EXPERT SCIENTIFIC OPINION ON THE TIER-2 METHODOLGY

Report to the

Wyoming Department of Environmental Quality

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September 2009

EXECUTIVE SUMMARY

At the invitation of the Department of Environmental Quality we have spent four days in the Powder River Basin to visit drainages around Gillette in the summer of 2009. During this period we have been briefed by the Department of Environmental Quality on the Tier 1, 2, and 3 methodology. In addition, we have had ample opportunities to talk with landowners as well as representatives of the industry and the Powder River Basin Resource Council. This report is based on our field observations, the scientific literature, and the wealth of information provided to us by all stakeholders.

We present scientific evidence that no unique relationship exists between irrigation water quality on the one hand and root zone soil salinity and crop productivity on the other. Therefore, we conclude that the **Tier 2 and Tier 1 methodology** as set forth in Appendix H section C(vi)(B) **is not reasonable nor scientifically valid for determining the EC of water that can be discharged into an ephemeral drainage in Wyoming so that degradation of the receiving water will not be of such an extent to cause a measurable decrease in crop production.**

We have observed in the field that the **Tier 2 and Tier 1 methodology has caused a rise of the ground water table that resulted in both "waterlogging and –most likely– increased soil salinity"**. Had a monitoring program be in place since the beginning of CBM water releases, it is almost certain that a decrease in crop production would have been measured due to waterlogging and/or increased soil salinity. The damage done by Tier 2 and Tier 1 starts by creating water logged conditions in the drainages: **the true problem is the quantity of CBM waters rather than its quality**.

Prominent agricultural salinity experts state "The successful use of saline ... waters for irrigation requires **appropriate management practices to control salinity**, not only within the irrigated fields, but also within the associated irrigation project and geo-hydrologic system" (Rhoades, 1999) and "**adequate control of soil salinity** changes requires that the farmer has access to multiple and dependable supplies of irrigation water where at least one supply is of good quality" (Maas and Grattan, 1999). The **Tier 2 and Tier 1 methodology results in uncontrolled and**

unmanageable releases of CBM waters since the farmers receive at unknown times, unknown volumes of water of unknown quality from hundreds of outlets controlled by different companies.

We recommend that **comprehensive monitoring of soils, ground water, and surface waters** is undertaken in all drainages that have received and are receiving CBM waters. The objectives are: (1) to determine where the salts are accumulating in the hydrologic system; (2) to assess where and when the salts will leave the system; (3) to design restoration measures for naturally and artificially irrigated lands that already have been affected or will be affected by "waterlogging and soil salinity".

We have observed in the field that Tier 3 and the "irrigation waiver" are viable alternatives for the Tier 2 and Tier 1 methodology. Under Tier 3 the CBM waters are managed in a proper manner and used for increased crop production to the satisfaction of the landowners. Therefore, **we recommend to abandon uncontrolled releases of CBM water into the drainages by Tier 2 and Tier 1 methodology in favor of the Tier 3 methodology that relies on appropriate management practices to control salinity.**

Tier 3 is best implemented over deep vadose zones so that the saline drainage waters percolating from the root zone enter the ground water gradually and minimize salt load to the Powder River.

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1. PURPOSE

In May 2009, the report “Expert Scientific Opinion on the Tier-2 Methodology” (Hendrickx and Buchanan) was presented to the Wyoming Environmental Quality Council. The findings and opinion from that report were the Tier 2 methodology as set forth in Appendix H section C(vi)(B) is not reasonable nor scientifically valid for determining the EC and SAR of water that can be discharged into an ephemeral drainage in Wyoming so that degradation of the receiving water will not be of such an extent to cause a measurable decrease in crop production.

The Wyoming Department of Environmental Quality (WDEQ) then contracted Hendrickx and Buchanan to visit Wyoming, review field conditions in the Gillette area and provide evaluation and clarification as to the use of the Tier 2 Method. The purpose of this report is to provide opinion regarding the Tier 2 Method.

The report includes general comments about the relationships of irrigation waters to affected crops and soils, the application of the Tier 2 methodology, and opinion of its validity in representative conditions found in the Powder River Basin (PRB).

The project included two visits to the PRB, one in July and one in August. The visits included field reviews of properties, discussions with landowners, industry, PRBRC and the DEQ.

2. SERVICES TO BE PROVIDED BY CONTRACTOR

Drs. Buchanan and Hendrickx have been contracted to provide further clarification on the report entitled "Expert Scientific Opinion on the Tier-2 Methodology" and discuss in more detail the DEQ permitting program as it pertains to agricultural use protection. The contractors shall provide advice to DEQ regarding their approach to permitting surface discharges of produced water.

The following tasks and questions were formulated during our two field visits:

1. Clarification of the Tier-2 evaluation.
2. Evaluate the application of the Tier system in the Powder River Basin. Provide a description of how different quality CBM waters are handled in the current system and how it is working.
3. Discuss the Tier-2 approach and how it should be modified.
4. Provide direction regarding existing Tier-2 permits.
5. Discuss other questions that consultants deem important.

3. HOW SALINE IRRIGATION WATER AFFECTS CROP PRODUCTIVITY

Three criteria are used to judge irrigation water quality as it affects crop productivity: (1) The possible toxicity of specific solutes in the irrigation water on plant growth; (2) Combined effect of Sodium Adsorption Ratio (SAR) and salt concentration or electrical conductivity (EC) of irrigation water on soil permeability; and (3) The salinity or EC of the irrigation water (Hanson et al., 2006; Maas and Grattan, 1999; Rhoades, 1999). Toxicity will not be discussed in this report due to time constraints. The SAR and EC of irrigation water are important since applications of irrigation water, with a relatively low EC and high SAR value, can substantially reduce infiltration rates of the soil. Since the SAR and EC thresholds used by the Wyoming Department of Environmental Quality are protective of soil infiltration rates, we will not address the issue of soil infiltration rates in this report but instead focus on the salinity or EC of the CBM waters.

