Final

Water Resource Monitoring of Streams in the Coal Bed Methane Production Area of the Powder River Basin, Wyoming

2003–2006 Water Years

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For:

PENNACO ENERGY, INC.
Wholly owned subsidiary of
MARATHON OIL COMPANY

WILLIAMS PRODUCTION RMT

YATES PETROLEUM CORPORATION

J.M. HUBER CORPORATION

ANADARKO PETROLEUM CORPORATION

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EXECUTIVE SUMMARY

This report presents an update of data collected since August, 2001, on storm discharges occurring in representative ephemeral streams in the Powder River Basin of NE Wyoming in the region of Coal Bed Methane (CBM) development. Detailed data presented include storms monitored during the 2003 through 2006 Water Years; the 2001 through 2002 Water Year detailed data has been previously summarized in Sanders et al (2003). All storm flow data from the 2001 through 2006 Water Years are used collectively in this report to evaluate whether there is any quantitative evidence of CBM discharges affecting the chemistry of storm flows in the study watersheds.

A total of 10 different watersheds, both with and without CBM development, were instrumented with 13 different Continuous Record (CR) stations that continuously monitored discharge stage height at 5 minute intervals and which collected a 24 bottle set of grab samples (used for major ion analysis) over preset intervals if a storm discharge was detected. The period of record beginning in 2001 does not include a pre-CBM development phase for most of the CR stations operated during this study. By the end of the 2006 Water Year, 41 storm events had been monitored at the CR stations. An additional three (3), non-CBM development watersheds were instrumented with Partial Record stations which continually monitored only discharge stage height and specific conductance. The period of study has coincided with a severe drought in NE Wyoming which undoubtedly has affected study results.

Observations on storm discharge obtained during this study show that far-field, down-channel runout of storm flows that originate in headwater areas of ephemeral streams are significantly truncated by channel storage processes and by on-channel reservoirs. Storm runoff events that occur in headwater reaches may not flow to lower reaches where irrigable flood plains are common.

Observations on the geochemistry of significant storm discharges indicate that chemistry varied widely among individual storm events both within and among the study watersheds. The high spatial and temporal variability of monitored events likely results from both: the spatial heterogeneity of diverse, exposed geologic strata of the Wasatch and Fort Union Formations which provide natural solutes to storm flow through mineral weathering and dissolution processes; and the apparent heterogeneity in intensity, percent of drainage affected, location of drainage areas affected, and frequency of significant precipitation events among the study watersheds over the period of record.

Results from analyses of the hydrological and geochemical storm discharge data collected among all CR stations are the following:

- Field observations support the understanding that natural landscape processes contribute significant quantities of solutes, including significant concentrations of sodium, to storm discharge in the absence of CBM discharges. The low ionic strength of direct precipitation (rainfall, snowfall) is clearly dramatically changed to high ionic strength channel pothole water and shallow alluvial groundwater through natural processes. The entrainment during storm

flushing events of natural surface evaporites formed from weathering of exposed geologic strata and of waters held in channel potholes lead to substantial natural solute transport. The sum of significant landscape-level solute generation (e.g., dissolution of accumulated salt evaporites) and transport during storm flow forms a variable geochemical background within which any affects of CBM-discharges among the study watersheds must be evaluated.

- Although only limited analysis of time trends in CBM-developed watersheds (initial low development to later more intensive development) was possible due to the low frequency of observed storm events, no significant trends in storm discharge chemistry were observed for three significantly developed watersheds (Pumpkin Creek, LX Bar Creek near Mouth prior to July, 2005, and Barker Draw near Mouth).

- Differences in storm flow geochemistry were observed between CBM-developed and undeveloped drainages, but results are confounded by physical and geochemical differences among study drainages. Overall, no meaningful statistical differences between these drainage types could be discerned from data collected in relation to CBM development.

- Because of the ubiquity of sodium in the surface geology and soils of the Powder River Basin and the near absence of sulfate in CBM produced water, useful indicators of the influences of CBM discharges on storm flow chemistry are the abundance of sulfate and the correlations of sodium to sulfate in individual storm events. Substantial dissolved sulfate concentrations were observed to be common in storm discharge. Comparisons of sodium versus sulfate concentrations for all individual storm events yielded an overall median R^2 value of 0.804. This relatively high correlation suggests that sodium observed in storm discharges has predominantly a landscape origin and does not originate from CBM discharges upstream. However, some storm data are equivocal and review of detailed geochemistries and drainage characteristics is required to evaluate individual events.

- Based on all data collected to date during the 2001 through 2006 Water Years and among the 13 study watersheds, CBM development has had little, if any, discernable influence on storm discharge chemistry. The primary exception to this general finding is the superimposition of storm discharge on WYPDES-permitted perennialized, relatively low flow (several CFS) occurring in the lower reach of LX Bar Creek.

- Streamflow at the LX Bar Creek near Mouth CR station (a naturally ephemeral reach) has been perennialized from upstream, permitted CBM discharges since July, 2005. Here, the geochemistries of several modest storm runoff events, having apparent landscape-level influences, were superimposed over the CBM-dominated perennial flow, and a CBM-chemical signature (predominance of sodium and bicarbonate) could be easily discerned in storm chemical data. It is anticipated that larger storm discharges are likely to swamp the chemistry of the CBM discharges and revert to a combined chemistry that reflects predominance of landscape-level influences on total and individual solute transport.

The ongoing study is an observational study that has limitations regarding the spatial array of monitored watersheds in CBM-developed and non-developed watersheds and regarding the inability to monitor selected watersheds both before and after significant CBM development. However, in the broad context of the study design and over the period of study, both spatially and temporally, little direct evidence has been found suggesting that CBM-discharges have significantly affected storm flow chemistry, with the exception of CBM-perennialized flow in the lower reach of one study watershed.

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Water Resource Monitoring of Streams in the Coal Bed Methane Production Area of the Powder River Basin, Wyoming

2003–-2006 Water Years

1.0 INTRODUCTION

This report provides an update of data collected in the Watershed Monitoring Project (the study) on the hydrology and geochemistry of natural storm flows occurring in selected watersheds in northeastern (NE) Wyoming where development and production of coal bed methane (CBM) has been ongoing since approximately 1998. This update includes new storm discharge data from the 2003 through 2006 water years (a water year is defined as the time period from October 1st of one year through September 30th of the following year). Data for the 2001 and 2002 water years, previously reported in Sanders et al. (2003), is also included herein where appropriate. Because of the current ongoing drought cycle, several years of additional study were required to provide a reasonable data set for an update. The study is being conducted primarily in the Powder River Basin (the PR Basin) with the exception of one watershed (Hay Creek), which is located on the Belle Fourche River drainage.

The authors gratefully acknowledge the CBM operators who have funded this study and the local landowners who have allowed property access to establish and maintain the automatic gage stations. Pennaco Energy, Inc., Williams Production RMT, Yates Petroleum Corporation, J.M. Huber Corporation, and Anadarko Petroleum Corporation provided funding for data collection and analysis. Landowners and ranches who allowed access to and installation of monitoring equipment on their property include John Daily, Allan and Jan Mooney, John and Marie Iberlin, John Flocchini, Penny and Joel Hjorth, Kenny Knudson, Giles Pritchard-Gordon, Jean Urruty, Joe Reculusa, Glenn Gay, The Seven Ranch, and the Harriet family.

1.1 PURPOSE

Groundwater is co-produced from underlying coal beds as part of CBM production in NE Wyoming and is commonly discharged to either surface impoundments or to stream channels. The discharge of CBM-produced groundwater to the semi-arid landscape of this region could potentially influence the yield (transport) of dissolved minerals, their flow-weighted concentrations, and the relative proportions of individual solutes (e.g., sodium relative to calcium and magnesium) in storm flows. Because infrequent storm flows in the naturally ephemeral watersheds of the Basin constitute the primary transport mechanism for salts down tributaries and eventually down the Powder River, the need to monitor changes in these parameters is apparent.

The purpose of the Watershed Monitoring Project is to investigate the frequency, magnitude and chemistry of significant storm flow events in representative watersheds with an emphasis on runoff associated with intense late spring through early fall rainstorms and to evaluate changes, if any, in the yields, flow-weighted mean concentrations, or relative proportions of solutes from CBM-developed drainages.

1.2 GENERAL STUDY DESIGN

The Watershed Monitoring Project is an observational study given that direct field experimentation is not practical. The study was started after the onset of CBM development within the Basin, which began accelerating during 1999. While many storm events have been monitored to date, very limited monitoring of both pre- and post-CBM development conditions has been possible in the study watersheds. The basic design of the study, therefore, includes evaluations of time trends within individual watersheds and comparisons among spatially distributed watersheds.

2.0 DESCRIPTION OF STUDY AREA

2.1 OVERVIEW

Geography

The study is being conducted in the central portion of the Powder River Basin in NE Wyoming. This region contains much of the ongoing development and production of methane gas from underlying coal beds. The climate of the central Basin is semi-arid, which is reflected by an extensive steppe sagebrush and grassland habitat. Trees (commonly cottonwood) are found only sparsely along stream channels (Knight, 1994). The general topography is dominated by rolling hills, scattered clinker-capped small buttes, and incised stream channels especially where tributaries join the mainstem Powder River. However, local topography may vary from rolling to steeply incised. Altitudes range from 3,000 to 6,000 ft above mean sea level (AMSL) for the plains region of the Basin (Lindner-Lunsford et al., 1992). The study watersheds described herein generally are 4,000 to 4,500 ft AMSL.

Climate

NE Wyoming has a severe continental climate with annual precipitation characteristic of semi-arid conditions (Curtis and Grimes, 2004). Most of the annual precipitation falls as snow during November through April, but storm conditions vary and snowfall can occur any month with the likely exception of July and August. Intense local thunderstorms and broad regional rainstorms can occur from late spring through early fall and can locally contribute substantial direct precipitation (Lowry et al., 1986). Estimated mean annual evapotranspiration (ET) considerably exceeds annual precipitation for the plains region of the Basin (Hodson et al., 1973; Bartos and Ogle, 2002).

Importantly, considerable spatial heterogeneity exists in the amount of annual precipitation from west to east across the larger Basin. In the Bighorn Mountains to the west, annual precipitation may exceed 40 inches per year, which results in perennial flow in streams that headwater in these high elevations. The orographic effect of the Bighorn Mountains causes many thunderstorms to develop which subsequently tract eastward through the plains region. In the central portion of the Basin, the plains have much lower annual precipitation commonly varying between 12 to 14 inches per year (Lowry et al., 1986; Curtis and Grimes, 2004). (See Figure 2.1-1.). A lesser north-south precipitation gradient also exists from Gillette in the north (averaging 14 inches per year) to Casper in the south (averaging 11.8 inches per year) (Hodson et al., 1973). The highest average monthly precipitation commonly is June, and average monthly precipitation rapidly declines from July through September. Figure 2.1-2 shows the seasonal precipitation trends for Gillette, WY.

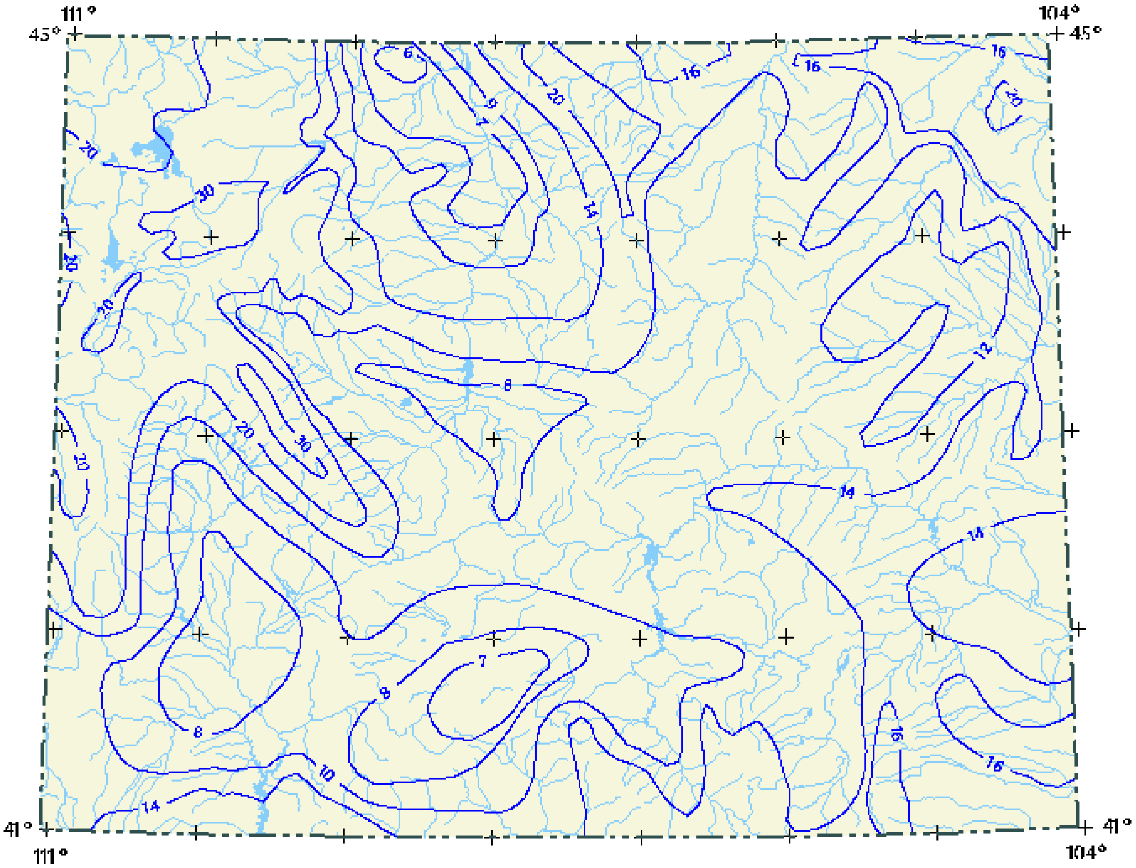

Figure 2.1-1. **Mean annual precipitation isopleths (inches per year) for Wyoming.**
[From Jennings et al., 1994.]

The annual amount of precipitation in the central Basin also is highly variable (Lowry et al., 1986). The NE Wyoming region tends to have prolonged drought cycles (approximately 8 years long) separated by shorter wet cycles (Druse, 1988). Currently the ongoing statewide drought, which began in the spring of 2000, is considered by many to be one of the most severe in collective memory (Curtis and Grimes, 2004; Gray, 2006). Figure 2.1-3 indicates that the ongoing drought has continued through March 2007, which is the date of most recent data available. During the past 100 years, the current severe drought is surpassed only by the 1950s drought and is worse than the Dust Bowl drought of the 1930s. Thus, below-average storm runoff and low frequency of runoff likely has occurred during most of the study period (2001 through 2006 water years).

In addition, local precipitation can be more variable than suggested by regional trends. Ranchers who are long-term residents of the Basin plains have noted to the authors that drainage-by-drainage precipitation

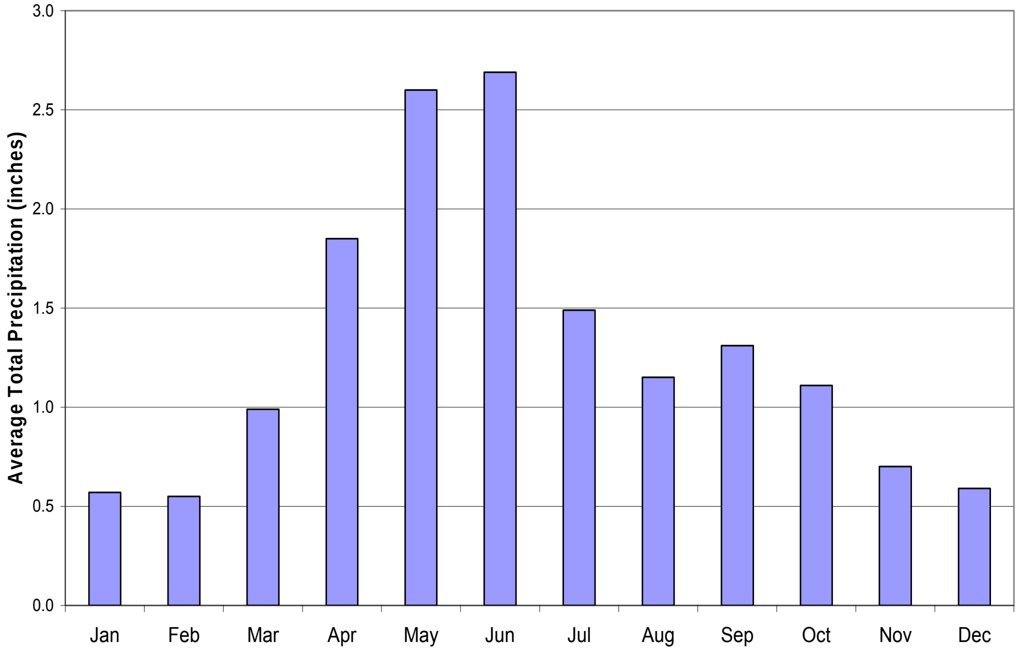

Figure 2.1-2. **Monthly average precipitation at Gillette, WY, January 1, 1925 through December 31, 2006.** [Data are from National Climate Data Center weather station number 483855, Gillette 9 ESE (WRCC 2007).]

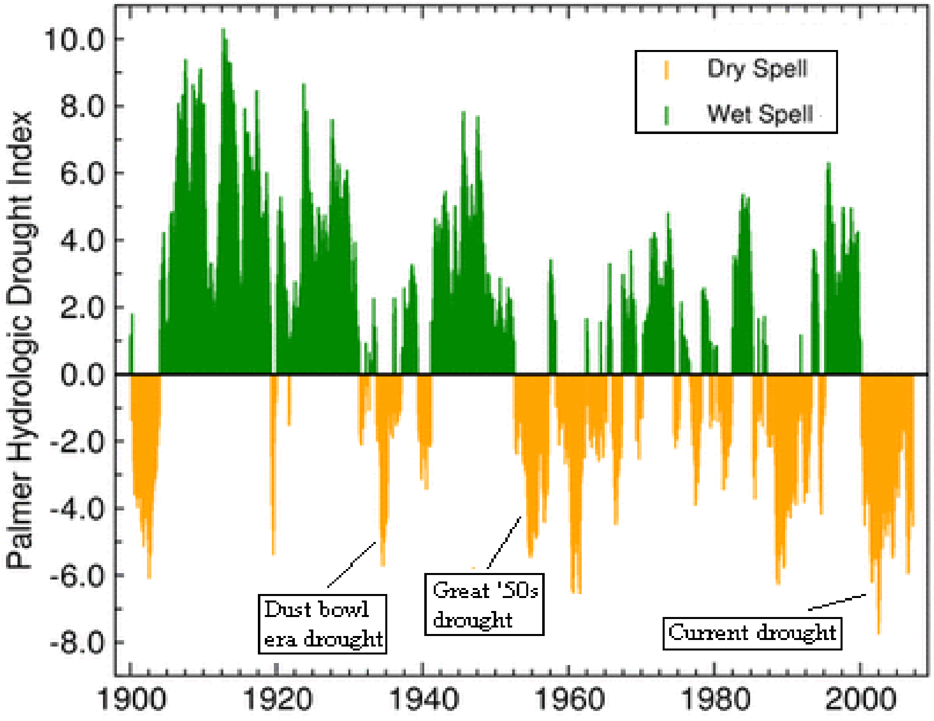

Figure 2.1-3. **Severity of the current drought in Wyoming, based on the Palmer Hydrological Drought Index (Palmer 1965), January 1900 through March 2007.** [Reproduced from NOAA, 2007.]

has high variability, which apparently is due to the characteristic narrow tracking of west-to-east moving thunderstorms during July, August, and September. Stream drainages lying in higher-frequency storm tracts east from the Bighorn Mountains likely receive a greater amount of summer rainfall than nearby drainages that do not apparently lie along such storm tracts.

Surface Geology

The geochemistry of stream water and near-surface (shallow alluvial) groundwater in tributaries to the Powder River is determined in part by the weathering of exposed bedrock and subsequent leaching of solutes from weathered rock (Hem, 1985). Leaching processes occurring subsequent to primary mineral weathering include precipitation-related dissolution and evapotranspirational concentration of solutes in near-surface environments. Chemical processes causing differential precipitation of salts (selective loss of salts such as calcium before sodium) can greatly modify the local geochemistry of natural waters. The type and relative proportions of geologic strata exposed to primary mineral weathering at the surface, combined with subsequent differentiating processes, are strong determinants of the natural chemistry of tributary water in the Basin.

Across the central PR Basin in NE Wyoming and in south-central Montana, geologic strata exposed at the surface consist of the Wasatch Formation (Eocene) in the south, which grades into the older Fort Union Formation (Paleocene) toward the Montana border and further north as the landscape trends topographically lower (Ellis and Colton, 1994). With the exception of LX Bar Creek, the study drainages are located south of the Clear Creek confluence with the Powder River in areas dominated at the surface by the Wasatch Formation (Lowry et al., 1986; Rankl and Lowry, 1990; Ellis and Colton, 1994; Flores and Bader, 1999; Zelt et al., 1999). Although present at depth, Fort Union Formation members are not well represented as outcrops in the study drainages with the exception of the lower drainage of LX Bar Creek.

Exposed geologic units of the Wasatch Formation include non-marine, interbedded and lenticular sandstones, siltstones/mudstones, and carbonaceous shales with numerous weathered coal outcrops (Boyd and Van Ploeg, 1998). Importantly, substantial deposits of sodium-rich feldspars (sodium-aluminosilicates) were incorporated into the Eocene topography during formation of these geologic units. These feldspars were derived from significant volcanic activity (and associated ash deposition) to the west, as represented for example, by present day Nevada (Davis, 1969; Robinson, 1972; Marlatt, 2007). Volcanic deposition has resulted in substantial deposits of reactive, volcanically-derived clays in the Basin (Van Voast, 2003), which are naturally rich in sodium, magnesium, iron, and other mafic minerals.

Additional sodium-rich clays and sediments were likely derived from erosion of Cretaceous marine rocks from the Bighorn Mountains and the Black Hills uplifts, which occurred during the Fort Union and Wasatch sedimentation (Jones, 2007).

In addition to exposed Wasatch and Fort Union strata, the present-day stream channels and associated flood plains in the PR Basin contain unconsolidated, fine to course residuum and alluvial deposits. These deposits commonly consist of clay, silt, sand, and gravels with thicknesses generally less than 50 ft but locally may be as much as 100 ft thick (Hodson et al., 1973; Halberg et al., 2000). Shallow alluvial groundwater is commonly found within the alluvial deposits along stream channels and such shallow groundwater may appear on the surface as potholes where confining lenses (e.g., mudstones) intersect the surface.

The deposition environment for the Fort Union and Wasatch Formations during the Paleocene and Eocene was low gradient, tropical, and near sea level (Lowry et al., 1986). This environment was typified by slowly meandering rivers flowing through lakes, ponds, and wetlands. As a result, the Wasatch and Fort Union Formation deposits became a complex of interbedded and interfingered rock types, which are highly variable spatially. It is also reasonable to assume that fluvial reworking of atmospheric deposits were not uniform across the Paleocene and Eocene topography in the region of NE Wyoming thus lending additional spatial heterogeneity to resulting rock types. Consequently, the dominant exposed lithology on today's landscape is highly dependent upon location within this complex system (Jones, 2007). The relative proportions of the various exposed strata including sandstones, siltstone/mudstone, shales, and clays vary broadly, among the study watersheds. The proportion of residuum and alluvial deposits in relation to exposed bedrock also appears to vary widely among tributary drainages of the Powder River (Halberg et al., 2000).

The inherent high spatial variability of exposed geologic strata and residuum suggests that considerable spatial heterogeneity also should be observed in the relative supply of different solutes (e.g., sodium, calcium, magnesium, sulfate, and bicarbonate) to surface waters derived from primary mineral weathering. The dominance of one cation versus another (e.g., sodium versus calcium) or one anion versus another (e.g., sulfate versus bicarbonate) in surface waters of a given PR tributary watershed is likely to be unpredictable *a priori* on the basis of the general surficial geology characterization presently available for the study watersheds.

An important characteristic of the semi-arid NE Wyoming plains region is that weathering of exposed geologic material likely proceeds at a rate sufficient to build up significant weathering products at the surface between infrequent flushing events caused by precipitation. Significant flushing events commonly occur less than once per year in Basin tributaries (see discussion in Section 5.1). Consequently, soluble evaporates, such as sulfate and carbonate salts of sodium, calcium and magnesium, formed as weathering products or as geologic evaporite deposits (e.g., gypsum; Hem, 1985), are expected to accumulate between significant flushing events and provide substantial yield of salts when fluvial transport does occur.

Considerable geologic uplift of the NE Wyoming region occurring after the formation of the Eocene and Paleocene strata has resulted in the present-day, highly erosional landscape characterized by high sediment yield during storm flow events. The name Powder River is derived from its high suspended clay and silt load.

2.2 STUDY DRAINAGES AND MONITORING SITES

The emphasis in the Watershed Monitoring Project is the monitoring of storm flows in representative tributaries to the Powder River and in one main tributary to the Belle Fourche River. Random selection of study watersheds was not possible due to practical limitations in the field. Study watersheds were selected primarily based on (1) desired geographic (spatial) distribution of monitoring gages across the CBM development region, (2) the ability to attain landowner permission for frequent access to preferred monitoring sites, and (3) accessibility to gage sites during poor weather and adverse road conditions. An acceptable gage site requires a stable stream channel and good stream cross-section relative to the adjacent flood plain to facilitate quantitative hydrologic monitoring under varying seasonal conditions. The resulting spatial distribution of monitoring gages is shown in Figure 2.2-1. Descriptive characteristics of each monitored watershed are summarized in Table 2.2-1; note that the sampling program currently includes 13 Continuous Record stations and three (3) Partial Record stations in 13 different watersheds (see further discussion Section 3). Detailed topographic maps of individual study watersheds and gage locations are provided in Appendix A. The overall study plan relies on observations among the spatial distributed study watersheds that differ according to level of CBM development and length of time that development occurred during the study period. The spatial array of monitoring gages shown in Figure 2.2-1 provides representative geographic coverage of the CBM development area of the PR Basin.

As shown in Figure 2.2-1, considerable water quality monitoring is ongoing in the Powder River watershed in association with CBM development. Results of the Watershed Monitoring Project reported here augment river flow and chemistry monitoring of the mainstem Powder River conducted by the U.S. Geological Survey (USGS; Clark and Mason, 2007) and by CBM Associates, Inc. at separate mainstem sites on behalf of CBM operators (e.g. CBMA 2007 Powder River Mainstem Monitoring Program Annual Report).

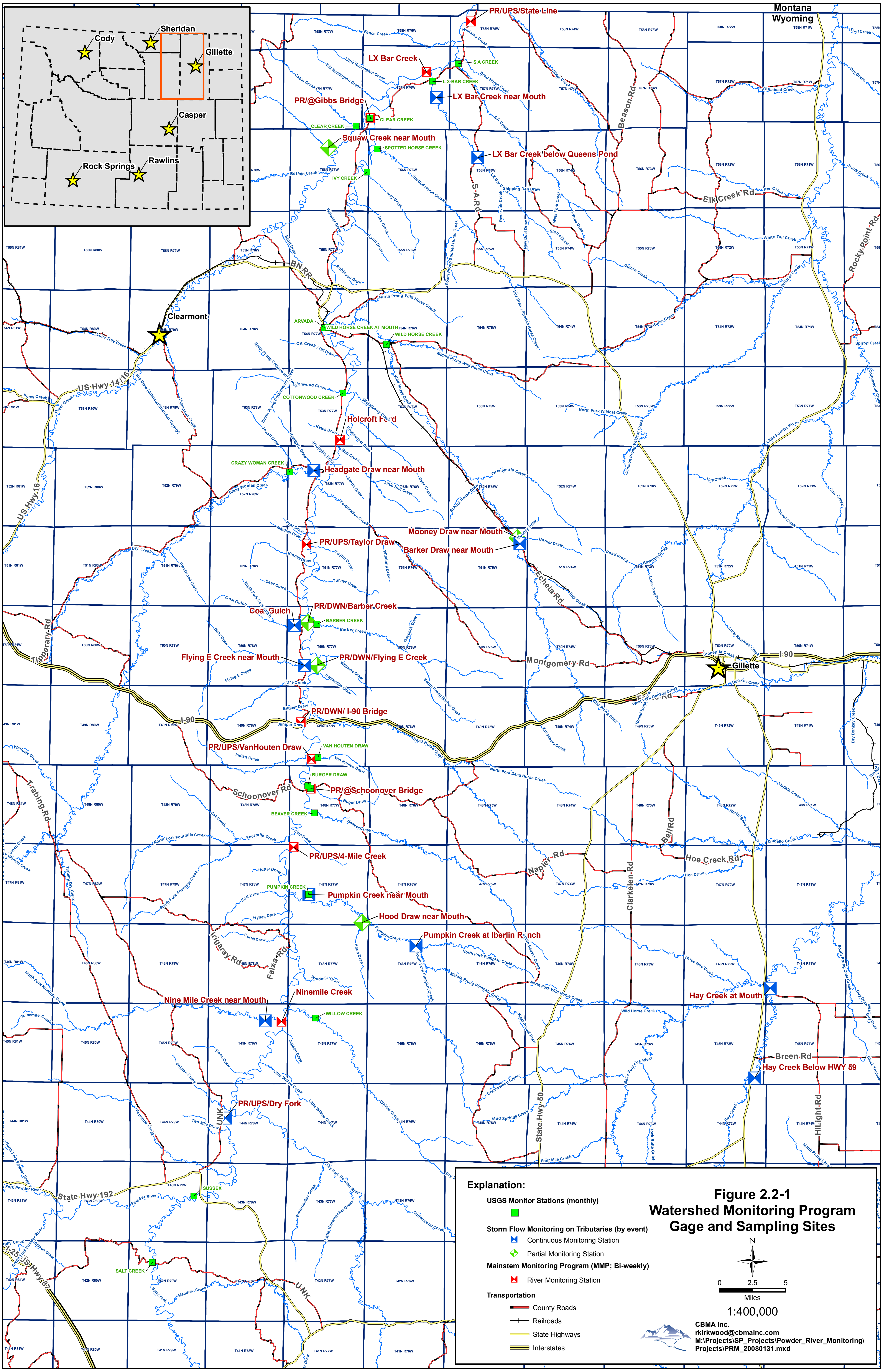

Figure 2.2-1
Watershed Monitoring Program Gage and Sampling Sites

CBMA Inc.
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Table 2.2-1. Descriptive characteristics of monitored watersheds.

