EFFECT OF COALBED METHANE PRODUCED WATER DISCHARGE ON NATIVE AND RECLAIMED STREAM CHANNELS AND AQUIFERS AT COAL MINES IN THE POWDER RIVER BASIN. CAMPBELL COUNTY, WYOMING[1]

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Abstract. Production of coalbed methane has released large amounts of ground water to native stream channels in the eastern Powder River Basin in the vicinity of the largest coal mines in the United States. Water is pumped from coalbed methane wells to relieve pressure in the coal seam and release methane gas from the seam into the well. Rapid drawdown of water levels in the coal due to coalbed methane production has been observed in mine monitoring wells. Optimally for methane production, water levels in the coal are kept near the top of the coal seam. Following a number of years of water production from coalbed methane wells, water levels in the coal aquifer decline to below optimal levels and pumping ceases. Discharge of coalbed methane produced water has rendered normally ephemeral and intermittent streams temporarily perennial and produced short and long term effects to surface and alluvial water quality. Through diversion or pumping, coalbed methane produced water has also flowed through reclaimed stream channels and temporarily changed the character of the channels. Within the mine sites, coalbed methane produced water has aided dust suppression efforts and reduced the need for pumping from deep water supply wells. Salts have been dissolved from native stream channels and often deposited on mine haul roads through road watering. Produced water flowing in reclaimed stream channels has aided wetlands establishment efforts, raised backfill water levels, and helped to enable pronounced changes in ground water quality.

Additional Key Words: Coalbed Methane, Geochemistry, Reclamation, Wetlands, Alluvial Valley Floors, Selenium, Dust Suppression.

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Introduction

Although production of coalbed methane in Campbell County, Wyoming, began in the late 1980's, large scale commercial production began in the county in the late 1990's. Large scale coalbed methane production began north of Gillette and has progressed south towards Converse County (Fig. 1). Wells are generally constructed at a density of eight wells per section, although some earlier projects were drilled at sixteen wells per section. Potentially, 89,000 coalbed methane wells may be constructed in the Wyoming portion of the Powder River Basin. Pipeline capacity and permitting difficulties have delayed the construction of many coalbed methane wells.

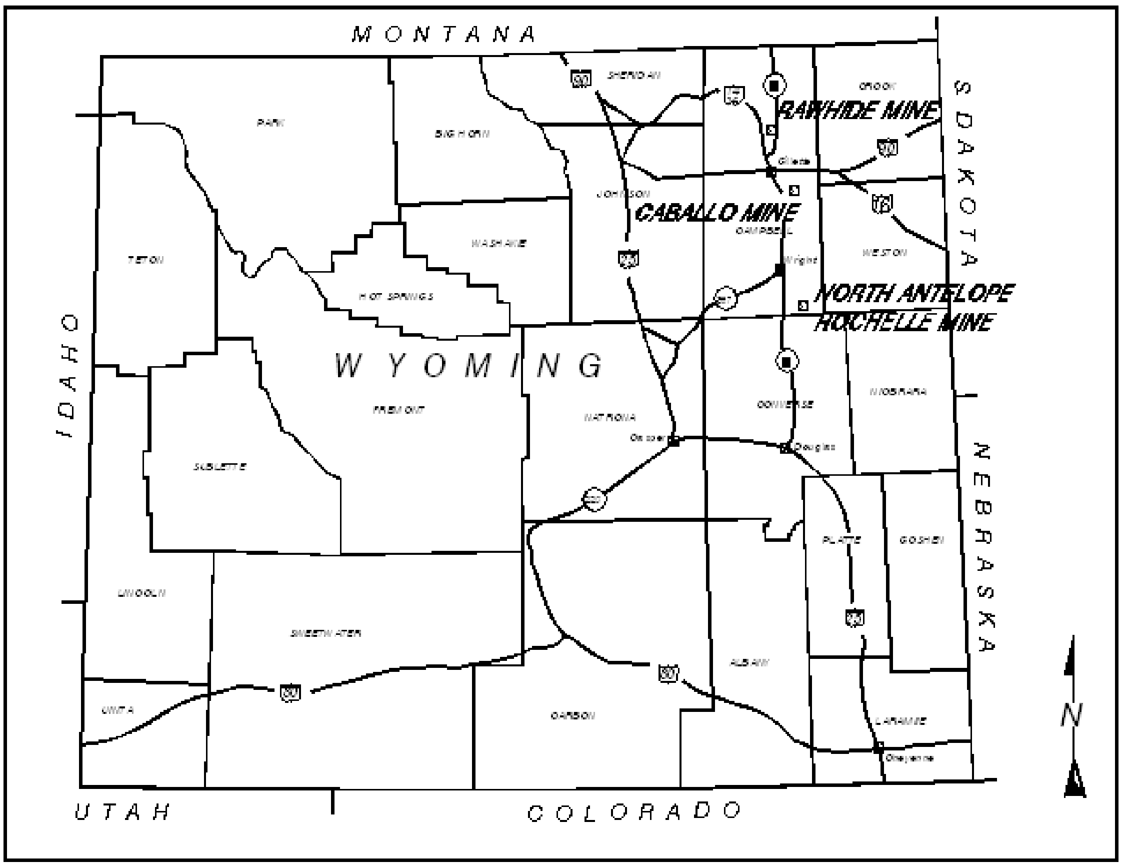

Figure 1: Location of Powder River Coal LLC Mines in Campbell County, Wyoming.

Due to the relatively shallow depth of the coal seams, the availability of large power distribution systems and the need to recover methane from seams before it escapes to the mine pits, the first large coalbed methane projects in the Powder River Basin began near the large coal mines in Campbell County. Approximately 32 percent of United States coal production comes from the thirteen operating mines in Campbell County. Based on federal court decisions, the rights to recover coalbed methane belong to the oil and gas lease holder and not to the coal lease holder. The Bureau of Land Management has generally followed the leasehold concept of first in time, first in right. This has occasionally placed coalbed methane producers in conflict with mining companies and necessitated cooperation to ensure maximum recovery of resources.

A typical coalbed methane well is sealed through the overburden and open in the producing coal seam as shown on Fig. 2. Often, the coal seam is under-reamed enlarging the size of void and perhaps open natural fractures in the coal to enhance gas production. The pump is placed near the bottom of the coal seam and water is pumped out to relieve confining pressure on the gas. The gas is then collected at the surface. In some wells, suction devices are used to enhance gas recovery. When the coal becomes hydraulically unconfined, gas may escape to another portion of the coal seam and oxygen may enter the coal seam causing wells to be shut down for safety or economic reasons. Although coalbed methane producers attempt to maintain water levels near the top of the coal seam, water levels in most coalbed methane wells will eventually become unconfined as the 1-2 degree dip of the coal seam and water production by adjacent coalbed methane producers will cause static water levels to fall below the top of coal.

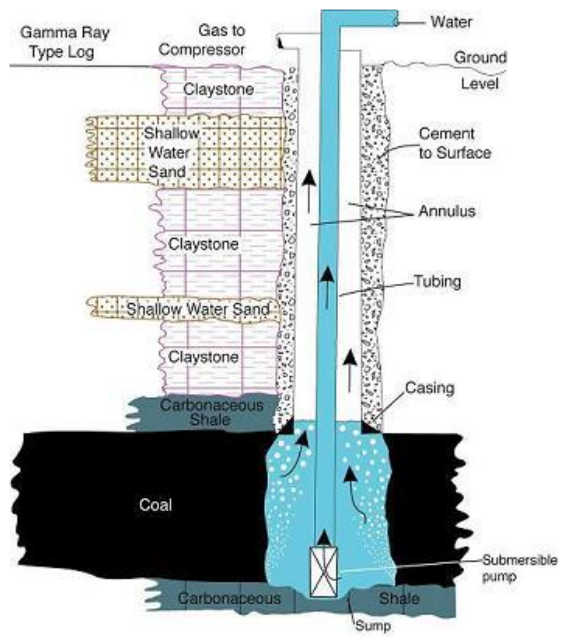

Figure 2: Typical Design of Coalbed Methane Well (Wyoming State Engineers Office).

