

May 4, 2006

Mr. Bill DiRienzo  
Wyoming Department of Environmental Quality  
Water Quality Division  
Herschler Building, 4<sup>th</sup> Floor West  
122 West 25<sup>th</sup> Street  
Cheyenne, Wyoming 82002

Subject: Comments pertaining to the proposed default SAR effluent limit cap of 10 in the Draft Section 20 Agricultural Use Protection Policy.

Dear Mr. DiRienzo:

I respectfully submit for your consideration the following comments regarding the fourth draft of the Section 20 Agricultural Use Protection Policy as it pertains to the derivation of effluent limits for SAR, particularly the proposed sodium adsorption ratio (SAR) cap of 10. These comments are being submitted on behalf of Yates Petroleum Company, Williams Production RMT Company, Petro-Canada Resources (USA) Inc., Marathon Oil Company, Lance Oil & Gas Company, Inc., Fidelity Exploration & Production Company, Devon Energy Production Company L.P., Bill Barrett Corporation, and Anadarko Petroleum Corporation. I have submitted additional comments regarding the derivation of effluent limits for electrical conductivity (EC) in a separate letter.

By way of introduction, I am a board-certified professional soil scientist having practiced as an environmental consultant in Montana and Wyoming, and throughout the world, for nearly 25 years. For the past seven years, my practice has focused on water management and soil and water salinity/sodicity issues associated with oil and gas development. I am credited as the first to research, develop, and apply managed irrigation techniques for the beneficial use of coalbed natural gas produced water. I have directed or participated in over 100 separate projects related to produced water management, WPDES permitting, soil and water chemistry investigations, and reclamation for coalbed and conventional natural gas projects in Wyoming, Colorado, and Montana. I have a M.S. degree in land rehabilitation (soil science emphasis) from Montana State University and a B.S. in Resource Conservation (soil science emphasis) from the University of Montana.

I would like to comment on the proposed changes made to the Agricultural Use Protection Policy by the WDEQ subsequent to the January 26, 2006 meeting of the Water and Waste Advisory Board. My comments will focus on the comments provided by Dr. Larry Munn in his letter to the DEQ dated December 5, 2005. It is my understanding that Dr. Munn's comments resulted in the changes made to the proposed Policy. Specifically, I comment on Dr. Munn's proposal that all WPDES default effluent limits for SAR be capped at 10 under the Tier 1 process.

## Summary of Findings

The fourth draft of the Agricultural Use Protection Policy describes a 3-tiered decision making process for deriving appropriate effluent limits for EC and SAR whenever a proposed discharge may reach irrigated lands. The Tier 1 process would be followed for deriving “default” limits, and as such, this procedure would require a minimum of background information from the applicant. The default SAR limits would be extrapolated from the Hanson et al. (1999) chart relating the established EC effluent limit to SAR, up to a maximum default value of 10. The effluent limit for SAR will be determined in conjunction with EC so that the relationship of SAR to EC remains within the “no reduction in rate of infiltration” zone of the Hanson et al. (1999) diagram.

Two key concerns arise from Dr. Munn’s letter regarding sodicity and the discharge of CBNG produced water in the Powder River Basin: (1) the potential impacts on the hydraulic function of irrigated soils during produced water discharge; and (2) the potential impacts of residual adsorbed sodium on the hydraulic function of irrigated fields after produced water discharge has ceased and rainfall/snowmelt leaches salts from the upper root zone. It is assumed that these concerns led Dr. Munn and the WDEQ to propose the SAR effluent limit cap of 10 under the Tier 1 process.

In addressing these concerns, I performed a considerable amount of research, including three months searching and reviewing the relevant scientific literature, and compiling and analyzing available and relevant soil, plant, and water data. The key conclusions of the literature review and data analysis are presented below and will be substantiated by the discussion that follows.

### Review of Soil Sodicity

- Plant growth problems associated with excess sodium adsorption are in response to negative changes in soil structure resulting in reduced air exchange, water infiltration and hydraulic conductivity.
- The universally applied sodic soil threshold is an exchangeable sodium percentage (ESP) greater than 15.
- SAR is a measure of the sodicity risk in irrigation water. The higher the salinity of irrigation water, the higher the SAR can be without impacting soil structure and impairing soil infiltration and permeability.

