SUBTASK 1.18 – A DECISION TOOL FOR WATERSHED-BASED EFFLUENT TRADING

Final Report

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ABSTRACT

Handling produced water in an economical and environmentally sound manner is vital to coalbed methane (CBM) development, which is expected to increase up to 60% in the next 10–15 years as the demand for natural gas increases. Current produced water-handling methods (e.g., shallow reinjection and infiltration impoundments) are too costly when implemented on a well-by-well basis. A watershed-based effluent credit trading approach may be a means of managing produced water at reduced cost while meeting or surpassing water quality regulations. This market-based approach allows for improved water quality management by enabling industrial, agricultural, and municipal discharge facilities to meet water quality permit requirements by purchasing pollutant reduction credits from other entities within the same watershed. An evaluation of this concept was conducted for the Powder River Basin (PRB) of Montana and Wyoming by the Energy & Environmental Research Center (EERC). To conduct this assessment, the EERC collected and evaluated existing water quality information and developed the appropriate tools needed to assess the environmental and economic feasibility of specific trading scenarios. The accomplishments of this study include 1) an exploration of the available PRB water quantity and quality data using advanced statistical techniques, 2) development of an integrated water quality model that predicts the impacts of CBM produced water on stream salinity and sodicity, 3) development of an economic model that estimates costs and benefits from implementing potential trading options, 4) evaluation of hypothetical trading scenarios between select watersheds of the PRB, and 5) communication of the project concept and results to key state and federal agencies, industry representatives, and stakeholders of the PRB. The preliminary results of a basinwide assessment indicate that up to $684 million could be saved basinwide without compromising water quality as a result of implementing a watershed-based credit-trading approach.

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EXECUTIVE SUMMARY

Watershed-based effluent credit trading is a market-based approach that allows for improved water quality management throughout an entire watershed while increasing options for industrial, agricultural, and municipal stakeholders. This approach is increasingly being implemented in watersheds where multiple water-discharging facilities are required to meet state or federal water quality regulations before releasing effluent (or wastewater) into a surface waterway. Effluent credit trading enables these facilities to meet water quality permit requirements by purchasing pollutant reduction credits from other entities located within the same watershed. An effluent credit is typically defined in terms of the mass of a particular potential water pollutant, such as phosphorus, nitrogen, or sediment. The credit market is driven by the fact that a credit "seller" is able to treat the water or improve water quality at a lower cost than the credit "buyer," thus allowing the credit buyer to discharge an untreated volume of water containing the equivalent mass of potential pollutants contained in the credit. In most cases, the credit seller must be located upstream of the credit buyer in order to maintain environmental safeguards and avoid the creation of localized "hotspots" that exceed water quality standards. Because this approach expands water treatment options from an individual facility to an entire watershed, it greatly improves the flexibility of dischargers to meet regulatory requirements in an environmentally friendly, cost-effective manner.

Through this project, the Energy & Environmental Research Center (EERC) evaluated the technical and economic feasibility of effluent credit trading in the Powder River Drainage Basin (PRB) of Wyoming and Montana. This watershed was selected as a focus area because of the large volumes of water regulated within the region as a result of extensive coalbed methane (CBM) development. Coalbed methane refers to the natural gas (methane) naturally contained within coal seams located in the subsurface. In order to harvest the methane contained in these formations, large volumes of water must be pumped from the subsurface until enough hydrostatic pressure is relieved to release the methane from the coal. In areas where water quality is poor, the CBM produced water is regulated and often requires treatment before being discharged to surface water systems; however, treatment is often more expensive than direct discharge to surface waterways and may hinder CBM development. In the PRB, millions of barrels of CBM produced water per day are currently generated and an additional three- to four-fold increase in the number of CBM wells is expected in the next 20–30 years (Montana Board of Oil and Gas Conservation, 2006). Current produced water-handling methods include discharge to surface impoundments, reinjection into the subsurface, and, in fewer cases, direct discharge. Direct discharge is by far the least expensive handling method; however, conventional regulatory approaches that manage CBM produced water on a site-by-site basis often preclude this handling method. Because effluent credit trading manages water quality on a watershed basis, it is more flexible and may allow for additional direct discharge in some areas while being offset by additional water treatment in other areas, ultimately at a lower cost, while maintaining water quality safeguards.

In order to evaluate the feasibility of effluent credit trading in the PRB, the EERC collected, compiled, and evaluated existing water quality data and developed the appropriate tools needed to assess the environmental and economic impacts of specific trading scenarios. Extensive outreach efforts were conducted to determine the current status of water-related activities being conducted by various organizations within the PRB, to communicate the effluent-trading concept, and to gain input from relevant entities regarding the EERC's approach to evaluation of this concept in the PRB. Data and information obtained through the outreach efforts were used to aid in the development of decision-support tools used in evaluating specific effluent-trading scenarios. The decision-support tools developed in this effort are comprised of three different computer models: a hydrologic model that predicts the water quantity and quality from individual CBM wells to their respective discharge points (outfalls); a hydrodynamic water quality model that predicts the impacts of CBM produced water contributions on the main streams and rivers of the PRB; and an economic model that evaluates the financial attractiveness of specific effluent-trading scenarios.

Results of this effort indicate that handling 25% of the produced water in the upper PRB, specifically the Upper Powder River subwatershed, would allow the remaining produced water in all the downstream watersheds to be directly discharged. This could reduce the costs of handling produced water in the PRB by $684 million or facilitate the development of 5.5 Tcf of natural gas. Based on estimated ultimate recovery values of CBM wells in the PRB, this volume of gas is equivalent to the development of 11,000 to 18,300 new CBM wells.

The general conclusions of this project are that effluent trading in the PRB could:

- Be an efficient and inexpensive handling method for CBM produced water.
- Provide a solution to balance CBM development with environmental protection.
- Increase producers' profits as a result of lower produced water-handling costs.
- Increase invaluable water resources.
- Encourage responsible CBM development.

Project results suggest that watershed-based effluent trading could play a significant role in the strategic national energy plan to maximize energy production without sacrificing environmental quality.

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INTRODUCTION AND BACKGROUND

Natural gas produced from coal beds (coalbed methane [CBM]) accounts for about 8% of the United States' dry gas production (NETL, 2006) and is expected to increase up to 60% as the demand for natural gas increases in the next 10–15 years (Nelson, 1999). Extraction of methane from coal seams necessitates reduction of the hydrostatic pressure in the coalbed by removal of water, called produced water. The large volume of produced water not only raises concerns about its impact on surface water quality but also negatively affects producers' profitability because of costs associated with handling the water in a manner consistent with environmental regulatory requirements imposed by the Clean Water Act. In some watersheds, coalbed methane (CBM) production generates millions of barrels (bbl) of produced water each day. At present, the produced water is primarily either reinjected for disposal or secondary recovery, evaporated, or discharged into surface waters, including streams, rivers, lakes, bays, and oceans. While handling and disposal costs can reach or exceed $1/bbl (Harju, 2004), depending on location and water quality, both water managers and landowners are still concerned about potential impacts of produced water on surface water quality. As a result, many states are in the process of reviewing and revising environmental regulations pertaining to produced water because of the high priority currently placed on clean water resources. With the increase in CBM production, the cost to manage the large volume of produced water under conventional regulatory mechanisms may have a strong impact on producer profitability and, in turn, on the supply of natural gas.

As a means of supplementing conventional regulatory approaches to achieve the Clean Water Act goals, the U.S. Environmental Protection Agency's (EPA's) Office of Water is renewing efforts to support the development and implementation of market-based approaches to improve water quality more quickly at less overall cost to industry. Effluent or watershed-based credit trading is one of these potential approaches, which may help achieve a reduction in particular constituents of concern at a lower cost. Effluent trading allows facilities facing higher pollution control costs to meet or exceed their regulatory obligations by purchasing environmentally equivalent or superior pollution reduction credits from other sources at lower overall costs. The driving force behind this concept is that certain entities, such as wastewater treatment plants and CBM produced water dischargers, are required to meet water quality discharge requirements through Total Maximum Daily Load (TMDL) program regulations or National Pollutant Discharge Elimination System (NPDES) permit program requirements. Entities regulated under these requirements are not allowed to discharge more than a certain mass of individual constituents to a stream or waterway, often measured in terms of "loading" or mass per time. Credit trading enables dischargers to meet water quality permit requirements by purchasing pollutant reduction credits from other entities located within the same watershed. The costs associated with reducing pollutant loading to required levels must vary significantly between permitted entities in order to create a market for credit trading.

The market is driven by the fact that a credit "seller" is able to treat the water at a lower cost than the credit "buyer." This cost difference could be a result of:

- Water quality prior to treatment.
- Volume of water treated.
- Treatment type and/or handling method.

In order to maintain environmental safeguards, credit trading must not result in the creation of "hot spots" that exceed water quality guidelines; therefore, the credit seller must usually be upstream of the credit buyer. This entails that by the time the credit buyer discharges their water to a stream or river, the waterway has the sufficient capacity to assimilate the additional load.

One of the most common applications of the effluent trading concept is between wastewater treatment facilities and nonpoint source dischargers, such as farmers. Wastewater treatment plants must meet permit requirements for nutrients; however, in some agricultural watersheds, a large portion of the nutrient loading comes from agricultural land runoff. Through credit trading, a wastewater treatment facility can pay upstream farmers to implement best management practices (BMPs), such as installation of buffer strips or conversion from till to no-till farming, as a means of reducing nutrient loading to waterways. In turn, the wastewater treatment plant does not have to spend the additional time and money necessary to meet nutrient loading requirements but is still able to discharge its water without adverse impacts to the environment.

Within the Powder River Basin (PRB), the most prevalent anthropogenic influences on the water quality of the Powder River and its tributaries include CBM development and irrigated agricultural activities. Thus, trading of water quality credits would be most likely to occur between CBM companies or between CBM companies and agricultural interests, specifically irrigators. The trading scenarios evaluated in this project are broad in nature and occur between CBM wells located within different subwatersheds of the PRB. Trading scenarios were evaluated based on the hypothetical premise that the poorest quality CBM produced water from the upper reaches of the PRB would be treated, and the water quality credits generated from this would be sold to downstream CBM discharges. This, in turn, would allow the downstream CBM entities to discharge directly to the Powder River or its tributaries.

Benefits of the effluent-trading approach over conventional regulatory approaches have been verified by a number of demonstration trading projects throughout the county (U.S. Environmental Protection Agency) and include the following:

- Cost savings to industry

- Incentives to reduce pollutant loading

- Incentives for technological innovation

- An emphasis on water quality rather than the installation of a particular abatement technology

- The possibility for independent groups to participate

Ultimately, this market-based approach allows for improved water quality management throughout an entire watershed while increasing options for industrial, agricultural, and municipal stakeholders.

Goals and Objectives

The Energy & Environmental Research Center (EERC) recognized that the projected growth of CBM development in the PRB may be limited by the current regulatory/economic model under which produced water is managed. The economics of produced water management are primarily driven by the need to comply with regulatory-mandated water quality standards. Current regulations in the PRB severely limit the ability of CBM operators to discharge untreated water into the PR drainage basin. These restrictions prompt operators to rely on more mechanically complex or robustly engineered, and therefore expensive, means of managing produced water. Higher costs associated with managing produced water and a lack of incentive to develop innovative water management approaches may ultimately lead to underdevelopment of the PRB CBM resources.

Having worked extensively with holistic basinwide water management issues as a part of previous research programs, the EERC also recognized that regulatory/economic models that attempt to manage the water quality of a drainage basin as a whole entity rather than as a network of individual point sources can effectively protect the environment, while improving the economic regime by broadening the types of water management options available to industrial operators. The implementation of effluent credit trading as a drainage basin approach to water management may remove some of the limitations currently facing future CBM development in the PRB. Furthermore, successful implementation of such an approach in the PRB could pave the way to the development of energy resources in other environmentally sensitive parts of the United States. Therefore, in 2004, the EERC proposed to evaluate the technical, economic, and environmental feasibility of CBM effluent credit trading within the Powder River drainage basin. The goals of the project were to:

- Evaluate the environmental and economic impacts of various effluent-trading scenarios.

- Define trading types and rules.

- Formulate a GIS-based decision support tool for assessing trading options.

- Communicate the effluent credit-trading concept to key agencies and stakeholders within the PRB.

In order to accomplish these goals, the EERC evaluated existing water quality information and developed the appropriate tools needed to assess the environmental and financial feasibility of specific trading scenarios. Key activities conducted as part of this study include 1) an exploration of the available water quantity and quality data using advanced statistical techniques,

2) development of an integrated water quality model that predicts the impacts of CBM produced water on stream salinity and sodicity, 3) development of an economic model that estimates costs and benefits from implementing potential trading options, 4) evaluation of hypothetical trading scenarios between select watersheds of the PRB, and 5) communication of the project concept and results to key state and federal agencies, industry representatives, and stakeholders of the PRB.

Powder River Drainage Basin

The PRB (Figure 1) encompasses approximately 33,785 km^2 (13,045 mi^2) in the states of Wyoming (23,650 km^2; 9132 mi^2) and Montana (10,135 km^2; 3913 mi^2). Originating from north central Wyoming, the 747-km (464-mi) Powder River meanders 393 km (244 mi) northeast within Wyoming into southeastern Montana, where it curves to the northwest and joins with the Yellowstone River approximately 35 miles northeast of Miles City, Montana. Major tributaries include the Crazy Woman Creek, Clear Creek, Mizpah Creek, Salt Creek, and Little Powder River. The average gradient along the Powder River decreases from 5.3 m/km (28 ft/mi) at Sussex to 1.0 m/km (5 ft/mi) at Locate (Table 1).

The Powder River structural basin (which includes the Powder, Tongue, and Belle Fourche River drainage basins) has become one of the most active new CBM production areas since the 1990s. The number of CBM-producing wells in the structural basin is expected to increase from the present 16,000 to perhaps 70,000 within the next 20–30 years (Montana Board of Oil and Gas Conservation, 2006), implying that approximately 5 to 50 million barrels (MMbbl) of produced water will be generated per day (McBeth et al., 2003; Rice et al., 2000).

The locations of CBM wells within the PRB as of 2002 are shown in Figure 1, and future well status is described in Table 1. Individual CBM wells in the PRB typically have water yields ranging from 0.006–16 L/s (3.4–8630 bbl/day), with a mean of 0.8–2 L/s (411–1199 bbl/day) and a standard deviation of 0.4–2 L/s (206–1199 bbl/day).

Of the common CBM produced water disposal methods, direct discharge to surface waters is the least expensive; however, this method is regulated based on the water quality of the CBM effluent and that of the waterway into which it is discharged. In general, the quality of the water generated by CBM production in the PRB deteriorates as one moves into the western (Sheridan, Wyoming, area) and northern (Montana) portions of the basin (Wheaton, 2001). For example, produced water from some CBM wells in the Gillette, Wyoming, area are of potable quality and have been used to replenish the city's water supply, while water from CBM wells in Montana typically do not meet surface discharge standards.

A key issue at the center of the debate over the development of CBM resources is the impact that produced water could have on the rivers of the PRB watershed. These rivers are critical components of farm and ranch operations in the area, specifically for irrigation purposes. A key concern for irrigators is the potential for increased salinity and sodicity within the waterways of the PRB as a result of CBM effluent discharge. Several crops are sensitive to the salinity and sodicity of the applied irrigation waters and certain soil physical and chemical characteristics can be impacted, such as infiltration rates (Montana State University, 2006).

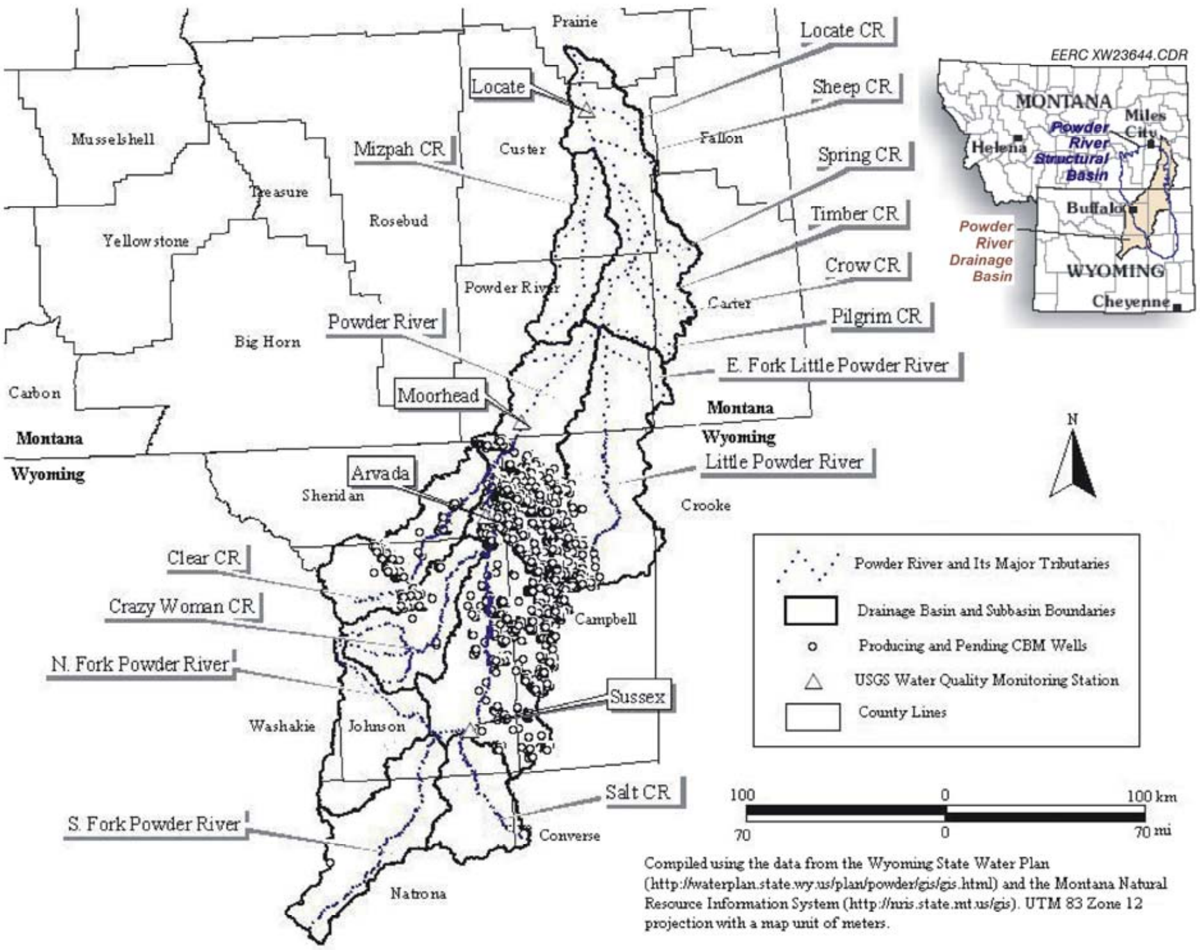

Figure 1. The Powder River drainage basin, showing streams, CBM wells, water quality monitoring stations, and county lines.

Table 1. Reach Characteristics for the Four Study Sites (data compiled from the Montana Board of Oil and Gas Conservation www.bogc.dnrc.state.mt.us/jdpintro.asp)

Reach	Length, km	Gradient, m/km		Approximate 2002 CBM Wells: Producing and Pending	Producing	Priority Date	Water Yield, gpm[♀]: Range	Mean	SD*	Major Tributaries
Headwaters to Sussex	180	5.3		1	0	—[†]	—[†]	—[†]	—[†]	S. Fork Powder River, N. Fork Powder River, Salt Creek
Sussex to Arvada	145	1.6		3882	822	03/25/98–03/09/01	0.1–200.0	35.0	35.0	Crazy Woman Creek
Arvada to Moorhead	65	1.2	Wyoming	1513	247	03/25/98–02/14/01	0.7–42.0	11.5	6.3	Clear Creek
			Montana	38	38	09/28/01–10/06/01	—[‡]	—[‡]	—[‡]	
Moorhead to Locate	290	1.0		2408	961	12/28/89–04/09/01	1.0–252.0	29.4	23.5	Little Powder River, Mizpah Creek, Pilgrim Creek, Crow Creek, Timber Creek, Spring Creek, Sheep Creek, Locate Creek
Total	680	—[#]		7842	2068	—[#]	—[#]	—[#]	—[#]	—[#]

[♀] In gallons per minute to be consistent with the unit in which it was originally reported: 1 m^3/s = 15,850.4 gpm. To convert to bbl/day, divide by 0.0292.
* Standard deviation.
[†] No producing wells.
[‡] No water yield data available for the CBM wells in Montana.
[#] No sense for the calculation.

Salinity is commonly determined by the electrical conductivity (EC) of the water, whereas sodicity is determined based on the ratio of sodium (Na^+) to calcium (Ca^{2+}) and magnesium (Mg^{2+}), referred to as sodium adsorption ratio (SAR) of the water.

SAR is defined as:

$$\mathrm{SAR} = \frac{\mathrm{Na}^+}{\sqrt{\frac{\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}}{2}}},$$

where the unit of Na^+, Ca^{2+}, and Mg^{2+} concentrations is milliequivalent per liter (meq/L). Figure 2 illustrates the ranges of EC and SAR and their combined impacts on infiltration. It is important to recognize that the suitability of water for irrigation is based on both its salinity and sodicity. Thus, water with low sodicity may not be appropriate for irrigation if its salinity is also low. Conversely, water with slightly higher sodicity may be suitable for irrigation if it also has a slightly higher salinity.

Because of the concern of water quality degradation from CBM discharges, the Montana Board of Environmental Review established and adopted water quality standards for EC and SAR in CBM discharge waters in March of 2003 (Montana Department of Environmental Quality [MDEQ], 2003). Table 2 illustrates the maximum values for EC and SAR for both the Powder and Little Powder Rivers. The numerical standards are listed based on acceptable monthly averages and maximum daily values.

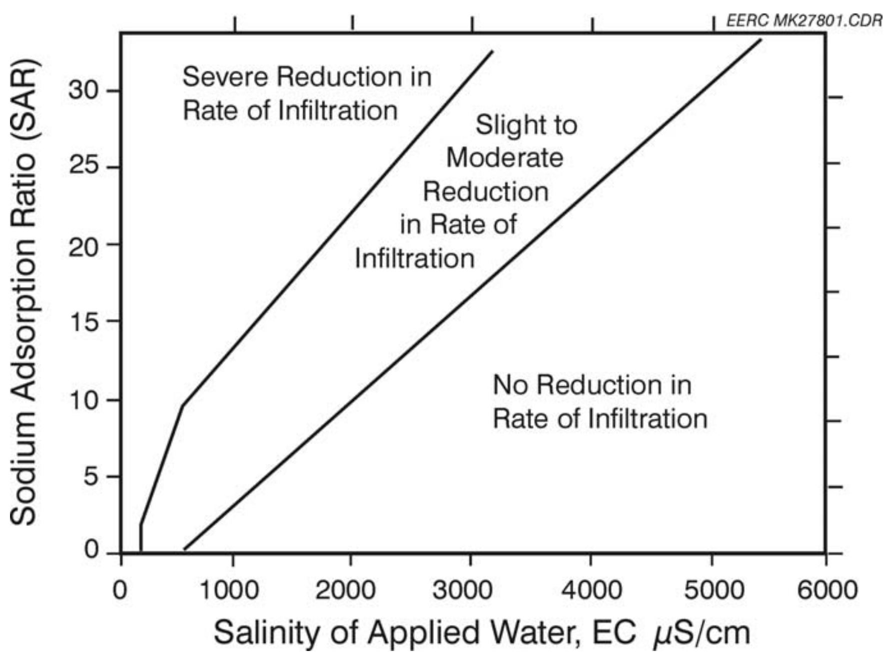

Figure 2. Irrigation thresholds as they relate to infiltration (University of Nebraska, 2004).

While the Wyoming DEQ does not intend to implement a TMDL standard for the Wyoming portion of the PRB, it made a commitment to support the MDEQ in meeting the TMDL goals in the Montana portion of the PRB. Meeting these water quality requirements may prove challenging or impede CBM development if flexible strategies, such as effluent credit trading, are not implemented.

Water Quality Evaluation

In order to gain a better understanding of the magnitude and scope of water quality issues in the PRB, an extensive literature review and water quality data evaluation was conducted. This also served to collect data for use in model development and to identify data gaps. A detailed summary of this effort is discussed in Appendix A.

Table 2. Coalbed Methane Discharge Water Quality Standards for the Powder and Little Powder Rivers **(Montana Department of Environmental Quality, 2003)**

Irrigation Season (March 2 – October 31)				Nonirrigation Season (November 1 – March 1)			
Monthly Average		Daily Maximum		Monthly Average		Daily Maximum	
EC, μS/cm	SAR	EC, μS/cm	SAR	EC, μS/cm	SAR	EC, μS/cm	SAR
2000	5.0	2500	7.5	2500	6.5	2500	9.75

For more than a century, the U.S. Geological Survey (USGS), in cooperation with federal, state, and local agencies, has been monitoring stream flow and water quality in the Powder River drainage basin. The number and location of monitoring sites have changed over time as study objectives, land use patterns, and available funding have varied. Although some data were available from the USGS National Water Information System Web site for the 68 monitoring sites located across the PRB, there were sometimes gaps ranging from months to years in the records. There were also data available for various temporary monitoring sites that were established for various purposes (e.g. permit application). Other data, such as climate, hydrology, topography, soil, and land use/land cover, were available from agencies such as the National Climate Data Center, USGS, and the U.S. Department of Agriculture Natural Resources Conservation Service. A major data gap is that little monitored water quantity and quality data are available on CBM produced water and on agricultural irrigation return flows.

Among the 68 USGS stations, four stations along the Powder River, Sussex and Arvada in Wyoming and Moorhead and Locate in Montana, were identified as having relatively long records. The Sussex station has data from 1938–2002, Arvada from 1931–2002, Moorhead from 1929–2002, and Locate from 1938–2002. The records used in this study are summarized in Table B-1. As with other stations, gaps from months to years exist for these four stations as well. Data from these stations were used to conduct an evaluation of surface water quality temporal trends and spatial patterns from the beginning of data collection to 2002.

A total of 14 parameters were evaluated, including discharge (Q), water temperature (T_W), air temperature (T_A), pH, EC, SAR, alkalinity, calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), chloride (Cl^-), sulfate (SO_4^{2-}), and bicarbonate (HCO_3^-). Linear regression, Kendall's S, and Seasonal Kendall's S′ were used to detect water quality trends over time, and ANOVA (analysis of variance) was used to analyze spatial differences in water quality between stations. For each of the 14 water quality parameters at each of the four stations, the analyses were conducted respectively on 1) the whole dataset that is composed of the data until 2002, 2) the pre-1990 dataset that is composed of the data before 1990, and 3) the post-1990 dataset that is composed of the data from 1990–2002. 1990 was selected as a dividing point in the analysis because this marks the date after which CBM development began in the PRB. The water quality conditions within the PRB during 1990 also served as the starting point, or baseline, for evaluating the water quality impacts of various effluent trading scenarios. While the three datasets exhibited different trends for some parameters and consistent trends for others, at each of the four stations the whole dataset and pre-1990 dataset exhibited more trends than the post-1990 dataset. Within an individual dataset, more trends were generally detected by using Kendall's S and Seasonal Kendall's S′ than linear regression.

Results indicate that pH increased at all four stations from the middle of the 20th century (1950s, 1960s) to 2002. The data prior to 1990 exhibited increased pH, SAR, Na^+, and Cl^- and decreased Ca^{2+} at all four stations. No such trends were detected from 1990 to 2002. The difference in trends may be a result of changes in water-handling practices, specifically within an oil field located upstream of Sussex. Until 1990, the produced water from this oil field was directly discharged to surface waterways. Following February of 1990, the produced water at this location was handled by reinjection (EDE Consultants, 2005). The water quality trends prior to 1990 suggest that the direct discharge of the produced water from this oil field had significant impacts on water quality in the Powder River.