Saline irrigation water affects crop growth and yield by osmotic influences that interfere with root water uptake. In plants, the concentration of solutes in root cells is higher than in soil water. This concentration difference allows water to move from the soil (low concentration) into the plant roots (high concentration). When the salinity of soil water increases the concentration difference becomes small; thus less water will move into the plant roots. The plant counteracts by increasing the solute concentration in its root cells by either accumulating salts or synthesizing organic compounds such as sugars and organic acids so that water movement into its roots is –at least partly– restored. Since these processes use energy that otherwise could have been used for crop growth, plants are smaller but otherwise often appear healthy in all other aspects concluding that **salinity is hard to detect by visual observations** (Bresler et al., 1982; Hanson et al., 2006; Lambers et al., 2008; Maas and Grattan, 1999).

During root water uptake, salts generally cannot move into the roots of agricultural crops and remain behind in the soil. Since the total amount of salt remains the same while soil water content decreases, the salt concentration of soil water is increasing when the soil dries out and crops growing on saline soils often appear to be suffering from drought (Bresler et al., 1982). Except under extreme levels of salinity, **salt-affected crops appear normal but yield losses**

from osmotic stress caused by saline soil water can be significant before any foliar injury occurs (Bresler et al., 1982; Maas and Grattan, 1999). Visual observations that relate crop appearance and "salt patches" to the salt content near or at the soil surface are quick and economical, but have the disadvantage that salinity development is detected after crop damage has occurred. Soil salinity measurements combined with established salt tolerance data are needed to diagnose salt problems well before major yield reductions occur (Bresler et al., 1982; Hendrickx et al., 1992; Rhoades, 1999).

During the last 100 years the salt tolerance of crops has been studied in the field and laboratory in many parts of the world (Kijne, 2003; Ulery et al., 1998). The salt tolerance bibliography of the US Salinity Laboratory contains 6,256 literature references[1] that have been used for the derivation of salt tolerance thresholds for agricultural crops (Maas and Hoffman, 1977; Maas and Grattan, 1999; Steppuhn et al., 2005a). It was found that a graph of crop yield versus irrigation water salinity often exhibit large variability, while crop yield versus root zone soil salinity yields stable graphs. For example, Figure 1 shows typical plots of wheat yield versus, respectively, irrigation water quality and root zone soil salinity in the Fordwah-Eastern Sadiqia Project of Pakistan (Kijne, 2003). The reason for the large variability of yield versus irrigation water quality is that there is no relationship between the salt content of irrigation water and root zone salinity as has been explained in our report to the Wyoming Environmental Quality Council (Hendrickx and Buchanan, 2009). As a matter of fact, most current salinity problems throughout the world occur in areas that are blessed with "good-quality" irrigation waters with low salt contents (Rhoades, 1999). Rhoades, who is one of the most prominent agricultural salinity experts in the world, states "The successful use of saline ... waters for irrigation requires an adequate understanding of how salts affect waters, soils and plants. But, the sustainability of a viable agriculture requires much more. It requires the implementation of appropriate management practices to control salinity, not only within the irrigated fields, but also within the associated irrigation project and geo-hydrologic system" (Rhoades, 1999).

[1] http://www.ars.usda.gov/Services/docs.htm?docid=8908 accessed on August 30, 2009.

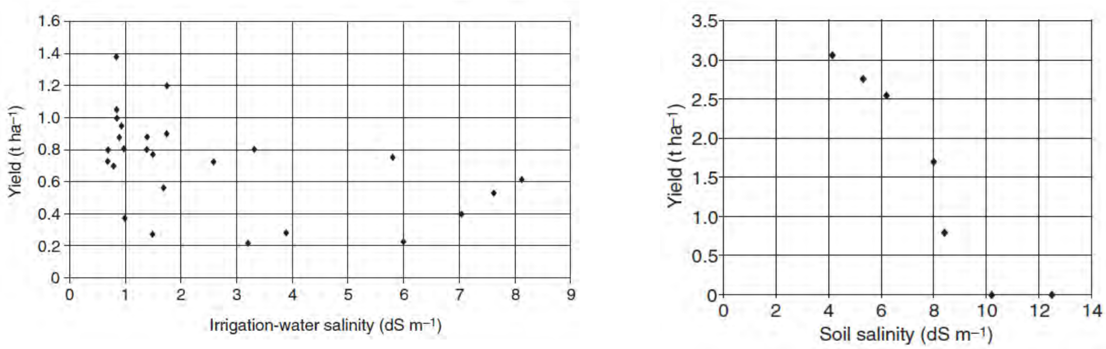

Figure 1. Typical plots of wheat yield versus irrigation water salinity (left) and root zone soil salinity (right). (Kahlown et al., 1998; Kijne, 2003).

In the next two sections we will first discuss crop productivity as a function of root zone soil salinity and then best irrigation management practices to optimize crop productivity when irrigation water is saline.

Crop Yield Response Functions

Crop salt tolerance provides a measure of the ability of plants to survive and produce economic yields under adverse conditions caused by root zone salinity (Bresler et al., 1982; Hanson et al., 2006). The salt tolerance of agricultural crops is expressed in terms of yield reductions while appearance is a more relevant measurement for ornamental plants. A common approach for agricultural crops is to compare yields on saline versus non-saline soils and to plot relative yields against mean root zone salinity (Maas and Hoffman, 1977; Maas and Grattan, 1999). The relative yield is found by dividing the absolute yield by the maximum yield obtained under non-saline optimal soil conditions. The absolute yields represent samples from fields with different root zone soil salinities or experimental plots.

For most crops the crop yield response function follows a sigmoidal relationship (Fig. 2). However, before the ubiquitous presence of computers it was much easier to represent the response function by two line segments: one with a zero slope at the maximum relative yield, and the second, a concentration-dependent line whose slope indicates the yield reduction per unit increase in salinity (Fig. 3) (Maas and Hoffman, 1977). In this report we prefer the sigmoidal curve since it fits the experimental data better than the two-piece linear model and it captures the variable rate of decrease in relative yield with increasing root zone soil salinity

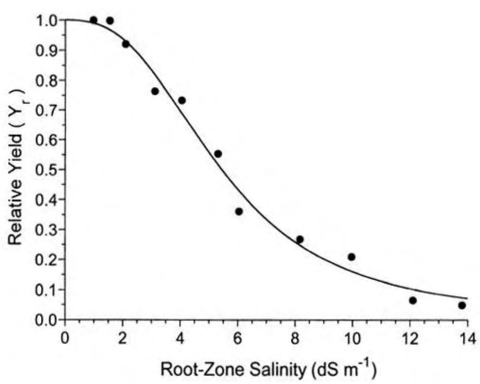

Figure 2. Sigmoidal function applied to Biggar spring wheat data (Steppuhn et al., 2005b).