Discharge of coalbed methane produced water has rendered normally ephemeral and intermittent streams temporarily perennial and changed the surface water quality of the streams and in some cases, changed the ground water quality of the alluvium. Most of the changes to the native areas will be temporary and will not last longer than produced water flows in the channel. Other changes will probably be long lasting and it will take many years before conditions return to the pre-coalbed methane condition, if at all. Through diversion or pumping, coalbed methane produced water often enters reclaimed areas at the mines, where it may flow through reclaimed stream channels or be held for use in dust suppression operations. Within the mine sites, coalbed methane produced water has aided dust suppression efforts and reduced the need to pump from deep water supply wells. Produced water flowing in reclaimed stream channels has been used to help establish wetlands, raise backfill water levels, and has helped enable pronounced changes in ground water quality. In most situations, in the vicinity of the mines, coalbed methane produced water flowing in native and reclaimed stream channels and aquifers has resulted in water quality improvement. However, in areas where generally good water quality was observed prior to coalbed methane production, water quality may have been degraded.

Powder River Coal LLC (PRC) operates three large surface mines in the Powder River Basin: the Rawhide Mine, producing 16.3 million metric tons of coal in 2006 and located 10 km north of Gillette; the Caballo Mine, producing 30.8 million metric tons in 2006 and located 20 km south of Gillette; and the North Antelope Rochelle Mine (NARM), producing 78.0 million metric tons in 2006 and located approximately 100 km south of Gillette. The mines are located on the eastern flank of the Powder River Basin. The topography is generally flat with most surface drainages flowing into ephemeral streams. The three Powder River Coal mine sites are very different, but generally, four landforms exist in the permit areas. Well-developed soils occur on upland tablelands. Highly erosive badlands are located in areas of head-cutting between uplands and major stream channels. The most conspicuous landforms in the permit areas are erosion resistant clinker (porcelainite) hills. Lastly, sheet-wash 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 hills with slopes of generally less than 5H:1V. Most of the stream channels in the permit areas are ephemeral, but some of the larger stream channels downstream of the mined areas are intermittent. Each of the PRC mines has at least one Alluvial Valley Floor (AVF), which are defined as stream channels with significant areas of flood irrigated or sub-irrigated stream-laid deposits, and special reclamation plans are in place to replace the AVF's that are mined.

The climate of the Powder River Basin 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, with 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 areas ranges from 1,265 to 1,525 m a.m.s.l. Mean annual precipitation ranges from 25 to 40 cm with most precipitation occurring as scattered thunderstorms during the late spring or early summer. Predicted annual evapotranspiration is nearly 58 cm (U.S. Dep't Commerce, 1969). Since 1999, the Powder River Basin has been in a severe drought, with the area south of Gillette being drier than the area to the north. In Campbell County, the period of intensive coalbed methane production has coincided with the drought. In many places, this resulted in the contrasting situation of unusually dry uplands and normally ephemeral stream channels with perennial or nearly perennial flow.

This paper discusses the effect of coalbed methane produced water on native and reclaimed stream channels and aquifers at two large coal mines in the Powder River Basin, as well as water quality prior to and following the discharge of coalbed methane produced water. The paper primarily discusses the North Antelope Rochelle Mine, but also includes discussions of the Caballo Mine. The use of coalbed methane produced water at the mines is also discussed.

Coalbed Methane Produced Water Effect on Aquifers and Stream Channels

Due to high gas pressure caused by dewatering of the coal seam, mine monitoring wells located in areas of coalbed methane development must often be plugged for safety reasons. One monitoring well at the North Antelope Rochelle Mine (NARM) drilled near a coalbed methane field blew water approximately 6 m above the well following completion and blew bentonite chips from the hole during plugging. In the first stage of pumping from a coalbed methane well (CBM), the discharge rate and drawdown are high, but these decline with time before water production is stopped. Production rates in fractured coal may be as high as 6 L/sec, but in most coal seams are closer to 1 L/sec. Besides the main coal seams, withdrawal of water for CBM production also affects the underlying units (underburden) of the Fort Union Formation. Drawdown of the underburden, which has been observed in a number of wells at NARM and Caballo and is generally not observed during the 6 to 24 hour pump tests run on adjacent coal and underburden monitoring wells by the mines, is probably most prominent where sands in the underburden abut the coal. Figure 3 shows the drawdown in the adjacent coal well PRCC-25A and underburden well PRCC-25D, which are located in a CBM field west of NARM. Production in the field began in mid-2003. Prior to plugging of both PRCC-25A and PRCC-25D in mid-2005, the latter because the casing cracked within the coal, over 50 m of drawdown was recorded in the wells. While coalbed methane wells should have a limited effect on water levels in the overburden because they are sealed in the overburden and confining layers in the overburden, there is some evidence from older CBM fields near Gillette that drainage to the underlying dewatered coal is slowly taking place (Kristiansen, Pers. Comm. 2005). Delayed drainage of the overburden has not yet been definitely observed at the PRC mines. Most stock wells near NARM are completed in the overburden or deep underburden and CBM production has not affected stock wells.

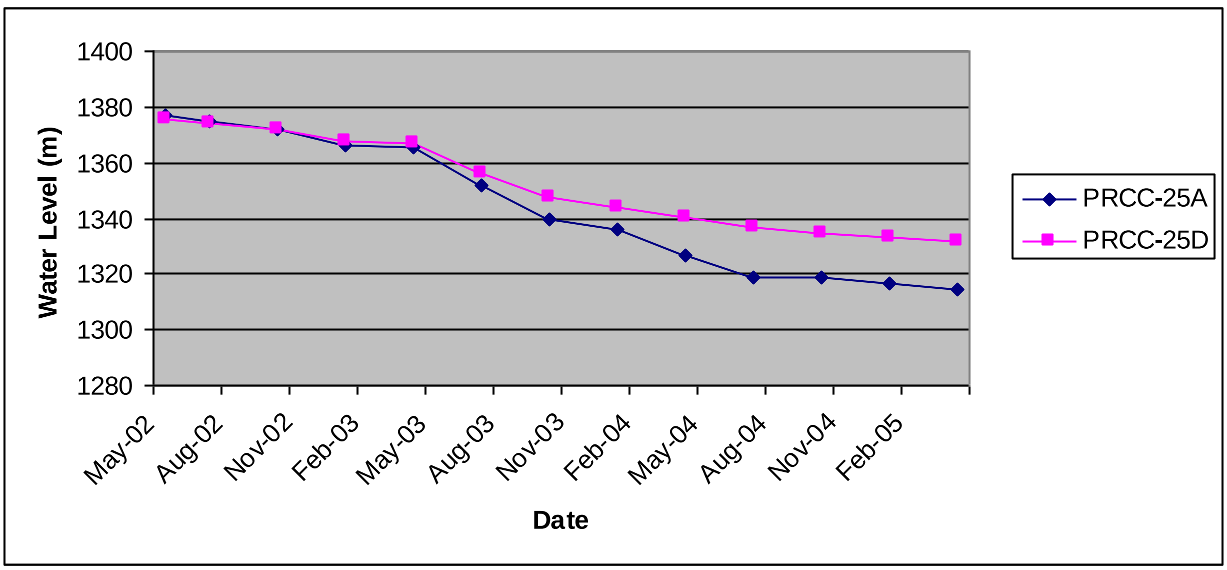

Figure 3: Water Level Elevation in Coal Well PRCC-25A and Under-burden Well PRCC-25D

When coalbed methane operations are proposed, estimates of water production from the projects are often given as a worst case basis. When the first large CBM project was proposed at the Caballo Mine, the estimates of water production were in excess of the mine's ability to convey the water around its operations and still maintain capacity for flood control in its reservoirs. An agreement was then negotiated with the CBM producer to pump water to a major stream channel east of the mine through a new pipeline. However, experience has shown us, as it did at Caballo, that CBM projects rarely proceed exactly as planned due to problems with infrastructure, permitting, land acquisition, or other concerns. Water production does not begin in all of the wells at the same time and declines in one set of wells as pumping from the newer wells is initiated. Eventually, it is expected that nearly 500 coalbed methane wells will be drilled in the Porcupine Creek drainage upstream of NARM. It is difficult to estimate the amount of water that these new CBM wells will produce and the amount of water from these wells that will reach the mine. Upstream storage for livestock use and/or irrigation may also consume some water as will seepage into alluvial and overburden aquifers. It is hoped that the construction period of the additional CBM wells will be long since that will reduce the expected flow rate to manageable levels and prolong the period in which produced water is available to the mine.

