APPENDIX B

Analysis of SAR Mixing

APPENDIX B
ANALYSIS OF SAR MIXING

This appendix addresses the estimation of sodium adsorption ratio (SAR) in rivers of the Powder River Basin after mixing with discharge of coal bed methane (CBM) produced water. The following sections provide (1) a summary of the analysis, (2) the definition of SAR, (3) an explanation of ideal mixing in a river, (4) an evaluation of the ambient SAR at the three stateline river stations (Powder River at Moorhead, Little Powder River above Dry Creek, and Tongue River at Stateline) and the SAR of CBM produced-water discharge, and (5) an analysis of mixing approaches for estimating SAR in the river after discharge of CBM produced water.

A.1. Summary and Conclusions

This analysis concludes that a simple mixing approach to estimating SAR in a river after mixing with CBM discharge provides an acceptable, reasonably conservative estimate of the mixed SAR. In this approach, SAR is treated as a constituent of water and mixed using a simple flow-weighted mass balance equation. The mixed SAR calculated using this approach over-predicts SAR by a consistently conservative average factor of about 1.6 for the Powder River Basin. This error is relatively insignificant when compared to the variability in the other parameters used in modeling impacts of CBM discharge on water quality . Therefore, this method of calculating SAR is appropriate for use in this EIS.

When site-specific, synoptic water quality data are available for a particular project, or when determining TMDLs, the resultant mixed water quality should be determined by mixing the individual constituents in the SAR formula –Ca, Mg, and Na.

A.2. Definition of SAR

Sodium adsorption ratio (SAR) is used as an index of the potential for irrigation water to lessen the permeability of a soil subject to swelling if sodium exchanges for calcium and magnesium in soil particles. SAR is calculated as:

$$SAR = \frac{[Na]}{\sqrt{\frac{[Ca]+[Mg]}{2}}} \qquad [1]$$

where [Na], [Ca], and [Mg] represent the concentrations of sodium, calcium, and magnesium, respectively, expressed in milliequivalents per liter (meq/L) (USDA, 1954).

A.3. Ideal Mixing

Estimation of SAR in a river after mixing with CBM discharge ideally is calculated using a flow-weighted mass balance model to estimate mixed concentrations of the individual constituents—Ca, Mg, and Na. If complete mixing is assumed, the mixed concentration of each constituent can be calculated as (US EPA, 1995):

$$C_{mix} = \frac{Q_{river}C_{river} + Q_{discharge}C_{discharge}}{Q_{river} + Q_{discharge}} \quad [2]$$

where

C_{mix}	=	concentration of constituent in the mixed zone,
Q_{river}	=	upstream (ambient) flow rate,
$Q_{discharge}$	=	discharge flow rate,
C_{river}	=	upstream (ambient) constituent concentration,
$C_{discharge}$	=	discharge constituent concentration,

This equation applies to any chemical constituent in the river and discharge that mixes conservatively (i.e., does not react upon mixing). Combining equations [1] and [2] yields the following equation for SAR mixing:

$$SAR_{mix} = \frac{\left\{\frac{(Q_{river} \times [Na]_{river}) + (Q_{CBM} \times [Na]_{CBM})}{(Q_{river} + Q_{CBM})}\right\}}{\sqrt{\frac{\left\{\frac{(Q_{river} \times Ca_{river}) + (Q_{CBM} \times Ca_{CBM})}{(Q_{river} + Q_{CBM})} + \frac{(Q_{river} \times Mg_{river}) + (Q_{CBM} \times Mg_{CBM})}{(Q_{river} + Q_{CBM})}\right\}}{2}}} \quad [3]$$

In order to ensure that a representative mixed value is calculated, the upstream river and discharge samples should have been collected synoptically (concurrent sampling of the water in each inflow that will ultimately mix at the confluence of the two flows). If synoptic data are not available, application of equation [3] implies estimating representative values of [Na], [Ca], and [Mg] for the upstream river water and the CBM discharge.

