Strategies, Monitoring and Data Needs for Preventing Impacts from Coal Bed Methane Produced Water to Crop and Forage Production in Wyoming

Gerald E. Schuman, George F. Vance and William Schafer[1]
September 2010

1 Role and Scope of Technical Advisory Team Review

The Wyoming Department of Environmental Quality (WDEQ) appointed a Technical Advisory Team (TAT) comprised of soil scientists Gerald E. Schuman, George F. Vance and William Schafer to provide recommendations concerning agricultural uses of coal bed methane (CBM) produced waters on the lands that are protected by Wyoming water quality statutes. The WDEQ asked for specific guidance on the kinds of broad scientific monitoring programs that would provide data needed to identify potential impacts and prevent or reduce degradation of soils and crop/forage production. It is the intent of this report to address possible water quality and quantity issues relating to CBM produced water discharge that have the potential to degrade the natural resources (soil, water, and plant communities) of the State. The TAT recommends that whatever regulatory programs WDEQ develop for CBM waters that they must be accompanied by an implementation and effective enforcement program.

The specific tasks given to the TAT were to provide the Working Group with the following:

1. Advice and recommendations concerning the soils and irrigation aspects of WDEQ's permitting policies for CBM produced water in the Powder River Basin; and

2. Advice and recommendations on all other soils and/or irrigation technical issues referred to it by the Working Group.

Our response is organized into the following key sections. We provide a response summary in Section 2 that identifies how we addressed key issues highlighted by the CBM Working Group. In Section 3, we provided a narrative report that provides some context for the basis of many of our opinions about how soil, crop/forage, surface water and groundwater monitoring can be used to protect agricultural production in areas where CBM produced waters are discharged or stored. The overall monitoring and contingency plan framework that was developed in conjunction with WDEQ-Water Quality Division is also described. Finally, in Section 4 we describe specific monitoring strategies for surface and groundwater, soils and crop/forage production.

[1] Appointed members of the Wyoming Coal Bed Methane Produced Water Working Group, Technical Advisory Team

2 Response to Working Group Summary

The CBM Working Group developed a general consensus on several specific issues that formed the basis for much of the deliberation by the TAT. The following summary shows how we addressed each of the recommendations provided by the CBM Working Group.

Introduction. The CBM Produced Water Working Group recommends that WDEQ incorporate the following provisions into its WYPDES permit program for CBM produced water discharges in the Powder River Basin.

Permitting Basis

Working Group Recommendation:

A. Permits shall protect historically existing (pre-CBM) indigenous plant or crop communities. Such communities shall remain capable of survival and maintenance under the conditions of increased soil moisture, salinity, and alkalinity from CBM discharge.

TAT Response:

The concern expressed by the Working Group about ensuring that the native plant species are maintained in the areas impacted by CBM discharge water is legitimate. Large increases in water flows in an ephemeral stream that bring the water table to within three feet of the surface, or sustained overland flow onto a flat drainage bottom, will result in a change in the plant species present. Continued high flows that inundate a land area or cause a near surface high water table will cause a major shift in the plant community from one of native species such as western wheatgrass, blue grasses (Poa sp.), bluegrama, etc., to species such as foxtail barley, rabbitfoot grass, general sedge species, cattails, etc. These replacement species will be those that desire or can tolerate a high water table/flooding and salt/sodium buildup and are not palatable or nutritious like the native species. When CBM water discharge ends or is terminated these species will not be sustainable. With time after water removal these species will die and the area likely invaded with weedy species such as kochia, Canada thistle, Russian thistle and other noxious weeds found in the area. These conditions should be prevented and areas impacted reclaimed back to native species. Such reclamation may require soil amendments to correct sodium accumulation, leaching of salts and seeding along with associated seedbed preparations.

Working Group Recommendation:

B. Permits shall be based on drainage-specific factors, such as soils, water quality, crop species, irrigation method/amount channel capacity, multiple operators, flow conditions, topography and water table factors.

TAT Response:

1. *Permits should require monitoring of the following parameters for both perennial and ephemeral streams:*

    a. *Flow: flow rates should be monitored continuously.*
    b. *Water Quality: Always monitor the following: pH, EC, Ca, Mg, and Na. Other parameters that should be monitored when appropriate include: K, SO_4, HCO_3, Cl, ^{13}C, and/or other isotopes.*

2. *Action thresholds for perennial streams:*

    a. *Water quality triggers -- statistical trend analysis or exceedence of the EC limit.*
    b. *USDA Salinity Tolerance Database EC, background or statistically increasing trends (though upward trend not necessarily a compliance issue). Trend analysis needs to account for seasonality, flow-chemistry variation, and non-normal distributions.*
    c. *Hanson Chart – primary utility for surface irrigation, not useful for subsurface water that may be subirrigating a field. Limit the Hanson Chart domain to >3 SAR, which corresponds to 1.0 dS/m EC. For default limits, also limit Hanson Chart to <10 SAR, which corresponds to 2.0 dS/m EC. Hanson Chart does not apply to high smectitic clay soils (e.g., these soils require more scrutiny). Smectitic soils are defined as having more than 50% smectite measured within the clay fraction.*

3. *Action thresholds for ephemeral streams:*

    a. *Presumptive agricultural use is surface overflow onto hay and native grass or subirrigation.*
    b. *If flow becomes perennial – need to monitor groundwater levels. Use water quality triggers as for perennial drainages.*
    c. *For ephemeral drainages, triggers may vary due to inherent variability, so we also need to rely on soil/crop monitoring and trends.*

4. *Action to be taken when thresholds are exceeded in perennial and ephemeral streams:*

    a. *Expand water quality parameters and constituents to be monitored.*
    b. *Failure of criterion triggers more intensive evaluation of CBM activities as the presumptive cause of surface water degradation that impairs crop/forage production, then curtail discharge or otherwise mitigate.*

Working Group Recommendation:

C. Permits shall be based on vetted, credentialed science, be preventative, not reactive and include meaningful and timely enforcement. Permits should prevent harm to lands and require the permittee to demonstrate compliance.