Porcupine Creek is the main stream flowing through the North Antelope Rochelle Mine. Porcupine Creek is tributary to Antelope Creek, which is tributary to the Cheyenne River. NARM maintains upstream and downstream gauging stations on Porcupine Creek. Generally, prior to CBM production, there was very little flow recorded upstream of the mine, due to the large number of stock ponds on upper Porcupine Creek and the sandy surface soils of the upstream tributaries. Despite a contributing drainage area of 248 km^2, an average of only 12,000 m^3 passed through the mine's upstream gauging station annually, prior to the onset of CBM produced water flow. Surface water quality was variable depending on flow, but was usually poor due to the amount of evapotranspiration taking place in the alluvium and pooled water, and the lack of flushing events.

GS-1 is the name given to NARM's upstream gauging station on Porcupine Creek. GS-1 has been operated since 1982, but it has been moved upstream as new leases are added to the mine and it has been at its current location since 1998. Flow of CBM produced water at GS-1 first occurred in January 2003. Since 2003, not only is base flow much greater at GS-1, but runoff events are more often observed at the station as the numerous pools in the Porcupine Creek channel are now full of water. Whereas flow was observed at GS-1 only following large runoff events prior to the onset of CBM produced water, Porcupine Creek at GS-1 has been perennial in all but the late summer months since produced water flow began. During the late summer, alluvial uptake and evapotranspiration as well as the upstream ranchers use of water for livestock appears to consume more water than is produced. During the summer, much water also remains in upstream reservoirs. Figure 4 shows typical views of pools on Porcupine Creek in 2001 and 2006. Figure 5 displays the flow observed at site GS-1. Total dissolves solids are shown on Fig. 6.

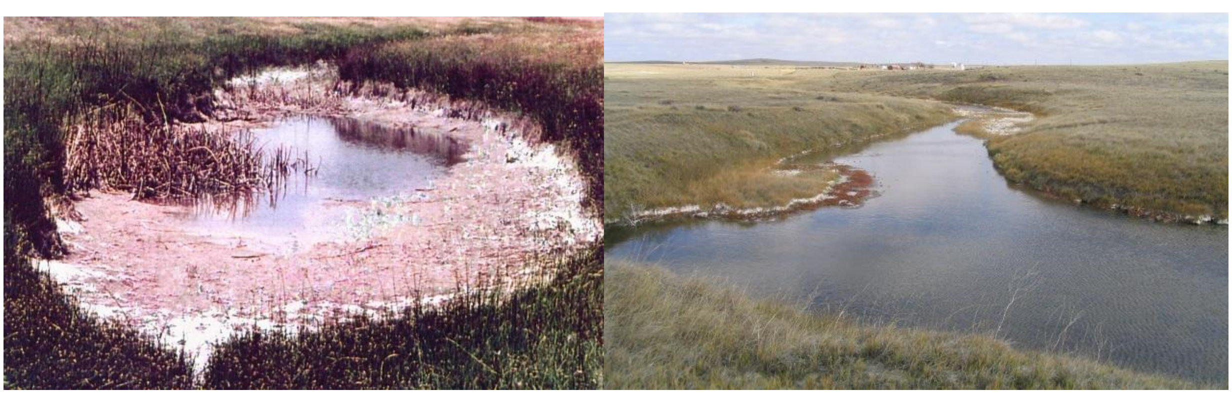

Figure 4: Typical Views of Porcupine Creek Upstream of the North Antelope Rochelle Mine in 2001 (Left) and 2006 (Right) (2001 Photo, M. Evers)

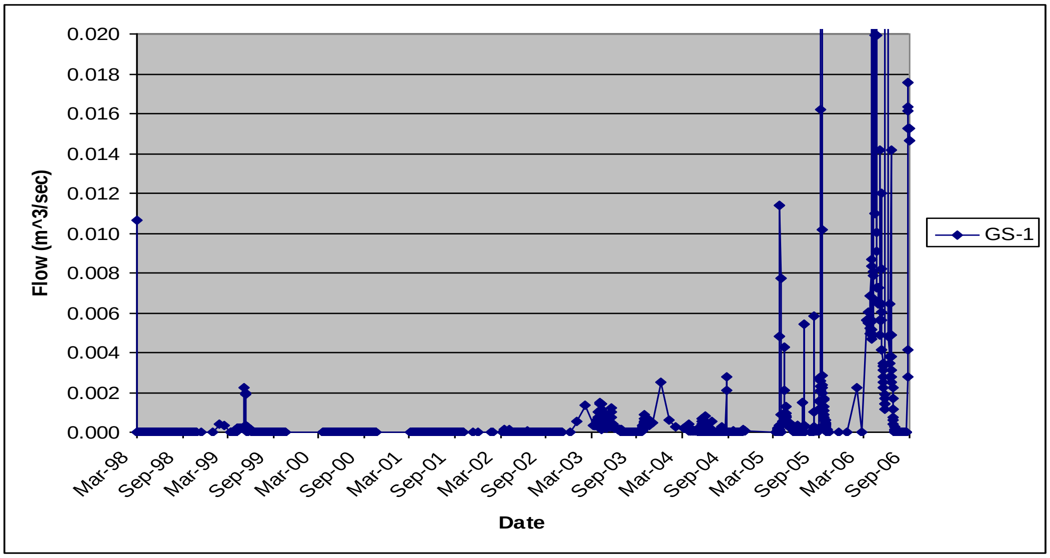

Figure 5: Mean Daily Flow at NARM Gauging Station GS-1

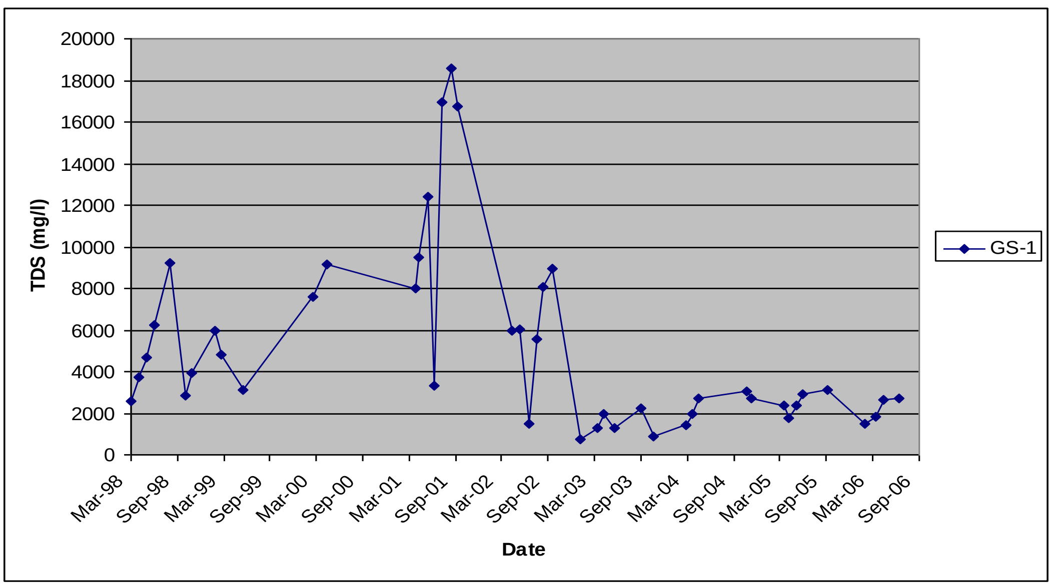

Figure 6: TDS Concentrations at NARM Gauging Station GS-1

Due to its surrounding lithology, low flow, and high evapotranspiration rate, the water quality of Porcupine Creek upstream of NARM has typically been poor. With a total dissolved solids (TDS) concentration over 3,000 mg/l, the water in Porcupine Creek frequently would not meet Wyoming Department of Environmental Quality standards for livestock use. During the first few weeks of produced water flow on Porcupine Creek, a large amount of saline foam derived from the salts in the normally dry stream bed passed through GS-1. As discussed in the section on utilization of CBM produced water, most of these salts probably ended up in water supply reservoirs at NARM and were placed on haul roads during dust suppression operations.

