# RECENT CHANGES IN THE GEOCHEMISTRY OF THE RECLAIMED PORCUPINE CREEK ALLUVIAL VALLEY FLOOR NORTH ANTELOPE ROCHELLE MINE CAMPBELL COUNTY, WYOMING[1]

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**Abstract.** Two sections of the Porcupine Creek alluvial valley floor have been reconstructed at Powder River Coal Company's North Antelope Rochelle Mine using specialized reclamation methods. The lower section of Porcupine Creek (AVF Reach 1) was re-constructed in 1985, but flow was bypassed by a diversion until early-2001. In addition, the lower creek was reconstructed using old channel design criteria that utilized a guide channel and limited the amount of pooled water. The lower reclaimed Porcupine Creek was constructed from native alluvium as required by the Wyoming Department of Environmental Quality / Land Quality Division (WDEQ/LQD) at the time. TDS and selenium concentrations in the alluvial monitoring wells in the lower reclaimed channel have been higher than in premining alluvial waters. The water quality reflected the new mobility of the constituents after mixing and oxidation of the highly mineralized alluvial material occurred during mining and aquifer construction. The alluvial water quality slowly improved between 1985 and 2001, but the future postmining water quality remained a concern. Following construction of pools and counter-weirs on AVF Reach 1 in early 2002 as part of a wetland establishment project, alluvial water levels have risen significantly. Boron concentrations spiked upward in the alluvial waters as water flushed through the vadose zone, but are now lower. Selenium concentrations are now much lower and geochemical conditions appear to be more reducing. The results of recent monitoring highlight the important geochemical processes ongoing in the aquifer and show that the construction of the pools and wetlands has improved the alluvial water quality in the AVF Reach 1. Further study of AVF Reach 1 is warranted as water quality in the reclaimed alluvium stabilizes. An upstream section of Porcupine Creek (AVF Reach 2) was reclaimed in 1999 primarily using selected overburden material as alluvium. TDS and selenium concentrations are much lower in AVF Reach 2.

Key Words: Alluvial Valley Floors, Geochemistry, Sulfate-Reducing Bacteria, Reclamation, Wetlands, Selenium, Backfill

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## Introduction

Powder River Coal Company's North Antelope Rochelle Mine (NARM) is located on the eastern flank of the Powder River Basin in Campbell County, approximately 100 km south of Gillette, Wyoming (Figure 1). The topography is generally flat with most surface drainages flowing into ephemeral streams. Four landforms originally existed in the permit area. Well-developed soils exist on the gentle sloping upland tablelands in the northern part of the permit area, which covers approximately 109 $km^2$. Highly erosive badlands, which have been mostly removed by mining, are characteristic of the central portion of the permit area. The most conspicuous landforms in the southern portion of the permit area are erosion resistant clinker (porcelainite) hills. Lastly, sheetwash deposits, colluvium, and lesser amounts of alluvium exist along portions of the ephemeral drainages. Reclaimed portions of the permit area, as required by law, are characterized by well-vegetated gently sloping hills. A downstream section of the main drainage in the permit area, Porcupine Creek, was classified as intermittent.

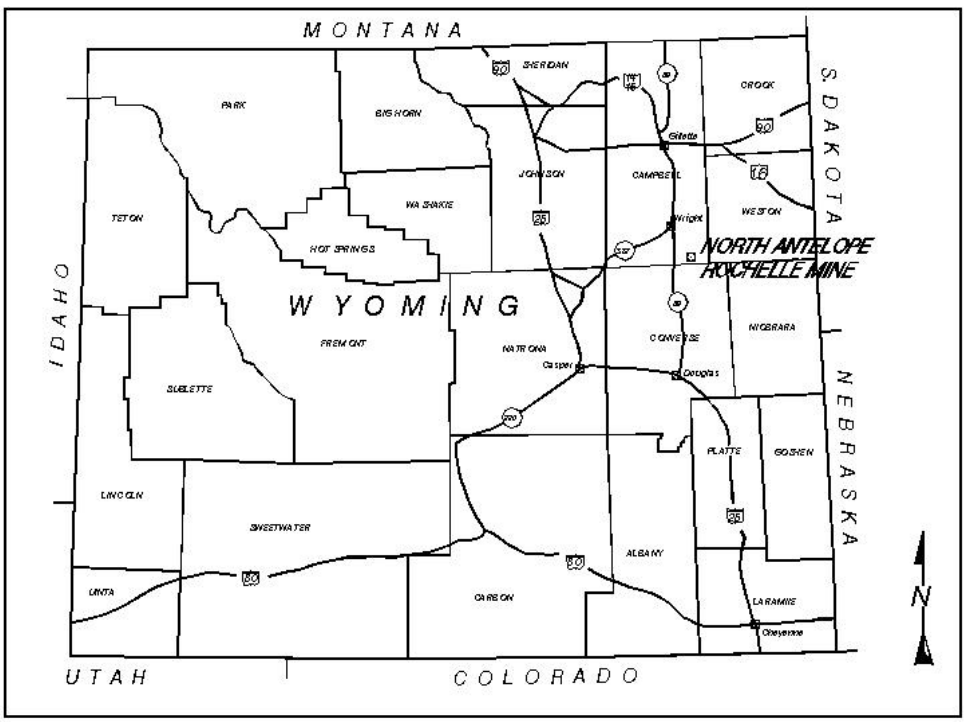


**Figure 1: Location of North Antelope Rochelle Mine: Campbell County, Wyoming.**

The climate at NARM is cool and semi-arid and is characterized by dry, cold winters and short, warm summers. Factors controlling the regional climate include elevation, abundant sunshine, and mountainous moisture barriers to the west and south. The generally open terrain of the region permits free movement of wind and weather systems through the area, allowing rapid and extreme weather changes. The elevation of the permit area ranges from 1,370 to 1,525 m a.m.s.l. Mean annual precipitation is approximately 25 cm with the major portion of precipitation occurring as scattered thunderstorms during the late spring or early summer. Predicted annual evapotranspiration at Douglas, Wyoming, approximately 100 km south of NARM is nearly 58 cm (U.S. Department of Commerce, 1969).