TAT Response:

A coordinated surface water, groundwater, soil and crop/forage monitoring plan is proposed that will provide the necessary information to develop appropriate enforcement. Monitoring of outfalls, reservoirs, channels, soils and groundwater is intended to prevent degradation of soil and crop/forage production.

Working Group Recommendation:

D. If the quantity of the water is causing unacceptable water quality or has the potential to cause unacceptable water quality, then the EQA gives DEQ the authority to regulate water quantity. (AG Formal Opinion No. 2006-001)

TAT Response:

The technical recommendations distinguish between water quality and water quantity impacts to crop/forage production. In regard to water quantity: (a) overland flooding caused by discharges should be prevented; (b) perennialization of flow occurring in the absence of flooding should not be allowed to cause an unacceptable increase in the water table.

Working Group Recommendation:

E. Within each drainage, where no economically feasible technical solutions exist to prevent salt loading and flooding problems, the permit shall require a water management or irrigation plan jointly developed by landowners and the permittee.

TAT Response:

We agree that effective water management is the most critical element in preventing impacts to crop/forage production. Water management plans need to be tailored to site-specific conditions. A coordinated watershed monitoring and contingency plan, as proposed by the TAT, will help determine the effectiveness of CBM water management. The monitoring plan needs to measure performance of the water management plan. Review of monitoring results needs to identify trends and distinguish cause/effect. In addition, the TAT made recommendations on managed irrigation programs including the transition from irrigation back to dryland conditions.

Definitions

Working Group Recommendation:

A. Define what constitutes a measurable decrease in crop or livestock production due to CBM discharged water. (This would involve development of the metrics and methodology for measuring whether or not such a decrease has occurred or would be likely to occur due to CBM discharged water.)

TAT Response:

1. *Monitor crop and forage yield at soil sampling locations.*
2. *Need to account for factors that affect crop/forage yields that are not related to CBM produced water such as climatic factors, disease, insects, soil fertility, stand age, etc. The TAT recognizes that crop yields are highly variable and that variations of 10-30% or more can occur absent CBM water influences. Crop yield monitoring alone is not the most effective means of identifying CBM impacts. Therefore the TAT recommends reliance on early warning monitoring such as described in the surface water, soils, and groundwater monitoring sections described in section 4.2 below.*

<u>Monitoring</u>

Working Group Recommendations:

A. Require baseline measurements of soil quality, plant communities, and shallow groundwater quality & depth before issuing a discharge permit. In the absence of baseline data on plants and soils due to CBM discharges, certification or documentation of baseline plant and soil inventories from landowners, aerial surveys, NRCS data, or other historical information should be used.
B. Require monitoring of surface water quality & flow and shallow groundwater quality & depth to ensure compliance with Chapter 1 – Section 20.
C. Require on-going monitoring of soils, crop yields, etc. at the point of use during the period of CBM discharge.

TAT Response:

*The TAT fully specified a watershed monitoring regime, thresholds, and contingent corrective actions for outfalls, surface water, groundwater, soils, and crops and forage for CBM permits in the Powder Ri*ver Basin.

3 Basis of TAT Opinions and Recommendations

Steve Smutko, Coal Bed Methane Working Group Facilitator, submitted a charter to the TAT that included a request for details on specific tasks (the matrix piece) needed for WDEQ to address CBM water issues. The Charter is as follows.

<u>Purpose:</u>

The scientific basis for the methodology used by the DEQ to establish CBM discharge permit limits has been questioned by consultants hired by the Environmental Quality Council (EQC) and the DEQ. As a result, the Department has put a hold on Tier 2 permits until the CBM Produced Water Working Group (Working Group) can develop recommendations that meet the needs of the various stakeholders. Additionally, the EQC is upholding CBM permit appeals and the Environmental Protection Agency (EPA) is placing interim objections on the issuance of new CBM permits.

A Technical Advisory Team (TAT) will be formed to review the Working Group's recommendations and DEQ's current methodology for setting CBM permit limits and to suggest recommendations for changes to that methodology. The TAT's suggested recommendations for changes shall be provided to the Working Group for its consideration.

Tasks: The TAT shall provide the Working Group with the following:

1. Advice and recommendations concerning the soils and irrigation aspects of DEQ's permitting policies for CBM produced water in the Powder River Basin; and

2. Advice and recommendations on all other soils and/or irrigation technical issues referred to it by the Working Group.

The following analytical matrix is an outline of the information being sought by WDEQ. Based on recommendations already generated by the larger Working Group, each empty box represents a potential review item or permit condition to be used by WDEQ in the future. The task of the TAT will be to populate each box with specific recommendations. If the TAT agrees that a particular box is unnecessary or irrelevant to meeting the ag protection goals outlined by the working group, then the box can be eliminated. Conversely, if there are necessary or relevant items which are not presented here, the TAT may add items. If the TAT agrees that a box should exist, then the box should be populated with a recommendation.

Membership

Membership in the TAT shall be three soils and/or irrigation experts selected by the DEQ. The DEQ CBM permitting specialist will serve as an ex-officio member of the team.

Coordination

The Working Group facilitator will coordinate the activities of the TAT and the Working Group.

Process

The TAT will accomplish the tasks identified above through one or more meetings. To the extent possible the TAT will attempt to reach consensus. If consensus cannot be reached, "majority" and "minority" recommendations will be provided to the Working Group.

Schedule

The TAT will make every effort to meet as often as necessary to complete the tasks; The TAT will develop recommendations for review by July 30.