Prior to the flow of CBM produced water, TDS concentrations in the Porcupine Creek surface water fluctuated greatly, but frequently exceeded 8,000 mg/l (Fig. 6). The average TDS of the coal aquifer upstream of NARM is approximately 1,200 mg/l. Following the arrival of produced water, TDS concentrations have typically been below 3,000 mg/l and have been of a more consistent quality. Declines in other major cation and anion concentrations at GS-1 have mirrored the decline in TDS. Prior to 2003, the water at GS-1 was of a mixed calcium-magnesium-sodium sulfate type, but since 2003, the water at GS-1 has typically been of a sodium sulfate type. Prior to 2003, the SAR at GS-1 ranged from 4.3 to 27.7, but since 2003, the SAR has ranged from 3.0 to 12.1.

To date at NARM's lower Porcupine Creek gauging station, little CBM derived flow has been recorded and the water is indistinguishable from the treated pit water that NARM pumped for years from the mine site. Thus, the effect of CBM operations has been negligible downstream of the mine site.

Where the typical surface water quality in major stream channels is good, as in the stream channels at the Caballo Mine, the effect of CBM produced water on the water quality is less noticeable. At Caballo, the TDS of the coal aquifer and the stream water are similar. Although the produced water is generally of a sodium-bicarbonate type and the stream water typically of a calcium-sulfate type, with sufficient residence time in the channel, the produced water acquires many of the characteristics of the natural stream water. A similar effect is observed at Porcupine Creek as evidenced by the general rise of the TDS concentrations of flows at GS-1 since 2003 as active CBM produced water production moves upstream and water production at wells closer to GS-1 is shut off.

In order to determine the effect of coalbed methane produced water discharge on the alluvial aquifer of native Porcupine Creek, samples were taken in October 2006 from seven alluvial wells located along Porcupine Creek upstream of the mine (Fig. 7). The wells were originally drilled for an alluvial valley floor study, and pump testing and sampling were conducted soon after the wells were drilled in 1996. The sampling in 1996 was conducted using a short suite of parameters with no trace metals analyses. The 2006 sampling was conducted using a full suite of parameters. All sampling was conducted using Wyoming Department of Environmental Quality standards. Within the area where the wells are located, the active channel of Porcupine Creek flows through a playa where well AW-76 is located. CBM produced water flow has caused a significant increase in the alluvial water levels along Porcupine Creek. The photo date for Fig. 7 is August 2003 and CBM produced water had been flowing in the active Porcupine Creek channel since January 2003. In 2006, some CBM related flow was being pumped into the abandoned channel of the creek where well AW-75 is located. White areas on the photo show salt deposits on the surface. Upstream and downstream of the abandoned playa through which the active channel of Porcupine Creek flows, the channel of the creek is deeply incised. A large flood control reservoir operated by the mine is located in the right-center of the photo, but the slide gate on this reservoir is left partially open to allow CBM produced water to pass, but retard large runoff events. The alluvial wells were completed to the base of the alluvium where the contact with the overburden was clear and approximately 20 feet in other locations. The alluvial material ranges from fine grained clays and silts to coarse grained sands and gravels derived from mountainous areas far to the west.

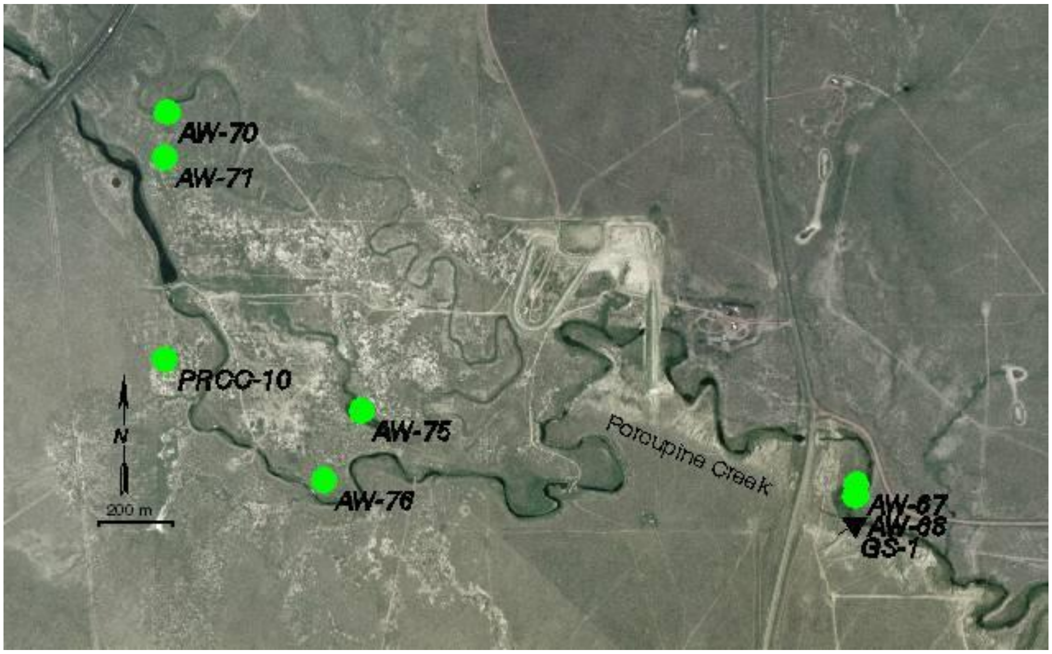

Figure 7: Location of Alluvial Wells and GS-1 Stream Gauging Station on Upper Porcupine Creek Upstream of NARM. Photo Date is August 2003.

Prior to the onset of CBM produced water on Porcupine Creek the alluvial wells shown on Fig. 7 were characterized as having water of a sodium-sulfate type or sodium-calcium-sulfate type with TDS concentrations ranging from 1,957 to 36,989 mg/l. During the October 2006 sampling, a number of significant chemical changes from the 1995 sampling were observed. In the upstream portion of Porcupine Creek shown on the photo, where Porcupine Creek flows through an incised channel and through a series of stock reservoirs, wells AW-70, AW-71, and PRCC-10 had the lowest pre-CBM TDS of the wells shown on Fig. 7. As shown on Table 1, wells AW-70 and PRCC-10 showed significant increase in TDS and well AW-71 showed an even greater increase in TDS. Well AW-70 is actually located on a tributary of Porcupine Creek that now receives CBM produced water. These increases in TDS are probably due to the dissolution of salts from near-surface sediments to the alluvium. Despite the CBM source water being of a sodium-bicarbonate nature, the sulfate concentrations of wells AW-70 and AW-71 rose sharply, while the bicarbonate concentrations in wells AW-70 and AW-71 decreased sharply. At PRCC-10, there was a slight increase in TDS and a slight decrease in both bicarbonate and sulfate concentrations. Chloride, which makes up a small component of the water in the Porcupine Creek alluvium, rose sharply in wells AW-70, AW-71, and PRCC-10. Calcium, Magnesium, and Sodium concentrations increased sharply at wells AW-70 and AW-71, while sodium concentrations rose a lesser amount at PRCC-10.

