drainage and put into service in late-1983. A bentonite/cement slurry wall, 60 to 80 feet deep, was emplaced into the SubMcKay around the pond with the intent of hydrologically isolating the pond. A fly-ash slurry is pumped from the power-generating plant at Colstrip to the pond. Pipeline failures resulted in five accidental releases of fly ash slurry between 1987 and 1989; the cumulative volume released exceeded 280,000 gallons (DNRC, 1990). All of the releases occurred near the head of a tributary to the upper Cow Creek drainage below the Area E mine (Figure 6).

Pump-back wells are used to control effluent from the main dam and saddle dam. Pumping rates range from 3 to 12 gallons per minute and the pumps are operated intermittently. Two pump-failures (in 1989 and 1990) resulted in the release of an estimated 63,000 gallons of effluent from the main dam (DNRC, 1990). Overall, however, recharge to the Cow Creek alluvium via the alluvium in the tributaries below the main dam and the saddle dam has been reduced by pumping. In order to evaluate the cumulative discharge to Cow Creek without including the effects of pumping, data were used from wells downgradient of the pump-back wells.

Using the hydraulic conductivity estimated by Olsen and others (1991) (900 gpd/ft^2) and a saturated thickness of 15 feet (average of 9 wells), and an estimated width of 200 feet for each tributary, the total discharge through the alluvium in the tributary drainage to Cow Creek is approximately 27 ft^3/day.

As will be discussed in later sections, the hydrologic relationship between the fly-ash pond, the McKay coal and the SubMcKay is complex and not well understood. To make an estimate of the ground-water flow through the McKay coal in the vicinity of the fly-ash pond, the "aquifer width" was taken as the portion of the aquifer in which monitoring well data indicate an impact to water-levels or water-quality. It is in this portion of the McKay that most of the loading to the Cow Creek drainage is likely to occur. Similarly, to make the best estimate of ground-water discharge through the SubMcKay, the "aquifer thickness" was taken as the interval of the SubMcKay from the present water level near the pond to the top of the alluvium in the Cow Creek drainage below the pond (approximately 100 feet); the aquifer width was determined the same way as for the McKay coal. Ground-water flow through the McKay coal in the vicinity of the fly-ash pond is approximately 700 ft^3/day based on a hydraulic conductivity of 13.8 gpd/ft^2, a thickness of 10 feet, a width of 7500 feet, and a hydraulic gradient of 0.005. Using a value of 0.22 gpd/ft^2 for hydraulic conductivity, a saturated thickness of 100 feet, a width of 9500 feet, and a hydraulic gradient of 0.035 (average of 4 pairs of wells), the ground-water discharge through the upper 100 feet of the SubMcKay to the Cow Creek drainage is approximately 1020 ft^3/day.

GROUND-WATER FLOW - MILLER COULEE AND LEE COULEE

Both the Rosebud and the McKay coal beds were mined at the Big Sky Area A mine (Figure 7) at the head of Miller Coulee and Emile Coulee southwest of the Rosebud mine. Ground-water flow is generally toward the southeast and discharges from the coal beds to the spoils, then to the alluvium and eventually to Rosebud Creek (Van Voast, et.al., 1977; Davis, 1984). Van Voast and others (1977) estimated a flow into the Big Sky Area A mine from the Rosebud and McKay coal beds at 2100 ft^3/day (1400 ft^3day through Rosebud coal and 700 ft^3/day through the McKay coal); 1990 data indicate only a slight increase in flow.

Hydrolgeologic data for the Area B mine in Lee Coulee (Figure 7) is not adequate for estimating the ground-water flow rate. Assuming that post-mining conditions in Area B will be similar to those in Area A, the post-mining discharge through the Rosebud coal/spoils will be 1400 ft^3/day.

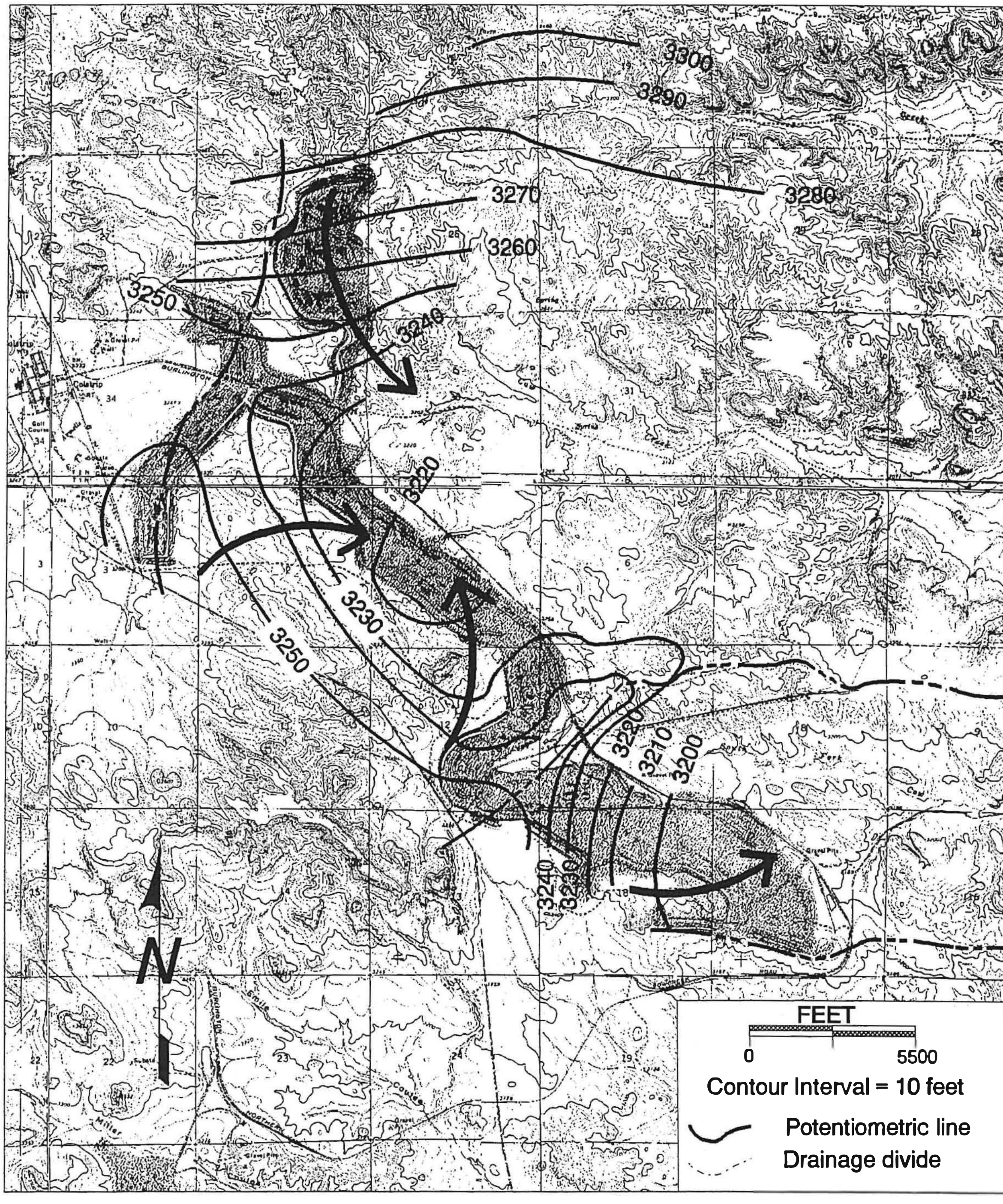


Figure 5. Flow patterns for Rosebud spoils water in the Cow Creek and South Fork Cow Creek drainages. Based upon water-levels (7/90) and topography.

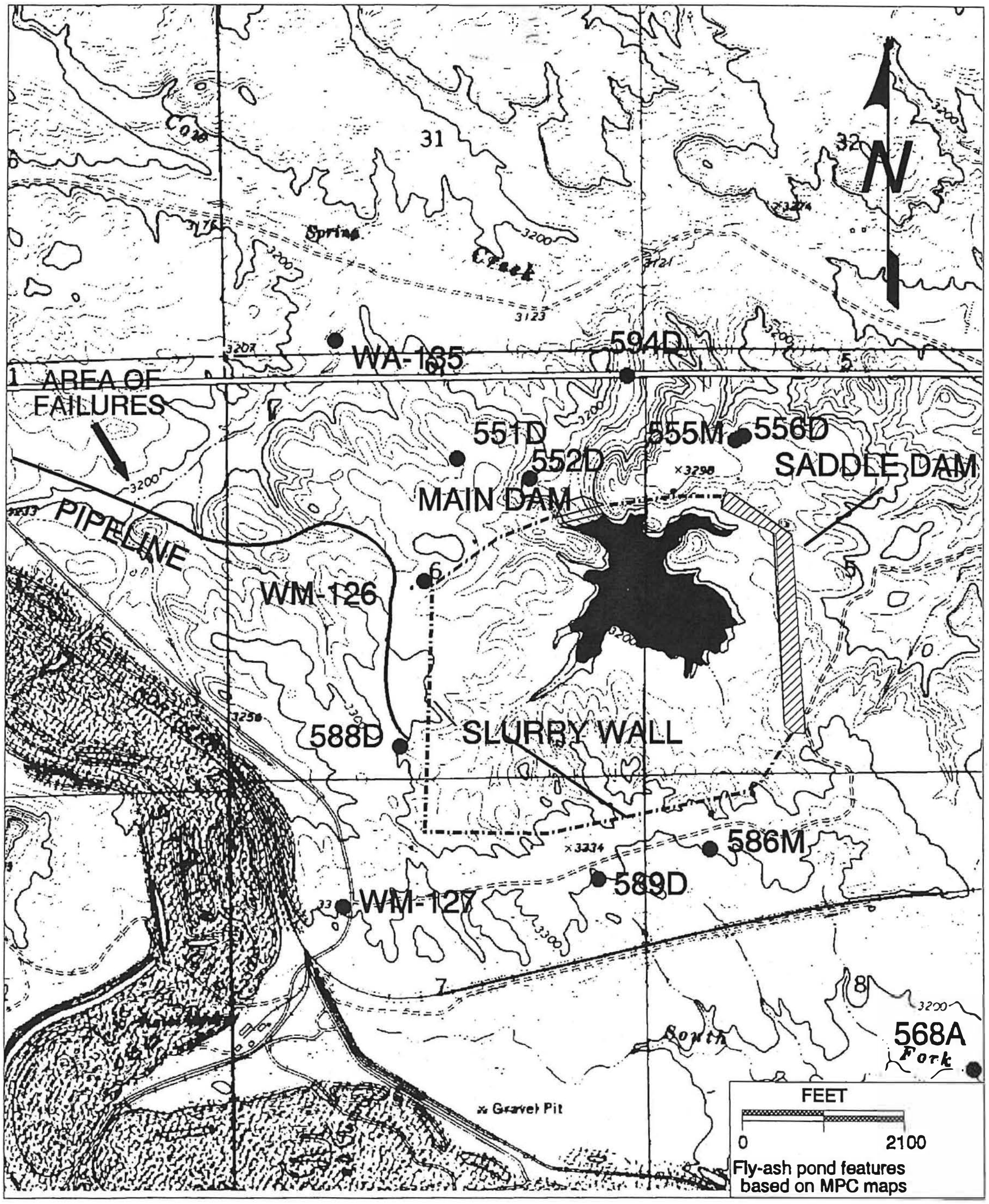


Figure 6. Detail map of the fly-ash pond area. Wells shown are those discussed in the text.