Analytical Matrix

Monitored Substrate	Siting Guidelines (sample locations and densities)	Chemical/ Physical parameters to be monitored	Frequency and timing of sampling	Action Thresholds (At what chemical/ physical point does the alarm go off)	Corrective Action (What should the permit do about it, in order to avoid damage to crops)
Outfall (end-of-pipe)	N/A (Known)				
Reservoir water					
Instream surface water (IMP)					
Soils					
Groundwater					
Crop					

3.1 Watershed Monitoring & Contingency Plan (WMCP)

Much of the monitoring described in this report is not well-suited to individual permits. Therefore, permits should not be issued until WMCPs are developed. There is a need for broad watershed scale planning, coordination among stakeholders, and data collection, management and interpretation. Also, we sought where possible to identify critical threshold levels for monitoring programs that would require a response. Consequently, contingency actions are a component of the plan, e.g., a watershed monitoring and contingency plan.

We recommend that a watershed group consisting of landowners, Conservation District personnel, gas/petroleum industry, and regulatory staff meet annually to review and discuss monitoring results and to identify specific issues and concerns. Monitoring locations, frequency, and constituents monitored may be adapted to changing issues and concerns. The watershed group should have access to an expert panel or person who can help interpret the extensive monitoring data collected through the proposed program.

<u>Suggested Elements of Watershed Monitoring and Contingency Plans</u>

- UW School of Energy, Cooperative Extension, NRCS, or conservation district personnel could assist with people on the ground to monitor and advise affected people in the watersheds.
- Annual meeting of independent experts and advisors should be conducted to assess data collected and make recommendations for further CBM discharge water management.
- Representative on-channel reservoirs for each drainage should be selected to study the complete water balance (vertical/horizontal seepage, evaporation).
- Develop watershed groups for each watershed-wide monitoring program.
- Flooding has to be controlled if you want the water quality controls to work.
- In watersheds with heavy clay smectite-dominant soils (for which Hanson Chart not designed), possibly increase monitoring.

3.2 Challenges in Assessing CBM Impacts

One of the tasks given to the TAT was to develop a comprehensive monitoring program whose objective is to prevent impacts to agricultural land uses by identifying changes in water, soils and crops/forages downstream of CBM operations. One of the many challenges of using a monitoring approach is how to determine whether changes detected in the monitoring program are caused by CBM water and also to derive early warning systems that help prevent crop/forage losses. Some users of monitoring data may conclude that CBM water should be assumed to cause any adverse change in water quality, soils or crops/forages unless there is clear evidence to the contrary. This is an example of "confirmation bias". When someone has a strongly held belief (e.g., CBM water is harming crops), then any information is assessed in a manner that tends to support that belief. Another challenge in interpreting monitoring data is the fact that "correlation does not imply causation". For example, if crop yields are observed to decrease over a five-year period during which CBM activity increased – there would be an inverse correlation between crop yield and CBM discharges. However, this does not prove that CBM caused the yield decrease. Decreased yield may have been caused by drought or increased stand age in case of alfalfa. To help alleviate errors in the interpretation of monitoring data, it is helpful to develop a conceptual model of the Powder River Basin that identifies the relationships between CBM water, surface water, groundwater, soils and crops/forage.

3.3 Conceptual Model of CBM waters Impacts on Crop/Forage Production

The quality of CBM waters can vary. Without proper management, some CBM water may harm crops or forages due to chemical changes to soils (e.g., increased EC or SAR), through sustained flooding, and through salinization due to an elevated water table. However, other CBM waters may not be suitable for agricultural use even with management due to unsuitable water quality and/or soil characteristics. Soils with high EC or SAR, floods and high water tables can also occur naturally throughout the Powder River Basin. A challenge of the proposed monitoring programs is to determine where these changes are caused by CBM water. A conceptual model (Figure 1 and following paragraphs) helps clarify the connection between CBM water and crop or forage systems.