Table 1: Changes in Major Cation and Anion Concentrations in Upstream Porcupine Creek Alluvial Wells

Sample Date	Parameter	Units	Well Name						
			AW-67	AW-68	AW-70	AW-71	AW-75	AW-76	PRCC-10
Feb-1995	TDS	mg/l	4221	7418	1957	3738	10109	36989	2188
Nov-2006	TDS	mg/l	4453	7067	2367	5733	6661	47765	2429
Δ %	TDS	%	5.50%	-4.73%	20.95%	53.37%	-34.11%	29.13%	11.01%
Feb-1995	SO_4^{2-}	meq/l	57.73	96.10	22.85	45.52	130.94	496.81	30.67
Nov-2006	SO_4^{2-}	meq/l	58.92	94.66	30.42	76.26	90.41	734.05	29.08
Δ %	SO_4^{2}	%	2.06%	-1.50%	33.09%	67.53%	-30.95%	47.75%	-5.18%
Feb-1995	HCO_3^-	meq/l	0.54	10.16	6.79	10.70	36.97	15.85	3.72
Nov-2006	HCO_3^-	meq/l	5.90	9.80	3.70	4.61	5.10	12.61	2.61
Δ %	HCO_3	%	990.91%	-3.55%	-45.41%	-56.97%	-86.21%	-20.48%	-29.96%
Feb-1995	Cl^-	meq/l	0.85	1.16	0.21	0.48	1.63	2.28	0.37
Nov-2006	Cl^-	meq/l	1.01	1.41	0.36	1.01	1.30	2.08	0.45
Δ %	Cl^-	%	19.67%	21.07%	72.00%	111.76%	-20.52%	-8.77%	22.90%
Feb-1995	Na^+	meq/l	43.39	67.39	13.57	30.30	95.22	379.39	15.52
Nov-2006	Na^+	meq/l	39.93	62.65	17.30	40.75	59.70	521.30	16.33
Δ %	Na^+	%	-7.98%	-7.03%	27.50%	34.48%	-37.31%	37.41%	5.24%
Feb-1995	Ca^{2+}	meq/l	15.40	20.25	9.40	13.45	38.25	18.15	12.20
Nov-2006	Ca^{2+}	meq/l	19.32	27.44	11.56	22.17	22.54	26.30	11.61
Δ %	Ca^{2+}	%	25.42%	35.51%	22.93%	64.83%	-41.07%	44.88%	-4.84%
Feb-1995	Mg^{2+}	meq/l	3.70	21.89	3.95	10.21	25.10	118.52	4.69
Nov-2006	Mg^{2+}	meq/l	12.18	22.49	4.80	17.05	14.43	165.43	4.08
Δ %	Mg^{2+}	%	228.89%	2.74%	21.60%	67.10%	-42.52%	39.58%	-12.96%

The TDS concentration at wells AW-75 and AW-76 was 10,109 and 36,989 mg/l prior to the onset of CBM produced water flow. At well AW-75, which is located along the incised abandoned channel of Porcupine Creek, the TDS concentration declined sharply between 1995 and 2006 from 10,109 mg/l to 6,661 mg/l. There was also a large decrease in concentrations of other parameters at well AW-75 with bicarbonate dropping 86 percent. At well AW-76, located where Porcupine Creek flows through a former playa, the TDS rose sharply from 36,989 to 47,765 mg/l. At well AW-76, most major cations and anions increased between 1996 and 2006, but there was a slight decrease in the bicarbonate and chloride concentrations.

At wells AW-67 and AW-68 located where Porcupine Creek is confined to a narrow incised channel adjacent to gauging station GS-1, the TDS at the lower TDS well, AW-67, showed a slight increase in TDS while the TDS concentration at the higher TDS well, AW-68, showed a slight decrease. One difference between well AW-67 and the other wells is that the bicarbonate concentration at well AW-67 showed a large increase from a very low 33 mg/l to a moderate 360 mg/l, while the bicarbonate concentration at AW-68 declined from 620 to 598 mg/l. At both AW-67 and AW-68, the Ca and Mg concentrations increased and the Na concentrations both decreased.

In summary, while a study consisting of two sampling periods does not provide definitive evidence of the effect of CBM produced water on the water quality of the alluvium, there are a number of conclusions that can be drawn from the data from the wells shown on Fig. 7. Past sampling of alluvial wells at NARM has not shown a great difference in the water quality between different samples from the same well. Where Porcupine Creek flowed through an incised channel, the flow of CBM produced water through the formerly salt encrusted channel caused flushing of salts from the surface sediments and mixing of the alluvial waters resulting in a slight increase in the TDS of the lower TDS wells and a decrease in the higher TDS wells as observed at wells AW-67, AW-68, and AW-75. In general, despite the sodium-bicarbonate nature of the CBM produced water, the bicarbonate concentrations decreased slightly in all of the wells, except the well located where the channel was most incised. Where the active Porcupine Creek channel crossed the former playa and a significant amount of gypsum and other sulfate sediments lay in the upper sediments, the TDS at well AW-76 actually rose sharply from an already high concentration even though the surface water was much lower in dissolved solids. Where CBM produced water collected in a stock pond that rarely spilled prior to the onset of CBM production, TDS also increased in the alluvium due to flushing of salts from the surface sediments as at wells AW-70, AW-71, and PRCC-10.

At the Caballo Mine, one alluvial well (NC-0169-A) located near a CBM produced water discharge point and located in an incised channel did show a change from a strongly calcium-sulfate type of water to a more calcium-sulfate-bicarbonate type during the period of discharge. A later sample taken from NC-0169-A in 2005 after CBM water production ceased showed that the water had reverted to a calcium-sulfate type and other nearby and downstream alluvial wells did not show any definite change. Due to the potential of CBM produced water to dissolve salts from the stream channel and either transport those salts downstream or concentrate them in the alluvium, it is preferred that, when discharging to streams, CBM producers discharge their water to well defined major channels. This also limits erosion. However, as shown by the surface water sampling at GS-1 and the alluvial well sampling at NARM and Caballo, it will rarely be possible to place enough CBM water in the channel to flush the natural stream channels of the large amount of available salts near the surface or to dilute the alluvial ground water except very near an incised channel. Thus, in most cases, the effect of CBM produced water flow on water quality stream channels and alluvial aquifers will be short lived. Other changes to water quality due to produced water discharge may be longer lived. It may take many years for a similar amount of salts to be deposited on the surface of many large channels and where the amount of produced water is insufficient to maintain flow, salts may accumulate due to evapotranspiration.

During the 2006 alluvial well sampling, no selenium was detected. The selenium that is known to be in the Porcupine Creek alluvium is fixed in the sediments. In samples taken soon following resaturation of previously dry alluvium from Porcupine Creek, small amounts of Se have been detected. In the surface water sampling at GS-1, Se has only been detected immediately following runoff events, when the deeper pools may be flushed.

Utilization of Produced Water

A large percentage of the CBM produced water flow that reaches the North Antelope Rochelle Mine (NARM) has been used for dust suppression operations (Murphree, 2003(2)). Agreements have been negotiated with neighboring CBM producers to manage the water that they produce. Water produced from CBM operations must be discharged under all applicable state and federal permits. If more water is being produced from coalbed methane wells than the mine can process, other options for water discharge, including construction of upstream storage reservoirs, re-injection, or pumping around the mine, will have to be utilized by the CBM producers. Points of discharge are specified in the agreements between PRC and CBM producers. Wherever possible, discharges will be directly to major drainages to limit uptake of salts from soils and lessen erosion. A concern of many regulators, landowners, and environmental groups is that produced water flowing in Antelope Creek and the Cheyenne River downstream of the mine would deposit accumulated salts along the streams due to the limited produced water flow and degrade the potential for irrigation along the Cheyenne River. By using the water at the mine, NARM has lessened the potential for artificial alteration of the water quality in the downstream channels while providing a number of environmental and economic benefits to the mine.