### The ESP-SAR Relationship for Soils in Northeastern Wyoming

- Using regression analysis, the relationship between ESP and soil SAR was determined for the Powder River Basin ( $n=382$ ,  $R^2=.74$ ).
- A 1:1 relationship of soil SAR to water SAR exists for soils in equilibrium with irrigation water. This relationship is widely accepted and confirmed by recent research led by Dr.

James Bauder at Montana State University. The relationship of ESP to soil SAR is therefore equivalent to the relationship of ESP to water SAR.

- Based on the regional specific relationship of ESP and SAR, an effluent limit of SAR = 16 corresponds to an ESP of 10, and provides a 33% margin of safety against the formation of sodic conditions (i.e., exceeding an ESP of 15). The proposed default SAR cap of 10 is, therefore, unnecessarily conservative.

#### The Effect of Rainwater Leaching on Soils Irrigated with Produced Water

- Concern has been raised that subsequent rainfall/snowmelt leaching of residual soil salinity may lower the electrolyte concentration and naturally raise the ESP past the dispersive sodic soil threshold.
- Research demonstrates that arid land soils can release 0.3 to 0.5 dS/m of Ca and Mg to solution as a result of the dissolution of primary minerals and the inherent calcium carbonate content of surface soils. Shainberg et al. (1981) indicates that these concentrations are sufficient to counter the deleterious effects of exchangeable sodium, even when the soil is leached with rainwater.

#### **A Review of Soil Sodicity**

The physical and chemical phenomena associated with soil sodicity are complex. Therefore, a brief summary is provided regarding the soil and water chemistry associated with the physical affects of soil sodicity.

A large body of research concerning sodic, or “black alkali” soils has been generated in response to the negative effects of high sodium concentrations on soils. Toxicity effects of sodium are rarely expressed in forage and grass crops, but do cause injury to selected woody plants (Lilleand et al., 1945; Ayers et al., 1951; Brown et al., 1953). Plant growth problems associated with high concentrations of sodium are generally a response to negative changes in soil structure. Sodic soils are “nonsaline soils containing sufficient exchangeable sodium to adversely affect crop production and soil structure (Soil Science Society of America, 2001).” High levels of adsorbed sodium tend to disperse soil particles thereby sealing the soil. The result can produce clogged soil pores, hard surface crusts, reduced infiltration, reduced permeability, and reduced oxygen diffusion rates, all of which interfere with or prevent plant growth. By definition, sodic soils are those that have an exchangeable sodium percentage (ESP) greater than 15. The universally applied ESP threshold of 15 percent is acknowledged in numerous publications, including Levy et al. (1998), Abrol et al., (1988), Evangelou (1998), McNeal and Coleman (1966), Sparks (1995), Sumner et al. (1998), Shainberg et al. (1971), the Soil Improvement Committee (2002), university extension publications, etc.

Clay minerals are the most physically and chemically reactive components of the sand, silt, and clay matrix in soil. The structural arrangement of clay minerals in soil is akin to a deck of cards; the clay mineral itself can be thought of as the deck, and the cards as individual layers. The

properties of the deck depend upon the arrangement of the cards and the electrochemical interlayer forces holding the cards together.

Clay minerals in soils are negatively charged and consequently attract ions with a positive charge such as calcium, magnesium, potassium, and sodium. Positively charged ions are called cations. Each cation competes with others in the soil solution for access to the bonding sites based on its valence and hydrated size. Every soil has a definite capacity to adsorb the positively charged cations. This is termed the cation exchange capacity (CEC). The various adsorbed cations (such as calcium and sodium) can be exchanged one for another and the extent of exchange depends upon their relative concentrations in the soil solution (dissolved), the ionic charge (valence), the nature and amount of other cations, etc. ESP is, accordingly, the amount of adsorbed sodium on the soil exchange complex expressed in percent of the cation exchange capacity in milliequivalents per 100 grams of soil (meq/100 g). Thus,

$$\text{ESP} = (\text{exchangeable sodium} / \text{cation exchange capacity}) \times 100.$$

Sodic soil conditions arise when greater than 15 percent of the ions bonded to the deck are sodium, which has a +1 valence and a large hydrated radius. When the ESP exceeds 15, the large hydrated sodium ions can wedge in-between the individual cards and cause "swelling" of the deck (Levy et al., 1998). This causes negative effects on the physical structure of the soil. Upon re-wetting, the individual decks may disperse and settle into soil pores, effectively clogging them and reducing the efficiency of air exchange, water infiltration, and permeability (i.e., hydraulic conductivity). In general, soils with moderately high, to high, clay contents are at higher risk.