A spatial analysis of the water quality parameters at each of the four stations revealed that EC, SAR, Na^+, Cl^-, and HCO_3^- were significantly lower in Montana and that flow, water temperature, pH, Mg^{2+}, and SO_4^{2-} were significantly lower in Wyoming. The post-1990 dataset indicated that alkalinity and Ca^{2+} were significantly lower in Montana; however, prior to 1990, these two parameters were significantly lower in Wyoming. This may be a result of more stringent produced water permitting requirements or dilution of streams and rivers with CBM produced water, which tends to be low in Ca^{2+}. An evaluation of individual water quality parameters seems to indicate that overall, the quality of water in the PRB is improving over time. However, a closer analysis reveals that the water quality in the Montana portion of the PRB has actually become worse over time. This trend has been offset by improved water quality in the Wyoming portion of the PRB. This only strengthens the case that watershed-based approaches, such as effluent trading, are necessary for achieving the water quality standards proposed by MDEQ.

An evaluation of EC and SAR exceedance with respect to the TMDLs proposed by MDEQ revealed that 72% of the EC measurements and 52% of the SAR measurements in Wyoming were higher than the TMDL standard. In Montana, 38% of the EC measurements and 16% of the SAR measurements exceeded the proposed TMDL standard. In addition, the exceedance of EC and SAR TMDL limits was more frequent prior to 1990 than after 1990 at the Sussex, Arvada, and Locate stations. A similar evaluation could not be conducted for the Moorhead station because of data gaps after 1982. Within a given year, the exceedances were higher in the growing season (March–October) than the nongrowing season (November–February).

EXPERIMENTAL

Outreach Activities

The first steps in the evaluation of the effluent-trading concept were to determine the current status of water-related activities being conducted by various organizations within the PRB, to communicate the effluent-trading concept, and to gain input from relevant entities regarding the EERC's approach to evaluation of this concept in the PRB. Data and information obtained from various agencies were used to shape the direction of this project and to aid in the development of the computer models used for evaluation of the concept.

The key components of the outreach task were to discuss project-related issues with interested state and local entities, attend various public meetings related to CBM issues, and prepare a project prospectus describing the EERC project and its potential applications. Each of these accomplishments is discussed in further detail below.

Communications with PRB-Related Entities

Throughout the duration of the project, several entities involved with water issues in the Powder River Basin were contacted. The communication was intended to solicit additional water-related information from various organizations, such as the Wyoming and Montana state regulatory agencies, environmental groups, industry, and various other organizations and individuals. A second objective of the communication was to notify these entities of the EERC project concept, including the hydrologic and economic model development, capabilities, and potential applications.

As a result of the communications with the various CBM-related entities, several project-specific documents and data were obtained that aided in the project and development of the computer models. An overview of this information is shown in Table 3.

Meetings and Presentations

EERC personnel attended meetings and several professional conferences to discuss issues related to coalbed methane produced water and Powder River Basin water quality. On August 3, 2006, EERC project representatives attended the Clear Creek CBM Watershed-Based Permitting Stakeholders Meeting, hosted by the Wyoming Department of Environmental Quality (WDEQ) in Buffalo, Wyoming. The meeting participants included landowners, irrigators, CBM industry operators, environmental groups, and representatives from state and federal agencies. The purpose of the meeting was to discuss watershed-based management of CBM effluent in the Clear Creek Basin. The EERC gave a presentation describing the effluent trading concept and explaining the capabilities of the hydraulic/hydrologic and economic models that have been developed. The EERC also met informally with the WDEQ after the meeting to explain the effluent trading project in greater detail.

Presentations of the watershed-based effluent-trading concept were also given at several key national conferences, including the American Water Resources Association's 2004 Annual Conference, held November 1–4 in Orlando, Florida; the 2004 American Geophysical Union Fall Meeting, held in San Francisco, California, December 13–17; and the Western Fuels Symposium: 19th International Conference on Lignite, Brown, and Subbituminous Coals held in Billings, Montana, October 12–14, 2004.

Project Prospectus

A project prospectus was prepared for distribution to various PRB stakeholders, including local, state, and federal groups and agencies, as well as CBM industry representatives. The prospectus describes the effluent-trading concept and the work that the EERC has conducted to evaluate the feasibility of effluent credit trading in the PRB. The prospectus is included in Appendix A.

Table 3. Data and Information Obtained Through the Project Outreach Activities

Data Type	Data/Information Source[1]	Brief Description	Usage
Miscellaneous PRB-Related Reports	Various sources	Documentation of previous study results and basic data	Generate project concept and provided basic model inputs
Water Quality and Quantity Data	PRBRC, USGS, USEPA, WDEQ, MDEQ, WSEO, Industry	Various data compilations	Amendments to the official data for the water quality trend and pattern analysis
CBM Well Databases	WDEQ, MDEQ, WOGCC, MOOGIS,	Well location, producing capacity, and water quality/quantity	Development of the overland routing model
Suggestions	WDEQ	Suggestions of an area of focus for a hypothetical trading evaluation	Formulation of trading scenarios

[1]PRBRC = Powder River Basin Resource Council
WDEQ = Wyoming Department of Environmental Quality
MDEQ = Montana Department of Environmental Quality
USGS = United States Geological Survey
USEPA =United States Environmental Protection Agency
WOGCC = Wyoming Oil and Gas Conservation Commission
WSEO = Wyoming State Engineer's Office
MOOGIS = Montana Online Oil and Gas Information System

Model Development

In order to assess the feasibility of the effluent credit-trading concept in the PRB and to evaluate the environmental and economic effects of various hypothetical trading scenarios, three different models were developed, including a hydrodynamic water quality model, a hydrologic model, and an economic model.

The hydrodynamic and hydrologic models were developed to evaluate water quality and flow impacts through the evaluation of various effluent-trading scenarios. Ultimately, the goal was to determine economically favorable trading scenarios that would minimize environmental impacts. As part of this project, an economic model was developed to evaluate the economic feasibility of trading options within the PRB. The inputs into this model are primarily the outputs from the water quality models developed through this project; however, the model also includes information on produced water-handling costs and capital costs for regulatory permitting.

An additional tool developed through this project was a model interface to allow users without modeling experience to simulate trading scenarios using the water quality and hydrologic models developed through this project. The user does not need prior experience running water quality models; however, it is assumed that he/she has a technical background with experience using GIS. A more detailed explanation of the model interface can be found in Appendix D.

Coupled with the water quality model user interface is an economic model in spreadsheet format. It was designed to incorporate the output files from the water quality modeling results to provide a general economic estimate of various effluent credit-trading scenarios. However, it can also be used to conduct general economic evaluations of trading scenarios regardless of the impacts to water quality; however, caution should be taken with this approach since water quality impacts are a key factor in evaluating the feasibility of trading scenarios. A more detailed explanation of the economic spreadsheet and its location can be found in Appendix D.

CE-QUAL-W2 Water Quality Model

A CE-QUAL-W2 model was developed for the pilot water system that comprises the Powder River and its major tributaries, including the South Fork Powder River, Salt Creek, Crazy Woman Creek, Clear Creek, and Little Powder River. CE-QUAL-W2 is a two-dimensional (longitudinal–vertical) hydrodynamic and water quality model. It is best suited for relatively long and narrow waterbodies, such as the Powder River and its tributaries, which exhibit longitudinal and vertical water quality gradients. CE-QUAL-W2 has been under continuous development since 1975. Since then, significant improvements to the mathematical description of the prototype, numerical solution scheme (computational stability, accuracy, and efficiency), and water quality algorithms have been made. The current CE-QUAL-W2 (version 3.2) has the following capabilities:

- Hydrodynamics. The model predicts water surface elevations, velocities, and temperature. Temperature is included in the hydrodynamic calculation because of its effect on water density and cannot be turned off.

- Water Quality. The model can simulate any combination of a group of 16 constituents, including salinity and alkalinity, and more than 60 derived variables including pH. When salinity is simulated, its effect on hydrodynamics is taken into account by the model.

The model uses multiple waterbodies, which allows any number of rivers, reservoirs, lakes, and estuaries linked in series to be modeled. Multiple branches allow the application of the model to geometrically complex waterbodies such as dendritic reservoirs or estuaries. It uses a variable timestep algorithm that attempts to ensure that the stability requirements for the hydrodynamics imposed by the numerical solution scheme are not violated. The model also has the ability to simulate several phenomena including long-term water quality responses, flexibility of defining computational grids whose lengths and thicknesses may vary, various options of boundary conditions (e.g., time-varying flows or heads), and various choices of specifying multiple inflows and outflow. In addition, output is available for the screen, hard copy, plotting, and restarts. Moreover, the user can specify the output, and when and how often during the simulation output is to begin.

The historical data on gauge heights at ten USGS stations were used to calibrate the hydrodynamic component of the CE-QUAL-W2 model. These stations are the Powder River at Kaycee, Sussex, and Arvada, Wyoming; Moorhead and Locate, Montana; the South Fork Powder River near Kaycee, Wyoming; the Salt Creek near Sussex, Wyoming; the Crazy Woman and Clear Creeks near Arvada, Wyoming; and the Little Powder River near Weston, Wyoming.

SPARROW Model

The SPARROW model was developed to route CBM produced water and its constituents from individual wells to their corresponding outfalls. The CBM well and outfall data used in this model was downloaded from the Montana Online Oil and Gas Information System available on the Montana Board of Oil and Gas Web site (2006) and included 7842 wells and 214 outfalls. The model consists of three components: 1) prediction of well water yield, 2) estimation of water discharge at an outfall, and 3) determination of constituent concentrations at an outfall.

Based on data and information contained within Horpestad et al. (2001), the model assumed the following in order to predict the water yield of individual wells:

- The well life is 10 years.
- Water yield is invariant for any time within a given day.
- Water yield is maximal at the first producing day.
- Water yield decreases to half of its maximal after producing 2 years.

The estimation of water discharge at the outfalls assumes that:

- Seepage and evaporation rates are uniform across the drainage basin.

- The effects of impoundments on water quantity and quality are accounted for.

- A well discharges its produced water at its geographically nearest outfall.

- The total water discharged at an outfall is equal to the linear summation of the water contributed from all of the wells.

To determine constituent concentrations at an outfall, the following assumptions were made:

- The concentrations of the constituents at a well are constant throughout the well life.

- The concentrations of the constituents follow a first-order increase equation from a well to its outfall.

The characteristics of the SPARROW model developed for this project are as follows:

- Includes 7842 wells and 214 outfalls.

- Predicts daily water yield using a first-order decrease equation on a daily basis.

- Estimates water quantity at an outfall using a water balance equation.

- Takes evaporation and seepage through the conveyance stream and impoundments, if any, into account.

- Routes water quality constituents from the wellhead to the outfall. Certain "indicator" constituents, such as alkalinity, total dissolved solids, and inorganic carbon, were used to infer parameters, such as salinity (EC) and sodicity (SAR) at the well outfalls. This was based on a relationship the EERC derived based on observed data.

Economic Model

The economic model and the assumptions and cost estimates in the following sections (pages 14–17) were obtained from Bank and Kuuskraa (2006). The costs for the current methods (e.g., infiltration impoundment) used by CBM operators in the PRB were verified by Stenberg and Doll (2006). Table 4 lists the capital costs per single CBM well and operating and maintenance (O&M) costs per barrel of produced water.

Surface Discharge Variables

Surface discharge involves building two water discharge points with limestone riprap for passive treatment of the produced water. The capital costs for surface discharge are set forth below, assuming a 16-well facility:

- The cost for 20 cubic yards of limestone rock (delivered) is estimated at $1200.

- The cost for building a discharge point is estimated at $6000.

- Contingency, insurance, and other costs of 10% are added to the above.

- The cost for the National Pollutant Discharge Elimination System (NPDES) permit is approximately $1000 per well.

- The total cost is estimated at $7920 for a 16-well facility or $500 per typical CBM well, plus $1000 per well for the NPDES permit.

The operating costs for monitoring surface discharge, including electricity and maintenance for the surface pumps, are estimated at $0.04 per barrel of produced water.

Table 4. CBM Produced Water Disposal Costs (based on Bank and Kuuskraa, 2006)

Disposal Method		Capital Costs ($/well)	O&M Costs ($/bbl)
Method I	Surface Discharge	1500	0.04
Method II	Infiltration Impoundment	20,900	0.10
Method III	Shallow Reinjection	36,400	0.10

Infiltration Impoundment Variables

Infiltration impoundment involves constructing an impoundment (pond) and installing enhanced evaporation equipment (atomizers) or a surface irrigation system. The capital costs for constructing the impoundments are set forth below:

- The size of the impoundment is 3 acres with a dam of 13 feet, providing 20 acre-feet (150,000 barrels) of water capacity. This is sufficient to hold 30 days of production from a 16-well unit.

- Annual water infiltration is estimated at 8 feet of water loss per year, with enhanced evaporation and surface irrigation providing 12 feet of water loss per year. Together, this provides 60 acre-feet (approximately 465,000 barrels) of water loss per year or about 1275 barrels per day (with more during summer months and less during winter months).

- An irrigation or atomizing system is added to the impoundment. One such unit is able to dispose of 45 gpm or 1500 barrels per day.

- At an average water rate of 320 barrels per well per day (during the first 2 years of well operation), the 16-well unit will produce about 5000 barrels per day of water. One impoundment with an irrigation system will accommodate about 8 wells (and more wells during subsequent years). A 16-well unit requires two such infiltration and evaporation impoundments.

- The cost for constructing one impoundment is estimated at $56,300, based on the handling of 32,300 cubic yards of material at $1.35 per cubic yard. The costs for design, permitting, and monitoring of the facility are $26,000. Surface use agreements add $16,000. Outfall construction is an additional $5500. The total capital costs required to construct one infiltration impoundment is $103,800.

- Reclamation costs, including refilling, soil replacement, and replanting for one impoundment, are $14,000 (on a present-value basis).

- The cost for one atomizer or irrigation system is estimated at $27,000 for a 1500-barrel-per-day (45 gpm) unit installed. Two such units are required.

- Contingency, insurance, right-of-way, and other costs of 10% are added.

The total cost for two infiltration and evaporation impoundments is $318,600, plus $1000 per well for the NPDES permit, or $20,900 per well, as shown below:

Construction	$207,600
Reclamation	$ 28,000
Atomizers/irrigation	$ 54,000
Contingency	$ 29,000
Total	$318,600

The operating cost for the infiltration and evaporation impoundment is estimated at $0.10 per barrel of water produced, including $0.03 per barrel for electricity and maintenance of the surface pumps, $0.02 per barrel for maintaining the impoundments, and $0.05 per barrel for operating the atomizer system.

Shallow Reinjection Variables

Shallow reinjection involves identifying shallow, relatively fresh water zones into which the CBM produced water could be reinjected. A handful of such shallow well injection projects exist, but with a mixed record of success. Shallow reinjection is still a high-risk option, requiring more in-depth geological study to identify favorable reinjection zones. Therefore, shallow reinjection was evaluated from the standpoint of its future potential impact on CBM development in the Powder River Basin. Ideally, the shallow reinjection zone would be under-pressured and highly permeable. This would help reduce or eliminate pumping costs and reduce the number of required injection wells.

The costs for a large, central shallow reinjection facility (or two smaller facilities) capable of dispersing 30,000 barrels per day from 96 producing CBM wells are as follows:

- The cost of two 3-acre (20 acre-foot) infiltration impoundments (with a combined capacity for 300,000 barrels) is estimated at $235,500. This would provide storage for about 10 days of water production from a 96-well unit. The annual water loss from two impoundments would be modest, on the order of 1500 barrels per day.

- Subsequently, after impoundment, the produced water would be injected into a series of shallow wells. Assuming a water injection capacity of 2000 barrels per day (based on water production and a select number of injection projects in the basin) and a success rate of 75%, approximately 20 shallow reinjection wells would be drilled (15 would become injectors).

- Each injection well is estimated to cost approximately $142,500. This includes water transportation, pumps, injection facilities, permits, etc. Assuming average shallow reinjection well drilling and completion costs per well of $142,500, the costs for 20 reinjection wells would be $2,850,000 plus $235,500 for the impoundment facilities. With 10% added for contingency, shallow reinjection requires $3,394,000 plus $1000 per CBM well for permitting and study. This would be sufficient to handle a capacity of 96 CBM wells at a cost of $36,350 per well. Total cost for wells, impoundment, facilities, contingency, and permitting is shown below:

Impoundments (2)	$ 235,500
Shallow wells (20)	$2,850,000
Contingency (@10%)	$ 308,550
NPDES permitting	$ 96,000
Total	$3,394,000

The operating costs for the shallow wells and impoundment (including electricity and maintenance for the surface pumps) are estimated at $0.10 per barrel of water produced.

Effluent Credit-Trading Scenario Evaluation

The challenge with effluent trading is allowing for innovative, market-based reforms without compromising existing safeguards or baselines in environmental protection. This is further complicated by the fact that many states have not yet established water quality baselines for streams and rivers, due, in part, to the difficulty of determining reasonable and achievable standards. One means of determining water quality baselines is by using TMDLs being developed by state regulatory agencies in cooperation with the EPA. Once realistic baselines are determined, additional conditions for effective trading include the following:

- The ability to monitor the problematic constituent(s) or pollutant(s)

- The availability of multiple control technologies

- The identification of multiple sources discharging the problematic constituent(s) or pollutant(s) in the same watershed

- The assurance that trading will not cause adverse environmental impacts, such as the creation of “hot spots” or highly degraded localized areas in a stream or lake

Example trading scenarios applicable to CBM effluent trading in the PRB may include the following:

- Trading between upstream and downstream wells located within one U.S. Geological Survey (USGS) hydrologic cataloging unit (HUC)
- Trading between wells located within different HUCs
- Trading between produced water and runoff from agricultural land modified by best management practices

Figures 3 and 4 illustrate the general trading concept between two dischargers for two different scenarios. The first scenario (Figure 3) entails trading between two dischargers when one meets permit requirements and the other does not. The second scenario (Figure 4) involves trading in which both dischargers' current loadings are higher than the permit requirements.

To avoid creating environmental "hot spots," a credit seller B must be located upstream of a credit buyer A. In Figure 3, the discharger B's current loading, L_B, is lower than the required water quality standard, L_P, whereas, the discharger A's present loading, L_A, is higher. For this situation, the discharger B would create a water quality credit of $(L_P\text{-}L_B)/k$, where k is a safety factor with a value greater than 1.0. Based on the previous studies (e.g., Fang et al., 2005), a k value ranging from 1.0 to 1.5 is usually appropriate. In this study, a k value of 1.0 was used to simplify the calculation. As a result, both the discharger A and B could benefit by saving the cost, C_A, that discharger A would otherwise have to spend to meet the water quality standard.

For the situation when neither A nor B meets the water quality standard, the discharger B could reduce its loading by $k \times (L_A + L_B) - 2 \times L_P$ (Figure 4) through adoption of treatment technologies. As a result, B would sell the additional reduction of $k \times L_B$ as the water quality credit to the discharger A. A then would directly discharge its water. Again, this would benefit both A and B by saving the total cost of C_A.

Since this project entailed evaluation of the effluent credit-trading concept from a planning approach, the scenarios that were evaluated do not take into account actual produced water-handling methods. Instead, potential water-handling practices were evaluated with respect to water quality baseline conditions by applying various water-handling practices to existing and planned CBM wells. Baseline conditions were established based on pre-1990 observed water quality data.

A total of four specific trading scenarios were evaluated within the PRB (Table 5). These scenarios were selected based on their potential to meet water quality standards and entail effluent trading between wells located in different HUCs, including the Clear Creek, Crazy Woman Creek, Upper Powder River, Little Powder River, and the Wyoming portion of the Middle Powder River subwatersheds (Figure 5).

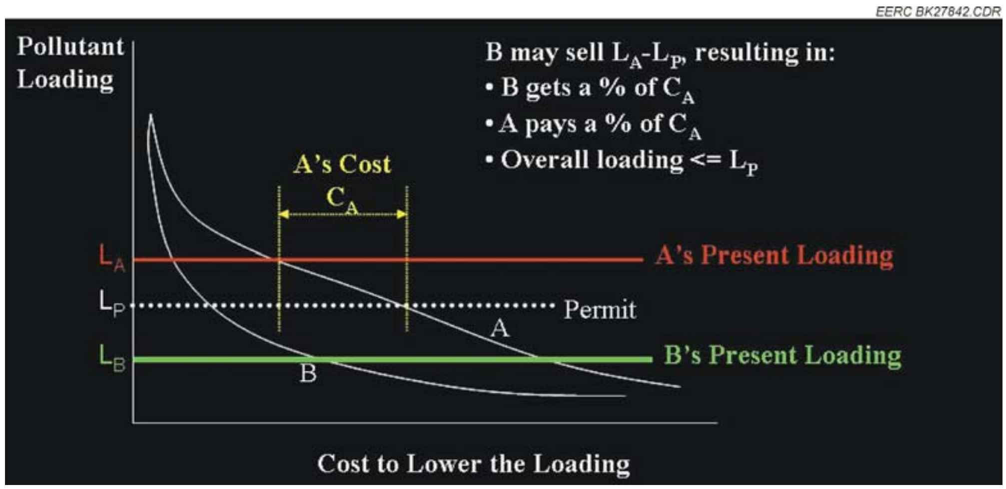

Figure 3. Benefits when discharger B's present loading is lower than the permit.

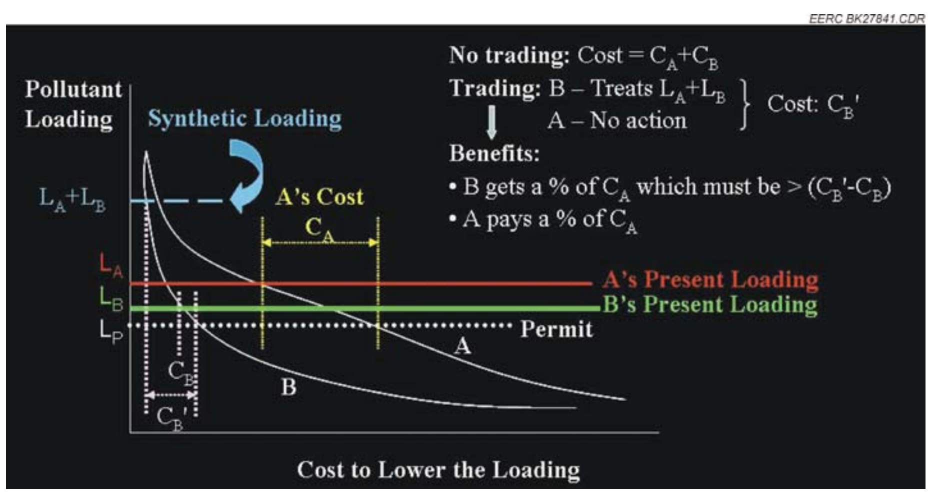

Figure 4. Benefits when dischargers A and B's present loadings are higher than the permit.

Table 5. Scenarios with Potential to Meet Water Quality Standards

Scenario	Description
I	All analyzed wells discharge
II	The wells, except ones in the Clear Creek subwatershed, discharge
III	The wells, except ones in the Clear Creek and Crazy Woman Creek subwatersheds, discharge
IV	25% of the produced water in the Upper Powder River subwatershed would be impounded or treated, but the remaining 75% and the water produced in the other subwatersheds would be discharged

Scenario I assumes that each of the 7842 wells included in the models are allowed to directly discharge to the nearest tributary or waterway. Scenarios II and III are similar to Scenario I, except that the CBM wells in the Clear Creek watershed, and Clear and Crazy Woman Creek watersheds, respectively, do not discharge. Scenario IV assumes that all planned and existing CBM wells discharge, except for 25% of the produced water in the Upper Powder River watershed, which would be treated or reinjected.

The environmental feasibility of the above scenarios was evaluated in terms of potential impacts to water quality. The economic feasibility of the option with the least environmental impacts was assessed and cost savings were determined based on various produced water handling methods. This is discussed further in the "Results" section of the report.

RESULTS

The following section discusses the predicted environmental and economic effects of the four trading scenarios listed in Table 5. The predicted impacts to flow, SAR, and alkalinity were very similar between Scenarios I, II, and III; therefore, only the model results from baseline conditions and from Scenarios I and IV are discussed and included in the figures.

Figures 6–8 illustrate the predicted impacts on the water quantity and quality at the Moorhead station, and Figures 9–11 show the predicted impacts on the water quantity and quality at the Locate station. As expected, Scenario I, where all wells discharge, was predicted to have the largest flow increase, whereas Scenario IV, which entailed retaining 25% of the produced water in the Upper Powder River subwatershed, was predicted to have the lowest increase. In terms of water quality standards (Table 1) and irrigation thresholds (Figure 2), the predicted SAR and EC values fall in the area of "no reduction in rate of infiltration," indicating that none of the analyzed scenarios would impair the Powder River for irrigation use. The predicted EC values for Scenarios I and IV were comparable to the values for the baseline condition (Figures 8 and 10). However, Scenario IV would have the least impact because it would result in a minimal elevation of SAR (Figures 7 and 9). For this scenario, the predicted SAR value at Moorhead would be even lower than the baseline condition during March, May, and June (Figure 7).

Because Scenario IV was predicted to have minimal impacts on water quality, it was determined to be an optimal trading option for economic evaluation. Results indicated that in the Upper Powder River subwatershed, the cost of handling the produced water would be reduced by \$343.1 to \$414.5 million (Table 6) through the sale of water quality credits, depending on the water-handling method. For the other four subwatersheds, the costs would also be reduced by \$12 to \$137 million. Overall, implementing Scenario IV would result in a total savings of \$548 to \$684 million in the Powder River watershed.

Table 7 presents the results of this study in terms of how much incremental natural gas production could be produced or how many additional CBM wells could be completed as a result of effluent trading in the PRB. Based on well data and the average volume of water produced from current and planned CBM wells (as estimated by the model), Scenario IV would allow for approximately 11,076 MMbbl of water to be directly discharged, assuming a well lifetime of 10 years. Assuming an average gas–water ratio of 0.5 thousand cubic feet (Mcf) of gas per barrel (bbl) of water, directly discharging this amount of produced water would facilitate the development of about 5,538,175 MMcf (5.5 Tcf) of CBM gas. Considering that estimated ultimate recovery (EUR) values of natural gas for an average CBM well in the PRB range from 300 to 500 MMcf (Williams, 2004), this volume of gas is equivalent to the development of approximately 11,000 to 18,300 new CBM wells.

Table 6. Estimated Cost Savings Achieved by Implementing Scenario IV

Economic Analysis of Scenario IV					
Assumptions	CBM produced water from discharge wells is handled by:	Infiltration Impoundment	Shallow Reinjection	Infiltration Impoundment	Shallow Reinjection
	25% of the produced water in the Upper Power River watershed would be handled by:	Infiltration Impoundment	Infiltration Impoundment	Shallow Reinjection	Shallow Reinjection
Estimated Savings per Subwatershed (in million $):	Upper Powder River	$357.4	$414.5	$344.0	$400.2
	Crazy Woman Creek	$12.2	$15.3	$12.2	$15.3
	Clear Creek	$22.3	$29.7	$22.3	$29.7
	WY portion of Powder River	$120.7	$137.2	$120.7	$137.2
	Little Powder River	$48.5	$86.8	$48.5	$86.8
Total Savings (in million $):		$561	$683.5	$547.7	$669.2

Table 7. Predicted Additional CBM Production under Produced Water-Handling Scenario IV[1]

Subwatershed	Number of Analyzed CBM Wells	10-Year CBM Produced Water Discharged at the Wellhead (MMbbl)	Gas Facilitated (MMcf)
Clear Creek	483	369	184,444
Crazy Woman Creek	199	231	115,388
Upper Powder	3683	7479 [2]	3,739,513
Little Powder	1068	2932	1,466,009
Middle Powder	2408	65	32,822
Total	7841	11076	5,538,175

[1] Assumes a gas/water ratio of 0.5 thousand cubic feet (Mcf) of gas per barrel (bbl) of water (based on data from Garfield County, Montana, and B.C. Technologies, available at www.garfield-county.com/docs/eab-_cbng_water_adobe.pdf)

[2] This volume of water is equivalent to 75% of the water produced within the watershed as described in the explanation for Scenario IV. IV.