As required by the mine's permit from the Wyoming Department of Environmental Quality / Land Quality Division (WDEQ/LQD), the North Antelope Rochelle Mine is required to reclaim the declared Alluvial Valley Floor (AVF) of Porcupine Creek using specialized methods. The reclaimed Porcupine Creek channel is underlain by a 24 m wide by 3 m deep reconstructed fill of material containing at least 60 percent sand (Figure 2). A compacted clay liner separates the reclaimed alluvial aquifer from the underlying backfill. Approximately three km of Porcupine Creek have been reconstructed, divided into two sections that are longitudinally separated by a section of native channel.

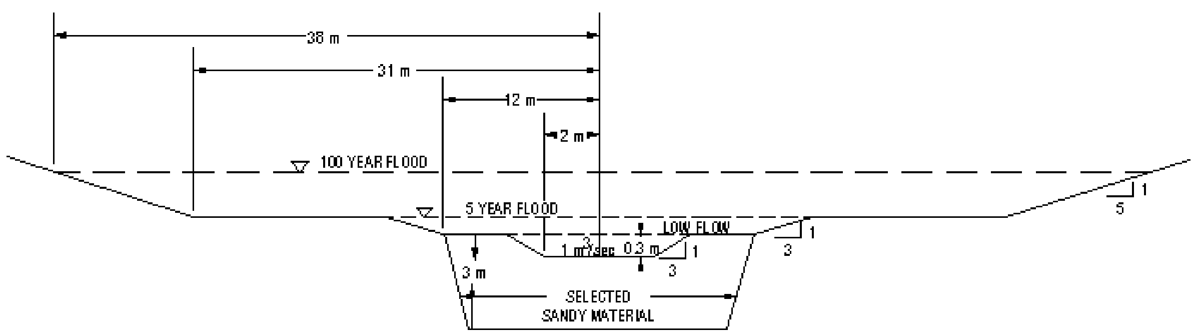


**Figure 2: Typical Geometry of Reconstructed Porcupine Creek**

The upper section of the reclaimed Porcupine Creek (AVF Reach 2) was reconstructed in 1998 and 1999, primarily using selected sandy overburden as replacement alluvium. Pools and counter-weirs were constructed on AVF Reach 2 channel in 1999, as well. Due to the direct flow of water from the native Porcupine Creek, through a now reclaimed diversion upstream of AVF Reach 2, and the constructed pools, this area already shows good development of wetland characteristics only a few years following reclamation (Hansen and Murphree, 2002). Alluvial water levels are still rising in the upper Porcupine reclamation, but the reclaimed alluvial water quality is generally good ranging from 1,200 to 2,200 mg/l, which is similar to the water quality in the overburden, from which the replacement alluvium originated, and adjacent backfill. This is an improvement compared to the water quality in the native Porcupine Creek, where TDS often exceeded 3,000 mg/l. Surface water quality is also good, with TDS concentrations at approximately 1,100 mg/l, as it is dominated by pit water and natural runoff. Trace metal concentrations have not been a major concern in AVF Reach 2.

Although a lower one-mile section of Porcupine Creek (AVF Reach 1) was reclaimed in 1985 and 1986, a diversion bypassed the section until January 2001. Flow in this section was limited to infrequent discharges from a sediment reservoir upstream of this channel. In addition, the lower creek was reconstructed using old channel design criteria that required a guide channel and limited the amount of pooled water. During construction of pools and counter-weirs on AVF Reach 1 for purposes of wetland replacement in January 2002, it was observed that in most portions of the channel, the topsoil on the reclaimed channel had effectively retarded infiltration and hydric soil development was limited to subsided areas that pooled water. Rather than recharging from the surface as designed, AVF Reach 1 primarily recharged from below through the underlying clay liner as water levels in the deeper backfill returned to premining levels. Table 1 shows the sequence of reclamation for AVF Reach 1. Figure 3 shows AVF Reach 1 and associated features.

**Table 1: AVF Reach 1 Reclamation Sequence**

| **Year** | **Event** |
|---|---|
| **1983** | Porcupine Creek diverted. Box-cut for dragline constructed in Porcupine Creek. Alluvial Material salvaged for reclamation use. |
| **1985-1986** | Reclamation of Porcupine Creek Alluvial Valley Floor (AVF Reach 1) using salvaged alluvial material. Wells SP-1-NA through SP-5-NA constructed. High TDS and Se concentrations are observed in reclaimed AVF wells. |
| **1989** | Well SP-10-NA constructed on upper AVF Reach 1 to further define water quality. High TDS and Se concentrations observed at SP-10-NA. |
| **1996** | 4E Reservoir constructed upstream of AVF Reach 1to treat facilities washdown water. Periodic flow begins. |
| **2001** | Portion of Porcupine Creek Diversion reclaimed allowing stream flow through AVF Reach 1. |
| **2002-2003** | Pools and counter-weirs constructed on AVF Reach 1 for wetland replacement purposes, significant reduction in Se concentrations observed. Boron levels spike upward, but soon decrease, sulfate-reducing bacteria measured in wells. |