A.4. Ambient River SAR and CBM Produced WaterSAR

This section analyzes different methods of calculating measures of central tendency (mean or median) to represent ambient river SAR and CBM produced water SAR. The mean and median SAR values calculated from individual samples are compared to the SAR values estimated from the mean and median values of Ca, Mg, and Na concentrations in individual samples. Because of the square root in the SAR formula, calculation of a mean SAR from sample SARs is not strictly correct. It is nevertheless investigated in this analysis in order to evaluate the use of a simplified mixing model for SAR when synoptic water quality data are not available.

The data evaluated include data sets from three river stations (Powder River at Moorhead, Little Powder River above Dry Creek, and Tongue River at Stateline) as well as water quality data compiled for CBM produced-water discharge. The river data was obtained from the USGS NWIS database. The CBM data was obtained from a USGS study of the Powder River Basin (Rice et al., in press) and from data submitted to EPA by Fidelity for a UIC permit for the CX Ranch development.

Table A-1 and Figure A-1 compare the mean of sample SAR values to the SAR value estimated from mean values of Ca, Mg, and Na. As is shown in Table A-1 and Figure A-1, either way of estimating a representative SAR for the data yields equivalent results for the river station data. However, for the CBM data sets, estimating SAR from the mean values of Ca, Mg, and Na results in a significant under-prediction of the mean SAR value and, consequently from a regulatory standpoint, results in a less conservative and less acceptable estimate of SAR.

Table A-1
Comparison of (1) Mean Values of Sample SARs and
(2) SARs Estimated from Mean Values of Sample Ca, Mg, and Na Concentrations

	(1)				(2)		
	Mean SAR	Mean Ca (mg/L)	Mean Mg (mg/L)	Mean Na (mg/L)	CaMgNa SAR	Ratio (1)/(2)	Ratio (2)/(1)
Powder River at Moorhead, MT	**4.94**	119	59	262	**4.91**	1.01	0.99
Little Powder River above Dry Creek, WY	**6.24**	141	96	404	**6.43**	0.97	1.03
Tongue River at State line near Decker, MT	**0.68**	55	33	27	**0.71**	0.95	1.05
Powder River Basin CBM Discharge	**20.7**	29	14	391	**15.0**	1.38	0.72
CX Ranch CBM Discharge	**44.7**	11	11	553	**28.5**	1.57	0.64
Fort Union Coal	**14.5**	161	192	401	**5.1**	2.86	0.35