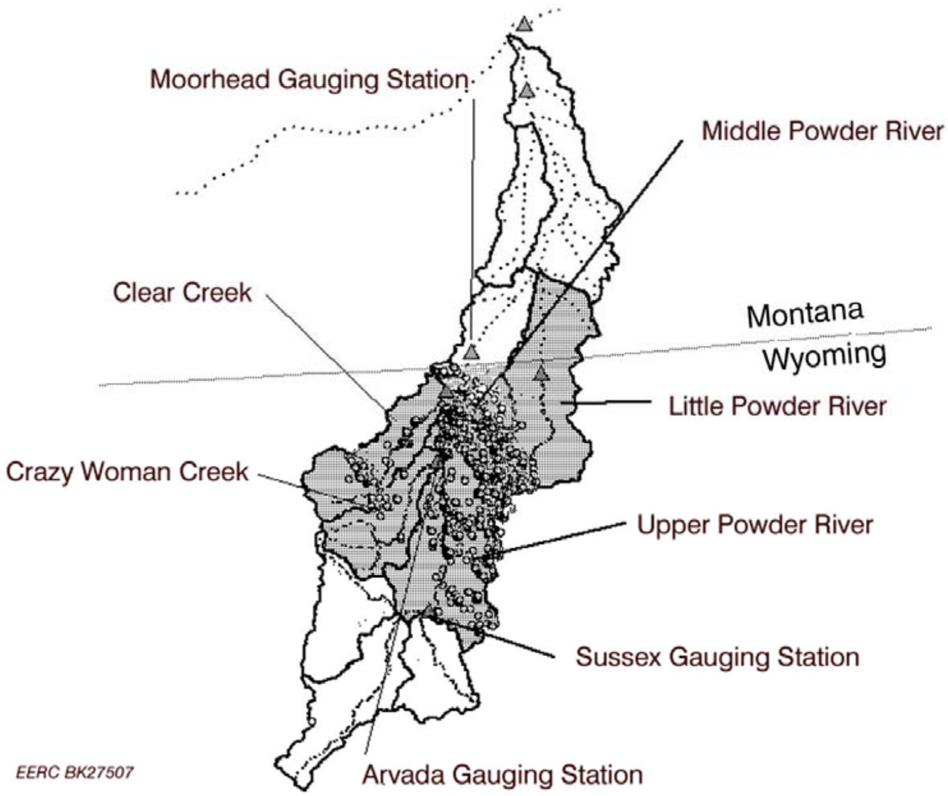

Figure 5. Subwatersheds included in the trading scenarios.

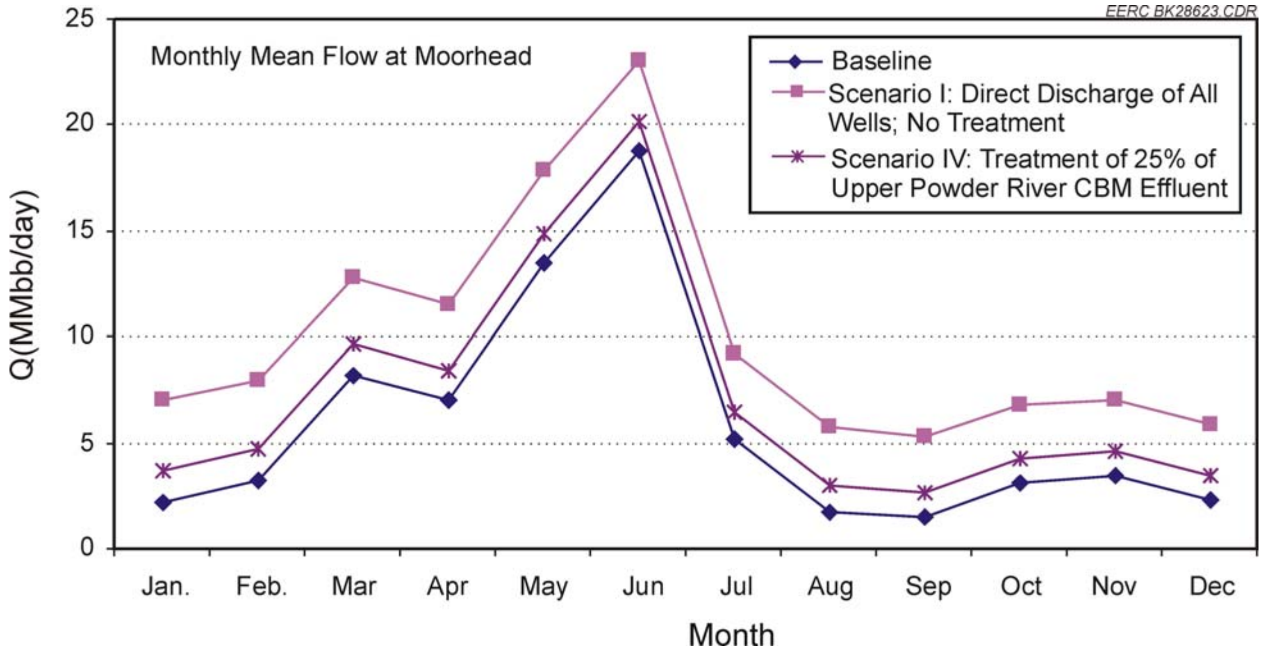

Figure 6. Monthly mean flows at Moorhead for the baseline condition and four scenarios.

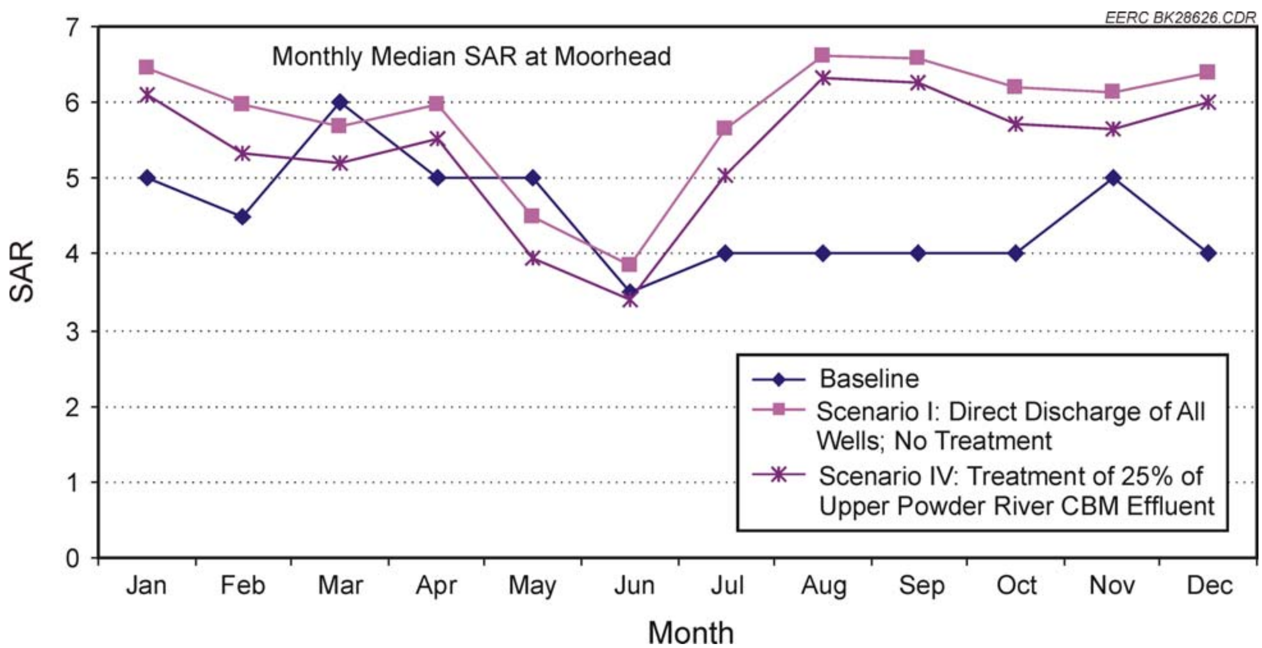

Figure 7. Monthly median SAR values at Moorhead for the baseline condition and four scenarios.

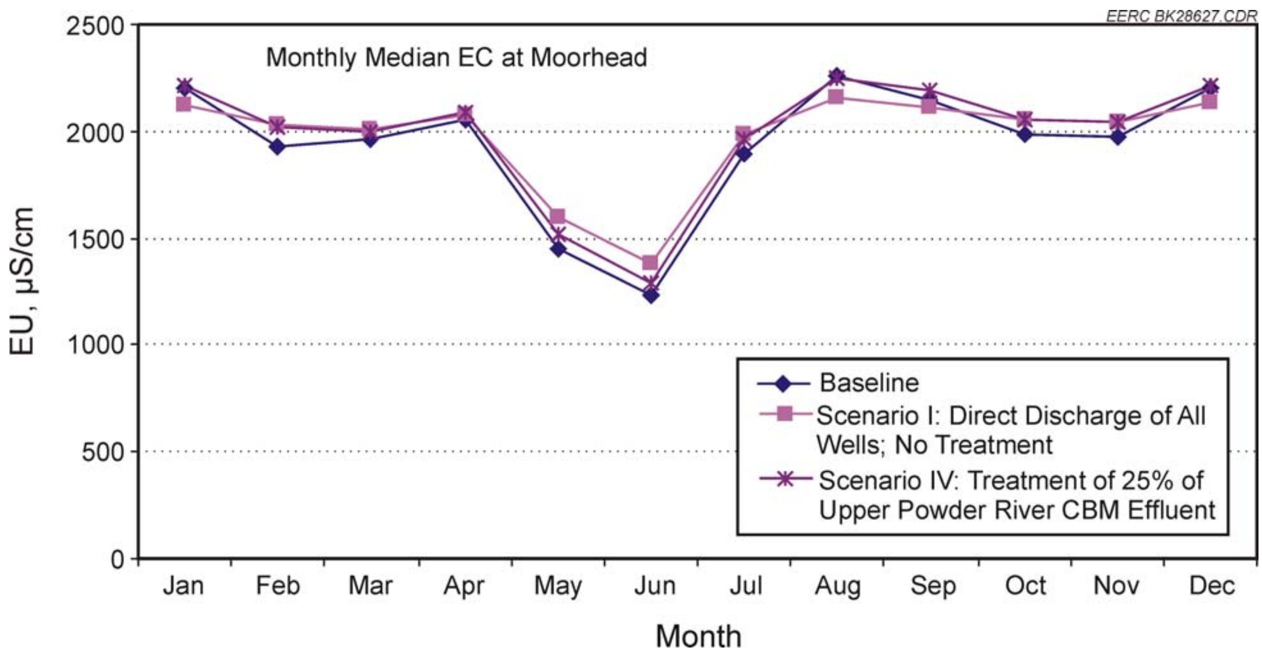

Figure 8. Monthly median EC values at Moorhead for the baseline condition and four scenarios.

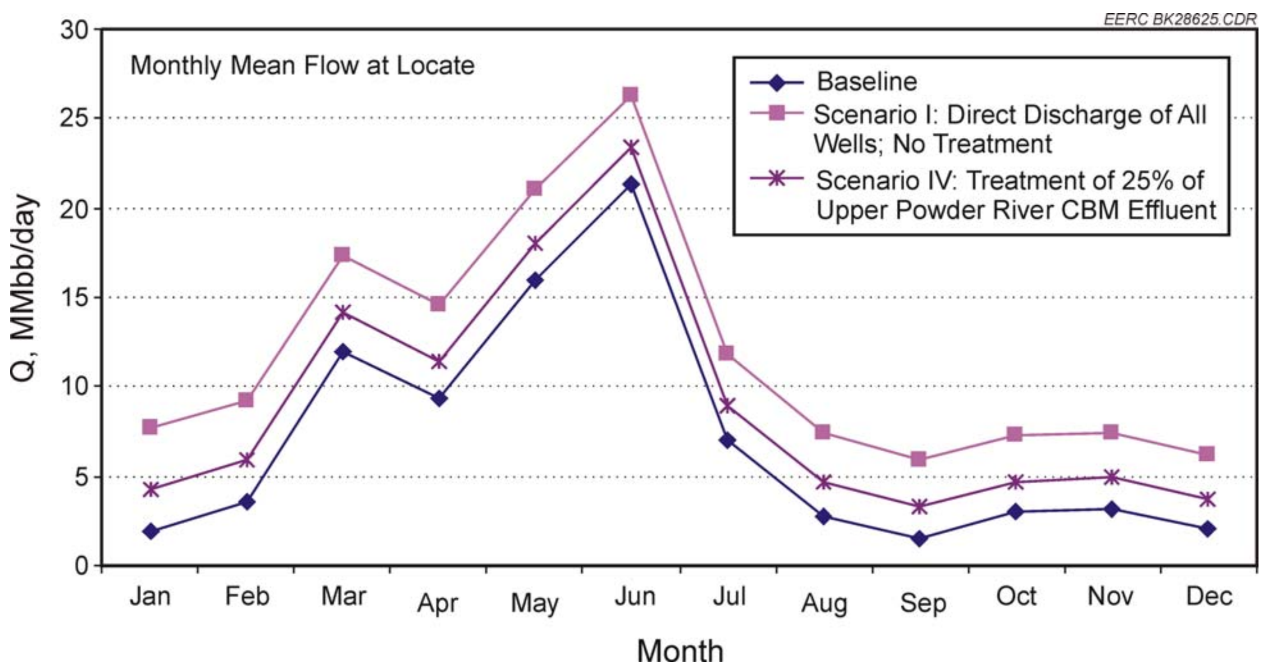

Figure 9. Monthly mean flows at Locate for the baseline condition and four scenarios.

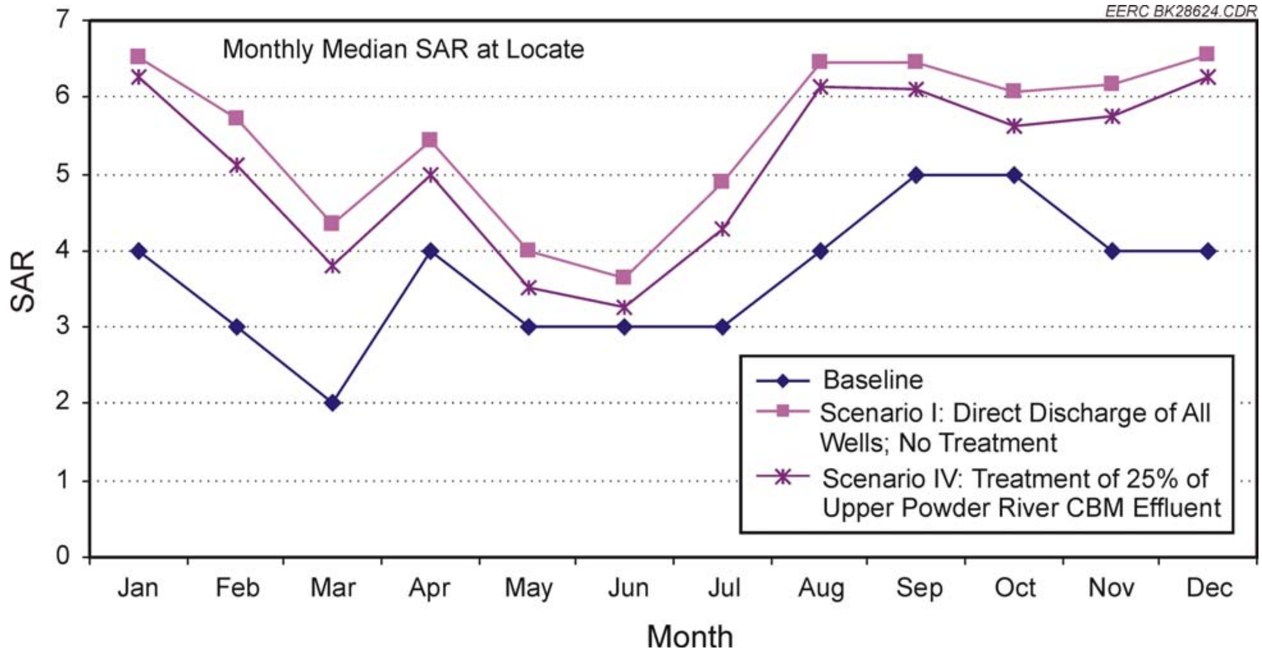

Figure 10. Monthly median SAR values at Locate for the baseline condition and four scenarios.

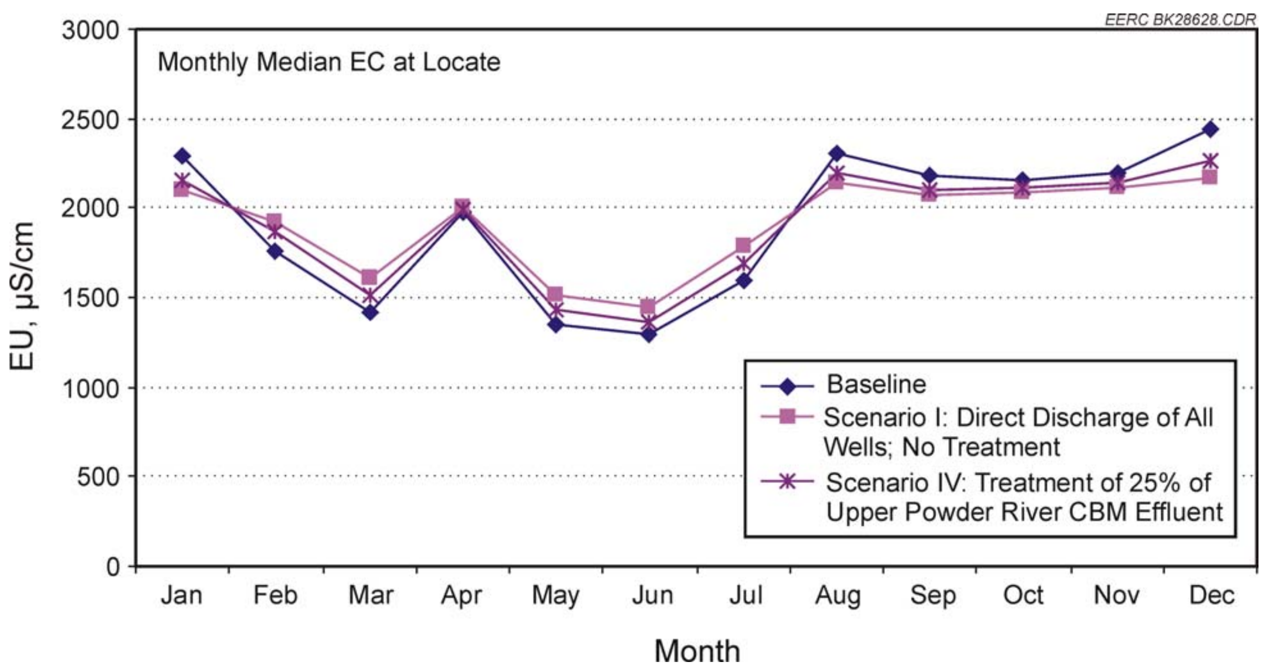

Figure 11. Monthly median EC values at Locate for the baseline condition and four scenarios.

CONCLUSIONS

The goal of this project was to evaluate the feasibility of effluent credit trading in the PRB and to communicate the concept and results to key stakeholders in Wyoming and Montana. To achieve this goal, the EERC evaluated existing water quality information and developed the appropriate tools needed to assess the environmental and economic feasibility of specific trading scenarios within the PRB.

The accomplishments of this project include the following:

- Development of an economically and environmentally feasible effluent credit-trading scenario for the PRB based on robust data sets and rigorous modeling efforts.

- Creation of three computer models, including a watershed model, an in-stream hydrodynamic and water quality model, and an economic model. These models comprise the core components of a decision support tool developed through the project and described in Appendix D. Users should contact the EERC with questions regarding the models or decision-support tool developed through this project.

- Completion of outreach products aimed at facilitating potential applications of the concept, dissemination of the concept, and development of trading options.

As CBM production increases to meet rising demands for natural gas, innovative market-based mechanisms are needed to streamline produced water handling, minimize costs, and ensure environmental sustainability. The results of this project indicate that watershed-based effluent credit trading could be a viable means of facilitating 5.5 Tcf of CBM development in the PRB while maintaining environmental safeguards. General conclusions based on this project suggest that for the PRB, watershed-based effluent trading could 1) facilitate implementation of efficient, low-cost handling methodologies for CBM produced water, 2) provide a solution to balance CBM development with environmental protection, 3) increase producers' profits as a result of lower produced water-handling costs, 4) increase invaluable water resources, and 5) encourage responsible CBM development. Ultimately, this market-based approach allows for improved water quality management throughout an entire watershed while increasing options for industrial, agricultural, and municipal stakeholders.

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APPENDIX A

PROJECT PROSPECTUS

Watershed-Based Effluent Credit Trading

An Innovative Strategy to Manage Coalbed Methane (CBM) Produced Water in the Powder River Basin (PRB)

Demonstration Prospectus

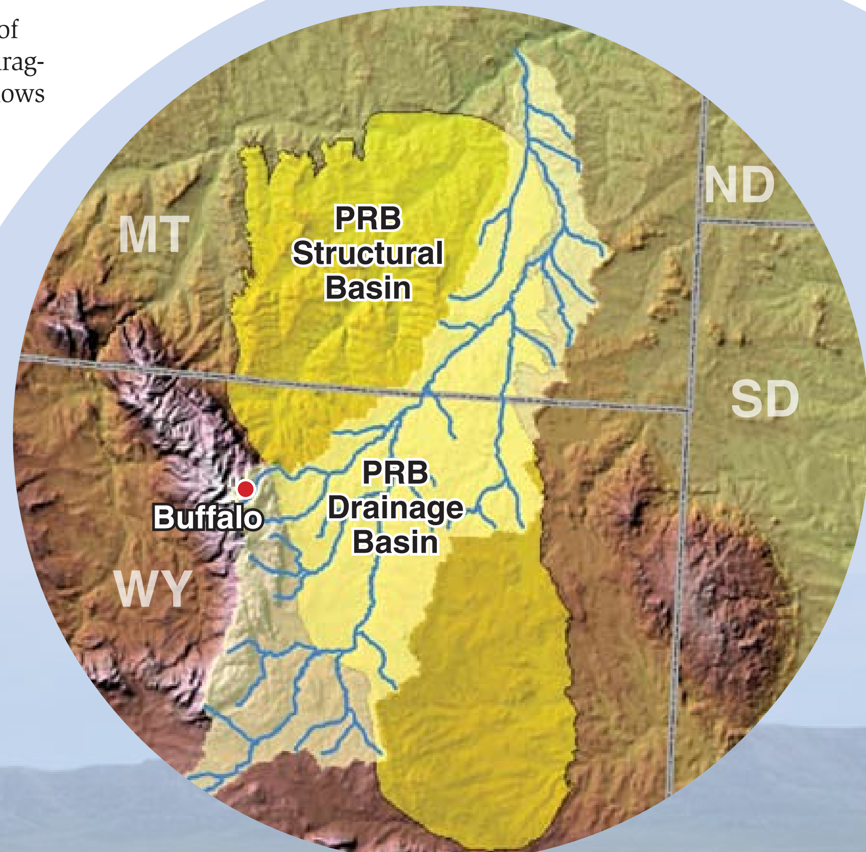
The Energy & Environmental Research Center (EERC) at the University of North Dakota is currently investigating the feasibility of water quality credit trading, or effluent credit trading, in the Powder River drainage basin of Montana and Wyoming. Effluent credit trading is increasingly being evaluated and implemented in watersheds throughout the United States as a means of cost-effective water quality management. This prospectus describes the effluent credit-trading concept and the tools being developed by the EERC to evaluate the effectiveness of this approach for managing water resources in the Powder River Basin (PRB).

The challenge with effluent credit trading is allowing for innovative, market-based reforms without compromising existing safeguards or baselines in environmental protection. One means of determining water quality baselines is by using total maximum daily loads (TMDLs) being developed by state regulatory agencies in cooperation with the U.S. Environmental Protection Agency (EPA). Once realistic baselines are determined, additional conditions for effective trading include:

- The ability to monitor the problem pollutant(s).
- The availability of multiple control technologies.
- The identification of multiple sources discharging the problem pollutant(s) in the same watershed.

What is effluent credit trading?

Effluent credit trading is an innovative, market-based approach for managing point and non-point sources of pollutants to achieve water quality goals while encouraging economic development. Effluent credit trading allows facilities facing higher pollution control costs to meet or exceed their regulatory obligations by purchasing environmentally equivalent or superior pollution reduction credits from other sources at overall lower cost. For example, a municipal wastewater treatment plant could exceed the treatment goals mandated by discharge permits and sell accumulated credits to a coalbed methane (CBM) producer, facilitating discharge while maintaining water quality goals. In order to ensure that the overall water quality of the waterway continues to meet regulatory guidelines, the credit seller would be located upstream of the credit buyer, and a site-specific analysis would be conducted to ensure no localized adverse impacts to water quality. Ultimately, this market-based approach allows for improved water quality management throughout an entire watershed while increasing options for industrial, agricultural, and municipal stakeholders.



Map of Drainage Basin and Structural Basin of the Powder River.

- The assurance that trading will not cause adverse environmental impacts, such as the creation of "hot spots" or highly degraded localized areas in a stream or lake.

Benefits of the effluent-trading approach over the conventional regulatory approach have been verified by a number of demonstration trading projects throughout the country and include:

- Cost savings to industry.
- Incentives to reduce pollutant loading.
- Incentives for technological innovation.
- An emphasis on water quality rather than the installation of a particular abatement technology.
- The possibility for independent groups to participate.

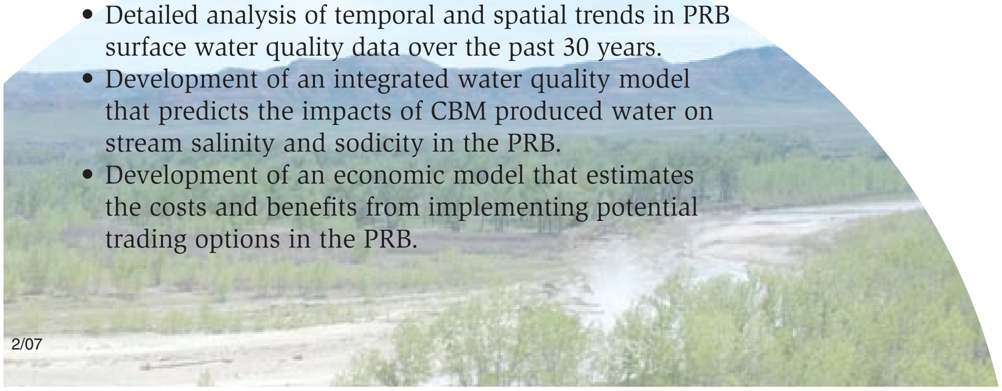
Why is it appropriate for the PRB?

The number of CBM-producing wells in the PRB, one of the most active areas of CBM production since 1997, is expected to increase from the present 16,000 to perhaps 70,000 within the next 20–30 years (www.bogc.dnrc.state.mt.us/OnlineData.htm). The development of this many CBM wells will likely increase produced water outputs within the watershed to levels of up to 25 MMbbl/day. As a result, many states are in the process of reviewing and revising environmental regulations pertaining to produced water because of the high priority currently placed on clean water resources. As a supplement to current regulatory approaches, the EPA Office of Water is renewing efforts to develop and implement market-based approaches to improve water quality more quickly at a reduced cost. Watershed-based effluent credit trading is one of these potential approaches. The intent is to achieve reductions in particular pollutants at a lower cost and provide for beneficial use of the produced water in a cost-effective manner.

What has been accomplished to date?

In 2003, the EERC received funding from the U.S. Department of Energy to investigate the feasibility of effluent credit trading in the PRB. The main goals of the study are to evaluate existing water quality data and to develop the tools necessary to investigate the environmental and financial feasibility of specific trading options in the PRB. The recent accomplishments of this study include:

- Detailed analysis of temporal and spatial trends in PRB surface water quality data over the past 30 years.
- Development of an integrated water quality model that predicts the impacts of CBM produced water on stream salinity and sodicity in the PRB.
- Development of an economic model that estimates the costs and benefits from implementing potential trading options in the PRB.