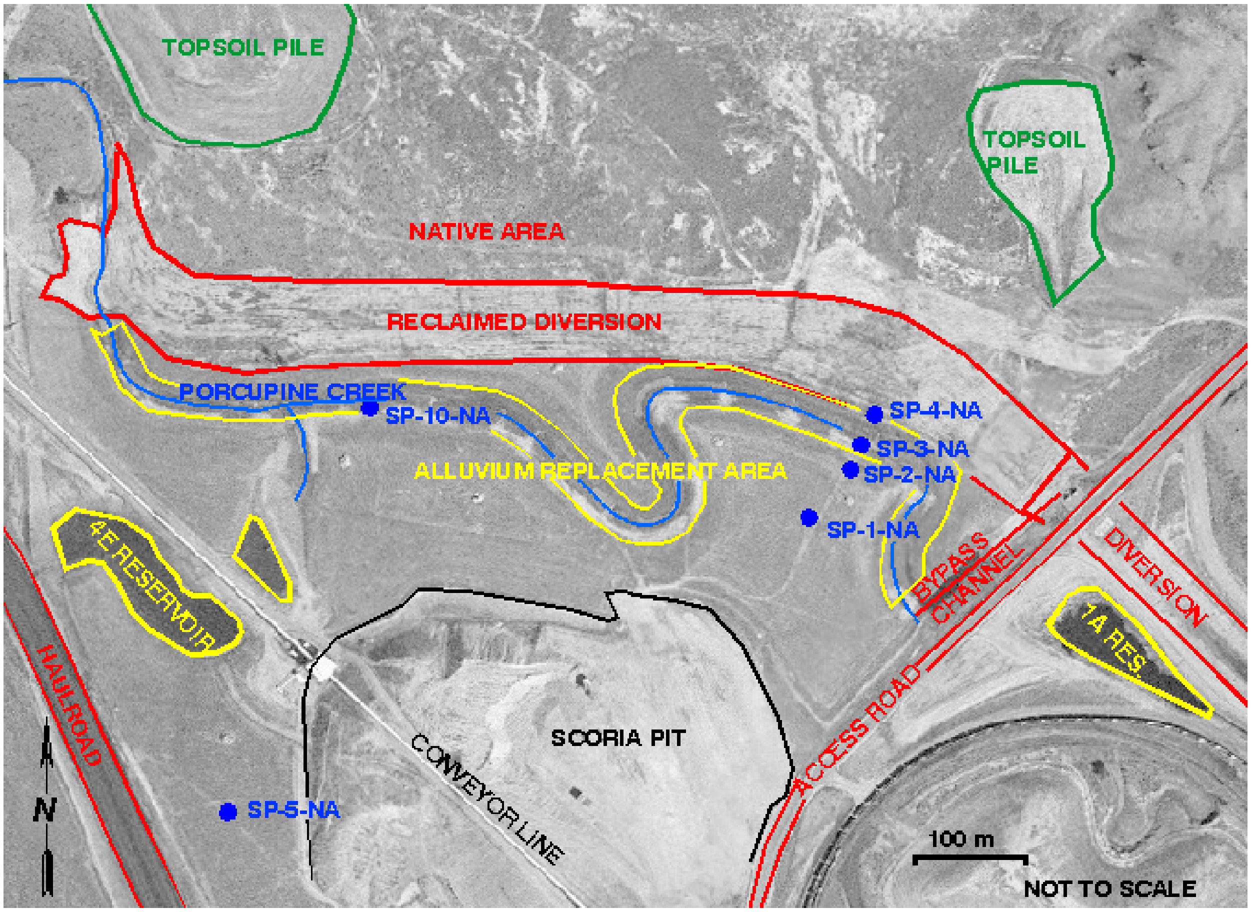


**Figure 3: Location on Monitoring Wells on or near AVF Reach 1.**

The pools on AVF Reach 1 are between 0.3 and 1.5 m deep and between approximately six and twenty meters in length. The counter weirs serve as grade-control structures and are strategically located downstream of each pool to facilitate the formation and maintenance of deeper pools and designed to retain and guide flows through the channel in proper locations. The retention of water in and around the pools aids in the support of wetland vegetation. Willow plantings and other vegetation will stabilize the counter-weirs. Figure 4 shows a typical pool and counter-weir sequence. Since construction of the pools, alluvial water levels have risen up to 1 m. Trees have been planted on the reclaimed channel and riparian vegetation along the channel is expected to improve, as more water is available. Water that is discharged from central portions of the mine to native Porcupine Creek, now flows through this reclaimed channel. Water exiting AVF Reach 1 flows through a culvert into the 1A Reservoir (Figure 3) and a downstream sediment pond prior to discharge to native Porcupine Creek. During high flow events, water may enter a bypass channel into the remaining portion of the Porcupine Creek

Diversion, which reenters Porcupine Creek downstream of the mine (Figure 3). Porcupine Creek is tributary to Antelope Creek, which is tributary to the Dry Fork of the Cheyenne River and the Cheyenne River.

AVF Reach 1 was constructed from native alluvium as required at the time by the Wyoming Department of Environmental Quality / Land Quality Division (WDEQ/LQD). Water Quality in the four alluvial monitor wells in AVF Reach 1 has been poor since reconstruction. Premining alluvial wells located in the general vicinity of AVF Reach 1 showed generally poor quality with TDS levels ranging from approximately 750 mg/l to 5,770 mg/l. When mixing and oxidation of the highly mineralized alluvial material occurred during mining and replacement, the resulting water quality reflected the new mobility of the constituents. Although one shallow reclaimed alluvial well, showing seasonal variations in water level, had a range in TDS concentrations of between 1,230 and 2,652 mg/l, TDS concentrations in the three other reclaimed alluvial wells ranged from 3,800 to 25,320 mg/l. Trace metal concentrations in AVF Reach 1 have fluctuated, but excepting selenium, are not presently elevated. Selenium concentrations have reached as high as 932 µg/l, but generally have ranged from below detection to 200 µg/l. In the wells in and surrounding AVF Reach 1, pH values are nearly neutral (6.2 to 7.9) and alkalinities are high (411 to 944 mg/l), which is typical of backfill wells in the Southern Powder River Basin.

**Figure 4: Typical Pool and Counter-Weir Sequence on AVF Reach 1 Channel with Caged Coyote Willow (Salix exigua) Plantings**

In 1996, the 4E Reservoir (Figure 3) was constructed a short distance upstream of well SP-10-NA to treat washdown water from mine facilities. The reservoir is not located on the reclaimed alluvial material (Figure 3), but discharge water from this reservoir has frequently flowed through the reclaimed AVF channel. In 2001, the native Porcupine Creek channel was connected to the reclaimed Porcupine Creek AVF following the reclamation of the portion of the Porcupine Creek Diversion adjacent to AVF Reach 1 (Figure 3). Floodwaters discharged from a sediment pond upstream of AVF Reach 1 passed through the reclaimed channel twice in 2001. Most of this flow is of high quality and has originated as pit water or surface runoff. Coal bed methane production has recently begun in the vicinity of NARM and up to 500 coal bed methane wells will be drilled in the Porcupine Creek drainage upstream of the mine (see Murphree, 2003). It is expected that as discharges of coal bed methane produced water increase to the mine and reclaimed drainage areas increase, more surface water will pass through AVF Reach 1.

While it was not the primary purpose of the project, it was felt that wetlands creation on AVF Reach 1 could be a mechanism for alleviating the long-standing ground water quality problem in the reclaimed alluvium. Since removal of the diversion in January 2001 and construction of pools and counter-weirs in January 2002, significant changes have also occurred in the geochemical conditions in the aquifer due to increased subsurface flow in the aquifer and the development of a more reducing environment. This paper discusses the long-standing problem of high TDS and selenium concentrations in AVF Reach 1 from the time when the aquifer was reclaimed in 1985 and 1986 and the subsequent changes observed in ground water quality following the removal of the diversion in early 2001 and the construction of wetlands on the channel in early 2002. Selenium concentrations have significantly decreased, while boron concentrations spiked upward as water flushed through the vadose zone, but have since decreased. TDS concentrations have fluctuated, but have not changed significantly since 2001. The paper also reports the results of tests for dissolved organic carbon analyses and sulfate-reducing bacteria conducted on the AVF Reach 1 monitoring wells.