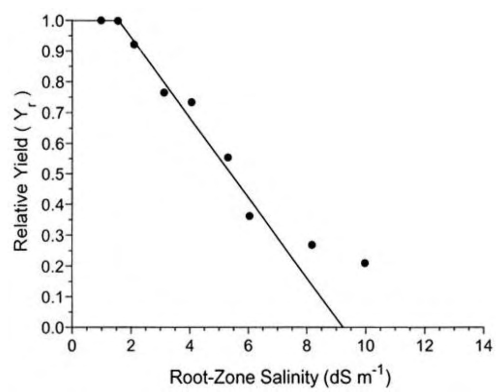

Figure 3. Two-piece linear function applied to Biggar spring wheat data (Steppuhn et al., 2005b).

(Steppuhn et al., 2005a; Steppuhn et al., 2005b). In addition, field observations indicate that yields can decline at much lower values of root zone soil salinity than predicted by the thresholds inherent in the two-piece linear functions (Katerji et al., 2000; Kijne, 2003; Shalhevet, 1994).

Two crop response functions for Alfalfa are available in the scientific literature (Steppuhn et al., 2005a). These functions are based on experiments conducted in the period 1943 through 1999 (Bernstein and Francois, 1973; Berstein and Ogata, 1966; Bower et al., 1969; Brown and Hayward, 1956; Gauch and Magistad, 1943; Hoffman et al., 1975; Steppuhn et al., 1999). Considering the memorandum of January 6, 2008, by Mr. Mark Majerus of the Natural Resources Conservation Service at Bridger Plant Materials Center in Montana we have selected the Alfalfa-Steppuhn response function for this report (Fig. 4). Mr. Majerus states that he and Dr. Harold Steppuhn agree that a threshold EC value of 4 dS/m in the root zone is an acceptable level for Alfalfa in Wyoming and “would best represent Alfalfa’s response to salinity in our region”.

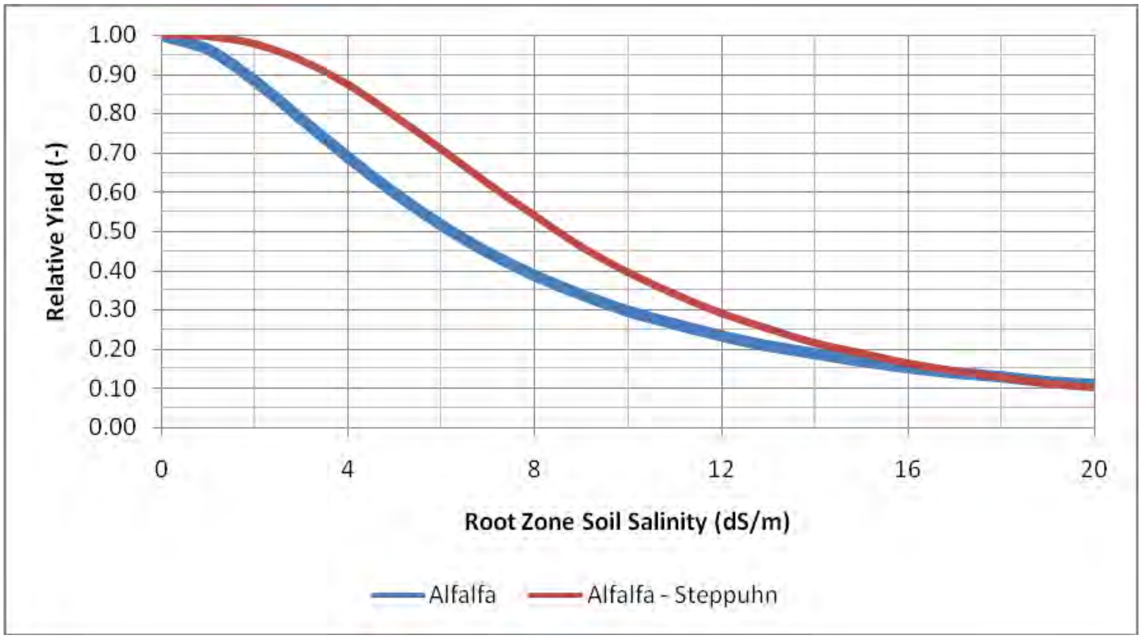

Figure 4. Two Alfalfa yield response functions to root zone salinity. The Alfalfa-Steppuhn response function is based upon field research in Canada and is selected for this report (Steppuhn et al., 2005a).

The Quality Standards for Wyoming Surface Water, Chapter I, §20, state:

> "All Wyoming surface waters which have the natural water quality potential for use as an agricultural water supply shall be maintained at a quality which allows continued use of such water for agricultural purposes. Degradation of such waters shall not be of such an extent to cause a measurable decrease in crop production".

The key phrase is "*measurable* decrease in crop production". A threshold EC value of 4 dS/m coincides with approximately 13% yield reduction on the sigmoidal response curve in Figure 4 and could, therefore, be interpreted to be an infringement of the Quality Standards for Wyoming Surface Water. However, one needs to take into account that this average curve is based on true yields that have an inherent natural variability. See, for example, Fig. 3 where the average response curve for wheat at 2 dS/m falls a little below the true yield sample measured in the field. Since the inherent natural variability of crop yields makes it very difficult to prove or

disprove that a ±10% yield reduction has truly occurred, we support an EC of 4 dS/m[2] as the regulatory threshold value for Alfalfa root zone soil salinity in the Powder River Basin.
The measurement of root zone soil salinity in the field is straightforward and well understood (Borchers et al., 1997; Corwin et al., 2006; Hendrickx et al., 1994; Hendrickx et al., 1992; Hendrickx et al., 2002; Lesch et al., 1995a; Lesch et al., 1995b; Lesch et al., 2000; Rhoades et al., 1999) so that regulators, land owners, and industry can easily inspect whether threshold values have been respected.