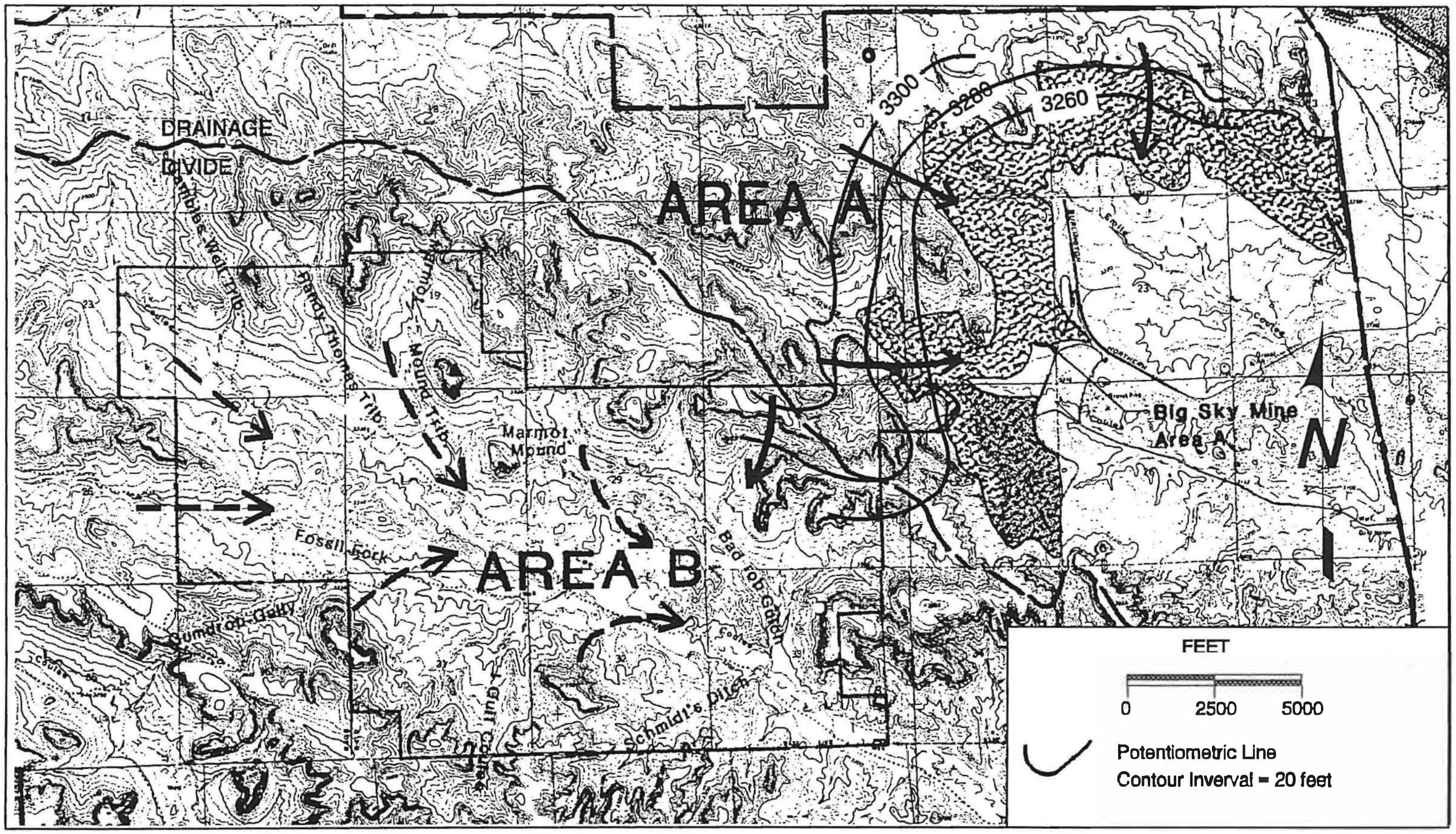


Figure 7. Flow patterns for Rosebud coal/spoils water in Miller Coulee and Lee Coulee drainages.

WATER-LEVEL HISTORIES

A review of the water-level histories of wells in the Cow Creek drainage provides a basis for defining the nature and extent of impact (namely, reduction or increase in ground-water flow to Cow Creek and Miller Coulee) and provides a basis for estimating the impact of new activities (namely, addition of a landfill) .

COW CREEK

There are at least four datums for site elevations and locations in the Colstrip area: USGS, MPC, Limbaugh, and Bechtel. As a result, inconsistencies in describing monitoring well location and elevation have occurred. In the fall of 1991, ground-water monitoring wells located near the power generation plant, within the active and inactive mine areas, and near the fly-ash pond were re-surveyed to a local datum based on existing wells. Wells on the Kluver property east of the fly-ash pond were not re-surveyed. The new X, Y, and Z coordinates indicated varying degrees of disparity between surveys. The data used in this assessment incorporate the more recent survey data with the assumption that these data are more accurate and are based on a single datum (referred to in this report as WECO Datum). Since these wells were not surveyed to USGS datum and cannot be reliably corrected, caution should be used in comparing water-elevation data presented in this report to reported data.

Hydrographs for monitoring wells in Area E tend to reflect the history of the mine. Old spoils produced by mining in the early part of the century were not reclaimed until the 1970's. The poorly drained, hummocky topography of the un-reclaimed spoils prevented run-off and thus provided for a higher than normal amount of vertical recharge to the spoils aquifer (Van Voast and Reiten, 1988). Before reclamation, the ground-water levels tended to rise rapidly and may even have exceeded pre-mining levels; regrading of the older spoils resulted in a water-level decline. Regrading spoils within a few years of placement, which is the current practice, reduced the amount of vertical recharge and, although water levels rise, the rate of rise was less and the post-mining ground-water elevation more closely reflected pre-mining conditions.

The alluvial aquifers in both the Cow Creek and South Fork Cow Creek drainages were indirectly affected by mining in Area E. The saturation of spoils in Area E reduced recharge to the alluvium and may have contributed to a 1- to 4-foot decline in water levels in some wells (Figure 8). Saturation of spoils required that ground water be taken into storage and reduced the amount of ground water that flowed through the spoils. Thus, the amount of recharge to the alluvial aquifer or deeper aquifers was reduced.

Water-level changes similar to that of the spoils aquifer are evident in wells completed in the Rosebud coal, the Rosebud-McKay interburden, the McKay coal and, in some cases, the SubMcKay. Hydrographs of nested wells have shown a similar response to mining-induced draw-down and the saturation of post-mining spoils. The vertical gradient between two aquifers also reversed for a short period of time in response to mining (Figure 9). As discussed previously, this similarity of water level response may indicate a vertical hydraulic connection caused by exploration drill-holes.

A decline in ground-water levels has occurred in the Rosebud coal, the Rosebud-McKay interburden, the McKay coal, and the SubMcKay near the active pit in Area D. A reversal of vertical gradient has also been observed in several monitoring-well nests, an example of which is shown in Figure 10. Regardless of the vertical gradient, the trend in water levels was always downward in near the active pit. The total decline since mining began in 1986 ranges from 10 feet in wells adjacent to the pit to 2-3 feet in wells approximately 400 feet from the pit.

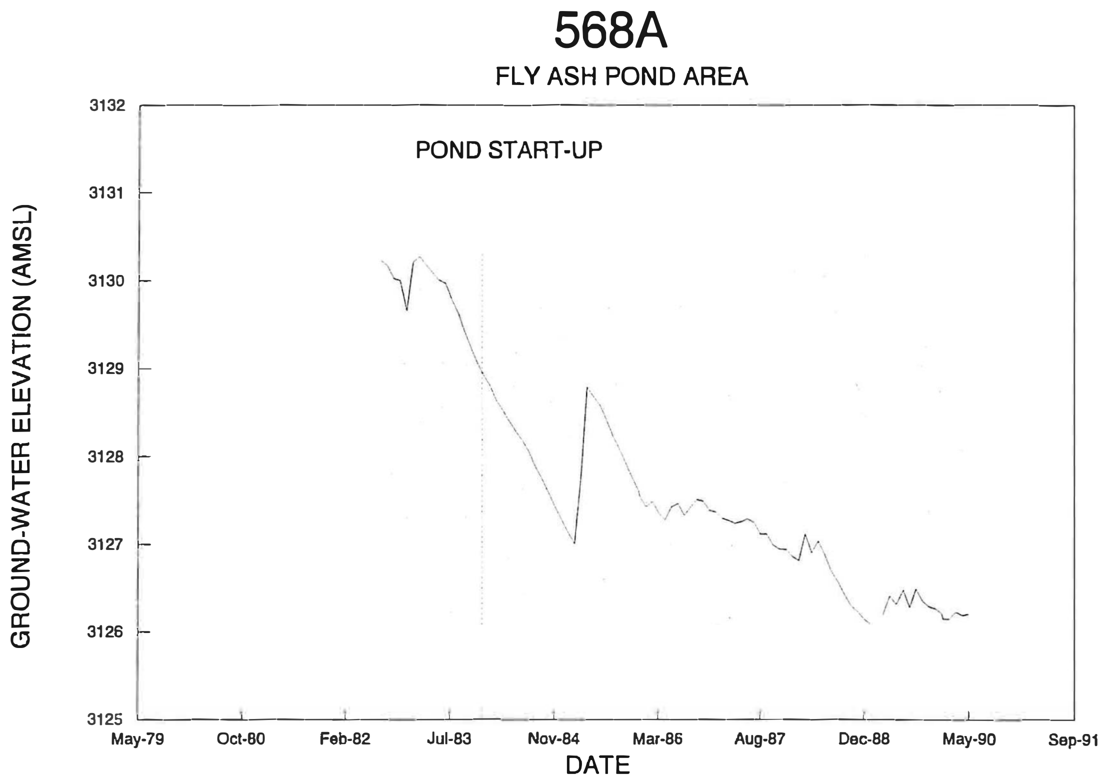


Figure 8 Hydrograph for alluvial monitoring well 568A in the upper South Fork Cow Creek drainage. See Figure 9 for its location.

Draw-down caused by mining in Area D has also significantly changed the horizontal gradient as well. Although ground-water flow in the Rosebud coal and spoils is still toward the south, recharge to Cow Creek alluvium via tributaries has likely been reduced.