## **Premining and Postmining Hydrology of Porcupine Creek**

Porcupine Creek flows southeast approximately 30 km from its headwaters towards the North Antelope Rochelle Mine. The drainage area of Porcupine Creek upstream of the mine is approximately 160 $km^2$. The mine occupies a segment of the Porcupine Creek drainage marked by a transition from subdued upland surface to extensive badland topography (WWC, 1998). The badland topography is due to an increase in channel gradient caused by the rapid headward erosion of Porcupine Creek necessary for Porcupine Creek to achieve grade with the local base level of Antelope Creek downstream of the mine. Upland areas upstream of the mine exhibit a subdued rolling topography characteristic of an aeolian deflation surface, with numerous playas (WWC, 1998).

Construction of numerous stockponds, both permitted and non-permitted, since the early-1900's has considerably reduced flows on Porcupine Creek upstream of the North Antelope Rochelle Mine. Many of these stockponds rarely, if ever, spill water. Inflows to the mine on Porcupine Creek have averaged only 12,000 $m^3$ per year during the twenty-four years of flow monitoring on the creek. One large stockpond, near the mine's upstream permit boundary, was capable of storing the 100-year, 24-hour storm. Upstream of the mine, Porcupine Creek flows through an abandoned playa, which has quite saline soils.

Downstream, within the mine, most natural flows in Porcupine Creek originate from ephemeral drainages. Prior to mining, many of these drainages were in badland areas and flows were of low quality and carried much sediment. Large flashy storm flows were often noted prior to and during mining until Porcupine Creek and the tributary drainages were controlled for mining purposes. Natural flows from the mine are estimated to have averaged 60,000 $m^3$ per year. Premining alluvial ground water quality was of much higher quality on Porcupine Creek downstream of the mine due to the greater frequency of flows and influx of water from the higher quality coal aquifer, which directly contacted the alluvial aquifer in a number of places (WWC, 1998).

Most surface water in upstream native Porcupine Creek drainage is stored in shallow pools along the drainage. These pools are between 10 m and 30 m in length and up to 3 m deep and partially filled by inflows from shallow sands in the overburden (WWC, 1998). Due to evapotranspiration and a lack of flushing events, the pools are brackish with TDS concentrations of well over 5,000 mg/l. The shorelines of the pools are often thickly salt-crusted. The premining alluvial water quality ranged from 3,500 to 37,000 mg/l. Trace-metals, such as selenium and arsenic, are usually below detection limits because these metals are fixed in the sediments and in organic-rich sulfidic material below the pools. However, the infrequent flushing events can produce high trace metal concentrations in Porcupine Creek due to disturbance of deeper stratified sulfide-rich pool and pore water.

The postmining surface flows should be of higher quality than the premining flows due to the designed stability of the postmining channels and the greater vegetation density in the drainages. The postmining channels are designed to be erosionally stable during the 100-yr 6-hr runoff event. The postmining reservoirs for the North Antelope Rochelle Mine are distributed more evenly across the mine than the premining reservoirs. Only one of the postmining reservoirs is placed on Porcupine Creek. The other postmining reservoirs will be placed on the ephemeral drainages that are tributary to Porcupine Creek. Total reservoir storage capacity is nearly equivalent to the capacity of the reservoirs disturbed by the mine. The postmining reservoirs are also designed to spill during the 10-year 24-hour runoff event, which will allow flushing of salts from the reservoirs and postmining stream channels, including Porcupine Creek.

Aquifer tests of wells in and around AVF Reach 1 show that postmining hydraulic conductivities are similar to premining hydraulic conductivities. Aquifer tests results show a conductivity range from 0.015 to 0.030 cm/sec. It is this rapid flow rate that has allowed for such rapid change in the water level and geochemistry of the alluvial aquifer following pool construction., but the same high flow rate also prevented conditions from becoming more reducing while the aquifer remained mostly unsaturated and was lacking in significant infiltration prior to pool construction. Deeper backfill wells SP-1-NA and SP-5-NA also have high hydraulic conductivities (0.0076 and 0.012 cm/sec respectively) as is typical of wells placed in dragline spoils. Now that water levels have stabilized in the alluvial aquifer and underlying backfill, actual subsurface flow rates are probably much less than the pump test results would suggest due to the low hydraulic gradient in the vicinity of AVF Reach 1.

## <u>Recent Changes in Ground Water Quality on AVF Reach 1</u>

Four monitoring wells, SP-2-NA, SP-3-NA, SP-4-NA, and SP-10-NA, which are between 10 and 25 feet deep, are all completed in or below the reclaimed alluvial material of AVF Reach 1 (Figure 3). Chemical analyses have been conducted by various laboratories as part of the mine's normal sampling regime utilizing methods approved by the WDEQ/LQD. Quarterly or semi-annual water quality monitoring has been conducted since 1986 for wells SP-2-NA, SP-3-NA, and SP-4-NA and quarterly water quality monitoring has been conducted since 1990 at well SP-10-NA.

The physical location of each monitoring well on AVF Reach 1 influences the water quality at that well. Well SP-4-NA is on the edge of the reclaimed alluvial aquifer adjacent to the native ground. Well SP-3-NA is a shallower well in the center of the reclaimed Porcupine Creek channel that shows seasonal variations in water level and well SP-2-NA is on the opposite edge of the channel approximately 100 feet distant from SP-4-NA. SP-3-NA is screened between 5 and 10 feet in depth, within the alluvium; and SP-2-NA and SP-4-NA are screened between 12 and 22 feet in depth, immediately below the alluvial aquifer. The TDS at SP-2-NA has ranged from 3,802 to 8,950 mg/l and from 1,230 to 2,652 mg/l at SP-3-NA. Historic TDS concentrations are shown on Figure 5. In general, TDS concentrations at SP-2-NA have been recently increasing, while those at SP-3-NA have been fluctuating based on the flow in the reclaimed stream channel. Well SP-10-NA, which is completed in a similar fashion as SP-2-NA and SP-4-NA, shows a TDS range from 5,488 to 12,250 mg/l, but the TDS in SP-10-NA has been fluctuating in the range from 5,500 to 7,700 mg/l since 1991. Water at SP-3-NA is of a mixed sodium-bicarbonate / calcium-sulfate type due to its shallow depth and the influence of surface water, while the water at SP-2-NA, SP-4-NA, and SP-10-NA is generally of a calcium-magnesium-sulfate type. Selenium concentrations at SP-3-NA have generally been below 10 μg/l, with minor fluctuations, while selenium concentrations at SP-2-NA have been as high as 130 μg/l.