Excessive adsorbed or exchangeable sodium can result from sustained use of irrigation water that is high in sodium and low in calcium and magnesium. Consequently, the ratio of sodium to calcium and magnesium ions in water is an important property affecting the infiltration and permeability hazard. The water quality index used to measure the hazard related to sodium abundance or sodicity in irrigation water is the sodium adsorption ratio or SAR.

The SAR is the ratio of the dissolved sodium concentration in water divided by the square root of the average calcium plus magnesium concentration. The SAR can be calculated from the sodium, calcium and magnesium concentrations via the formula:

$$\text{SAR} = [\text{sodium}] / (([\text{calcium}] + [\text{magnesium}])/2)^{1/2}$$

where the concentrations are in milliequivalents per liter (meq/L).

What is not apparent from the SAR formula is the fact that the higher the salinity of the water, the higher the SAR can be without impacting soil structure and impairing soil infiltration and permeability. Put another way, for a given SAR, infiltration rates generally increase as salinity (measured by the EC) increases. The changes in soil infiltration and permeability occur at varying SAR levels, higher if the salinity is high, and lower if the salinity is low. Therefore, in order to evaluate the sodicity risk of irrigation water, the EC must be considered. To this end,

the SAR-EC guidelines presented in Ayers and Westcot (1985) and Hanson et al. (1999) are used to assess the potential sodicity risk of irrigation water.

### The ESP-SAR Relationship for Soils in Northeastern Wyoming

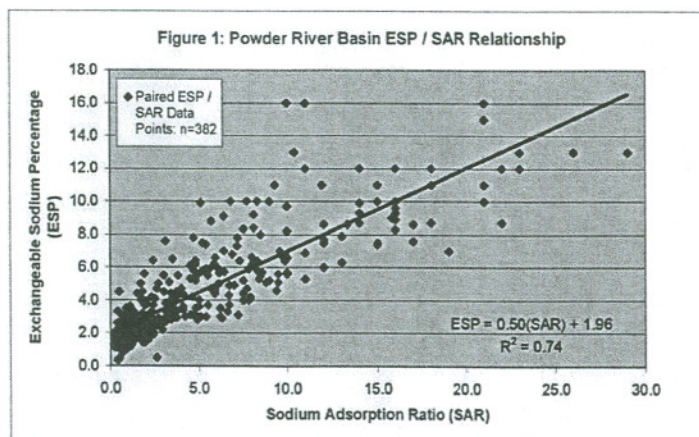
In addition to measuring the SAR of irrigation water, one can also measure the SAR of the soil solution via a saturated paste extract (i.e., the dissolved concentrations of sodium, calcium, and magnesium are measured in a saturated paste extract and applied via the SAR formula presented above). The soil SAR was developed to serve as a rapid and relatively inexpensive index of ESP. It is widely accepted that the SAR of the soil in equilibrium with the SAR of the irrigation water is equal to the long-term average SAR of the irrigation water.

The fourth draft of the Agricultural Use Protection Policy includes a proposed SAR cap of 10 for Tier 1 default effluent limits. To evaluate the appropriateness of the proposed cap, an analysis was performed using 382 ESP-SAR data pairs generated from ongoing soils assessment work in the Powder River Basin of Wyoming (KC Harvey LLC, 2006). This database represents flood plain soils associated with tributaries to the Powder River and the Tongue River, including spreader dike irrigated fields. This database represents baseline soil chemical conditions. In no case were any of these soils irrigated with or influenced by coalbed natural gas produced water. The soil samples from which the analyses were made were collected during soil profile descriptions to five feet, and with a Giddings hydraulic probe up to eight feet in depth. The numerous soil investigations involved were required for various coalbed natural gas water management planning, permitting, and design purposes.