Water levels in the Rosebud coal aquifer and the Rosebud-McKay interburden are generally not monitored near the fly-ash pond. A single well completed in the Rosebud coal bed adjacent to the northwest corner of the slurry wall indicates a slight upward trend in water-level (0.3 feet). Data from a well completed in the interburden, also located adjacent to the northwest corner, indicates no significant changes in water levels.

Water-level data for the McKay coal aquifer near the fly-ash pond are also limited. Hydrographs of the only wells with a period of record predating the pond are presented in Figure 11; all three indicate a water-level rise of 2 to 4 feet associated with the start of the pond in late-1983. Water-levels in wells located within the slurry wall have risen 15 to 20 feet since the startup of the pond.

Ground-water elevations, well screen elevations, and lithologic logs suggests at least two distinct, albeit areally discontinuous, aquifers in the upper portion of the SubMcKay. Data from wells completed in the upper portion of the SubMcKay indicate a significant rise in ground-water levels since the startup of th0e pond (Figure 12).

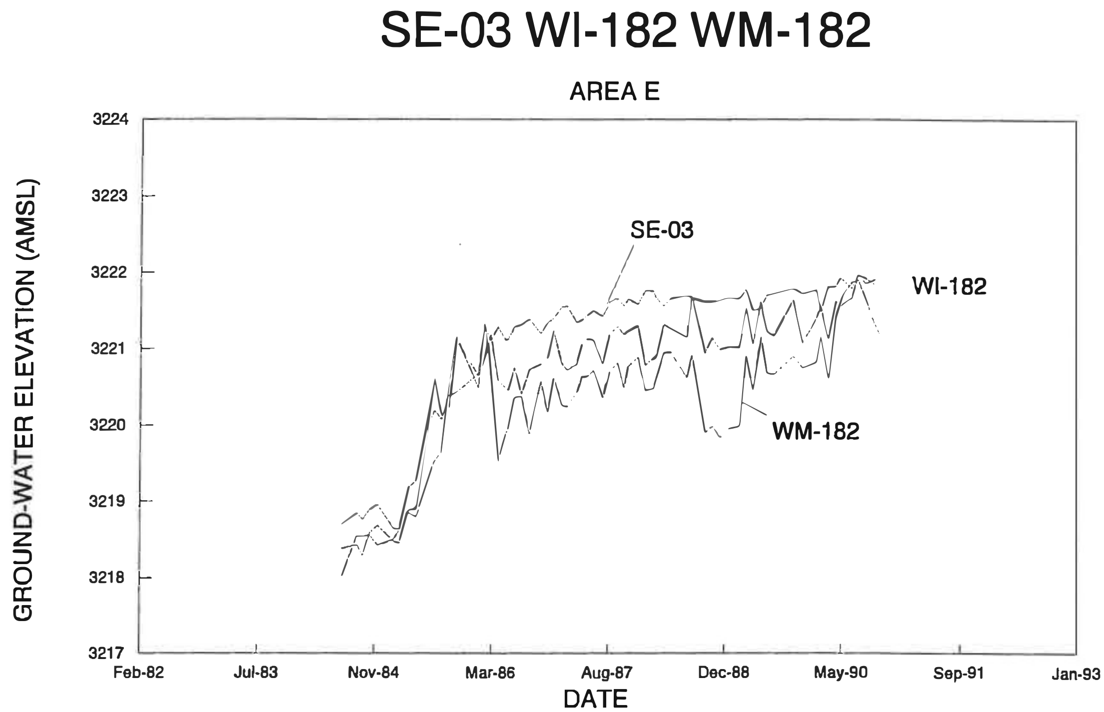


Figure 9 Hydrograph for nested wells completed in the Rosebud spoils (SE-03), the interburden (WI-182), and the McKay coal (WM-182). The wells are located just north of the final pit of Area E.

While pump-back wells have somewhat controlled the hydraulic loading to the drainages north and east of the fly-ash pond, water levels continue to rise. Ground-water levels in SubMcKay wells located 1100 to 500 feet north of the slurry wall have risen 2.5 to 20 feet since 1984; water levels in SubMcKay wells upgradient of a pump-back well in the drainage below the saddle dam have risen 4 to 20 feet in this same period. The pump-back wells have been successful in maintaining or reducing ground-water levels, but only for a limited area.

The fly-ash pond and slurry wall are within the Cow Creek drainage; however, SubMcKay wells on the South Fork Cow Creek side of the drainage divide indicate a water-level rise of as much as 10 feet since operation of the pond began.

MILLER COULEE AND LEE COULEE

Water levels in the Rosebud coal/spoils aquifer at the Big Sky Area A mine have responded in a similar manner to those in the Area E mine. Dramatic water-level rises have been observed in spoils wells as mining advances. Van Voast and Reiten (1988) reported a water-level rise of approximately 20 feet over three years in the spoils aquifer.

In Lee Coulee, ground-water level data are limited for the Rosebud coal and no spoils wells have been installed. As the Area B mine expands, water-level changes similar to those in the Rosebud mine are probable.

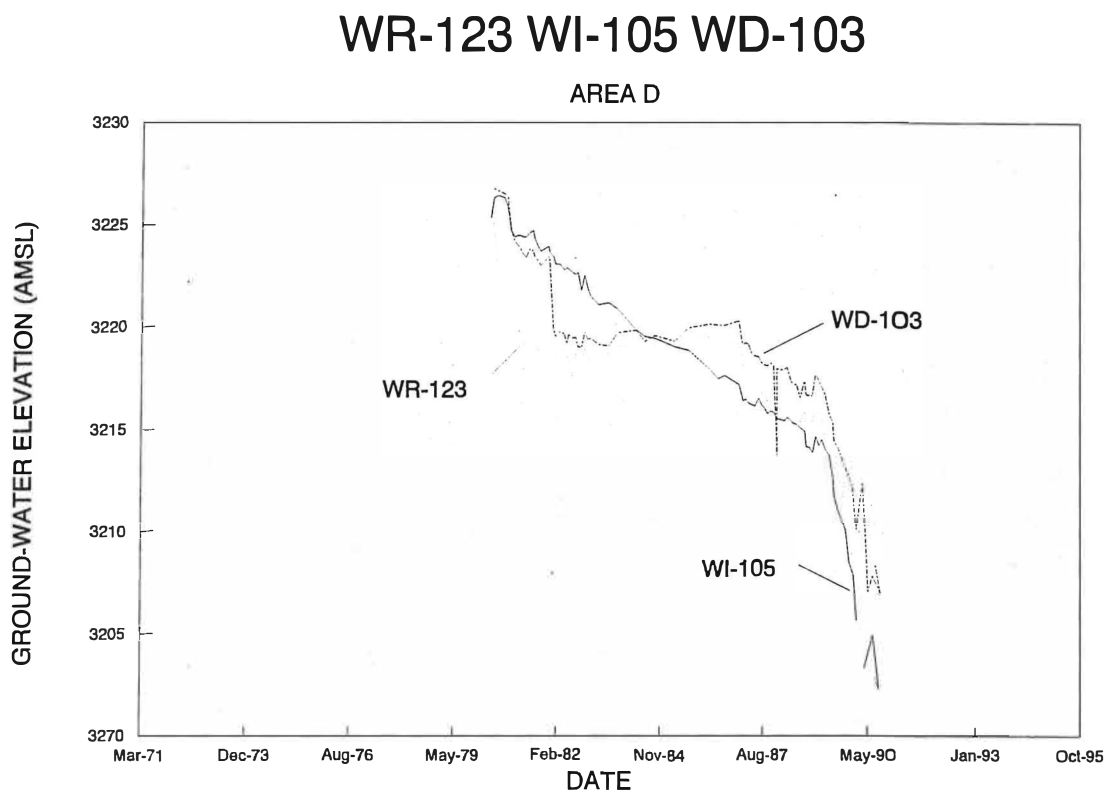


Figure 10 Hydrographs for nested wells completed in the Rosebud coal (WR-123), the interburden (WI-105), and the SubMcKay (WD-103). The wells are located north (up-gradient) of the old spoils and the active pit in Area D.

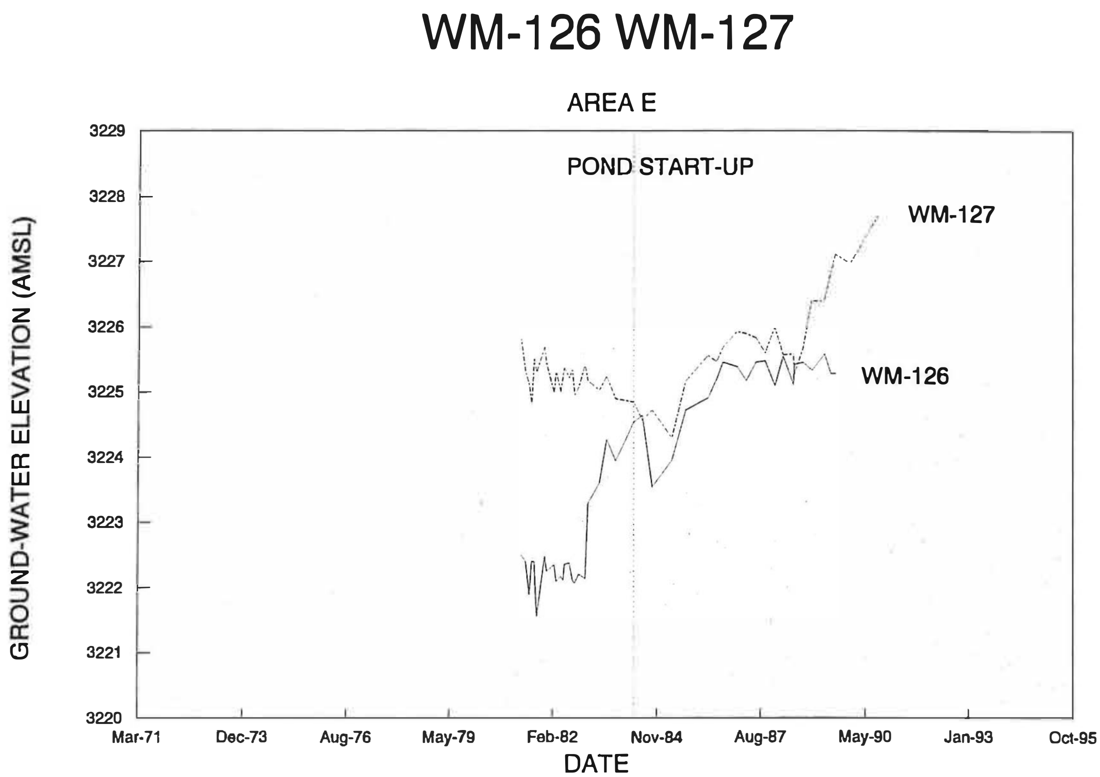


Figure 11 Hydrographs for McKay wells WM-126 just northwest of the slurry wall and WM-127 southwest of the slurry wall near Area E.