TDS concentrations in SP-4-NA have decreased from 28,270 mg/l in 1986 to approximately 15,000 mg/l presently. Selenium concentrations at SP-4-NA have historically averaged 544 μg/l, but since 1997, have been below 250 μg/l. Since 1997, the selenium concentrations in SP-4-NA have been below the detection limit (1 μg/l or 5 μg/l) seven times and above the limit seventeen times. The trend in the selenium concentration at SP-4-NA is not mirrored in the concentrations of other parameters. Since 2001, when the diversion around Reach 1 was removed, the selenium concentration has fluctuated between the detection limit and slightly greater than 150 μg/l. Historic selenium concentrations are shown in Figure 6.

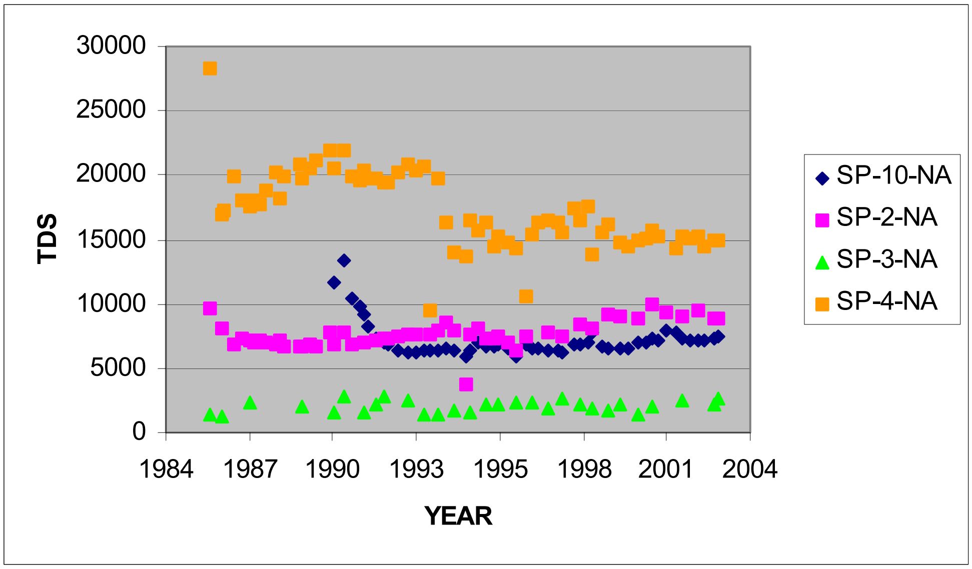


**Figure 5: TDS Concentrations (mg/l) in AVF Reach 1.**

As shown by sampling at SP-4-NA and SP-2-NA, the past high selenium and TDS concentrations at SP-4-NA were highly localized in the reclaimed alluvial aquifer. SP-4-NA is close to the former pit highwall. During mining, it was noted that there was a particularly saline zone in the highwall adjacent to the area where SP-4-NA was later located and it is probable that this is the source of the high salinity (D. Trueblood to R. Haroian, Pers. Comm., 1988). The reclaimed alluvial material and much of the backfill originated from nearly the same location as they are now placed. The top twenty feet of backfill was, however, tested for chemical suitability prior to placement of the alluvium and found to be suitable. In July 1993, over 400 liters of water (or about ten times the necessary amount) was bailed from SP-4-NA prior to sampling. The TDS concentration during this sampling was 9,114 mg/l versus 20,204 mg/l the previous quarter. The TDS concentration then returned to 18,868 mg/l the following quarterly. The selenium concentration at SP-4-NA dropped over 200 μg/l during that 1993 sampling. Currently, it appears that as frequent flow events pass through AVF Reach 1, dispersion is occurring in the alluvial aquifer as the TDS concentrations at SP-2-NA rise and those at SP-4-NA fall. The selenium concentrations in the two wells have recently been very similar.

Well SP-10-NA is approximately 2,200 feet upstream of wells SP-2-NA, SP-3-NA, and SP-4-NA on the reclaimed Porcupine Creek channel. As stated previously, the TDS concentrations at SP-10-NA have ranged from approximately 5,500 to 7,700 mg/l since 1991. The selenium results at SP-10-NA were at or near detection limit from 1993 to 1999, but have since been higher.

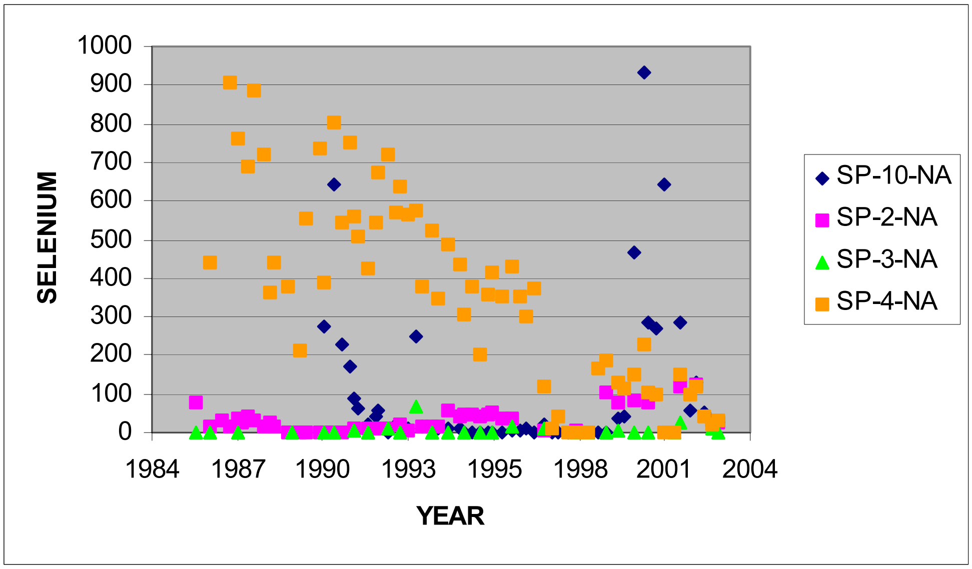


**Figure 6: Selenium Concentrations (µg/l) in AVF Reach 1.**

Wells SP-1-NA and SP-5-NA (Figure 3) are completed in the backfill adjacent to AVF Reach 1 and are screened between the surface and the former bottom of coal. TDS concentrations at SP-1-NA have ranged from 2,100 mg/l to slightly over 3,000 mg/l in recent years. Selenium concentrations at SP-1-NA, have generally been below the detection limit, but since 2001, have been as high as 32 µg/l. At SP-5-NA, TDS levels have ranged from 3,500 mg/l to over 4,500 mg/l and have been approximately 4,000 mg/l in recent years. Selenium measurements at SP-5-NA are similar to those at SP-1-NA, with years of below detection limit readings followed by an upward spike in selenium concentrations in 2001.