Water used at NARM for dust suppression originates from a variety of sources, including deep water supply wells, pit pumping of ground water, and surface runoff. The mine formerly operated ahead-of-mining dewatering wells placed in the coal, but has replaced the coal dewatering wells with coalbed methane (CBM) wells as gas rights were acquired in the vicinity of the mine. A small number of overburden dewatering wells continue to be operated by the mine. Haulroad dust suppression, which may account for the use of up to 12,000 m^3 per day of water in summer, is the major use of water at NARM, followed by facilities wash-down, with potable water use comprising the remainder.

Prior to 2001, NARM utilized a diversion system for flood control and to route most storm water through the mine. However, operational concerns, including the limited reclamation that could be performed with the diversion in place, dictated removal of the diversion. Large reservoirs on the upstream drainages have now replaced the diversion for the purpose of flood control. A small sump located on Porcupine Creek is used to pump water from the creek to the reservoirs. The four largest of these flood control structures have been designed to contain the 100-year 24-hour runoff event. The additional capacity to temporarily hold and pump water produced from nearby coalbed methane operations was taken into account in the design of the structures. In addition, designed water supply reservoirs have been constructed on the mine backfill to hold water for dust suppression use. Between the fall and spring, water may be pumped into the water supply reservoirs for use during the summer. Since 2003, CBM produced water has provided approximately 20 percent of the total water supply at NARM. The use of coalbed methane water allows NARM to reduce the use of water from deep water supply wells, while at the same time, continuing to meet ever stricter air quality regulations and improve the quality of reclamation efforts. During 2003, use of CBM produced water pumped through the mine's flood control system resulted in a power savings of approximately 380,000 kilowatt-hours versus the amount that it would have taken to pump that water from deep water supply wells. As mentioned previously, the period of greatest CBM production coincided with a period of severe drought and there were few runoff events at NARM to supply water to the mine. In addition, water production from CBM wells removed much of the potential for pit water that would also have provided the mine with a portion of water supply.

The North Antelope Rochelle Mine has reduced its consumptive water use considerably through conservation efforts and recycling of facilities water. These efforts include recycling of facilities water for reuse or use in haulroad dust suppression, increased chemical dust suppressant use on haulroads, and improved water truck operation. Although water use will probably continue to increase due to lengthening of haulroad, mine expansion, and greater regulation of air quality, conservation of water will both increase the long-term viability of the mine and allow the mine to continue good relationships with its neighbors, some of whom hold senior water rights.

At the Caballo Mine, a limited amount of CBM produced water was used for dust suppression. Produced water flowing into the Caballo Mine passed through a large flood control structure, where the water could be diverted for haul road use. However, due to the smaller size of the mine and the greater amount of water normally available, the need for additional dust suppression water at Caballo was limited. At Caballo, much of the produced water was discharged from the mine site, after being mixed with similar pit water, to ephemeral and intermittent stream channels which normally displayed good water quality. During the course of its flow through Caballo, as at NARM, much of the produced water flowed into reclaimed stream channels in its course through the mine and was used to aid reclamation efforts. CBM produced water production has now mostly ceased at the Caballo Mine.

Although many CBM producers have constructed stock reservoirs to hold produced water for livestock use and infiltration in cooperation with landowners, these reservoirs typically hold produced water for only a short period of time, and often retard or retain runoff events that are important for maintenance of downstream wetlands and filling and flushing of stock reservoirs and natural pools on the stream channels. The United States Forest Service has been insisting on reservoirs to hold all CBM water produced from their lands. In addition, environmental groups and others have been encouraging reinjection of produced water to deeper aquifers. Reinjection wells often require a large amount of electricity to supply the pumps. In the western and central portions of the Powder River Basin (PRB), where the produced water may be very saline, the construction of reservoirs, reinjection wells, or treatment systems may make sense; but in the eastern PRB, the low salinity of the water and the close proximity of the mines to the CBM fields generally make direct discharge to the surface a preferred option for produced water for both economic and environmental reasons.

Use of Produced Water for Reclamation and Backfill Aquifer Recharge

In addition to improving the dust suppression capability at NARM and Caballo and reducing deep water supply well production, CBM produced water has been used to improve reclamation at the mines. At Caballo, produced water flowed through the reclaimed Tisdale Creek channel and helped in wetland establishment along the reclaimed channel and the permanent Avocet Reservoir (Fig. 8).

Figure 8: Avocet Reservoir on Reclaimed Tisdale Creek at Caballo Mine with Reconstructed Scoria Bluff and Trees with Protective Fencing (S. Storie, 2003).

At NARM, much of the CBM produced water flows through the reclaimed Porcupine Creek Alluvial Valley Floor (AVF) after being mixed with water from a variety of sources at the mine.

Water discharged from coalbed methane wells and used for dust control has also given NARM the flexibility to discharge water directly to the reclaimed stream channel that might otherwise be needed for dust suppression.

As required by the mine's permit from the Wyoming Department of Environmental Quality / Land Quality Division (WDEQ/LQD), the reclaimed Porcupine Creek channel is underlain by a 25 m wide by 3 m deep reconstructed fill of material containing at least 60 percent sand (Fig. 9). Approximately 3.7 km of Porcupine Creek have been reconstructed and the reclamation of the section declared as Alluvial Valley Floor is nearly complete. The upper section of the reclaimed Porcupine Creek (AVF Reach 2) was reconstructed using replacement alluvial material in 1999. Pools and counter-weirs were constructed on the channel in 1999 as well. Due to direct flow of water from the native Porcupine Creek through the Porcupine Creek Diversion for a short period, this area showed good development of wetland characteristics only a few years following reclamation. Alluvial water levels are still rising in AVF Reach 2, but the reclaimed alluvial water quality is generally good and is similar to the water quality in the overburden (TDS of 1200 to 2200 mg/l) from which the replacement alluvium and adjacent backfill originated. This is superior to the water quality in the alluvium of the native Porcupine Creek, where TDS often exceeded 3,000 mg/l. Surface water quality is also good since the source is primarily pit-water and surface runoff, with TDS concentrations at approximately 1,100 mg/l. Trace metal concentrations have not been a concern in this section.

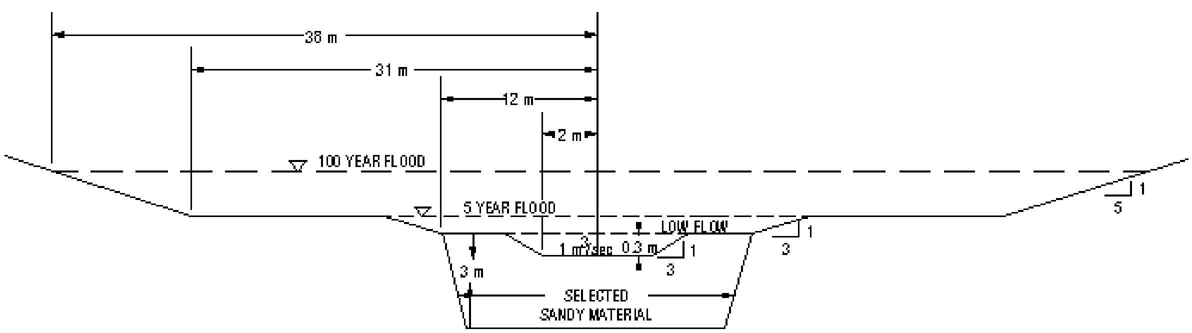

Figure 9: Typical Geometry of Reconstructed Porcupine Creek Alluvial Valley Floor

Although a lower section of Porcupine Creek (AVF Reach 1) was constructed in 1985 and 1986, a diversion bypassed the section until early-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 channelization and limited the amount of pooled water. In early-2002, the adjacent diversion was removed and pools and counter-weirs were constructed on the lower reclaimed Porcupine Creek (Fig. 10). Trees have been planted on the reclaimed channels and riparian vegetation along the channel is expected to improve as more water is available. If water is discharged from the mine to the native Porcupine Creek, it flows through this reclaimed channel.