The ESP-SAR data pairs were graphed in Microsoft Excel using simple scatter-plot and trend line analysis. The best fit line resulted in a linear regression which yielded the equation:

$$\text{ESP} = 0.5(\text{SAR}) + 1.96, \text{ with an } R^2 \text{ value of } 0.74.$$

The regional-specific "Powder River Basin" relationship, based on 382 soil samples, is shown on Figure 1. According to the Powder River Basin equation, a soil SAR of 26 corresponds to the critical ESP threshold of 15 percent.



It is widely accepted that the SAR of soil in equilibrium with irrigation water equals the long-term average SAR of irrigation water. Recent Department of Energy funded research directed by Dr. James Bauder at Montana State University (Robinson and Bauder, 2003) confirms this relationship. Their research, which is related to the potential effects of coalbed natural gas produced water on soils, reports that in general, soil solution SAR

represents the SAR of the applied water. The 1:1 soil SAR to water SAR relationship allows one to relate the SAR of discharge water to the SAR of the soil in the Powder River Basin ESP-SAR graph and equation described above. For example, after long-term irrigation with water exhibiting an SAR of 15, the equilibrated ESP of the irrigated soil would be approximately 9.5 percent. The proposed SAR cap of 10 would equate to a corresponding ESP of 7. An ESP cap of 7 appears to be unnecessarily conservative given the regional specific relationship of ESP and SAR. While an ESP threshold of 15 is widely accepted to be the point at which clay swelling and dispersion occurs, we respectfully suggest that the WDEQ consider establishing a Tier 1 default SAR effluent limit cap of 16, which corresponds to an ESP of 10. An ESP value of 10 provides a 33 percent margin of safety.

### **The Effect of Rainwater Leaching on Soils Irrigated with Produced Water**

In his December 5, 2005 letter, Dr. Munn indicates his concern about the potential effects of rainwater leaching of fields that had received produced water due to upstream permitted discharges. In particular, what is the effect of leaching on the sodicity status and hydraulic function of soils after discharge and irrigation with produced water ceases? Fortunately, the considerable research on this subject has been well documented in the scientific literature.

Discontinuation of produced water discharge in the Powder River Basin will effectively reduce the EC and SAR of irrigation waters from tributaries and mainstems so long as the surface water is of higher quality than the produced water. In the case of fields that are irrigated opportunistically (e.g., in response to runoff events that are captured behind spreader dike systems), there can be three sources of water supplying soil moisture: (1) meteoric water (rain and snowmelt); (2) natural runoff water; and (3) subirrigation from a shallow aquifer. In the case of rainfall and snowmelt, the EC of these waters will be similar to that of distilled water, i.e., they will exhibit very low dissolved solids. Owing to the dissolution of soluble constituents within the watershed, natural runoff EC values can range up to 5 dS/m or higher. Regarding subirrigation, shallow aquifers can be relatively saline due to the entrainment of dissolved minerals along the groundwater flowpath.

The concern arises from leaching of residual surface soil salinity with rainfall and snowmelt. Intermittent rainfall and snowmelt may lower the electrolyte concentration (i.e., EC) sufficiently to promote clay dispersion, depending on soil properties (Levy et al., 1998). Conversely, when the electrolyte concentration in the soil solution reaches a moderate level (1-2 dS/m), high sodicity levels (ESP between 10 and 30) cause only small to moderate changes in the physical and hydraulic properties of the soils, which are mostly reversible (Levy et al., 1998). Shainberg et al. (1981) showed that a major factor causing differences among various sodic soils in their susceptibility to hydraulic failure when leached with low electrolyte concentrations (i.e., a low EC) was their rate of salt release from mineral dissolution.

Arid land soils can release 0.3 to 0.5 dS/m of calcium and magnesium to solution as a result of the dissolution of plagioclase, feldspars, hornblends and other sparingly soluble minerals within the soil matrix (Rhoades et al. 1968). The solution composition of a calcareous soil at a given ESP in contact with distilled water (i.e., rainwater or snowmelt) can be calculated (Shainberg et al., 1981). As calcium carbonate ( $\text{CaCO}_3$ ) dissolves, the EC of the soil solution increases and

calcium replaces sodium on exchange sites until the solution is in equilibrium with the cation exchange system and the  $\text{CaCO}_3$  solid phase. Shainberg et al. (1981) calculated that the EC values of solutions in equilibrium with soils having ESP values of 5, 10, and 20 are 0.4, 0.6, and 1.2 dS/m, respectively. Shainberg et al. (1981) indicates that these concentrations are sufficient to counter the deleterious effects of exchangeable sodium, even when the soil is leached with rainwater.