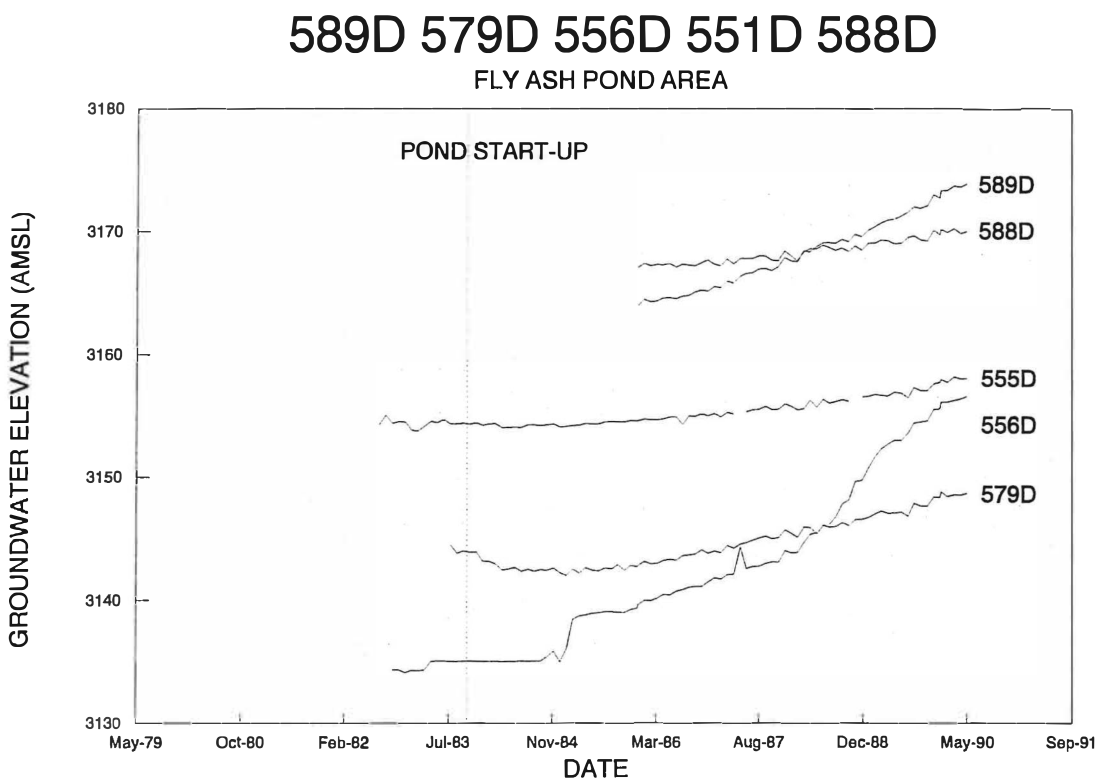


Figure 12 Hydrograph for wells completed in the SubMcKay. The wells are located northwest (551D), west (588D), south (589D), east (579D), and northeast (556D) of the fly ash pond, outside of the slurry wall.

WATER QUALITY - GROUND WATER

GENERAL CONSIDERATIONS

The primary concern regarding impacts caused by mining and related activities is the increase in dissolved constituents in ground waters and surface waters. The degradation of water quality resulting from the saturation of mine spoils is well documented in previous investigations. The impacts caused by the fly-ash pond, however, have not been well defined. Since the concentration of dissolved constituents must be known in order estimate the loading to Rosebud Creek, the history of water-quality must be known to further define the extent of the impact and provide a basis for estimating future impacts caused by new activities.

The major constituents in ground water throughout the investigation area are Ca, Mg, Na, SO_4, and HCO_3. These account for up to 98 percent of the total dissolved constituents. On average, approximately 66 percent of the total dissolved constituents is comprised of sulfate. Common sources for sulfate are oxidation of pyrite or dissolution of gypsum. Computer-based geochemical modeling of water-quality data using PHREEQE (Parkhurst and others, 1985) for each hydrostratigraphic unit indicates that ground water is under-saturated with respect to gypsum and that little if any $FeOH_3$, which is a product of pyrite weathering, will be generated. The presence of NaCl occurs in quantities that may be sufficient to lower the transition temperature of gypsum to form anhydrite; dissolution of gypsum is the most likely source for sulfate. Saturated-paste data compiled by Harrington (1984) suggests that the gypsum is a secondary mineral, however, and the sulfate is initially generated by oxidation and weathering of the shallow overburden (Van Voast and Reiten, 1988).

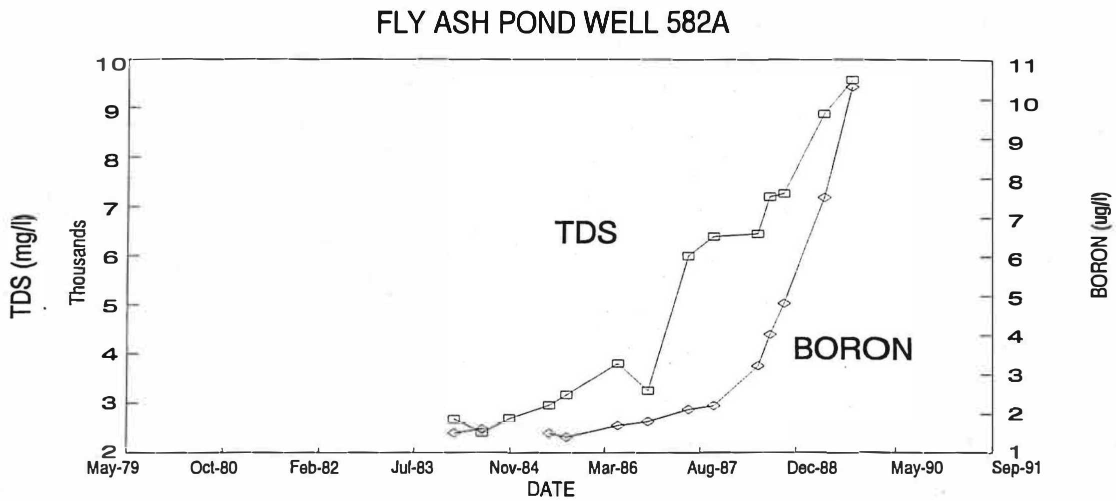
Alluvial ground water is most often a $MgSO_4$-type water although $CaSO_4$-type waters are common. The quality of ground water in the Rosebud coal aquifer is variable but is restricted to Mg- or $CaSO_4$-type waters. Rosebud-spoils ground water is generally of the same type as the coal bed; however, the dominant cation is sodium in waters of high TDS (>2500 mg/L). The interburden ground water is predominantly a calcium sulfate-type water or, to a lesser degree, a magnesium sulfate-type water. Ground water in the McKay coal is most often a $CaSO_4$ in the mined areas, but is dominated by a $MgSO_4$-type water in the fly-ash pond area. The relative concentrations of Ca and Mg in the SubMcKay aquifer have decreased over time while Na has increased. This change to a $NaSO_4$-dominated water occurs in the fly-ash pond area and, to lesser degree, in the mined areas.

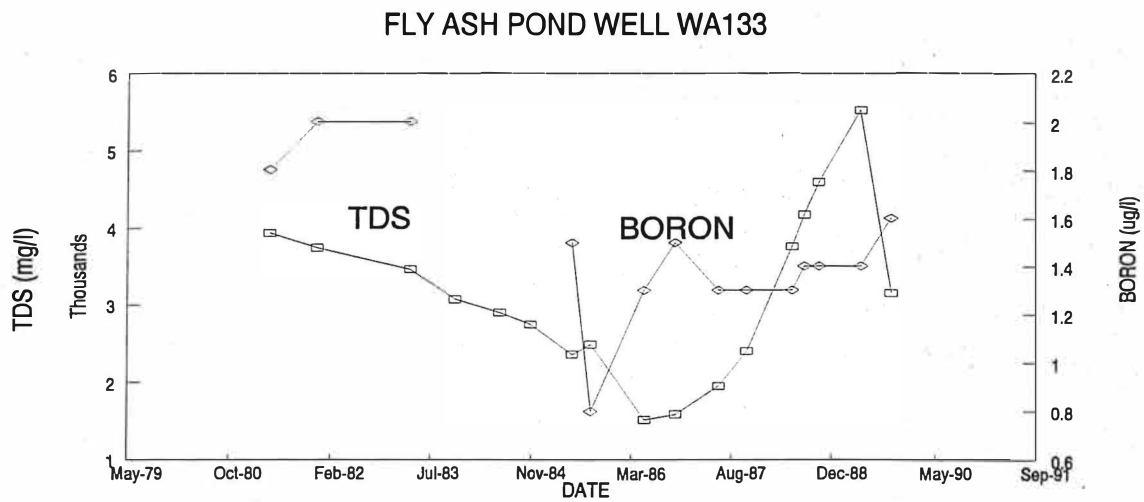
In order to predict the impact of fly-ash water on ground water in the SubMcKay, the two waters were "mixed" in a computer simulation; the equilibrium TDS concentration was as high as 20,000 mg/L and was supersaturated with respect to gypsum. The concentrations of trace metals in fly ash waters are consistently higher than concentrations found in non-impacted ground water; however, the fly-ash / ground-water mix solutions are always undersaturated with respect to any of the metals species detected. This undersaturation is likely a result of high pH and the presence of abundant clay minerals in the shale beds within the SubMcKay. Trace-metals tend to precipitate under alkaline pH conditions and are attenuated in most cases by clay-minerals. Trace-metals concentrations in samples collected from wells that otherwise indicate water-quality degradation attributable to the fly ash pond are usually below laboratory detection limits.

THE BORON QUESTION

Elevated concentration of boron has been used as an indicator of pond-effluent in ground water (Olsen and others, 1991; P. Groll and T. Ring: DNRC, pers. comm., 1990). Boron concentrations in fly-ash pond waters are often more than 100 mg/L. The geochemical model PHREEQE (Parkhurst and others,

1985) was used to determine the equilibrium concentration of boron under several conditions. The fly-ash-pond water is saturated or supersaturated with respect to several aluminum and calcium species. However, species or phases associated with boron were either under-saturated or did not form. Similar results were obtained when the fly-ash pond solution was modeled as a mix with water from the SubMcKay aquifer. The models indicate that speciation of boron complexes will attenuate boron and retard its advancement. Thus, an increased concentration of boron is not likely to precede an advancing plume unless concentrations of Ca or Na are high enough for the solution to become saturated with respect to colemanite ($Ca_2 B_6 O_{11} * 5H_2O$) or kernite ($Na_2 B_4 O_7 * 4H_2O$) after preferentially precipitating other Ca and Na minerals. Field data show that boron concentrations indeed lag behind those of other ions and there is no clear association between boron and TDS concentrations near the fly-ash pond (Figures 13 and 14).