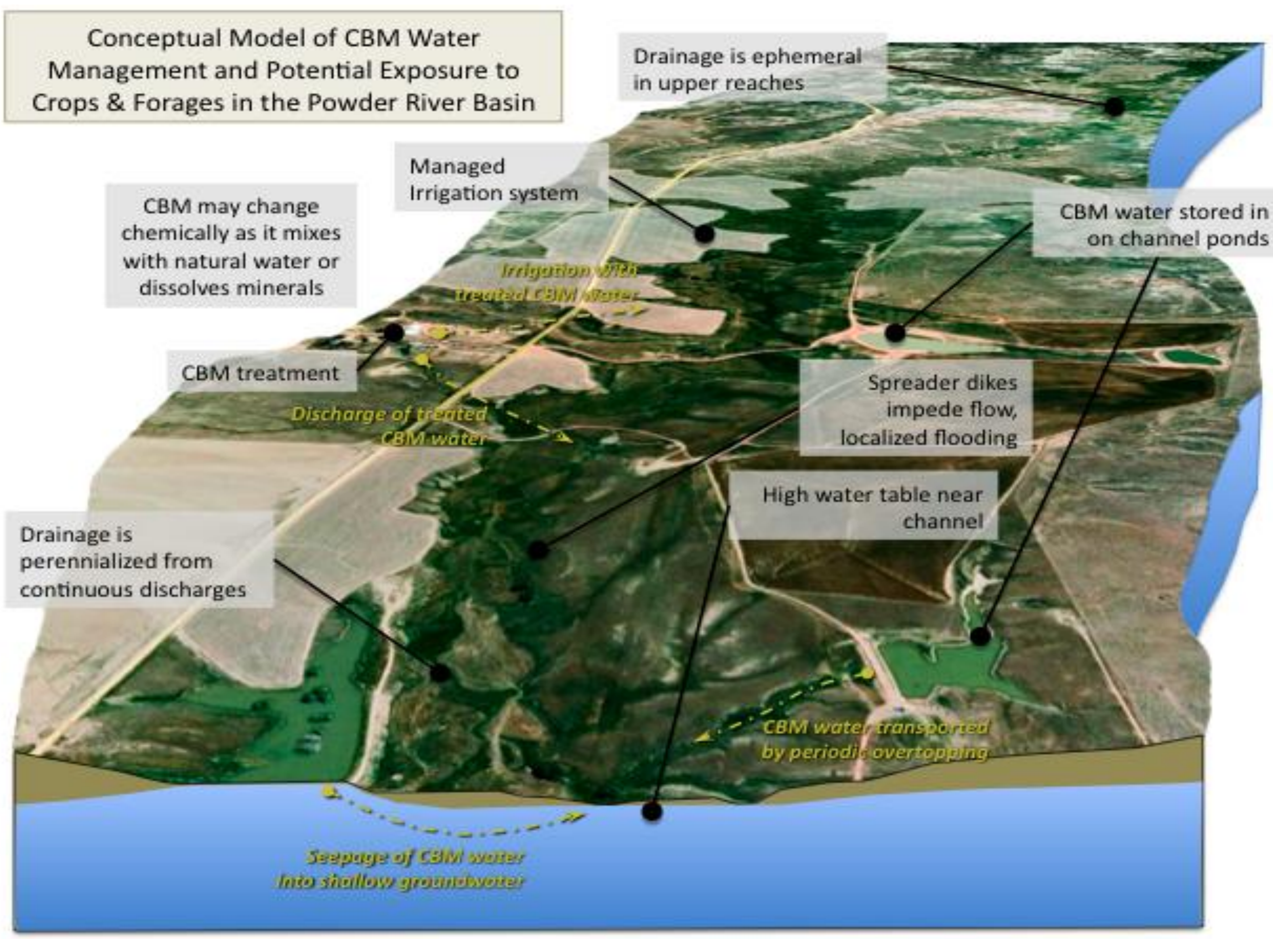

Figure 1. Conceptual model of CBM water migration routes and potential impacts in the Powder River Basin of Wyoming.

The amount and duration of exposure to CBM water may differ for each water management method. Application of CBM water to crops may impair soils or vegetation but continuous long-term exposure to CBM water is of greater concern than short-term or periodic exposures. Additionally, historic water quality monitoring programs have established that the chemistry of CBM water often changes as it migrates in surface or groundwater systems. Typically, the EC increases and SAR decreases as water migrates, mixes with natural waters and dissolves naturally-occurring soil salts, minerals and exchangeable ions. Higher ECs may contribute to changes in plant communities, particularly in stream channels and bottomlands used for agricultural purposes. In addition, high water tables created by CBM waters in some stream channels have altered soil characteristics and vegetation communities.

It is useful to distinguish the ways that CBM water may reach irrigated soils and crops. The potential for exposure of CBM water to irrigated soils and crops/forages depends on CBM water management unless exposure is unintentionally. The following sections describe the risks and manner in which impacts could occur for each CBM water management approach.

3.3.1 Direct Application of CBM water – Managed Irrigation

Use of CBM water for managed irrigation systems is exempt from discharge permits in Wyoming. However, managed irrigation requires utmost care in selecting suitable soils and crops or forages, needs consistent irrigation scheduling, and may necessitate soil reclamation to reverse sodic conditions after irrigation ceases. Properly sited and managed, irrigation is unlikely to cause extensive offsite impacts; however, any potential impact should be addressed prior to implementation of a managed irrigation operation.

3.3.2 Intermittent Surface Water Discharge – Reservoir Overtopping

Discharge of CBM water into on-channel ponds is currently the most common means of managing CBM water. Ponds are designed so that water placed in them will evaporate or infiltrate into the groundwater so that pond capacity remains available for continuous CBM discharges. On-channel ponds are designed to retain CBM water plus some natural runoff. When storms exceed a particular recurrence interval, excess water may discharge from the ponds for a 24 hour period through over-topping of the reservoir following the event. Water samples collected by the WDEQ that were downgradient of over-topping reservoirs nearly always met the Hanson Chart limits (Figure 2) for impacts related to soil infiltration, (which does apply to clay soils with more than 50% smectite clays). While the water flowing out of on-channel ponds typically has lower SAR than CBM waters, the increased salinity of these waters can exceed general limits for irrigation of salt intolerant crops/forages.