Stream	**Tributary to**	**Hydrology**	**Drainage Area above Station (sq. miles)**	**Stream Length above Station (miles)**	**Percent stream slope (%)**	**Predominant Surface Geology**	**Monitoring Start Date**
Continuous Record Stations:							
Barker Draw near Mouth	Wild Horse Creek, tributary of Powder River	Ephemeral	7.41	6.8	16.42	Tertiary: Wasatch Formation	May, 2001
Pumpkin Creek near Mouth	Powder River	Ephemeral	165.63	39.74	7.62	Tertiary: Wasatch Formation	May, 2001
Pumpkin Creek at Iberlin Ranch	Powder River	Ephemeral	106.76	21.49 (along South Prong)	6.27	Tertiary: Wasatch Formation	May, 2001
Hay Creek at Mouth	Belle Fourche River	Perennial	95.8	40.95	5.34	Tertiary: Wasatch Formation	October, 2001
Hay Creek at Hwy 59	Belle Fourche River	Perennial	58.7	22.24	5.42	Tertiary: Wasatch Formation	September, 2001
LX Bar Creek near Mouth	Powder River	Ephemeral	56.64	25.8	9.81	Tertiary: Fort Union Formation	March, 2003
LX Bar Creek above Kline Draw	Powder River	Ephemeral	36.25	15.13	8.35	Tertiary: Fort Union Formation	July, 2003
Bloom Creek near Mouth; Montana	Powder River	Ephemeral	46.9	16.8	17.82	Tertiary: Fort Union Formation	August, 2003
Flying E Creek near Mouth	Powder River	Ephemeral	41.35	16.91	14.46	Tertiary: Wasatch Formation	Feb, 2004
Coal Gulch near Mouth	Powder River	Ephemeral	21.74	9.24	17.29	Tertiary: Wasatch Formation	May, 2004
Headgate Draw near Mouth	Crazy Woman Creek, tributary of Powder River	Ephemeral	4.5	6.4	15.96	Tertiary: Wasatch Formation	May, 2004
Dry Fork near Mouth	Powder River	Ephemeral	273.8	58.32	11.32	Tertiary: Wasatch Formation	Sept, 2005
Nine Mile Creek near Mouth	Powder River	Ephemeral	149.6	42.66	8.57	Tertiary: Wasatch Formation	Sept, 2005
Partial Record Stations:							
Mooney Draw near Mouth	Wildhorse Creek, tributary of Powder River	Ephemeral	1.8	3.4	21.45	Tertiary: Wasatch Formation	August, 2001
Hood Draw near Mouth	Pumpkin Creek, tributary of Powder River	Ephemeral	10.4	8.47	9.76	Tertiary: Wasatch Formation	May, 2002
Squaw Creek near Mouth	Clear Creek, tributary of Powder River	Ephemeral	13.59	10	13.44	Tertiary: Fort Union Formation	May, 2003

3.0 METHODS

Two types of monitoring stations have been installed in the study watersheds: Continuous Record stations and Partial Record stations.

3.1 CONTINUOUS RECORD STATIONS

Continuous Record (CR) stations were established on representative tributaries both with and without CBM development. These stations were established where high quality hydrograph data could be collected and linked to discrete water samples obtained during storm flow. The stations are equipped to provide continuous monitoring of stream discharge by measuring stream gage height (typically at 5 minute intervals) and to automatically collect discrete water samples over pre-set time intervals beginning when a specified discharge gage height is reached. At each station, a commercially available discharge gage-height monitoring unit using pressure-sensing transducer technology is electronically linked to an automatic water sampler containing a 24 bottle array maintained in a sealed housing. The automatic samplers are triggered during the rising limb of a storm discharge hydrograph when the water surface elevation in the stream channel reaches a preset height (high alarm setting) on the site staff gage. This preset height is separately determined for each monitoring site as the sum of the estimated staff-gage elevation of base flow (which may include consideration of drainage area above the gage) plus a small preset gage-height increment added to avoid spurious collection of chemical data. Discharge at and above the height of the point-of-zero flow is considered indicative of storm discharge (note that most monitored drainages are ephemeral and primarily have zero flow except for infrequent storm or snowmelt discharge). Once the automatic water sampler is activated, it collects 24 discrete water samples at pre-set time intervals between each bottle. Continuous power is provided at each gage site using solar panels with battery storage. A photograph of a typical CR station gage is provided in Figure 3.1-1.

The monitoring plan consisted of collecting a continuous gage-height hydrograph record year-round, to the extent practical and collecting samples of storm discharge during ice-out conditions. Operating the CR station equipment during winter is problematic due to ice-damming of stream channels and freezing of water sampling lines (see further discussion below). Generally, these stations were fully operational from early spring snowmelt to late fall ice-up (March through October). Surface flows in ephemeral NE Wyoming watersheds are rare during winter. To the extent that field conditions allowed, discharge measurements and water quality samples were obtained during significant storm runoff events. Water samples collected were retrieved as soon as possible after each event.

Figure 3.1-1. **Continuous Record station at LX Bar Creek near Mouth consists of shelter containing automatic discharge and water sampling equipment, solar panels leading to inside battery storage, buried sampling lines to creek channel, staff gage in creek channel and on-shore cantilever stage-height gage (not included with every CR station).**

Although spring snowmelt may constitute a significant proportion of total annual discharge for some study watersheds during the present drought cycle, operation of the automatic sampling equipment at CR stations was difficult during the freeze-thaw conditions in spring. Daily grab sampling for snowmelt discharge was attempted but was limited by insufficient field access at some gage sites. Consequently, collection of snowmelt discharge and chemistry data varied among study sites. Interpretation of snowmelt chemistry also presents difficulties regarding landscape interactions. Field observations indicate that surface runoff in stream channels during early snowmelt varies with time of day and commonly is a mixture of waters derived from direct melt-water inflow from snowfields, surface runoff over frozen soils and flow over frozen stream channels. The interactions between snowmelt and associated soils and sediments appear highly variable during snowmelt. Limited groundwater/surface water interactions also may occur during early snowmelt. For example, streamflows at some gage locations during early spring were observed to occur above a residual layer of thick anchor ice at the creek bottom suggesting little contact of flow with stream sediments and bank soils. Consequently, daily measurements of specific conductance of snowmelt discharge were highly variable and generally were much lower than those of storm discharge occurring later in the year suggesting limited contact with soils and sediments (Unpublished data, this study; see Sanders et al., 2007). Field observations also suggest that the chemistry of daily grab samples taken during snowmelt are highly dependent upon the individual sampling day within the spring snowmelt sequence and upon the time of day samples were collected.

Given the difficult field conditions encountered during winter and early spring, surface discharges resulting from intense rainstorms occurring in late spring through summer and fall are emphasized in this study. Significant discharges are characterized by peak flows exceeding 1 cfs above the point-of-zero flow estimated by standard hydrological techniques for each gage site.

3.2 PARTIAL RECORD STATIONS

A Partial Record (PR) station was established in each of three (3) ephemeral tributaries without CBM development where a reduced suite of monitoring data was deemed desirable. The purpose of the PR stations is to collect representative data for specific conductance versus storm discharge in non-CBM watersheds. This was accomplished using a stand alone, remote monitoring instrument with an integral data logger. The PR stations continuously record the hydrographic pressure (gage height) and specific conductance at a constant time interval. Sampling intervals generally were 10 minutes, but 5-minute sampling intervals were used for high frequency, short-duration storm discharge sites such as Headgate Draw (Table 2.2-1). These monitoring stations do not sample the bulk storm flow at timed intervals as do the CR stations but rely on bulk water collection by single-stage samplers at two (2) or more discrete gage heights. Single-stage samplers are designed to collect discharge at pre-set height intervals during a rising storm hydrograph. Figure 3.2-1 shows a typical PR station setup with v-notch weir, perforated plastic-pipe housing for the monitoring instrument (in this case an In Situ, Inc. Troll 9500), and single-stage samplers set at two (2) different gage heights.

The PR stations are checked approximately bi-weekly or as soon as practical if a storm discharge event occurred. The Partial Record stations were not operated during winter months to protect the instruments from damage due to freeze-thaw cycles.

Figure 3.2-1. Partial Record station (Squaw Creek near Mouth) consisting of In Situ, Inc. Troll remote sampler housed in a perforated pipe, two-level single-stage water sampler array, and v-notch trapezoidal weir with staff gage.

3.3 ANALYTICAL CHEMISTRY

All water samples were retrieved from the gage sites as soon as field conditions would allow after individual storm events (usually within one to several days). Upon collection, bulk, raw water samples were immediately transported in closed coolers to Energy Laboratories, Inc., Gillette, WY, (a U.S. Environmental Protection Agency certified analytical laboratory) for analysis using a standard chain-of-custody record procedure (CBM Associates, Inc., 2007). Laboratory analytical techniques used to determine concentrations of major ions followed methodologies approved by the U.S. Environmental Protection Agency, as required by the Wyoming Department of Environmental Quality.

3.4 DATA ANALYSIS

The statistical evaluations presented herein were developed using the standard statistical features of Microsoft EXCEL. The trilinear diagrams for comparison of water types and relative ionic strengths were generated using HydroChem software by RockWare, Inc. Hydrologic parameters, such as peak discharge and total volume of discharge for a given storm flow event, were calculated according to standard procedures developed by the USGS as outlined in Section 3.5.

3.5 EQUIPMENT MAINTENANCE AND MEASUREMENT ERROR

A detailed overview of quality assurance information for the CR and PR stations will be presented separately as an addendum to this report. Quality assurance procedures for routine water sample collection in the field were established by CBM Associates, Inc. (2007). Similar protocols for quality assurance procedures associated with stream discharge measurements including use of current meters and CR station hydrograph monitors were prepared by Lowham Engineering, LLC (updated versions: Ibek and Druse, 2006a and b). A brief overview of station inspection and maintenance activities and estimates of measurement error associated with operation of the sampling equipment that were conducted during the course of the study is as follows. For the CR stations, individual gages were inspected approximately bi-weekly during the sampling season. Maintenance was performed as required on the gage housing, solar panels, sampling lines, and sampling equipment. Results of bi-weekly inspections and all maintenance activities were recorded in permanent field logs for each gage site. Results of inspections and maintenance were used to assess data quality at the end of each water year. PR stations were similarly inspected and repaired as required on two to three week intervals during the sampling season.

<u>Measurement Error Associated with Stream Discharge Records at CR and PR Stations</u>

The gage-height hydrograph monitoring equipment (pressure-sensing bubbler units on CR stations and pressure transducer units on PR stations) are pre-calibrated by the manufacturer and do not require further calibration. The accuracy of stream discharge data from the CR stations was checked in the field during streamflow periods by conducting outside staff gage readings in conjunction with simultaneous bubble unit readings inside the gage house. Agreement was generally within 0.01 ft. Any significant discrepancies between these two measurements was used in annual (internal) Stage Analysis reports to provide corrections, if needed, to the final individual storm hydrographs and Daily Discharge Tables developed each year for each CR gage and used in the analyses for this report (see further discussion below). The Troll instruments were refurbished annually by the manufacturer which included recalibration of the pressure transducer units. Annual calibration checks for the Troll transducers was conducted in the laboratory using a small water tower after instruments were removed from the field each fall. Calibration drifts were negligible during the sampling season and no corrections were applied to the field stage height data (see further discussion below).

<u>Current Meter Discharge Measurements:</u>

A wading discharge measurement is most commonly used at the CR network gages. The appropriate meter, either a Price AA or a Pygmy, is selected based on discharge depth and velocity. Accuracy of the discharge measurement is affected by cross-section site selection—preferably, the monitored reach is straight with a uniform and smooth bed, velocities are uniform without upstream disturbance or turbulence, and flowlines are parallel and perpendicular to the cross-section. Subsection widths, where depths and velocities are measured, are determined so that each subsection ideally has 5% or less of the total flow. After the measurement is complete, the above factors must be considered before assigning accuracy to the measurement. If the hydrographer estimates that the measurement is within 2% of the actual discharge, the measurement is considered excellent, 5% is considered good, 8% is considered fair, and more than 8% is considered poor. An average gage height is determined for the discharge measurement.

Indirect Measurements of Peak Discharge:

The CR and PR stations are not equipped with peak flow measuring structures (separate from the bubble and transducer units). High flow discharges associated with flood peaks were determined by theoretical means. Typically, an indirect measurement of peak discharge is done using the slope area method. The method includes (1) recording and surveying highwater marks left by the flood; (2) surveying three or more cross sections of the channel during some stage of the flood if possible; and (3) selecting an appropriate roughness coefficient for the channel. These data are used in adaptations of the Manning equation, and a peak discharge is computed. The accuracy of the indirect measurement is affected by the hydraulic features of the channel reach surveyed—uniformity, straightness, and quality of the high-water marks. Accuracy is evaluated from analysis of channel hydraulics and comparison of discharges computed for each channel subreach. A good indirect estimate has favorable hydraulic conditions and is considered to have less than 10% possible error, 10% error is considered fair, and 25% or more is considered poor. A maximum discharge gage height is determined from the gage record and the surveyed high-water marks.

Step Backwater Computations:

A step backwater survey is another method used in this study to determine the gage height (water surface elevation) for a given storm discharge. This method uses the same theoretical procedures as with the slope area method discussed above with indirect measurements, except that instead of solving for discharge, the method assumes a discharge and solves for the water surface elevation at each cross section.

Gage Height:

Each gaging station is equipped with either a bubbler system or pressure-sensing transducer and data logger that records the water surface elevation (gage height) above a fixed orifice elevation. An outside gage is used to verify observed versus recorded maximum gage height of a storm discharge and to compare instantaneous measurements made by the hydrographer during storm flow. The location of the gaging station is an important factor in the accuracy of a discharge record. The preferable location is where the hydraulic features that control the stage at the gage are stable. That is, for a given discharge, the gage height will stay the same through time. However, in a channel with a natural control, changes can occur because of scour and fill of the channel, trash accumulation, changes in bank vegetation, beaver activity, as well as human-caused changes. Any apparent site-specific effects of channel changes on the accuracy of the gage-height data versus flow estimate are noted by the hydrographer, and appropriate adjustments made to the discharge estimates for each significant flow event.

The elevation of the pressure-transducer orifice also can change because of flood damage or heaving during the winter. To determine that elevations of the orifice and outside gage remain at datum, station levels are surveyed at least annually or when site inspection reveals apparent damage.

Quantitative Gage Height Versus Discharge Relation:

The gage height versus discharge relation provides the basis for computation of the discharge record. In determining this relation, accuracy is improved by having discharge measurements over a wide range of gage heights and by giving the most weight to the most accurate measurements of discharge and associated gage height. The relation, if developed using arithmetic scales, plots as a parabola. Accuracy is generally improved by using semi-logarithmic scales where the relation will plot nearly as a straight line. Generally, current meter measurements are given the most weight when developing this relation, followed by slope area measurements of peak discharge, and then step backwater computations.

The discharge record is computed by assigning discharge to each time interval of the flow record (e.g., each 5-minute interval). Integrating the results over a 24-hour period yields mean daily discharge. If discharge measurements indicate a departure from the gage height versus discharge relationship because of changed channel conditions which control the gage height, a shift is determined to compensate and correct the recorded gage height so that a corrected discharge can be computed. Consequently, the overall accuracy of a discharge record is affected by the accuracy of and interactions among the measured discharge, the associated gage height, and the recorded gage height record.

Overall, gaging stations that have had the gage height versus discharge relation validated by current meter measurements produce records of good to fair accuracy; those relying mostly on theoretical means (indirect measurements or step backwater) produce records of fair to poor accuracy.

Bulk Water Samples Retrieved from Gage Sites:

The collection of discrete, bulk water samplers by automatic sampling devices was followed using standard methods devised for each automatic sampler by the manufacturer. A standard protocol was used for sample bottle cleaning and storage prior to installation in the automatic water samplers (CBM Associates, Inc. 2007). The collection bottles (with caps) are acid washed, rinsed with de-ionized water, and stored in an onsite closed cooler before use. While installed in the automatic samplers, the sample bottles are protected by the sealed housing of the sampling device, which is inside the gage shelter. Visual inspections of the sampling bottle arrays were made periodically, but opening the sealed sampling units too frequently was avoided. The primary concern was dust contamination of the open bottles during storage in the sampling units while waiting (sometimes prolonged) for the next storm sampling event. Because storm runoff from the landscape of NE Wyoming is typified by high ionic strength discharge (see Section 5) combined with considerable sediment transport, unavoidable small amounts of dust contamination should have only a small effect on total ionic strength of the storm discharge solutions. To test this assumption, field blanks containing de-ionized water were left in the automatic samplers at various gage shelters on several occasions and collected after one to several weeks. In addition, de-ionized water rinses of other randomly-selected sample bottles (having resided in automatic devices for several weeks) also were collected. Both of these types of field blanks acquired: (1) very low specific conductance (on order of 2 μS/cm); (2) low total dissolved solids (TDS) of less than 10 mg/L (analytical laboratory reported detection limit); (3) major ion concentrations less than the analytical laboratory quantitation limit; and (4) only microgram amounts per liter, if any, of trace metals. For example, an extended field blank study at five (5) CR gage sites conducted over six (6) consecutive weeks with weekly sampling found that contamination of sample bottles sitting in the automatic samplers was negligible for either dry bottles (normal wait-state) or for bottles containing de-ionized water over the 6-week period. Based on these field studies, there is no indication that contamination of sample bottles before storm water collection is a problem regarding the accurate chemical characterization of storm flow.

As previously discussed, bulk water samples also were collected by single-stage sampling devices (see Figure 3.2-1). These samplers are exposed to the weather during zero-flow periods and are replaced with clean bottles every few months. Observations of sampler functioning indicate that a considerable amount of sediment is commonly entrained during filling of the samplers during the rising limb of a storm hydrograph. The entrained sediment should render insignificant any small levels of dust accumulation in these samplers during the zero-flow wait periods.

Specific Conductance Measurements at PR Stations using Troll Instruments:

The specific conductance (commonly referred to as electrical conductance or EC; specific conductance is EC normalized to 25 degrees Celsius) probes in the Troll units used at the PR gage sites were calibrated against a known, traceable solution (1413 µS/cm) according to instrument instructions. During field visits, occurring at 2 to 3 week intervals and before cleaning or any maintenance of the instrument, the calibration of the EC probe was checked against two known, traceable EC standards (1,413 and 4,500 µS/cm solutions). Calibration accuracy was found to be stable within +/- 5% (commonly within +/- 1 to 2%). Calibration stability is likely attributable in part to the instrument sitting in dry air for most of the monitoring period. The only significant problem encountered in the field was from insects nesting in the Troll instrument; this problem was solved by placing a fine mesh screen over the flow ports, which allowed storm flow to enter but not small insects. The Troll EC probes used in the field had approximately the same measurement error of independent measurements taken by the analytical laboratory (Energy Laboratories, Inc.) on aliquots of the same calibration solutions (range of near zero to +/- 3% to 4%) on the day of each field visit to the PR stations. Following field calibration checks, the Troll instruments were cleaned with de-ionized water and compressed air and then reset into the gage sites. Re-calibration against the 1,413-µS/cm standard was done if instrument calibration had drifted to +/-5% or greater.

4.0 RESULTS

As briefly discussed in Section 3, difficulties were encountered when trying to monitor streamflow during the winter ice-in and spring snowmelt periods. Access to the remote gage sites during early spring mud conditions and inconsistent operation and accuracy of the automatic sampling devices proved problematic. Neither the automatic streamflow instruments nor the water sampling instruments could be operated effectively during the freeze-thaw conditions of early spring and not at all during winter. For example, ice-damming of stream channels rendered winter and spring hydrographs inaccurate and water intake lines were frozen which precluded water sampling. While it is useful to evaluate the hydrology and chemistry of snowmelt discharge, results of this study are focused primarily on spring through fall (the sampling season) storm flow data that are the most accurate measurements obtained. This sampling period likely constitutes the majority of solute yield from the monitoring watersheds during the multi-year period of record. Storm flow data are summarized below and discussed in detail in Section 5.

4.1 CONTINUOUS RECORD STATIONS

By the end of the 2006 water year (October 1, 2006), 13 CR stations had been established in 10 drainages in the PR Basin study area. Beginning in the late 2001 water year, 41 storm flow events were recorded at the CR stations. The 2001 and 2002 events are detailed in Sanders et al. (2003). The 2003 through 2006 events are described in this report; however, data and important observations from the 2001 and 2002 events are also included in analyses presented in this report for completeness of study findings to date. Overviews of individual storm discharge hydrographs and observed chemistry are provided in Appendix B. Yearly hydrograph summary information by watershed is provided in Appendix C and detailed chemistry data is provided in Appendix D. No significant storm events occurred at two (2) CR stations (Nine Mile Creek near Mouth and LX Bar Creek above Kline Draw) since installation. The Nine Mile Creek near Mouth gage is relatively new, having been established in September 2005, (Table 2.2-1).

A summary of all significant storm flow events observed from 2001 through 2006 water years is provided in Table 4.1-1. This table contains only non-snowmelt flow events with peak discharges greater than 1 cfs relative to the point-of-zero flow estimates for each gage site and which were deemed to be significant discharges relative to landscape flushing. During the 2001 through 2006 period of record, significant storm flow events were observed throughout most of the monitoring network.

Table 4.1-1. Significant storm flow events in study watersheds recorded at Continuous Record stations, 2001–2006 water years.
[Note that 2001 was an incomplete monitored year and that there were smaller flows generally less than 1 cfs peak discharge, primarily associated with snowmelt, which are not included in this table.]

Drainage	Event Date	Days Between Flows	Peak Discharge (cfs)
Barker Draw	8/22/2002	>450	23.0
Barker Draw	8/27/2002	5	11.0
Barker Draw	4/21/2005	968	16.0
Barker Draw	5/8/2005	17	2.0
Barker Draw	5/23/2006	380	3.2
Bloom Creek	7/4/2004	>350	12.0
Bloom Creek	7/5/2004	1	15.0
Bloom Creek	8/3/2004	29	82.0
Bloom Creek	6/11/2005	312	13.0
Bloom Creek	6/26/2005	15	48.0
Bloom Creek	7/2/2005	6	87.0
Bloom Creek	8/18/2005	47	9.7
Bloom Creek	10/5/2005	48	22.0
Bloom Creek	6/20/2006	258	6.4
Coal Gulch	7/22/2005	>425	481
Coal Gulch	7/31/2005	9	567
Coal Gulch	8/12/2006	377	306
Dry Fork	8/26/2006	>325	671
Nine Mile Creek		>450*	
Flying E Creek	4/21/2005	>425	2.7
Flying E Creek	5/11/2005	20	25.0
Flying E Creek	7/22/2005	72	190
Flying E Creek	7/31/2005	9	297
Flying E Creek	6/9/2006	313	31.0
Hay Creek Hwy 59	6/16/2003	>650	36.0
Hay Creek Hwy 59	7/13/2004	393	1080.0
Hay Creek Hwy 59		>850**	
Hay Creek at mouth	6/1/2002	>225	22.0
Hay Creek at mouth	6/13/2003	377	292.0
Hay Creek at mouth	7/13/2004	396	991.0
Hay Creek at mouth	4/23/2005	284	6.9
Hay Creek at mouth	5/11/2005	18	17.0
Hay Creek at mouth	6/9/2006	394	2.7
Headgate Draw	5/18/2004	>30	14.0
Headgate Draw	6/30/2004	43	32.0
Headgate Draw	7/2/2004	2	183.0
Headgate Draw	7/23/2004	21	253.0
Headgate Draw	7/28/2004	5	87.0
Headgate Draw	6/7/2005	314	15.0

Table 4.1-1 - Continued

Drainage	Event Date	Days Between Flows	Peak Discharge (cfs)
Headgate Draw	6/24/2005	17	4.2
Headgate Draw	7/31/2005	37	7.1
Headgate Draw	7/1/2006	335	7.0
Headgate Draw	8/12/2006	42	26.0
LX Bar near Mouth	7/5/2004	>475	2.9
LX Bar near Mouth	5/11/2005	310	7.2
LX Bar near Mouth	6/9/2005	29	13.0
LX Bar near Mouth	10/9/2005	123	12.0
LX Bar near Mouth	6/23/2006	256	5.1
LX Bar above Kline Draw		>1200*	
Pumpkin Creek Iberlin	7/11/2001	>57	120.0***
Pumpkin Creek Iberlin	8/24/2002	409	293.0
Pumpkin Creek Iberlin	5/27/2003	275	160.0
Pumpkin Creek Iberlin	6/16/2003	20	1580.0
Pumpkin Creek Iberlin	8/12/2005	789	44.0
Pumpkin Creek near Mouth	8/21/2002	>450	25.0
Pumpkin Creek near Mouth	8/28/2002	7	705.0
Pumpkin Creek near Mouth	3/14/2003	****	---
Pumpkin Creek near Mouth	5/28/2003	272	29.0
Pumpkin Creek near Mouth	6/17/2003	20	222.0
Pumpkin Creek near Mouth	5/17/2005	701	15.0
Pumpkin Creek near Mouth	8/10/2005	85	7.0

* From date of gage installation to end of 2006 Water Year
** From date of last significant flow event to end of 2006 Water Year
*** Peak discharge estimate only; no hydrograph or chemistry data available
**** Was substantial snowmelt discharge but not a storm flushing event

Flow-weighted water chemistry calculated for each significant flow event from 2001 through 2006 water years is summarized in Table 4.1-2. Summary statistics across all events at CR stations are presented in Table 4.1-3. The values listed are based on the entire approximated flow volumes and cumulative calculated solute loads. Discharge for an event that continued beyond the time period encompassed by water samples collected was assumed to have water chemistry values equal to those from the last water sample obtained during the event. Storm discharge volume occurring after the final water quality sample was obtained was usually small compared to earlier discharge. Although the final water quality sample may not be representative of the entire trailing limb of the storm hydrograph, the weighted contribution of this subsequent discharge to event average solute concentrations usually was small as well. This calculation procedure, however, does allow for a potential source of bias for some events. The significance of the storm discharge chemistry data in relation to discharges of CBM-produced waters is discussed in Sections 5.3 and 5.4.

Table 4.1-2. Summary of flow-weighted water chemistry for all recorded storm flow events at Continuous Record stations, 2001–2006 water years.

Station	Event Start Date	Duration (hours)	Peak discharge (cfs)	Mean discharge (cfs)	Total flow volume (acre-feet)	Flow weighted mean EC (uS/cm)	Flow weighted mean TDS (mg/L)	Flow weighted pH (standard units)*	Flow weighted mean SAR**	Flow weighted mean sodium (mg/L)	Flow weighted mean sodium (meq/L)	Flow weighted mean calcium (mg/L)	Flow weighted mean calcium (meq/L)	Flow weighted mean magnesium (mg/L)	Flow weighted mean magnesium (meq/L)	Flow weighted mean potassium (mg/L)	Flow weighted mean bicarbonate (mg/L)	Flow weighted mean sulfate (mg/L)	Flow weighted mean chloride (mg/L)	Total event TDS load (kg)	Total event sodium load (kg)
Barker Draw	August 21, 2002	14.8	23.0	7.8	9.5	1366	1135	7.50	0.5	28.6	1.2	196.2	9.8	39.0	3.2	13.4	95.8	682.3	4.2	13276	334
	August 27, 2002	35.3	11.0	4.5	13.1	1182	894	8.00	1.2	62.5	2.7	121.8	6.1	42.6	3.5	11.3	146.8	536.1	6.5	14314	1000
	April 22, 2005	71.5	16.0	2.6	15.4	3844	3332	8.17	4.1	383.9	16.7	206.2	10.3	283.2	23.3	15.1	509.7	2099.3	15.8	63012	7258
	May 8, 2005	245.8	2.0	0.4	8.7	5156	4817	8.20	4.8	523.3	22.8	250.8	12.5	394.8	32.5	16.3	577.1	2879.8	21.9	51410	5584
Bloom Creek	June 11, 2005	30.0	12.0	1.4	3.6	656	470	7.84	1.1	38.7	1.7	55.4	2.8	22.3	1.8	7.3	86.5	251.0	2.5	2048	169
	June 26, 2005	25.3	48.0	2.2	4.7	1250	980	7.37	0.9	51.3	2.2	141.8	7.1	51.9	4.3	11.0	127.4	592.0	4.2	5635	295
	July 2, 2005	38.9	87.0	4.0	12.9	772	569	7.34	0.8	32.4	1.4	84.4	4.2	30.4	2.5	8.9	125.6	290.7	2.7	8958	511
	August 18, 2005	19.7	9.7	1.1	1.7	768	583	7.50	0.7	29.9	1.3	80.0	4.0	29.3	2.4	8.7	103.0	297.9	2.4	1243	64
	October 5, 2005	137.3	22.0	0.6	7.2	418	296	7.33	0.6	22.2	1.0	68.0	3.4	14.1	1.2	9.0	68.0	135.2	2.0	2619	197
	June 20, 2006	25.4	6.4	0.8	1.7	1184	970	7.38	0.9	48.4	2.1	136.2	6.8	50.9	4.2	11.4	121.8	528.2	2.3	1992	99
Coal Gulch near Mouth	August 12, 2006	12.8	306.0	32.5	34.8	1548	1388	6.98	0.4	24.8	1.1	291.0	14.5	36.9	3.0	15.5	108.2	818.0	4.8	59074	1058
Dry Fork near Mouth	August 26, 2006	15.9	671.0	58.3	77.2	257	158	7.02	0.6	12.2	0.5	27.8	1.4	4.2	0.3	6.7	100.0	44.6	0.2	14930	1156
Flying E Creek near Mouth	April 22, 2005	44.8	2.7	0.2	0.8	391	282	7.60	4.4	66.0	2.9	13.4	0.7	2.4	0.2	8.2	208.2	25.3	6.4	276	65
	May 11, 2005	41.8	25.0	4.5	15.7	406	294	7.43	0.9	23.6	1.0	38.1	1.9	7.2	0.6	6.6	79.9	118.0	1.9	5668	455
	June 9, 2006	30.3	31.0	1.5	3.8	1255	1071	7.23	0.8	43.9	1.9	208.7	10.4	31.2	2.6	14.2	89.9	631.2	5.8	5000	205
Hay Creek at Mouth	June 1, 2002	123.0	22.0	10.2	104.7	2855	2394	8.27	3.3	269.4	11.7	198.8	9.9	179.4	14.8	14.0	449.1	1387.0	14.0	306905	34542
	July 13, 2004	145.5	991.0	75.1	909.6	306	158	6.78	1.1	23.6	1.0	18.6	0.9	9.3	0.8	7.4	54.9	92.8	2.6	176126	26307
Hay Creek Hwy 59 ‡	June 16, 2003	370.2	36.0	9.0	276.9	832	530	7.88	1.3	53.6	2.3	53.3	2.7	43.3	3.6	6.9	90.6	322.3	3.0	179607	18163
	July 13, 2004	55.3	1080.0	21.2	97.4	244	151	6.77	0.5	11.2	0.5	22.9	1.1	7.1	0.6	6.3	61.0	61.5	4.0	18027	1333
Headgate Draw	June 30, 2004	7.3	32.0	3.4	2.1	1771	1601	7.01	0.5	34.2	1.5	301.9	15.1	45.8	3.8	15.2	128.9	928.7	3.1	4021	86
	July 23, 2004	15.3	253.0	13.1	16.7	1247	1091	7.42	0.2	13.6	0.6	231.0	11.5	25.1	2.1	8.2	78.0	633.1	0.5	22358	279
	July 28, 2004	11.4	87.0	7.7	7.3	1087	875	7.42	0.2	10.2	0.4	186.3	9.3	20.3	1.7	6.0	82.0	529.2	0.1	7800	91
	June 7, 2005	15.1	15.0	1.0	1.3	1912	1751	7.49	0.7	50.8	2.2	319.9	16.0	65.7	5.4	9.7	91.1	1112.5	3.0	2815	82
	June 24, 2005	2.2	4.2	0.9	0.2	1279	1076	7.11	0.4	25.5	1.1	211.4	10.5	35.9	3.0	8.4	107.5	639.5	3.7	212	5
	July 31, 2005	3.7	7.1	1.3	0.4	1031	845	7.33	0.4	19.0	0.8	177.5	8.9	26.6	2.2	11.8	90.9	480.6	2.0	416	9
	July 1, 2006	9.3	7.0	1.4	1.1	1734	1649	6.90	0.4	30.2	1.3	312.0	15.6	48.7	4.0	16.0	107.0	953.9	4.5	2250	41
	August 12, 2006	7.9	26.0	2.6	1.7	1453	1298	7.01	0.3	16.8	0.7	274.6	13.7	33.3	2.7	14.9	107.0	752.1	2.7	2701	35
LX Bar Creek near Mouth	July 5, 2004	38.3	2.9	0.3	1.0	2957	2393	7.59	6.3	403.0	17.5	120.1	6.0	116.4	9.6	19.4	110.6	1501.8	6.5	3035	511
	May 11, 2005	111.4	7.2	2.8	25.9	3065	2091	8.19	13.4	667.0	29.0	42.0	2.1	88.1	7.2	9.4	1155.8	778.0	10.1	66263	21133
	June 9, 2005	157.9	13.0	3.6	47.0	2174	1665	8.02	4.1	247.0	10.7	103.4	5.2	100.9	8.3	15.9	341.8	912.8	9.6	95917	14231
	October 9, 2005	61.5	12.0	1.9	9.8	1832	1291	8.26	7.1	310.7	13.5	63.4	3.2	48.6	4.0	9.7	587.6	502.9	9.2	15468	3722
‡ ‡	June 23, 2006	10.5	5.1	1.9	1.6	2662	1798	8.92	25.1	664.2	28.9	12.0	0.6	24.9	2.0	10.2	1317.8	244.1	17.6	3609	1333
Pumpkin Creek at Iberlin Ranch	August 24, 2002	188.9	293.0	10.6	167.3	540	364	7.64	2.1	54.2	2.4	34.7	1.7	9.5	0.8	5.4	96.6	188.1	2.8	74603	11107
	May 27, 2003	70.5	160.0	12.8	75.3	2378	1847	7.73	6.5	345.2	15.0	119.9	6.0	58.6	4.8	8.6	147.3	1144.0	6.7	170242	31822
	June 16, 2003	172.4	1580.0	42.1	603.7	542	303	7.62	2.1	55.8	2.4	37.5	1.9	9.4	0.8	5.4	121.6	149.0	1.6	224109	41230
	August 12, 2005	32.8	44.0	2.5	6.8	389	298	7.61	1.0	26.1	1.1	38.7	1.9	8.3	0.7	6.1	90.5	118.7	2.0	2486	218
Pumpkin Creek near Mouth	August 21, 2002	17.8	25.0	0.6	1.0	1154	930	7.42	1.0	51.0	2.2	157.9	7.9	25.8	2.1	10.6	156.5	522.7	4.0	1085	59
	August 28, 2002	88.9	705.0	37.2	275.2	1135	795	8.01	5.1	170.4	7.4	55.0	2.7	17.8	1.5	9.7	295.1	348.1	5.5	268020	57454
	May 28, 2003	87.5	29.0	6.3	46.2	4521	3555	8.29	10.8	739.5	32.2	149.9	7.5	124.8	10.3	18.8	677.7	1975.1	18.8	201229	41866
	June 17, 2003	237.5	222.0	33.2	655.3	880	599	7.83	2.3	90.0	3.9	49.8	2.5	15.5	1.3	8.4	150.0	304.1	3.3	480731	72210
	August 10, 2005	72.1	7.0	1.2	7.4	3089	2363	8.29	10.8	538.7	23.4	90.5	4.5	59.7	4.9	22.2	554.0	1189.0	17.2	21338	4864

* Flow weighted event average pH values are based on calculated hydrogen ion activities.