Management of Root Zone Soil Salinity

In the previous section we have shown how in a scientific manner an unambiguous threshold value for root zone soil salinity can be determined for Alfalfa and other crops. However, the Department of Environmental Quality needs an end-of-pipe salt concentration for its regulatory Tier 2 process. Therefore, we will discuss in this section the link between irrigation water salinity and root zone soil salinity.

As explained in our May 2009 report to the Wyoming Environmental Quality Council, major causes for soil salinity are soil characteristics, ground water table depth, climate, presence of saline seepages, and water management but not the quality of the irrigation water. No evidence has been found in the peer-reviewed literature (Bresler et al., 1982; Corwin et al., 2007; Kijne, 2003; Letey and Feng, 2007; Rhoades, 1999) in support of the assumption on which Tier 2 is based: soil salinity in artificially and naturally irrigated lands in ephemeral drainages is entirely determined by pre-existing background water quality. Since for any artificially or naturally irrigated land in the Powder River Basin soil characteristics, ground water table depth, climate, and presence of saline seepages are beyond control of the landowners, the critical link between the salinity of irrigation water and root zone soil salinity is water management. Not only management on the field scale by landowners but also the overall institutional management structure.

[2] The Department of Environmental Quality uses μmho/cm to express electrical soil and water conductivity. In this report we use the generally accepted unit of dS/m (Hanson et al., 2006).
1 dS/m = 1 mmho/cm = 1000 μmho/cm.

In irrigated agriculture there is only one economical way to control root zone soil salinity: ensure a net downward flow of water (drainage) through the root zone to leach out the salts. If leaching is inadequate, salts can accumulate in the root zone within a few seasons to harmful levels that decrease crop yields (Hoffman and Durnford, 1999). The leaching fraction is a critical management parameter for root zone soil salinity control since it determines the relationship between irrigation water salinity and root zone soil salinity. In its simplest form the leaching fraction, *LF*, for steady state conditions can be defined as

$$LF = \frac{D_d}{D_a} \qquad \textbf{[1]}$$

where D_d is the volume of water draining from the root zone expressed as an equivalent depth (inch or mm) and D_a is the volume of water applied to the land and entering the root zone. For example, if LF=0.2 the volume of drainage water will be equal to 0.2 times the volume of applied water or in other words 20% of the volume of applied water will leave the root zone. The higher the leaching fraction the less likely that the root zone soil salinity will rise to harmful levels since the drainage waters remove salts from the root zone. Farmers try to manage irrigations in such a way that the leaching fraction is sufficient to keep root zone soil salinity at a level that will not reduce yields.

Tables and graphics have been developed that present the relationships between root zone soil salinity, irrigation water salinity, and the leaching fraction (Hoffman and van Genuchten, 1983; Hoffman and Durnford, 1999; Rhoades, 1982; Rhoades, 1999). These tables have been used for almost thirty years for the successful management of saline irrigation waters. Table 1 presents the relationship between the leaching fraction and the ratio of root zone soil salinity (expressed as the electrical conductivity of the saturation extract EC_e) to that of irrigation water salinity (expressed as the electrical conductivity of the water) developed by Rhoades (1999) for conventional irrigation management and high-frequency irrigation management. Figure 5 presents the same information but in the form of graphics. This visual presentation of the information in Table 1 immediately demonstrates that no unique relationship exists between irrigation water salinity and root zone soil salinity. The root zone soil salinity resulting from a

Table 1. Relationship between the ratio of average root zone EC_e (dS/m) and the *EC* of irrigation water ($R_{soil/water}$) and the leaching fraction (*LF*) (Rhoades, 1982; Rhoades, 1999).

	$R_{soil/water}$					
	Leaching Fraction (*LF*)					
	0.05	0.10	0.20	0.30	0.40	0.50
Low-frequency Irrigation Management	2.79	1.88	1.29	1.03	0.87[#]	0.77
High-frequency Irrigation Management	1.79	1.35	1.03	0.87	0.77	0.70

[#] Ratio values less than 1.0 are not an indication that the quality of the drainage water has become better than that of the irrigation water; it is impossible. In order to relate irrigation water salinity directly to crop response functions the average root zone soil salinity is expressed as the EC of the saturation extract, EC_e . Since the water content at which EC_e is determined is about twice the soil water content at field capacity, the EC of the soil water at field capacity just after irrigation is about twice the value of EC_e (Pratt and Suarez, 1990).