Figure 10: CBM Produced Water Flowing through Pool and Counter-Weir Sequence on AVF Reach 1 with Caged Coyote Willow (Salix exigua) Plantings.

AVF Reach 1 was constructed from native alluvium as required by the WDEQ/LQD at the time. As reported in Murphree (2003 (1)), water quality in the four reclaimed alluvial wells in the lower channel has been poor. Premining alluvial wells located in the general vicinity of AVF Reach 1 showed generally poor water quality with TDS levels ranging from approximately 750 mg/l to 5,770 mg/l. However, alluvial wells in Porcupine Creek often show native water quality much worse than that reported above. Figure 11 shows the location of reclaimed alluvial wells SP-2-NA through SP-4-NA and SP-10-NA; and two deeper backfill wells SP-1-NA and SP-5-NA. When mixing and oxidation of the highly mineralized alluvial material occurred during mining and the material was placed in the reclaimed alluvial valley floor, the resulting water quality reflected the new mobility of the constituents. Although one shallow reclaimed alluvial well showing seasonal variations in water level has 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 5,500 to 12,250 mg/l (Fig. 12). TDS concentrations in and around AVF Reach 1 are shown on Figure 13. Since the diversion was removed, the TDS concentration of the higher TDS well SP-4-NA has declined, while the TDS concentration at the lower TDS well SP-2-NA has increased. Trace metal concentrations in AVF Reach 1 have fluctuated. Selenium concentrations have reached as high as 932 μg/l, but generally have ranged from 0 to 200 μg/l.

Following construction of the pools and counter-weirs on AVF Reach 1 in January 2002, reclaimed alluvial water levels have risen approximately 1 m. Selenium concentrations declined rapidly as shown on Fig. 13. In 2003, the maximum selenium concentration in AVF Reach 1 was 33 μg/l but shortly after, the channel dried, the sediments became oxidized, and Se concentrations in the upstream section of AVF Reach 1 at well SP-10-NA quickly rose. Since 2003, selenium concentrations at SP-10-NA have risen when the channel dries and have fallen when water is in the channel. Selenium concentrations at the reclaimed alluvial wells downstream have fluctuated slightly, but remain near the detection limit. Due to the drought and dewatering at a nearby coal hopper, the channel of AVF Reach 1 has rarely contained water for more than two months at a time since 2003.

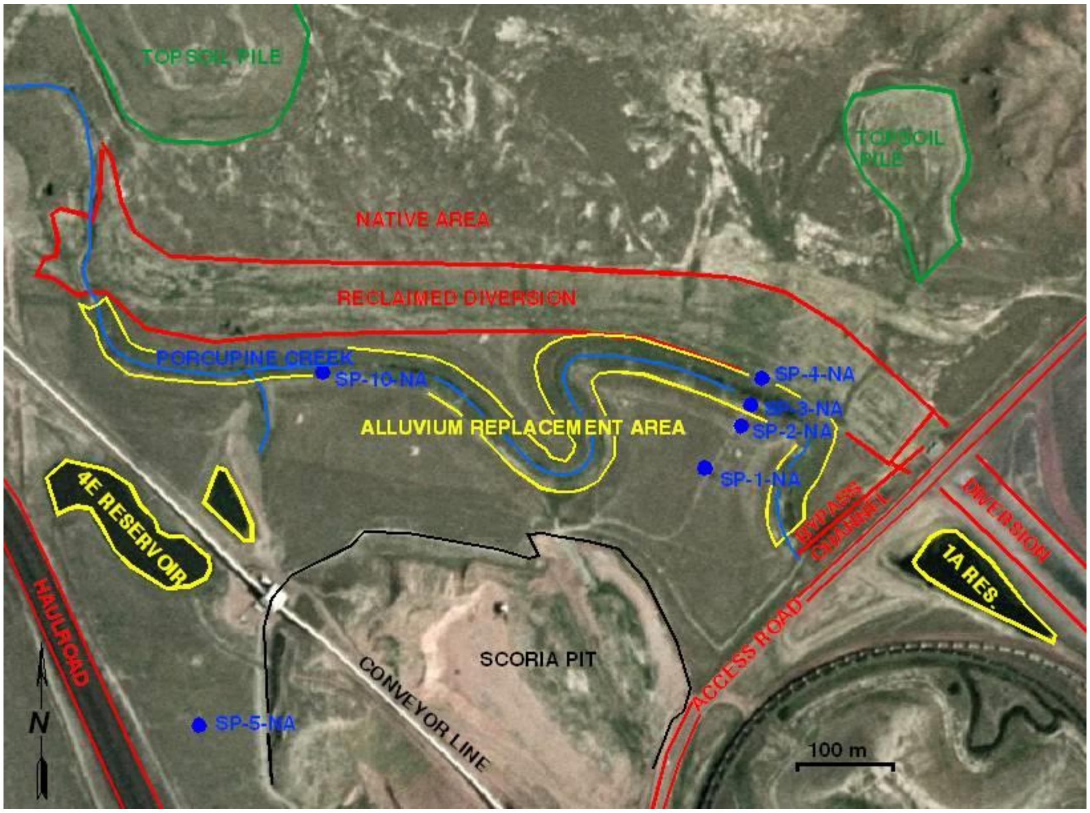

Figure 11: Location on Monitoring Wells on or near AVF Reach 1.