** Flow weighted event average SAR values are calculated using respective average sodium, calcium, and magnesium values.

‡ Recorded values represent one channel of a split flow. Estimated event peak discharge for all flow channels combined was 440 cfs. No other data exists for other channels of this split flow.

‡‡ For this event, estimated base flow discharge was subtracted from all calculations of flow weighted average water chemistry.

Table 4.1-3. Summary statistics for flow-weighted event water chemistry at Continuous Record stations, 2001–2006 water years.

	Duration (hours)	Peak discharge (cfs)	Mean discharge (cfs)	Total flow volume (acre-feet)	Flow weighted mean EC (uS/cm)	Flow weighted mean TDS (mg/L)	Flow weighted pH (standard units)*	Flow weighted mean SAR**	Flow weighted mean sodium (mg/L)	Flow weighted mean calcium (mg/L)	Flow weighted mean magnesium (mg/L)	Flow weighted mean potassium (mg/L)	Flow weighted mean bicarbonate (mg/L)	Flow weighted mean sulfate (mg/L)	Flow weighted mean chloride (mg/L)	Total event TDS load (kg)	Total event sodium load (kg)
Minimum	2.2	2.0	0.2	0.2	244	151	6.77	0.2	10.2	12.0	2.4	5.4	54.9	25.3	0.1	212	5
Maximum	370.2	1580.0	75.1	909.6	5156	4817	8.92	25.1	739.5	319.9	394.8	22.2	1317.8	2879.8	21.9	480731	72210
Median	38.3	25.0	2.8	9.5	1247	980	7.50	1.5	50.8	119.9	33.3	9.7	110.6	529.2	4.0	13276	511
Weighted Averages:																	
All events	70.8	169.2	10.4	86.7	856	598	7.21	2.5	92.2	52.6	26.2	8.0	150.1	319.7	3.8	63435	9785
Baseline drainages	24.9	44.0	3.0	4.5	1031	850	7.35	0.5	25.6	159.8	29.2	9.1	96.6	483.8	1.9	4648	140
CBM Developed drainages	94.6	234.1	14.3	129.3	853	593	7.20	2.6	93.4	50.7	26.1	8.0	151.0	316.8	3.8	93917	14786

* pH averages are based on calculated hydrogen ion activities from each event.

** SAR averages were calculated using respective average sodium, calcium, and magnesium values.

4.2 PARTIAL RECORD STATIONS

Three Partial Record stations were established in baseline drainages (no CBM development) to measure discharge and specific conductance during surface flow events. These were in operation at the end of the 2006 water year. Earlier, two (2) additional PR stations (LX Bar Creek and Flying E Creek) were briefly operated to develop comparative data with Continuous Record gages but success was limited due to field conditions; all significant storm flows observed at these sites are included herein as CR station data only (Tables 4.1-1 through 4.1-3 above). A Partial Record station was originally installed on Headgate Draw in 2002; however, due to the high number of observed storm flows, a Continuous Record station was also added to this site in 2004. The CR and PR stations on Headgate Draw remained active through the 2006 water year. Comparative data obtained from these paired stations will be presented in an addendum to this report.

Storm flows at PR stations from 2001 and 2002 have been reported elsewhere (Sanders et al., 2003), including detailed descriptions and graphical representations of those events. Descriptions and graphical representation of 17 additional storm flows recorded at PR stations from 2003 through 2006 water years are given In Appendix B. To facilitate comparisons, the same scaling of plots was used for all events occurring within the same drainage, where possible.

Table 4.2-1 provides summary information on the observed storm events recorded at PR stations. The significance of these data is evaluated in Section 5.4.

Table 4.2-1. Summary of all storm flow events recorded at Partial Record stations. [Total dissolved solids values are based on derivations from recorded specific conductance using drainage-specific conversions; see Section 5.4.5 for further explanation.]

Station	Event Start Date	Duration (hours)	Peak discharge (cfs)	Mean discharge (cfs)	Total flow volume (acre-feet)	Peak EC (uS/cm)	Flow weighted mean EC (uS/cm)	Flow weighted mean TDS (mg/L)	Total event TDS load (kg)
Mooney Draw	August 7, 2002	10.7	>10.4*	1.51	1.34	1513.0	1357	1140	1868.8
	August 21, 2002	11.3	>10.4*	0.92	0.87	2063.0	600	504	537.3
	August 26, 2002	2.3	0.2	0.05	0.01	577.0	452	380	4.6
	August 27, 2002	12.3	1.5	0.17	0.17	951.0	303	254	53.1
	August 7, 2006	11.8	7.4	1.02	1.01	1221.0	1081	908	1122.1
Hood Draw	July 20, 2002	20.7	5.0	0.53	0.91	568.0	395	26	29.0
	** September 30, 2004	1.3	<0.22**			201.0			
	August 10, 2005	4.5	0.7	0.07	0.03	310.0	262	173	5.5
	August 16, 2005	13.0	3.8	0.04	0.04	403.0	332	219	11.4
Squaw Creek	May 16, 2004	17.0	9.0	0.92	1.31	1194.0	1106	807	1294.0
	August 3, 2004	16.8	3.7	0.41	0.57	1259.0	725	530	372.5
	June 26, 2005	20.0	16.3	1.18	1.96	1111.0	813	594	1424.8
	August 10, 2005	20.0	40.9	3.09	5.14	1257.0	808	590	3715.1
	August 16, 2005	1.5	0.1	0.04	<0.01	556.0	390	284	1.7
	August 18, 2005	4.8	0.3	0.09	0.04	588.0	449	328	14.8
	October 9, 2005	2.8	0.2	0.06	0.02	357.0	340	248	4.6
Headgate Draw ***	July 6, 2002	2.7				2779.0			
	July 21, 2002	8.0				2542.0			
	July 26, 2002	20.7				1728.0			
	August 21, 2002	11.8				2519.0			
	August 27, 2002	4.2				2112.0			
	June 12, 2003	0.3				873.0			
	June 17, 2003	9.0				1150.0			
	June 24, 2003	9.3				1210.0			
	August 12, 2003	9.3				2725.0			
	September 10, 2003	2.5				1883.0			
	May 18, 2004	1.2				2003.0			
Summary Statistics‡									
	Minimum	0.3	0.1	0.0	0.0	201.0	261.6	26.0	1.7
	Maximum	20.7	40.9	3.1	5.1	2779.0	1357.4	1140.2	3715.1
	Median	9.3	3.7	0.4	0.7	1210.0	452.2	379.9	53.1
	Weighted averages	9.3	6.9	0.7	1.0	1320.5	857	637	697.3

* Recorded gage height for these events exceeded the maximum gage height for which a discharge rating was available.

** Recorded gage height for this event was less than the minimum gage height for which a discharge rating was available. Discharge-dependent parameters could not be calculated for this flow.

*** An accurate discharge rating curve is not available for the Headgate Draw station. Discharge-dependent parameters could not be calculated for flows at the Headgate Draw Partial Record Station.

‡ Summary statistics other than those for Event Duration and Peak EC include only events for which discharge-dependent parameters were available.

5.0 DISCUSSION

5.1 HYDROLOGY OF STUDY WATERSHEDS

The surface hydrology of the Powder River Basin is highly variable due to large differences in local topography and precipitation. Thus, streamflows are highly variable in location and time. Streams in the Bighorn Mountains on the western side of the PR Basin are well-known prime trout fisheries, and their waters are a vital source of irrigation for ranches. Streams in the central and eastern plains are generally dry during most of the year, and reservoirs commonly are constructed to store the sporadic flows for livestock use. The essence of runoff in the plains is vividly described by Marc Reisner (1993) in his book, Cadillac Desert. During the drought and depression of the 1930s (Figure 2.1-3), Floyd Dominy (who later became Commissioner of the U.S. Bureau of Reclamation) directed a program for the Agriculture Department to construct reservoirs in Campbell County, WY, which is part of the study area. As a county agent, he oversaw construction of 300 dams to store the runoff that occasionally pours down the creeks. According to Dominy (Reisner, 1993, p. 217-218):

> "I said to myself, 'It's stupid to let a drop of that stuff escape. We've got to capture that water.'… 'We had a drought, grasshoppers, crickets. I tell you it was something else. It looked as if nothing could live. Under the federal regulations, five thousand cattle were to be bought in the whole state of Wyoming. Fifty thousand were dying in Campbell County alone"… "I said to the farmers, 'You capture that water and at least your cows won't die of thirst.'"

5.1.1 Perennial Streams

Streams that have headwaters in the Bighorn Mountains generally are perennial and are the sources of most of the runoff leading to flow in the mainstem Powder River. Average annual runoff in the mountains exceeds 200 acre ft per square mile (Lowry and others, 1986). Several major streams (such as Piney, Clear, and Crazy Woman Creeks; and North Fork Powder and Middle Fork Powder Rivers); originate in the mountains and flow across the plains. Runoff in these streams is mainly from snowmelt that occurs during May and June. By late July and August, most of the snow has melted and evapotranspiration rates have increased, causing a substantial decrease in streamflow during the summer (Druse and others, 1988). More than 90% of the total water use in the Basin is for irrigation, usually for hayfields, along the stream channels (Lowry and others, 1986).

5.1.2 Ephemeral Streams

Streams that originate in the plains generally are ephemeral and flow mainly in response to local snowmelt and rainfall runoff. Average annual runoff in the plains is less than 10 acre ft per square mile for much of the Basin (Lowry and others, 1986). Plains streams usually have short periods of high runoff separated by long periods of little or no flow (Wahl, 1970). Runoff rarely occurs during October through January. Runoff during February through April is generally from snowmelt. Snowfall in the plains is largely sublimated by the wind and sun, and the remaining snowpack occurs mainly as drifts in draws and shaded areas (Lowham, 1988). Runoff during May through September is generally from convective storms (thunderstorms). Precipitation during thunderstorms is often intensive, and can result in large floods from tributaries having relatively small drainage areas. Figure 5.1-1 shows a runoff event in North Prong Dead Horse Creek, which was the result of a thunderstorm that occurred in 2001 on only part of the upstream drainage.

Figure 5.1-1. Thunderstorm runoff in North Prong Dead Horse Creek; view is downstream.

5.1.3 Streamflow Data

Several different types of monitoring equipment are used for collecting streamflow data, depending on the purpose and expected use. For design of bridges and culverts, only peak-flow data may be required, but a gage that transmits an alert that flow is occurring may be needed to comply with environmental regulations. Relatively inexpensive PR station equipment that records the maximum flood stage or that transmits an alert of a rising stage is used to collect these types of data. Additional equipment is needed when continuous-flow data are required. As previously discussed, a CR streamflow gaging station has a recorder that tracks and records the stage in the stream. Using discharge measurements for the site, a stage-discharge relation is developed to enable discharge to be determined for any stage of the stream. A continuous record of discharge can then be determined by combining the rating with the record of stage. The discharge or volume for any time can then be determined.

5.1.4 Occurrence and Nature of Flows in the Plains

Before streamflow monitoring equipment was installed in the study watersheds beginning in 2001, very few CR streamflow gaging stations were operated on ephemeral streams in the plains area of the Powder River Basin. The USGS operated a CR station on Dead Horse Creek (station number 06313700) during 1972-90 and 2001 water years. This is the longest continuous-flow record available for any ephemeral stream in the Basin and is representative of ephemeral stream hydrology of other watersheds monitored in this study. The annual runoff varied from 19.6 acre ft (0.13 acre ft per square mile) in 1988 to 7,695 acre ft (51.0 acre ft per square mile) in 1978. Table 5.1-1 summarizes the monthly streamflow data, and Figure 5.1-2 shows mean monthly streamflows for this gage. As shown in Figure 5.1-2, the greatest monthly runoff occurs during June, and the least occurs during December. This graph shows average runoff by month; however, runoff is highly variable and zero or near-zero flow has occurred every month for two (2) or more years. An analysis of the 19 years of record for Dead Horse Creek showed only 5% of days with daily-mean discharges exceeding 1.0 cfs Wahl, 2005). The stream is dry 48% of the time and flows less than 1 cfs occur another 47% of the time.

Table 5.1-1. Monthly mean streamflow data for 1972-90 and 2001 water years for USGS station number 06313700 on Dead Horse Creek, in cubic ft per second.
[Data from USGS, 2001]

	Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**
Mean	0.11	0.044	0.016	0.10	3.83	2.65	0.16	4.92	5.43	4.58	2.05	1.00
Max	1.11	0.28	0.12	1.81	58.3	44.4	2.13	71.3	32.4	29.1	12.6	13.4
Year	**1981**	**1985**	**1983**	**1983**	**1972**	**1978**	**1973**	**1978**	**1979**	**1982**	**1990**	**1986**
Min	0	0	0	0	0	0	.005	0	0	0	0	0
Year	**1972**	**1973**	**1973**	**1972**	**1973**	**1976**	**1972**	**2001**	**1990**	**1976**	**1989**	**1972**

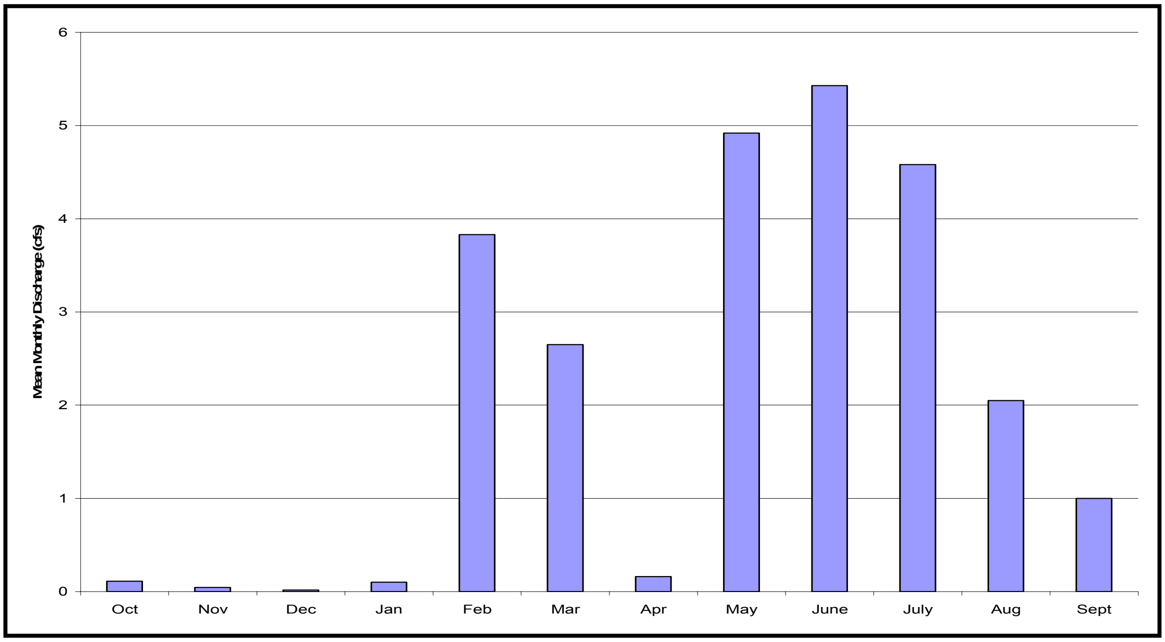


Figure 5.1-2. **Mean monthly streamflow for Dead Horse Creek at USGS station number 06313700, 1972-90 and 2001 water years.** [Data from USGS, 2001]

Figure 5.1-3 illustrates the tracking of a thunderstorm across a hypothetical drainage basin with only several small tributaries receiving precipitation. This is a common type of rainstorm event for ephemeral streams in the plains region. It often results in a high intensity, localized runoff event.

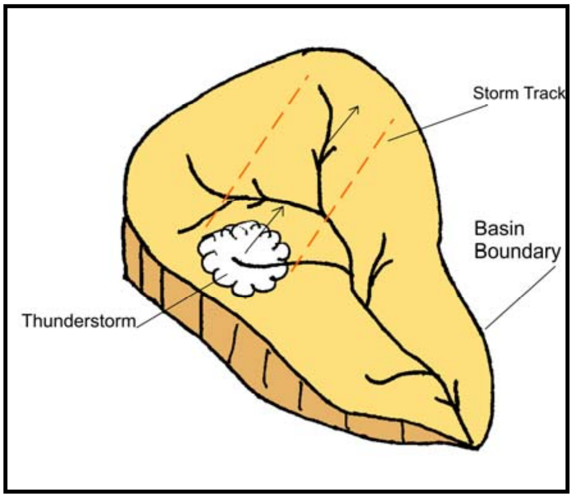


Figure 5.1-3. **Example thunderstorm moving across a basin in the plains area.**

5.1.5 Flood Attenuation

When a storm occurs in one or more of the headwater tributaries, the initial hydrograph often has a sharp profile. As the flood moves down the stream channel, the hydrograph flattens over distance from the initial source of flow. Figure 5.1-4 shows the attenuation of a theoretical flood runoff event as it flows downstream. The peak discharge is reduced and the duration of the event is increased downstream. Infiltration losses and channel storage processes consume storm discharge water such that a relatively large event in the headwater tributaries may never reach very far downstream.

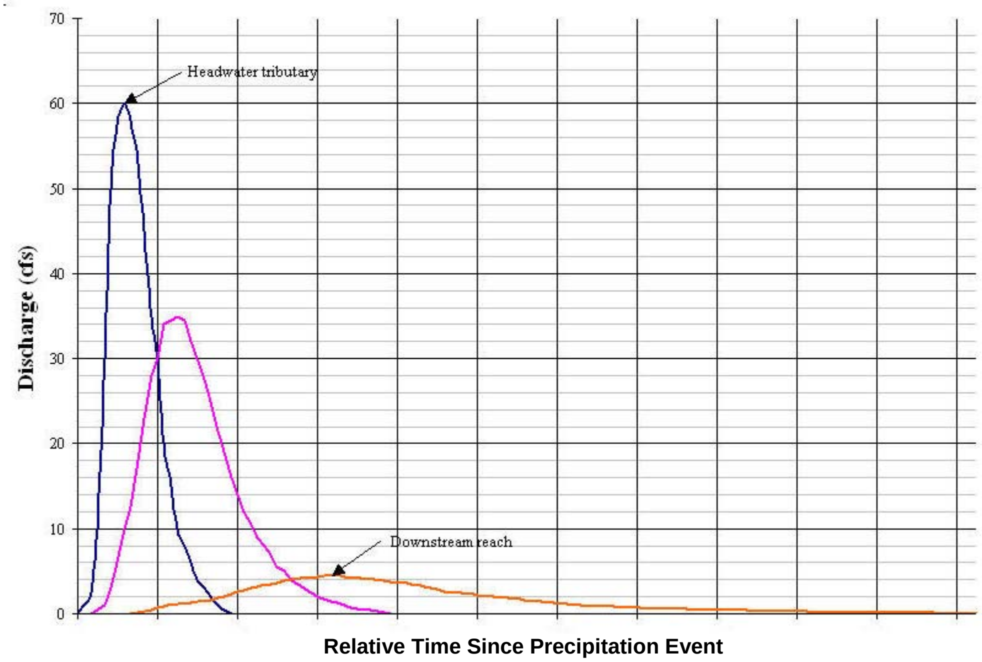


Figure 5.1-4. **Theoretical flow event showing attenuation of the hydrograph as the flood moves downstream.**

To illustrate the large amount of flow that can be consumed in a stream channel, a major storm event that occurred on Pumpkin Creek is used as an example. Two streamflow gages are operated on Pumpkin Creek approximately 18.25 stream miles apart (Table 2.2-1; Appendix A). A flood on August 24, 2002, had a peak discharge of 293 cfs at the upstream gage, but the flow did not reach the gage at the mouth due to the intervening channel storage and losses (Sanders et al., 2003).

Because of downgradient flood flow attenuation, a flood with a given recurrence interval (such as a 2-year peak discharge) at the mouth of a stream may have a much greater recurrence interval in the upstream source tributaries, especially if a thunderstorm is the source of the flood. Although runoff generally increases as drainage area increases, the unit values (peak discharge and runoff volume per square mile) of floods decrease with drainage area due to the above-described relationships.

5.1.6 Frequency of Flow Events

Most of the runoff in the ephemeral streams of the plains is the result of short duration events, and there often are long periods of a year or more between significant flow events. The graphs shown in Figure 5.1-5 illustrate peak discharges at CR stations for significant storm events occurring from 2001 through 2006 water years. These graphs illustrate the rareness of flow events in the plains region and are consistent with the findings of Wahl (1970) discussed in Section 5.1.4.

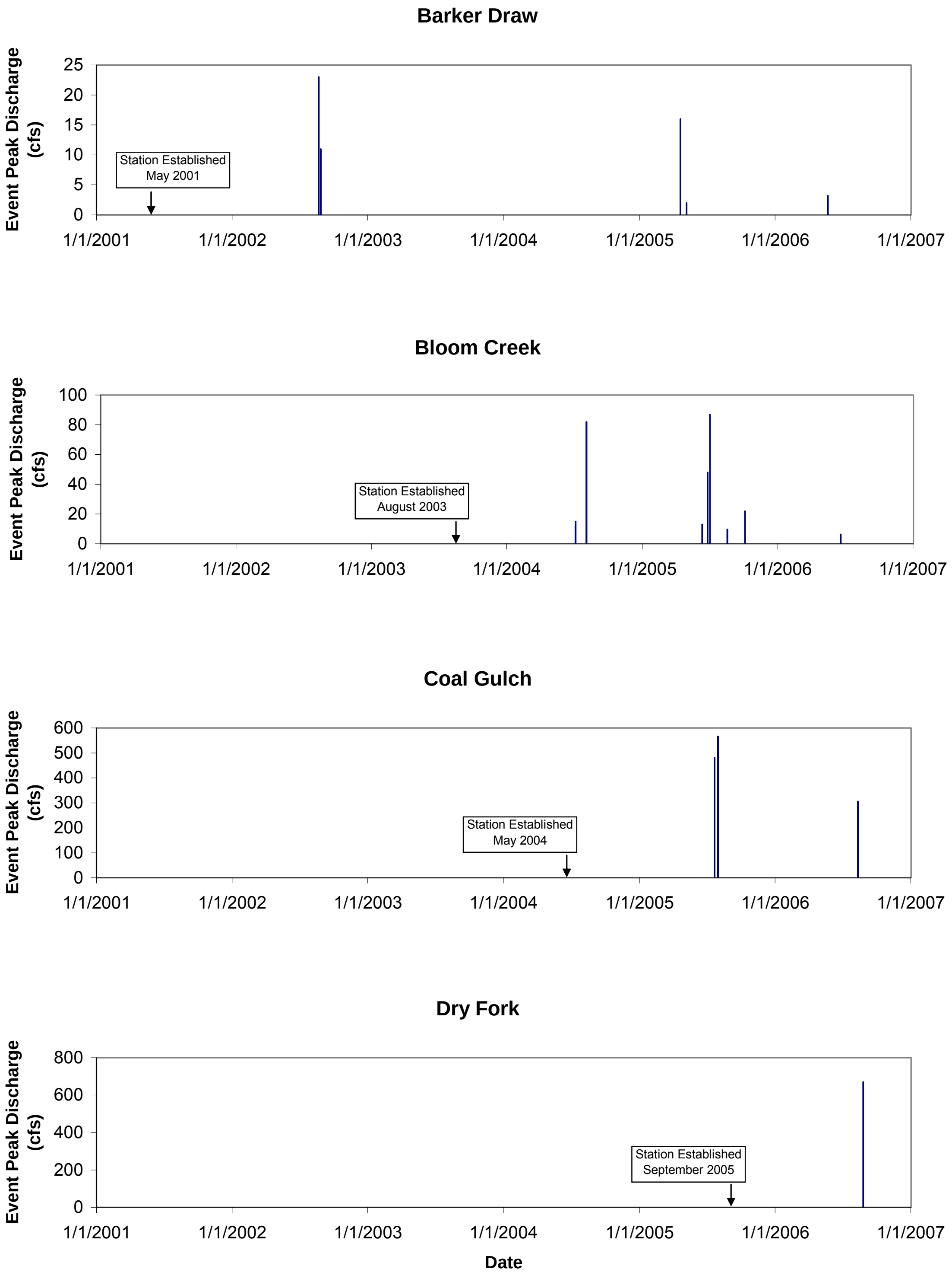
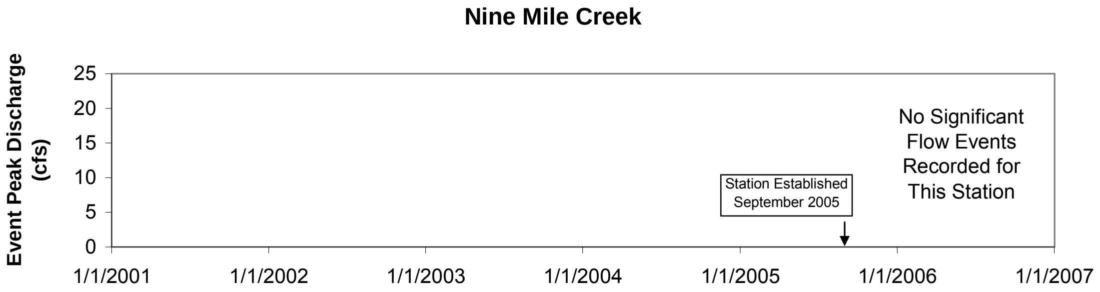
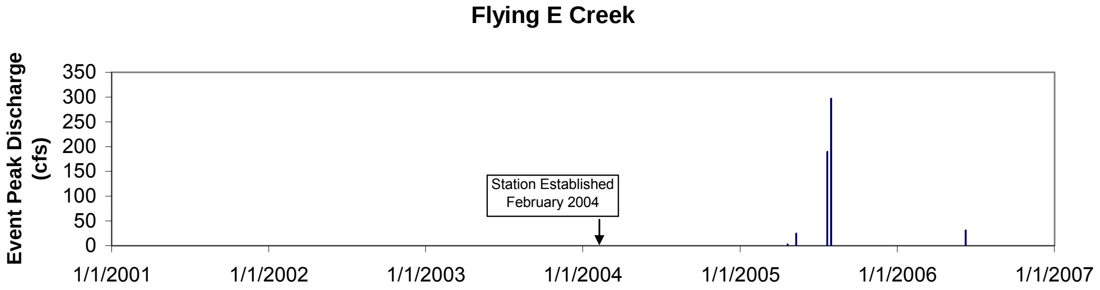
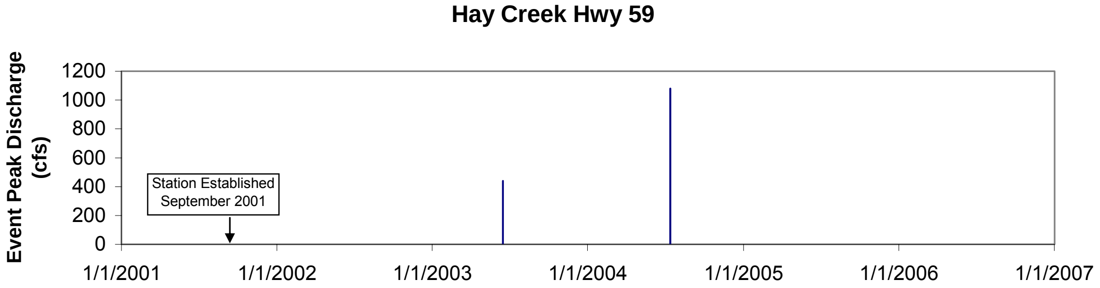
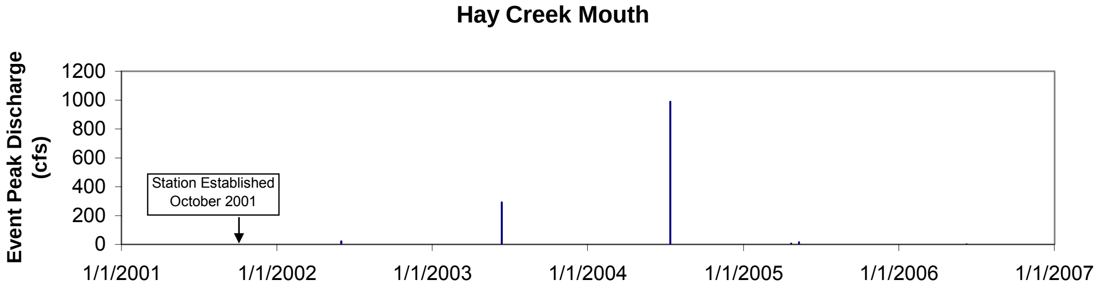


Figure 5.1-5. Storm flow occurrences and peak flow discharges from significant storm flow events at Continuous Record stations, 2001–2006 water years.
[Arrows on time scales indicate dates when stations were established.]