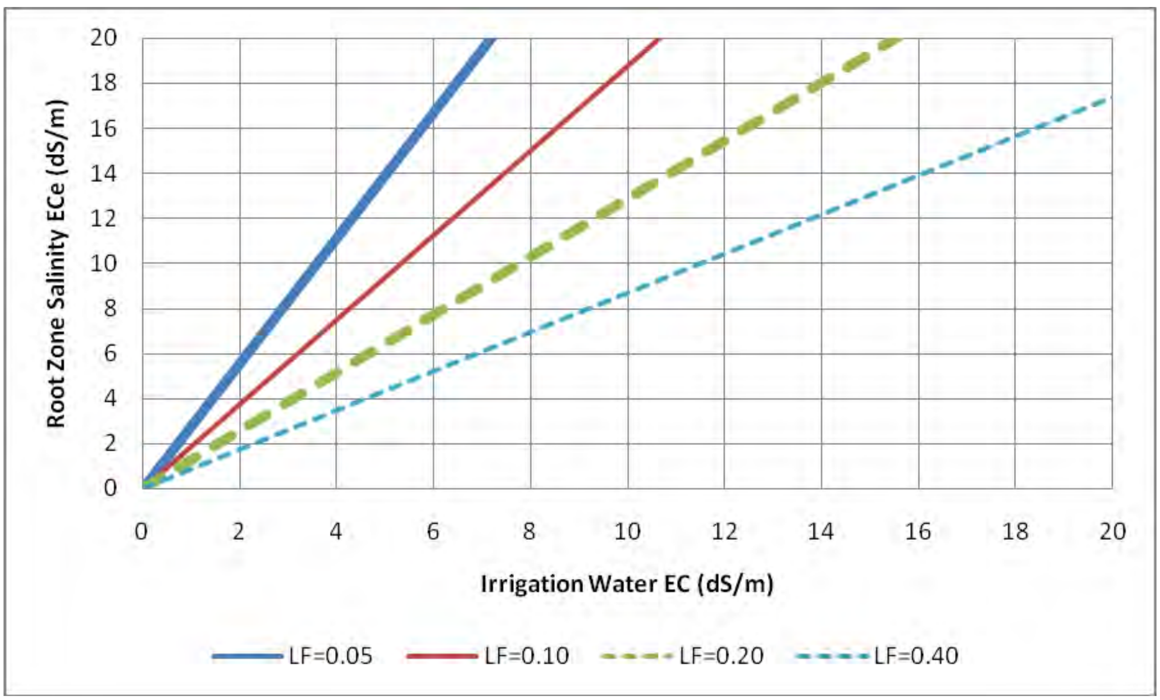

Figure 5. Relationships between leaching fraction (*LR*), average root zone salinity (EC_e, dS/m) and irrigation water salinity (*EC*, dS/m) under conventional (low frequency) irrigation management (Rhoades, 1999).

given irrigation water salinity depends on the leaching fraction. For example, irrigation water with EC of 2.0 dS/m can result in root zone salinities of 2 to 6 dS/m when leaching factors vary from 0.4 to 0.05 . Thus, irrigation water of reasonable quality can result in zero or 30 percent crop yield reduction (Fig. 4) depending on the leaching fraction, i.e. irrigation water management.

Figure 5 clearly demonstrates that no unique relationship exists between average root zone soil salinity and historic irrigation water quality which is the conceptual basis for Tier 2. For example, using the Tier 2 approach an average root zone salinity of 4 dS/m would lead to the conclusion that the historic water EC in the creek was 4/1.5=2.7 dS/m. However, Fig. 5 demonstrates that historic water EC could have fluctuated between approximately 1.5 and 5 dS/m depending on the leaching fraction. Fig. 5 also demonstrates that allowing releases of CBM water with an EC of 2.7 dS/m could result in average root zone soil salinities between approximately 2 and 8 dS/m depending on the leaching fraction. Thus, CBM water with an EC of 2.7 dS/m can result in zero to 45% yield reduction (Fig. 4).

We repeat our previous findings and opinion that the **Tier 2 methodology** as set forth in Appendix H section C(vi)(B) **is not reasonable nor scientifically valid for determining the EC of water that can be discharged into an ephemeral drainage in Wyoming** so that degradation of the receiving water will not be of such an extent to cause a measurable decrease in crop production (Hendrickx and Buchanan, 2009). Based on the current scientific analysis we conclude that the **Tier 2 methodology can cause degradation of the receiving water to such an extent to cause a considerable measurable decrease in crop production.**

4. EVALUATION OF THE TIER SYSTEM IN THE POWDER RIVER BASIN

Since crop yield reductions due to soil salinity cannot be observed visually until severe damage has occurred, it is a common strategy on agricultural lands at risk to implement monitoring programs for soil salinity as well as surface and ground water salinity. The data from such monitoring programs indicate whether salinity risks are increasing or decreasing and can guide prevention and restoration programs (Kaddah and Rhoades, 1976; Rhoades et al., 1999). Unfortunately, few comprehensive salinity data sets are available for the Powder River Basin and, therefore, we are grateful that the Department of Environmental Quality (DEQ) has invited us to visit the field in order to become familiar with the physical environment of the Powder River Basin and how the Tier 2 policy was implemented to regulate water quality. We have observed the basin from the air during a 45 minutes over-flight, visited several watersheds near Gillette during four field days, and through discussions with DEQ, land owners, and representatives of industry and the Powder River Basin Resource Council we have become accustomed with site conditions and water management practices.

In this chapter we will distill our field observations, information provided in reports and the literature, and comments by industrial and farmer water managers into a conceptual model that explains how CBM waters are likely to affect the watersheds in the Powder River Basin. But first we have to explain the “twin menace of water logging and soil salinity” that has challenged irrigation water managers for more than six thousand years (Hillel, 2000).

Waterlogging and Soil Salinity

The environmental conditions of arid and semi-arid watersheds change considerably when irrigation waters are introduced. A typical scenario is that water tables rise due to excessive irrigation, canal seepage, and inadequate natural drainage. Then, the soils become waterlogged while evapotranspiration depletes the applied water but leaves the salts behind which leads to increased salinity in the root zone and the shallow ground water. Upward capillary water flow occurs from shallow ground water and crop yields decrease due to a combination of inadequate aeration and high salinity levels in the root zone (Figure 6). These problems do not occur