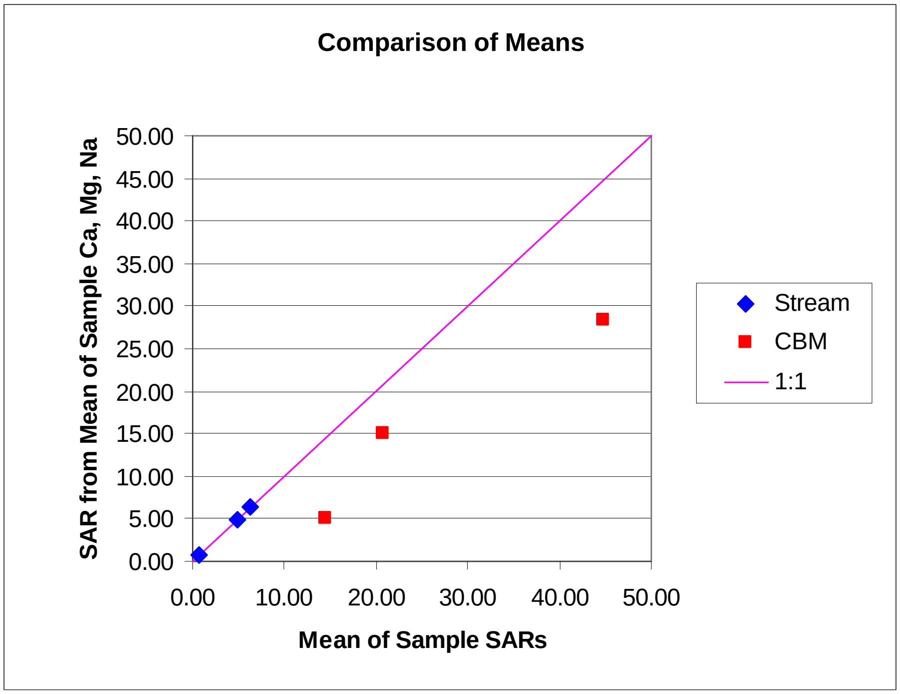

Figure A-1. Comparison of mean values of individual sample SARs and SARs estimated from mean values of sample Ca, Mg, and Na concentrations.

Similar information is presented in Table A-2 and Figure A-2 using median rather than mean values. For data from the river stations, either way of estimating a representative SAR yields equivalent results. This is the same result as was found when using mean values. For the CBM data sets, however, SAR estimated from the median values of Ca, Mg, and Na appears to over-predict SAR. The over-prediction in these examples is not as large as the under-prediction that results from using mean values as shown in Table A-1 and Figure A-1. From a regulatory standpoint, reasonable over-prediction is acceptable and, consequently, either method of calculating SAR using median values yields an acceptable estimate.

Table A-2
Comparison of (1) Median Values of Sample SARs and
(2) SARs Estimated from Median Values of Sample Ca, Mg, and Na Concentrations

	(1) Median SAR	Median Ca (mg/L)	Median Mg (mg/L)	Median Na (mg/L)	(2) CaMgNa SAR	Ratio (1)/(2)	Ratio (2)/(1)
Powder River at Moorhead, MT	**4.94**	120	56	267	**5.05**	0.98	1.02
Little Powder River above Dry Creek, WY	**6.61**	150	108	438	**6.66**	0.99	1.01
Tongue River at State line near Decker, MT	**0.66**	59	36	26	**0.66**	1.00	1.00
Powder River Basin CBM Discharge	**11.5**	26	13	353	**14.1**	0.81	1.23
CX Ranch CBM Discharge	**47.5**	6	2	549	**47.9**	0.99	1.01
Fort Union Coal	**4.6**	109	102	329	**5.4**	0.85	1.18