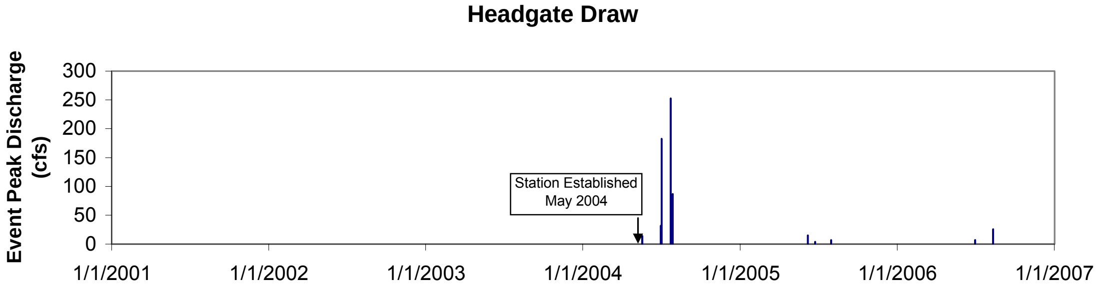
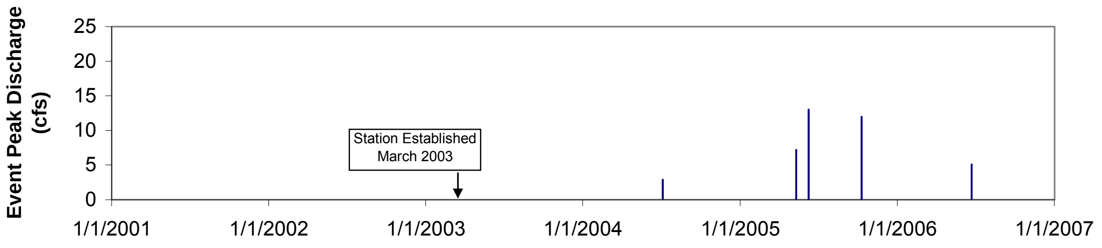
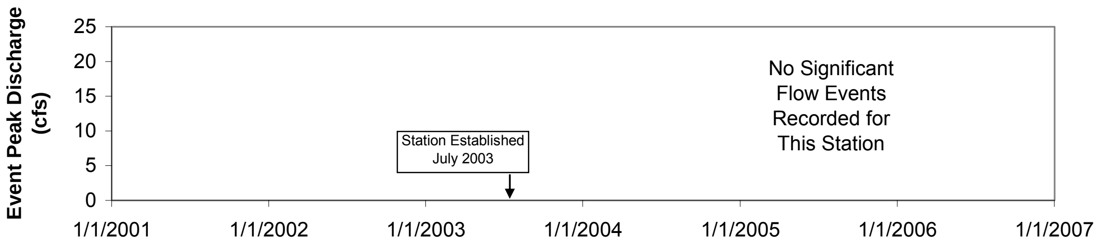


Figure 5.1-5. (Continued)

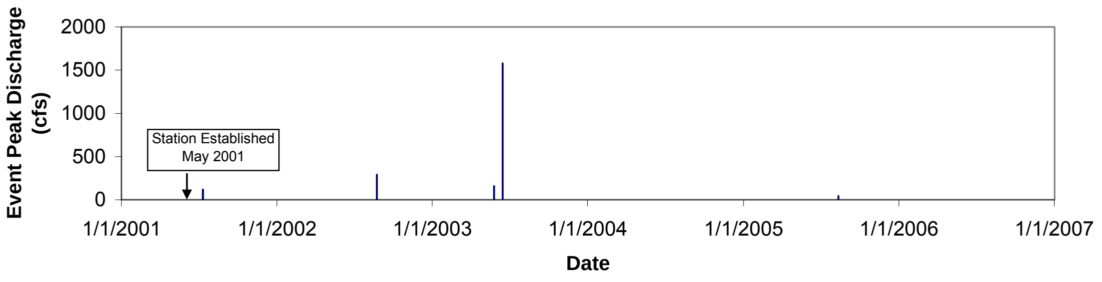
LX Bar Creek Mouth



LX Bar Creek Above Kline Draw



Pumpkin Creek at Iberlin Ranch



Pumpkin Creek Mouth

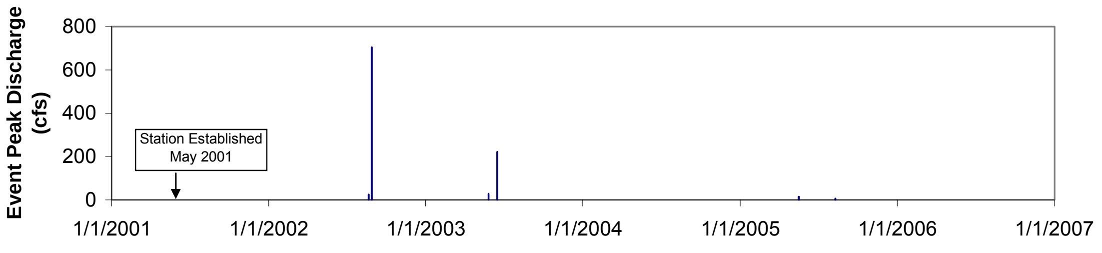


Figure 5.1-5. (Continued)

The observed intervals between significant flow events is further illustrated by the histogram of recurrent intervals for gaged study watersheds shown in Figure 5.1-6. An interval of eight (8) months to longer than two (2) years between storm flows often occurred during the study period. The decreased frequency of storm flows that appears to be resulting from the ongoing severe drought can also result in increased concentrations of dissolved solutes during flushing events (Zelt et al., 1999). The overall median frequency for significant storm flows in the study watersheds during the 2001 through 2006 water year time period was 257 days.

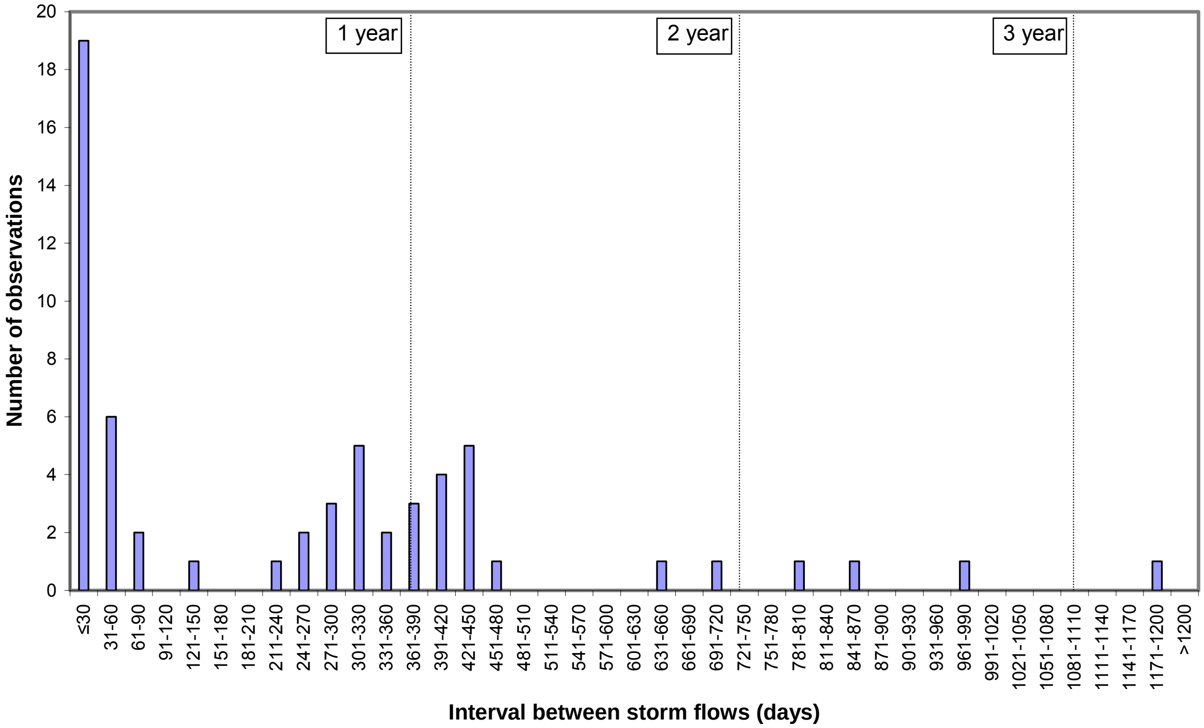


Figure 5.1-6. **Recurrence intervals (days) between consecutive significant storm flow events among all data combined at Continuous Record stations.**

5.1.7 Irrigation Events

Although this study has not focused on irrigation-related storm discharges, the observed hydrograph data allow some useful comments related to the potential frequency of natural irrigation flows in the study watersheds. Irrigation by natural flow is dependent upon storm discharge exceeding the height of the banks and overflowing onto the adjacent flood plain. Numerous studies have shown that bankfull discharge has a return interval of 1.5 to 2 years (Leopold et al., 1964). Exceedance of the magnitude of the 2-year flow provides a reasonable estimation for overbank flow.

By the above definition, irrigation events occur every two (2) years on average. When overbank flows do occur, the duration of flow across the flood plain is generally short. If a landowner along an ephemeral stream in the plains area of the PR Basin wants significant irrigation to occur, installation of a spreader dam or diversion generally is necessary to detain the flood and cause the water to spread overbank and onto the flood plain. If an overbank event occurs when CBM water is being discharged into a stream, then a mixture of the CBM water and natural runoff would overflow onto the flood plain. A comprehensive analysis of the quantity and quality of such overbank flows for the study watersheds is being done as part of the Watershed Monitoring Project. Results of that analysis will be provided as an addendum to this report.

5.1.8 Effect of Reservoirs

Numerous reservoirs for livestock use were constructed in the plains areas of the Basin before CBM development. Many additional reservoirs were constructed to assist with water management since CBM development began. Reservoirs store and dampen natural runoff events. Empty reservoirs have a greater effect than full reservoirs on streamflows and runoff. As part of a hydrologic analysis, CBM Associates, Inc., et al. (2006) used a streamflow model (DAFLOW) to describe natural streamflows on No Name Creek, a major tributary of Dead Horse Creek, and to examine the effect of reservoirs on the runoff. Based on the size and numbers of reservoirs previously constructed or newly developed for managing CBM-produced waters, an average of five (5) reservoirs per section (640 acres) with an average storage capacity of 9.2 acre ft were assumed to exist in the drainage. The hydrologic analysis indicated the following:

- **Small floods (2-year event) -** Empty reservoirs significantly reduce natural flows in the headwaters where the reservoirs are constructed. Full reservoirs have a moderate effect on the runoff.
- **Large floods (100-year event) -** Empty reservoirs have a moderate effect on runoff; full reservoirs have a negligible effect.
- **Runoff volume -** At the mouth of No Name Creek, a full buildout of reservoirs in the upstream drainage would decrease the runoff volumes of the 2-year and 100-year events by a maximum of 22% and 23%, respectively, if the reservoirs were all empty.

5.2 SODIUM – SULFATE CORRELATIONS IN STORM FLOW CHEMISTRY

Sodium is the dominant cation in CBM-produced waters derived from coal beds; at the same time sulfate is essentially non-existent in these waters (see Section 5.3). Sulfate exhibits low concentrations in deep-lying groundwater including CBM-produced water because it has been consumed by bacterially-mediated reduction over geologic time (Van Voast, 2003). Extensive sampling of CBM-produced water indicates that sulfate concentrations above 50 mg/L are rare and that the vast majority of observed concentrations are less than 10 mg/L (Figure 5.2-1). In marked contrast, sulfate is abundant in the natural landscape of the Basin. Many surface waters have sulfate concentrations exceeding many hundreds of milligrams per liter (Section 5.3; see also USGS chemical data on the Powder River at Arvada, WY; http://nwis.waterdata.usgs.gov/WY/nwis). Based on these general relationships, a strong positive correlation between observed sodium and sulfate concentrations in storm discharges suggests that the sodium is largely derived from landscape weathering and dissolution processes, and not from loadings associated with discharges of CBM-produced water (Section 5.3). Conclusions as to the origin of sodium (natural landscape versus CBM water discharges) are more ambiguous where a strong positive sodium:sulfate correlation is lacking. For example, poor correlation or strongly negative correlation between sodium and sulfate concentrations of surface flows may be indicative of local heterogeneity in exposed geologic strata and associated geochemical makeup of surficial weathered materials, rather than any effects of local CBM water discharges. It is useful, therefore, to compare the relative concentrations of these two (2) solutes in storm discharge chemistry as a general indicator of potential CBM water effects.

The correlations between reported sodium and sulfate concentrations were examined for each storm flow, for all flows within individual drainages, and across all recorded storm flows. Table 5.2-1 shows the sodium:sulfate correlations for each storm flow. The coefficients of determination (R^2) for individual storms ranged from 0.000 (a random relationship) to 0.994 (strong correlation). The median R^2 for storm events was 0.804. Most of the correlations were positive suggesting that sodium in associated storm flows was derived in part from landscape materials. However, six (6) of the 41 storm flow events showed a negative relationship between sodium and sulfate, and some were strongly so.

When examining results within individual drainages, some drainages consistently exhibited strong correlation between sodium and sulfate (e.g., Barker Draw, Figure 5.2-2) while others showed poor correlation (e.g., LX Bar Creek near Mouth, Figure 5.2-3). It should be noted that the LX Bar Creek near Mouth CR station has been affected by continuous channel flow (in comparison to the natural ephemeral flow condition) derived from upstream permitted CBM discharges since approximately July 2005. These discharges undoubtedly affected sodium:sulfate relationships in subsequent storm discharges (see further discussion Section 5.3. Sodium-sulfate R^2 correlation values for individual drainages (all paired samples from all storms within a given drainage considered in one correlation analysis) ranged from 0.000 (Coal Gulch and LX Bar Creek near Mouth) to 0.988 (Hay Creek at Mouth). When paired sodium and sulfate concentration data for all recorded storm flows across all drainages were considered together (all paired concentration data for all drainages and storms pooled for a single correlation analysis), an overall R^2 of 0.445 was observed (Figure 5.2-4).

The high median R^2 correlation coefficient of sodium:sulfate for individual storm events provides considerable evidence that sodium observed in storm flows is derived largely from natural landscape materials. However, some data are equivocal, and further review of the detailed geochemistries of such events is required to evaluate the potential for CBM discharge-related effects in these discharge events.

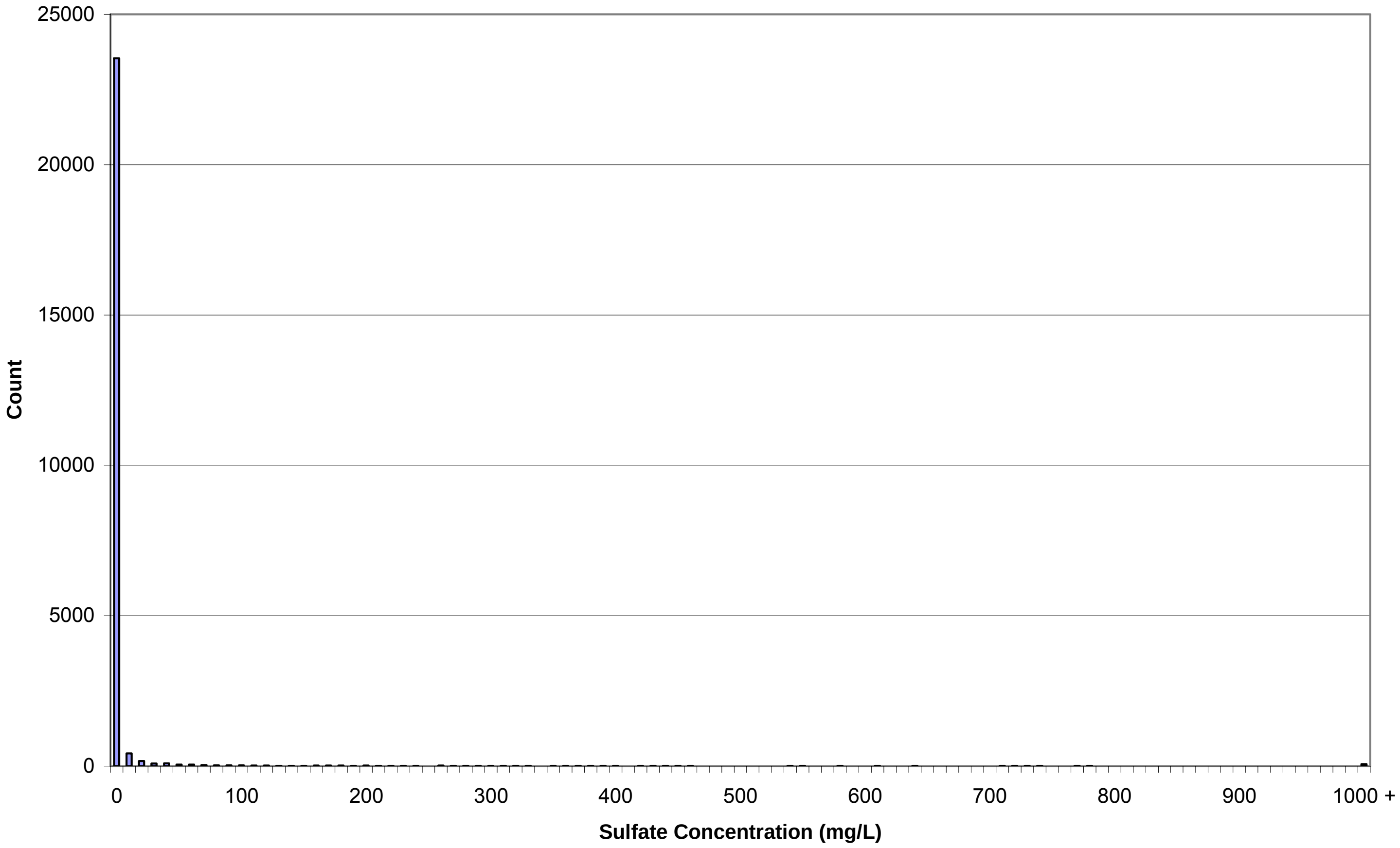


Figure 5.2-1. Frequency histogram of sulfate concentrations from laboratory analysis of samples collected from CBM outfalls in the Powder River Basin (n=25,041; CBM Associates Inc., 2006). January 2000 to January 2007.
[Sulfate concentrations above approximately 50 mg/L are rare. The resolution of bars in the histogram is 10 mg/L.]

Table 5.2-1. Correlations between sodium and sulfate for all storm flows at Continuous Record stations, 2001–2006 water years.
[R values are included to show directionality of correlations.]

Drainage	Event Date	R	R^2
Barker Draw	8/22/2002	0.810	0.656
Barker Draw	8/27/2002	0.951	0.904
Barker Draw	4/21/2005	-0.064	0.004
Barker Draw	5/8/2005	0.963	0.928
Bloom Creek	6/11/2005	0.909	0.827
Bloom Creek	6/26/2005	0.005	0.000
Bloom Creek	7/2/2005	0.679	0.461
Bloom Creek	8/18/2005	0.368	0.136
Bloom Creek	10/5/2005	0.897	0.804
Bloom Creek	6/20/2006	0.828	0.686
Coal Gulch	8/12/2006	-0.014	0.000
Dry Fork	8/26/2006	0.716	0.512
Flying E Creek	4/21/2005	-0.887	0.787
Flying E Creek	5/11/2005	-0.678	0.460
Flying E Creek	6/9/2006	0.241	0.058
Hay Creek Hwy 59	6/16/2003	0.867	0.751
Hay Creek Hwy 59	7/13/2004	0.935	0.875
Hay Creek at Mouth	6/1/2002	0.993	0.987
Hay Creek at Mouth	7/13/2004	0.994	0.988
Headgate Draw	6/30/2004	0.967	0.935
Headgate Draw	7/23/2004	0.800	0.640
Headgate Draw	7/28/2004	0.815	0.664
Headgate Draw	6/7/2005	0.929	0.864
Headgate Draw	6/24/2005	0.990	0.980
Headgate Draw	7/31/2005	0.938	0.879
Headgate Draw	7/1/2006	0.967	0.936
Headgate Draw	8/12/2006	0.990	0.981
LX Bar near Mouth	7/5/2004	0.962	0.925
LX Bar near Mouth	5/10/2005	0.778	0.605
LX Bar near Mouth	6/9/2005	-0.328	0.108
LX Bar near Mouth	10/10/2005	0.602	0.363
LX Bar near Mouth	6/23/2006	-0.646	0.417
Pumpkin Creek Iberlin	8/24/2002	0.995	0.990
Pumpkin Creek Iberlin	5/26/2003	0.975	0.951
Pumpkin Creek Iberlin	6/15/2003	0.921	0.849
Pumpkin Creek Iberlin	8/12/2005	0.997	0.994
Pumpkin Creek near Mouth	8/21/2002	0.978	0.956
Pumpkin Creek near Mouth	8/28/2002	0.958	0.917
Pumpkin Creek near Mouth	5/27/2003	0.846	0.716
Pumpkin Creek near Mouth	6/16/2003	0.996	0.992
Pumpkin Creek near Mouth	8/10/2005	0.819	0.671
Individual Storm Median		**0.897**	**0.804**
Pool of all Paired Concentration Data		**0.667**	**0.445**

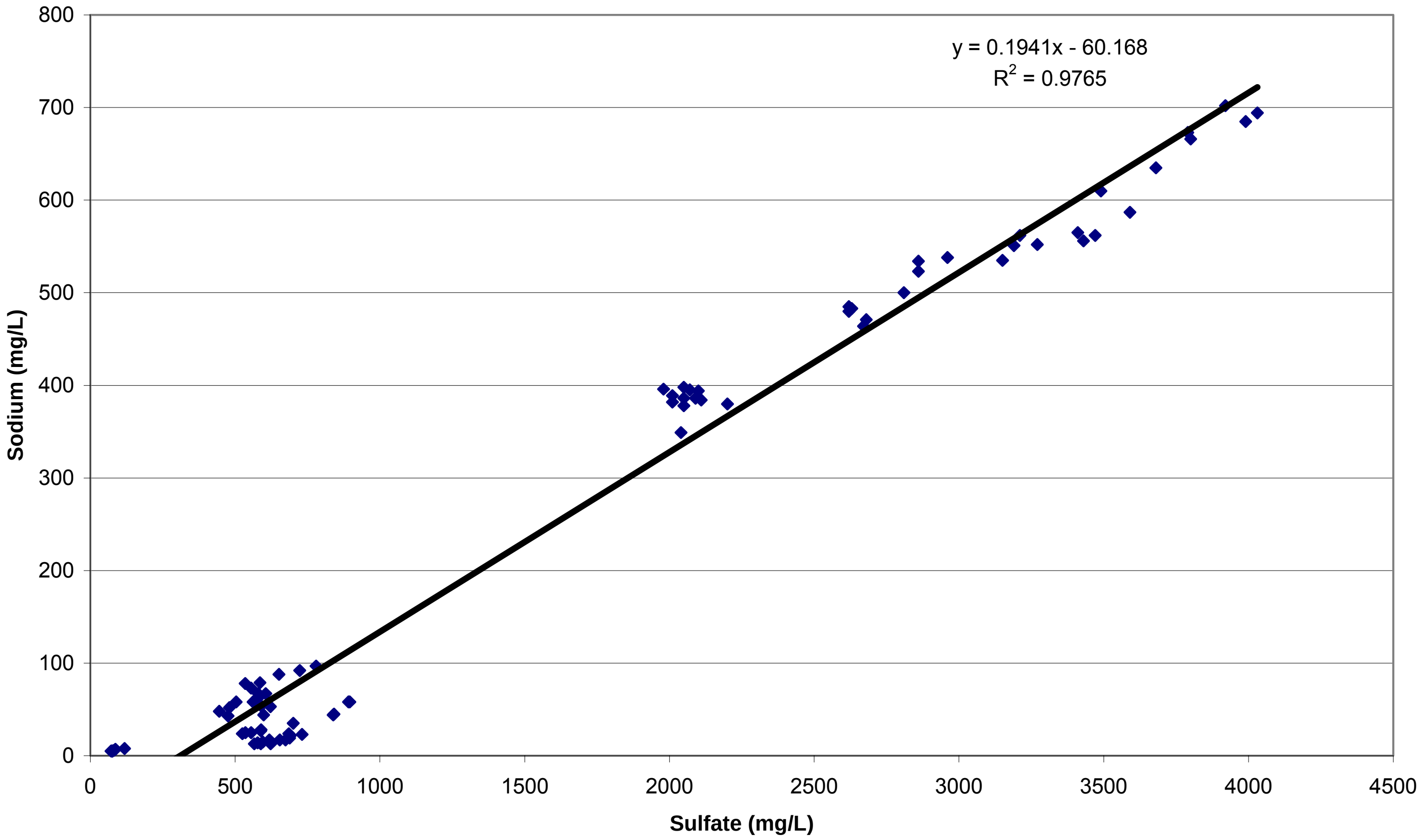


Figure 5.2-2. **Sodium-sulfate correlation for Barker Draw storm events. 2001 through 2006 water years.**
[The data represent 83 samples collected across 4 storm flows in the drainage.]

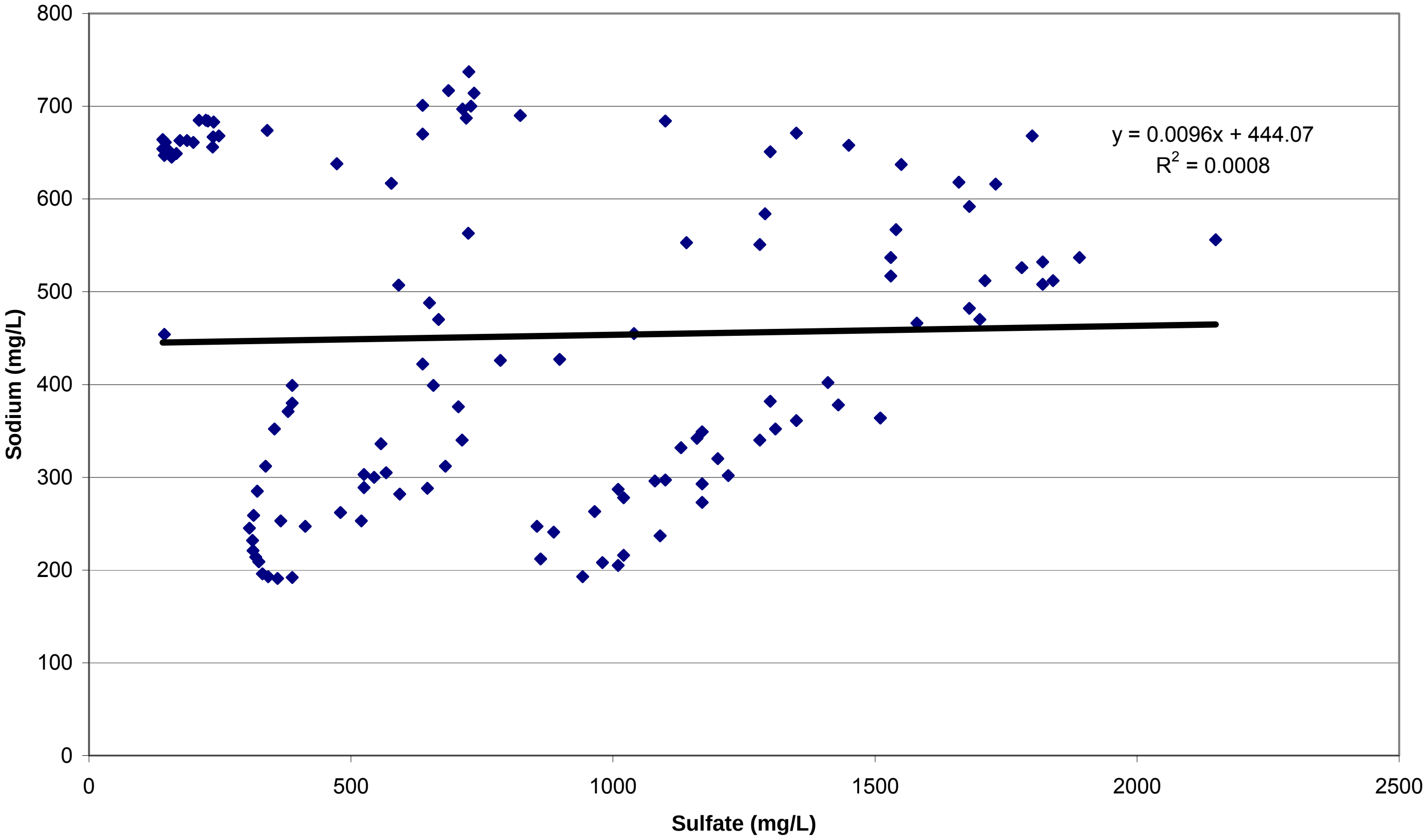


Figure 5.2-3. **Sodium-sulfate correlation for LX Bar Creek near Mouth storm events. 2003 through 2006 water years.** [The data represent 121 samples collected across 5 storm flows in the drainage.]

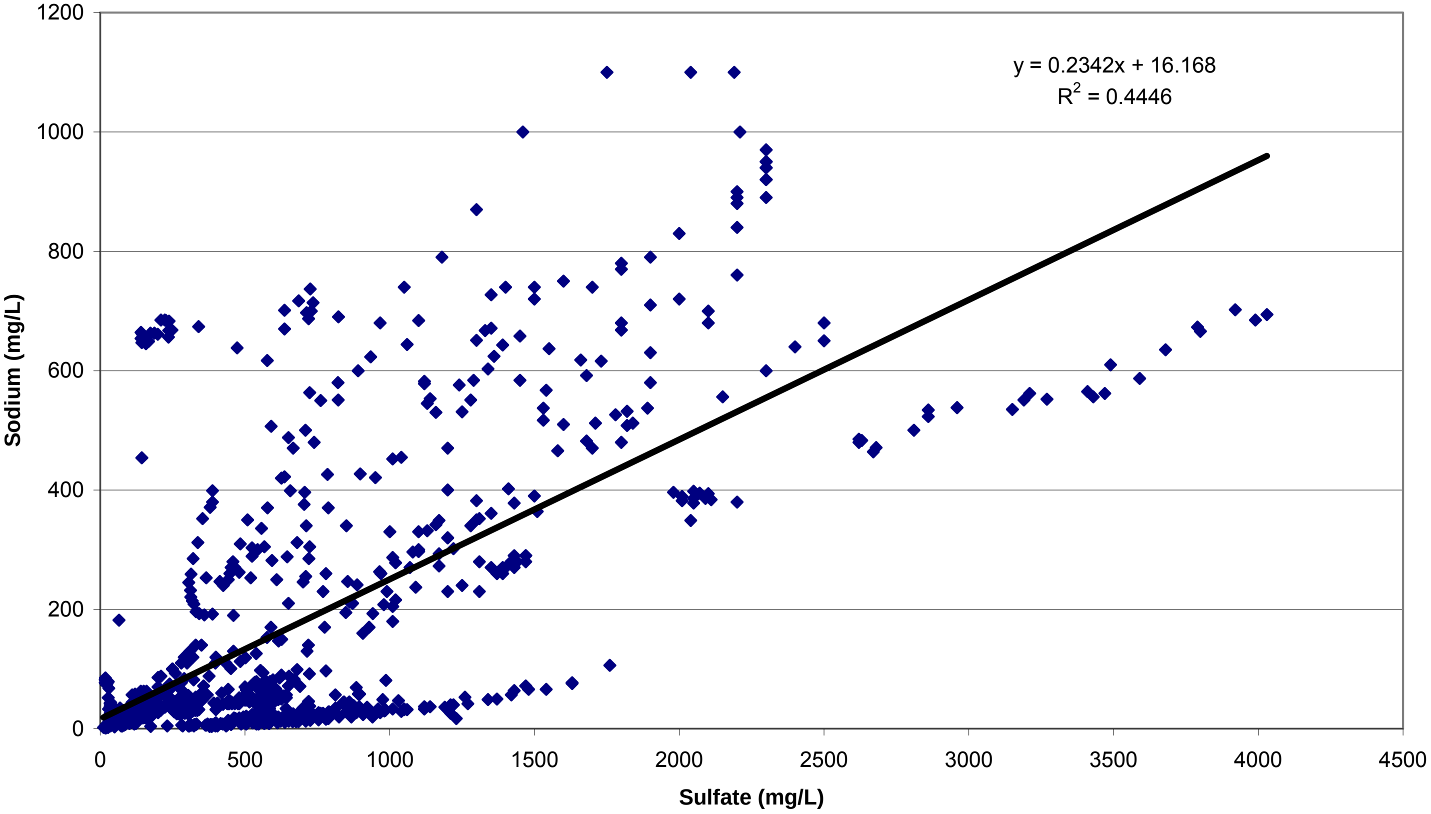


Figure 5.2-4. Sodium-sulfate correlation for all recorded storm flow events at Continuous Record stations in all monitored drainages, 2001–2006 water years.
[The data represent 890 samples collected across 41 storm flows in 9 drainages. The tightly correlated points beyond 2,500 mg/L sulfate are all from Barker Draw.]