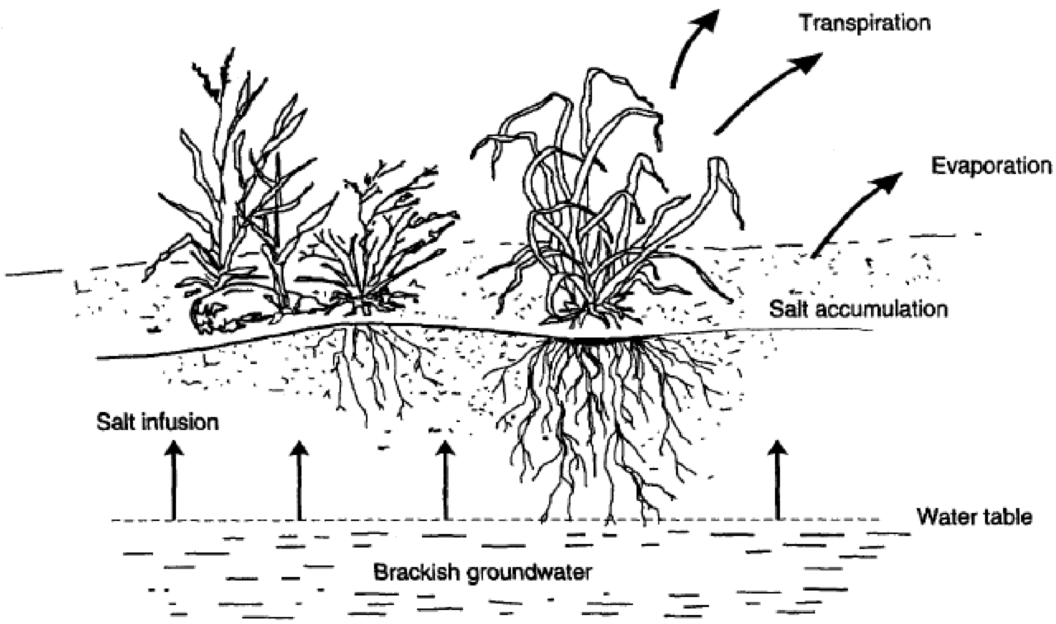

Figure 6. The process of waterlogging and soil salinity (Hillel, 2000). When irrigation waters are introduced in semi-arid systems the water table rises, capillary upward fluxes increase, and salts accumulate in the root zone unless sufficient leaching water is available. Salt accumulation will occur even if the irrigation and groundwater have low salt contents.

immediately after the start of irrigation but take time to develop. Sometimes it takes a decade as in Fallon, Nevada, or twenty years as in the Imperial Valley of California or more than fifty years as in the Indus Valley of Pakistan and India (Hoffman and Durnford, 1999).

One major exception is the irrigated lands of ancient Egypt that thrived for several millennia without developing root zone salinity problems. Before the construction of the Aswan High Dam in 1970, in the autumn the river Nile crested and inundated the flood plain as seepage naturally raised the ground water table. As the river discharge diminished water levels dropped and the ground water tables went down well below the soil surface. Due to this annual fluctuation of the ground water table under a free-draining floodplain the salts were leached from the root zone and carried away by the Nile itself (Hillel, 2000). A similar salt leaching mechanism has been observed by Hendrickx and his students in the Middle Rio Grande Basin (Hong, 2002).

The amount of water and salts that move with capillary rise from a shallow ground water table into the root zone depends on the soil texture and the depths of the root zone and the ground water table. For example, for a root zone with depth 0.5 m underlain by a water table at 1.0 m below the land surface the capillary flux that rises over a height of 0.5 m from 1.0 to 0.5 m height is critical. Under shallow ground water tables the volume of water entering the root zone by capillary rise can be of the same order of magnitude as that of annual precipitation. Figure 7 demonstrates that a capillary flux of 2 mm/day can be maintained in a clay loam over a height of about 2.4 m (8 feet) while such a flux in a sand soil will hardly reach 0.15 m (0.5 foot). For this report it is of more importance to consider how much the capillary rise can change due to a change of ground water table depth. Table 2 demonstrates that a rise of 30 cm (1 foot) of the ground water table can increase the capillary flux considerably. For example, in sandy loam (1) the capillary flux from a ground water table 91 cm (3 feet) below the bottom of the root zone will increase from 0.01 cm/day to 0.1 cm day when the water tables rises to 61 cm (2 feet) or from 0.1 cm/day at 61 cm depth to 0.6 cm/day at 32 cm depth. Thus, Table 2 indicates that a one foot rise in ground water table depth can result in a large increase in capillary upward water flow into the root zone and –as a consequence– a large increase in root zone salinity as well as a decrease in aeration due to waterlogging. Since the processes described in this section have been so often observed in arid and semi-arid watersheds when additional water is introduced one speaks about the “twin menace of water logging and soil salinity”.

One relevant case study on the agricultural impacts of irrigation induced waterlogging and soil salinity is found in the Lower Arkansas river valley (Houk et al., 2006) with historic water qualities similar to those found in the Powder River and Little Powder River[3]. As a consequence of rising ground water levels since 1870 saline water tables began to develop by the early part of the 20th century. In 1999, the average water table depth of the study area was 2.1 m below the surface, with approximately 25% of the region’s water table depth less than 1.5 m (Gates et al., 2002) while the minimum drain depth for salinity control in semi-arid regions is about 2.0 m (Hoffman and Durnford, 1999). Houk and his colleagues estimated the impact of both soil salinity and waterlogging on crop production. For Alfalfa in the Lower Arkansas river valley

[3] http://pubs.usgs.gov/fs/fs166-97/ accessed on September 12, 2009.

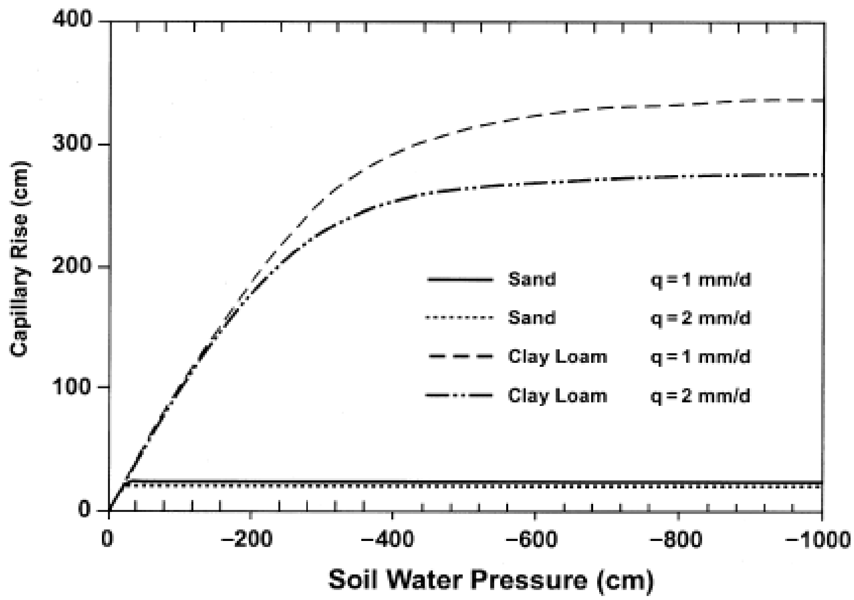

Figure 7. The height of capillary rise in homogeneous sand and clay loam profiles as a function of soil water pressure for evaporation fluxes of 1 and 2 mm/day (Hendrickx et al., 2003).