The water quality model itself consists of two components: an overland routing model and an in-stream hydrodynamic model.

What is the next step?

To ensure that the prospective results are applicable in practice and consistent with state environmental guidelines, the next steps are to develop and evaluate potential future trading options. This involves consideration and quantitative evaluation of four criteria: implementation feasibility, environmental effects, economic effects, and equity effects. The models being developed by the EERC can be used to evaluate potential trading options in accordance with these criteria and determine the suitability of effluent credit-trading deployment in the PRB. Our goal is to use these tools in conjunction with the appropriate industry representatives and regulatory agencies to evaluate the most cost-effective and environmentally sound produced water management options in the PRB.

How can you get involved in the evaluation of potential trading options?

The EERC is currently seeking regulatory and industry participation to evaluate hypothetical CBM effluent credit trading and its impacts on water quality within the PRB using the models developed through our projects. For general information, contact:

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APPENDIX B

WATER QUALITY EVALUATION

SUMMARY

Surface water quality temporal trends and spatial patterns were analyzed using U.S. Geological Survey (USGS) water quality data collected until 2002 along the Powder River. Data on discharge (Q), water temperature (T_W), air temperature (T_A), pH, electrical conductivity (EC), sodium adsorption ratio (SAR), alkalinity, calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), chloride (Cl^-), sulfate (SO_4^{2-}), and biocarbonate (HCO_3^-) came from four USGS stations: Sussex and Arvada in Wyoming and Moorhead and Locate in Montana. Linear regression, Kendall's S, and Seasonal Kendall's S′ were used to detect trends, and ANOVA (analysis of variance) was used to analyze spatial differences between stations. For each of the 14 water quality parameters at each of the four stations, the analyses were conducted respectively on 1) the whole dataset that is composed of the data until 2002; 2) the pre-1990 dataset that is composed of the data before 1990; and 3) the post-1990 dataset that is composed of the data from 1990–2002. While the three datasets exhibited a different trend for some parameters but a consistent trend for the others, at each of the four stations the whole dataset and pre-1990 dataset exhibited more trends than the post-1990 dataset. For a dataset, more trends were generally detected by using Kendall's S and Seasonal Kendall's S′ than linear regression.

Across the stations, a significant positive trend for pH was detected by at least one of the three methods from the four whole datasets. A significant positive trend for pH, SAR, Na^+, and Cl^- and a significant negative trend for Ca^{2+} were detected by at least one of the three methods from the four pre-1990 datasets. No common significant trend was detected from the four post-1990 datasets. The other parameters might have a significant positive trend at one station but a significant negative or insignificant trend at another station. At one of the stations, a significant positive trend might be detected by one or all of the methods from one dataset but a significant negative or insignificant trend might be detected from another dataset. Spatially, all three datasets indicated that the salinity (EC), sodicity (SAR), Na^+, Cl^-, and HCO_3^- were significantly lower in Montana and that seven parameters, including Q, T_W, pH, Mg^{2+}, and SO_4^{2-}, were significantly lower in Wyoming. There was no significant difference for T_A and K^+ between the two states. In addition, the post-1990 dataset indicated that alkalinity and Ca^{2+} were significantly lower in Montana, but the whole dataset and pre-1990 dataset indicated that these two parameters were significantly lower in Wyoming.

These results might imply that in terms of the 14 parameters, except for alkalinity and Ca^{2+}, the surface water quality spatial patterns in the Powder River have not significantly changed in spite of the aforementioned temporal trends. The EC exceedance, in accordance with the Total Maximum Daily Loads proposed by the Montana Department of Environmental Quality on December 6, 2002, might be as high as 72% in Wyoming but could be as low as 38% in Montana, whereas the SAR exceedance might be as high as 52% in Wyoming but could be as low as 16% in Montana. For all of the four stations, both EC and SAR exhibited a higher exceedance in the years before 1990 than after 1990 (except Moorhead, where data with EC and SAR observations were unavailable after 1982), with the highest exceedances occurring before 1980. Within a year, the exceedances were higher in the growing season (March 2 – October 31) than the nongrowing season (November 1 – March 1).

MATERIALS AND METHODS

Data

The data used were collected by the USGS at four sampling stations along the Powder River, including Sussex and Arvada in Wyoming and Moorhead and Locate in Montana (Table B-1). The number of record years of the data varies greatly from station to station, and the record for each of the stations might include a gap of anywhere from months to years. For each of the stations, no data collection occurred in some months, while in other months, data for some years were recorded for two or more different dates. Table B-2 summarizes the availability of data across the four stations for the 14 water quality parameters analyzed in this study, including Q, T_W, T_A, pH, EC, SAR, alkalinity, Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, SO_4^{2-}, and HCO_3^-.

At Sussex, data for T_W, SAR, Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, and SO_4^{2-} were recorded from 1966–1968 and 1976–2002, during which 230–239 months had at least one observation, whereas data for Q, T_A, pH, EC, alkalinity, and HCO_3^- had 4-, 4-, 7-, 26-, and 22-year gaps during the 30-year record. The number of months when there was at least one observation varies from 18 to 263 across the parameters, with a mean of 196 and a standard deviation of 72.4.

Arvada has recorded data from 1946, 1948–1953, 1955, and 1967–2002. During the 44-year data record, Q, Ca^{2+}, and Mg^{2+} had at least one observation per year, but T_W, T_A, pH, EC, SAR, alkalinity, Na^+, K^+, Cl^-, SO_4^{2-}, and HCO_3^- had a 4–40-year gap. The number of months when there was at least one observation varies from 24–527 across the 14 parameters, with a mean of 272 and a standard deviation of 111.

Moorhead has recorded data from 1969–1972 and from 1974–2002. During the 33-year data record, Q, T_W, and EC had at least one observation for each year, whereas the other 11 parameters were not observed at all for 1–31 years. The number of months when there was at least one observation varies from 17–384, with a mean of 181 and a standard deviation of 93.1.

Locate has the longest data record, including 1948–1962, 1965, and 1974–2002. However, only Q had at least one observation for each of the 45 record years and the other 13 parameters had a 5–41-year gap. The number of months when there was at least one observation varies from 38–360, with a mean of 276 and a SD of 87.3.

To examine whether the surface water quality had different temporal trends and spatial patterns, for each of the 14 water quality parameters at each of the four stations, the analyses were conducted respectively on 1) the whole dataset that is composed of the data until 2002, 2) the pre-1990 dataset that is composed of the data before 1990, and 3) the post-1990 dataset that is composed of the data from 1990–2002. The number of months when there was at least one observation has a similar dispersion with a coefficient of variation (C_v) of 0.3–0.5 across the four stations for the three datasets, except that the post-1990 dataset at Moorhead has a larger C_v of 1.17.

Table B-1. Water Quality Parameters Analyzed in This Study, and Summary Statistics, Listed by Recording Stations

		Q	T_W	T_A	pH	EC	SAR	Alkalinity	Ca^{2+}*	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	HCO_3^{-}	Mean	Median	SD
Sussex	Record Years		←					1966–1968 1976–2002							→	—[‡]	—[‡]	—[‡]
	Missing Years	1976 1999–2001	—[†]	1966–1968 1976	1984–1987 1990–1992	1984–1987	—[†]	1966–1968 1976–1997 1999	—[†]	—[†]	—[†]	—[†]	—[†]	—[†]	1981–2002	—[‡]	—[‡]	—[‡]
	No. of Years Analyzed	26	30	26	23	26	30	4	30	30	30	30	30	30	8	25	30	8.5
Arvada	Record Years		←					1946 1948–1953 1955 1967–2002							→	—[‡]	—[‡]	—[‡]
	Missing Years	—[†]	1946 1948–1953 1955	1946 1948–1953 1955 1967–1977 1979	1955 1975 1983–1987 1990–1992	1983	1946 1948–1951	1946 1948–1953 1955 1967–1997 1999	—[†]	—[†]	1946 1948–1950	1946 1948–1952	1953 1955	1953 1955	1953 1955 1982–2002	—[‡]	—[‡]	—[‡]
	No. of Years Analyzed	44	36	24	34	43	39	4	44	44	40	38	42	42	21	35	40	11.5
Moorhead	Record Years		←					1969–1972 1974–2002							→	—[‡]	—[‡]	—[‡]
	Missing Years	—[†]	—[†]	1969	1985 1990–2000	—[†]	1969 1983–2002	1969–1972 1974–2000	1969 1985 1990–2000	1969 1985 1990–2000	1969 1985 1990–2000	1969–1971 1985 1990–2000	1969 1985 1990–2000	1985 1990–2000	1969–1971 1979–2002	—[‡]	—[‡]	—[‡]
	No. of Years Analyzed	33	33	32	21	33	12	2	20	20	20	18	20	21	6	21	20	9.9
Locate	Record Years		←					1948–1962 1965 1974–2002							→	—[‡]	—[‡]	—[‡]
	Missing Years	—[†]	1948–1962	1948–1962 1965	1965 1995–1998	1965	1948–1949 1965 1995–1998	1948–1962 1965 1974–1998	1965 1995–1998	1965 1995–1998	1948–1949 1965 1995–1998	1948–1949 1952 1965 1995–1998	1965 1995–1998	1965 1995–1998	1965 1979–2002	—[‡]	—[‡]	—[‡]
	No. of Years Analyzed	45	30	29	40	44	38	4	40	40	38	37	40	40	20	35	39	11.0
Sussex	Record Months	263	239	216	155	184	231	18	231	231	232	230	231	231	57	196	231	72.4
	Pre-1990 Months	156	141	118	92	92	133	0	133	133	134	133	135	135	57	114	133	41.6
	Post-1990 Months	107	98	98	63	92	98	18	98	98	98	97	96	96	0	83	98	32.9
Arvada	Record Months	527	274	151	221	313	282	24	314	314	288	281	317	317	191	272	285	111.0
	Pre-1990 Months	371	200	77	170	239	209	0	241	241	215	208	243	243	191	203	212	85.1
	Post-1990 Months	156	74	74	51	74	73	24	73	73	73	73	74	74	0	69	73	33.8
Moorhead	Record Months	384	278	247	190	270	103	17	180	181	166	158	180	189	54	186	181	93.1
	Pre-1990 Months	228	190	161	173	186	103	0	163	164	149	141	163	172	54	146	163	58.5
	Post-1990 Months	156	88	86	17	84	0	17	17	17	17	17	17	17	0	39	17	45.8
Locate	Record Months	252	258	253	360	413	271	38	289	288	341	248	306	338	205	276	280	87.3
	Pre-1990 Months	154	157	153	294	312	205	0	223	223	275	182	240	272	205	207	214	78.8
	Post-1990 Months	98	101	100	66	101	66	38	66	65	66	66	66	66	0	69	66	27.2

* All ions are dissolved.
[‡] The summary statistic has no sense for either Record Years or Missing Years.
[†] No annual median value was missed for the parameter at the station.

Table B-2. EC and SAR Exceedances Summarized by the Four USGS Stations: Sussex and Arvada in Wyoming and Moorhead and Locate in Montana*

	EC (µS/cm)			SAR		
Station	> EC TMDL†	Data Size	% > EC TMDL	> SAR TMDL‡	Data Size	% > SAR TMDL
Sussex	114	199	57.3	103	199	51.8
Arvada	244	342	71.3	164	342	48.0
Moorhead	45	111	40.5	18	111	16.2
Locate	131	343	38.2	86	343	25.1
Total	534	995	53.7	371	995	37.3

* Based on all of the data with both EC and SAR available from 1966–2002 at Sussex, 1952–2002 at Arvada, 1970–1982 at Moorhead, and 1950–2002 at Locate.

† Evaluated in accordance with the TMDL for EC proposed by MDEQ on December 6, 2002. The proposed EC TMDL is 2000 µS/cm for the growing season (March 2 – October 31) and 2500 µS/cm for the nongrowing season (November 1 – March 1).

‡ Evaluated in accordance with the TMDL for SAR proposed by MDEQ on December 6, 2002. The proposed SAR TMDL is 5.0 for the growing season (March 2 – October 31) and 7.5 for the nongrowing season (November 1 – March 1).

Identification of EC and SAR Exceedances

On December 6, 2002, the Montana Department of Environmental Quality (MDEQ) proposed an electrical conductance (EC) total maximum daily load (TMDL) of 2000 µS/cm for the growing season (March 2 – October 31) and 2500 µS/cm for the nongrowing season (November 1 – March 1), and a sodium adsorption ratio (SAR) TMDL of 5.0 for the growing season and 7.5 for the nongrowing season. While the Wyoming Department of Environmental Quality (WDEQ) does not intend to implement a TMDL program for the Wyoming portion of the Powder River drainage basin, WDEQ made a commitment to support MDEQ to meet the TMDL goals in the Montana portion of the PRB. The exceedances of EC and SAR in accordance with the TMDLs proposed by the MDEQ were evaluated using plots and summary tables of the data with both EC and SAR observations available.

Analysis of Temporal Trends

The size and the wide variation of the raw datasets, including the whole datasets, pre-1990 datasets, and post-1990 datasets, required an effort to reduce the data into a more manageable form, using the following method. When a parameter was measured on two or more dates in a single month, those values were used to identify a monthly median. When no data in a month were available, no monthly median was recorded. Monthly medians across each calendar year were then used to identify an annual median.

Three types of trend analyses were performed on the monthly and annual medians to thoroughly explore the existence and strength of trends in the data. First, annual medians over the record period were used in least squares linear regression models. Extensive testing of linearity, normality, serial correlation, and distribution of residuals verified that these data met the assumptions for the use of linear regression. No transformations were required for meeting these assumptions. Estimated slopes and p-values from linear regression were used to detect and quantify trends. The annual medians used in the linear regression were used in the second trend analysis to calculate the Mann-Kendall statistic, S, and a p-value was used to determine the significance of S. The third trend analysis applied the Seasonal Kendall Test, in which the monthly medians were used to calculate the Seasonal Mann-Kendall statistic, S′, and a p-value was used to determine the significance of S′. The Seasonal Kendall's Test is appropriate when seasonal cycles may be present in the data, which is the situation for some parameters such as Q.

Analysis of Spatial Patterns

Table B-2 indicates that for any given year from 1976–2002, a station may have sufficient annual medians needed to conduct spatial analyses. However, there is no single year from 1976–2002 when all of the 14 parameters have annual medians across the four stations because of the asynchronous data gaps. Therefore, the EM (estimate and maximum) algorithm, a widely used multivariate statistical method for inputting missing values, was used to input the annual medians missed during 1976–2002 to create a complete dataset for each of the four stations. As with trend analysis, for each of the 14 water quality parameters at each of the four stations, the complete dataset was subdivided into a whole dataset, a pre-1990 dataset, and a post-1990 dataset. ANOVA with Tukey's multiple comparisons was used to examine the spatial differences in mean parameter values computed from the yearly medians among stations.

Software Used

The raw data was manipulated in Microsoft Excel® 2000 and ArcView® 3.2a. The trend and pattern analyses were made using SAS®. In addition, several computer programs were written in Visual Basic® 6.0 and Avenue® to facilitate data transmission between the software packages.

RESULTS AND DISCUSSION

Exceedances of EC and SAR

Figures B-1 through B-4 plot the EC and SAR classified by growing season and nongrowing season at Sussex, Arvada, Moorhead, and Locate, respectively. These plots also show the EC and SAR TMDLs proposed by the MDEQ on December 6, 2002. For each station, both EC and SAR have higher exceedances in the growing season than the nongrowing season. Across the stations, Sussex and Arvada have higher exceedances than Moorhead and Locate.

The exceedances summarized by station are shown in Table 3. The EC exceedance increased from 57% at Sussex to 71% at Arvada but decreased to 38% at Locate, and the SAR exceedance decreased from 52% to 16% from Sussex to Moorhead but increased to 25% at Locate. An examination indicated that the exceedances are uncorrelated with data size (number of observations).

Figures B-5 through B-8 show the EC and SAR exceedances summarized by year for the Powder River at Sussex, Arvada, Moorhead, and Locate, respectively. The pink dots represent the total number of observations available in each of the record years, and the blue dots represent the number of the observations that exceeded the TMDLs in the given year. Across the stations of Sussex, Arvada, and Locate, the years before 1990 (particularly before 1980) exhibited a higher exceedance. At Moorhead, while the exceedances could not be evaluated for the years after 1982 because there was no data with both EC and SAR available, they were higher in the years from 1975 through 1980 than the later years, which is consistent with the other three stations. In addition, Sussex and Arvada exhibited higher exceedances than Moorhead and Locate.

Figures B-5 through B-8 show EC and SAR exceedances summarized by year for the Powder River at Sussex, Wyoming, Arvada, Wyoming, Moorhead, Montana, and Locate, Montana. The EC exceedances are evaluated in accordance with the TMDL for EC proposed by MDEQ on December 6, 2002. The proposed EC TMDL is 2000 μS/cm for the growing season (March 2 – October 31) and 2500 μS/cm for the nongrowing season (November 1 – March 1), and the SAR exceedances are evaluated in accordance with the TMDL for SAR proposed by MDEQ on December 6, 2002. The proposed SAR TMDL is 5.0 for the growing season (March 2 – October 31) and 7.5 for the nongrowing season (November 1 – March 1).

The EC and SAR exceedances summarized by month are shown in Tables B-3 through B-6 for the Powder River at Sussex, Arvada, Moorhead, and Locate, respectively. Across the four stations, the growing months from March to October exhibited higher exceedances than the nongrowing months from November to March. In particular, the three growing months of April, August, and September consistently exhibited the highest exceedances for both EC and SAR across the stations. In addition, as indicated by the exceedances summarized by year, the exceedances tend to decrease from Sussex to Locate. Using the data pooled from the four stations, the overall EC and SAR exceedances were summarized by month and shown in Table B-7. Similarly, the growing months of April, August, and September exhibited the highest exceedances as well.

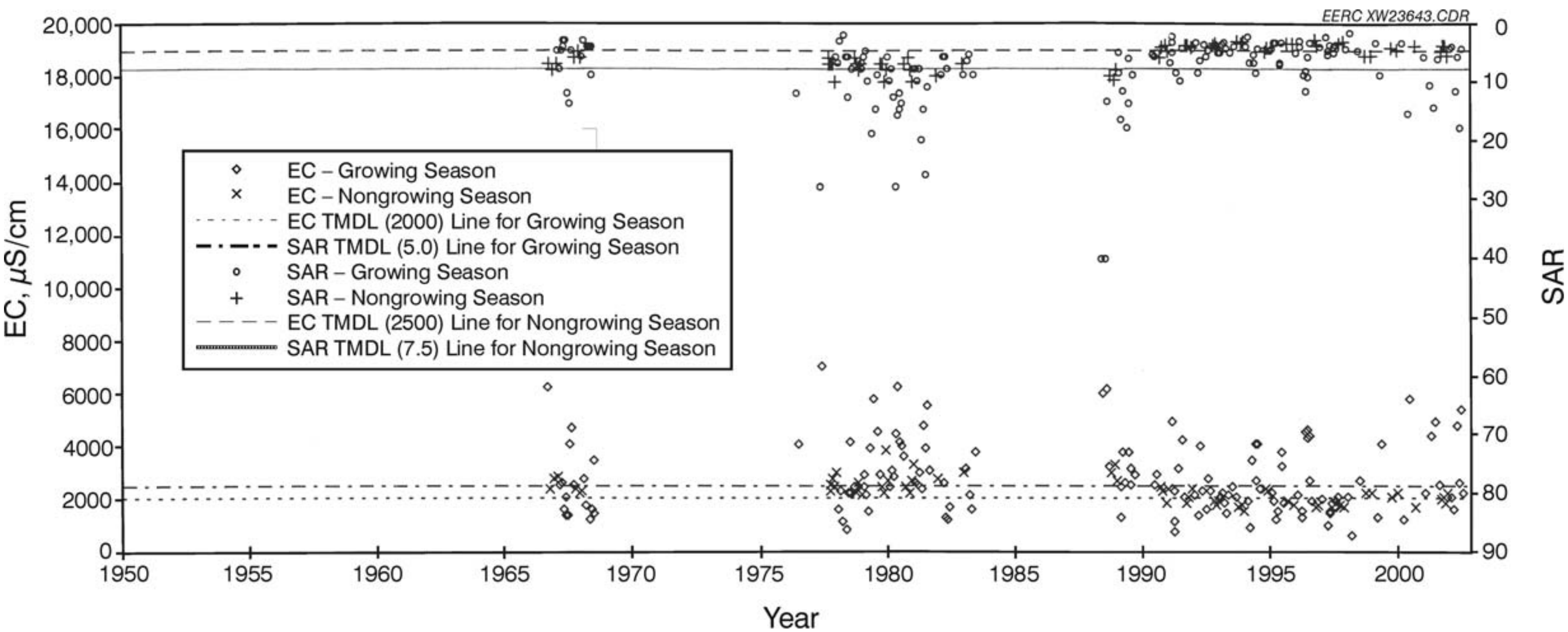

Figure B-1. Instantaneous EC and SAR for the Powder River at Sussex, Wyoming (USGS 06313500).

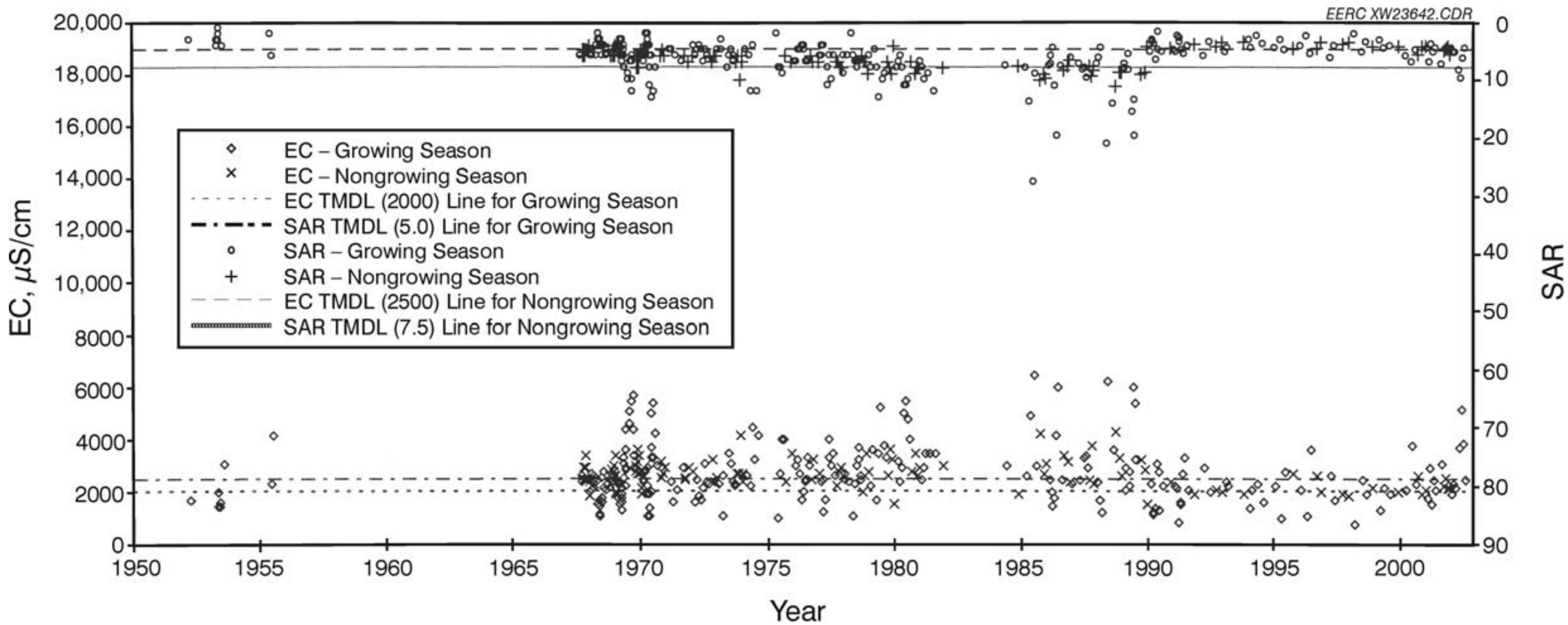

Figure B-2. Instantaneous EC and SAR for the Powder River at Arvada, Wyoming (USGS 06317000).

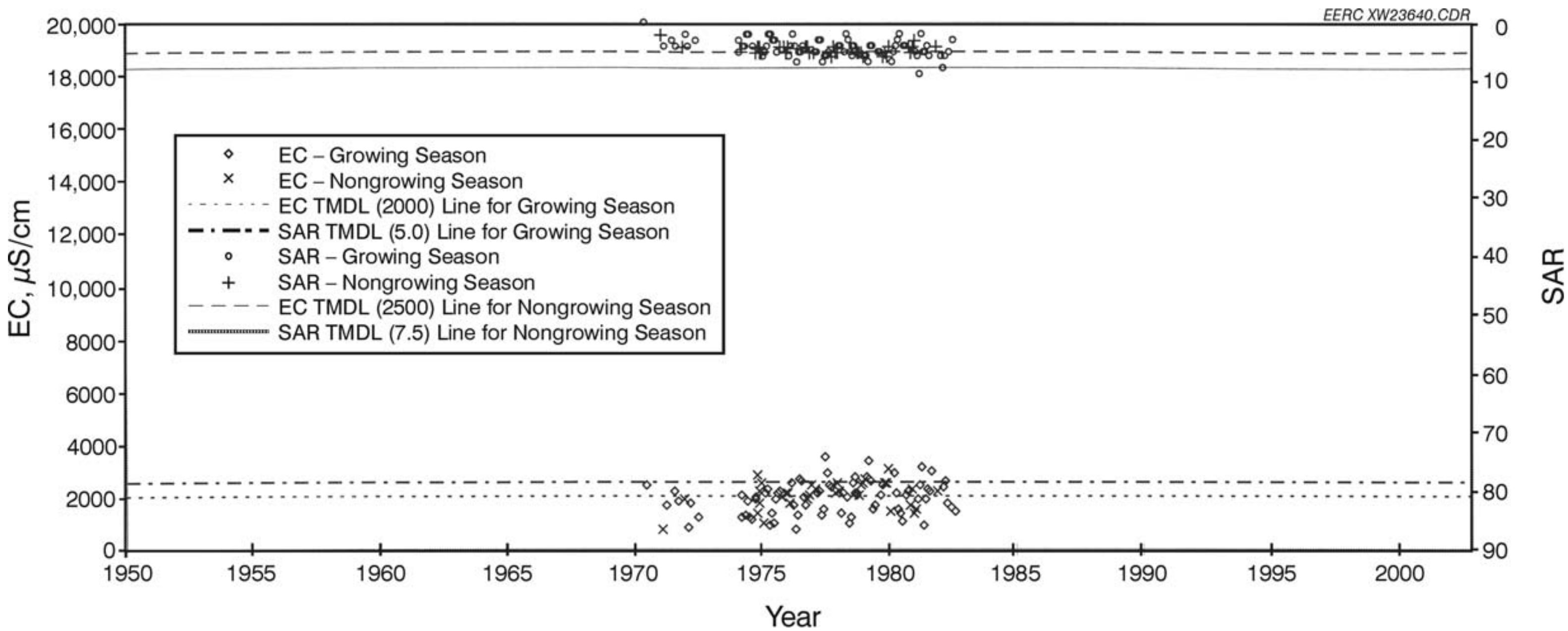

Figure B-3. Instantaneous EC and SAR for the Powder River at Moorhead, Montana (USGS 06324500).