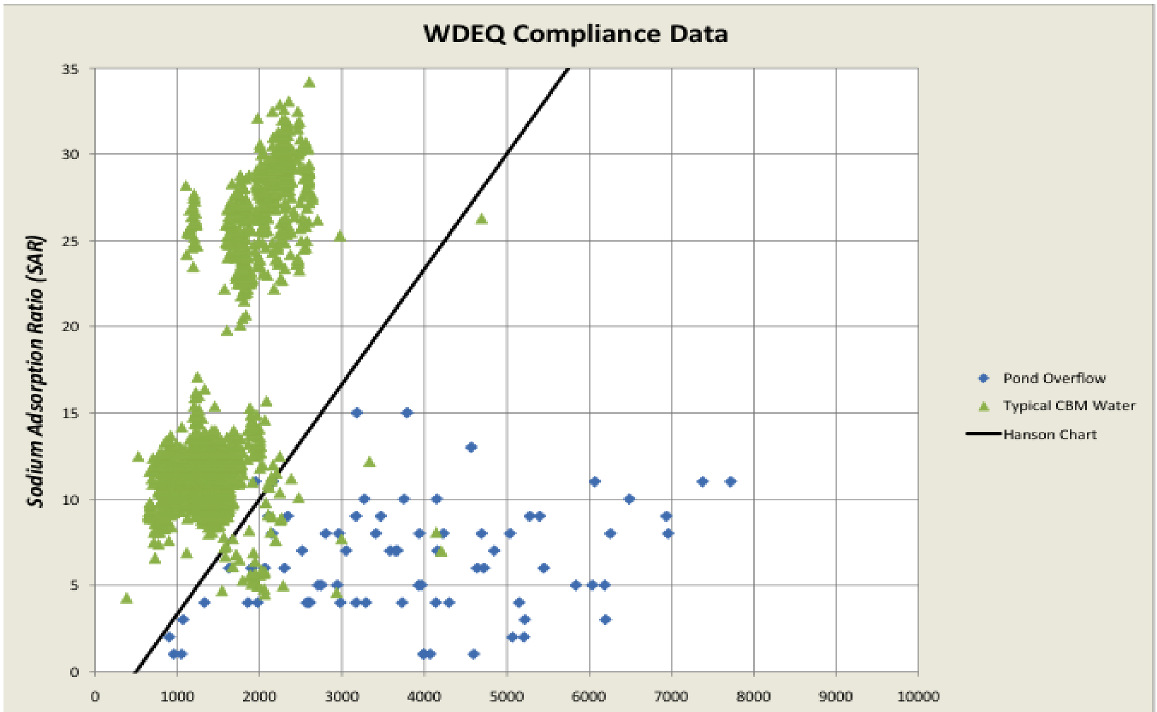

Figure 2. Chemistry of CBM water and water downgradient of over-flowing ponds (WDEQ permit data), and CBM water from middle and upper Wild Horse Creek.

Reservoirs are designed to leak, but the design principle is that pond infiltration will enter a bedrock groundwater system that does not have a hydrologic connection to surface water. Where pond infiltration flows laterally and reaches surface waters or shallow groundwaters in irrigated fields, localized impacts may occur. Various techniques can be used to detect lateral seepage including visual inspection of vegetation, monitoring wells, and GEM (geophysical electromagnetic surveys).

3.3.3 Continuous Surface Water Discharge – Reservoir Overtopping

Direct discharge of untreated CBM water is relatively uncommon in Wyoming and would only be permitted where the CBM water quality is better than background conditions. It is more common for treated CBM water to be discharged to surface water or to be used for irrigation. Typically there are few water quality concerns related to direct discharge of treated water, although quantity can be a problem. Continuous discharge into ephemeral drainages is more likely to cause perennial flows to occur in parts of watersheds that become inundated, which is usually due to alteration in the alluvial groundwater levels. If water tables increase to within 3 to 8 feet of the soil surface, crop production may increase. Where water tables rise to less than 3 feet of surface, surface salinization is a potential problem regardless of instream water quality. If water tables are within 1 foot of the soil surface for extended periods, lack of oxygen may kill portions of the crop or forage plants. Only plants tolerant of wet conditions will grow where water tables are close to the surface. If channel capacity is severely restricted, small flows may cause localized flooding upstream of where channel constrictions occur.

3.3.4 Discharge to Perennial Streams

The procedures for developing permit effluent limits developed in the Clean Water Act are suited for permitting discharges to perennial streams. Therefore policies and procedures are well-established for these conditions. Typically, effluent limits are calculated in such a way that water quality is protected when flows are at or above some critical flow. For constituents such as EC and SAR, effluent limits should be protective for "average" flow conditions. Mean or median flows may not be the best measure of "average" conditions in all cases because streamflow measurements are strongly skewed. EPA recommends use of harmonic mean flows in these cases.

4 Monitoring Approaches

The risk of occurrence of water quality and water quantity impacts is quite different for different water management strategies. Effective monitoring needs to assess watershed processes and the entire migration pathway from the point of CBM discharge to the potentially affected crop or forage. Monitoring may involve sampling at the outfall, in ponds, in surface water, in groundwater, and in soil and crops/forage. In order to determine that a crop/forage impact is cause by CBM, it is necessary to find a reasonable connection between CBM water and the irrigated field through multi-media sampling and monitoring.

4.1 What can be retained from the AUPP?

The proposed monitoring program described below is not meant to completely replace the current Agricultural Use Protection Policy. There are elements of the Policy that may remain useful in a revised regulatory program. For example, the Hanson Chart is generally applicable for consideration of soil infiltration except for the conditions described below:

- For soils dominated with smectite type clays, it is possible that adverse effects could occur at lower SAR levels than are prescribed by the Hanson Chart suggesting that both soil and crop responses must be carefully monitored in these cases or that these sites be eliminated from CBM water operations.
- The Hanson Chart should not be applied below an EC 1.0 dS/m, e.g. SAR > 3, particularly at water EC levels less than 0.5 dS/cm because of the potential for reduced infiltration
- The Hanson Chart, which is specific to soil infiltration only, may provide a reasonable assessment of the interaction of SAR and EC at EC levels of 2.0 dS/cm (SAR < 10), but should not be used to permit direct discharge of water with SAR > 10 .
- Crop/forage tolerances to soil and water salinity must also be taken into consideration.

The concept of maintaining water at equal or better than background conditions, which was a cornerstone of Tier 2 is useful, but new methodologies for assessing background are required. The WDEQ may consider having an expert panel develop estimates of background water quality for individual watersheds or stream segments based on consensus based scientific methods.

4.2 Intended Use of Monitoring Data

The following tables describe specific monitoring approaches for outfalls, reservoirs, surface waters, groundwaters, soils and crops/forage. The individual monitoring programs are not meant to be used or interpreted independently but rather should be designed, implemented and interpreted in an integrated watershed-based manner. Interpretation of monitoring results requires careful consideration of likely relationships between CBM produced water, natural surface water, groundwater, soils and crops/forage. Therefore, if a decrease in crop yield is detected, this does not necessarily mean that CBM discharge water caused the decrease. In order to establish that CBM discharge water is the cause of a measured decrease in crop/forage yield, complimentary impacts to soils, surface waters and groundwaters must also be evaluated. When using a multiple approach monitoring system [chemical, physical, water flow aspects (surface and groundwater responses)], an overall pattern of change in surface water, groundwater and soil conditions would precede crop/forage impact evaluation/determination. In this way, early warning can help prevent the impacts of CBM discharge water on further and greater soil degradation and crop/forage production.