5.3 GEOCHEMICAL SIGNATURES OF SURFACE AND NEAR-SURFACE WATERS

As noted in Sanders et al. (2003) and in Section 2 of this report, various landscape-level processes have strong influence on the observed chemistries of storm discharges in the study watersheds. In addition to natural processes that influence the chemistry of surface waters, discharges of CBM-produced waters may add an additional chemical signature. The following discussion considers CBM influences in the geochemical data of monitored storm events to date, within the context of the natural chemistry of surface and near-surface (shallow alluvial) waters. Trilinear, or Piper, diagrams are presented herein to graphically illustrate the geochemical similarities and differences among water types.

Coal Bed Methane Produced Water

As described elsewhere, the chemistry of CBM-produced waters may be represented by groundwater quality samples collected by the USGS from CBM wells in Campbell County (Rice et al., 2000; Rice et al., 2002). Resulting data are plotted on a trilinear diagram in Figure 5.3-1. For these data, the plot resulted in a non-variable sodium (Na), bicarbonate (HCO_3) signature with Na representing 89.2 of the median mole percentage of major cations and HCO_3 representing 98.1 of the median mole percentage of major anions. However, as now commonly recognized, the 47 CBM samples from Rice et al. (2000) and the 83 samples from Rice et al. (2002) show a trend of higher sodium adsorption ratio (SAR) and TDS towards the north and west. Median TDS and EC for all samples were 838.0 mg/L and 1,130.0 µS/cm, respectively. The median calculated SAR and pH values were 10.6 and 7.30, respectively. CBM-produced water is distinguished from surface and shallow groundwaters by the near absence of sulfate (SO_4), with Na and HCO_3 accounting for a high mole percentage of cations and anions, respectively.

Meteoric Water

Atmospheric deposition of meteoric water (direct precipitation as either rainfall or snowfall) are the beginning stage of surface runoff for stream channels. Precipitation chemistry provides a regional baseline from which to evaluate contributions of dissolved solutes from natural landscape sources that sum to the observed stream discharge chemistry. However, data on meteoric (especially direct rainfall) water chemistry is sparse for the Basin. Therefore, to provide a basis for comparison to other water types, we used precipitation chemistry data collected at Newcastle, WY, as part of the National Atmospheric Deposition Program/National Trends Network (NADP/NTN) monitoring for the continental United States. The Newcastle monitoring station is east of the Basin at an elevation of approximately 4,810 ft AMSL. Given the general regional climatology, the general tracking of spring through fall rain storms from west to east,

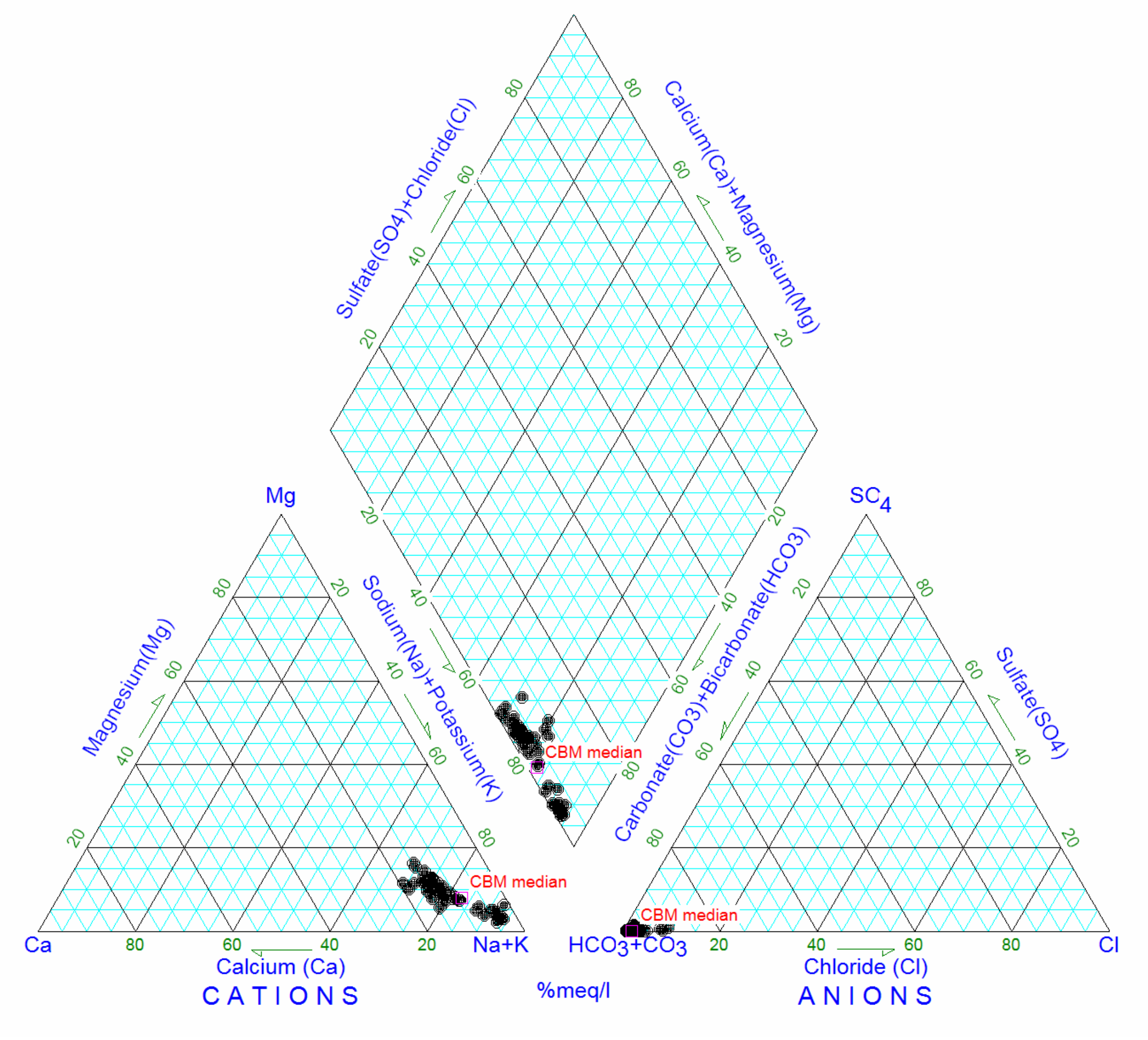


Figure 5.3-1. Coal bed methane produced water types.
[From Rice et al., 2000; Rice et al., 2002.]

and the scarcity of other regional data, the Newcastle data obtained during the CBM development period is the most representative precipitation chemistry available (Gray, 2007). Table 5.3-1 provides summary data from the Newcastle station during CBM-development during 2000 to 2005. Figure 5.3-2 also shows the Newcastle station data on a trilinear diagram and includes a deduction of HCO_3 concentration determined by attributing all of missing anionic charge to HCO_3.

Table 5.3-1. Annual volume-weighted mean concentrations of solutes (mg/L) in bulk precipitation for indicated years for Newcastle, WY NADP/NTN station. [Source: NADP/NTN annual data; http://nadp.sws.uiuc.edu).]

Year	Ca	Mg	K	Na	Cl	SO_4	pH (lab)	pH (field)
2000	0.30	0.024	0.038	0.023	0.06	0.74	5.32	5.23
2001	0.28	0.023	0.023	0.035	0.05	0.71	5.43	5.38
2002	0.28	0.024	0.020	0.029	0.05	0.73	5.34	5.47
2003	0.27	0.024	0.016	0.028	0.05	0.60	5.34	5.34
2004	0.33	0.029	0.022	0.031	0.05	0.74	5.43	5.27
2005	0.21	0.019	0.025	0.024	0.05	0.59	5.47	--
Median:	**0.28**	**0.024**	**0.023**	**0.029**	**0.05**	**0.72**	**5.39**	**5.34**

These data indicate that direct precipitation has low concentrations of solutes relative to commonly observed concentrations in surface and near-surface waters of the Basin (see discussion below).

In addition to the NADP/NTN precipitation data and as previously reported in Sanders et al. (2003), four water samples were collected from newly formed pools in grassy swales in the upper Pumpkin Creek watershed immediately following a rainstorm event that had occurred the previous evening. These samples approximate meteoric water after only short-term interaction with landscape minerals, as evidenced by their low solute concentrations (Figure 5.3−2). These samples indicated a Ca, HCO_3 signature, with Na being nearly absent. In fact, K exceeded Na in each sample. The median calculated SAR and pH values were 0.0 and 6.63. The low pH and median TDS concentration of 78 mg/L indicated limited geochemical interaction with the surface landscape when compared to the median field pH of 5.34 and solute concentrations from the NADP/NTN data (Table 5.3-1).

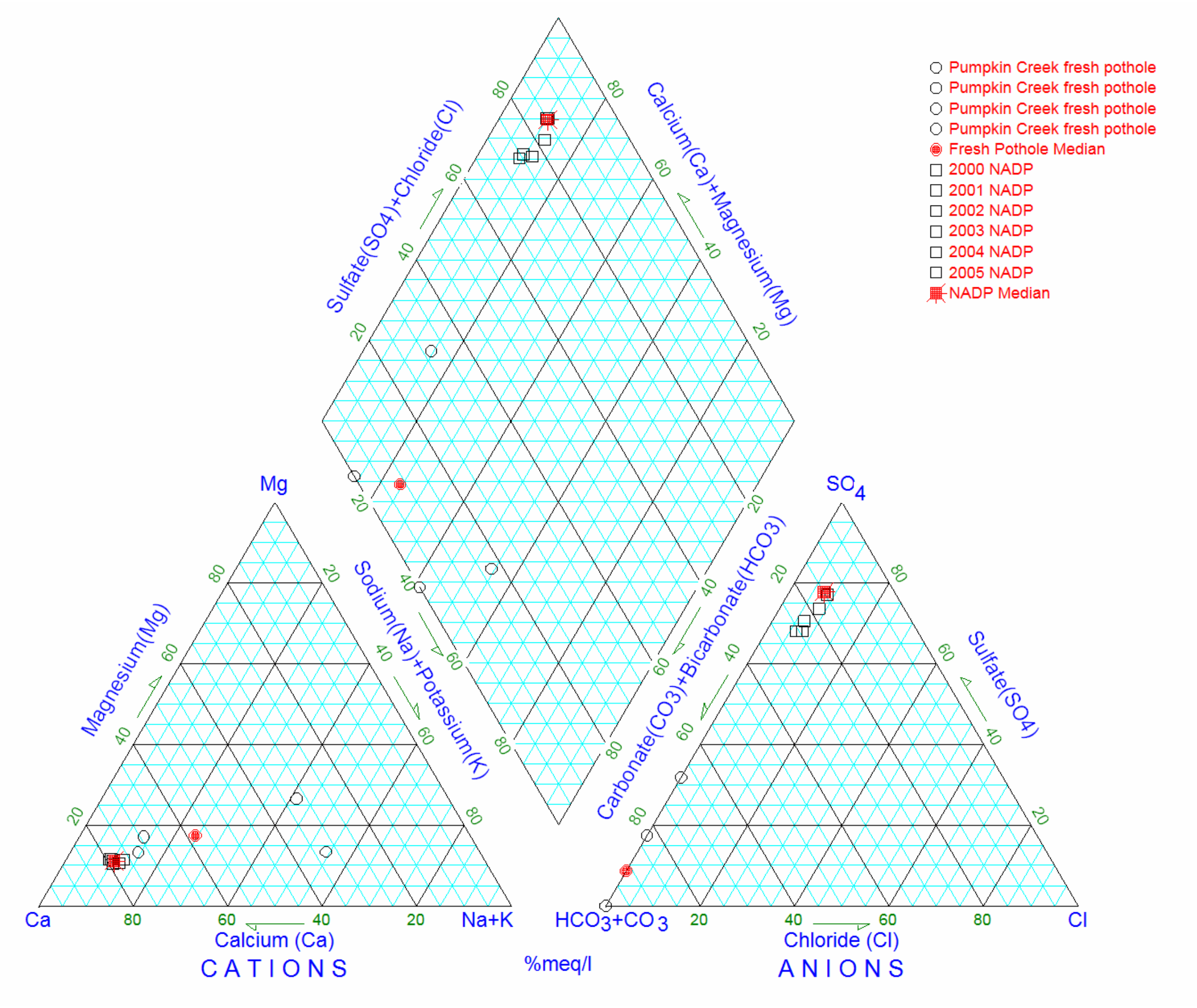


Figure 5.3-2. **Meteoric (rain) water types, Powder River Basin.**
[Pumpkin Creek fresh pothole refers to samples collected from potholes within hours of a storm (Sanders et al., 2003). The National Atmospheric Deposition Program (NADP) data is from the Newcastle, WY gage. NADP HCO3 is determined by attributing all of the missing anionic charge to HCO3.]

Shallow Alluvial Groundwater

In contrast to meteoric water having no or limited contact with landscape materials, the geochemistry of shallow alluvial groundwater demonstrates extensive contact with landscape materials. Solute geochemistry resulting from such contact also reflects the effects of concentration mechanisms as provided, for example, by evapotranspiration. To characterize this type of landscape interaction, two groups of data from shallow alluvial groundwater samples from NE Wyoming were evaluated. The first group is groundwater samples collected by the USGS from wells in Campbell County that pre-date CBM development (USGS, 2006). These samples only included groundwater observed to be less than 30 ft deep. The data are from 20 samples from 11 wells, with five (5) wells in the Belle Fourche River watershed and six (6) wells in the Little Powder River watershed. Apart from three (3) outliers, the alluvial groundwaters yielded a calcium plus magnesium (Ca+Mg) sulfate signature, with little variability (Figure 5.3−3). Two of the outliers yielded a Na, HCO_3 signature, while the other yielded a Ca+Mg, HCO_3 signature. For all samples, Na, Ca, and Mg represented 48.8, 25.2, and 24.7 of the median mole percentage of major cations, respectively. Sulfate, HCO_3, and Cl (chloride) represented 52.1, 34.6, and 13.3 of the median mole percentage of major anions. TDS is calculated using the standard method of adding the major ions in milligrams per liter, but using only one-half of the bicarbonate. Median TDS was 3,368 mg/L with a standard deviation of 1,537; and values ranged from 442 to 6,599 mg/L. As noted above, shallow alluvial groundwaters have relatively high TDS due to water-mineral interactions resulting from long contact times and possible effects of high ET losses, which concentrate salts. Median calculated SAR value was 4.2 and ranged from 1.1 to 9.0. The median calculated pH was 7.50. Although these samples provided important baseline data for discussion, they may not be representative of the entire Basin because of the small number of samples and wells and the likelihood that some shallow alluvial groundwater contains considerably less salt than indicated in these samples. These data are consistent with the variability in shallow groundwater chemistry in the PR Basin reported by Bartos and Ogle (2002).

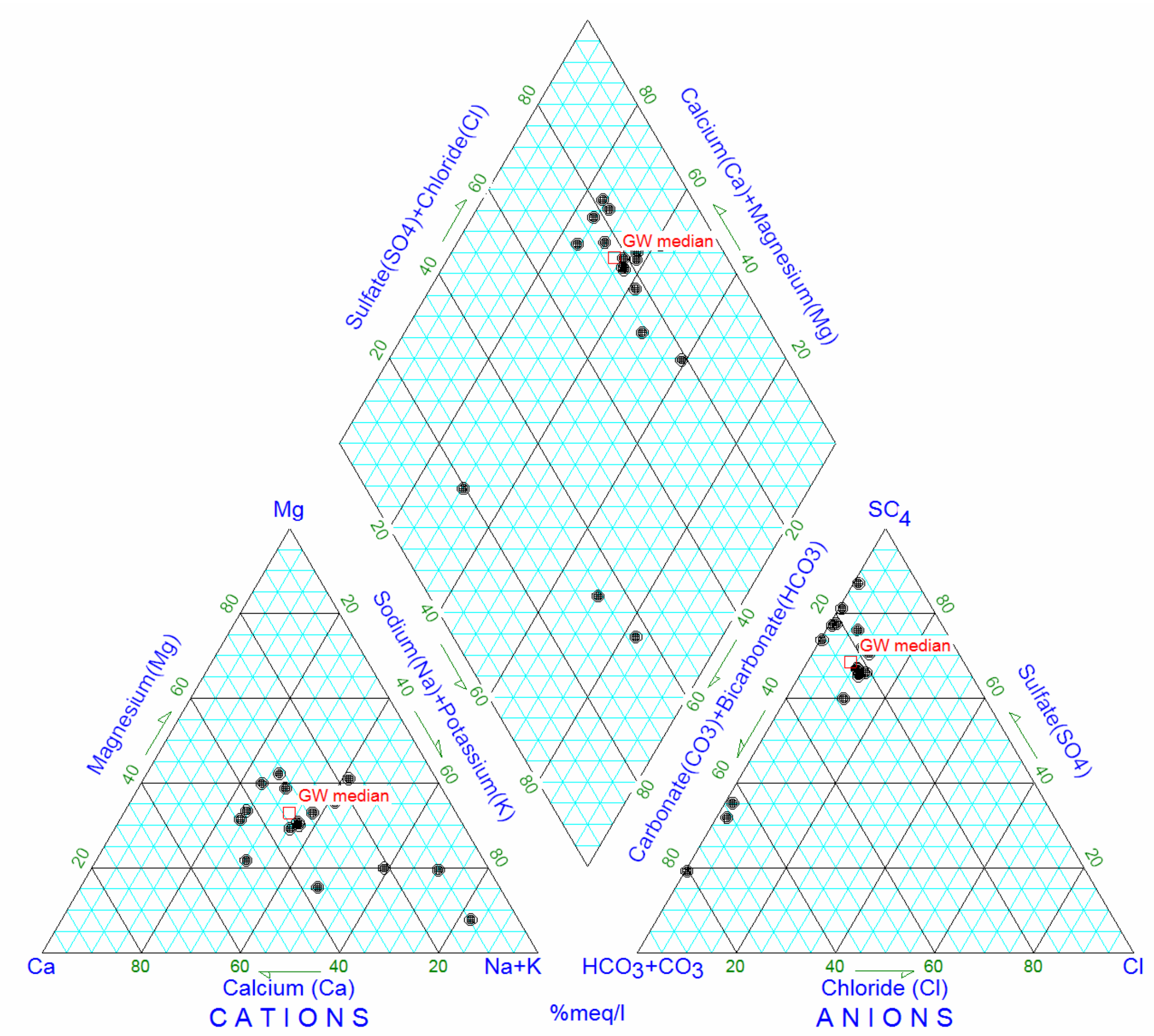


Figure 5.3-3. Alluvial groundwater types from depths less than 30 ft.

The second group of groundwater samples was collected near the mouth of LX Bar Creek by CBM Associates, Inc. as part of initial reconnaissance of the lower watershed. This group included 86 samples from 18 shallow groundwater wells located along the stream channel downgradient of the SA Road crossing (below Queen's Pond). These samples were collected during 2003 and 2004 before the extensive buildout of CBM wells in the lower drainage. While CBM influences cannot be eliminated from these data, the chemical signatures are considered representative of the natural heterogeneity of shallow alluvial groundwater found in the lower channel reach of LX Bar Creek. The medians of observed solute concentrations from these samples yield a Na+Ca+Mg, SO_4 signature (Figure 5.3−4). Sodium represented 62.2 of the median mole percentage of major cations while SO_4 and HCO_3

represented 75.4 and 24.2 of the median mole percentage of major anions. Median TDS was 6,930 mg/L with a standard deviation of 2,844, and values ranged from 1,900 to 14,300. Median calculated SAR value was 8.6 and ranged from 4.0 to 27.3, while median pH was 7.30. The high TDS and relatively high Na indicated the natural poor quality of shallow alluvial groundwater in this sub-region as has been observed elsewhere in the Basin (e.g., Larson and Daddow, 1984; Wells, 1982).

Both data sets indicate that shallow alluvial groundwater in the study area may be high in dissolved solutes. However, the relative proportions of solutes may vary among sample groups. Because near-surface alluvial groundwater may contribute solutes to storm flows, especially during the descending limb of the storm hydrograph, these data provide a useful reference point relative to the observed chemistry of the storm discharges.

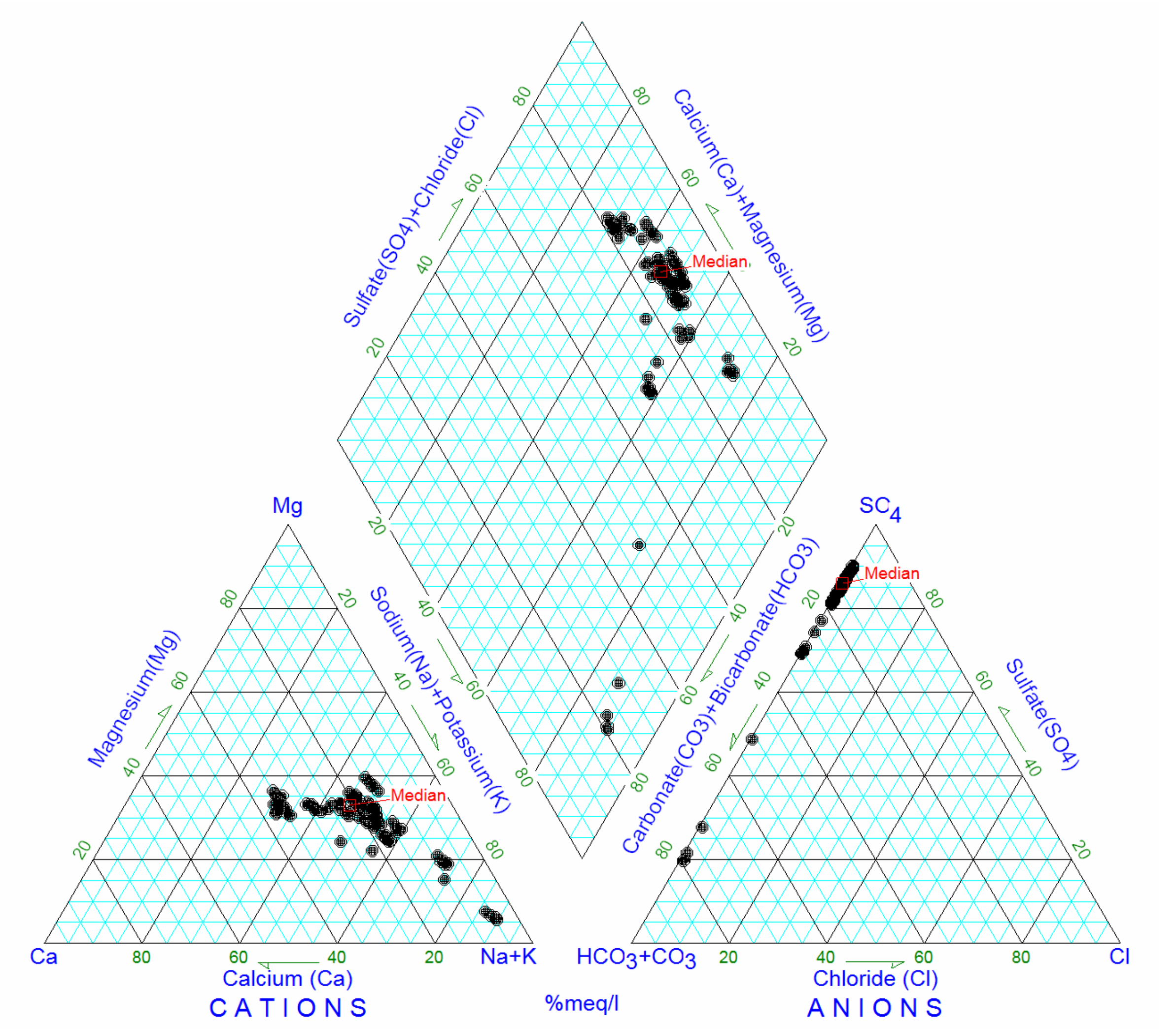


Figure 5.3-4. Alluvial groundwater types from near the confluence of LX Bar Creek and the Powder River.

Pothole Water

Potholes are natural scour features in stream channels. They may continually hold water due to constant upwelling of groundwater associated with surface outcropping of confining geologic strata or temporarily hold water due to retention of storm discharge or some combination of both. If a hydrologic connection between pothole and local groundwater occurs, groundwater may upwell into a pothole sequence with subsequent outflow into alluvial materials downgradient of the sequence. Because of varying sources and subsequent concentration mechanisms for salts (e.g., ET), pothole water chemistry can vary considerably especially with regard to TDS concentration. If a pothole has high ET losses during summer, resulting concentration of solutes may proceed to saturation limits (e.g., calcium salts) causing differential mineral precipitation. For example, some samples that have high TDS concentration may have previously precipitated calcium carbonate, thereby concentrating all solutes relative to Ca and HCO_3. Calcium and HCO_3 may have been incorporated into local sediments as calcium carbonate precipitates, which may be transported in particulate or dissolved phase in subsequent storm flow events. In contrast, pothole water samples with very low TDS concentration likely consist of runoff from recent storm events that have not had extensive water-mineral interaction on the landscape surface or sometimes indicate upwelling of high quality groundwater associated with well-leached surficial geologic strata, such as scoria or sandstones. With some limitations, pothole water chemistry is an indicator of associated shallow alluvial groundwater and types of local geologic strata.

Representative chemical data from pothole water samples considered here are from samples collected in June 2001 from Pumpkin Creek and Barker Draw, previously summarized in Sanders et al. (2003), and from more recent samples collected from other study watersheds. At the time of pothole sampling in Pumpkin Creek and Barker Draw, CBM buildout was relatively modest compared to 2006; therefore, these data are believed to represent natural pothole water chemistry with only limited CBM influence. Pothole samples were collected from eight (8) locations along Barker Draw. These samples indicated a Ca+Mg, SO_4 signature (Figure 5.3−5). Magnesium and SO_4 concentrations were particularly high, with the median mole Mg concentration exceeding Ca by a factor of 2.9 and median mole SO_4 concentration exceeding HCO_3 by a factor of 8.7. Concentrations of Na and Mg also were relatively high with Na and Mg representing 44.0 and 40.9 of the median mole percentage of major cations, respectively. Presumably, Ca and HCO_3 had been partially removed through precipitation of $CaCO_3$ due in part to ET concentration effects. The high median TDS concentration of 7,022 mg/L presumably also resulted from ET and water-mineral interaction. A calculated median SAR and pH values were 3.9 and 8.21. Two outlier samples seem to represent more meteoric values; however, potassium (K) exceeded sodium by a factor of 17 in those two (2) samples.

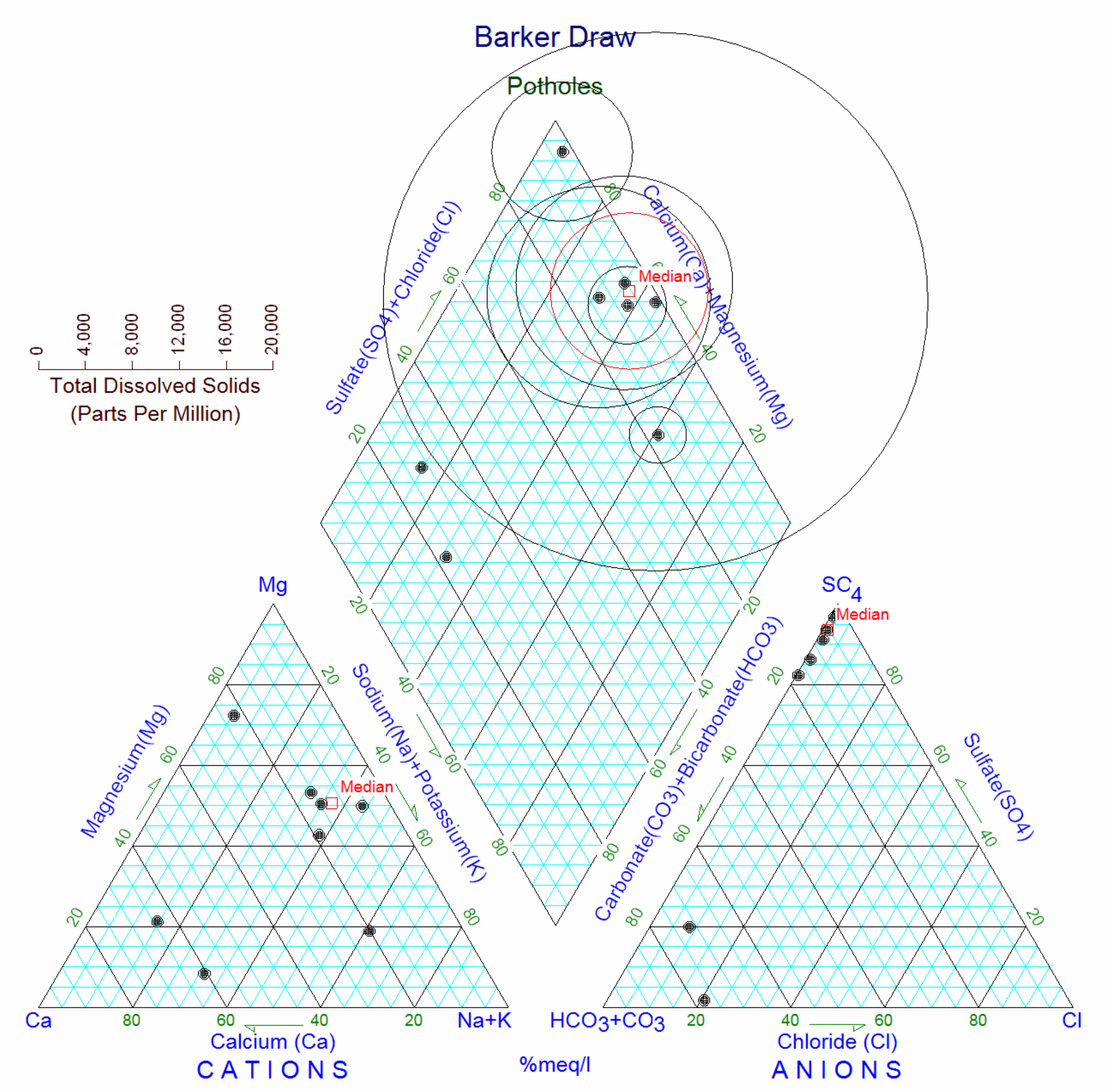


Figure 5.3-5. Barker Draw pothole water types.
[The radius length of each plotted circle represents total dissolved solids concentration (mg/L) as provided in the legend.]

Pothole water samples also were collected from 10 locations along Pumpkin Creek during 2001, many in areas with only distant (many miles) CBM development. These samples demonstrated a tendency for a Na, SO_4 signature, with Ca and Mg concentrations also being high (Figure 5.3−6). Sodium represented 71.4 of the median mole percentage of major cations. The median mole SO_4 concentration exceeded HCO_3 by a factor of 13.1. As for the Barker Draw pothole samples, some Ca and HCO_3 had probably been removed through precipitation of $CaCO_3$. A high median TDS concentration of 5,150 mg/L suggests concentration by ET and water-mineral interaction. Median calculated SAR and pH values were 10.8 and 8.00.