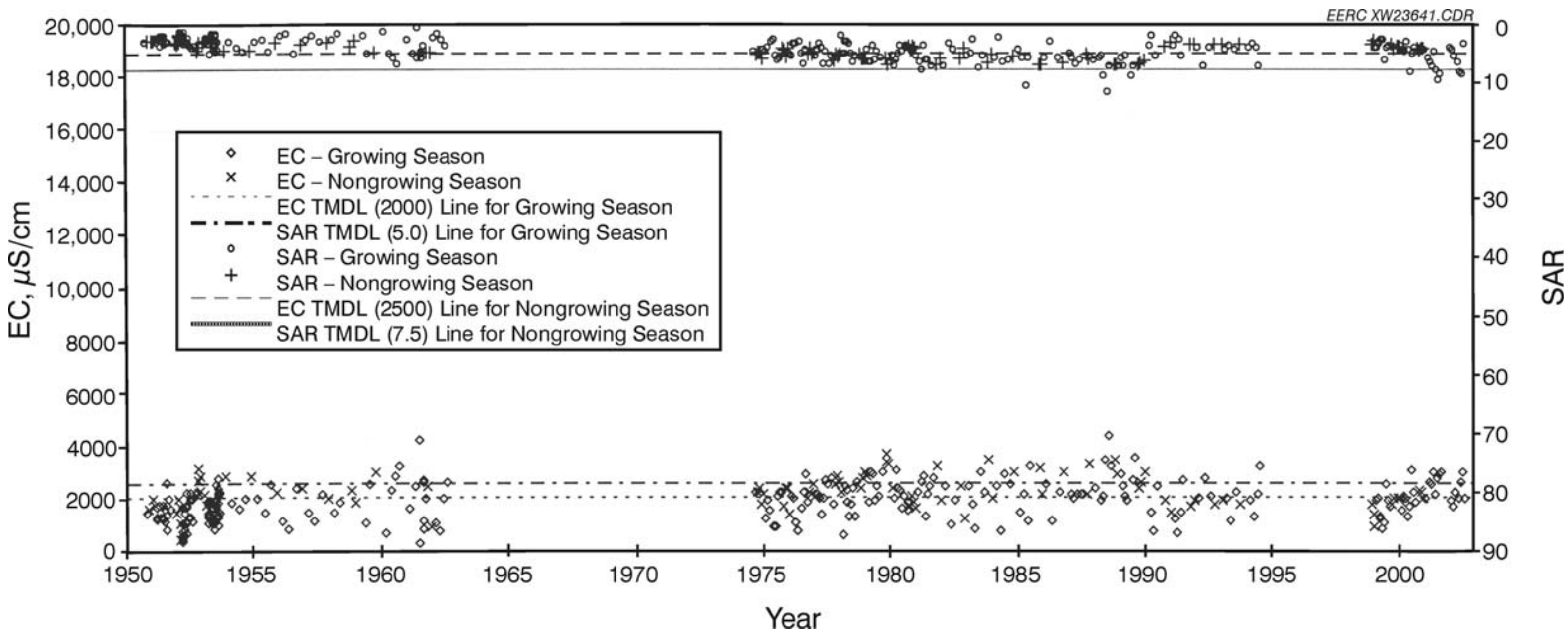

Figure B-4. Instantaneous EC and SAR for the Powder River at Moorhead, Montana (USGS 06324500).

Table B-3. EC and SAR Exceedances Summarized by Month for the Powder River at Sussex, Wyoming (USGS 06313500)*

Month	EC (µS/cm)			SAR		
	> EC TMDL†	Data Size	% > EC TMDL	> SAR TMDL‡	Data Size	% > SAR TMDL
1	4	15	26.7	5	15	33.3
2	7	16	43.8	5	16	31.3
3	13	15	86.7	10	15	66.7
4	10	15	66.7	10	15	66.7
5	6	23	26.1	7	23	30.4
6	9	18	50.0	11	18	61.1
7	12	16	75.0	12	16	75.0
8	20	21	95.2	19	21	90.5
9	15	18	83.3	15	18	83.3
10	14	15	93.3	8	15	53.3
11	2	17	11.8	1	17	5.9
12	2	10	20.0	0	10	0.0
Total	114	199	57.3	103	199	51.8

* Based on all of the data with both EC and SAR available 1966–2002.

† Evaluated in accordance with the TMDL for EC proposed by MDEQ on December 6, 2002. The proposed EC TMDL is 2000 µS/cm for the growing season (March 2 – October 31) and 2500 µS/cm for the nongrowing season (November 1 – March 1).

‡ Evaluated in accordance with the TMDL for SAR proposed by MDEQ on December 6, 2002. The proposed SAR TMDL is 5.0 for the growing season (March 2 – October 31) and 7.5 for the nongrowing season (November 1 – March 1).

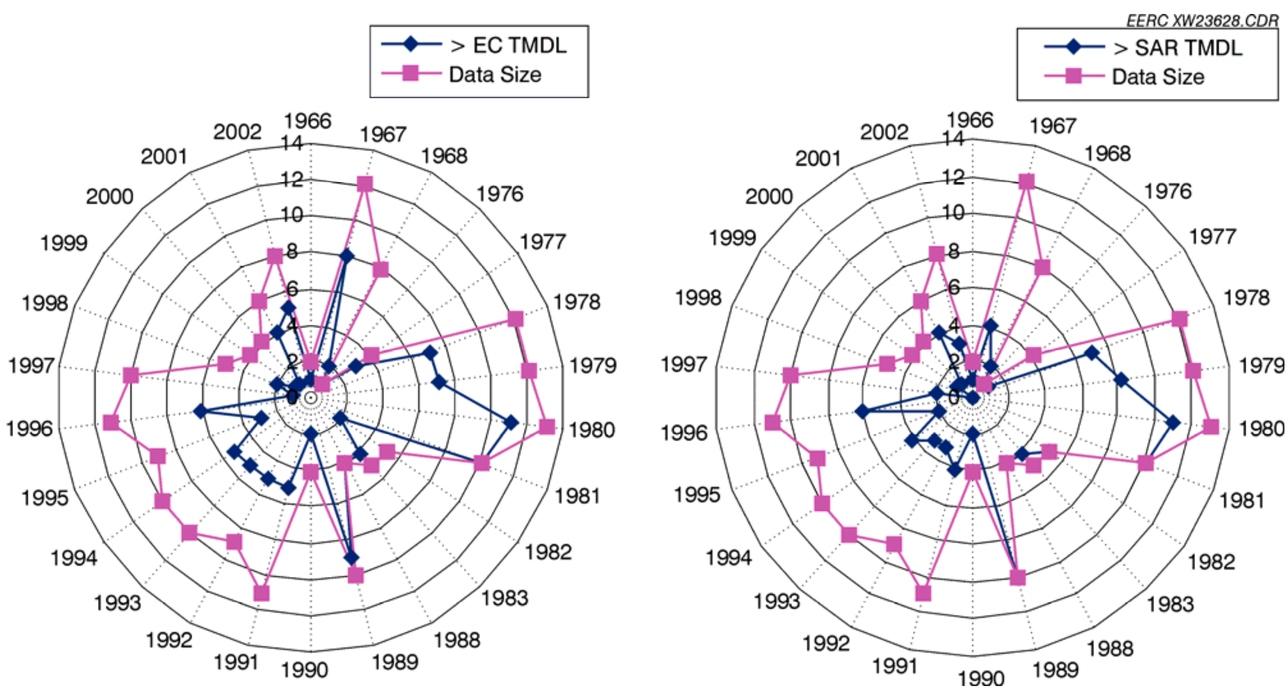

Figure B-5. EC and SAR exceedances summarized by year for the Powder River at Sussex, Wyoming (USGS 06313500).

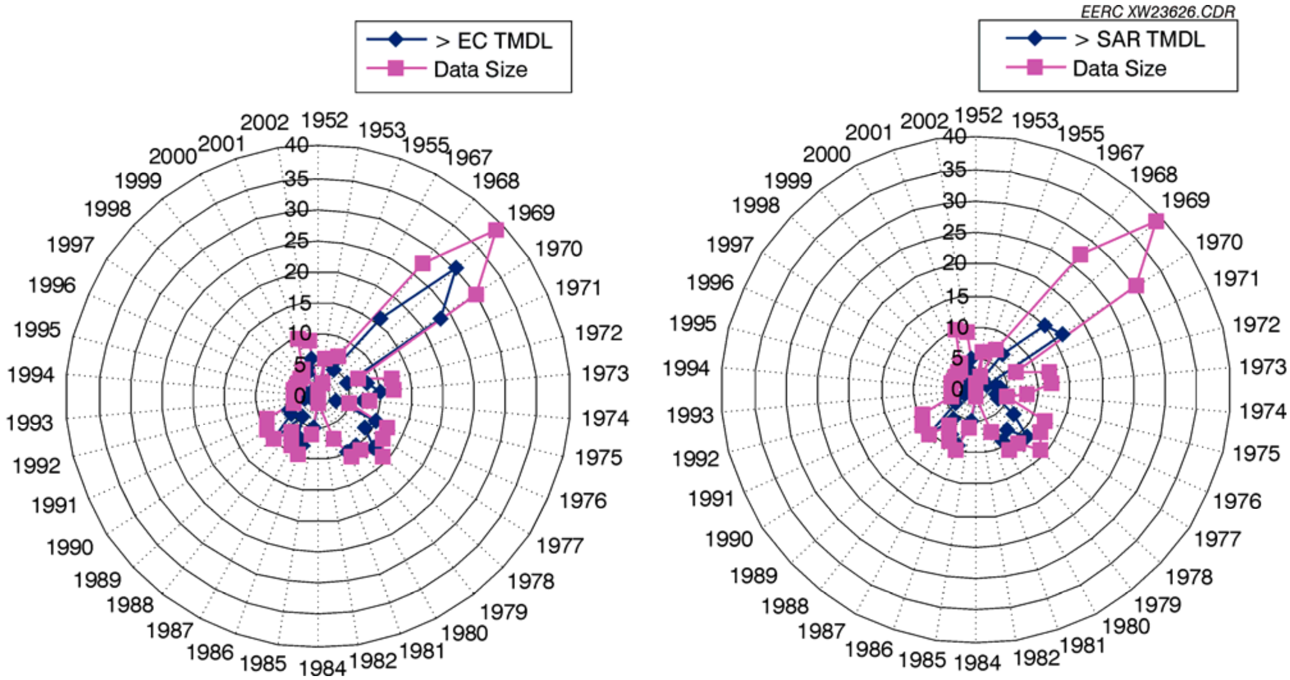

Figure B-6. EC and SAR exceedances summarized by year for the Powder River at Arvada, Wyoming (USGS 06317000).

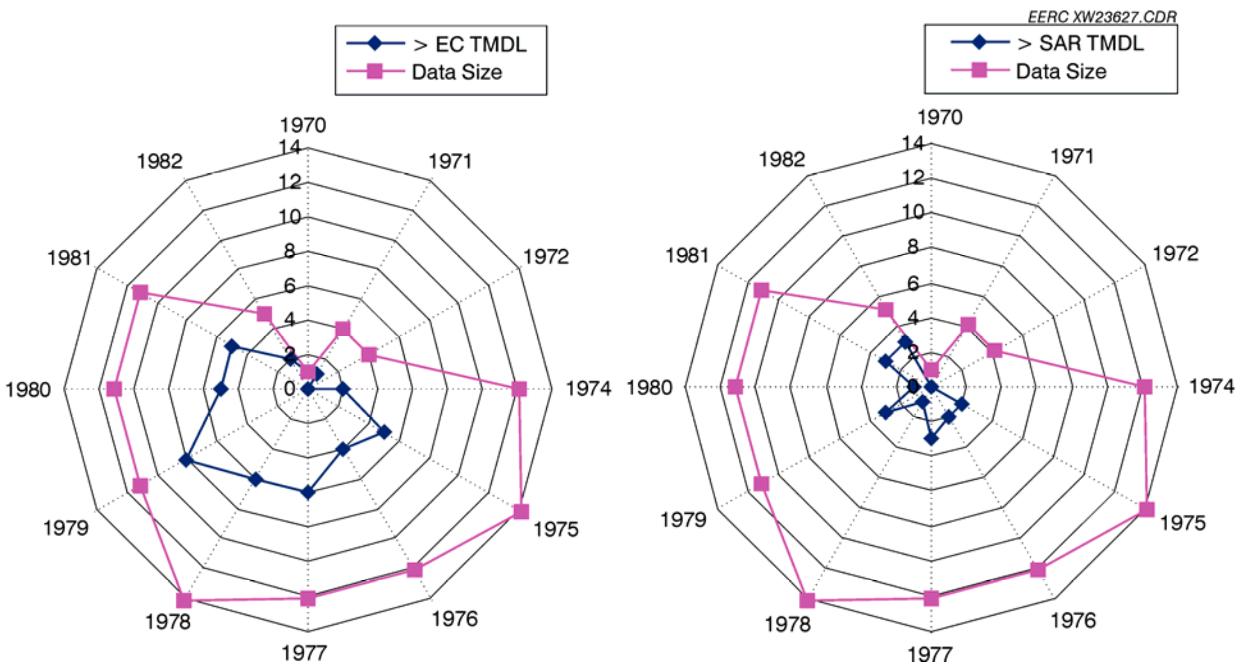

Figure B-7. EC and SAR exceedances summarized by year for the Powder River at Moorhead, Montana (USGS 06324500).

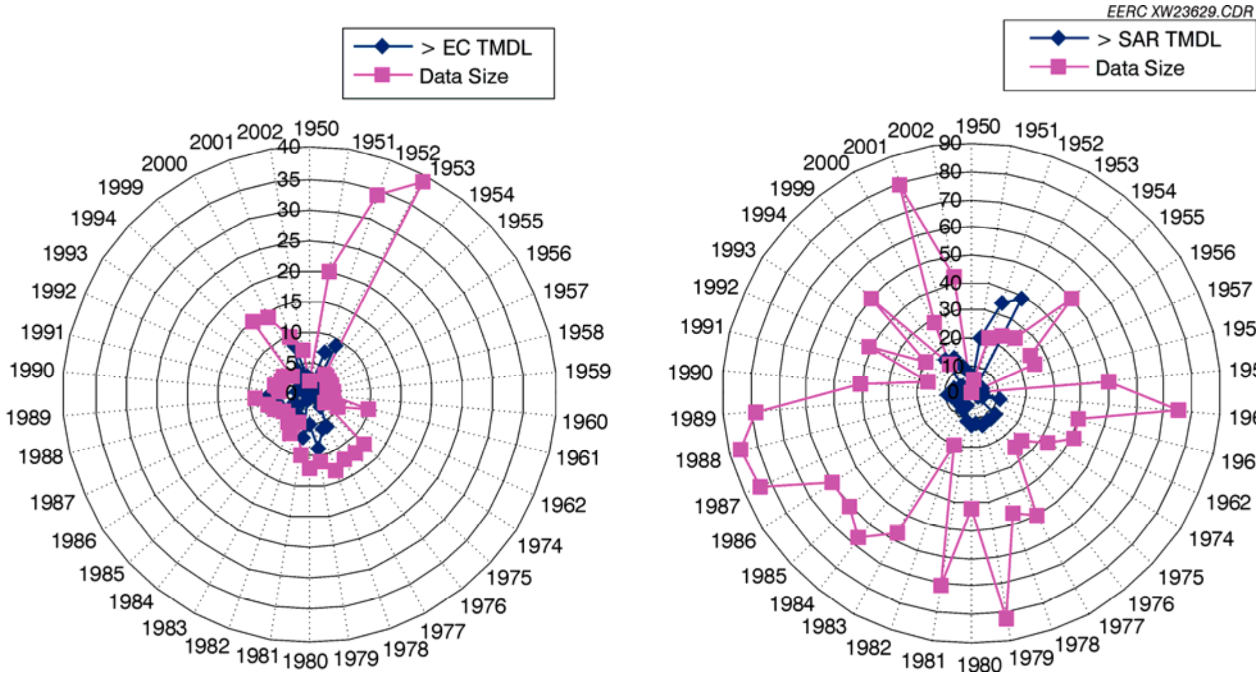

Figure B-8. EC and SAR exceedances summarized by year for the Powder River at Locate, Montana (USGS 06326500).

Table B-4. EC and SAR Exceedances Summarized by Month for the Powder River at Arvada, Wyoming (USGS 06317000)*

	EC (µS/cm)			SAR		
Month	> EC TMDL†	Data Size	% > EC TMDL	> SAR TMDL‡	Data Size	% > SAR TMDL
1	18	29	62.1	10	29	34.5
2	13	28	46.4	6	28	21.4
3	19	24	79.2	12	24	50.0
4	25	29	86.2	21	29	72.4
5	17	37	45.9	13	37	35.1
6	11	31	35.5	10	31	32.3
7	32	36	88.9	21	36	58.3
8	29	31	93.5	22	31	71.0
9	18	18	100.0	14	18	77.8
10	29	32	90.6	26	32	81.3
11	15	27	55.6	4	27	14.8
12	18	20	90.0	5	20	25.0
Total	244	342	71.3	164	342	48.0

* Based on all of the data with both EC and SAR available 1952–2002.

† Evaluated in accordance with the TMDL for EC proposed by MDEQ on December 6, 2002. The proposed EC TMDL is 2000 µS/cm for the growing season (March 2 – October 31) and 2500 µS/cm for the nongrowing season (November 1 – March 1).

‡ Evaluated in accordance with the TMDL for SAR proposed by MDEQ on December 6, 2002. The proposed SAR TMDL is 5.0 for the growing season (March 2 – October 31) and 7.5 for the nongrowing season (November 1 – March 1).

Table B-5. EC and SAR Exceedances Summarized by Month for the Powder River at Moorhead, Montana (USGS 06324500)*

Month	EC (µS/cm)			SAR		
	> EC TMDL†	Data Size	% > EC TMDL	> SAR TMDL‡	Data Size	% > SAR TMDL
1	2	9	22.2	0	9	0.0
2	1	8	12.5	0	8	0.0
3	6	9	66.7	5	9	55.6
4	8	12	66.7	4	12	33.3
5	3	8	37.5	3	8	37.5
6	0	8	0.0	0	8	0.0
7	3	11	27.3	2	11	18.2
8	5	8	62.5	1	8	12.5
9	8	10	80.0	2	10	20.0
10	7	11	63.6	1	11	9.1
11	2	8	25.0	0	8	0.0
12	0	9	0.0	0	9	0.0
Total	45	111	40.5	18	111	16.2

* Based on all of the data with both EC and SAR available 1970–1982.
† Evaluated in accordance with the TMDL for EC proposed by MDEQ on December 6, 2002. The proposed EC TMDL is 2000 µS/cm for the growing season (March 2 – October 31) and 2500 µS/cm for the nongrowing season (November 1 – March 1).
‡ Evaluated in accordance with the TMDL for SAR proposed by MDEQ on December 6, 2002. The proposed SAR TMDL is 5.0 for the growing season (March 2 – October 31) and 7.5 for the nongrowing season (November 1 – March 1).

Table B-6. EC and SAR Exceedances Summarized by Month for the Powder River at Locate, Montana (USGS 06326500)*

Month	EC (µS/cm)			SAR		
	> EC TMDL†	Data Size	% > EC TMDL	> SAR TMDL‡	Data Size	% > SAR TMDL
1	5	19	26.3	0	19	0.0
2	2	21	9.5	0	21	0.0
3	11	47	23.4	9	47	19.1
4	11	22	50.0	10	22	45.5
5	10	34	29.4	12	34	35.3
6	7	39	17.9	8	39	20.5
7	10	27	37.0	7	27	25.9
8	29	41	70.7	18	41	43.9
9	16	24	66.7	11	24	45.8
10	12	21	57.1	11	21	52.4
11	3	22	13.6	0	22	0.0
12	15	26	57.7	0	26	0.0
Total	131	343	38.2	86	343	25.1

* Based on all of the data with both EC and SAR available 1950–2002.
† Evaluated in accordance with the TMDL for EC proposed by MDEQ on December 6, 2002. The proposed EC TMDL is 2000 µS/cm for the growing season (March 2 – October 31) and 2500 µS/cm for the nongrowing season (November 1 – March 1).
‡ Evaluated in accordance with the TMDL for SAR proposed by MDEQ on December 6, 2002. The proposed SAR TMDL is 5.0 for the growing season (March 2 – October 31) and 7.5 for the nongrowing season (November 1 – March 1).

Table B-7. EC and SAR Exceedances Summarized by Month for the Powder River across the Four USGS Stations: Sussex and Arvada in Wyoming and Moorhead and Locate in Montana*

	EC (μS/cm)			SAR		
Month	> EC TMDL†	Data Size	% > EC TMDL	> SAR TMDL‡	Data Size	% > SAR TMDL
1	29	72	40.3	15	72	20.8
2	23	73	31.5	11	73	15.1
3	49	95	51.6	36	95	37.9
4	54	78	69.2	45	78	57.7
5	36	102	35.3	35	102	34.3
6	27	96	28.1	29	96	30.2
7	57	90	63.3	42	90	46.7
8	83	101	82.2	60	101	59.4
9	57	70	81.4	42	70	60.0
10	62	79	78.5	46	79	58.2
11	22	74	29.7	5	74	6.8
12	35	65	53.8	5	65	7.7
Total	534	995	53.7	371	995	37.3

* Based on all of the data with both EC and SAR available 1966–2002 at Sussex, 1952–2002 at Arvada, 1970–1982 at Moorhead, and 1950–2002 at Locate.

† Evaluated in accordance with the TMDL for EC proposed by MDEQ on December 6, 2002. The proposed EC TMDL is 2000 μS/cm for the growing season (March 2 – October 31) and 2500 μS/cm for the nongrowing season (November 1 – March 1).

‡ Evaluated in accordance with the TMDL for SAR proposed by MDEQ on December 6, 2002. The proposed SAR TMDL is 5.0 for the growing season (March 2 – October 31) and 7.5 for the nongrowing season (November 1 – March 1).

Temporal Trends

The linear regression analysis (Figures B-9 and B-10) detected fewer trends in the data than either Kendall's S or Seasonal Kendall's S′. Across the four stations, more parameters exhibited significant positive trends before 1990 than after 1990. The observed significant positive trends for SAR might be a result of the positive trends of Na^+ and the negative trends of Ca^{2+} and Mg^{2+} because of $SAR = \frac{Na^+}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}}$, where the unit of Na^+, Ca^{2+}, and Mg^{2+} concentrations is milliequivalent per liter (meq/L). Significant positive trends of EC were detected concurrently with one or more ions in Na^+, K^+, Cl^-, SO_4^{2-}, and HCO_3^-. The post-1990 data exhibited fewer trends (either positive or negative) at the stations of Sussex, Arvada, and Moorhead than Locate. At Locate, linear regression and Kendall's S only detected positive trends for SAR, Na^+, K^+, and SO_4^{2-} and negative trends for T_W and pH, but Seasonal Kendall's S′ detected additional positive trends for T_A, EC, and alkalinity and only a negative trend for pH. The p-values of all three tests for trends are shown in Tables B-8–B-11 for the Powder River at Sussex, Arvada, Moorhead, and Locate, respectively. The significance was evaluated at a confidence level of $\alpha = 0.1$. In the tables, the significant positive trends are shaded as black, whereas the significant negative trends are shaded as gray.

Spatial Patterns

For each of the 14 water quality parameters at each of the four stations, the parameter values averaged from the annual medians of 1976–2002 (whole dataset), 1976–1989 (pre-1990 dataset), and 1990–2002 (post-1990 dataset) are shown in Tables B-12–B-14, respectively, with the corresponding p-values for Tukey's multiple comparison tests shown in Figures B-11–B-13, respectively. The tests based on the whole datasets and pre-1990 datasets indicated that the salinity (EC), sodicity (SAR), Na^+, and HCO_3^- were significantly lower in Montana than Wyoming, whereas the tests based on the post-1990 datasets indicated that only the alkalinity, Ca^{2+}, Cl^-, and HCO_3^- were significantly lower in Montana while the average values of the EC, SAR, Na^+, and K^+ at Locate could be over 4% smaller than those at Sussex. The spatial homogeneity exhibited by the post-1990 datasets is consistent with that of the EC, SAR, Na^+, and K^+ which had either an insignificant positive trend or a significant negative trend at Sussex and Arvada but had a significant positive trend at Locate, particularly since 1990. On the other hand, all three datasets indicated that the Q, T_W, pH, Mg^{2+}, and SO_4^{2-} were significantly higher in Montana than Wyoming. However, while the whole datasets and pre-1990 datasets indicated that the alkalinity, Ca^{2+}, and K^+ were significantly higher in Montana, the post-1990 datasets indicated an opposite spatial pattern. None of the three datasets indicated a significant spatial pattern for T_A.

Water Quality from 1976–1989 versus from 1990–2002

T-tests were conducted to test the null hypothesis H_0: the distributions of the 1976–1989 and 1990–2002 annual median values are identical for each parameter at each station and overall. Table B-15 shows the p-values for these tests. At Sussex, six parameters of EC, SAR, Ca^{2+}, Na^+, Cl^-, and HCO_3^- are significantly different, and Arvada has one additional parameter of T_W significantly different. EC, SAR, Mg^{2+}, Na^+, Cl^-, and HCO_3^- are significantly different at Moorhead, but only SAR, Na^+, K^+, and Cl^- are significantly different at Locate. Across the four stations, the parameters, which are significantly different, include EC, SAR, Mg^{2+}, Na^+, Cl^-, and SO_4^{2-}. The results indicated that the surface water quality was different after 1990 than before 1990 in terms of EC, SAR, Na^+, and Cl^-, which decreased overall (Table B-16).

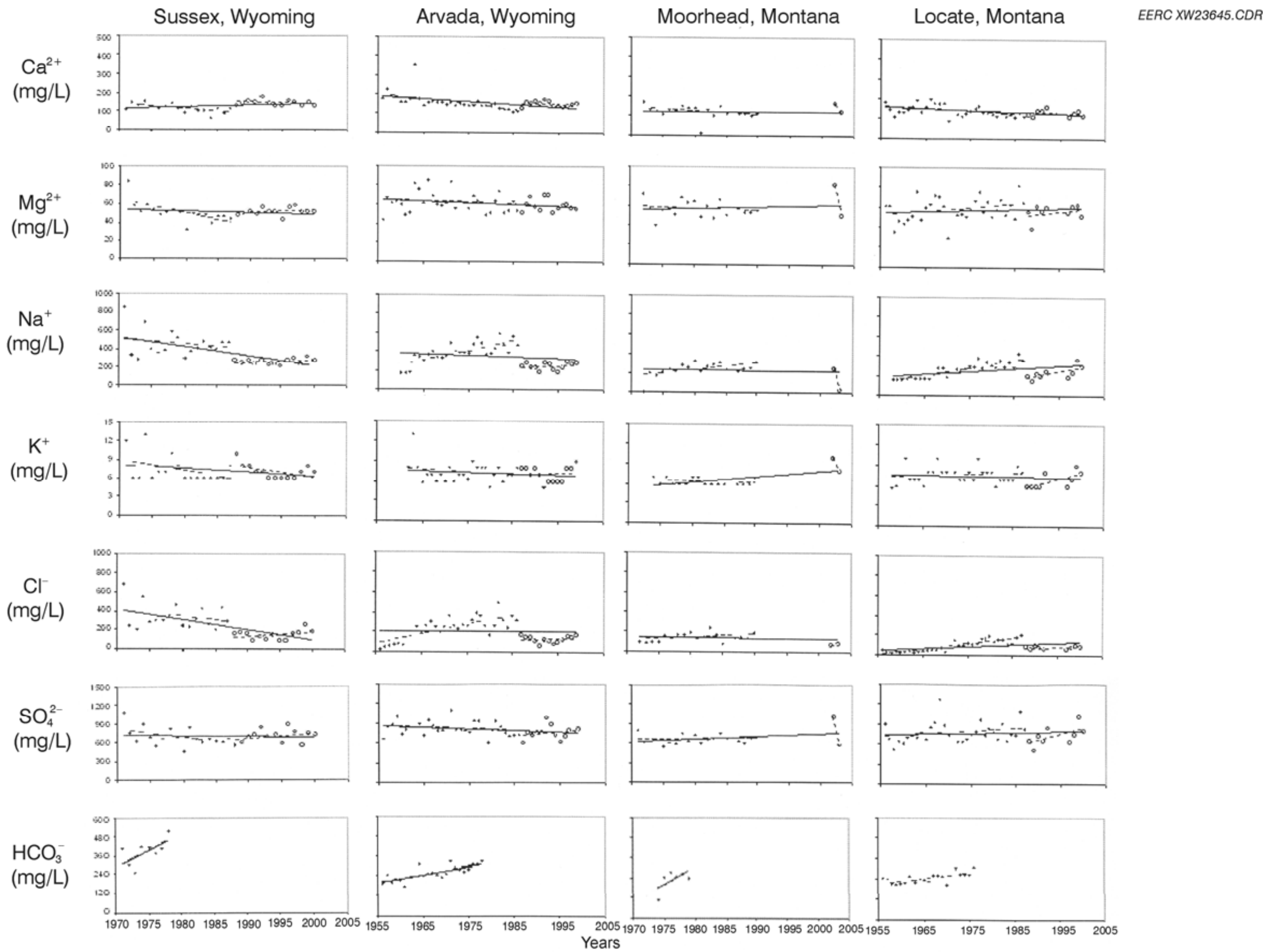

Figure B-9. Least squares regression analysis for Q, T_W, T_A, pH, specific conductance (EC), SAR, and alkalinity. Q is reported in cubic feet per second (cfs) to be consistent with the unit in which it was originally reported. (1 m^3/s = 35.3 cfs).