It is evident that water equilibrated with a calcareous soil can never be a very low salinity (Shainberg et al., 1981). Using the same database discussed above for evaluation of the ESP-SAR relationship in 382 soil samples from the Powder River Basin, we can compute an average percent lime ( $\text{CaCO}_3$ ) content in surface soil samples ( $n=81$ ), which is 4.3 percent. This represents a considerable reserve of calcium. Other sources of calcium include residual gypsum ( $\text{CaSO}_4$ ) which we know to be prevalent in Wyoming soils.

Various soil SAR-EC relationships (not to be confused with irrigation water SAR-EC relationships) have been reported in the literature by introducing low electrolyte concentration waters to sodic soils. Felhendler et al. (1974) measured the hydraulic conductivity of two montmorillonitic soils as a function of the SAR and found that both were only slightly affected by the SAR of the percolating solution up to a SAR of 20 as long as the concentration of the percolating solution exceeded 1 dS/m. Shainberg et al. (1981) studied the effects of leaching a 1:1 sand-soil column with distilled water and increasing concentrations of a weak electrolyte solution. His findings concluded that an electrolyte concentration of 0.3 dS/m in the percolating solution was adequate to prevent the adverse effects of a SAR of 15 on the hydraulic conductivity of the soil-sand mixture. These findings are very similar to the conclusions of the U.S. Salinity Laboratory Staff (1954) who used electrolyte concentrations equal to or greater than 0.3 dS/m in their regression analysis to determine the sodic soils threshold of  $\text{ESP} = 15$ .

As a review, an electrolyte concentration of 0.3 dS/m is the minimum value of calcium and magnesium contributions to soil solution associated solely to arid soil weathering. This suggests that an arid Powder River Basin soil with a SAR of 16 ( $\text{ESP} = 10$ ), will have no sodicity related impacts to the hydraulic conductivity, even when the salt concentration of the irrigation or rainwater is equal to that of distilled water.

Of course, irrigation water in the Powder River Basin has an intrinsic electrical conductivity greater than that of distilled water. Use of surface water for irrigation will actually supplement the inputs of calcium and magnesium from weathering and carbonate dissolution alone.

Using the aforementioned Powder River Basin soils assessment database (KC Harvey LLC, 2006), an average surface soil  $\text{EC}_e$  of 1.64 dS/m was calculated from 81 individual surface soil samples. This value suggests that electrolyte concentrations in surface soils of the Powder River Basin, in equilibrium with mineral dissolution, the salinity of runoff irrigation water, and rainwater/snowmelt, is about 1.6 dS/m, or five times (1.6 dS/m divided by 0.3 dS/m) the concentration required to maintain the hydraulic conductivity of a soil at an  $\text{ESP}$  of 16.

### Closing Statement

Results of the Powder River Basin regression analysis indicates that a relationship between ESP and soil/water SAR exists, which allows the calculation of one parameter from the other. Using the proposed, default ESP cap of 10 percent, the scientific literature indicates that water with a SAR of 16 can be effectively used for irrigation without adverse effects on the physical structure or hydraulic conductivity of Powder River Basin soils during irrigation. Furthermore, it has been shown that inputs of Ca and Mg from the natural dissolution of plagioclase, feldspars, hornblends and other sparingly soluble minerals, especially calcium carbonate and gypsum, will provide an effective buffer to residual soil sodicity after the discontinuation of produced water discharge and the transition back to native irrigation, precipitation, and runoff regimes.