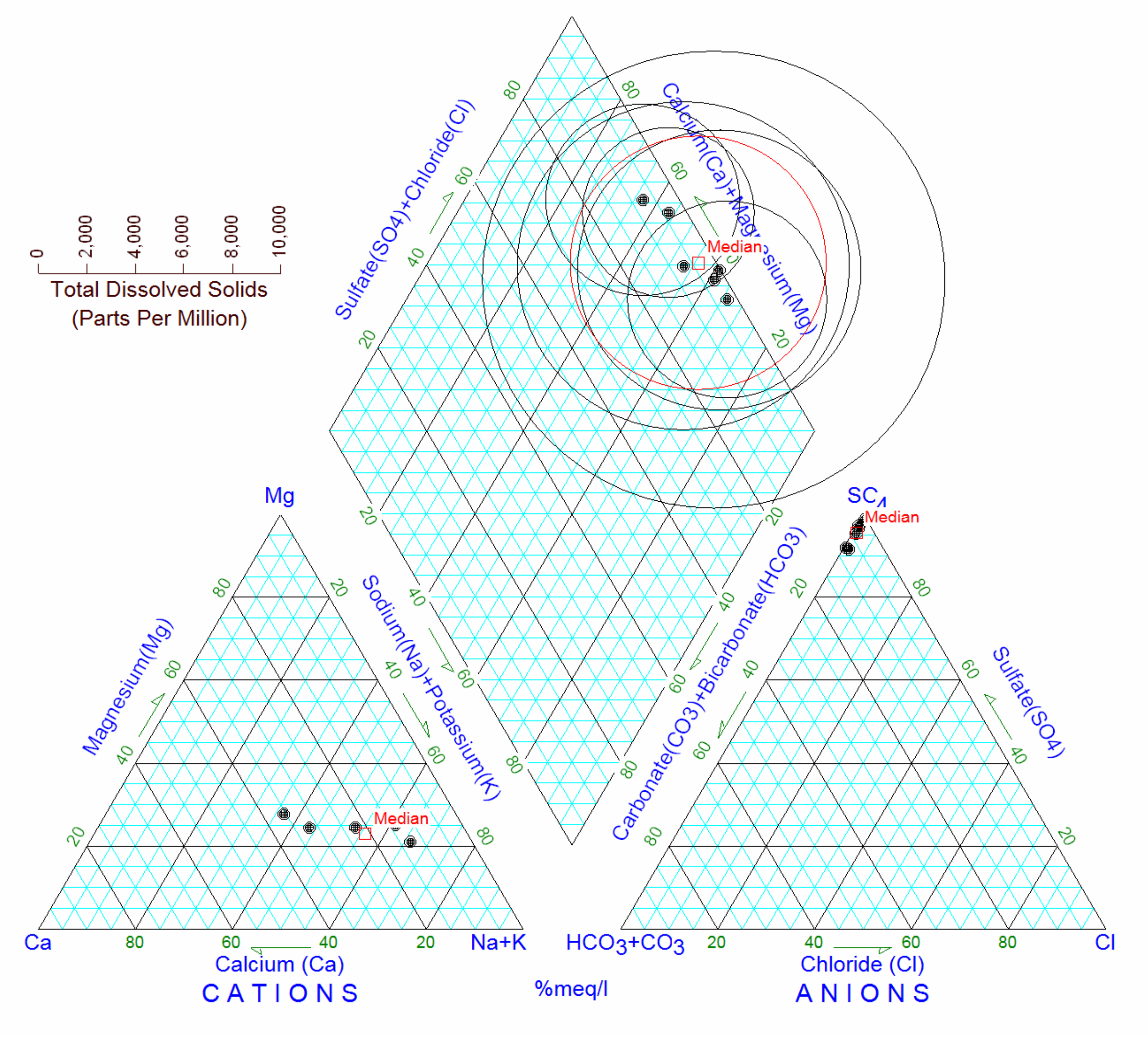


Figure 5.3-6. Pumpkin Creek pothole water types.
[The radius length of each plotted circle represents total dissolved solids concentration (mg/L) as provided in the legend.]

Water samples were collected from three pothole locations along Headgate Draw, a non-CBM developed watershed, in September 2004. These were the only potholes observed during field reconnaissance of this watershed. Each sample resulted in a Ca+Mg, SO_4 signature (Figure 5.3−7). Median mole percentages of the major cations Na, Ca, and Mg were nearly equal, representing 29.9, 33.2, and 35.9 percent, respectively. The low Na concentrations relative to other major cations (Ca and Mg) suggest that the watershed may be poor in sodium-yielding geologic strata compared to other drainages and that the sodium available for transport is rapidly leached from the drainage given its relatively high frequency of observed storm discharge (flushing events) compared to other study drainages (Section 5.1). The median mole SO_4/HCO_3 ratio is 6.8. The calculated median SAR and pH values were 1.7 and 8.26, and the median TDS concentration was relatively high at 3,810 mg/L.

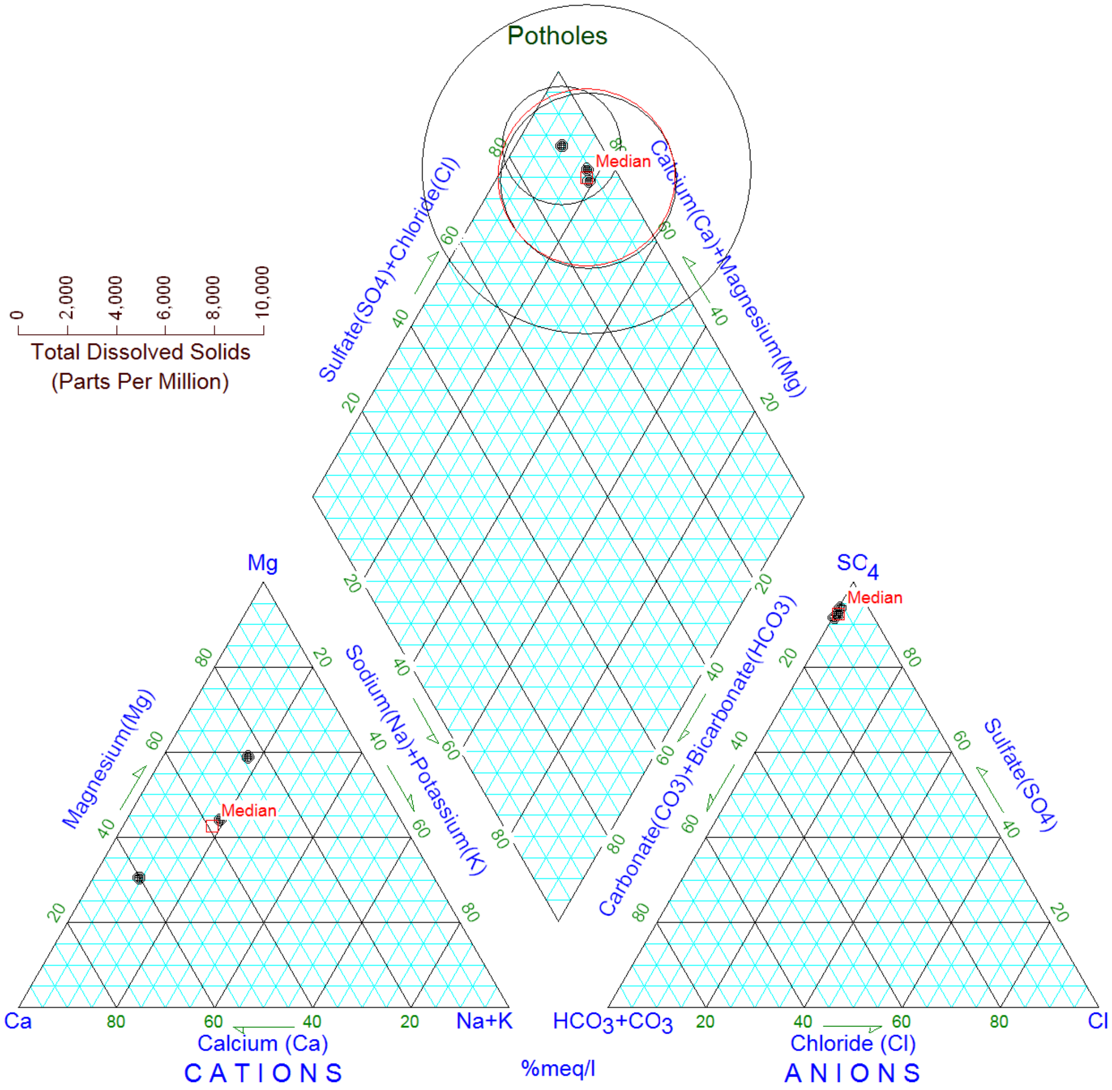


Figure 5.3-7. Headgate Draw pothole water types.
[The radius length of each plotted circle represents total dissolved solids concentration (mg/L) as provided in the legend.]

Pothole water samples were collected from 11 locations along the lower portion of LX Bar Creek below the SA Road crossing and above PeeGee Meadows in 2003 and 2004 before the more extensive buildout of CBM wells that currently exist. These samples demonstrate a Na+Ca+Mg, SO4 signature (Figure 5.3−8). Sodium represented 67.1 of the median mole percentage of major cations, while SO4 and HCO3 represented 87.1 and 11.7 of the median mole percentage of major anions, respectively. LX Bar Creek potholes had 2.4 times more dissolved Mg than Ca, suggesting possible CaCO3 precipitation. The calculated median SAR and pH values were 11.0 and 8.18. TDS concentration and EC were both relatively high with medians of 8,080 mg/L and 8,490 µS/cm. The observed pothole chemistry along LX Bar Creek agreed well with alluvial groundwater chemistry from the same general channel area, suggesting major groundwater influence on potholes.

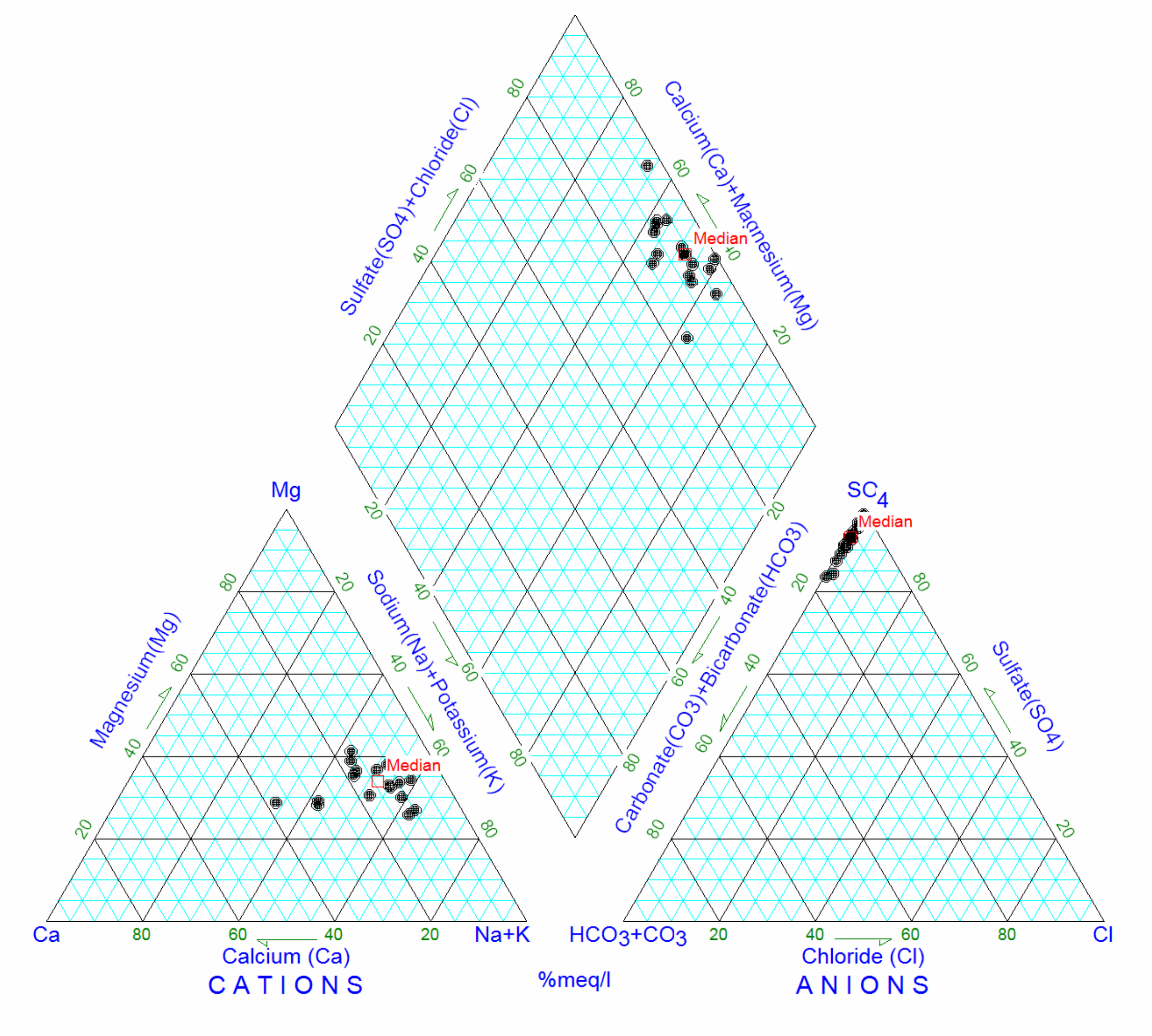


Figure 5.3-8. **LX Bar Creek pothole water types.**

Peterson (1990) reported limited chemistry for several potholes sampled along Dead Horse Creek during spring to early fall in 1980, far in advance of CBM development. His data indicate a median specific conductance of 4,250 (range 1,800 to >8,000 µS/cm) and a median field pH of 7.8. These data indicate that very high dissolved solute concentrations were prevalent in this drainage in naturally occurring potholes before pre-CBM development.

The pothole and shallow alluvial groundwater geochemistries discussed above demonstrate that initially low ionic strength meteoric waters undergo significant increases in solute concentrations as they contact natural landscape materials and as the waters age in surface and near-surface environments. Thus, any effects of the discharge of CBM-produced water needs to be evaluated in this context.

Natural Springs

Natural springs represent one type of solute loading to surface drainages in the Basin and may profoundly influence the local geochemistry of potholes and shallow alluvial groundwater in ephemeral drainages. Water chemistry grab samples were obtained from two (2) springs that are prominent in the study watersheds and are not associated with CBM development: a large spring near Breen Road on the lower Hay Creek drainage (previously noted in Sanders et al., 2003) and Coal Spring located on lower Squaw Creek near its confluence with Clear Creek. Chemical data from these natural springs obtained during the study period are provided in Table 5.3-2 and are plotted in Figure 5.3-9.

Table 5.3-2. Concentration of selected ions (mg/L) in grab samples taken from the indicated natural springs (a large spring near Breen Road on the lower Hay Creek drainage and Coal Spring on lower Squaw Creek).

Sampling Date	Ca	Mg	K	Na	SO_4	HCO_3	Cl	pH (std units)	Specific Conduct. (µS/cm)	TDS	SAR
Coal Spring on lower Squaw Creek											
March 24, 2004	325	316	14	763	3,340	605	13	8.01	5,890	5400	7.2
May 25, 2004	318	318	13	779	3,460	602	15	8.07	5,960	5590	7.4
April 7, 2005	294	294	14	822	3,280	637	15	7.89	5,930	5300	8.0
May 3, 2005	298	298	11	788	2,910	585	15	7.89	5,540	5010	7.7
May 17, 2005	315	315	12	718	3,190	620	15	7.87	5,840	4860	6.9
June 7, 2005	318	318	11	815	3,340	606	16	8.01	6,010	5490	7.7
April 12, 2006	321	321	14	822	3,270	646	17	8.12	5,730	5450	7.8
May 3, 2006	318	335	16	912	3,250	611	13	8.20	3,010	5570	8.5
Median:	**318**	**317**	**14**	**802**	**3,275**	**609**	**15**	**8.01**	**5,910**	**5425**	**7.62**
Hay Creek Spring at Breen Road											
July 26, 2001	520	360	16	95	3,080	6	10	5.54	4,110	4490	0.78
April 16, 2002	470	360	14	98	2,880	6	13	5.58	3,890	4140	0.80
Median:	**495**	**360**	**15**	**97**	**2,980**	**6**	**12**	**5.56**	**4,000**	**4315**	**0.80**

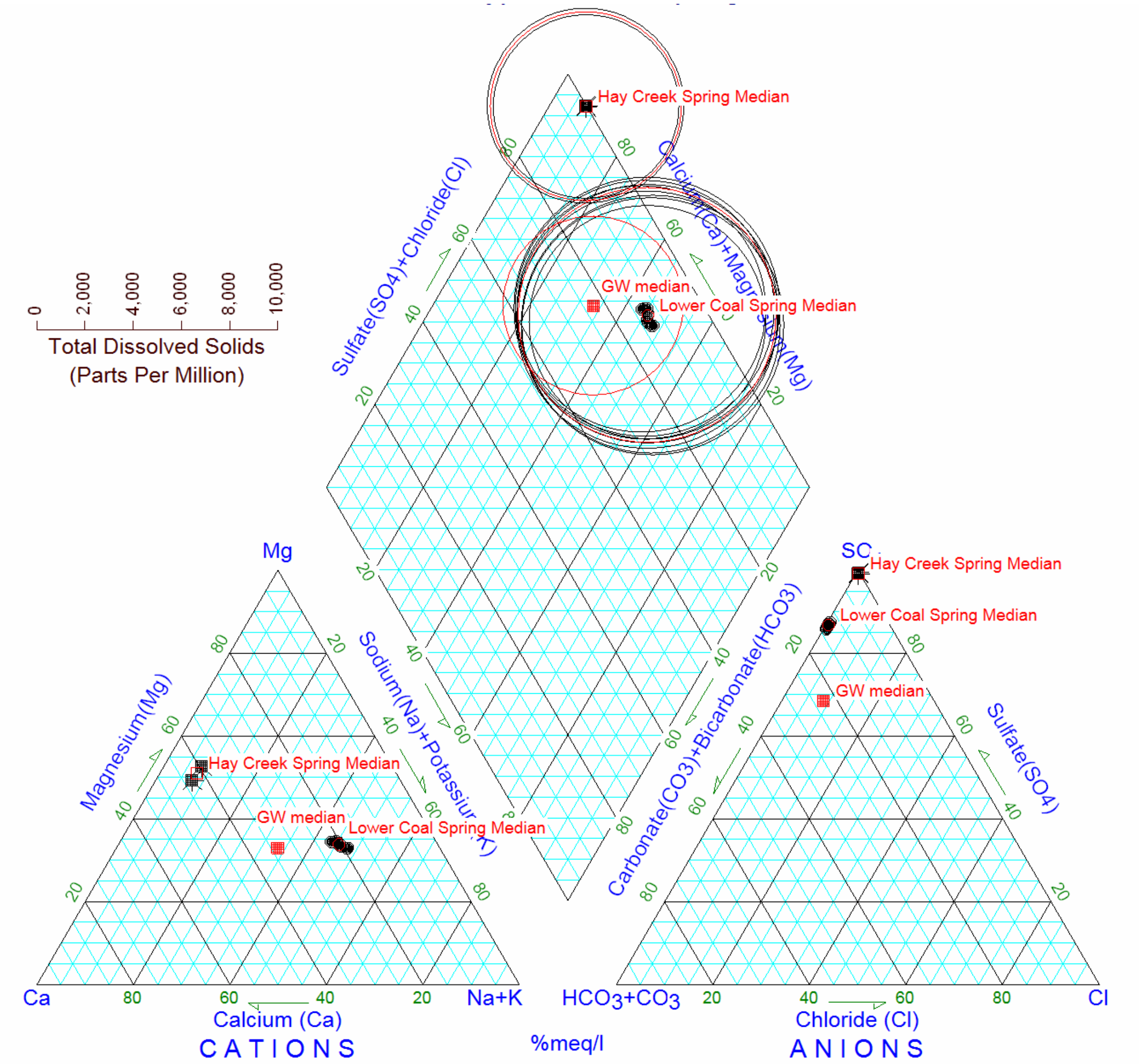


Figure 5.3-9. Water types of two natural springs in the study area (see text for locations). [The radius length of each plotted circle represents total dissolved solids concentration (mg/L) as provided in the legend.]

Two samples were taken from the Breen Road spring on lower Hay Creek, one sampling each in 2001 and in 2002. Each sample yielded very consistent data. The median TDS concentration and pH were 4,315 mg/L and 5.56, respectively. The dominant cations were Ca and Mg, which together represented 85.7 of the mole percent of major cations; Na represented just 13 mole percent. The dominant anion was SO_4, which represented 98.7 of the mole percent of major anions; HCO_3 represented 0.3 mole percent.

A small spring flowing into lower Squaw Creek, Coal Spring, emanates from a coal stringer (approximate 8- to 10-foot thick) exposed at the surface over a distance of several hundred feet along the creek channel. A total of eight (8) water samples were taken from March 2004 through May 2006, which yielded consistent chemical data. The chemistry of the Squaw Creek spring is very different from the spring on lower Hay Creek. At Squaw Creek, the median TDS concentration and pH were 5,425 mg/L and 8.0, respectively. The dominant cation was sodium, which represented 62.1 of the mole percent of major cations; Ca and Mg represented 14.1 and 23.2 mole percent, respectively. The dominant anion was SO_4, which represented 76.6 of the mole percent of major anions; HCO_3 represented 22.4 mole percent. Landowners have noted anecdotally that the very high sodium concentrations (median 802 mg/L) evident at the Coal Spring on Squaw Creek (Table 5.3-2) were present at other locations in the study area before CBM development. The data from Squaw Creek indicate that sodium concentrations of many hundreds of milligrams per liter may be found naturally in springs located in NE Wyoming ephemeral drainages.

Storm Water

As overviewed in Section 4, water samples were collected at 11 sites on nine (9) study drainages during storm flow events occurring from August 2001 through August 2006. We consider here whether the observed concentrations of dominant ions by watershed and by storm event indicate influence of CBM development. The context for such an evaluation includes the spatial heterogeneity evident in the study watersheds related to both the natural chemistry of existing surface waters and to the diversity of exposed geologic strata, whose constant weathering is a primary source of natural solutes in transport during storm flows (Section 2.1). To highlight this heterogeneity in the context of CBM development, the geochemical variability among individual storm events are compared below. Significant chemical effects of CBM discharges would be characterized by increases in the relative mole percentages of Na and HCO_3, and decreases in the relative mole percentage of SO_4, either over time as CBM development ensues or on the basis of spatial comparisons among the study watersheds. In the evaluation presented below, median values of chemical attributes are variously compared to grand flow-weighted mean values among water types. The authors feel that the best measures of central tendency—median and flow-weighted grand means—should be used to compare individual water types based on available data. Our observations on storm water geochemistry are as follows.

The June 2002 storm event on Hay Creek at Mouth (a CBM-developed watershed), which is a perennial stream segment having significant inflow of natural groundwater, yielded a Ca + Mg, HCO_3 signature (Figure 5.3-10). The strong positive correlation between sodium and sulfate in the Hay Creek data (Table 5.2-1) suggests a landscape source for the sodium and does not suggest strong influence of upstream CBM discharges. In comparison, the August 2006 storm event recorded on Dry Fork, which has CBM development in its upper reaches, yielded a Ca, HCO_3 signature with much lower concentrations of Na and SO_4. However, given the high calcium and bicarbonate background of surficial geologic materials in the Basin, significant CBM influences cannot be unambiguously inferred. Overall, storm data from both of these drainages do not suggest that CBM influences predominate.

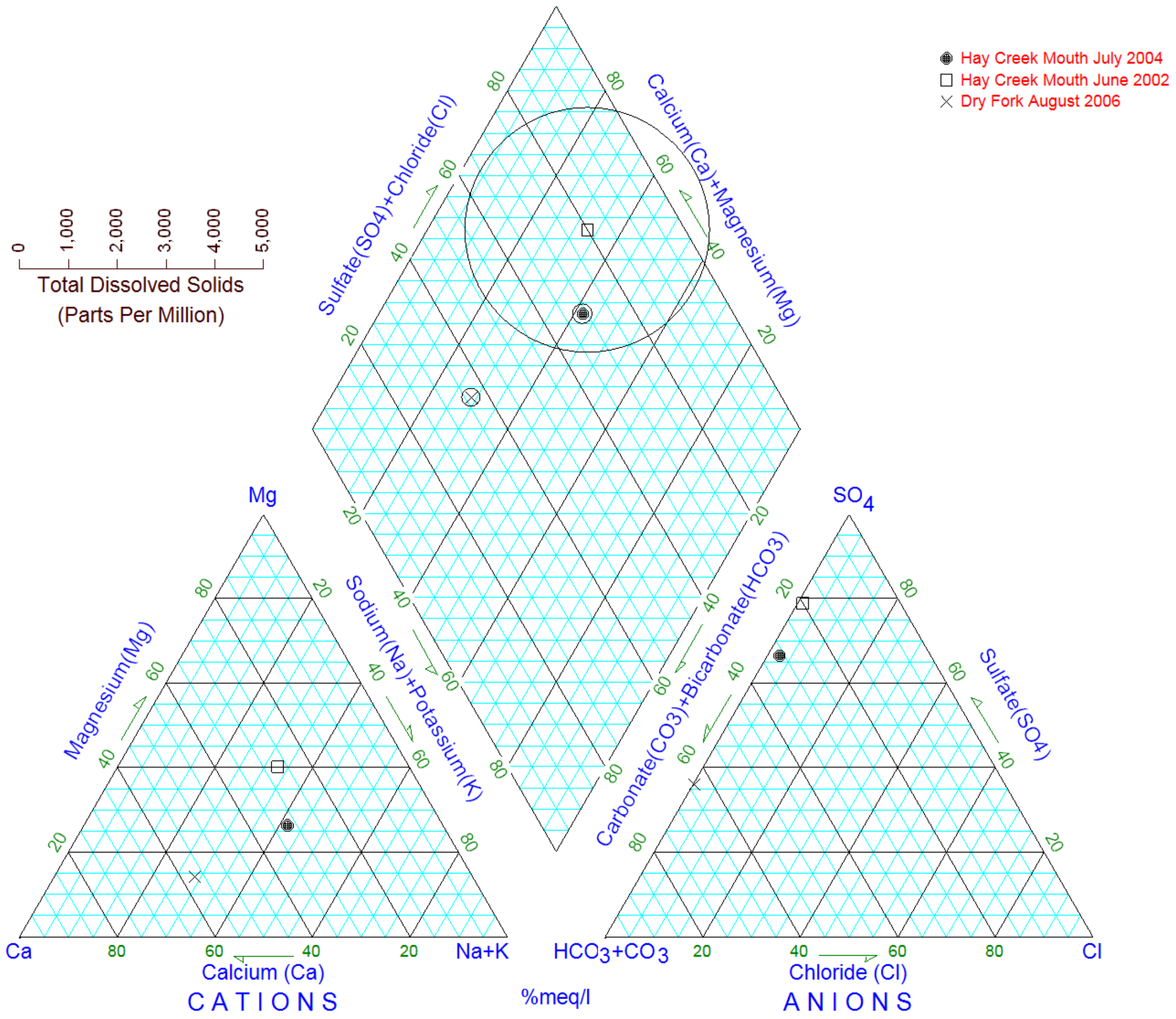


Figure 5.3-10. Hay Creek and Dry Fork storm event water types.
[The radius length of each plotted circle represents total dissolved solids concentration (mg/L) as provided in the legend.]

Three storm events on Flying E Creek, a CBM-developed watershed, each showed markedly different water chemistry signatures: Ca + Mg, SO_4; Ca + Mg, HCO_3; and Na, HCO_3 (Figure 5.3−11). The modest June 2006 flow event (31.0 cfs peak discharge, 1.51 cfs mean discharge) was characterized by relatively low concentrations of Na and relatively high concentrations of SO_4, neither of which suggests significant CBM influences. A small discharge event in April 2005 (2.7 cfs peak discharge, 0.21 cfs mean discharge) showed a Na, HCO_3 signature. The high correlation between Na and HCO_3 suggests potential CBM influence given the large number of CBM outfalls located in the lower drainage. The low peak discharge and low SO_4 concentrations suggest that near-field precipitation occurred and entrained solutes dominated by Na and HCO_3. Spatially broad landscape interactions apparently were low. The relatively large May 2005 discharge event (25.0 cfs peak discharge, 4.54 cfs mean discharge) had an intermediate chemistry that included substantial SO_4

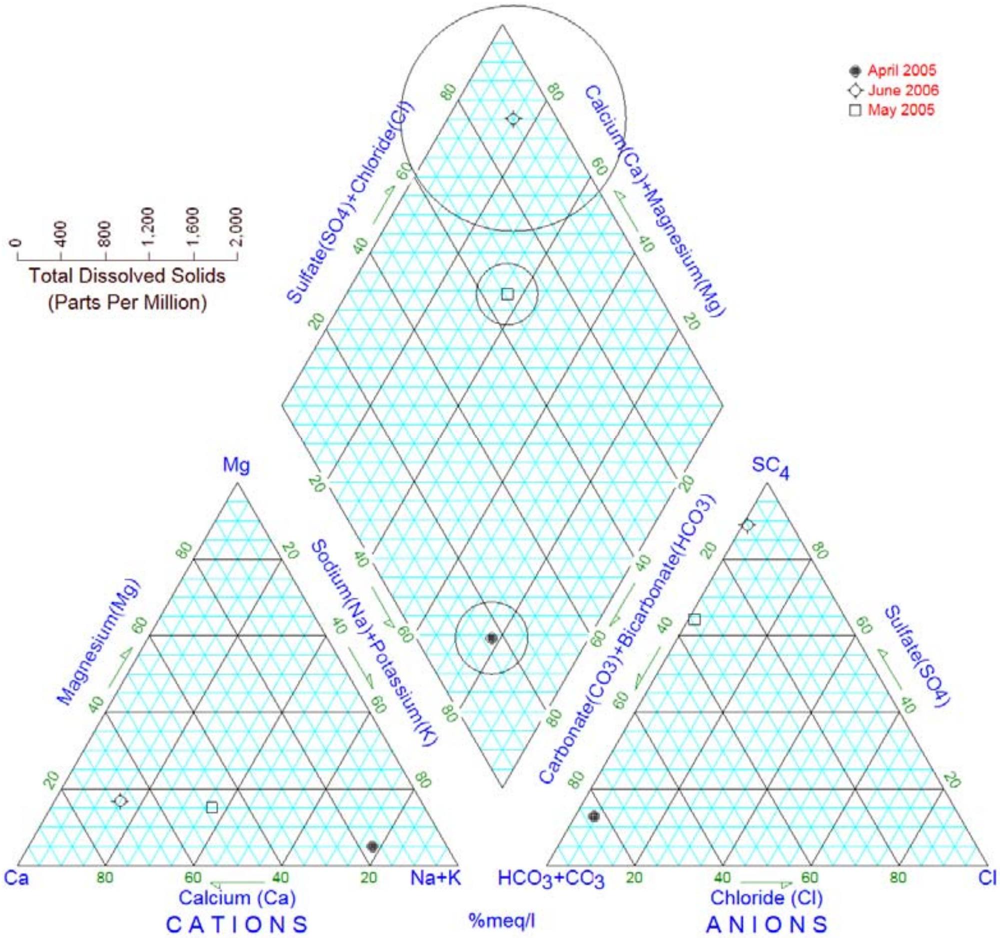


Figure 5.3-11. Flying E Creek storm event water types.
[The radius length of each plotted circle represents total dissolved solids concentration (mg/L) as provided in the legend.]

concentrations indicating significant landscape contributions to observed solute concentrations. Overall, the storm flow data for the Flying E Creek gage site do not suggest consistent, significant influences of CBM discharges given that chemistry data for the larger observed storm events indicate that landscape influences primarily control their discharge chemistry. The possible exception is near-field precipitation relative to the gage site that results in limited storm discharge and presumably limited landscape interaction. It is also important to restate, as previously discussed in Section 5.1, that minor storm flows as observed in April 2005 are expected to have relatively short flow distances down a stream channel due to the high channel storage capacity characteristic of ephemeral streams in the PR Basin. The high within-site variability of these data indicates the difficulty of quantifying relative CBM effects at a single gage site.