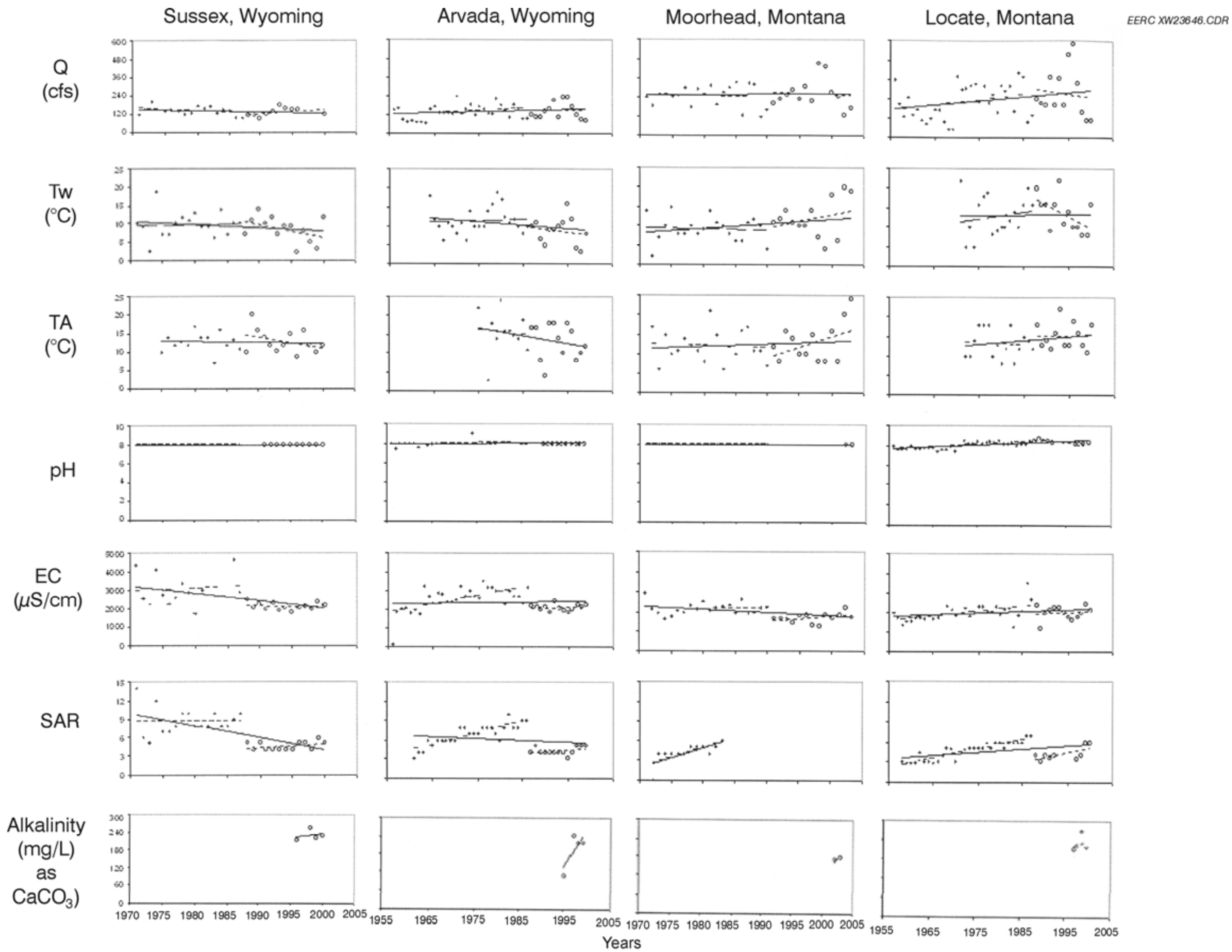

Figure B-10. Least squares regression analysis for cations (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}) and anions (Cl^{-}, SO_4^{2-}, and HCO_3^{-}).

Table B-8. P-Values of All Three Trend Tests at Powder River at Sussex, Wyoming (USGS 06313500)

	Whole Dataset			Pre-1990 Dataset			Post-1990 Dataset		
	Linear Regression	Kendall's S	Seasonal Kendall's S′	Linear Regression	Kendall's S	Seasonal Kendall's S′	Linear Regression	Kendall's S	Seasonal Kendall's S′
Q	0.300	0.190	0.280	0.200	0.120	0.200	0.300	0.053	0.037
T_W	0.230	0.170	0.420	0.900	0.370	0.009	0.150	0.079	0.010
T_A	0.780	0.300	0.496	0.989	0.500	0.263	0.255	0.160	0.073
pH	0.100	—†	0.270	—†	—†	0.059	—†	—†	0.290
EC	0.008	0.003	0.005	0.800	0.310	0.180	0.600	0.430	0.400
SAR	0.000	0.001	0.006	1.000	0.150	0.007	0.230	0.150	0.200
Alkalinity	0.800	0.248	0.150	—‡	—‡	—‡	—‡	0.248	0.150
Ca^{2+}	0.070	0.046	0.046	0.010	0.006	0.012	0.500	0.178	0.100
Mg^{2+}	0.300	0.367	0.220	0.004	0.000	0.009	0.300	0.027	0.150
Na^{+}	0.000	0.000	0.005	0.400	0.310	0.015	0.300	0.230	0.215
K^{+}	0.130	0.310	0.440	0.090	0.100	0.330	0.090	0.069	0.110
Cl^{-}	0.000	0.000	0.005	0.300	0.330	0.042	0.300	0.213	0.220
SO_4^{2-}	0.600	0.500	0.490	0.060	0.035	0.100	0.380	0.140	0.230
HCO_3^{-}	0.100	0.130	0.032	0.100	0.130	0.032	0.800	—‡	—‡

† The variance is too small to conduct the test.
‡ The sample size is too small to conduct the test.
Significant (α = 0.1) negative trend. Significant (α = 0.1) positive trend.

Table B-9. P-Values of All Three Trend Tests at Powder River at Arvada, Wyoming (USGS 06317000)

	Whole Dataset			Pre-1990 Dataset			Post-1990 Dataset		
	Linear Regression	Kendall's S	Seasonal Kendall's S′	Linear Regression	Kendall's S	Seasonal Kendall's S′	Linear Regression	Kendall's S	Seasonal Kendall's S′
Q	0.200	0.187	0.098	0.100	0.100	0.036	0.970	0.430	0.430
T_W	0.090	0.049	0.350	0.710	0.400	0.125	0.600	0.380	0.013
T_A	0.200	0.070	0.240	0.800	0.190	0.394	0.600	0.270	0.184
pH	0.300	0.016	0.000	0.147	0.019	0.000	—†	—†	0.360
EC	0.700	0.320	0.150	0.000	0.000	0.000	0.900	0.480	0.118
SAR	0.220	0.290	0.490	0.000	0.000	0.000	0.340	0.160	0.085
Alkalinity	0.200	0.248	0.000	—‡	—‡	—‡	0.200	0.248	0.000
Ca^{2+}	0.003	0.000	0.000	0.001	0.000	0.000	0.600	0.230	0.360
Mg^{2+}	0.200	0.120	0.028	0.500	0.260	0.022	0.658	0.430	0.130
Na^{+}	0.400	0.220	0.490	0.000	0.000	0.000	0.600	0.380	0.088
K^{+}	0.340	0.440	0.023	0.340	0.480	0.039	0.860	0.470	0.340
Cl^{-}	0.900	0.470	0.125	0.000	0.000	0.000	0.700	0.360	0.120
SO_4^{2-}	0.060	0.017	0.031	0.300	0.074	0.180	0.530	0.150	0.150
HCO_3^{-}	0.000	0.000	0.000	0.000	0.000	0.000	—‡	—‡	—‡

† The variance is too small to conduct the test.
‡ The sample size is too small to conduct the test.
Significant ($\alpha = 0.1$) negative trend. Significant ($\alpha = 0.1$) positive trend.

Table B-10. P-Values of All Three Trend Tests at Powder River at Moorhead, Montana (USGS 06324500)

	Whole Dataset			Pre-1990 Dataset			Post-1990 Dataset		
	Linear Regression	Kendall's S	Seasonal Kendall's S′	Linear Regression	Kendall's S	Seasonal Kendall's S′	Linear Regression	Kendall's S	Seasonal Kendall's S′
Q	0.700	0.400	0.460	0.800	0.230	0.235	0.900	0.430	0.169
T_W	0.080	0.080	0.080	0.700	0.410	0.407	0.400	0.380	0.024
T_A	0.450	0.400	0.188	0.770	0.360	0.373	0.200	0.190	0.160
pH	0.200	—[†]	0.098	—[†]	—[†]	0.023	—[†]	—[†]	—[†]
EC	0.000	0.011	0.115	0.800	0.182	0.013	0.200	0.063	0.136
SAR	0.008	0.002	0.006	0.008	0.002	0.006	—[‡]	—[‡]	—[‡]
Alkalinity	—[‡]	—[‡]	—[‡]	—[‡]	—[‡]	—[‡]	—[‡]	—[‡]	—[‡]
Ca^{2+}	0.900	0.150	0.359	0.200	0.043	0.059	—[‡]	—[‡]	—[‡]
Mg^{2+}	0.500	0.350	0.209	0.600	0.250	0.440	—[‡]	—[‡]	—[‡]
Na^+	0.960	0.026	0.014	0.010	0.002	0.006	—[‡]	—[‡]	—[‡]
K^+	0.006	0.240	0.068	0.430	0.200	0.461	—[‡]	—[‡]	—[‡]
Cl^-	0.600	0.348	0.117	0.100	0.050	0.005	—[‡]	—[‡]	—[‡]
SO_4^{2-}	0.200	0.234	0.094	0.800	0.210	0.294	—[‡]	—[‡]	—[‡]
HCO_3^-	0.200	0.290	0.293	0.200	0.290	0.293	—[‡]	—[‡]	—[‡]

[†] The variance is too small to conduct the test.
[‡] The sample size is too small to conduct the test.
Significant (α = 0.1) negative trend. Significant (α = 0.1) positive trend.

Table B-11. P-Values of All Three Trend Tests at Powder River near Locate, Montana (USGS 06326500)

	Whole Dataset			Pre-1990 Dataset			Post-1990 Dataset		
	Linear Regression	Kendall's S	Seasonal Kendall's S′	Linear Regression	Kendall's S	Seasonal Kendall's S′	Linear Regression	Kendall's S	Seasonal Kendall's S′
Q	0.050	0.075	0.030	0.100	0.097	0.006	0.700	0.120	0.120
T_W	0.907	0.450	0.200	0.500	0.091	0.500	0.063	0.017	0.104
T_A	0.210	0.110	0.290	0.830	0.460	0.340	0.920	0.400	0.037
pH	0.000	0.000	0.000	0.000	0.000	0.001	0.008	0.020	0.030
EC	0.020	0.003	0.003	0.001	0.000	0.000	0.700	0.430	0.035
SAR	0.003	0.000	0.000	0.000	0.000	0.000	0.040	0.049	0.021
Alkalinity	0.690	0.250	—‡	—‡	—‡	—‡	0.690	0.250	0.023
Ca^{2+}	0.008	0.011	0.007	0.010	0.006	0.024	0.620	0.460	0.280
Mg^{2+}	0.400	0.190	0.080	0.100	0.044	0.017	0.400	0.230	0.156
Na^{+}	0.004	0.000	0.000	0.000	0.000	0.000	0.050	0.023	0.050
K^{+}	0.680	0.367	0.473	0.520	0.200	0.153	0.050	0.014	0.110
Cl^{-}	0.001	0.000	0.000	0.000	0.000	0.000	0.800	0.500	0.240
SO_4^{2-}	0.600	0.180	0.100	0.200	0.032	0.041	0.090	0.030	0.029
HCO_3^{-}	0.001	0.001	0.007	0.001	0.001	0.007	—‡	—‡	—‡

‡ The sample size is too small to conduct the test.

Significant (α = 0.1) negative trend. Significant (α = 0.1) positive trend.

Table B-12. Average Parameter Values (from the 27 annual medians of 1976–2002 when the values of the missing years in Table 2 were inputted using the EM algorithm) and Standard Deviations for All Four Stations and Percent of Change from Sussex to Locate

	Sussex	SD	Arvada	SD	Moorhead	SD	Locate	SD	% Change
Q	136.1	25.1	148.4	46.0	257.8	84.1	269.0	121.5	97.6
T_W	9.4	3.6	10.7	3.8	10.5	4.1	13.3	4.5	42.0
T_A	12.9	2.8	13.7	5.6	12.6	4.5	14.4	3.4	11.3
pH	8.0	0.0	8.0	0.2	8.0	0.0	8.3	0.1	4.0
EC	2593.5	691.0	2487.1	469.7	1954.7	351.7	2116.3	433.9	−18.4
SAR	6.7	2.4	6.1	2.0	4.3	1.0	5.1	1.1	−24.8
Alkalinity	230.6	11.7	187.4	40.1	174.3	1.1	230.7	13.6	0.0
Ca^{2+}	124.4	24.4	140.4	15.9	117.0	27.3	127.9	15.0	2.8
Mg^{2+}	49.7	5.8	59.6	6.7	54.3	10.8	59.1	8.9	19.0
Na^{+}	352.6	123.7	349.4	121.9	215.6	68.4	276.8	65.8	−21.5
K^{+}	7.1	1.7	7.2	1.1	6.4	1.0	7.2	1.1	1.3
Cl^{-}	243.2	124.0	220.2	109.8	128.2	48.9	118.2	41.6	−51.4
SO_4^{2-}	685.2	110.7	781.7	98.8	644.2	107.2	762.7	133.2	11.3
HCO_3^{-}	400.6	70.7	257.8	49.4	204.7	55.4	276.5	47.7	−31.0

Table B-13. Average Parameter Values (from the 1976–1989 annual medians of the 27 values in Table 13) and Standard Deviations for All Four Stations and Percent of Change from Sussex to Locate

	Sussex	SD	Arvada	SD	Moorhead	SD	Locate	SD	% Change
Q	133.5	26.8	150.0	38.7	250.9	78.6	260.1	95.1	94.8
T_W	10.3	3.5	12.4	3.2	9.1	2.6	13.1	4.5	27.2
T_A	12.9	2.5	14.3	6.5	12.2	4.1	13.6	3.5	5.5
pH	8.0	0.0	8.1	0.3	8.0	0.0	8.3	0.1	3.4
EC	3005.0	733.1	2823.0	402.0	2196.2	229.2	2207.1	493.8	−26.6
SAR	8.8	1.4	7.9	1.0	4.7	0.7	5.8	0.7	−34.2
Alkalinity	228.9	10.9	194.2	41.5	174.0	0.7	233.6	11.0	2.1
Ca^{2+}	109.0	22.4	134.2	15.8	116.4	34.7	126.3	15.3	15.9
Mg^{2+}	47.9	6.7	59.9	7.2	58.8	8.4	61.7	9.7	29.0
Na^{+}	446.4	100.1	449.3	78.8	257.0	35.3	318.2	46.1	−28.7
K^{+}	7.2	2.0	7.2	1.0	6.3	0.5	7.6	1.0	5.9
Cl^{-}	332.1	104.5	305.7	82.0	161.7	36.6	147.5	34.3	−55.6
SO_4^{2-}	669.3	119.1	798.9	96.8	677.2	60.4	803.2	124.0	20.0
HCO_3^{-}	427.1	75.3	298.4	29.5	234.8	47.7	284.8	52.8	−33.3

Table B-14. Average Parameter Values (from the 1990–2002 annual medians of the 27 values in Table 13) and Standard Deviations for All Four Stations and Percent of Change from Sussex to Locate

	Sussex	SD	Arvada	SD	Moorhead	SD	Locate	SD	% Change
Q	139.0	23.9	146.8	54.3	265.2	92.4	278.5	148.4	100.4
T_W	8.4	3.6	8.8	3.6	12.0	4.9	13.5	4.6	61.5
T_A	13.0	3.1	13.1	4.7	13.0	5.1	15.2	3.2	17.5
pH	8.0	0.0	8.0	0.0	8.0	0.0	8.4	0.1	4.6
EC	2150.4	205.1	2125.4	171.8	1694.6	264.3	2018.5	351.6	−6.1
SAR	4.5	0.7	4.2	0.6	3.8	1.1	4.3	0.9	−5.3
Alkalinity	232.5	12.6	180.1	38.8	174.7	1.3	227.5	15.8	−2.1
Ca^{2+}	141.0	13.1	147.0	13.6	117.6	17.5	129.7	15.1	−8.0
Mg^{2+}	51.6	4.1	59.3	6.3	49.4	11.3	56.3	7.4	9.1
Na^{+}	251.5	31.0	241.8	35.8	171.1	68.0	232.2	54.1	−7.6
K^{+}	7.1	1.2	7.1	1.2	6.5	1.4	6.8	1.0	−3.8
Cl^{-}	147.4	48.3	128.2	33.6	92.2	31.7	86.6	19.7	−41.3
SO_4^{2-}	702.3	102.9	763.1	101.4	608.8	135.3	719.1	133.5	2.4
HCO_3^{-}	372.2	54.7	214.0	18.7	172.4	44.7	267.7	41.8	−28.1

Table B-15. P-Values of t-Tests for H_0: The Distributions of the 1976–1989 and 1990–2002 Annual Median Values (from the 27 annual medians of 1976–2002 when the values of the missing years in Table 2 were inputted using the EM algorithm) Are Identical for Each Parameter at Each Station and Overall

	Sussex	Arvada	Moorhead	Locate	Combined*
Q	0.579	0.861	0.671	0.707	0.387
T_W	0.173	**0.011**	0.073	0.799	0.554
T_A	0.933	0.589	0.665	0.216	0.837
pH	–†	0.336	–†	0.055	0.752
EC	**0.001**	**0.000**	**0.000**	0.262	**0.000**
SAR	**0.000**	**0.000**	**0.009**	**0.000**	**0.000**
Alkalinity	0.428	0.369	0.152	0.265	0.516
Ca^{2+}	**0.000**	**0.033**	0.908	0.569	0.095
Mg^{2+}	0.091	0.834	**0.023**	0.113	**0.002**
Na^{+}	**0.000**	**0.000**	**0.001**	**0.000**	**0.000**
K^{+}	0.832	0.701	0.662	**0.046**	0.568
Cl^{-}	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
SO_4^{2-}	0.447	0.357	0.113	0.103	**0.034**
HCO_3^{-}	**0.040**	**0.000**	**0.002**	0.359	0.457

* The test is based on the dataset combined from the four stations.

† The variance is too small to conduct the test.

■ indicates significance at α = 0.1.

	1	2	3	4	1	2	3	4	1	2	3	4
1				**Q**				**SAR**				**K^+**
2	0.939				0.549				1.000			
3	**0.000**	**0.000**			**0.000**	**0.001**			0.138	0.126		
4	**0.000**	**0.000**	0.953		**0.003**	0.128	0.350		0.993	0.996	**0.075**	
1				**T_W**				**Alkalinity**				**Cl^-**
2	0.639				**0.000**				0.778			
3	0.739	0.998			**0.000**	0.134			**0.000**	**0.001**		
4	**0.003**	**0.079**	**0.053**		1.000	**0.000**	**0.000**		**0.000**	**0.000**	0.975	
1				**T_A**				**Ca^{2+}**				**SO_4^{2-}**
2	0.906				**0.035**				**0.012**			
3	0.992	0.775			0.577	**0.001**			0.546	**0.000**		
4	0.588	0.935	0.415		0.930	0.145	0.240		**0.063**	0.927	**0.001**	
1				**pH**				**Mg^{2+}**				**HCO_3^-**
2	0.651				**0.000**				**0.000**			
3	1.000	0.651			0.178	**0.093**			**0.000**	**0.005**		
4	**0.000**	**0.000**	**0.000**		**0.000**	0.996	0.148		**0.000**	0.616	**0.000**	
1				**EC**				**Na^+**				
2	0.864				0.999							
3	**0.000**	**0.001**			**0.000**	**0.000**						
4	**0.004**	**0.039**	0.640		**0.030**	**0.040**	0.111					

Figure B-11. P-values for Tukey's multiple comparison tests on the distributions of the 27 annual median values (1976–2002 when the values of the missing years in Table 2 were imputed using the EM algorithm) for each parameter across all stations (1 = Sussex, 2 = Arvada, 3 = Moorhead, 4 = Locate. ■ indicates significance at $\alpha = 0.1$).

	1	2	3	4	1	2	3	4	1	2	3	4
1				**Q**				**SAR**				**K^+**
2	0.911				**0.080**				1.000			
3	**0.000**	**0.001**			**0.000**	**0.000**			0.263	0.237		
4	**0.000**	**0.000**	0.983		**0.000**	**0.000**	**0.041**		0.811	0.841	**0.041**	
1				**T_W**				**Alkalinity**				**Cl^-**
2	0.399				**0.001**				0.759			
3	0.800	**0.073**			**0.000**	**0.087**			**0.000**	**0.000**		
4	0.167	0.954	**0.020**		0.941	**0.000**	**0.000**		**0.000**	**0.000**	0.951	
1				**T_A**				**Ca^{2+}**				**SO_4^{2-}**
2	0.837				**0.031**				**0.009**			
3	0.979	0.610			0.837	0.195			0.997	**0.015**		
4	0.975	0.975	0.847		0.218	0.807	0.679		**0.006**	1.000	**0.011**	
1				**pH**				**Mg^{2+}**				**HCO_3^-**
2	0.581				**0.001**				**0.000**			
3	1.000	0.581			**0.004**	0.986			**0.000**	**0.015**		
4	**0.000**	**0.004**	**0.000**		**0.000**	0.929	0.776		**0.000**	0.908	**0.079**	
1				**EC**				**Na^+**				
2	0.770				1.000							
3	**0.000**	**0.009**			**0.000**	**0.000**						
4	**0.001**	**0.010**	1.000		**0.000**	**0.000**	0.108					

Figure B-12. P-values for Tukey's multiple comparison tests on the distributions of the pre-1990 annual median values (1976–1989 medians of the 27 values in Figure B-11) for each parameter across all stations (1 = Sussex, 2 = Arvada, 3 = Moorhead, 4 = Locate. ■ indicates significance at $\alpha = 0.1$).

Q

	1	2	3	4
1				
2	0.996			
3	**0.006**	**0.010**		
4	**0.002**	**0.004**	0.983	

SAR

	1	2	3	4
1				
2	0.782			
3	**0.099**	0.496		
4	0.874	0.998	0.386	

K^+

	1	2	3	4
1				
2	1.000			
3	0.638	0.638		
4	0.941	0.941	0.926	

T_W

	1	2	3	4
1				
2	0.995			
3	0.140	0.224		
4	**0.016**	**0.030**	0.788	

Alkalinity

	1	2	3	4
1				
2	**0.000**			
3	**0.000**	0.922		
4	0.937	**0.000**	**0.000**	

Cl^-

	1	2	3	4
1				
2	0.500			
3	**0.001**	**0.053**		
4	**0.000**	**0.019**	0.976	

T_A

	1	2	3	4
1				
2	1.000			
3	1.000	1.000		
4	0.507	0.550	0.521	

Ca^{2+}

	1	2	3	4
1				
2	0.736			
3	**0.001**	**0.000**		
4	0.228	**0.024**	0.181	

SO_4^{2-}

	1	2	3	4
1				
2	0.569			
3	0.203	**0.010**		
4	0.984	0.784	**0.100**	

pH

	1	2	3	4
1				
2	1.000			
3	1.000	1.000		
4	**0.000**	**0.000**	**0.000**	

Mg^{2+}

	1	2	3	4
1				
2	**0.066**			
3	0.886	**0.010**		
4	0.419	0.752	0.119	

HCO_3^-

	1	2	3	4
1				
2	**0.000**			
3	**0.000**	**0.069**		
4	**0.000**	**0.011**	**0.000**	

EC

	1	2	3	4
1				
2	0.995			
3	**0.000**	**0.001**		
4	0.563	0.716	**0.012**	

Na^+

	1	2	3	4
1				
2	0.960			
3	**0.001**	**0.004**		
4	0.755	0.960	**0.014**	

Figure B-13. P-values for Tukey's multiple comparison tests on the distributions of the post-1990 annual median values (1990–2002 medians of the 27 values in Figure B-11) for each parameter across all stations (1 = Sussex, 2 = Arvada, 3 = Moorhead, 4 = Locate. ■ indicates significance at $\alpha = 0.1$).

Table B-16. Average Parameter Values (from the dataset pooled from the four stations, each of which has 27 annual medians of 1976–2002 when the values of the missing years in Table 2 were imputed using the EM algorithm) and Standard Deviations

	1976–1989		1990–2002		1976–2002	
	Average	SD	Average	SD	Average	SD
Q	225.4	87.7	207.4	110.8	213.2	101.2
T_W	11.2	3.7	10.7	4.6	11.1	4.3
T_A	13.4	4.9	13.6	4.1	13.5	4.4
pH	8.1	0.2	8.1	0.2	8.1	0.2
EC	2374.3	459.4	1997.2	309.8	2181.1	444.7
SAR	6.1	1.6	4.2	0.9	5.1	1.5
Alkalinity	199.0	34.6	203.7	34.1	202.3	34.3
Ca^{2+}	125.9	24.7	133.8	18.4	130.2	21.5
Mg^{2+}	59.5	7.8	54.2	8.4	56.8	8.9
Na^+	339.1	99.6	224.2	57.5	276.6	97.5
K^+	7.0	1.0	6.9	1.2	7.0	1.1
Cl^-	205.5	92.5	113.6	42.3	154.4	81.6
SO_4^{2-}	749.5	99.7	698.3	129.0	725.8	124.8
HCO_3^-	267.0	45.2	256.6	85.9	263.8	72.6

APPENDIX C

HYDROLOGIC AND WATER QUALITY MODEL DEVELOPMENT

CE-QUAL-W2 MODEL DEVELOPMENT

Description of the CE-QUAL-W2 Model

CE-QUAL-W2 is a two-dimensional (longitudinal–vertical) hydrodynamic and water quality model. It is best suited for relatively long and narrow waterbodies, such as the Powder River and its tributaries, that exhibit longitudinal and vertical water quality gradients. CE-QUAL-W2 has been under continuous development since 1975. Since then, significant improvements to the mathematical description of the prototype, numerical solution scheme (computational stability, accuracy, and efficiency), and water quality algorithms have been made. The current CE-QUAL-W2 (version 3.2) has the following capabilities:

- Hydrodynamics. The model predicts water surface elevations, velocities, and temperature. Temperature is included in the hydrodynamic calculation because of its effect on water density and cannot be turned off.

- Water Quality. The model can simulate any combination of the 16 constituent groups, including salinity and alkalinity, and more than 60 derived variables including pH. When salinity is simulated, its effect on the hydrodynamics is taken into account by the model.