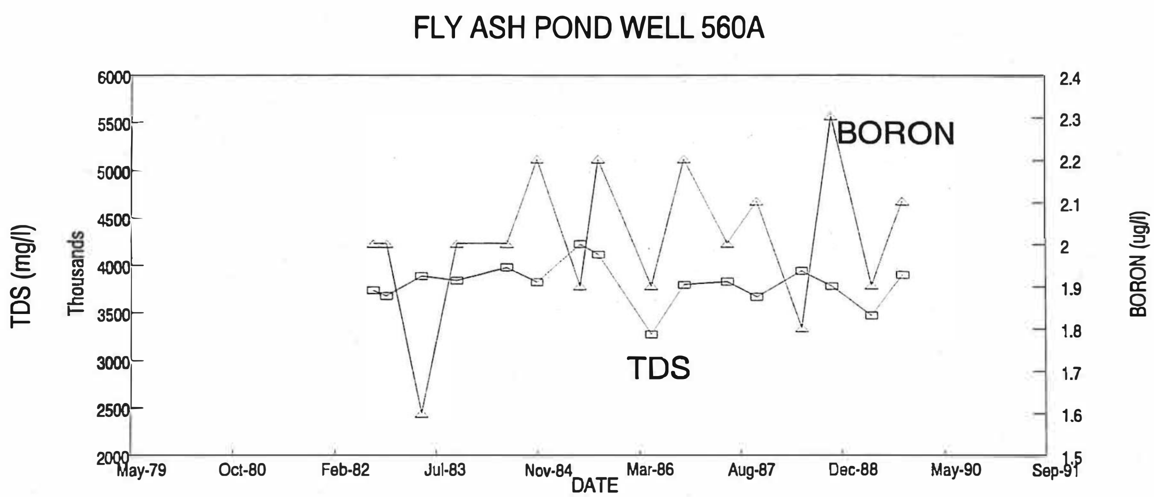
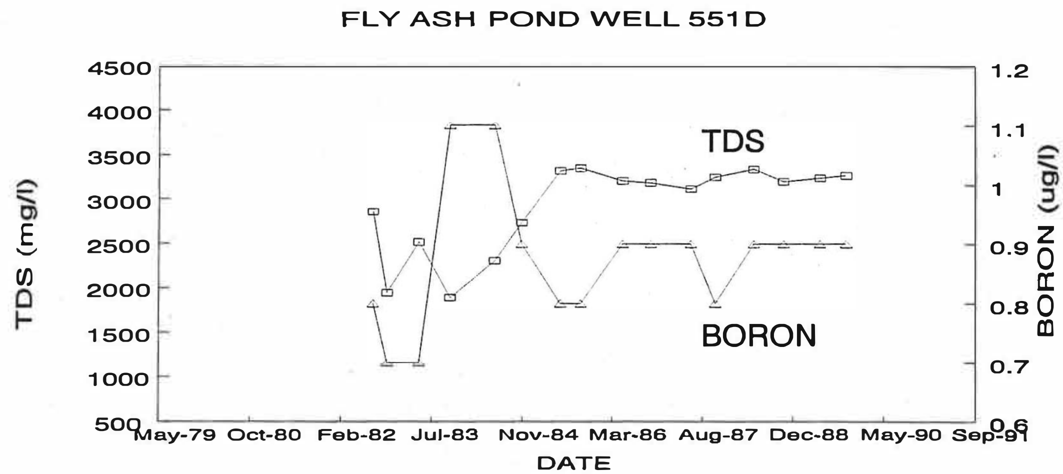
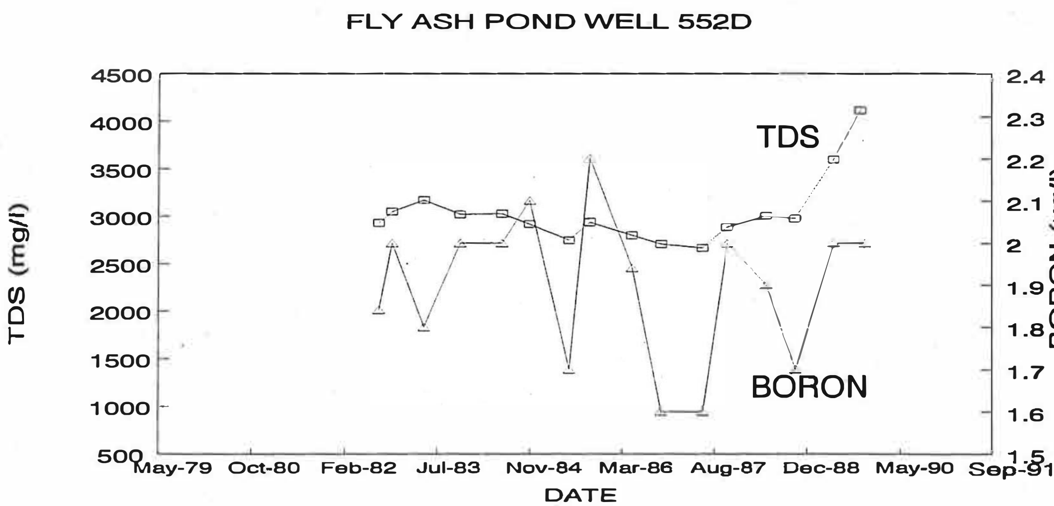


Figure 13. Comparison of total dissolved solids and boron with respect to time for alluvial wells.





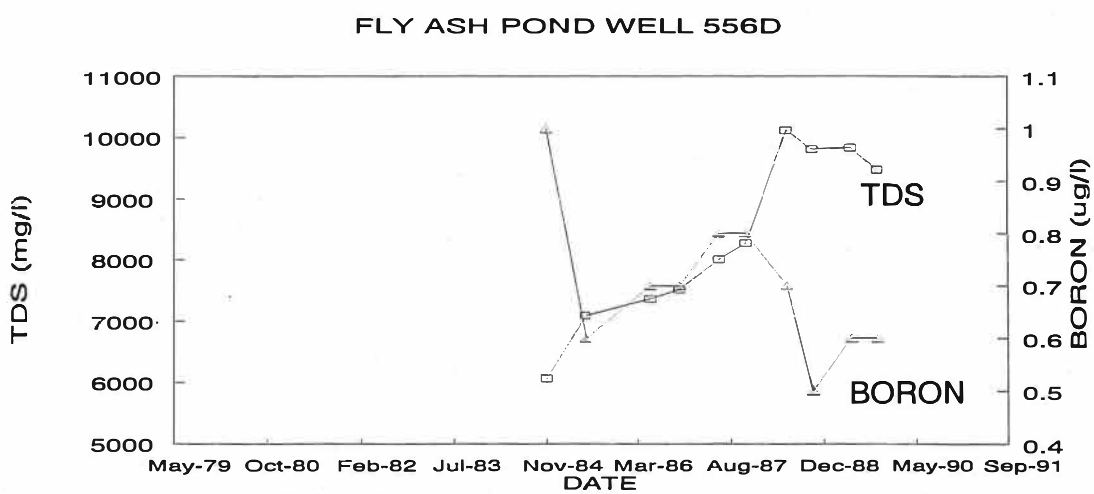


Figure 14. Comparison of total dissolved solids and boron with respect to time for SubMcKay wells

The assessment of the impact to ground-water quality by mining and the fly-ash pond included trace metals, major cations and anions, and other parameters such as pH and alkalinity. Total dissolved solids data are presented to offer a more consistent means of comparison across the area and provides a basis for estimating cumulative impacts.

WATER QUALITY - COW CREEK DRAINAGE

The quality of alluvial ground water in tributary drainages to Cow Creek downgradient of the Area E mine has been degraded to varying degrees. It is difficult to distinguish the impact of the mine versus the impact of accidental releases of fly-ash slurry from the pipeline. Samples from wells closest to the mined area show the greatest increases in total dissolved solids; but they also coincide with proximity to the pipeline breaks. Data for well WA-135 (Figure 15), in the tributary below the mine and the fly-ash

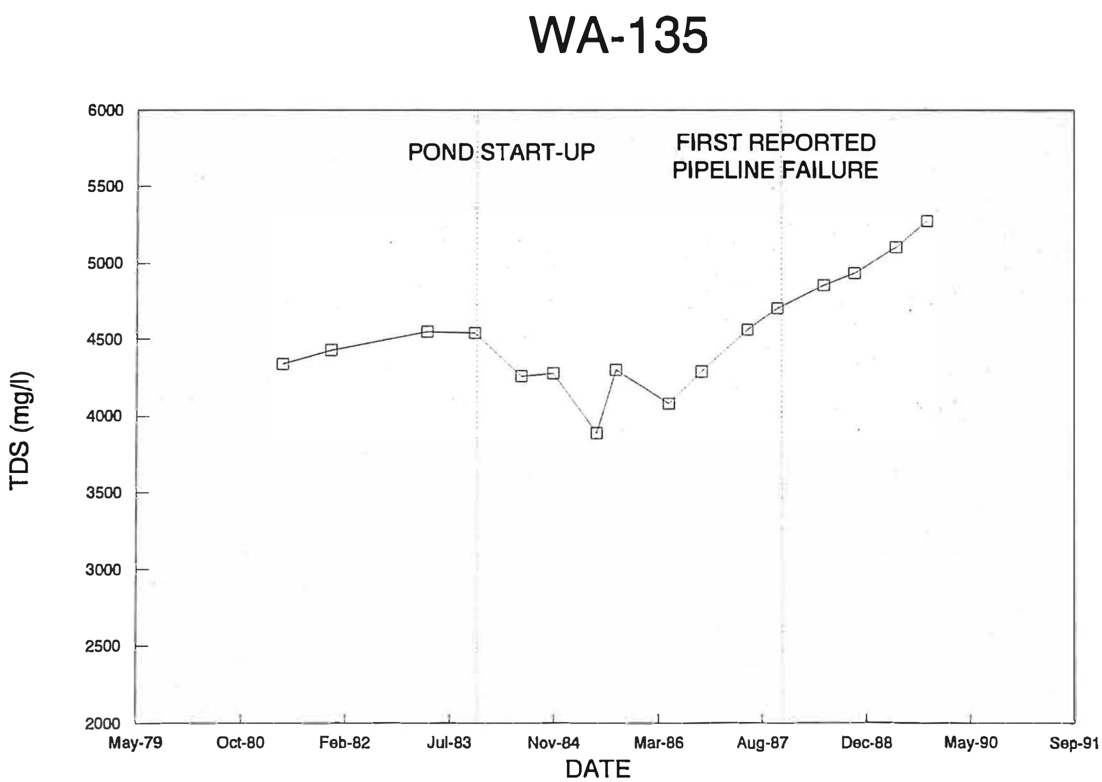


Figure 15 TDS concentrations for alluvial well WA-135 in a tributary drainage below the Area E Mine and the area where failures of the fly-ash-slurry pipeline occurred.

slurry pipeline, indicate that TDS concentrations have increased approximately 1000 mg/L since 1984. Wells located upgradient, closer to the spoils material and the pipeline exhibit TDS concentration increases of up to 10,000 mg/L during the same period.