Table 2 shows the TDS, selenium, and selenite concentrations for the wells in this study for selected recent sampling periods. Since 2000, the TDS levels have fluctuated at all of the wells, but no substantial change has been noted. For selenium, at wells SP-2-NA, SP-4-NA, and SP-10-NA, high concentrations were noted from May 2000 to April 2002, soon after wetlands were constructed on AVF Reach 1. In fact, the historic peak selenium concentration for SP-2-NA was seen in April 2002. For SP-3-NA, below detection selenium concentrations were recorded prior to October 2001, when a relatively high selenium concentration was observed. The results at shallow well SP-3-NA, were also similar to the results seen at SP-1-NA and SP-5-NA. However, beginning in July 2002, greatly decreased selenium concentrations were observed at all of the wells indicating a probable positive influence on selenium concentrations due to wetland construction. The selenite levels shown on Table 2 are discussed in the next section.

| Table 2: TDS, Se, and Selenite Concentrations for Selected Recent Sample Periods | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Dates Sampled | | | | | |
| **Well** | **Depth (m)** | **5/2000** | **10/2000** | **10/2001** | **4/2002** | **10/2002** | **1/2003** |
| **TDS (mg/l)** | | | | | | | |
| SP-1-NA | 19.5 | 3,012 | 2,910 | 2,890 | 2,877 | 2,676 | 2,778 |
| SP-2-NA | 6.7 | 8,836 | 9,920 | 8,938 | 9,447 | 8,828 | 8,872 |
| SP-3-NA | 3.2 | 1,342 | 2,010 | 2,415 | **** | 2,178 | 2,592 |
| SP-4-NA | 6.8 | 14,980 | 15,700 | 15,207 | 15,193 | 14,858 | 14,948 |
| SP-5-NA | 30.5 | 4,144 | 3,970 | 3,946 | 4,139 | 4,076 | 4,038 |
| SP-10-NA | 6.4 | 7,072 | 7,300 | 7,272 | 7,161 | 7,238 | 7,504 |
| **Se (µg/l)** | | | | | | | |
| SP-1-NA | | <5 | <5 | 32 | 26 | 12 | <5 |
| SP-2-NA | | 82 | 77 | 119 | 129 | 30 | 24 |
| SP-3-NA | | <5 | <5 | 26 | **** | 8 | <5 |
| SP-4-NA | | 152 | 103 | 150 | 119 | 19 | 33 |
| SP-5-NA | | <5 | <5 | 85 | 31 | 13 | <5 |
| SP-10-NA | | 466 | 284 | 285 | 129 | 24 | 27 |
| **Selenite $SeO_3^{-2}$ (µg/l)** | | | | | | | |
| SP-1-NA | | | | | <5 | 15 | 5 |
| SP-2-NA | | | | | <5 | 35 | 37 |
| SP-3-NA | | | | | **** | 15 | 8 |
| SP-4-NA | | | | | <5 | 25 | 56 |
| SP-5-NA | | | | | <5 | 18 | 6 |
| SP-10-NA | | | | | <5 | 31 | 27 |

Samples selected because all wells were sampled in same period. Se concentrations were 39 and 53 µg/l at wells SP-4-NA and SP-10-NA respectively in July 2002. Selenite levels were 98 and 30 µg/l. Wells SP-4-NA and SP-10-NA are sampled quarterly. All other wells sampled semi-annually

**** - Not sampled

Note: TDS in overburden aquifers ranges from 500 to 10,000 mg/l and is of calcium-sulfate type.
TDS is coal aquifers, ranges from 1,000 to 3,000 mg/l and is of a calcium-sulfate type near the outcrops, and ranges from 450 to 1,200 mg/l and is a sodium-bicarbonate type downdip.

Naftz and Rice (1989) studied the processes controlling selenium at selected coal and in-situ uranium mines in the Powder River Basin. These authors found that, in similar shallow backfill wells at a coal mine, dissolved selenium concentrations in backfill wells may be related to dissolved organic carbon (DOC) in coal and carbonaceous shales, and conversion of organic selenides to selenite ($SeO_3^{-2}$) and selenate ($SeO_4^{-3}$). Highly mobile selenate was the major constituent in the wells at that time. Selenite is less mobile and adsorption of selenite, and to a lesser extent selenate, on clays and iron oxides is a possible sink for selenium following mining (Caballo Coal Company, 1985). High concentrations of dissolved organic carbon may saturate adsorption sites on goethite and similar materials (Balistrieri and Chao, 1987; Naftz and Rice, 1989). See, et al (1993) studied wells SP-2-NA and SP-4-NA as part of a study of the role of natural organic solutes in the mobility of selenium in coal mine backfill ground water. They found that at SP-2-NA, where there was little selenium in the ground water at that time, the dissolved organic carbon level was very low. At SP-4-NA, dissolved organic and selenium concentrations were both very high. Dreher and Finkelman (1992), studying backfill wells at a mine near to Gillette, including some of the wells discussed in Naftz and Rice (1989), stated that because the selenium concentrations were decreasing, competition of organic acids for sorption sites is not a strong factor at those wells.

In order to update the previous testing at wells SP-2-NA and SP-4-NA, DOC was analyzed in January 2003 for wells SP-1-NA, SP-2-NA, SP-3-NA, SP-4-NA, SP-5-NA, and SP-10-NA. As shown on Table 3, DOC and Se concentrations were low at SP-1-NA, and moderate at SP-2-NA, SP-4-NA, and SP-10-NA. At both SP-3-NA, where surface water has a direct impact on the water quality, and SP-5-NA, where coal from thin seams in the overburden were recovered during well drilling; DOC levels are high, but selenium concentrations are below detection limits. Small amounts of selenium were detected in these wells during the previous quarter. Therefore, as contended by Dreher and Finkelman (1992), decreasing selenium concentrations indicate competition of organic acids for sorption sites is probably not a strong factor in AVF Reach 1.