The model uses multiple water bodies, which allow any number of rivers, reservoirs, lakes, and estuaries linked in series to be modeled. Multiple branches allow the application of the model to geometrically complex water bodies such as dendritic reservoirs or estuaries. It uses a variable timestep algorithm that attempts to ensure that the stability requirements for the hydrodynamics, imposed by the numerical solution scheme, are not violated. The model also has the ability to simulate several phenomena including long-term water quality responses, flexibility of defining computational grids whose lengths and thicknesses may be varied, various options of boundary conditions (e.g., time-varying flows or heads), and various choices of specifying multiple inflows and outflow. In addition, output is available for the screen, hard copy, plotting, and restarts. Moreover, the user can specify the output and when and how often during the simulation output is to begin.

MODEL INPUT DATA

The National Elevation Dataset (NED) and the National Hydrography Dataset (NHD) were obtained from the U.S. Geological Survey (USGS) at http://edc.usgs.gov/geodata. Using the ArcToolBox®, these datasets were projected to the UTM 83 (Universal Transverse Mercator 83), Zone 12, coordinate system. Up to 35 typical cross sections were identified along the aforementioned streams. It was assumed that the stream reach between two typical cross sections has a constant slope and a linearly varied width. The geometric data (distance–elevation pairs) for these typical cross sections were extracted from the projected NED and NHD using the PE 6.0 for Spatial Analyst®, an extension of ArcView® (version 3.2a). The distance–elevation pairs were then imported into Microsoft Excel® to plot the typical cross sections. The depths of the cross sections were divided into 27 layers with heights of 0.5 to 2.5 m. The lines that correspond to these layers were superimposed on the plots to determine the average widths of the layers. The streams were divided into segments with lengths of 50 to 350 m. The widths of the segments were determined using linear interpolation between two typical cross sections. Geographically paired, a layer within a segment forms a computational cell or grid. The bathymetry of the cell is defined by the height of the layer and the slope and length of the segment. Other required data (e.g., meteorological data) were obtained from USGS, National Climate Data Center (NCDC), and state agencies (e.g., Wyoming and Montana Departments of Environmental Quality).

To ensure computational efficiency and accuracy, the water system was modeled as four water bodies (Figure C-1). Water Body 1 comprises three river reaches: 1) the Powder River from the USGS Kaycee Station to Sussex Station, 2) the South Fork Powder River from the USGS Kaycee Station to its confluence with the Powder River, and 3) the Salt Creek from the USGS Sussex Station to its confluence with the Powder River. Water Body 2 comprises two river reaches: 1) the Powder River from the USGS Sussex Station to Arvada Station, and 2) the Crazy Woman Creek from the USGS Arvada Station to its confluence with the Powder River. Water Body 3 comprises two river reaches: 1) the Powder River from the USGS Arvada Station to Moorhead Station, and 2) the Clear Creek from the USGS Arvada Station to its confluence with the Powder River. Water Body 4 comprises the reaches of the Powder River from the USGS Moorhead Station to the Locate Station and of the Little Powder River from the USGS Weston Station to its confluence with the Powder River. Accurate boundaries of these four water bodies are shown in Figures C-2–C-5.

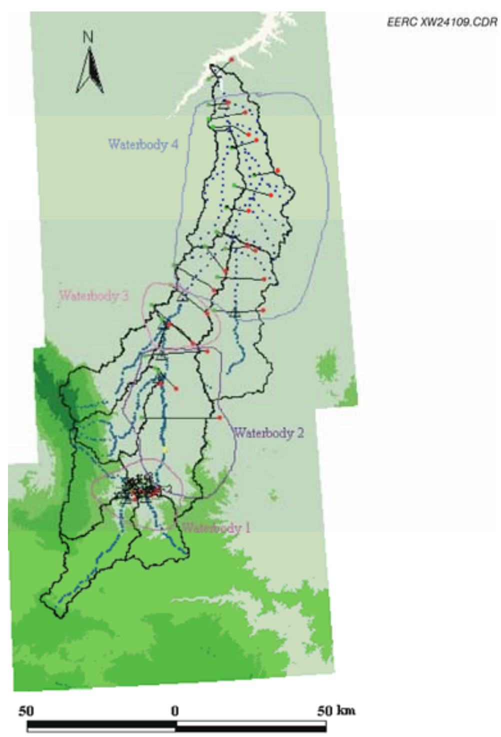

Figure C-1. The Powder River drainage basin showing the four water bodies in the CE-QUAL-W2 model.

The geometric data (distance–elevation pairs) for the typical cross sections were extracted from the projected NED and NHD using the PE 6.0 for Spatial Analyst®, an extension of ArcView® (version 3.2a). The distance–elevation pairs were then imported into Microsoft Excel® to plot the typical cross sections. The depths of the cross sections were divided into 27 layers with heights of 0.5 to 2.5 m. The streams were divided into segments with lengths of 50 to 350 m. The widths of the segments were determined using linear interpolation between two typical cross sections. Geographically paired, a layer within a segment forms a computational cell or grid. The bathymetry of the cell is defined by the height of the layer and the slope and length of the segment. As an example, the bathymetry data for Water Body 1 is shown in Table C-1. Figures C-6 and C-7 show top and end views of the computation grid for Water Body 1.

Thus the outputs from an upstream water body are the inputs into the downstream water body (the outputs from Water Body 1 are the inputs into Water Body 2, and so on). This model has sufficient accuracy to capture the hot spots from a trading option if any, and is one of the three core models of the decision support tool.

HYDROLOGIC MODEL DEVELOPMENT

In order to produce inputs to the CE-QUAL-W2 model, a hydrologic model was developed for the PRB. This model can predict daily water yield of the coalbed methane (CBM) wells, and route produced water and transport its associated constituents from producing well to outfall. From its producing well to outfall, CBM produced water could be lost as a result of evaporation, seepage, and impoundment. This quantity decrease, in addition to interactions with conveyance streambed sediment, usually results in increased concentrations of constituents associated with the produced water, including alkalinity, total dissolved solids (TDS), and inorganic carbon. Further, while concentrations of the constituents at CBM wellheads might be constant, water yield decreases with well age. In order to address these issues, development of a watershed model for the Powder River drainage basin was necessary. This model can predict daily water yield of the CBM wells and route produced water and transport its associated constituents from producing well to outfall. The model assumes that water yield follows a first-order decrease equation on a daily basis. Water quantity at an outfall is estimated using a water balance equation, considering translation through conveyance stream and impoundments if any, and losses resulting from evaporation and seepage. Concentrations of the constituents at the outfall are determined using first-order increase equations. Water temperature is assumed to be conservative; i.e., it does not change from wellhead to outfall. The model includes 7842 wells and 214 outfalls located on the Powder River and its major tributaries modeled in the CE-QUAL-W2 model.

The routing of produced water and transportation of the constituents from the wells to their corresponding outfalls was conducted for each of the U.S. Geological Survey (USGS) 8-digit hydrological cataloging units (HCUs). The schematic of the model is shown in Figure C-8. The model consists of 1) prediction of well water yield, 2) estimation of water discharge at an outfall, and 3) determination of constituent concentrations at an outfall.

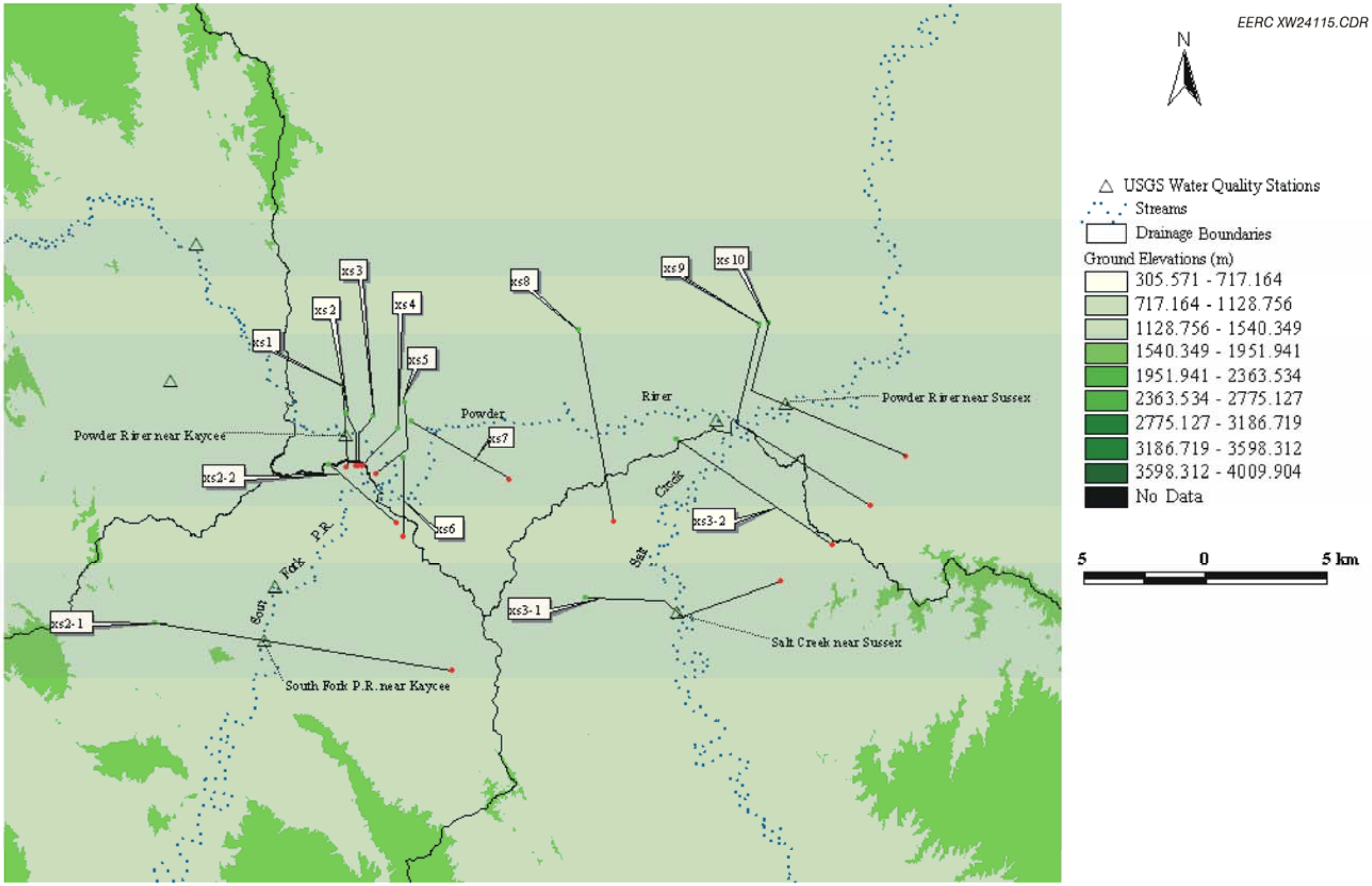

Figure C-2. Map showing the river reaches comprising Water Body 1 and the locations of the 14 typical cross sections.

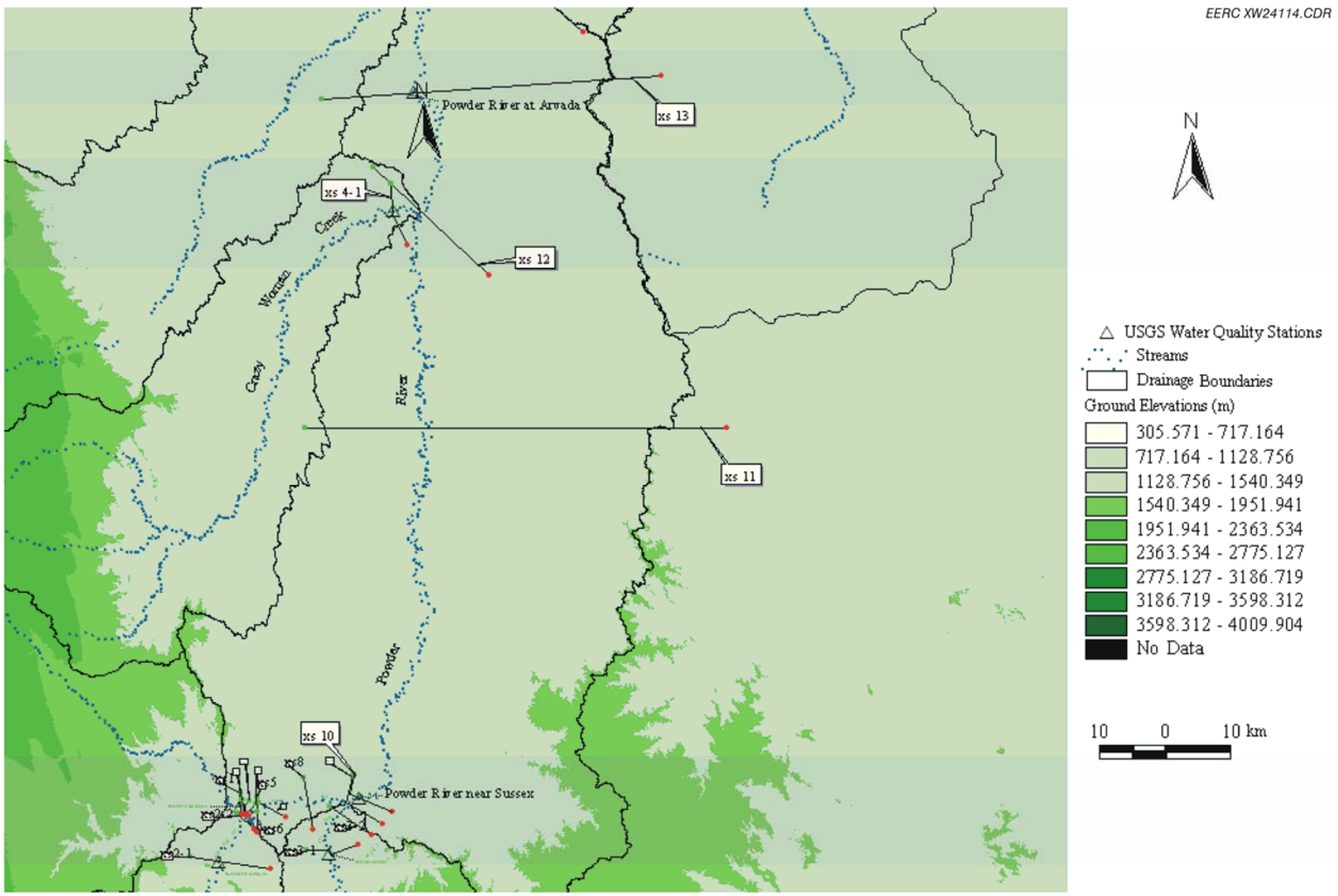

Figure C-2. Map showing the river reaches comprising Water Body 2 and the locations of the five typical cross sections.

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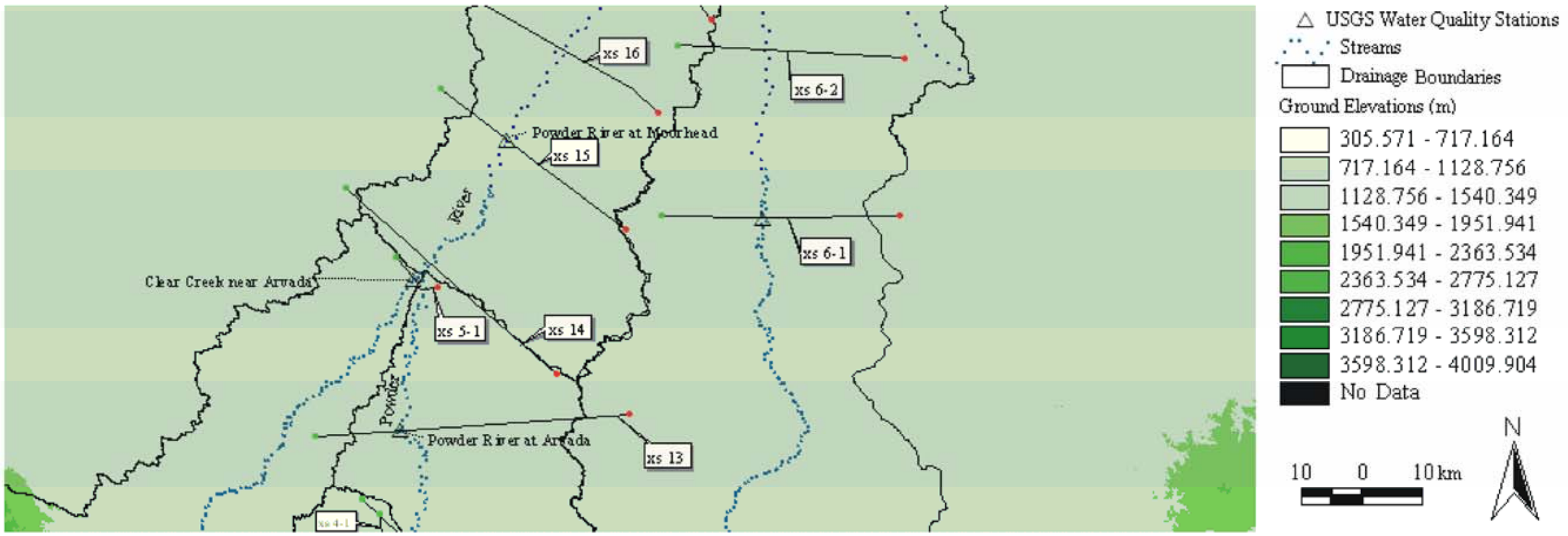

Figure C-3. Map showing the river reaches comprising Water Body 3 and the locations of the four typical cross sections.

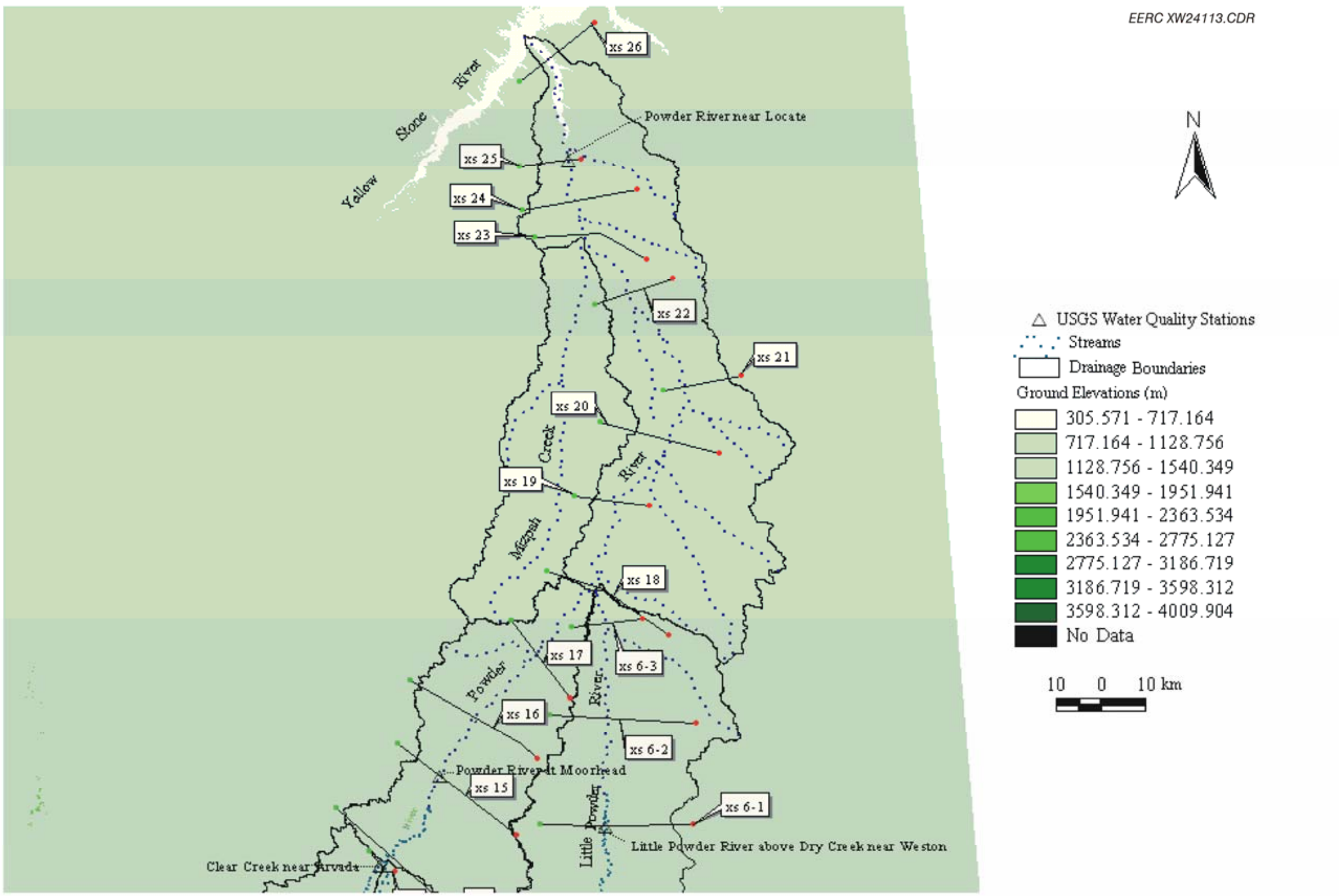

Figure C-4. Map showing the river reaches comprising Water Body 4 and the locations of the 14 typical cross sections.

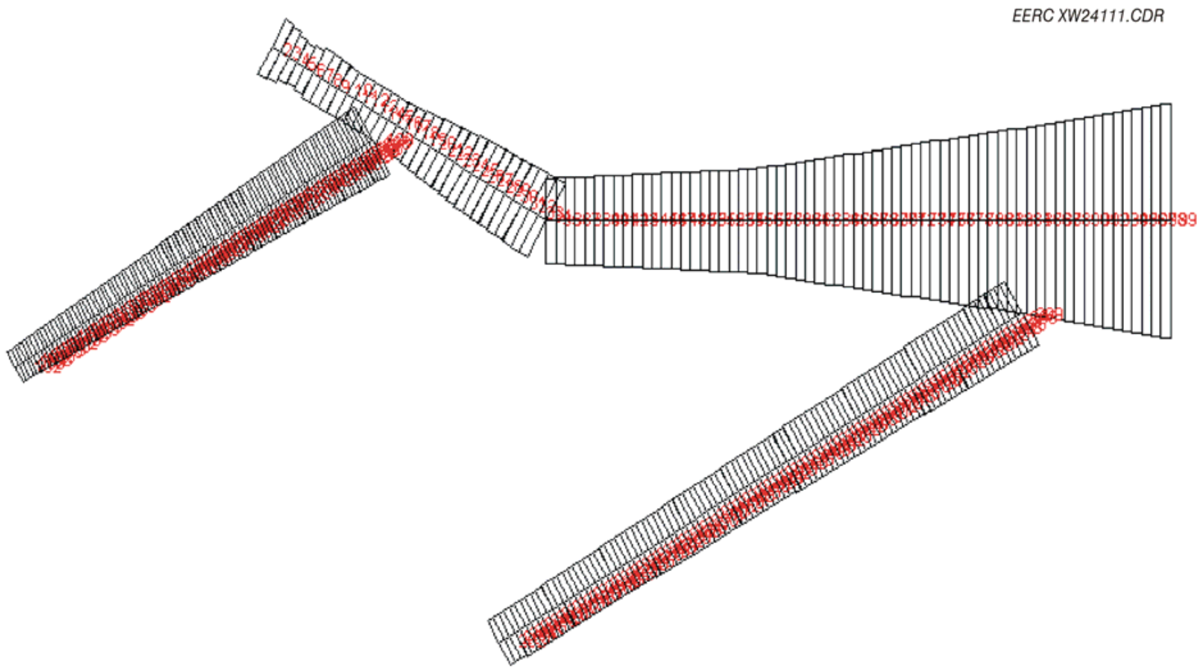

Figure C-5. Top view of the computation grid for Water Body 1.

PREDICTION OF WELL WATER YIELD

Predicting water yield of the wells assumes that:

- The well life is 10 years.
- Water yield is invariant for any time within a given day.
- Water yield is maximal at the first producing day.
- Water yield decreases to half of its maximal after producing 2 years.

For a given well, the water yield after producing t days, WY_t, is predicted as:

$$WY_t = e^{[-9.4952\times 10^{-4}\,t + \ln(WY_0)]} \qquad \text{[Eq. 1]}$$

where WY_0 = the maximum water yield of the well.

Data on the maximum water yields for the 7842 CBM wells in the Powder River drainage basin were downloaded from the Wyoming Department of Environmental Quality Web site at http://www.wolverineenergy.com/powder_river_basin.htm. However, data were unavailable for 52 wells (38 wells in Montana and 14 wells in Wyoming). The maximum water yield for these wells was assumed be 25 gal/min.

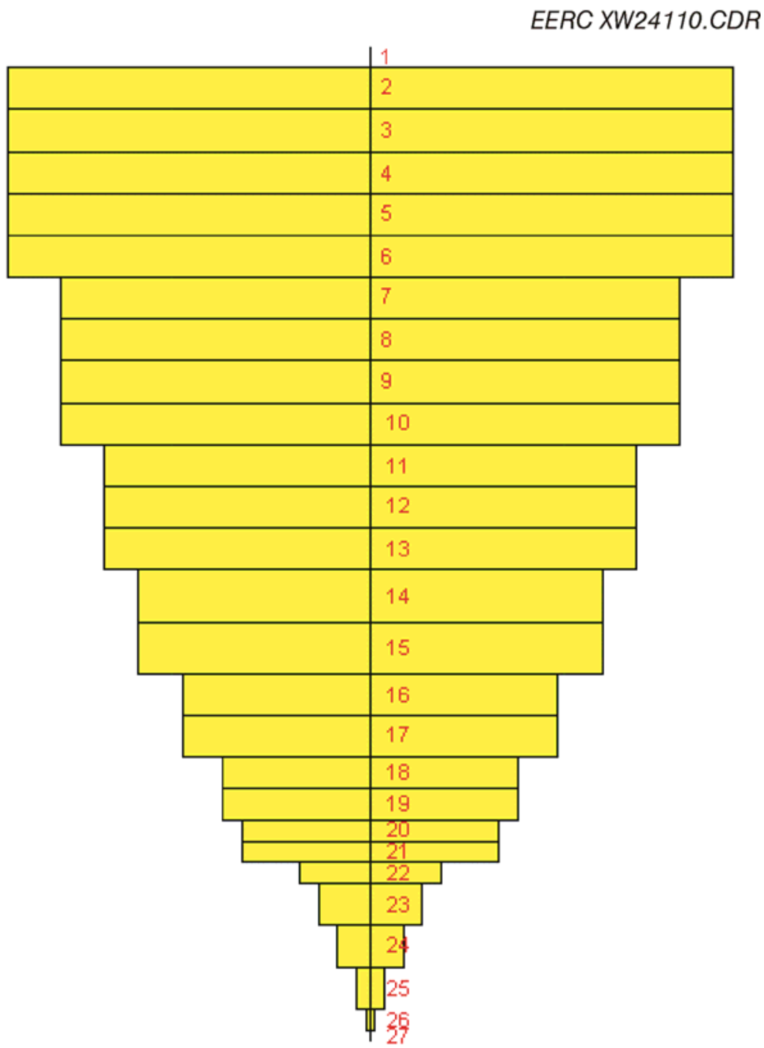

Figure C-6. End view of the computation grid for Water Body 1.

ESTIMATION OF WATER DISCHARGE AT OUTFALL

This model component makes the following assumptions:

- Seepage and evaporation rates are uniform across the drainage basin.
- Affects of impoundments, if any, can be accounted for using an equivalent river reach.
- A well discharges its produced water at its geographically nearest outfall.
- The total water discharged at an outfall equals to the linear summation of the water contributed from all of the wells.

Table C-1. Portion of the Bathymetry Data for Water Body 1, Including Three Branches and 300 Segments. Reference the User Manual of the CE-QUAL-W2 Model to Interpret the Data.