Barker Draw, an intensively CBM-developed watershed, experienced four (4) storm events, two (2) in August 2002, and two (2) in spring 2005 (Figure 5.3−12). The 2005 storms had high TDS values (3,332 and 4,817 mg/L), whereas the 2002 storms exhibited low TDS values (1,135 and 894 mg/L). The 2005 storms yielded slightly more sodic waters but still had a Ca+Mg, SO_4 signature. Additionally, the Ca/Mg ratios had a reciprocal relationship with regard to the 2002 versus 2005 storms. The 2002 storms had Ca/Mg mole ratios of 1.7 and 3.1, whereas 2005 storms each had Ca/Mg mole ratios of 0.4. These observations suggest that evaporite minerals (especially Na and Mg salts) may have accumulated in the watershed during the 3-year interval between significant storm discharges and were subsequently leached during the 2005 storms. These data are consistent with the known, relatively high rates of dissolution of prevalent Na salts of SO_4 and HCO_3 and of $MgSO_4$ from landscapes (Dove and Czank, 1995). The SO_4-HCO_3 ratios remained nearly equal for all storm events, suggesting little, if any, CBM water influence in the storm water chemistries. A comparison of Barker Draw pothole chemistries with Barker Draw storm events shows good agreement with regard to their Ca+Mg, SO_4 signatures, SAR, pH, and major ion ratios (Table 5.3−3; Figure 5.3−13). However, median pothole TDS concentrations were 2.4 times those of the storm events, which is consistent with potholes having concentrated solutes due to ET effects. All data analyzed for Barker Draw suggest little, if any, overall influence of CBM water.

Table 5.3-3. Barker Draw pothole chemistries versus storm event data.

Parameter	Barker Draw Pothole Medians	Barker Draw Storm Events Flow-weighted Grand Means
TDS (mg/L)	5265	2479
SAR	3.9	3.1
SO_4/HCO_3 mole (%)	8.7	2.9
Na/(Ca + Mg) mole (%)	0.8	0.9
pH	8.2	7.9

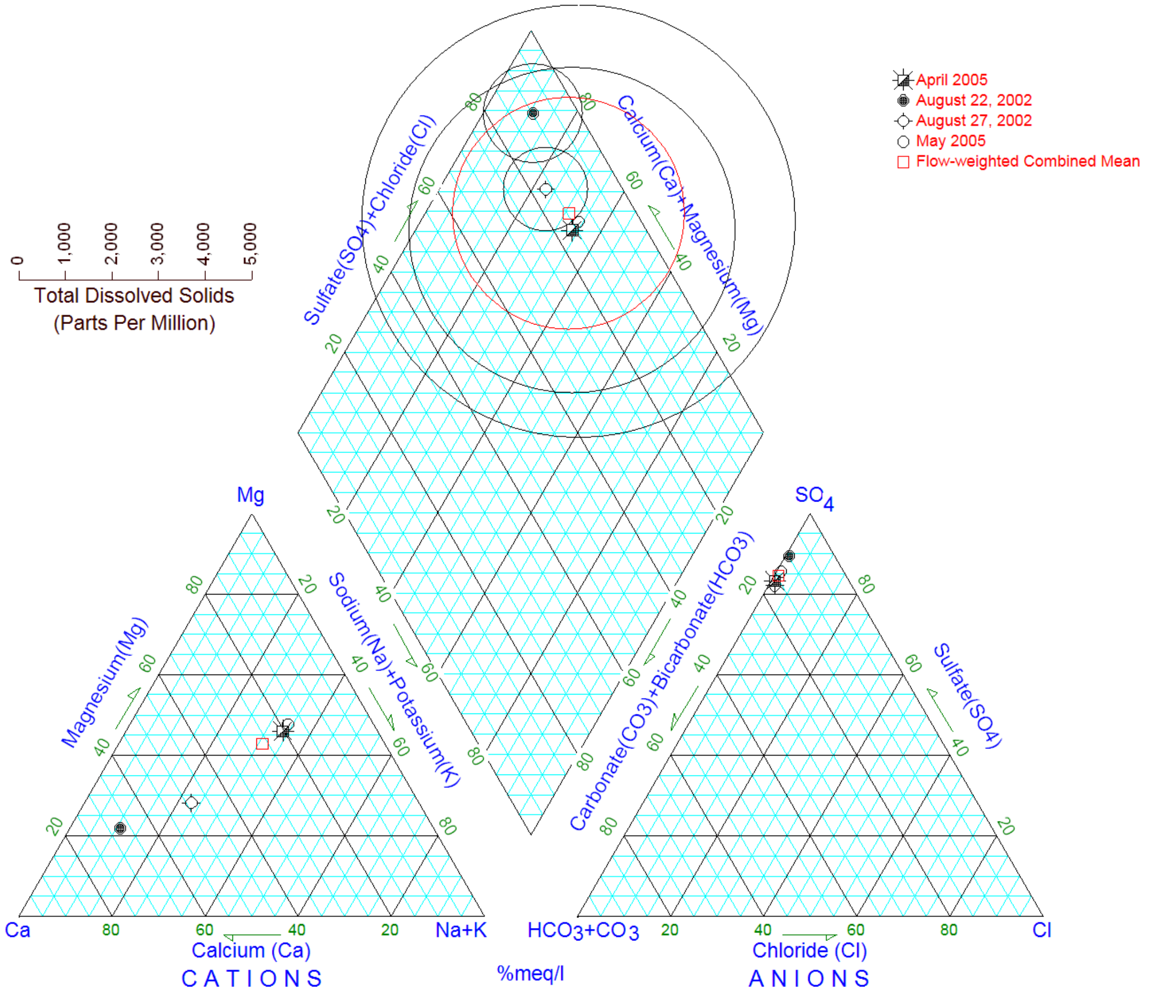


Figure 5.3-12. Barker Draw storm event water types.
[The radius length of each plotted circle represents total dissolved solids concentration (mg/L) as provided in the legend.]

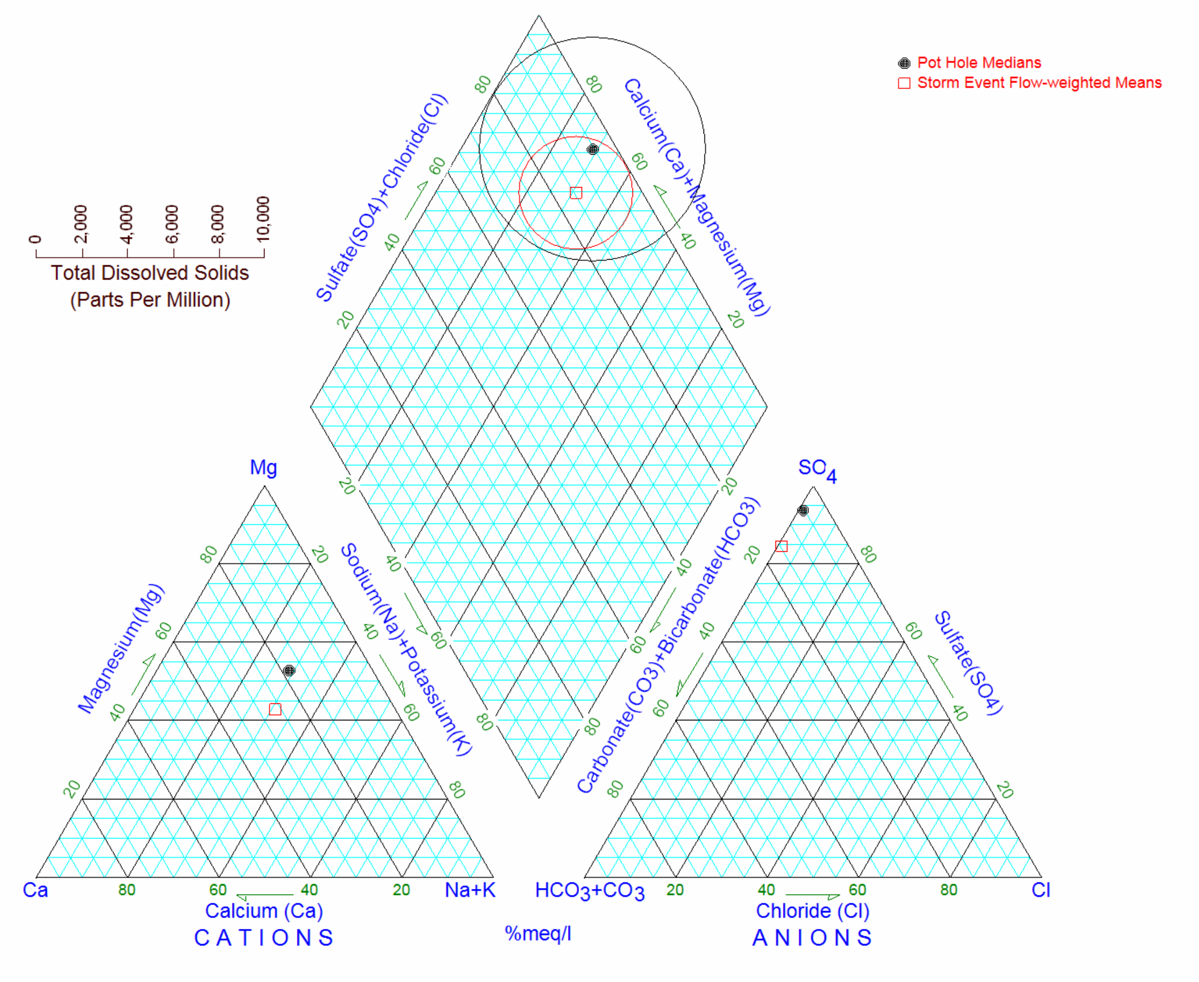


Figure 5.3-13. Comparison of Barker Draw water types: pothole medians and storm event flow-weighted means. [The radius length of each plotted circle represents total dissolved solids concentration (mg/L) as provided in the legend.]

On Pumpkin Creek, four (4) storm events were monitored at the Iberlin gage site and five (5) events were monitored at the Near Mouth gage site during the study period. These include four (4) events observed simultaneously at both sites: two (2) large storm events in August 2002 and in June 2003; and two (2) small storm events in May 2003 and in August 2005 (Figures 5.3−14, 15). The two (2) largest storm events had lower TDS concentrations than the two (2) smaller storms. This observation is consistent with larger storm events producing more runoff and presumably higher dilution of solute concentrations relative to the loading rate from precipitation-affected areas. The observed water chemistries from these events commonly had a Na, SO_4 signature, with Na representing 76.9 of the average mole percentage of major cations and SO_4 and HCO_3 representing 52.6 and 45.2 of the average mole percentage of major anions. No clear trend of storm discharge water chemistries exists over the period of record: the earliest storm had a pronounced Na, HCO_3 signature, and the June 2003 storm had the lowest Na proportion of major cations. Available data do not suggest significant effects of CBM discharges on storm water chemistry even though this watershed has undergone considerable CBM development during the study period.

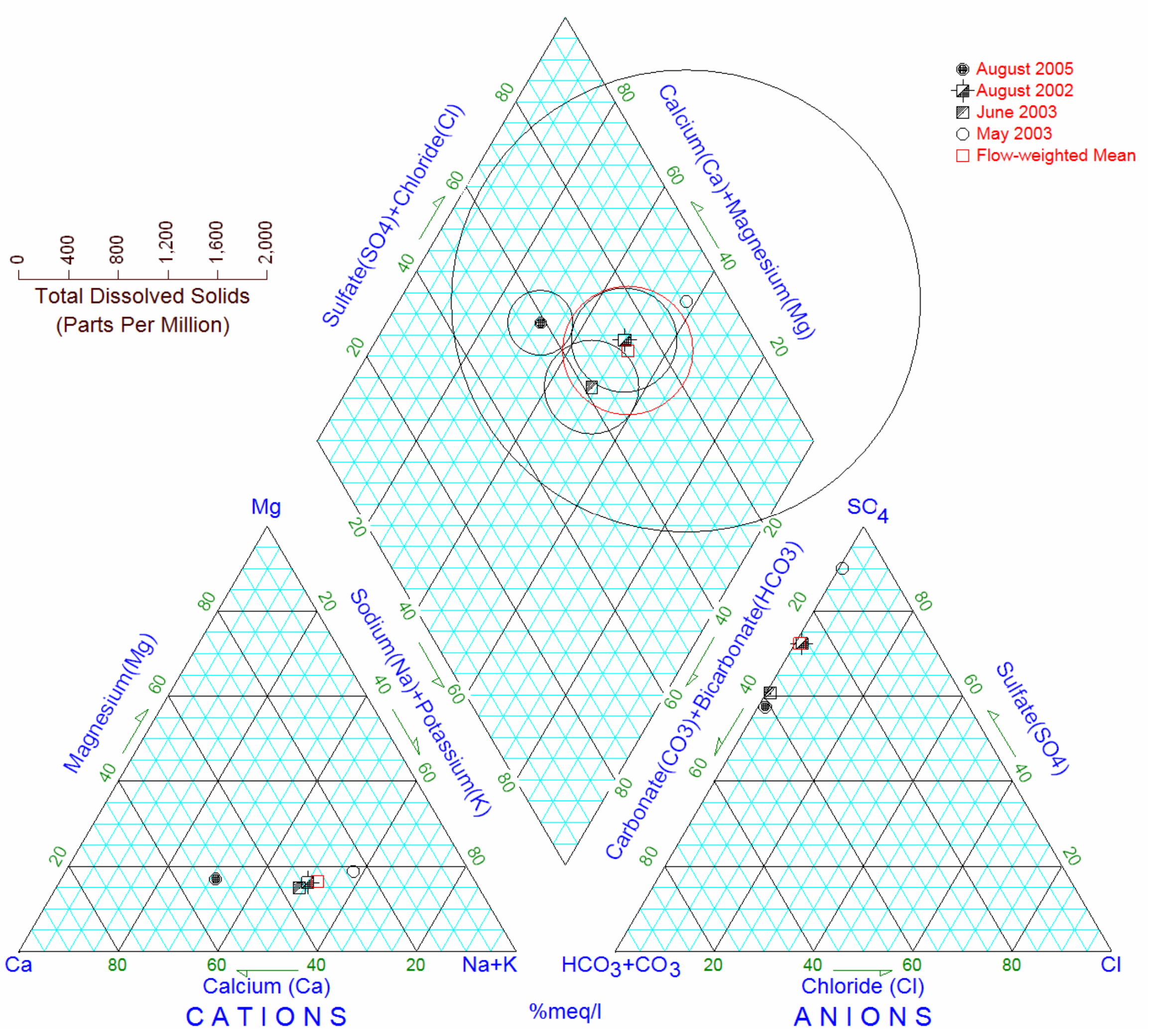


Figure 5.3-14. Pumpkin Creek at Iberlin storm event water types.
[The radius length of each plotted circle represents total dissolved solids concentration (mg/L) as provided in the legend.]

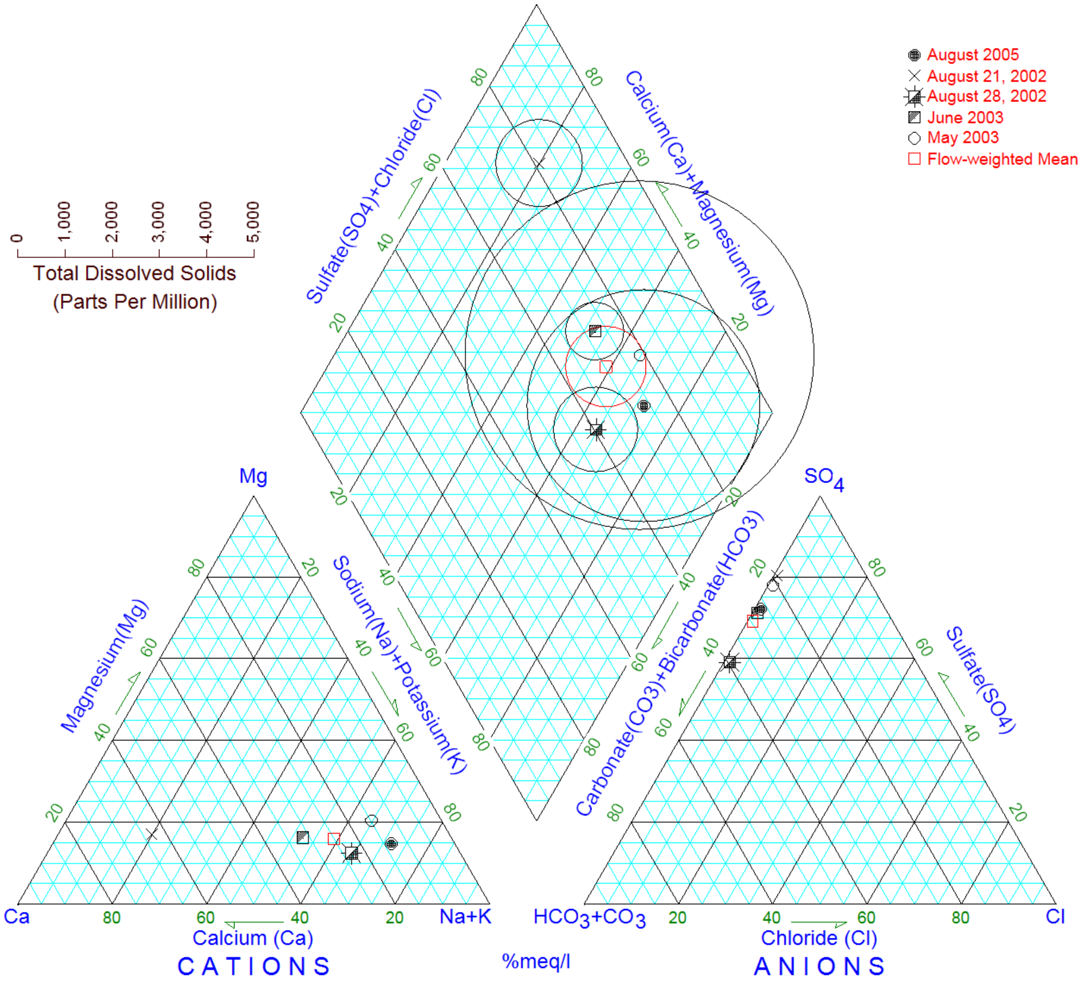


Figure 5.3-15. Pumpkin Creek near Mouth storm event water types.
[The radius length of each plotted circle represents total dissolved solids concentration (mg/L) as provided in the legend.]

Several additional observations are warranted regarding the two (2) storm events in the Pumpkin Creek drainage that have the highest proportional concentrations of Na and HCO_3: August 28, 2002 and August 10, 2005. During the August 28, 2002, event, concentrations of Na, Ca, Mg, HCO_3, and SO_4 followed patterns suggesting a landscape influence (Sanders et al., 2003). The R^2 correlation value for the Na-SO_4 correlation was 0.956 (Table 5.2-1), which indicates that Na is derived from the landscape and reflects dominance of landscape influences in storm flow chemistry. In contrast, the August 10, 2005 storm event had opposite patterns between SO_4 and HCO_3 and between Na and Ca concentrations (Appendix B; Figures B.1.2.2.3-3 and -4). This storm event also yielded the lowest R^2 correlation value between Na and SO_4 (0.671; Table 5.2-1) of any storm event monitored at the Pumpkin Creek near Mouth gage during the study period. Although this lower correlation may reflect limited influence of upstream CBM discharges, the magnitude of the possible CBM influence is low, if present at all, because the sodium-sulfate R^2 value was still substantial. Both of these storm events had pronounced Na, SO_4 water types; overall, their respective chemical data do not suggest significant CBM-related influences on storm discharge chemistry in Pumpkin Creek.

In addition to the above, a comparison of Pumpkin Creek pothole chemistries with those of Pumpkin Creek storm is informative (Table 5.3−4; Figure 5.3−16). Both potholes and storm events yielded Na, SO_4, or Na+Ca, SO_4 water types. Combined storm events exhibited lower SO_4/HCO_3 (1.2) and higher Na/(Ca + Mg) (2.5) mole ratios than those of potholes (13.1) and (2.5), respectively. Potholes yielded an SAR value of 10.8, while storm events yielded an SAR of 3.6. Interestingly, while potholes had a much higher SAR than storm events, the Na/(Ca + Mg) mole ratio for potholes was somewhat *lower* than that for storm events (Table 5.3-4). This result occurred because of the high TDS concentrations of potholes relative to storm events, and underscores the need to consider SAR in relation to TDS and EC. Although both the SO_4/HCO_3 and the Na/(Ca + Mg) mole ratios may reflect limited CBM water influences, data from monitored storm events are variable and little, if any, degradation of storm water quality was apparent during the 2002 through 2006 sampling period even though the Pumpkin Creek underwent considerable CBM development during this same period.

Table 5.3-4. Comparisons of water chemistries at Pumpkin Creek gage sites.

Parameter	Pumpkin Creek Pothole Data Medians	Pumpkin Creek Storm Events Flow-weighted Grand Means from Both Gage Sites
TDS (mg/L)	5,150	641.4
SAR	10.8	3.6
SO4/HCO3 mole (%)	13.1	1.2
Na/(Ca + Mg) mole (%)	2.5	2.5
pH	8.0	7.8

For lower LX Bar Creek near Mouth, the gage station recorded five (5) small storm events from July 2004 through June 2006 (Figure 5.3-17). The July 2004 storm was quite small (2.90 cfs peak discharge, 0.33 cfs mean discharge,) and occurred after at least a two (2) year interval with no significant storm discharge. The high TDS concentration found in the July 2004 storm is consistent with a buildup of soluble materials on the landscape and possible ET concentration of dissolved salts in residual pothole water entrained during storm discharge. This storm yielded a Na, SO_4 water type with Na accounting for 67.9 of the mole percentage of major cations and SO_4 accounting for 88.8 of the mole percentage of major anions.

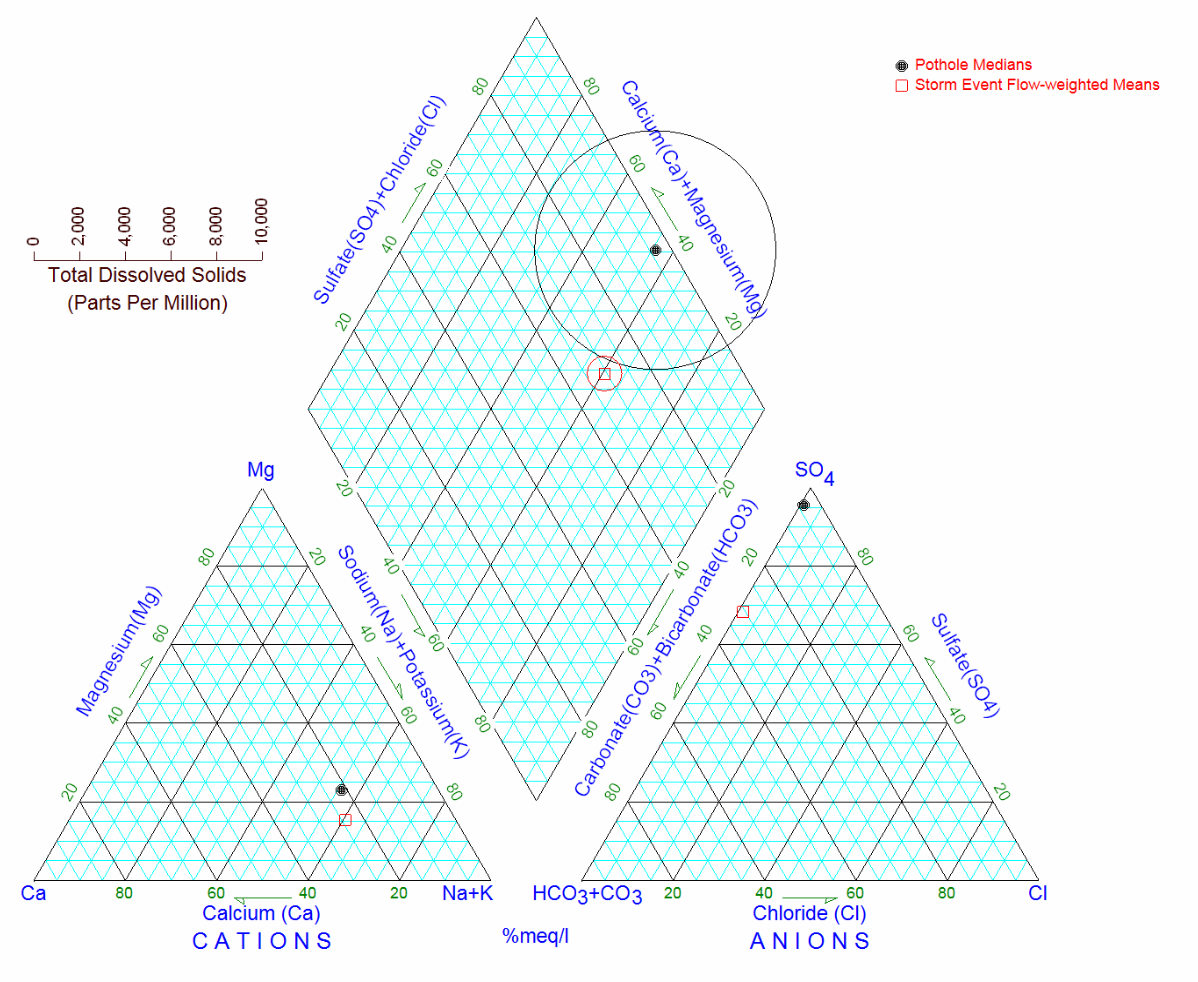


Figure 5.3-16. Comparison of pothole medians and storm event flow-weighted means, Pumpkin Creek.
[The radius length of each plotted circle represents total dissolved solids concentration (mg/L) as provided in the legend.]

The July 2004 storm event at the lower LX Bar Creek gage contrasts significantly with the June 2006 storm because the lower channel was allowed under Wyoming Pollution Discharge Elimination System (WYPDES) permit to contain a small, continuous and time-limited CBM flow beginning in July 2005. Thus, the June 2006 rainstorm event (5.1 cfs peak discharge; 1.87 cfs mean discharge) was superimposed on a pre-existing CBM flow, which was estimated to be approximately 1.4 cfs based on before- and after-event hydrograph data (combined event peak discharge of approximately 6.5 cfs; Appendix B; Figure B.1.3.5-3). The June 2006 rainstorm/CBM mixture had a Na, HCO_3 signature with the following attributes: Na accounted for 94.8 of the mole percentage of major cations; SO_4 accounted for 10.5 of the mole percentage of major anions; and HCO_3 accounted for 87.5 of the anion mole percentage. The relatively modest June 2006 combined storm discharge had a negative correlation of Na to SO_4 and a high positive correlation of Na to HCO_3. The June 2006 storm data suggest that a Na, SO_4 water type was derived from the landscape during the storm and that the effect of the perennial flow of CBM water was to increase the relative concentrations of Na and especially HCO_3. The June 2006 rainstorm event was relatively minor and a much greater dilution of CBM influences would be expected had the rainfall runoff been of higher magnitude. Samples from the small October 2005 storm at LX Bar Creek near Mouth also indicated similar patterns with time for Na and HCO_3 and yielded a negative correlation between Na and SO_4. Such relationships in mixed storm runoff/CBM waters are expected in other stream segments in the PR Basin perennialized under time-limited WYPDES permits.

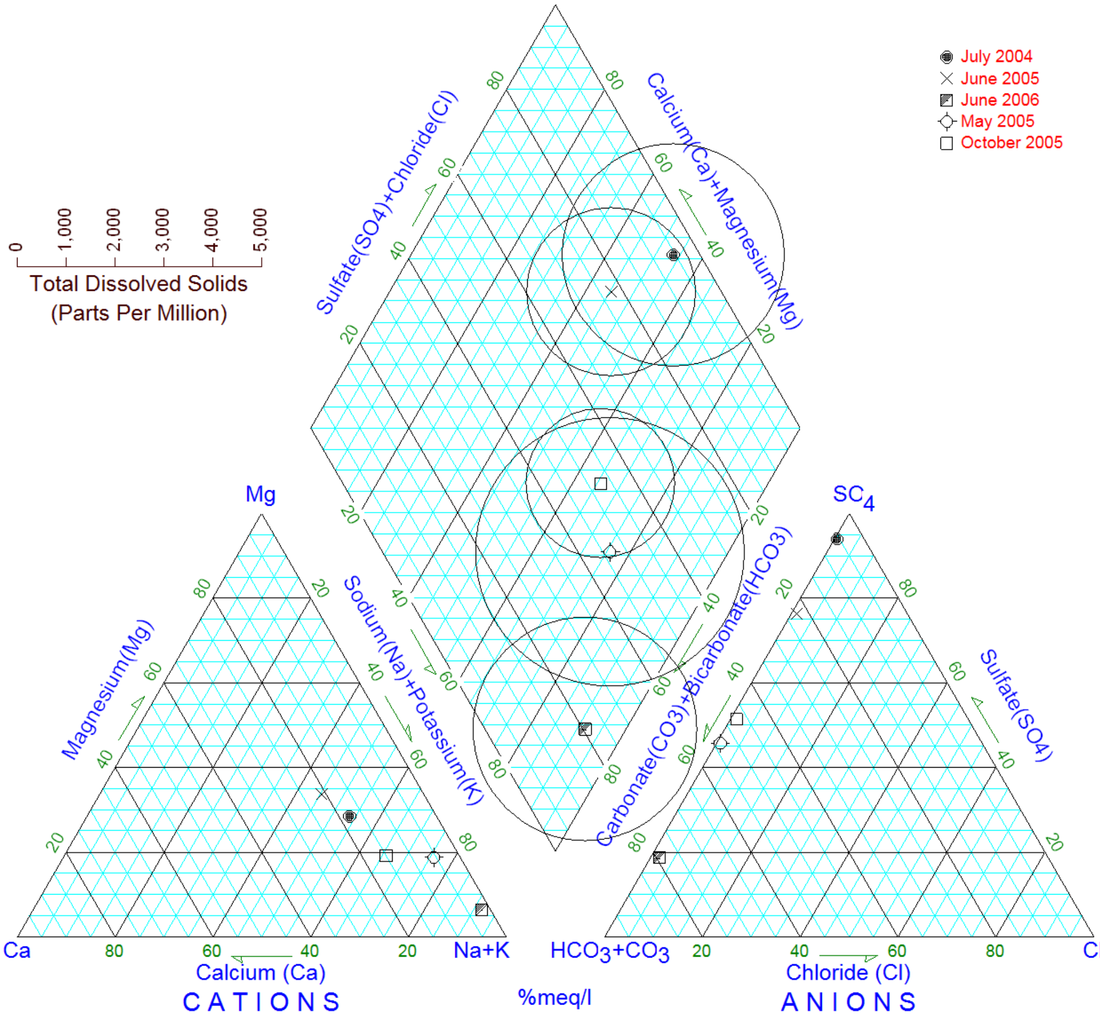


Figure 5.3-17. LX Bar Creek near Mouth storm event water types.
[The radius length of each plotted circle represents total dissolved solids concentration (mg/L) as provided in the legend.]

For lower LX Bar Creek, a comparison of data from storm events, potholes, alluvial groundwater, and perennialized (CBM) flow is provided in Table 5.3−5 and Figures 5.3-18 and 5.3-19. As noted above, the chemistry of perennialized streamflow, determined from grab samples obtained in August and September 2005, show strong CBM influence as evidenced by the dominant Na, HCO3 water type (Figure 5.3−18). Pothole samples from LX Bar Creek and shallow alluvial groundwater collected near the LX Bar Creek channel prior to July 2005 had similar chemistries, suggesting that groundwater significantly influenced pothole chemistry before July 2005. Available chemical data from storm events, potholes, alluvial groundwater, and perennialized non-storm flow indicates significant influence from continuous CBM discharges to the lower creek channel during low to modest storm discharges in the lower drainage with a presumed decreasing influence as storm discharge increases.