We recommend that WDEQ consider conducting pilot watershed-scale monitoring programs as described in this document prior to implementation of individual permits.

4.3 Monitoring Test Methods

References for soil chemical, physical and biological properties.

Many of the following references were produced by the Soil Science Society of America, which can be accessed at 5585 Guilford Rd., Madison, WI 53711-5801, 608-273-8080 or www.SocietyStore.org.

Soil Science: Step-by-Step Field Analysis. 2008. Edited by S. Logsdon, D. Clay, D. Moore, and T. Tsegaye. *Natural resource manager, agronomist, land use consultant, educator, environmental consultant.... The lines are blurred, the questions are complicated, and soil science is required knowledge. Soil Science: Step-by-Step Field Analysis provides the knowledge for conducting specific activities related to improved natural resource management. Readers will learn both new procedures and tips for improved performance in the field, without a lot of background theory and with a focus on usefulness for real-life applications (SSSA)*. 255 pp.

<u>Methods of Soil Analysis Series</u>

Part 1. Physical & Mineralogical Methods. 1986. Edited by A. Klute. *This is the classic text on physical and mineralogical characteristics of soils and how they relate to each other and to chemical properties. Methods of Soil Analysis, Part 1 provides a uniform set of procedures that can be used by soil scientists, engineers, students and more to conduct precise soil analysis (SSSA).* 1188 pp.

Part 2. Microbiological & Biochemical Properties. 1994. Edited by R.W. Weaver, S. Angle, P. Bottomley. *One of the primary references on analytical methods in soil science, Part 2 of the Methods series will be useful to all biogeoscientists, especially those with an interest in microbiology or bioremediation (SSSA)*. 1121 pp.

Part 3. Chemical Methods. 1996. Edited by D.L. Sparks. *A thorough presentation of analytical methods for characterizing soil chemical properties and processes, Methods, Part 3 includes chapters on Fourier transform infrared, Raman, electron spin resonance, x-ray photoelectron, and x-ray absorption fine structure spectroscopies, and more (SSSA)*. 1358 pp.

Part 4. Physical Methods. 2002. Edited by J.H. Dane and G.C. Topp. *The best single reference for both the theory and practice of soil physical measurements, Methods, Part 4 adopts a more hierarchical approach to allow readers to easily find their specific topic or measurement of interest. As such it is divided into eight main chapters on soil sampling and statistics, the solid, solution, and gas phases, soil heat, solute transport, multi-fluid flow, and erosion. More than 100 world experts contribute detailed sections (SSSA)*. 1692 pp.

Part 5. Mineralogical Methods. 2008. Edited by A.L. Ulery and L.R. Drees. *The latest installment in the well-received Methods of Soil Analysis series presents valuable techniques that will enable researchers to analyze mineralogy for a wide variety of applications. An understanding of mineralogical composition provides crucial insight into the fundamental behavior of soils and their response to environmental conditions and management. Highlights include extensive coverage of new techniques, such as X-ray absorption and diffuse reflectance spectroscopy, and updated chapters on thermal analysis and selective dissolution methodologies. Each chapter provides the basic principles of the method, the method itself, and assists in the interpretation and analysis of results (SSSA)*. 544 pp.

Chemical Processes in Soils. 2005. Edited by M.A. Tabatabai and D.L. Sparks. *A thorough understanding of the chemical and biological processes taking place within the soil is critical for those studying or working in the agricultural, ecological, environmental, earth, and soil sciences. Designed to complement the methods series, this book details the foundation of the chemical and biological processes of soils (SSSA).* 723 pp.

Soil Mineralogy with Environmental Applications. 2002. Edited by J.B. Dixon and D.G. Schulze. *Few books achieve a connection between scientific theory and real world environmental problems, but this one does. Generous use of color images, exercises, and case studies make it friendly for the classroom or non-mineralogist. Discover crystallography, surface chemistry, mineral-solution equilibria, organic matter, and soil mineral analysis, as well as world-wide applications of mineralogy in soil taxonomy, tectonics, radionuclides, pesticides, enzymes, and more (SSSA).* 866 pp.

References for Surface Water and Groundwater Monitoring Methods.

Groundwater and Surface Water Pollution. 2000. David H.F. Liu, Bela G. Liptak. CRC Press, Boca Raton FL. 150 pp.

Statistical Methods for Groundwater Monitoring, 2nd Edition. 2009. Robert D. Gibbons, Dulal Bhaumik, Subhash Aryal. John Wiley and Sons, Inc., Hoboken, NJ. 374 pp.

Crop Production Monitoring.

It is suggested that 1 m^2 quadrats be clipped/harvested and compared to samples taken in years before discharge was initiated or compared to nearby fields outside of the affected watershed. We believe this data can also be compared to historic yields from specific fields or to historic yields in the area or county. As was mentioned earlier, there are fairly large fluctuations in crop/forage yields due to rainfall amounts and timing and also spring snow accumulations.

Rangeland Production Monitoring and Plant Community Dynamics.

Range Research: Basic Problems and Techniques. 1986. C. Wayne Cook and Jan Stubbendieck (eds.). Society for Range Management. Denver, CO. This reference includes descriptions of line transect and belt transect measurement methods that can be used to assess plant community composition changes and it also includes references for estimating rangeland forage production. 317 pp.