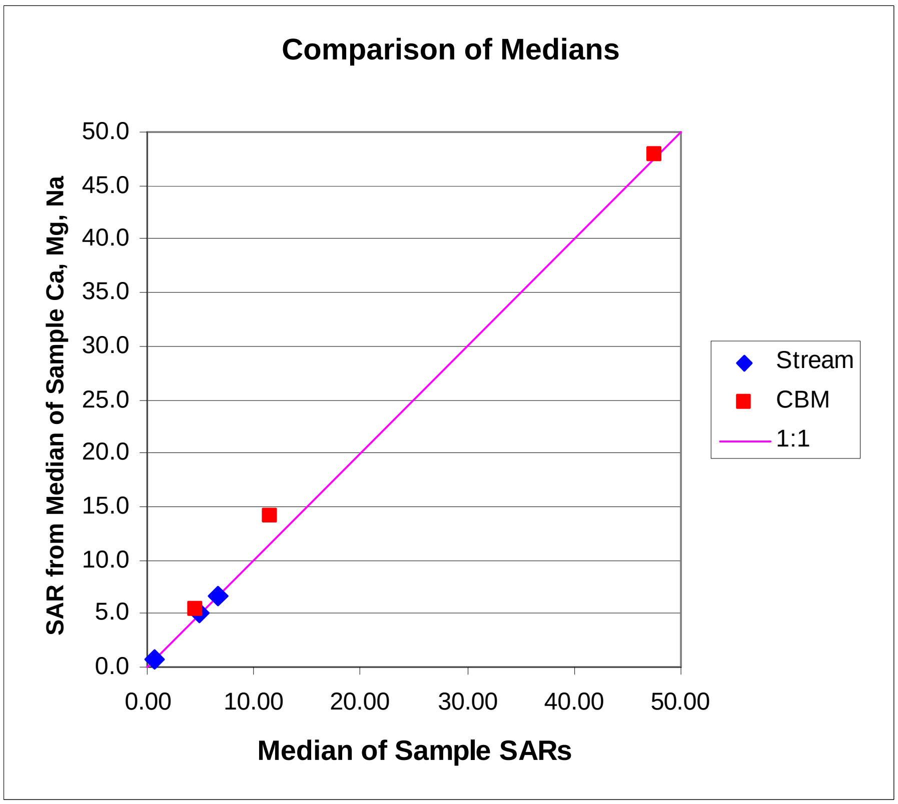

Figure A-2. Comparison of median values of sample SARs and SARs calculated from median values of sample Ca, Mg, and Na concentrations.

A. 5. SAR Mixing

As described above, estimation of SAR in a river after mixing with CBM discharge ideally is calculated using synoptic data and equation [3]. However, because synoptic data generally are not available for the streams or CBM discharges evaluated in the EIS, this section evaluates using the simple flow-weighted mass balance model, shown in equation [2], to estimate SAR after mixing. The corresponding simple mixing model for SAR is:

$$SAR_{simple\ mix} = \frac{\left(Q_{River} \times SAR_{River}\right) + \left(Q_{CBM} \times SAR_{CBM}\right)}{\left(Q_{River} + Q_{CBM}\right)} \qquad [4]$$

Two approaches are used to evaluate the use of equation [4] in place of equation [3]. One approach considers fractional mixing of stream water with CBM discharge using representative mean or median values of SAR, Ca, Mg, and Na for both the stream and CBM discharge. The other approach mixes CBM discharge characterized by representative mean values for water quality parameters with individual samples from each of the stateline stations.

A.5.1. Fractional Mixing Analysis

The fractional mixing analysis is illustrated in Figure A-3 using mean values of SAR, Ca, Mg, and Na from the Powder River at Moorhead station and CBM discharge in the Power River watershed. The figure compares the simple mix SAR values estimated using equation [4] to SAR values estimated using equation [3]. As shown, the simple SAR mixing approach overestimates SAR in the Powder River station at Moorhead by a factor ranging up to 1.33 at the reasonably foreseeable development (RFD) CBM discharge.

Table A-3 presents a summary of the results of the fractional mixing analysis for each of the stateline stations. This table shows that the simple mix approach—equation [4]—over-predicts SAR by a factor of at most 1.4 at the Powder River and Little Powder River stateline stations. At the Tongue River stateline station, the simple mix approach overestimates SAR by a factor of at most 1.6 using mean values and 2.7 using median values.

The over-prediction in SAR that results from using the simple mass balance approach is small when compared to the other uncertainties inherent in the impact analysis modeling. Consequently, this approach is considered appropriate for purposes of this EIS, as it yields a reasonably conservative estimate of SAR.

Powder River at Moorhead: Mean Values					
Flow	Sample SAR	Ca	Mg	Na	CaMgNa SAR
388	4.94	118	58	261	4.91

CBM Discharge: Mean Values					
Flow	Sample SAR	Ca	Mg	Na	CaMgNa SAR
206	**20.7**	29	14	540	**20.7**