Selenate, was assumed to be the dominant form of selenium in the ground waters of AVF Reach 1 based on previous backfill geochemistry studies and the high concentration of selenium. However, since January 2002, selenite concentrations have been measured at the NARM backfill monitoring wells. Selenite measurements from early 2002 were below detection limits. However, as shown in Table 2, significant concentrations of selenite have been detected in the AVF Reach 1 wells since July 2002, confirming that geochemical conditions are becoming more reducing following pool construction.

The mechanism causing the recent decrease in selenium concentrations in AVF Reach 1 is not known, but it is probable that selenate is being converted to selenite either chemically or microbially and then adsorbed on clays and other particles. It is also possible that some flushing of the aquifer is occurring in AVF Reach 1 and the surrounding backfill as indicated by the rise in selenium concentrations in wells SP-1-NA and SP-5-NA following wetland construction.

However, because of the recently detected selenite, and the rapid decrease in selenium concentrations at all of the AVF Reach 1 wells, it is probable that adsorption of selenite within the aquifer is causing the decrease in selenium concentrations.

In 1996, sulfate-reducing bacteria were discovered in water sampled from deep backfill well SP-5-NA after laboratory balance problems were encountered in a sample from this well. In order to check the potential for sulfate-reducing bacteria to influence the water quality in AVF Reach 1 and the surrounding backfill, testing for sulfate-reducing bacteria was conducted in January 2003. Energy Laboratories of Casper, WY conducted the testing using Droycon Bioconcepts SRB-Bart test kits. As shown in Table 3, sulfate-reducing bacteria counts ranged from 1-10 colonies/ml at SP-1-NA, where sulfate concentrations are low to >1,000,000 colonies/ml at SP-4-NA, adjacent to native ground and where the sulfate concentration is very high. Sulfate-reducing bacteria counts ranged from 10-100 colonies/ml at wells SP-2-NA, SP-5-NA, and SP-10-NA. At shallow well SP-3-NA, sulfate-reducing bacteria counts ranged from 100-1000 colonies/ml.

**Table 3: Comparison of DOC, Se, Sulfate Reducing Bacteria, and Sulfate Levels; 1991 and 2003**

| Well | Date Sampled | DOC (mg/l) | Se (ug/l) | Sulfate Reducing Bacteria (colonies/ml) | $SO_4$ (mg/l) |
|---|---|---|---|---|---|
| SP-1-NA | Jan. 2003 | 9.7 | <5 | 1-10 | 1,313 |
| SP-2-NA | Sept. 1991* | 11 | 3 | *** | 4,447 |
| SP-2-NA | Jan. 2003 | 54.6 | 24 | 10-100 | 5,151 |
| SP-3-NA | Jan. 2003 | 99.9 | <5 | 100-1000 | 1,186 |
| SP-4-NA | Sept. 1991* | 88 | 165 | *** | 11,100 |
| SP-4-NA | Jan. 2003 | 27.2 | 33 | >1,000,000 | 8,283 |
| SP-5-NA | Jan. 2003 | 148 | <5 | 10-100 | 2,101 |
| SP-10-NA | Jan. 2003 | 52.7 | 27 | 10-100 | 3,821 |

* - See See, et al (1993)
*** - Not analyzed

As shown in Table 2, TDS concentrations have not changed significantly in the last few years, but bacterial sulfate reduction has the potential to improve the water quality in AVF Reach 1 and the proliferation of sulfate-reducing bacteria in backfill aquifers lends itself to further study. With the construction of the wetlands in AVF Reach 1, the potential for conditions in the alluvium to alternate between oxidizing and reducing is decreased, thereby improving the chance for sulfate and selenium reduction to occur (Clark, 1995). As discussed in Dreher and Finkelman (1992), the mechanism for chemical conversion for selenate to selenite is slow (Leutwein, 1978). However, in AVF Reach 1, the conditions for microbial or chemical conversion of selenate to selenite may have existed prior to wetlands construction and the subsequent more saturated environment allowed for the rapid selenate-selenite conversion to occur. It may also be possible that formation of organic selenides is occurring or will occur in the near future.

The conversion of selenate to less mobile forms of selenium and subsequent fixation in the sediments, the migration of selenium to deeper portions of the alluvial and backfill aquifers, and improved nutrient cycling will reduce the availability of selenium in AVF Reach 1 to flora and fauna. The postmining land use at NARM will be rangeland grazing and wildlife habitat. The reclaimed Porcupine Creek already supports three species of non-game fish, two amphibian species, numerous insects and invertebrates, as well as waterfowl, mule deer, and pronghorn antelope (Hansen and Murphree, 2002). Trees were planted on AVF Reach 1 following pool construction. Establishment of coyote willows (Salix exigua) in 2002 was highly successful (Figure 3). Sedges, cattails and other riparian species, located in the few shallow pools that did exist on the reclaimed channel prior to pool creation, proliferated on the margins of the pools. The mine's riparian seed mix was also planted along the reclaimed stream channel. It is anticipated that improved vegetation along the AVF Reach 1 channel following pool construction will aid in reducing dissolved contaminant levels due to improved nutrient cycling.

Finally, in the first quarter of 2002, following pool and counter-weir construction, it was noticed that boron levels spiked at wells SP-4-NA and SP-10-NA. This is probably due to flushing of boron from the unsaturated zone due to increased infiltration from the pools. Boron concentrations have moderated in later samples from 2002. The charts of boron concentrations at wells SP-2-NA, SP-4-NA, and SP-10-NA were very similar until 2002, with a large spike in early 1992 followed by a decline (Figure 7). The large spike in boron concentrations at SP-4-NA and SP-10-NA in 2002 was probably not recorded at SP-2-NA because water had previously pooled near to SP-2-NA and SP-3-NA. Construction of pools and counter-weirs caused the surface water levels to rise in Porcupine Creek. Boron levels at SP-3-NA, located in the center of the channel, spiked in 1987 and have since declined with some fluctuation.