There has been little or no change in water quality over the period of record (1981 to 1990). Fluctuations of 200 mg/L in TDS concentrations are common, but most often are attributable to seasonal variations.

The quality of ground water in the alluvium in the South Fork Cow Creek drainage generally has not changed. As discussed in earlier sections, water levels have declined due to decreased recharge from the mine area. As water levels in the spoils materials reach equilibrium, increased hydrologic and dissolved-constituent loading to the alluvium is likely to occur. TDS in these wells currently average approximately 2700 mg/L.

Since the data do not permit separating the impact of pipeline failures and spoils leachate on the water quality of the alluvial aquifer, an estimate of increased loading from the Area E mine is best based on comparisons made within the mine area above the pipeline. Van Voast and Reiten (1988) estimated an average TDS concentration of 3660 mg/L for spoils water and 1750 mg/L for coal-bed water in the Colstrip area. A comparison of water-quality data from spoils wells upgradient of the Area E mine to wells downgradient of the mine indicates a TDS increase of 1500 to 2500 mg/L. A comparison of Rosebud coal wells upgradient of the mine to spoils wells indicates a similar increase of approximately 2000 mg/L. The TDS increase indicated by the comparisons made in the Area E mine agrees well with the average increase of 1910 mg/L described by Van Voast and Reiten (1988).

The data did not permit an estimate of the impact of mining to water quality in the McKay coal aquifer or SubMcKay; for the purposes of the cumulative impact on Rosebud Creek, the increased TDS concentration in these aquifers is assumed to be negligible. This negligible impact may change, however, as water-levels rise and discharge to the Cow Creek drainage increases.

Ground-water samples from alluvial wells in the Cow Creek drainage below the Area D mine show no indication of impact to water quality attributable to mining. As the mine expands to include more of the drainage area and spoils water is generated, water-quality degradation in the tributary drainages will likely occur in a manner similar to that of the Area E mine.

A single well has been completed in the old spoils near the active mine area. TDS concentrations in this well have fluctuated by 2000 mg/L since 1982 (three measurements), but the net change has been minimal. TDS concentration is approximately 5000 mg/L at present.

Very few data are available for wells completed in the Rosebud coal near the Area D mine. Based on the limited data, mining activities have had little effect on water quality. The most significant change has been 500 mg/L increase in TDS in wells upgradient of the active pit; concentrations range from 1000 mg/L near the active pit to less than 500 mg/L upgradient and away from the active pit.

Ground-water quality in the McKay coal Area D has behaved in a manner similar to ground-water quality in the Rosebud coal in that area. Water-quality data are also limited for the McKay, but indicate little change. The most significant is a 1000 mg/L fluctuation in TDS for a well upgradient of the active pit; the net change from 1982 to 1990, however is less than 500 mg/L. TDS concentrations range from 1500 mg/L to 1000 mg/L.

TDS concentrations in the SubMcKay increased by 500 to 1000 mg/L (3 to 4 observations) in the active mine area. This upward trend was apparent in some wells prior to the re-activation of mining in 1986.

As with the Area E mine, the impact to water-quality at Area D is largely restricted to the Rosebud coal/spoils aquifer. The increased concentration in TDS attributed to mining in Area D is estimated as 500 mg/L. As mining continues and more spoils are generated, this is expected to increase to concentrations similar to those found in the Area E mine. Thus, a post-mining increase of 1910 mg/L in TDS is assumed.

Water-quality monitoring near the fly-ash pond is limited primarily to the alluvial aquifer, the McKay coal bed, and the upper SubMcKay in tributary drainages of the Cow Creek and South Fork Cow Creek drainages.

Alluvial ground water in the tributary drainage below the main dam has been strongly impacted by solute migration from the fly-ash pond. Increases in total dissolved solids concentration of 3000 mg/L or more since the pond began operating are common in all wells within this tributary drainage to Cow Creek. Pump-back wells have stabilized concentrations by reducing ground-water flow toward Cow Creek; however, TDS concentrations remain as high as 8500 mg/L in alluvial wells between the pump-back wells and Cow Creek.

Samples from wells completed in the alluvium in the Cow Creek and South Fork Cow Creek drainages indicate no significant increase in TDS attributable to the fly-ash pond; dilution and attenuation are probable factors. Although releases of fly-ash slurry from the pipeline connecting the power plant and the pond have temporarily "spiked" ground water in the Cow Creek alluvium, long-term effects are not yet apparent.

McKay wells with a sufficient period of record exhibit a TDS-concentration "spike" coincident with startup of the fly-ash pond in late 1983; this spike also occurs in a well in Area E, but the overall trend is still downward there. Conversely, the upward trend continues or the elevated concentrations continue in wells near the fly-ash pond. In well 586M, south of the slurry wall, TDS has increased 3000 mg/L since the startup of the fly-ash pond. Well 555M, northeast of the slurry wall and downgradient from the fly-ash pond saw an initial decrease in TDS concentrations of approximately

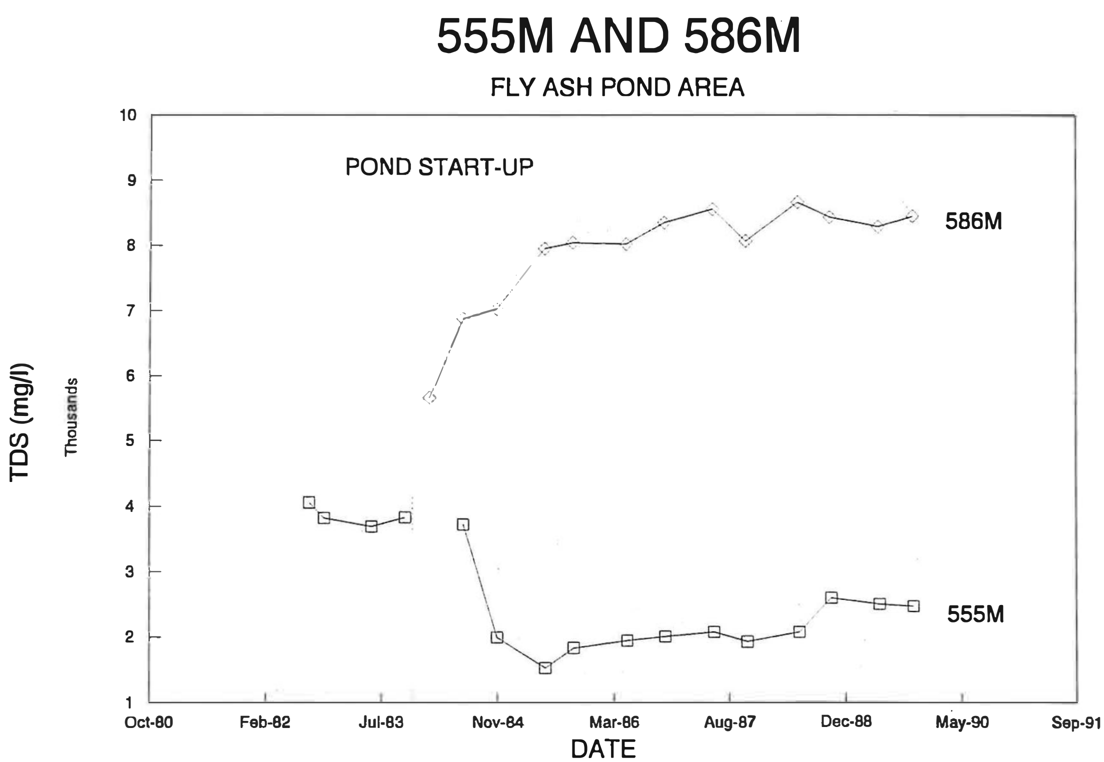


Figure 16 TDS concentrations for McKay wells 555M northeast of the fly ash pond and 586M south of the fly ash pond.

2000 mg/L from 4000 mg/L at the startup of the pond (Figure 16), but a renewed upward trend has been established.

As discussed in previous sections, the water-level history of SubMcKay wells near the fly-ash pond indicates a developing ground-water mound. Limited data for wells upgradient (west) of the fly-ash pond indicate no impact directly attributable to the fly-ash pond. TDS concentrations have increased significantly in SubMcKay wells upgradient of pump-back wells in both the east and north drainages.

TDS concentrations have also increased in the SubMcKay in areas not controlled by pump-back wells; wells north, northwest, and northeast of the

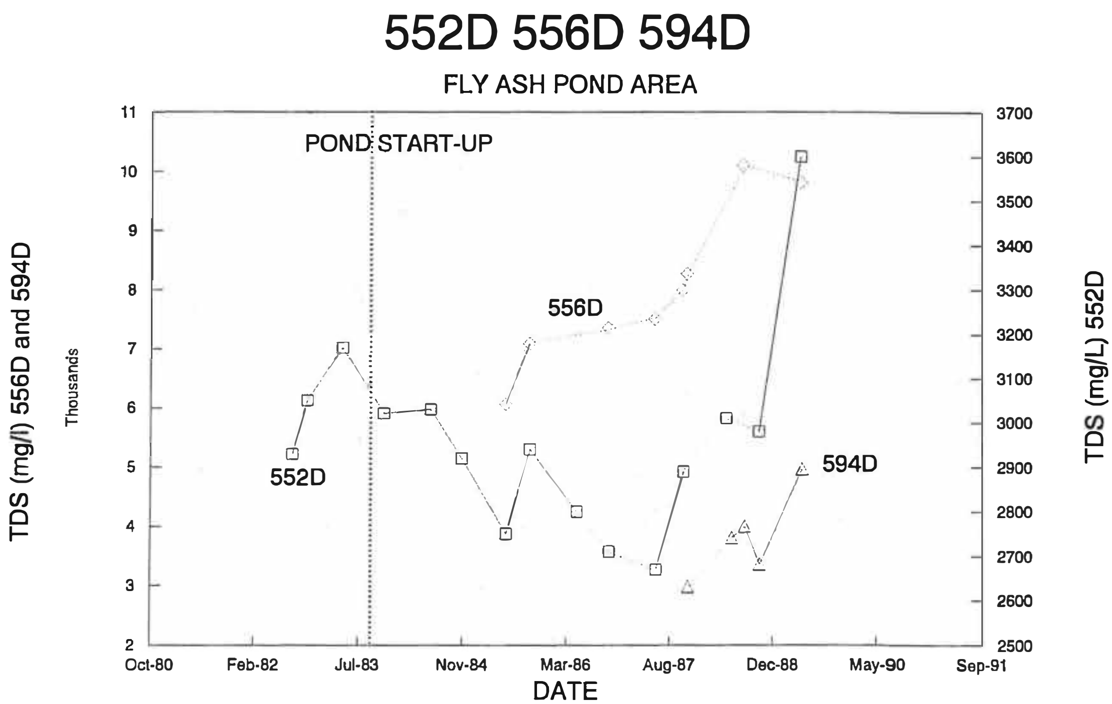


Figure 17 TDS concentrations for SubMcKay wells located north (594D), northwest (551D), and northeast (556D) of the fly ash pond outside the slurry wall.

pond indicate increases of 1500 to 4000 mg/L since startup of the pond (Figure 17). All of the affected areas are downgradient and within the Cow Creek drainage.