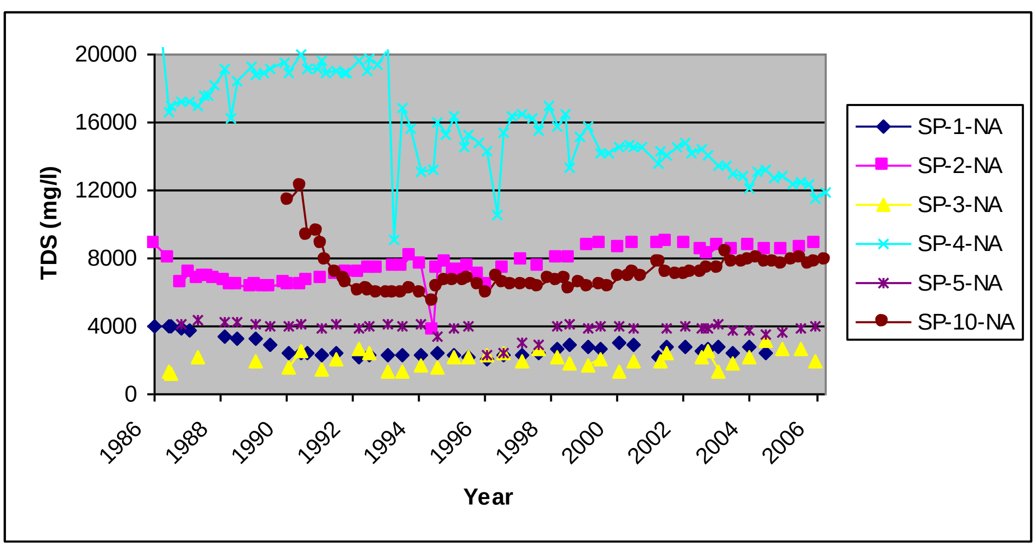

Figure 12: TDS Concentrations in Original Porcupine Creek AVF

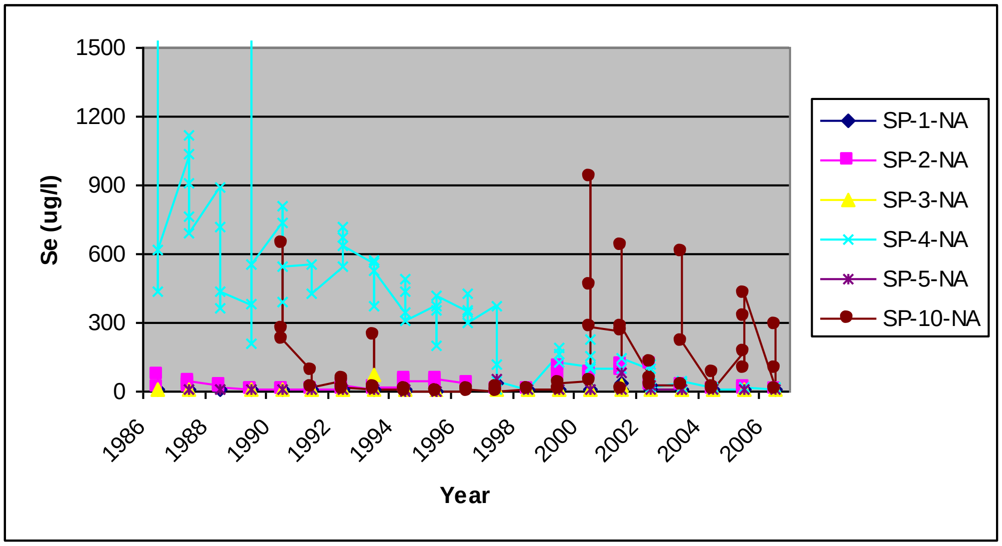

Figure 13: Se Concentrations in Original Porcupine Creek AVF

Current modeled estimates of water level recovery at North Antelope Rochelle show that it may take over 1,000 years for complete recovery to premining water levels in the coal due to the mine alone. Fifty percent of the water level recovery will take place in the first 200 years following mining. With the development of coalbed methane, these recovery estimates will increase significantly due to the large area of coalbed methane development and the great depth of coalbed methane wells towards the center of the Powder River Basin. Around the facilities areas, estimates of recovery to premining water levels are in the hundreds of years. However, seepage from water supply and sediment reservoirs on the mine backfill and water seeping into the backfill from the reclaimed alluvial aquifers and clinker has raised backfill water levels at NARM much faster than predicted by mine and area ground water models. Water levels near the facilities area near Porcupine Creek are near premining water levels approximately 20 years following mining. It is expected that water from coalbed methane operations being held in storage reservoirs or flowing through the mine for discharge or use in operations and reclamation use will similarly seep into the backfill aquifers. This will allow for more rapid than predicted recharge near the coal outcrop while farther west from the outcrop near the CBM fields, water level recovery may take longer than predicted by mine ground water models.

The post-mining land use at NARM will be rangeland grazing and wildlife habitat. Water stored in sediment and water supply reservoirs as well as in reclaimed stream channels already supplies water to abundant populations of deer and antelope as well as numerous bird species. The reclaimed Porcupine Creek supports two species of non-game fish, salamanders, one frog species, and numerous insects and invertebrates (Hansen and Murphree, 2002). The fish species, including Plains minnow (*Hybognathus placitus*) and Plains killifish (*Fundulus kansae*) have thrived in the produced water and Double-crested Cormorants (*Phalacrocorax auritus*) have been observed feeding on fish and salamanders in one of the mine's flood control impoundments. Tree farming has also been practiced along stream channels.

Release of Water from the Mine

Most flow downstream of NARM has been due to discharge of pumped water from the mine's facilities area. This flow has been significantly reduced since 1999 because the mine's water use has approached the volume of the mine's available water supply and recycling capacity. Water quality downstream of the mine is generally very good due to the amount of water pumped from the coal, clinker, and lower Fort Union aquifers and the amount of vegetation in the final mine impoundment. The mean TDS concentration since the mine began monitoring has been 1,644 mg/l and the mean SAR of the discharge is 3.23. Trace metal concentrations are very low. Downstream of the mine, at the confluence of Porcupine and Antelope Creeks, is the 407,000 m^3 Porcupine Reservoir, owned and operated by a local rancher. Flow to Antelope Creek below the reservoir has only been recorded once over the last ten years and this occurred following a storm event of greater than 100-yr 24-hr frequency on the east side of the mine.

Although it was once expected that some water would be discharged from Porcupine Reservoir into Antelope Creek due to mine discharges and the associated CBM produced water, because the drought has coincided with the peak of CBM production and the drought-caused drawdown in the alluvium of Porcupine Creek downstream of the mine, it does not appear that CBM produced water will reach Antelope Creek from Porcupine Creek. As mentioned previously, irrigators in the Cheyenne River drainage have raised concern that CBM discharges on Antelope Creek will remove salts from the stream sediments and deposit them downstream, and that the flows would detrimentally affect irrigation on the Cheyenne River. In the winter of 2002, NARM attempted to send water down Porcupine Creek to Porcupine Reservoir for the use of the rancher, but even at a rate of 50 l/sec, water did not reach the embankment of Porcupine Reservoir after two weeks of pumping. During the ongoing drought, precipitation has been less, temperatures have been higher, and drawdown of the alluvial water table has increased. Water quality at Porcupine Reservoir is monitored monthly by NARM. TDS concentrations at Porcupine Reservoir average 1,088 mg/l with the mean SAR being 3.0. Water quality in the Porcupine Creek alluvium downstream of the mine has actually improved since the opening of the mine due to dilution by mine discharges and uptake of solutes by the improved vegetation. Flows from Porcupine Creek to Antelope Creek should only take place during extremely large runoff events as they did prior to mining and detrimental water quality impacts to irrigators should not occur.

Conclusion

Production of coalbed methane has released a large amount of ground water to native stream channels in the eastern Powder River Basin in the vicinity of the largest coal mines in the United States. Water is pumped from coalbed methane wells to relieve pressure in the coal seam and release methane gas from the wells and rapid drawdown of water levels in the coal has been observed in mine monitoring wells. Optimally for methane production, water levels in the coal are kept near the top of the coal seam. Following a number of years of water production from coalbed methane wells, water levels in the coal aquifer decline to below optimal levels and pumping ceases. Although initial pumping rates from coalbed methane wells are high, pumping rates quickly decline. Near most coal mines in the eastern Powder River Basin, pumping of water from coalbed methane wells has either ceased or is on the decline.

The major period of coalbed methane production in the eastern Powder River Basin has coincided with an extended seven year drought and the discharge of coalbed methane produced water has rendered normally ephemeral and intermittent streams temporarily perennial. Accumulated salts in the stream channels and adjacent alluvium have been dissolved and transported downstream. The surface water quality of the streams has been changed and often improved by the discharge. In some cases the ground water quality of the alluvium has been changed, with solute concentrations in alluvial ground water rising or decreasing. Within the Powder River Coal, LLC mine sites, coalbed methane produced water has also been used to aid dust suppression efforts and to reduce pumping from deep water supply wells. Produced water flowing in reclaimed stream channels has aided wetlands establishment efforts, raised backfill water levels, and helped to enable pronounced changes in ground water quality. Although initial estimated pumping rates from many coalbed methane fields predicted flows that would threaten the flood control capacities of the mines, actual pumping rates have proven to be well below the flood carrying capacities. At the North Antelope Rochelle Mine, no coalbed methane produced water has been discharged to Antelope Creek, downstream of the mine, where landowners have been concerned that salts dissolved from upstream channels might be deposited on their lands by coalbed methane water. The use of coalbed methane produced water for dust suppression by mines has also resulted in salts from upstream ephemeral channels being deposited on haul roads where they will be stored in the backfill when reclamation is complete, and also has resulted in significant energy savings due to the resulting reduction in pumping from deep ground water wells.

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