Texture	Capillary flux (cm day^{-1})									
	3	2	1	0.8	0.6	0.4	0.2	0.1	0.1	0.01
Sand[1]	14	15	17	18	19	20	23	26	29	37
Sand[2]	35	40	48	51	55	61	73	87	103	152
Loamy sand[1]	16	17	20	21	22	24	28	32	37	51
Loamy sand[3]	133	151	185	197	213	237	282	334	394	572
Sandy loam[1]	20	23	28	30	32	36	43	51	61	91
Sandy loam[2]	37	44	59	64	72	84	107	135	169	277
Loam[1]	21	26	35	38	43	50	65	82	103	171
Loam[2]	32	41	60	66	78	95	130	176	234	425
Clay loam[1]	10	14	23	27	32	40	58	82	112	219
Clay loam[3]	106	126	165	179	197	226	279	342	415	639

Table 2. Maximum height of capillary rise (cm) for ten fluxes in homogeneous soil profiles with different soil textures taken from the literature (Hendrickx et al., 2003). 1) (Carsel and Parrish, 1988); 2) (Wösten and Van Genuchten, 1988); 3) (Van Genuchten, 1978).

they estimated that relative yields decline about 11% for each one foot decrease in ground water table depth if the ground water table depth is shallower than 1.34 m (4.5 feet) due to lack of aeration caused by waterlogging. They estimated the relative yield due to root zone salinity using the Alfalfa response function with a threshold value of 2 dS/m (blue line in Fig. 4). The combined impact of waterlogging and root zone salinity was estimated by multiplying the relative yields estimated for, respectively, waterlogging and root zone salinity. For example, the total relative yield of Alfalfa on a field with a shallow ground water table of 1.0 m and a root zone salinity of 6 dS/m is estimated as follows: (1) water logging reduces yield by 11% for each 30 cm decrease of ground water table depth from the threshold depth of 1.34 m so that a ground water table depth of 1.00 m results in a relative yield of 0.89 due to waterlogging; (2) the relative yield due to soil salinity is 0.7 (brown line in Fig. 4); (3) the relative yield due to waterlogging and root zone salinity is 0.89 times 0.7 which equals 0.62.

The study by Houk and his colleagues is relevant for this report since it provides the tools to quantify independently the effects of waterlogging and root zone salinity for Alfalfa in a river valley with conditions somewhat similar to those in the creeks of the Powder River Basin.

In summary, adding water to a semi-arid watershed will often lead to a rise of ground water tables toward the land surface. If the water tables come within 3 to 1 m of the land surface, waterlogging and/or root zone salinity can occur even if the quality of the irrigation water is excellent. There is no relationship between irrigation water quality and the extent of waterlogging and/or root zone salinity and, therefore, there is no scientific basis for Tier 2 and even Tier 1. Tier 1 and Tier 2 permits are no guarantee that landowners will not suffer a measurable decrease in crop production. Since both Tier 2 and Tier 1 add water to a semi-arid hydrologic system they have the potential to cause more harm than good.

Conceptual Model of CBM Water and Salt Movement in the Powder River Basin

In Chapter 3 and the previous section of this Chapter we have explained the basic hydrologic principles of water and salt movement through semi-arid systems together with relevant examples from the literature. The purpose of this section is to develop a conceptual model of CBM water and salt movement in the Powder River Basin and to use this model to develop guidelines for environmentally safe disposal practices that will not lead to measurable decreases in crop production. Due to time constrains this section is written in a qualitative manner and all points discussed need more in-depth study before used for policy making or developing monitoring programs.

Historic Water and Soil Quality in the Powder River Basin.

The watersheds that we have visited in the Powder River Basin are located in the Gillette area with an average annual precipitation of about 14 to 16 inches (350 to 400 mm). Annual pan evaporation is estimated somewhere between 44 and 70 inches (1100 and 1800 mm). As a consequence deep aquifer recharge rates are estimated to vary from 0.5 to 2.0 mm per year (Puckett, 2008) which is characteristic for many arid and semi-arid regions (Hendrickx and Walker, 1997). Therefore, salinity is expected to be an integral part of the landscape. Historic water quality measurements by the USGS show that water quality in the Powder River varies from high EC at low discharge rates to low EC at high discharge rates[4] which reflects low salt contents during runoff of snowmelt and rainstorms but high salt contents when only saline seeps contribute to the flow in the river. In the field Mr. James Wolff showed us a saline seepage that was not caused by CBM waters but by the practice of leaving uphill dry land farm fields fallow during one year. Then, no plant roots will take up precipitation, water accumulates in the soil and percolates to deeper depths. At locations where soluble salts are present in the subsoil such as in geological layers formed in marine environments, the percolating water will dissolve salts and transport those downward. When the water finally daylights at the toe of a hill, a saline seepage will result; or the saline water can discharge into one of the creeks. This may explain relatively high EC's in creek water when snowmelt or storm runoff are absent.

Since the creeks in the Powder River Basin meander through small sloping valleys surface water and ground water will be well mixed and the water quality of the surface water in the creek is expected to be quite similar to the water quality of the ground water. As a result of the elevated EC of ground water, soil salinity is expected to occur in some of the valley soils, especially the higher ones that are not inundated on a regular basis.

Thus, saline soils and saline seepage waters as well as high quality snow melt and precipitation waters are all part of the semi-arid hydrologic system in the creeks of the Powder River Basin. The landowners of the Powder River Basin have been able to make these lands productive since the late 1800's and were able to overcome salinity and an extremely short growing season. They know when and where to put spreader dikes to make their challenging environment produce a

[4] http://pubs.usgs.gov/wri/wri014279/pdf/figs3-4.pdf accessed on September 13, 2009.

decent crop yield. Just as the Egyptian farmers in the floodplain of the Nile, the farmers of the Powder River Basin depend on snowmelt and storm runoff to crest their creeks, inundate their bottom lands, irrigate their hay meadows, and –most of all– wash their salts away when water levels fall. Without this annual cycle of high creek flow to wet the lands and low creek flow to pull the salts away, the system will not be viable.