The increase in TDS concentrations in the alluvial aquifers within the tributary drainages is estimated as 3000 mg/L. The variable water-quality trends in the McKay aquifer make an estimate of increased TDS concentrations difficult; however, an increase is apparent and is estimated to be 1500 mg/L. The increased TDS concentration in the upper SubMcKay is estimated to be 2000 mg/L.

WATER QUALITY - MILLER COULEE AND LEE COULEE

Both the Rosebud coal and the McKay coal exhibit similar changes caused by mining as with the Area E and Area D mines. As discussed earlier, Van Voast and Reiten (1988) estimated an average TDS concentration of 3660 mg/L for spoils and 1750 mg/L for the coal beds. The balance of 1910 mg/L is used as an estimate of the increased TDS concentrations downgradient from the Area A mine. The data are not sufficient to estimate the increased TDS concentration due to mining in Area B, but it is assumed that the increase will be the same 1910 mg/L as for Area A.

WATER QUALITY - SURFACE WATER

COW CREEK

Water-quality data for surface waters have been collected for several sites in the Cow Creek drainage and its tributaries. However, the intermittent and ephemeral nature of flow in the creek prevents detailed monitoring of surface-water \ ground-water interactions. Surface-water quality and discharge are largely controlled by precipitation, pond and pit discharges (Area D) and, on occasion, by accidental releases of fly-ash slurry from the pipeline connecting the fly-ash pond and the power-generating plant. Mine-pit discharges and pond discharges also contribute to flow in Cow Creek. An examination of data for this creek provides another means for describing the impact of the various sources on water quality.

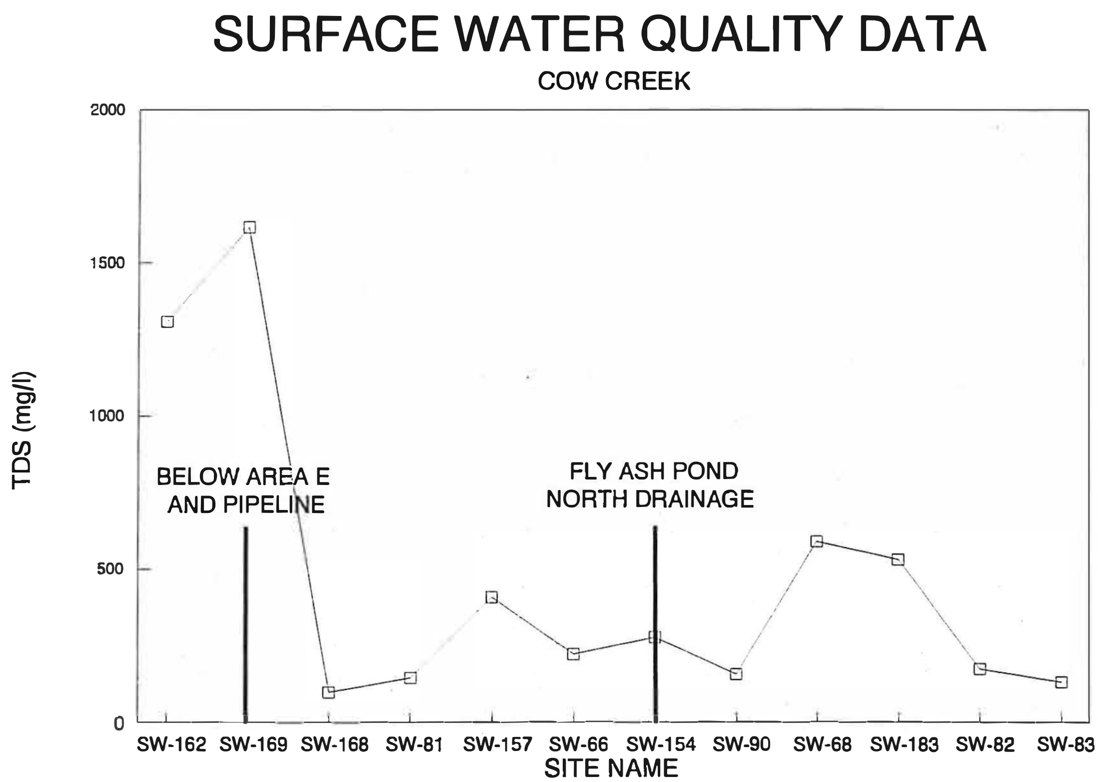


Figure 18 TDS concentrations at surface-water sampling sites along Cow Creek.

Figure 18 presents time-weighted average TDS concentrations in samples collected at sites along Cow Creek. The data are limited to 2 to 5 samples per site collected over a period from 1982 to 1989; much of the data predates 1986. With two areas of exception, concentrations of dissolved constituents are greatest near the mine and decrease with distance downstream. TDS concentrations at a site near the confluence of Cow Creek and a tributary drainage below Area E and the fly-ash slurry pipeline is 200 mg/L greater than sites upstream; TDS concentrations are 300 mg/L greater downstream of the confluence of Cow Creek and the tributary drainage below the main dam of the fly-ash pond. Below this point, TDS concentrations in surface water again decrease with distance downstream. No data were available for the confluence of Cow Creek and the tributary drainage below the saddle dam; within the tributary drainage, however, TDS in the alluvial ground water is above 3500 mg/L and increasing.

Concentrations of total-dissolved-solids are generally increasing with time in streams and springs within the Cow Creek drainage. Notable exceptions are those tributary drainages below Area D where, based on limited data, TDS concentrations appear to have decreased since mining began.

MILLER COULEE - LEE COULEE

Surface water flows in Miller Coulee and Lee Coulee have been greatly influenced by the pumping of mine effluent to settling ponds. Surface water flow below the active mine area is intermittent and ephemeral; the estimate of discharge rate and quality from the Big Sky mine to Rosebud Creek is best based on the ground water contribution.

CUMULATIVE INCREASED LOADING

COW CREEK, MINING

Each of the three areas considered (Area E, Area D, and the fly ash pond) contributes ground water to the Cow Creek drainage and ultimately to the Rosebud Creek drainage. Water quality has been impacted to varying degrees in each of the areas, and each contributes to the total dissolved constituent load to Rosebud Creek (Summary-Table 1).

The loading rate of 632 pounds per day from Area E (Figure 19) is based on the discharge of the spoils water to the Cow Creek drainage. At present, ground water is discharging to the South Cow Creek drainage; however, since ground-water quality in the alluvium has remained unchanged for several years, a conservative estimate of loading would exclude that component. When water levels are re-established in Area E, discharge of spoils water to the South Fork Cow Creek drainage will likely resume and additional loading will occur.

Area D discharges about 280 pounds of dissolved solids per day (Figure 19) and has had less influence on ground-water quality than other areas. As spoils are generated and ground-water levels recover, the future loading rate to the Cow Creek drainage will probably be similar the present loading rate of the Area E mine.

COW CREEK, FLY-ASH

The TDS values used for the fly-ash-pond area reflect the changes that have occurred since the startup of the pond. Ground-water levels are rising in the SubMcKay and, to a lesser degree, in the McKay in direct response to pond leakage. The increased hydraulic gradient and dissolved constituents combine with the large discharge area to provide a loading rate of about 200 pounds per day to the Cow Creek drainage and, ultimately, to Rosebud Creek (Figure 19).

COW CREEK, LANDFILL

The potential impacts of any additional development on Rosebud Creek can be determined by estimating the discharge and increased dissolved constituent load. For example, an alternative reclamation plan was proposed for the Area E mine that included the construction of a municipal landfill in the final pit. The detailed plan included an estimated leachate volume of 56 ft^3/day based on a computer-simulated landfill model. Driscol (1987) presented a range of TDS values for "typical" leachate from municipal landfills of 5,000 to 40,000 mg/L. Using these values for discharge and concentration and an existing loading rate of 1530 pounds per day, a landfill in Area E would increase the dissolved-constituent load from Area E by 1.6 to 12.6 percent (Table 2).

MILLER COULEE AND LEE COULEE, MINING

In order to provide a more complete estimate of impact from mining and related activities to the Rosebud Creek drainage, the Peabody Company's Big Sky mine is also considered. Van Voast and Reiten (1988) estimated an average TDS concentration of 3660 mg/L for spoils and 1750 mg/L for the coal beds. Assuming this difference (1910 mg/L) to be the increase in TDS due to mining, the loading rate of the Big Sky Area A mine to Rosebud Creek is approximately 250 pounds per day (Figure 19).

Similar assumptions are made for estimating the loading from the Big Sky Area B mine. The post-mine increase in TDS is assumed to be 1910 mg/L. The ground-water discharge estimate (1400 ft^3/day) includes only the Rosebud coal. The additional loading to Rosebud Creek from Area B is about 170 pounds per day (Figure 19).

SUMMARY – TABLE 1 – LOADING RATES

	Discharge (ft^3/day)	TDS post–mining increase (mg/L)	Additional Loading (lbs/day)
COW CREEK DRAINAGE			
AREA E MINE			
COAL/SPOILS	5300	1910	632
AREA D MINE			
COAL/SPOILS	2370	1910	283
FLY ASH POND			
ALLUVIUM	27	3000	5
McKAY	700	1500	66
"SUBMcKAY"	1020	2000	127
TOTAL			**1113**
MILLER COULEE			
BIG SKY MINE (Area A)			
COAL/SPOILS	2100	1910	**250**
LEE COULEE			
BIG SKY MINE (Area B)			
COAL/SPOILS	1400	1910	**167**
INCREASED LOADING TO ROSEBUD CREEK			**1530**