Stream Name	Branch	Segment	Length, m	WSEL, m	PHI0, radian	Layer Height, m	U/S	D/S	Width of the Layer, m								
									1	2	3	4	5	6	7	8	9
Powder R.	1	1	318.6	1392.67	5.23599	1.0	2	99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
U/S Elev.	1385.66	2	318.6	1392.14	5.23599	2.0			0.0	1873.5	1873.5	1873.5	1873.5	1873.5	1583.8	1583.8	1583.8
D/S Elev.	1336.31	3	318.6	1391.61	5.23599	2.0			0.0	1737.9	1737.9	1737.9	1737.9	1737.9	1483.8	1483.8	1483.8
Length, m	31860	4	318.6	1391.08	5.23599	2.0			0.0	1477.6	1477.6	1477.6	1477.6	1477.6	1285.3	1285.3	1285.3
Slope	0.00155	5	318.6	1390.55	5.23599	2.0			0.0	1361.5	1361.5	1361.5	1361.5	1361.5	1209.2	1209.2	1209.2
	0.00167	6	318.6	1390.01	5.23599	2.0			0.0	1506.6	1506.6	1506.6	1506.6	1506.6	1355.0	1355.0	1355.0
S. Fork	2	101	140.1	1410.19	4.18879	2.0	102	15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
U/S Elev.	1411.70	102	140.1	1409.94	4.18879	1.0			0.0	1032.3	1032.3	1032.3	1032.3	1032.3	629.3	629.3	629.3
D/S Elev.	1372.37	103	140.1	1409.69	4.18879	0.2			0.0	1045.9	1045.9	1045.9	1045.9	1045.9	641.3	641.3	641.3
Length, m	14012	104	140.1	1409.44	4.18879				0.0	1059.5	1059.5	1059.5	1059.5	1059.5	653.2	653.2	653.2
Slope	0.00281	105	140.1	1409.19	4.18879				0.0	1073.2	1073.2	1073.2	1073.2	1073.2	665.2	665.2	665.2
	0.00180	106	140.1	1408.93	4.18879				0.0	1086.8	1086.8	1086.8	1086.8	1086.8	677.1	677.1	677.1
Salt Cr.	3	201	203.6	1376.73	3.66519		202	84	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
U/S Elev.	1367.60	202	203.6	1376.45	3.66519				0.0	1519.5	1519.5	1519.5	1519.5	1519.5	1241.3	1241.3	1241.3
D/S Elev.	1338.76	203	203.6	1376.16	3.66519				0.0	1526.9	1526.9	1526.9	1526.9	1526.9	1245.6	1245.6	1245.6
Length, m	20360	204	203.6	1375.88	3.66519				0.0	1534.3	1534.3	1534.3	1534.3	1534.3	1249.9	1249.9	1249.9
Slope	0.00142	205	203.6	1375.59	3.66519				0.0	1541.7	1541.7	1541.7	1541.7	1541.7	1254.2	1254.2	1254.2
	0.00140	206	203.6	1375.31	3.66519				0.0	1549.1	1549.1	1549.1	1549.1	1549.1	1258.5	1258.5	1258.5

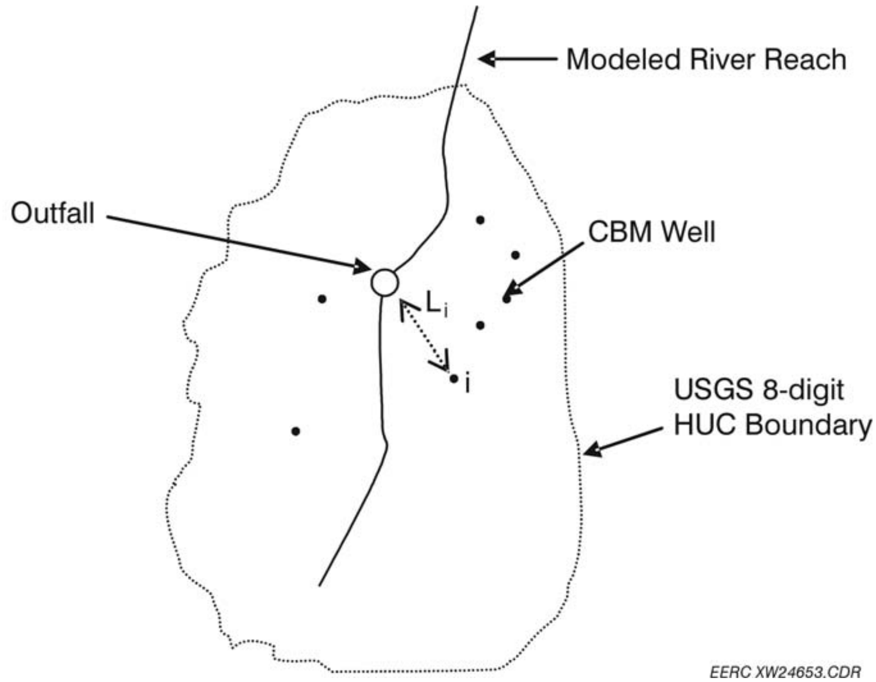

Figure C-7. The watershed model schematic, showing a U.S. Geological Survey (USGS) 8-digit hydrological cataloging unit (HCU) drained by a stream reach modeled in CE-QUAL-W2 and coalbed methane (CBM) wells and their outlet.

For a well, i, its discharge on day t at outfall, o, can be computed as:

$$WY_{io,t} = WY_{i,t-k_t} - (f + e)(L_i B_i) \qquad \text{[Eq. 2]}$$

where $WY_{io,t}$ = the discharge of well i on day t at outfall o; WY_{i-k_t} = the water yield of well i at day t-k_t ; f and e = the seepage and evaporation rates, respectively; B_i = the average width of the conveyance stream between well i and outfall o; and L_i = the equivalent length of conveyance stream between well i and outfall o.

L_i is computed as:

$$L_i = d_i + \sum_{j=1}^{m} [\frac{V_i}{(\frac{WY_{i,t-k_t}}{A_j})}(Len_j) \qquad \text{[Eq. 3]}$$

where d_i = the linear geographic distance between well i and outfall o; V_i = the average flow velocity in the conveyance stream between well i and outfall o; A_j = the average surface area of impoundment j; Len_j = the average longitudinal length of impoundment j.

B_i is computed as:

$$B_i = a(WY_{i,t-k_t})^b \qquad \text{[Eq. 4]}$$

where a and b = coefficients, usually having values of 1.0 and 0.26, respectively.

V_i is computed as:

$$V_i = k(WY_{i,t-k_t})^m \qquad \text{[Eq. 5]}$$

where k and m = coefficients, usually having values of 1.0 and 0.34, respectively.

k_t is computed as:

$$k_t = \text{ceil}[\frac{L_i}{V_i}] \qquad \text{[Eq. 6]}$$

Equations 2–6 need to be solved iteratively to estimate $WY_{io,t}$.

DETERMINATION OF CONSTITUENT CONCENTRATIONS AT AN OUTFALL

This model component makes the following assumptions:

- Concentrations of the constituents at a well are constant throughout the well life.
- Concentrations of the constituents follow a first-order increase equation from a well to its outfall.

For a constituent, its concentration on day t at outfall o is determined as:

$$C_{io,t} = e^{(kt+C_{i,0})} \qquad \text{[Eq. 7]}$$

where $C_{i,0}$ = the concentration at the head of well i; $C_{io,t}$ = the concentration contribution on day t at outfall o from well i; and k = coefficient, which is specific for a constituent and conveyance condition (Table C-2).

Table C-2. Coefficients for Transporting Alkalinity, Total Dissolved Solids (TDS), and Inorganic Carbon from Well, i, to Its Outfall, o.

Conveyance Condition	Alkalinity	TDS	Inorganic Carbon
Without Impoundment	0.0186–0.0232	0.0162–0.0245	0.0186–0.0232
With Impoundment(s)	0.0120–0.0170	0.0272–0.0294	0.0120–0.0170

The constituent concentration of the discharge into the stream reach on day t at outfall o, $C_{o,t}$, is computed using a mixing equation:

$$C_{o,t} = \frac{\sum_{i=1}^{N}(WY_{io,t} \times C_{io,t})}{\sum_{i=1}^{N} WY_{io,t}} \quad \text{[Eq. 8]}$$

The water temperature is modeled to be conservative. The temperature of the discharge into the stream reach on day t at outfall o, $T_{o,t}$, is computed using a mixing equation:

$$T_{o,t} = \frac{\sum_{i=1}^{N}(WY_{io,t} \times T_{io,t})}{\sum_{i=1}^{N} WY_{io,t}} \quad \text{[Eq. 9]}$$

where $T_{io,t}$ = temperature of the produced water on day t at well i.

EXECUTION OF THE MODEL

The model was written in Microsoft Visual Basic® (Version 6.0). It is executed through a user-friendly interface shown in Figure C-8.

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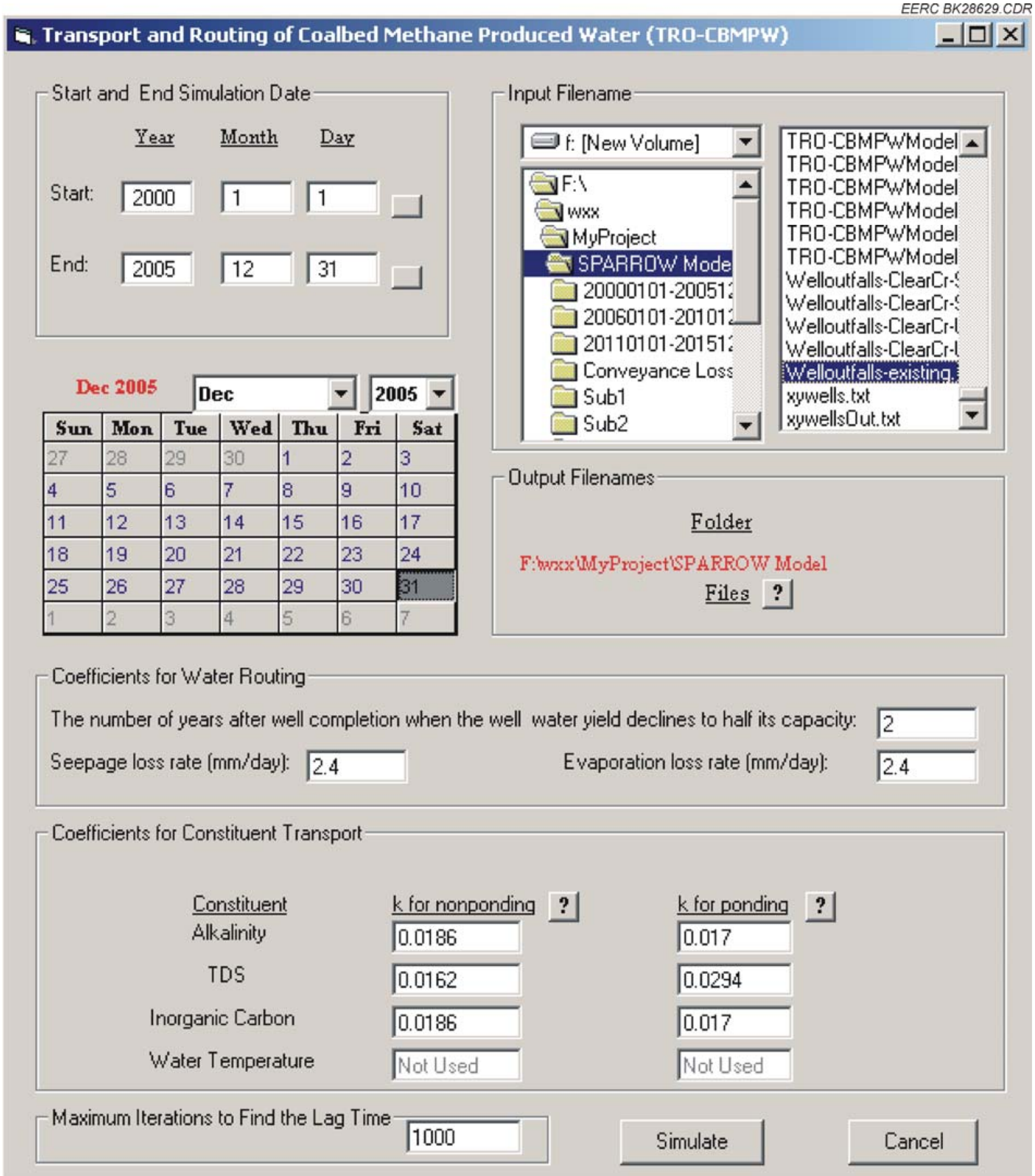

Figure C-8. Interface of the watershed model routing produced water and transporting the constituents from the wells to their corresponding outfalls for the Powder River drainage basin.

APPENDIX D

DESCRIPTION OF THE DECISION SUPPORT TOOL

DESCRIPTION OF THE DECISION SUPPORT TOOL

The decision support tool developed through this project is comprised of two main components: an interface to run the water quality and hydrologic models and a spreadsheet designed to evaluate basic effluent trading scenarios. Both tools can be found in a CD included with this report and are discussed further in the following text.

Model Interface

The model interface allows users with no surface water modeling experience to simulate trading scenarios using the water quality and hydrologic models developed through this project. Although prior knowledge of running water quality models is not necessary, the interface was designed for users with a technical background and/or experience using geographic information systems (GIS). Input to the model interface includes information related to specific CBM well locations and identification numbers, as well as water quality and flow information. The information for all existing and planned wells (up to 2009) is included with the model and user interface. (The data on existing and planned wells was downloaded in 2002, so periodic updates may be necessary.)

Economic Evaluation Spreadsheet

Coupled with the water quality model user interface is an economic model in spreadsheet format. It was designed to incorporate the output files from the water quality modeling results to provide a general economic estimate of various effluent credit-trading scenarios. However, it can also be used to conduct general economic evaluations of trading scenarios regardless of the impacts to water quality. The later application of the spreadsheet should be conducted while keeping in mind that the potential impacts to water quality as a result of trading are important and should be taken into consideration.

The general parameters included in the economic spreadsheet include:

- The capital costs per well for three different disposal types, including surface discharge, infiltration impoundment, and shallow reinjection.

- The operation and maintenance costs for the three aforementioned disposal types.

- The number of wells located in each subwatershed.

- The total CBM discharge volume from each subwatershed, assuming a CBM well lifetime of 10 years.

The total estimated costs to treat the CBM discharge in each subwatershed over the 10-year well lifetime is estimated using the above parameters coupled with the well discharge estimates derived from the water quality and hydrologic models. Any of the above parameters can be changed by the user, either indirectly by altering the water quality model output parameters or directly if additional information is known regarding costs, the number of wells, and/or discharge volumes.

The potential economic impacts of trading scenarios can also be evaluated in the spreadsheet. The default scenario evaluated in the spreadsheet is described in this report as "Scenario IV," where 25% of the CBM produced water in the Upper Powder River watershed is withheld, allowing for the direct surface discharge of all remaining CBM produced water throughout the Powder River Basin. The costs and benefits are broken down based on current and proposed handling methods. The default percentage of water withheld can be changed for each subwatershed so that the economics of additional trading scenarios can be evaluated; however, as previously mentioned, this should be conducted with caution if the evaluation is conducted without taking into account impacts to water quality.

Model Installation and Use

The enclosed CD includes the model files and input data for the Powder River Basin. The model files are organized into two folders, namely *Support* and *TRO-CBMWModel* (Transport and Routing of Coalbed Methane Produced Water), and need to be installed on a computer hard drive by running the program, "Setup.exe." The file of "Setup.LST" is used by "Setup.exe" to complete the installation process. In addition, the user needs to copy the "*PowderRiver*" folder to the hard drive to run the model for the Powder River Basin.

To install the model, navigate to the CD drive in My Computer and double click "Setup.exe." Follow the self-explanatory dialog boxes to complete the installation. Next, copy the "*PowderRiver*" folder onto the hard drive. The economic spreadsheet, called "EconomicAnalysis.xls," is also located within this folder.

To run the model, navigate to, and click on, the model program from the Start Menu. The interface shown in Figure D-1 will be activated and is used to conduct model simulations. The input data includes the desired start and end date of the model simulation, input data file name, coefficients for water routing, and coefficients for constituent transport.

Coefficients for Water Routing and Constituent Transport

The coefficients for water routing and constituent transport relate to the decay of three constituents, namely total dissolved solids (TDS), inorganic carbon (TIC), and alkalinity (ALK), from each wellhead to the subbasin outlet. The details on the transport mechanism and mathematical equations can be found in Appendix C. The rate at which the aforementioned constituents are lost and/or gained from the system during transport is defined by the decay coefficient, "k." In this study, "k" values were determined from data collected just downstream of the U.S. Geological Survey's flow gauging station at Arvada (06317000). It was assumed that these values are applicable for the entire Powder River watershed and, therefore, they were used as the default model parameters (Table D-1). In

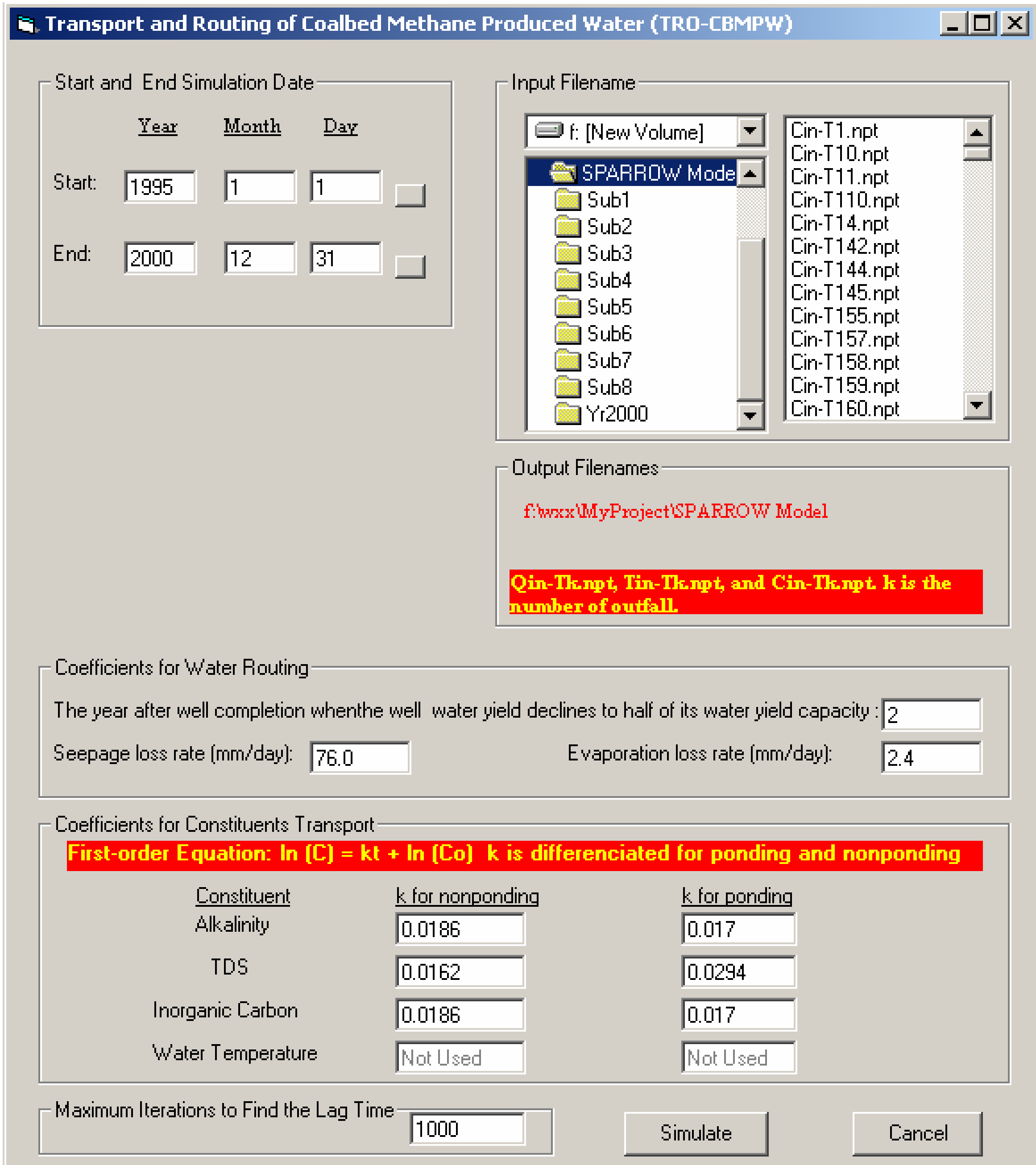

Figure D-1. Watershed model interface.

Table D-1. Values for the Decay Parameter, "k"

Conveyance Condition	Alkalinity			TDS		Inorganic Carbon
Without Impoundments	0.0186	0.0232	0.0162	0.0245	0.0186	0.0232
With Impoundments	0.0120	0.0170	0.0272	0.0294	0.0120	0.0710

addition, "k" values were determined to reflect conditions with and without impoundments between the well and the subbasin outlet, since impoundments may facilitate the deposition and/or suspension of particular constituents. The user should be reminded that these values may need to be further refined as additional data are available in the future. For additional information on water quality data collected within the Powder River Basin, please refer to Rice et al., 2000; McBeth et al., 2003; and Patz et al., 2004.

Preparation of the Input Data File

In addition to setting the model simulation start and end date and adjusting the coefficients for water routing and transported (if desired), the key information needed for conducting model simulations is contained in the input data file, which is prepared by the user. Table D-1 shows an example data input file for the model. The first line provides a brief explanation of the input parameters listed in each column, followed by the corresponding parameter values. The parameters are:

- **Modelid:** The unique identification number of the CBM well to be modeled

- **Outfallid:** The unique identification number for the outfall at which the produced water from **Modelid** would be discharged

- **DistanceM:** The distance in meters from **Modelid** to the outlet of its subwatershed along the drainage path

- **QmaxCms:** The maximum water yield of **Modelid**

- **cpYr:** The year when **Modelid** starts producing

- **cpMn:** The month when **Modelid** starts producing

- **cpDay:** The day when **Modelid** starts producing

- **numPonds:** The number of ponds along the drainage path from **Modelid** to its subwatershed outlet. When **numPonds** is greater than one, the total area and longitudinal length of the **numPonds** ponds must be specified in the followed two columns, respectively.

- **observedWellid**: The unique identification number of the observation well, whose produced water is assumed to have water quality parameters identical to that of **Modelid**

- **DistanceM:** The geometric distance in meters between **Modelid** and **observedWellid**

- **TempoC:** The temperature, in ºC, of the produced watershed at the well head of **observedWellid**

- **TDS:** The total dissolved solids, in mg/L, of the produced watershed at the well head of **observedWellid**

- **Alkalinity:** The alkalinity, in mg/L, of the produced watershed at the well head of **observedWellid**

- **InorganicCarbon:** The inorganic carbon, in mg/L, of the produced watershed at the well head of **observedWellid**

In the "*PowderRiver*" folder, "welloutfalls-existing.txt" is the input file used to simulate the impacts of all 7842 wells. The other four files, namely "welloutfalls-ClearCr-Side50%TDS.txt,""welloutfalls-ClearCr-SideRejection.txt,""welloutfalls-ClearCr-Upstream 50%TDS.txt," and "welloutfalls-ClearCr-UpstreamRejection.txt," were prepared to simulate the various trading scenarios discussed in the report. In addition, a Microsoft Excel spreadsheet labeled "Information on wells and outfalls.xls," can be used as a template for preparing the model input file.

To derive the above required model input data, the user needs to compile GIS data layers on 1) boundaries of a watershed and its subwatersheds, 2) drainage networks, 3) locations and geometry of infiltration ponds, 4) locations of outfalls, 5) locations and water quality parameters of observation wells, and 6) soil types. These layers can be compiled in ArcGIS/ArcView to extract the input data.

Model Outputs

The model generates three types of output files, organized by well number. These files have a plain text format and can be loaded into a Microsoft Excel spreadsheet for further analysis. For each well, *x*, the model will generate three output files that store:

1) Simulated daily discharge at the subbasin outlets with a file name of Qin-T[*x*].npt

2) Simulated temperatures of the discharge with a file name Tin-T[*x*].npt

3) Simulated concentrations of total dissolved solids (TDS), inorganic carbon (TIC), and alkalinity (ALK) with a file name Cin-T[*x*].npt

In the file names, [*x*] is replaced by the actual number of the well. For example, for well 8, the corresponding output files will be designated Qin-T8.npt, Tin-T8.npt, and Cin-T8.npt. These files are stored in plain text format and can be opened using a text editor (e.g., Notepad) or loaded into Microsoft Excel for plotting. In the files, the dates are expressed as the corresponding Julian days. Examples of the three types of output files are shown in Tables 2–4.

The Microsoft Excel spreadsheet, "ConveyanceLossEval.xls," located in the folder of *PowderRiver/Conveyance Loss*, can be used as a template to further analyze the outputs and estimate the corresponding SAR and EC values based on the simulated TDS, alkalinity, and inorganic carbon.

Contact Information

For additional information on the model interface, economic spreadsheet, and/or the hydrologic and water quality models developed through this project, please contact Bethany Kurz at the Energy & Environmental Research Center (EERC), (701) 777-5050 or bkurz@undeerc.org.

The following is an example of a model input file:

Table D-2. An Example Model Input File

Modelid	Outfallid	DistanceM	QmaxCms	cpYr	cpMn	cpDay	numPonds	ObservedWellid	DistanceM	TempoC	TDS	Alkalinity	InorganicCarbon
1	214	76997.3	0.00158	2003	12	31	0	-17	55735.0	11.7	2010.0	2320.0	594.6
2	212	42480.8	0.00221	2003	12	31	0	-24	5696.3	26.5	1060.0	1220.0	309.6
3	212	43532.8	0.00221	2003	12	31	0	-24	4086.8	26.5	1060.0	1220.0	309.6
4	212	43008.4	0.00221	2003	12	31	0	-24	4893.6	26.5	1060.0	1220.0	309.6
5	212	43108.0	0.00221	2003	12	31	0	-24	5748.6	26.5	1060.0	1220.0	309.6
6	212	42433.6	0.00221	2003	12	31	0	-24	5316.3	26.5	1060.0	1220.0	309.6
7	212	42538.5	0.00221	2003	12	31	0	-24	6111.3	26.5	1060.0	1220.0	309.6
8	212	40903.6	0.00221	2003	12	31	0	-24	7728.7	26.5	1060.0	1220.0	309.6
9	212	43179.0	0.00221	2003	12	31	0	-24	6210.4	26.5	1060.0	1220.0	309.6
10	212	41473.1	0.00221	2003	12	31	0	-24	7309.4	26.5	1060.0	1220.0	309.6

An example of the Type I output files ("JDAY" indicates Julian Day and "QWD" is CBM well discharge per day):

Table D-3. Inflow from the CBM Wells at the Subbasin Outlet

JDAY	QWD
40544.0	0.00
40545.00	0.00
40546.00	0.00
40547.00	0.01
40548.00	0.01
40549.00	0.01
40550.00	0.02
40551.00	0.02
40552.00	0.02

An example of the Type II output files. "T" indicates temperature in degrees Celsius:

Table D-4. Inflow Temperature of CBM Produced Water at the Subbasin Outlet

JDAY	T
40544.00	17.57
40545.00	20.40
40546.00	20.40
40547.00	16.62
40548.00	16.78
40549.00	16.90
40550.00	17.00
40551.00	17.01
40552.00	17.00
40553.00	17.00
40554.00	17.00
40555.00	17.00
40556.00	17.00

An example of the Type III output files. The units for total dissolved solids (TDS), total inorganic carbon (TIC), and alkalinity (ALK) are in mg/L.

Table D-5. Inflow Constituent Concentrations of CBM Produced Water at the Subbasin Outlet

JDAY	TDS	TIC	ALK
40544.00	1274.90	365.81	1440.77
40545.00	2000.00	579.10	2260.00
40546.00	2000.00	579.10	2260.00
40547.00	1455.01	420.18	1647.62
40548.00	1391.64	400.99	1573.76
40549.00	1374.64	395.72	1553.48
40550.00	1361.08	391.53	1537.37
40551.00	1352.54	388.95	1527.45
40552.00	1352.59	388.96	1527.51
40553.00	1352.64	388.98	1527.56

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