Mix						
Frac	Simple SAR Mix (1)	Ca Mix	Mg Mix	Na Mix	CaMgNa Mix SAR (2)	Ratio (1):(2)
0	4.94	118	58	261	4.91	1.01
0.05	5.35	116	57	268	5.10	1.05
0.1	5.73	114	56	275	5.28	1.09
0.15	6.10	112	55	282	5.45	1.12
0.2	6.45	110	54	288	5.62	1.15
0.25	6.79	108	53	294	5.79	1.17
0.3	7.10	106	52	299	5.95	1.19
0.35	7.41	104	51	305	6.10	1.21
0.4	7.70	103	51	310	6.26	1.23
0.45	7.98	101	50	315	6.41	1.25
0.5	8.24	100	49	320	6.55	1.26
0.55	8.50	98	48	324	6.69	1.27
0.6	8.75	97	48	328	6.83	1.28
0.65	8.98	95	47	333	6.97	1.29
0.7	9.21	94	46	337	7.10	1.30
0.75	9.43	93	46	340	7.23	1.30
0.8	9.64	92	45	344	7.35	1.31
0.85	9.84	91	45	348	7.48	1.32
0.9	10.03	89	44	351	7.60	1.32
0.95	10.22	88	43	354	7.72	1.32
1	10.41	87	43	358	7.83	1.33

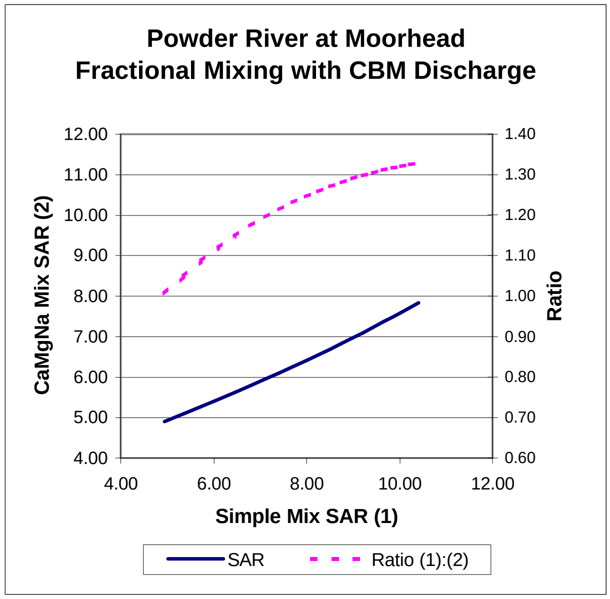

Figure A-3. Fractional mixing of stream water and CBM discharge. Comparison of SAR values calculated using (1) simple mixing as in equation [4] and (2) flow-weighted mixing of Ca, Mg, and Na as in equation [3].

Table A-3
Summary of Fractional Mixing Results. Comparison of SAR values calculated using simple mixing versus flow-weighted mixing of Ca, Mg, and Na.

Station	Statistic Used to Represent Water Quality	Average Ratio of Simple SAR Mix to Ca, Mg, Na Mixed SAR	Ratio of Simple SAR Mix to Ca, Mg, Na Mixed SAR at RFD CBM Discharge
Tongue River	Mean	1.40	1.60
Tongue River	Median	2.33	2.67
Powder River	Mean	1.23	1.33
Powder River	Median	1.12	1.20
Little Powder River	Mean	1.24	1.36
Little Powder River	Median	1.17	1.12

A.5.2. Distribution Mixing Analysis

Results similar to those obtained in the fractional mixing analysis are obtained by mixing individual samples of river water at the stateline stations (USGS data) with CBM discharge (mean values). The results are illustrated in Figures A-4 and A-5. These figures both indicate that the simple mix approach—equation [4]—over-predicts SAR by a factor of approximately 1.6 at both the Tongue River and Powder River stateline stations. As above, this over-prediction of SAR represents a conservative, yet reasonable estimate of SAR and, consequently, the simple mixing approach is the approach used in the analysis of impacts for the EIS.

References:

U.S. Dept. of Agriculture (USDA), 1954, *Agriculture Handbook 60*. www.ussl.ars.usda.gov/hb60/hb60requ.htm

U.S. EPA Region VIII, 1995, *Mixing Zones and Dilution Policy*.