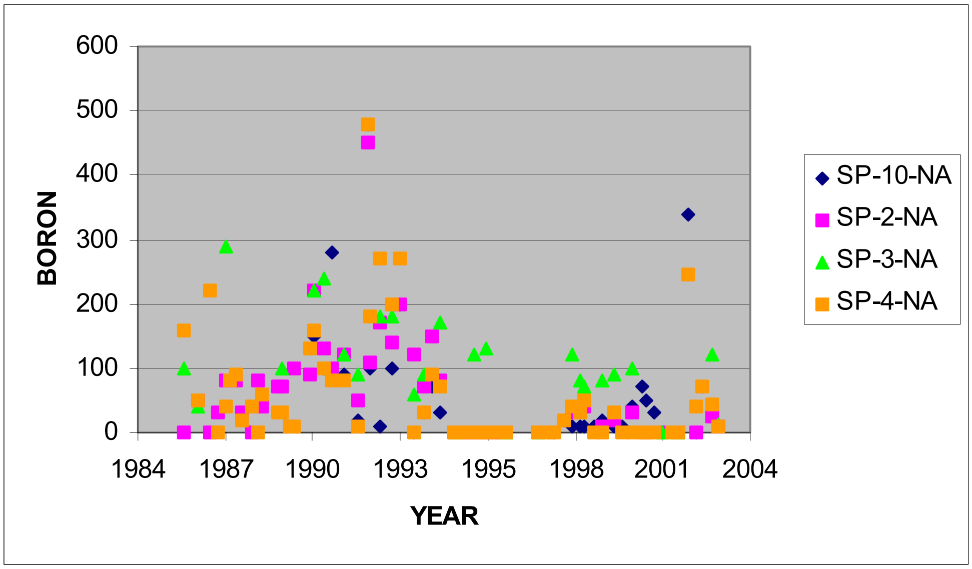


**Figure 7: Boron Levels (µg/l) in AVF Reach 1.**

## Conclusion

High TDS and selenium concentrations in the original reclaimed alluvial aquifer (AVF Reach 1) of Porcupine Creek at the North Antelope Rochelle Mine have been a cause of concern since this channel section was reclaimed in the mid 1980's. AVF Reach 1 was constructed with native alluvial material and with a guide channel that limited pooling and infiltration of water. Topsoil placed on the channel severely limited infiltration. A newer alluvial channel (AVF Reach 2), constructed using selected overburden material and utilizing constructed pool and counter-weirs, has much lower dissolved solids and selenium concentrations. Prior to 2002, the ground water quality of AVF Reach 1 was generally slowly improving with time, but most constituent concentrations remained high. Following the removal of a diversion (which bypassed AVF Reach 1) in January 2001, and construction of pools and counter-weirs for wetland replacement purposes in January 2002, significant alteration in the ground water geochemistry occurred. The results of water quality monitoring demonstrate a secondary benefit to constructing wetlands on reclaimed lands. Boron levels spiked upward, but have since decreased. Selenium levels have significantly decreased since April 2002.

The construction of the pools and counter-weirs has significantly raised ground water levels and subsurface flow in AVF Reach 1. It is expected that this will lead to greatly improved shortterm and long-term water quality in AVF Reach 1. Selenite is now being detected in significant concentrations in the reclaimed alluvial ground water, confirming that conditions are becoming more reducing and sorption of selenite on clays and other particles is probably removing selenium from solution. Sulfate-reducing bacteria have been detected in the AVF Reach 1 and backfill wells, but TDS concentrations in the sulfate-rich ground water have not changed significantly in recent years. However, the new more saturated environment may allow sulfate reduction to occur. Pool construction has also allowed for enhanced postmining vegetation establishment along the reclaimed channel, which is anticipated to decrease contaminant concentrations due to improved nutrient cycling.

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## References

Balistrieri, L.S., and Chao, T.T. 1987. Selenium adsorption by goethite. Soil Sci. Soc. Am. J. Vol. 51, 1145-1151. http://dx.doi.org/10.2136/sssaj1987.03615995005100050009x

Caballo Coal Company. 1985. Predicted post-mining ground-water quality and existing backfill water quality at the Caballo Mine. WDEQ/LQD permit 433.

Clark, D.W. 1995. Geochemical Processes in Ground Water Resulting from Surface Mining at the Big Sky and West Decker Mine Areas, Southeastern Montana. U.S. Geological Survey Water-Resources Investigations Report 95-4097. 80p.

Dreher, G.B. and Finkelman, R.B. 1992. Selenium mobilization in a surface coal mine, Powder River Basin, Wyoming, U.S.A., Environ Geol Water Sci, Vol. 19, No. 3, 155-167. http://dx.doi.org/10.1007/BF01704083

Hansen, B.W. and Murphree, P.A. 2002. Reclaiming for Wildlife: Habitat Conservation at the North Antelope / Rochelle Complex. Award submittal for Mine Reclamation and Wildlife Stewardship Award: Wyoming Hunting and Fishing Heritage Exposition, 2002.

Leutwein, F. 1978. Selenium, in K.H. Wedepohl, ed., Handbook of Geochemistry, v II-3, Chapter 34, Sections B-O. Berlin, Springer-Verlag.

Murphree, P.A. 2003. Utilization of Coal Bed Methane Produced Water at the North Antelope Rochelle Mine, Campbell County, Wyoming. Presentation to the 2003 National Meeting of the American Society of Mining and Reclamation and The 9th Billings Land Reclamation Symposium, Billings MT, June 3-6, 2003. ASMR, Lexington, KY.

Naftz, D.L and Rice, J.A.. 1989. Geochemical processes controlling selenium in ground water after mining, Powder River Basin, Wyoming, U.S.A. Applied Geochemistry, Vol. 4, 565-575 http://dx.doi.org/10.1016/0883-2927(89)90067-X

See, R.B., Reddy, K.J., Vance, G.F., and Fadlemawla, A.A. 1993. Semi-Annual Report #4: The role of natural organic solutes in the mobility of selenium in coal mine backfill-ground-water systems. Submission to the Abandoned Coal Mine Land Research Program. May 1993. Office of Research, University of Wyoming.

U.S. Department of Commerce. 1969. Climatography of the United States No. 20-48. Climatological Summaries. Environmental Science Services Administration, Washington D.C.

WWC (Western Water Consultants). 1998. AVF Studies within and adjacent to the Powder River LBA tract. Prepared for Powder River Coal Company as part of the North Antelope Rochelle 569-T5 permit.