4.3 Specific Monitoring Approaches

1. Outfall Monitoring

Monitored Substrate	Siting Guidelines (sample locations and densities)	Chemical / Physical parameters to be monitored	Frequency and timing of sampling	Action Thresholds (At what chemical / physical point does the alarm go off)	Corrective Action (What should the permit do about it, in order to avoid damage to crops)
Direct Discharge to ephemeral channels	At the outfall	pH, EC, SAR, HCO_3, metals, trace elements (F, Ba, As, Se, Fe, others as appropriate).	Monthly for 1st 12 months, quarterly then on if within thresholds.	<u>Ephemeral channels</u>: Discharge quantity should be limited so as to prevent flooding. End of pipe limits (based on default published thresholds) may consider dissolution of salts that may occur within the watershed, but maintenance of water quality must be monitored instream.	If flooding is due to CBM discharges, then curtail direct discharges. If end-of-pipe limits fail to preserve downstream water quality at required levels (see surface water table 3), then amend end-of-pipe limits.
Direct discharge to perennial channels	Same as above	Same as above	Same as above	<u>Natural perennial channels:</u> Permit limits based on waste load allocation to support designated uses. Agricultural use limits should apply at median growing season flow. Instantaneous maximum limits apply year-round.	WDEQ enforcement policy to apply.
On-channel reservoirs (Option 2)	Same as above	Same as above	Same as above	End of pipe limits to protect livestock use.	WDEQ enforcement policy to apply.
50-yr Headwater reservoirs (Option 1.b.)	Same as above	Same as above	Annually	End of pipe limits to protect livestock use.	WDEQ enforcement policy to apply.
50-yr Off-channel pits (Option 1.a.)	Same as above	Same as above	Annually	End of pipe limits to protect livestock use.	WDEQ enforcement policy to apply.

2. Reservoir Monitoring

Monitored Substrate	Siting Guidelines (sample locations and densities)	Chemical / Physical parameters to be monitored	Frequency and timing of sampling	Action Thresholds (At what chemical / physical point does the alarm go off)	Corrective Action (What should the permit do about it, in order to avoid damage to crops)
On-channel Reservoir	Minimum 5 ft. from shore and 50 ft. from inlet.	Same as outfall plus SO_4. Seepage monitoring WDEQ may require stage monitoring within 0.1 feet.	Effluent: Monthly for 1st 12 months, quarterly then on if within thresholds Seepage monitoring: monthly/quarterly (as above) Stage monitoring: monthly/quarterly (as above)	Leakage: Visible surface seepage flow attributable to reservoir leakage (consider using EM methods to detect subsurface migration of saline water). When EC value in reservoir water is 150% of outfall water due to evapo-concentration of CBM water. Water release from on-channel reservoirs may be permitted if load credits are available and will not be detrimental to downstream agricultural uses. Advance notice to downstream landowners required.	Leakage: cease discharge; repair reservoir. Close reservoir or increase freeboard to 50-yr level.
50-yr Headwater reservoirs (Option 1.b.)	Same as above	Same as above	Same as above	Leakage: Visible surface seepage flow attributable to reservoir leakage (consider using EM to detect subsurface migration of saline water).	Leakage: cease discharge; repair reservoir.
50-yr Off-channel pits (Option 1.a.)	Same as above	Same as above	Same as above	Leakage: Visible surface seepage flow attributable to reservoir leakage (consider using EM to detect subsurface migration of saline water).	Leakage: cease discharge; repair reservoir.

3. Surface Water Monitoring

Monitored Substrate	Siting Guidelines (sample locations and densities)	Chemical / Physical parameters to be monitored	Frequency and timing of sampling	Action Thresholds (At what chemical / physical point does the alarm go off)	Corrective Action (What should the permit do about it, in order to avoid damage to crops)
Instream surface water (IMP)	Perennial streams	Flow Water Quality Always monitor the following: pH, EC, Ca, Mg, Na. Monitor the following as appropriate: K, SO_4, HCO_3, Cl, ^{13}C, and/or other isotopes.	Continuous/ monthly streamflow.	**PERENNIAL** Water Quality trigger (statistical trend analysis or exceed EC limit, then expand parameter list and constituents). Use USDA Salinity Tolerance Database EC or background. Or statistically increasing trends (though upward trend not necessarily a compliance issue) Trend analysis needs to account for seasonality, flow-chemistry variation, and non-normal distributions. Hanson Chart – primary utility for surface irrigation, not useful for subsurface. Limit the Hanson Chart domain to >3 SAR, which corresponds to 1.0 dS/m EC. For default limits, also limit Hanson Chart to <10 SAR, which corresponds to 2.0 dS/m EC. High-clay smectitic soils are of particular concern (e.g., these soils will require more scrutiny). Smectitic soils are defined as having more than 50% smectite measured within the clay fraction.	Failure of criterion triggers more intensive evaluation for cause. If CBM is the presumptive cause of surface water degradation that impairs crop/forage production then curtail discharge or otherwise mitigate.
	Ephemeral Streams Locate stations within WS to characterize contributions from sub-basins and on mainstem. Also try to have stations nearer discharge and nearer beneficial use.	Flow Water Quality pH, EC, Ca, Mg, Na, [K, SO_4, HCO_3, Cl, ^{13}C, and/or other isotopes as appropriate].	Monthly Water Quality	**EPHEMERAL** Presumptive agricultural use is surface overflow onto hay and native grass or subirrigation. Prevent or mitigate flooding. If flow becomes perennial – need to monitor groundwater level. Use water quality triggers as for perennial drainages. For ephemeral drainages triggers have limited value due to inherent variability so we need to rely more on soil/crop monitoring and trends – need to think about auto-samplers.	Failure of criterion triggers more intensive evaluation of cause if flow becomes perennial. If CBM is the presumptive cause of surface water degradation that impairs crop/forage production then curtail discharge or otherwise mitigate.