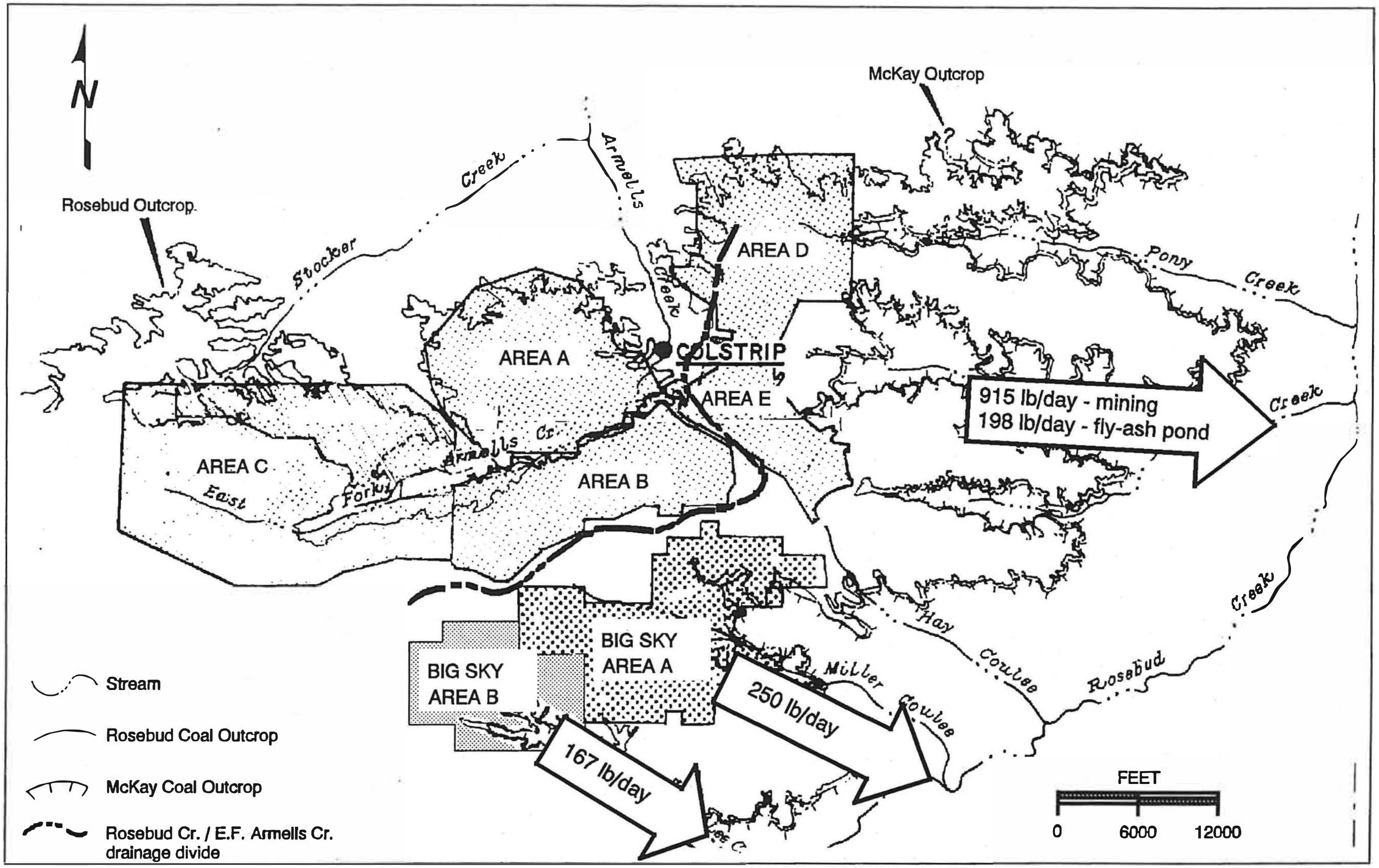


Figure 19. Increased post-development TDS loading (pounds/day) to Rosebud Creek due to surface and ancillary activities.

SUMMARY–TABLE 2 – IMPACTS ON ROSEBUD CREEK

	Discharge (acre–ft/day)	Average TDS * pre–development (mg/L)	Pre–development load (lbs/day)	Additional loading (lbs/day)	Increase (percent)
ROSEBUD CREEK					
WY 75–77	117 average	1065	338000	339530	0.45%
Adjusted	20 average	1065	58000	59530	2.64%
LANDFILL (hypothetical)					
TDS = 5000 mg/L	0.0013			17 to	1.57% to Cow Creek Drainage
TDS = 40000 mg/L	0.0013			140	12.56% to Cow Creek Drainage
					0.01% to Rosebud Creek
					0.24% to Rosebud Creek

Equation used:
Loading (lb/day) = TDS (mg/L) * 0.001 * 0.06242621 * Discharge (acre–ft/day) * 43560

* Adjusted from USGS records; calculated sum of dissolved consituents

CUMULATIVE IMPACT ON ROSEBUD CREEK

The cumulative impact of mining and ancillary activities can be estimated by comparing the increased loading from each of the developed drainages to the pre-development load in Rosebud Creek. Data were collected on Rosebud Creek above Pony Creek (Figure 1) by the U.S. Geological Survey over a three year period (USGS, 1975, 1976, 1977). These data provide a partial basis for estimating the predevelopment load. For water years 1975 to 1977, the average discharge was 117 acre-ft per day and the average TDS concentration was 1065 mg/L. The dissolved-constituent load in Rosebud Creek under these conditions is approximately 338000 pounds per day. The additional 1530 pounds per day from the developed areas represents a 0.45% increase (Table 2); the relative impact, however, depends on the amount of flow in Rosebud Creek.

Data have been collected over a longer period on Rosebud Creek below Lee Coulee, approximately 12 miles upstream. The average discharge over a seven-year period (1974 to 1981) was approximately 104 acre-ft per day (USGS, 1981). More recent data indicates a 15 year discharge average of 61 acre-ft per day (USGS, 1990) and a 2 year average discharge of about 20 acre-ft per day (1988-1990). The ratio of the long-term and short-term average discharge from this station can be used to adjust the average discharge at the downstream station to reflect recent trends. With an adjusted discharge of about 20 acre-ft per day, the increased loading of 1530 pounds per day from the developed areas represents a 2.6% increase of the dissolved-constituent load in Rosebud Creek (Table 2).

Potential impacts of future development can be estimated by the mass balance of dissolved-solids and water flow with flow and quality conditions of Rosebud Creek. Regrettably, those conditions are not well defined. With the available data however, the change in average dissolved-solids load in Rosebud Creek can be estimated by summing the product of the discharge (Q_n) from each development area and the increase in dissolved-solids concentration in each development area (TDS_n):

$$(Q_1 * TDS_1) + (Q_2 * TDS_2) \ldots + (Q_n * TDS_n) = (Q_R * TDS_R)$$

The result is the product of the increased discharge to the creek (Q_R) and the increased dissolved-solids concentration in the creek(TDS_R) which is the increased load to the creek.

Most developments such as mining or landfills will not introduce significant changes in the area's water budget, but will substantially change the water quality. In these cases, estimates of potential impacts can be made by the relationship that every 1000 mg/L increase in dissolve-solids discharging to Rosebud Creek will increase the average dissolved-solids load in Rosebud Creek by 64 pounds per day and will increase the average dissolved-solids concentration by 1.2 mg/L based on the adjusted flow rate.

REFERENCES

Balster, C.A., 1973, Structure contour map, Upper Cretaceous, south-eastern Montana, Montana Bureau of Mines and Geology Special Publication 54, 448pp.

Bass, N.W., 1932, The Ashland Coal Field Rosebud, Powder River, and Custer Counties, Montana, USGS Bulletin 831-B, Contributions to Economic Geology, 1931-32, Part II, p19-105.

Davis, R.E., 1984, Geochemistry and Geohydrology of the West Decker and Big Sky Coal-mining Areas, Southeastern Montana, USGS Water-resources Investigations Report 83-4225, 109 pp.

Department of Natural Resources and Conservation (DNRC), 1990, Un-published records obtained from DNRC - Energy Division, Helena, Montana 59620-2301.

Driscoll, F.G., 1987, Groundwater and Wells, Second Edition, Published by Johnson Division, St. Paul MN, 55112, p707-708.

Dobbin, C.E., 1929, The Forsyth Coal Field, Rosebud, Treasure, and Bighorn Counties, Montana, USGS Bulletin 812, 55pp.

Fetter, C.W., 1980, Applied Hydrogeology, Charles E Merril Publishing Co., Columbus, Ohio, 488pp.

Ferreira, R.F., Lambing, J.H., and Davis, R.E., 1985, Chemical Characteristics, Including Stable-Isotope Ratios, of Surface Water and Ground Water from Selected Sources In and Near East Fork Armells Creek Basin, Southeastern Montana, USGS WRI Report No. 89-4024, 32pp.

Harrington, A. H., 1984, Compilation of Overburden Saturated Paste Analyses from the Fort Union Coal Region, Montana Bureau of Mines and Geology, Open-file Report MBMG-141, 301pp.

Montana Department of State Lands and U.S. Office of Surface Mining, 1983, Final Comprehensive Environmental Impact Study, Western Energy Company's Rosebud Mine, July 1983, OSM 83-10, 388pp with appendix.

Matson, R.E and Blumer, J.W, 1973, Quality and Reserves of Strippable Coal, Selected Deposits, Southeastern Montana, Montana Bureau of Mines and Geology Bulletin 91, 135pp.

Olsen, K.B., Smoot, J.L., and Johnston, J.W., 1991, Hydrogeochemical Study of Cow and Pony Creek Drainages, Rosebud County, Montana for CY 1991, Battelle Pacific Northwest Laboratories, Richland, WA 99352, 57pp.

Parkhurst, D.L., Thorstenson, D.C., and Plummer L.N., 1985, PHREEQE - A Computer Program for Geochemical Calculations, USGS WRI 80-96, November 1980, revised and reprinted May, 1982, revised and reprinted, January 1985.

Pierce, W.G., 1936, The Rosebud Coal Field Rosebud and Custer Counties, Montana, USGS Bulletin 847-B, Contribution to Economic Geology, 1934-36, p43-120.

U.S. Geological Survey, 1975 Water Resources Data for Montana, Vol. 1, Hudson Bay Basin and Missouri River Basin: USGS Water-data Report MT-75-01, 604 pp.

References - continued

U.S. Geological Survey, 1976 Water Resources Data for Montana, Vol. 1, Hudson Bay Basin and Missouri River Basin: USGS Water-data Report MT-76-01, 766 pp.

U.S. Geological Survey, 1977 Water Resources Data for Montana, Vol. 1, Hudson Bay Basin and Missouri River Basin: USGS Water-data Report MT-77-01, 751 pp.

U.S. Geological Survey, 1981 Water Resources Data for Montana, Vol. 1, Hudson Bay Basin and Missouri River Basin: USGS Water-data Report MT-81-01, 647 pp.

U.S. Geological Survey, 1990 Water Resources Data for Montana, Vol. 1, Hudson Bay Basin and Missouri River Basin: USGS Water-data Report MT-90-01, 540 pp.

Van Voast, W.A., Hedges, R.B., and McDermott, J.J., 1977, Hydrogeologic Conditions and Projections Related to Mining Near Colstrip, Southeastern Montana, Montana Bureau of Mines and Geology, Bulletin 102, 43pp, 7 Plates.

Van Voast, W.A and Reiten, J.C., 1988, Hydrogeologic Responses: Twenty Years of Surface Coal Mining in southeastern Montana, Montana bureau of Mines and Geology Memoir 62, 30pp.

Western Energy Company (WECO), 1990, Area E Alternate Reclamation Plan for Rosebud County Landfill, Application #00142, July 31, 1990, Submitted to Montana Department of State Lands - Coal and Uranium Bureau, Helena MT.