### References Cited

- Abrol, I.P., Yadav, J.S.P. and Massoud, F.I. 1988. Salt-affected soils and their management. FAO Land and Water Management Division, Soils Bulletin 39.
- Ayers, A.D., Aldrich, D.G. and Coony, J.J. 1951. Sodium chloride and injury of Fuerte avocado leaf. California Avocado Soc. Yearbook: 1951 174-178 illus.
- Ayers, R.S. and Wescot, D.W. 1985. Water quality for agriculture. FAO Irrigation and Drainage Paper, 29 (rev. 1).
- Brown, J.W., Wadleigh, C.H. and Hayward, H.E. 1953. Foliar analysis of stone fruit and almond trees on saline substrates. Amer. Soc. Hort. Proc. 61: 49-55.
- Evangelou, V.P. 1998. Environmental soil and water chemistry principles and applications. John Wiley and Sons (Pub), New York, NY.
- Felhendler, R.I., Shainberg, I. and Frenkel, H. 1974. Dispersion and hydraulic conductivity of soils in mixed solutions. Int. Congr. Soil Sci., Trans. 10<sup>th</sup> (Moscow) 1:103-112.
- Hanson, B., Grattan, S.R. and Fulton, A.F. 1999. Agricultural salinity and drainage. Division of Agriculture and Natural Resources Publication 3375. University of California Irrigation Program. University of California, Davis, CA.
- KC Harvey, LLC. 2006. Unpublished data. Compilation of various soil investigation sampling and analysis data from Sheridan, Johnson and Campbell Counties, Wyoming. Bozeman, MT.
- Levy, G.J., Shainberg, I. and Miller, W.P. 1998. Physical Properties of Sodic Soils. In: Sumner, M.E. and Naidu, R. 1998. Sodic soils: Distribution, properties, management and environmental consequences. Oxford University Press, Inc. New York, NY.
- Lilleand, O., Brown, J.G. and Swanson, C. 1945. Research shows sodium may cause leaf tip burn. Almond Facts 9 (2): 1, 5, illus.

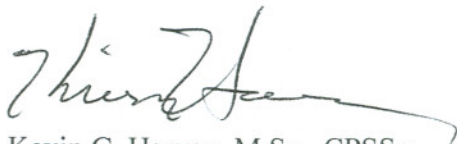


- McNeal, B.L and Coleman, N.T. 1966. Effect of solution composition on hydraulic conductivity. *Soil Sci. Soc. Am. Proc.*, 30, 308-312.
- Rhoades, L.D. 1968. Mineral weathering correction for estimating the sodium hazard of irrigation waters. *Soil Sci. Soc. Am. Proc.* 32:648-652.
- Robinson, K.M. and Bauder, J.W. 2003. Soil behavior upon wetting with saline sodic water part 2: Soil chemical responses. Adapted from Robinson, K.M. 2003. Effects of saline-sodic water on EC, SAR, and water retention.
- Shainberg, I., Bresler, E., and Klausner, Y. 1971. Studies on Na/Ca montmorillonite systems, I: The swelling pressure. *Soil Sci.* 111:214-219.
- Shainberg, I., Rhoades, J.D., Suarez, D.L. and Prather, R.J. 1981. Effect of mineral weathering on clay dispersion and hydraulic conductivity of sodic soils. *Soil Sci. Soc. Am. J.* 45:287-291.
- Soil Improvement Committee, California Plant Health Association. 2002. *Western Fertilizer Handbook*, ninth edition. Interstate Publishers, Inc. Danville, Illinois.
- Soil Science Society of America. 2001. *Glossary of Soil Science Terms*. Madison, WI.
- Sparks, D.L. 1995. *Environmental Soil Chemistry*. Academic Press, San Diego, Ca.
- Sumner, M.E., Rengasamy, P. and Naidu, R. 1998. Sodic soils: A reappraisal. In: Sumner, M.E and Naidu, R. 1998. *Sodic soils: Distribution, properties, management and environmental consequences*. Oxford University Press, Inc. New York, NY.
- U.S. Salinity Laboratory Staff. 1954. *Diagnosis and improvement of saline and alkali soils*. USDA Agric. Handbook no. 60, Washington, D.C.

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Thank you very much for your time and consideration of this review and the recommendations stemming from it. If you, your WDEQ colleagues, or the members of the Water and Waste Advisory Board have any questions or comments regarding our findings, please contact me.

Sincerely,



Kevin C. Harvey, M.Sc., CPSSc.  
Principal Soil Scientist