Effect of CBM Waters on Creek Watershed Hydrology

Finding a new source of water in a semi-arid environment creates expectations and with good reason. Many are the testimonies of land owners who use CBM waters for managed live stock watering and advanced Tier 3 highly managed productive irrigation projects. However, where CBM waters have been released in the fragile creek system under the false assumption that "good" water cannot result in "bad" soils and crop yield reductions, the twin menace of waterlogging and salinity has appeared.

As in many other arid and semi-arid locations of the world, adding CBM waters to the Powder River Basin creeks almost immediately resulted in prolonged flooding due to inadequate natural drainage and ice dams. Although ice dams can be prevented by timing of CBM water releases, inadequate natural drainage is not so easy to adjust. Too much drainage may convert productive bottom lands and hay meadows in dry range lands while too little drainage may salinize the soils. The most extreme case is the property of Mr. Clabaugh that is frequently inundated for long periods of time. He is right: waterlogging and increasing soil salinity are reducing the productivity of his land. Restoration should start as soon as possible to prevent more permanent damage.

More subtle and much less visible are the lands where the ground water table has risen but stayed below the land surface. This is the case in all creeks that have converted from ephemeral to permanent streams. When an ephemeral stream loses its water, the ground water level has fallen below the bottom of the stream; when a stream doesn't lose its water anymore, the ground water level has not fallen below the bottom of the stream and is located above the bottom of the stream. Then, as explained above the process of soil salinization and crop yield reduction start due to the shallow ground water tables, even when the quality of the water added to the system is good. A clear example is the property of Mr. Tooter Rodgers where the surface water in the SA creek is piped around his property during the summer period. Yet, the creek is still flowing due to the fact that the ground water table has risen. The quality of the creek has now become equal to the quality of the saline ground water and is measured to be around 6 dS/m. This ground water quality is a result of historic water quality, CBM salts, and lack of leaching after the creek converted from an ephemeral into a permanent creek due to shallower ground water table levels.

In summary: there is no doubt that CBM waters have resulted in shallower ground water tables. This in turn will have increased capillary upward fluxes, soil salinization, crop yield depression, and ground water salinity. Since no systematic monitoring is conducted in the basin, it is difficult to quantify these increases but there is no doubt about the overall process.

CBM Waters and Tier 2

As the Tier 3 farmers demonstrate there is a successful way to manage CBM waters for crop production. However, whereas Tier 3 farmers have a clear agreement with industry, are assisted by experts, and know when, how much, and what quality water they will receive, a Tier 2 farmer is in a completely different position. For example, Mr. Swartz who manages about 300 acres of irrigated land does not know when he will have irrigation water, how much irrigation water he will receive, nor what the quality of his irrigation water will be. His water comes from about 150 outlets operated by about 10 different companies, his water quality is regulated by DEQ that sets an end-of-pipe CBM water quality limit, and his water quantity is regulated by the State Engineer’s Office. TIER 2 is an impediment against farmer water management and puts out salts without any control or monitoring because adequate control of soil salinity changes requires that the farmer has access to multiple and dependable supplies of irrigation water where at least one supply is of good quality (Maas and Grattan, 1999)

In Ivy Creek CBM water discharged in the creek and never makes it to the downstream landowner. This is considered a success but is it? Where did the water and the salts go? Nobody knows since monitoring is not part of a Tier 2 or Tier 1 permit. The water is probably decreasing the depth of an existing water table and will sooner or later reach the root zone and result in soil salinization. Or the saline waters may start seeping towards the downstream landowner.

5. EXPERT SCIENTIFIC OPINIONS

We have presented scientific evidence that no unique relationship exists between irrigation water quality on the one hand and root zone soil salinity and crop productivity on the other. Therefore, we conclude that the **Tier 2 and Tier 1 methodology** as set forth in Appendix H section C(vi)(B) **is not reasonable nor scientifically valid for determining the EC of water that can be discharged into an ephemeral drainage in Wyoming so that degradation of the receiving water will not be of such an extent to cause a measurable decrease in crop production.**

We have observed in the field (Clabaugh, Swartz, Rodgers) that the **Tier 2 and Tier 1 methodology has caused a rise of the ground water table that resulted in both "waterlogging and –most likely– increased soil salinity"**. Had a monitoring program be in place since the beginning of CBM water releases, it is almost certain that a decrease in crop production would have been measured due to waterlogging and/or increased soil salinity. The damage done by Tier 2 and Tier 1 starts by creating water logged conditions in the drainages: **the true problem is the quantity of CBM waters rather than its quality**.

Prominent agricultural salinity experts state "The successful use of saline ... waters for irrigation requires **appropriate management practices to control salinity**, not only within the irrigated fields, but also within the associated irrigation project and geo-hydrologic system" (Rhoades, 1999) and "**adequate control of soil salinity** changes requires that the farmer has access to multiple and dependable supplies of irrigation water where at least one supply is of good quality" (Maas and Grattan, 1999). The **Tier 2 and Tier 1 methodology results in the uncontrolled and unmanageable release of CBM waters** since the farmers receive at unknown times, unknown volumes of water of unknown quality from hundreds of outlets controlled by different companies.

We recommend that **comprehensive monitoring of soils, ground water, and surface waters** is undertaken in all drainages that have received and are receiving CBM waters. The objectives are: (1) to determine where the salts are accumulating in the hydrologic system; (2) to assess where and when the salts will leave the system; (3) to design restoration measures for naturally and artificially irrigated lands that already have been affected or will be affected by “waterlogging and soil salinity”.

We have observed in the field (Creswell, Werner, Williamson) that Tier 3 and the “irrigation waiver” are viable alternatives for the Tier 2 and Tier 1 methodology. Under Tier 3 the CBM waters are managed in a proper manner and used for increased crop production to the satisfaction of the landowners. Therefore, **we recommend to abandon uncontrolled releases of CBM water into the drainages by Tier 2 and Tier 1 methodology in favor of the Tier 3 methodology that relies on appropriate management practices to control salinity.**

Tier 3 is best implemented over deep vadose zones so that the saline drainage waters percolating from the root zone enter the ground water gradually and minimize salt load to the Powder River (Hendrickx et al., 2005).

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