4. Soil Monitoring

Monitored Substrate	Siting Guidelines (sample locations and densities)	Chemical / Physical parameters to be monitored	Frequency and timing of sampling	Action Thresholds (At what chemical / physical point does the alarm go off)	Corrective Action (What should the permit do about it, in order to avoid damage to crops)
Soils	Detailed Monitoring: Fields should be segmented according to differences in soil characteristics or depth to groundwater (e.g., evidenced by distinct differences in vegetation). Minimum of 1 subsample per acre, but not less than 5 and not more than 15 subsamples per soil unit. Survey Monitoring: As above for one sample location.	**Initial** – texture, clay mineralogy, ESP, pH, EC, SAR, SO_4, HCO_3, lime, OC (N, P, K for alfalfa or irrigated grass). **Resampling** - pH, EC, SAR, N, P, K [SO_4, HCO_3, Cl]. Provide for less detailed and more detailed monitoring as needed – not all fields in a watershed need detailed monitoring. Alfalfa = 6 ft. Grass=4 ft. Recommend using GEM tool along with sampling to correlate results. Also use GEM to help choose sample sites.	Annual fall sampling. Composite within similar soil/groundwater systems using co-located composited samples. Initial EC/pH on all grabs initially Composite only results on resampling. Depth 0-6, 6-12, ea 12" to 6' or less in high water table areas. Intake rate – good to have for research purposes, but questionable utility for compliance purposes. Should evaluate ground GEM with variable dipole (could partially offset soil sampling with ground truth – but could also assess restoration performance).	Separating trends from cause and effect is challenging. Trend - >40 % increase EC or SAR in 1 year, >15 % over 2 yrs or more. Trend analysis may not always identify CBM impacts where development pre-dates watershed monitoring. Other site specific evaluations will be required. Focus on groundwater-soil water pathway. Regardless of trend, ESP > 10% or EC > 4 dS/m from 0"-12" is a trigger for more frequent soil monitoring. If there is a trigger, the action is more detailed study to identify cause (e.g., assess climate, groundwater, soil water, agricultural management, watershed-wide trends).	If damage to soil is identified that is expected to impair crop/forage production and damage is due to CBM discharges, then a. Curtailing CBM discharges b. Changing discharge locations c. Providing improved drainage d. Adding chemical amendments.
Managed irrigation (land application)	Siting and management guidelines: (see cells to the right).	Texture, mineralogy, EC, SAR.	Monitoring should be tied to site specific irrigation scheduling and chemical amendment plan. Need to consider transition from irrigation back to dryland.	Need to create a separate designated use for water use on upland sites. Soils that are best suited for managed irrigation should be coarse loamy and sandy. Clay minerals should consist of less than 50% smectite.	CBM irrigated soils may become saline/sodic. After CBM water is no longer applied, soils may become sodic. Amelioration of saline/sodic or sodic soils must be addressed.

5. Groundwater Monitoring

Monitored Substrate	Siting Guidelines (sample locations and densities)	Chemical / Physical parameters to be monitored	Frequency and timing of sampling	Action Thresholds (At what chemical/physical point does the alarm go off)	Corrective Action (What should the permit do about it, in order to avoid damage to crops)
Leakage from ponds	Selective reservoir sampling – highest risk.	Water levels Water Quality: pH, EC, Ca, Mg, Na, [K, SO_4, HCO_3, Cl, ^{13}C, and/or other isotopes as appropriate].	Monthly water level and water quality monitoring May, June, and July , quarterly otherwise Continuous if threshold is triggered. Quarterly water quality	Evidence of surface leakage and/or lateral migration into stream channels.	Investigation is needed to determine cause and corrective actions. Cessation of contributing discharges. Underlying aquifer protected under the Groundwater Pollution Control Program.
Shallow groundwater near fields	Transect arrays of piezometers and wells. At least one array per field oriented normal to channel. Groundwater monitoring array to be co-located with soil, crop, and surface water monitoring.	Water levels Water Quality: pH, EC, Ca, Mg, Na, [K, SO_4, HCO_3, Cl, ^{13}C, and/or other isotopes as appropriate].	At least one continuous water level monitoring station per site, otherwise quarterly. Quarterly water quality.	Depth between 3’ and 6’. Depth less than 3’ and attributable to CBM. Water quality parameters	Investigation is needed to detect cause and corrective actions. Cessation of contributing discharges.

Notes: (1) This recommendation is not intended to ensure aquifer protection beneath reservoirs, which is handled under a separate program;
(2) Supplement this groundwater monitoring program to more clearly define nature and extent of groundwater flows within the watershed. This table is meant to focus on groundwater-soil interactions in irrigated fields.
(3) We recommend that DEQ develop a groundwater monitoring program for each watershed.

6. Crop & Forage Monitoring

Monitored Substrate	Siting Guidelines (sample locations and densities)	Chemical / Physical parameters to be monitored	Frequency and timing of sampling	Action Thresholds (At what chemical/physical point does the alarm go off)	Corrective Action (What should the permit do about it, in order to avoid damage to crops)
Crop and forage	Same area as detailed monitoring soil sites.	Yield/production at soil sampling locations.	Annual peak standing crop (late June-early July). Or pre-cutting for hayed fields – (can also use field harvest as t/ac). Forage quality – bulk sample CP (crude protein), Ca, P, K, Na [trace elements not an intrinsic CBM issue relative to forage quality, but mobilization of naturally occurring trace elements could be issue, e.g., Se).	Statistically significant decrease that correlates with causative mechanism such as soil water or groundwater impacts.	The other monitoring programs are meant to prevent crop/forage degradation. Corrective action will require reclamation of damaged fields.