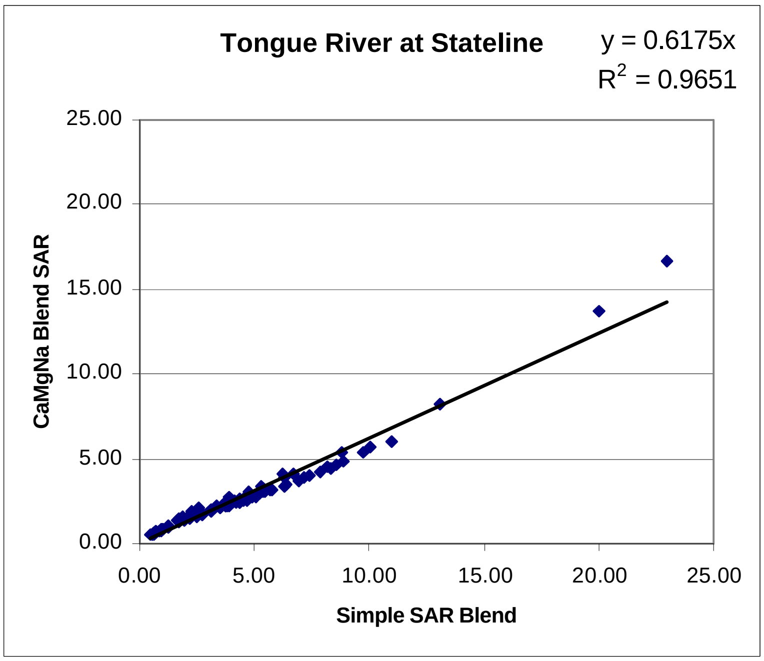

Figure 4. Tongue River at Stateline (USGS data) mixed with CX Ranch CBM discharge (mean values). Comparison of SAR values calculated using simple mixing as in equation [4] and flow-weighted mixing of Ca, Mg, and Na as in equation [3].

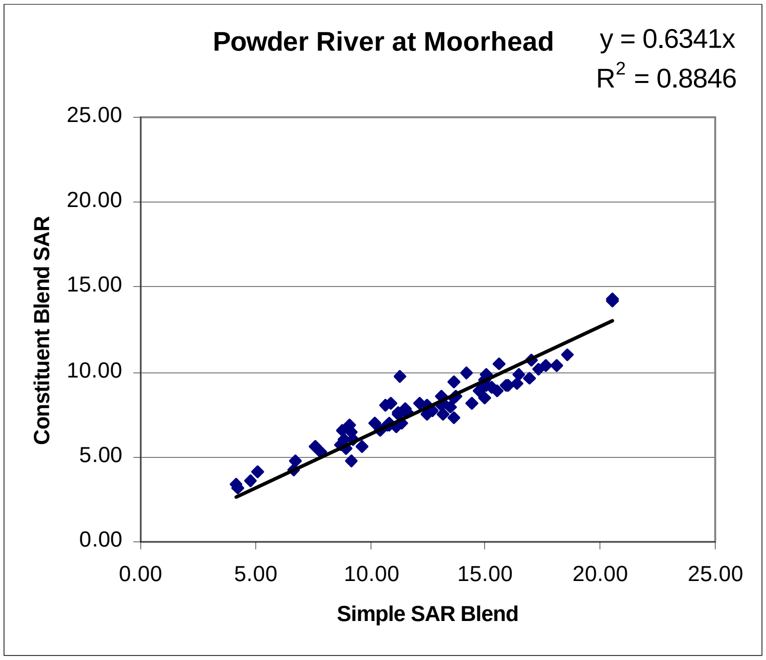

Figure 5. Powder River at Moorhead (USGS data) mixed with Powder River Basin CBM discharge (mean values). Comparison of SAR values calculated using simple mixing as in equation [4] and flow-weighted mixing of Ca, Mg, and Na as in equation [3].