Further heterogeneity of observed storm flow chemistry among study watersheds is illustrated by data obtained at Headgate Draw and Bloom Creek gages; neither drainage is CBM developed. During the study period, the Headgate Draw gage site experienced at least eight (8) storm events, and the Bloom Creek site experienced six (6) storm events. The frequency of storm flow in these watersheds is among the highest observed among the study sites suggesting that surface materials are relatively well leached in these drainages. Both sites yielded consistent water chemistry with a Ca, SO_4 signature (Figures 5.3−20 and 5.3−21). Headgate Draw and Bloom Creek discharges exhibited low Na concentrations, with flow-weighted means of 16.7 and 34.3 mg/L, compared to Ca concentrations of 233.5 and 88.4 mg/L, respectively. These concentrations resulted in low SAR values of 0.3 for Headgate Draw and 0.9 for Bloom Creek. For the respective gages at Headgate Draw and Bloom Creek, average mole concentrations of SO_4 exceeded those of HCO_3 by factors of 5.0 and 1.8; and TDS concentrations and pH averaged 1,131 and 579 mg/L and 7.31 and 7.39 units. Importantly, these data exhibit the low end of natural sodium concentrations observed in the study watersheds but do not constitute a representative baseline condition for ephemeral tributaries to the Powder River. Determination of actual baseline conditions in the diverse Powder River ephemeral tributaries has not been accomplished by required systematic study. Storm flow chemistries observed for these two (2) watersheds, however, do illustrate that the concept of geochemical baseline for Powder River ephemeral tributaries is not easily quantified given the high natural heterogeneity apparent within the Basin including both poorly leached and highly leached drainages.

Table 5.3-5. Comparisons of chemistries of various water types in lower LX Bar Creek.

Parameter	LX Bar Creek Pot Hole Data Medians	LX Bar Creek Alluvial Groundwater Data Medians	LX Bar Creek near Mouth Storm Events Flow-weighted Grand Means	LX Bar Creek near Mouth Non-Storm Perennialized Flow Medians
TDS (mg/L)	8,080	6,930	1,763	1,690
SAR	11.0	8.6	7.2	26.2
SO4/HCO3 mole (%)	7.5	3.1	0.8	0.04
Na/(Ca + Mg) mole (%)	2.1	1.7	3.0	24.5
pH	8.2	7.3	8.1	8.6

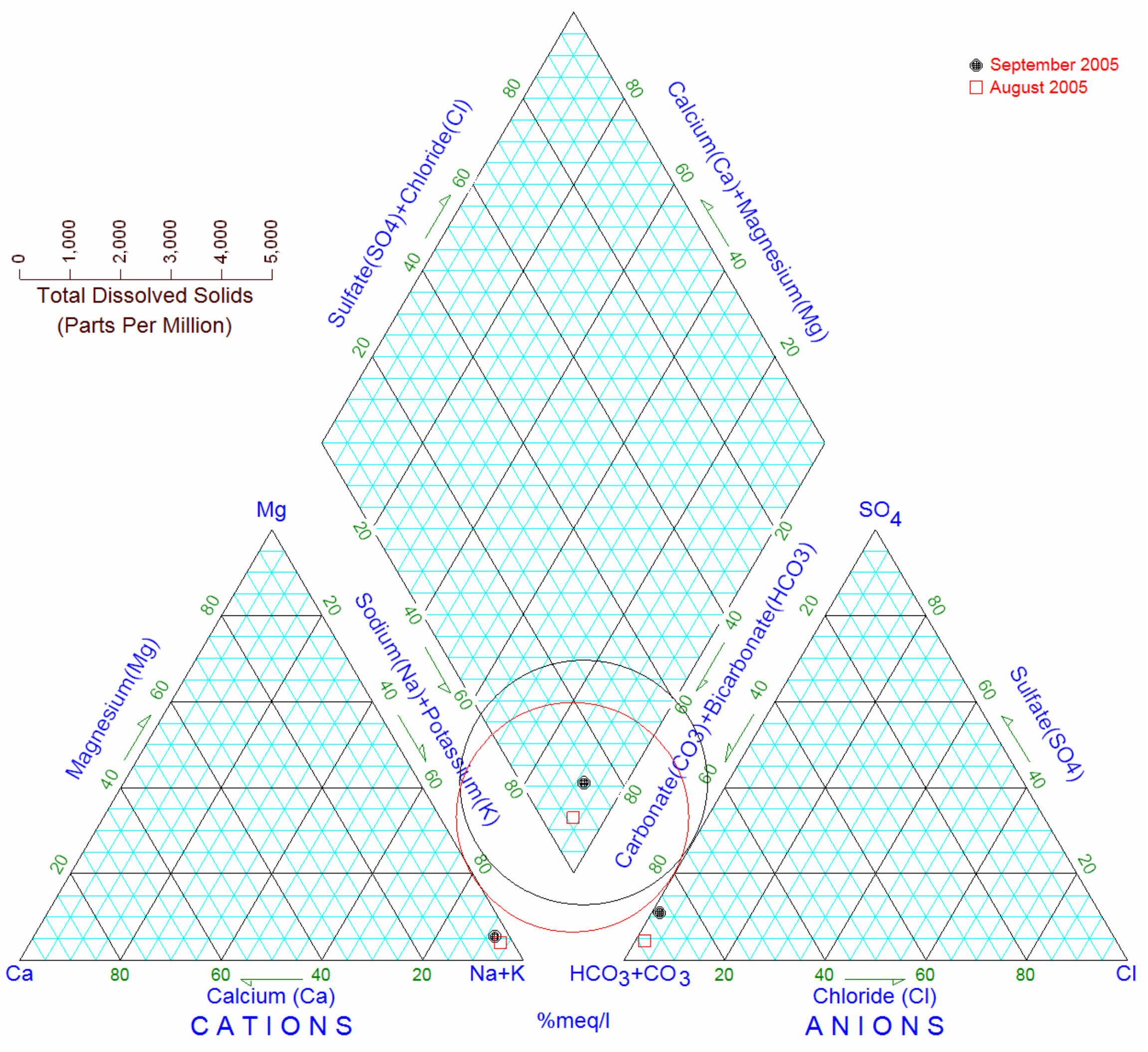


Figure 5.3-18. CBM water perennialized flow medians, LX Bar Creek near Mouth.
[The radius length of each plotted circle represents total dissolved solids concentration (mg/L) as provided in the legend.]

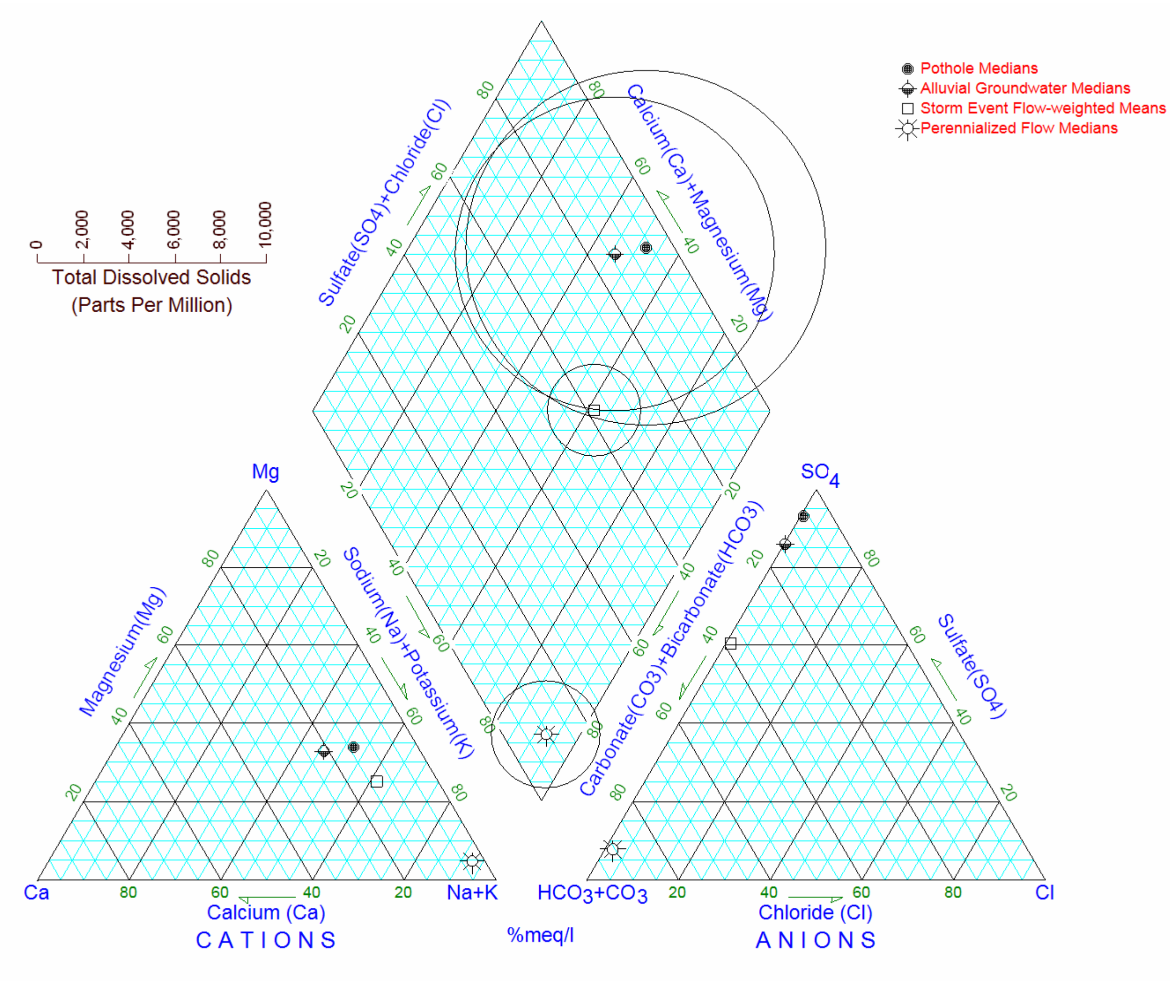


Figure 5.3-19. Comparison of pothole medians, alluvial groundwater medians, CBM water perennialized flow medians, and storm event flow-weighted means at LX Bar Creek near Mouth.

[The radius length of each plotted circle represents total dissolved solids concentration (mg/L) as provided in the legend.]

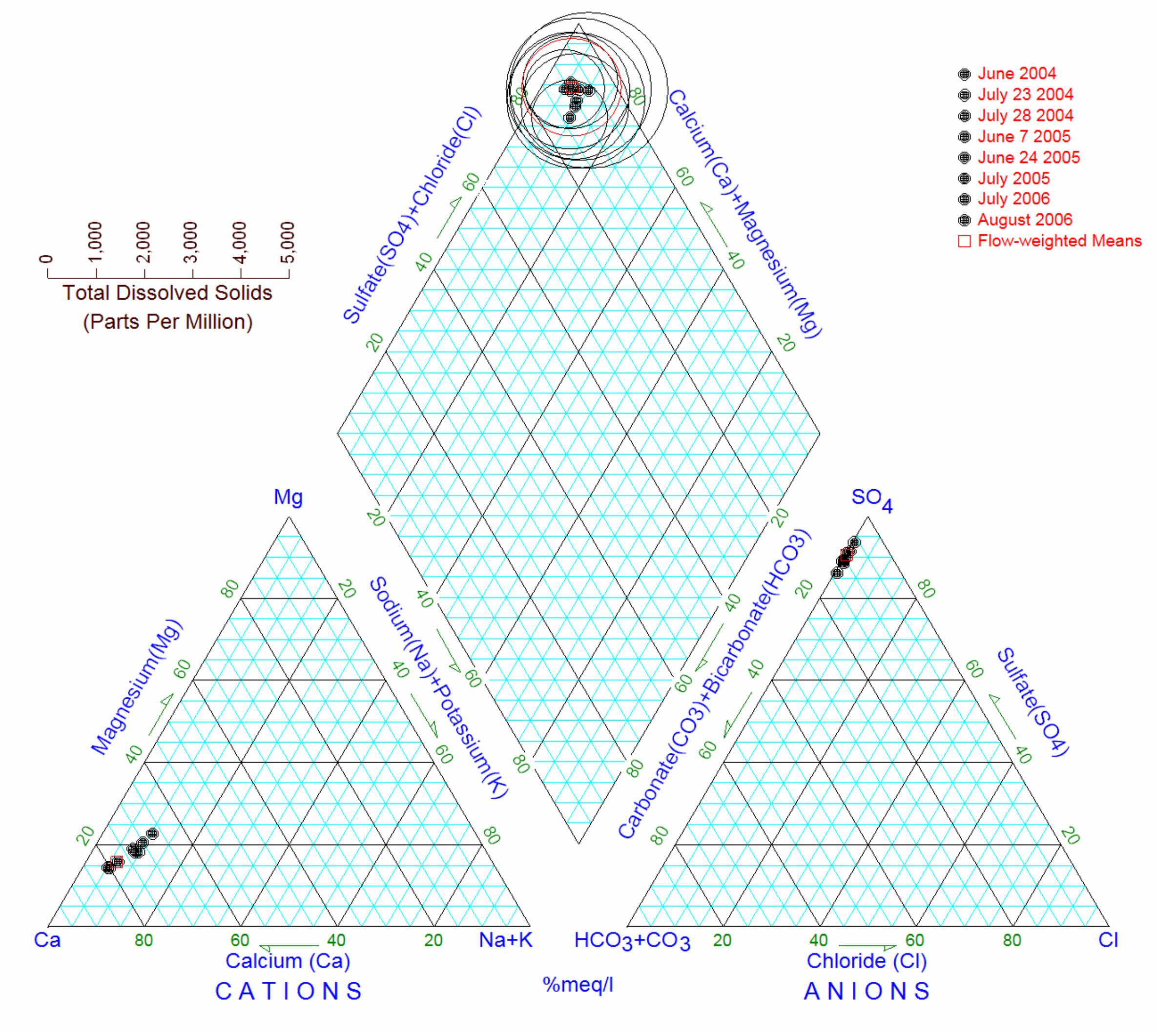


Figure 5.3-20. Headgate Draw storm event water types.
[The radius length of each plotted circle represents total dissolved solids concentration (mg/L) as provided in the legend.]

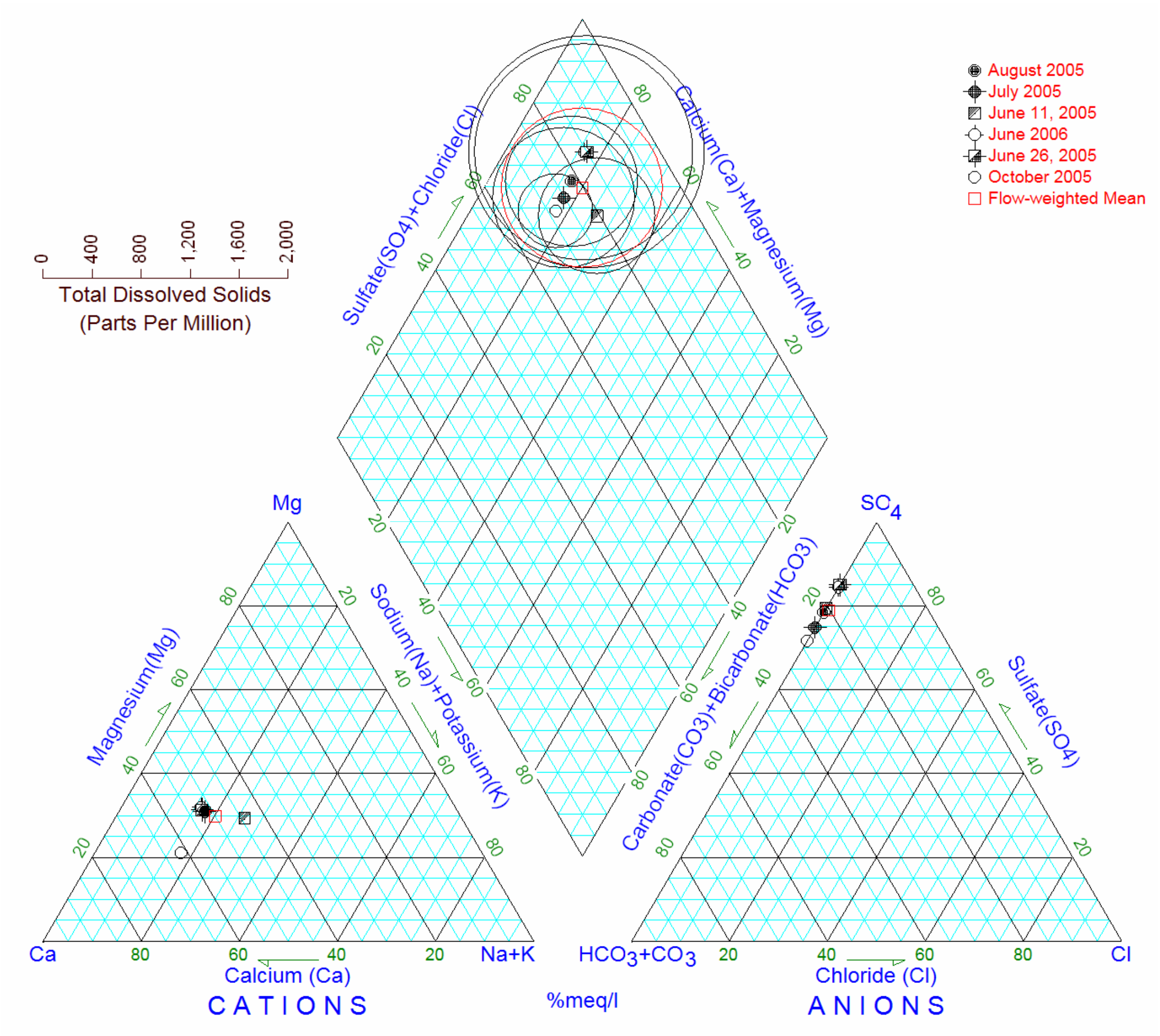


Figure 5.3-21. **Bloom Creek storm event water types.**
[The radius length of each plotted circle represents total dissolved solids concentration (mg/L) as provided in the legend.]

Summary

A comparison of the geochemistries of direct precipitation pothole water, and shallow alluvial groundwater in study watersheds provides evidence for considerable natural sources for solutes transported down ephemeral stream channels during storm flow events. Any deviations from natural storm water chemistry caused by discharges of CBM-produced water to the surface must be evaluated in this context of high natural solute flux. Such an evaluation should consider the natural, relative mole ratios of individual ions. Furthermore, the apparent high spatial heterogeneity of natural solute mole ratios derived from the weathering of diverse, exposed geologic strata also must be considered in the evaluation of potential CBM water-related changes in storm flow chemistry.

Within the apparent heterogeneity of natural waters found in the study watersheds, the observed geochemistries of near-surface alluvial groundwater, pothole water, and storm flows taken as a group can be summarized as: the Na:Ca:Mg mole ratio was on the order of 2:5:1.0:1.0; and the SO_4:HCO_3:Cl ratio was on the order of 12.0:7.0:1.0. Because of the ubiquity of Na in the surficial geology of the Powder River Basin (Section 2.1) and with the near absence of SO_4 in the presence of high concentrations of HCO_3 in CBM water, useful indicators of CBM water influence on natural waters are the relative abundance of SO_4 in relation to Na and the HCO_3/SO_4 mole ratios.

The evaluation of the geochemistry of storm flows in relation to pothole water, alluvial groundwater, and CBM-produced water demonstrates a limited ability to quantitatively discern a chemical signature from releases of CBM-produced water due to high natural background solute loadings and high spatial heterogeneity in storm discharge chemistry. The observed storm waters were most commonly typified by a Ca+Mg, SO_4 signature but contained abundant natural Na and HCO_3, which are also associated with CBM water discharges. The high and variable natural background concentrations of Na and HCO_3 do not facilitate quantitative estimation of relative CBM water discharge influence.

Data collected from the 2001 through 2006 water years in the study drainages when evaluated against potential chemical changes due to CBM effects indicate that the chemical influences of CBM water discharges on storm event chemistry with limited exceptions (see below) are not quantitatively apparent. Overall, the direct influence of CBM surface discharges during the study time period do not appear to be quantitatively significant to storm discharge chemistry observed in the study watersheds. Natural landscape processes, which provide for considerable solute flux during storm flows, appear to dominate most observed storm events and largely determine the geochemistry of the storm flows.

The limited exceptions in the 2001 through 2006 storm flow data include: possible near-field, relatively small precipitation events in areas with CBM discharges that have little apparent landscape interaction in the intervening distance between the origin (location) of resulting low-level storm runoff and the gage station; and small to modest storm event discharges superimposed on existing, WYPDES-permitted perennialized flow from direct CBM discharge in one lower reach of a PR tributary stream, lower LX Bar Creek. The first exception is not likely to produce significant long distance (many miles) runout of storm discharge given observed high channel storage capacity of storm flow (see discussion Section 5.1); the second exception also would be expected to be observed in other CBM-perennialized lower sections of naturally-ephemeral PR tributaries.

5.4 TRENDS IN STORM CHEMICAL DATA

As previously noted, this study was started after the onset of CBM development in most of the study watersheds. Therefore, the preferred method to quantity effects of CBM development on storm discharge geochemistry in study watersheds, that of a before-and-after development analysis, was not possible. In lieu of pre-versus post-development comparisons, the evaluation of time trends for individual watersheds is a useful approach. However, the low frequency of surface flow events resulting, in part, from the severe drought cycle occurring during the study period (Section 2) has prevented meaningful time trend analyses for most study drainages. After continuous record monitoring at nine (9) stations in CBM developed drainages over six (6) water years (2001 through 2006), only three (3) of those stations have experienced a sufficient number of flow events for trend analysis to be attempted. Some drainages have had no significant or measurable surface flows during the entire period of the study (Section 5.1). Thus, the observed low frequency of storm flows, while an important hydrologic feature of the Basin landscape, has largely precluded the time-trend method of assessing effects of CBM development on storm discharge chemistry and yield of solutes for most study watersheds. Time-trend analysis is expected to have more applicability as this study continues and more storm flow events are observed in CBM developed drainages.

Given the relatively sparse number of storm flows observed to date, the set of monitored flows lends itself primarily to comparisons over various spatial dimensions of the study area. However, concurrent observations over broad areas of the PR Basin during the CBM development cycle has their own set of limitations. Landscape heterogeneity in primary surface geologic and hydrographic features (Section 2) appears to significantly effect the chemistry of observed storm discharge (Section 5.3) and confounds interpretation of spatial differences among the study watersheds in relation to CBM development. To the extent practical, correlations and contrasts in storm discharge chemistry have been made among the study watersheds as follows.

A note is warranted regarding the multiple instances of hypothesis testing found in the following sections, particularly Sections 5.4.2 and 5.4.3, and the resulting statistical probabilities that are listed. The performance of large numbers of hypothesis tests, both tests of regression line slopes and two (2) sample comparisons of means, creates a high likelihood that one or more listed "significant" results actually represents a Type I error (i.e., concluding that a difference exists when it really does not). The multiple hypothesis tests performed do not represent sub-tests of multivariate analyses or multi-sample hypothesis testing, so the adjustment of statistical significance (alpha) levels was not necessarily appropriate and was not done (Zar 1984). Because the number of hypothesis tests performed and resulting probabilities (p values) reported create a strong likelihood that Type I errors exist in the reported results, emphasis should be placed on the overall pattern of statistical results rather than the p value from any individual test (Motulsky, 1995).

5.4.1 Analysis of Time Trends

Of the nine (9) Continuous Record stations in CBM developed drainages where storm flows were recorded, three (3) stations had a sufficient number of events for time trend analysis to be attempted. Those stations are Pumpkin Creek at Iberlin Ranch (four (4) events from 2002 through 2005), Pumpkin Creek near Mouth (five (5) events from 2002 through 2005), and LX Bar Creek near Mouth (five (5) events from 2004 through 2006). Although these stations are in drainages experiencing extensive CBM development during the study period, the time span and the number of events for each of these stations are minimal for attempting trend-in-time analyses. Nevertheless, such analyses may offer valuable insight into the overall watershed-level geochemistry of storm discharges in these drainages as development has progressed.

Table 5.4.1-1 presents results of the trend analyses performed for the above three (3) stations. For each station, analyses were performed for parameters of interest regarding CBM development. Those parameters were flow weighted means for EC, SAR, sodium concentration, and bicarbonate concentration, and finally total event sodium load. Increases in any of these parameters over time in developed drainages could potentially be a sign of impact from CBM development.

No significant trends (ά=0.05) were observed for any of the parameters of interest at any of the three (3) monitoring stations. As with results for other analyses described below, high observed variability in the data is likely the result of landscape heterogeneity and unpredictable patterns of precipitation events during the study period.

Table 5.4.1-1. Trend analysis results for storm flows in CBM developed drainages.
[Parameters examined are those for which an increase over time could potentially be considered indicative of impacts from CBM development. Regression analyses showed no statistically significant (ά=0.05) trends over the time periods of record at each station for any of the storm flow parameters.]

Station	Event Start Date	Flow weighted mean EC (uS/cm)	Flow weighted mean SAR	Flow weighted mean sodium (mg/L)	Flow weighted mean bicarbonate (mg/L)	Total event sodium load (kg)
LX Bar Creek near Mouth	July 5, 2004	2957	6.3	403.0	110.6	511
	May 11, 2005	3065	13.4	667.0	1155.8	21133
	June 9, 2005	2174	4.1	247.0	341.8	14231
	October 9, 2005	1832	7.1	310.7	587.6	3722
	June 23, 2006	2662	25.1	664.2	1317.8	1333
Trend Analysis Results:						
R^2		**0.13**	**0.52**	**0.13**	**0.57**	**0.01**
p		**0.55**	**0.17**	**0.56**	**0.14**	**0.88**
Pumpkin Creek at Iberlin Ranch	8/24/2002	540	2.1	54.2	96.6	11107
	5/27/2003	2378	6.5	345.2	147.3	31822
	6/16/2003	542	2.1	55.8	121.6	41230
	8/12/2005	389	1.0	26.1	90.5	218
Trend Analysis Results:						
R^2		**0.07**	**0.16**	**0.08**	**0.15**	**0.27**
p		**0.73**	**0.60**	**0.72**	**0.61**	**0.48**
Pumpkin Creek near Mouth	August 21, 2002	1154	1.0	51.0	156.5	59
	August 28, 2002	1135	5.1	170.4	295.1	57454
	May 28, 2003	4521	10.8	739.5	677.7	41866
	June 17, 2003	880	2.3	90.0	150.0	72210
	August 10, 2005	3089	10.8	538.7	554.0	4864
Trend Analysis Results:						
R^2		**0.21**	**0.44**	**0.28**	**0.28**	**0.12**
p		**0.44**	**0.22**	**0.35**	**0.36**	**0.56**

5.4.2 Physiographic Relationships in Storm Discharge Chemistry at Continuous Record Stations

Water chemistry data from individual storm flow events at CR stations are summarized in Tables 4.1-1 and 4.1-2. The most notable aspect of these data is the high degree of variability observed across all recorded storm flow events. Variability for all water chemistry parameters was higher than that anticipated based on an examination of Basin surficial geology available in published geologic maps (overviewed in Section 2.1; e.g., Rankl and Lowry, 1990; Halberg et al, 2000).

Regression analyses were performed in an effort to relate the observed variability in storm flow total quantity and chemistry to watershed physical characteristics. All measured storm flow parameters listed in Table 4.1-1 were compared to the respective drainage areas, stream channel lengths, and average gradients above the monitoring stations. These combinations of comparisons were performed for: flows from undeveloped drainages (Bloom Creek and Headgate Draw); developed drainages (all other drainages in which CBM activity occurred); and all storm flows combined. Results for these regression analyses are summarized in Tables 5.4.2-1 through 5.4.2-3 respectively.

While the slopes of many regression lines were statistically significant (ά=0.05), overall goodness of fit for these analyses was poor. R^2 values ranged from <0.01 to 0.74, but most tended towards the lower end of this range, even for those regressions with statistically significant slopes. The generally poor correlations between storm flow water chemistry and watershed physical characteristics applied to comparisons within undeveloped drainages, within CBM developed drainages, and across all drainages. While results of these analyses suggest that loose relationships exist between certain storm flow parameters and some watershed physiographic characteristics, the predictive value of the relationships is minimal.

Examples of bi-variate scattergram plots of these comparisons are shown in Figures 5.4.2-1 through 5.4.2-3. These include a typical statistically significant regression with an R^2 value of 0.26 (Figure 5.4.2-1), a comparison with a very poor relationship (Figure 5.4.2-2), and a comparison of a regression relationship among the best observed (Figure 5.4.2-3).

Table 5.4.2-1. Regression summaries for storm flow parameters versus drainage characteristics in seven (7) developed drainages.
[Data are from 27 storm flow events. Statistically significant (ά=0.05) regression slopes are indicated in red.]

	Characteristic of Drainage Above Monitoring Station: Developed Drainages					
	Drainage Area		Stream Channel Length		Average Drainage Gradient	
Storm Flow Parameter	p (slope = 0)	R^2	p (slope = 0)	R^2	p (slope = 0)	R^2
Duration	>0.99	<0.01	0.88	<0.01	0.07	0.13
Peak discharge	0.13	0.09	0.22	0.06	0.05 (-)	0.14
Mean discharge	0.02 (+)	0.21	0.01 (+)	0.22	0.18	0.07
Total flow volume	0.18	0.07	0.09	0.11	0.02 (-)	0.21
Flow weighted mean EC	0.35	0.04	0.54	0.01	0.31	0.04
Flow weighted mean TDS concentration	0.26	0.05	0.38	0.03	0.18	0.07
Flow weighted mean pH	0.65	<0.01	0.88	<0.01	0.94	<0.01
Flow weighted mean SAR	0.97	<0.01	0.53	0.02	0.59	0.01
Flow weighted mean sodium concentration	0.92	<0.01	0.69	0.01	0.88	<0.01
Flow weighted mean calcium concentration	0.07	0.13	0.04 (-)	0.15	<0.01 (+)	0.29
Flow weighted mean magnesium concentration	0.09	0.11	0.15	0.08	0.10	0.10
Flow weighted mean potassium concentration	0.48	0.02	0.76	<0.01	0.10	0.10
Flow weighted mean bicarbonate concentration	0.66	0.01	0.76	<0.01	0.90	<0.01
Flow weighted mean sulfate concentration	0.25	0.05	0.28	0.05	0.14	0.08
Flow weighted mean chloride concentration	0.34	0.04	0.66	0.01	0.39	0.03
Total event TDS load	0.07	0.12	0.05 (+)	0.15	0.02 (-)	0.21
Total event sodium load	0.03 (+)	0.18	0.03 (+)	0.18	0.01 (-)	0.23
Total event calcium load	0.15	0.08	0.11	0.10	0.03 (-)	0.18
Total event magnesium load	0.52	0.02	0.13	0.09	0.02 (-)	0.20
Total event potassium load	0.13	0.09	0.04 (+)	0.15	0.02 (-)	0.20
Total event bicarbonate load	0.04 (+)	0.15	0.03 (+)	0.18	0.01 (-)	0.22
Total event sulfate load	0.11	0.10	0.06	0.13	0.01 (-)	0.22
Total event chloride load	0.11	0.10	0.02 (+)	0.20	0.01 (-)	0.27

Table 5.4.2-2. Regression summaries for storm flow parameters versus drainage characteristics in two (2) undeveloped drainages.
[Data are from 14 storm flow events. Statistically significant (ά=0.05) regression slopes are indicated in red. Apparent duplication of results is caused by data coming from only 2 drainages.]

	Characteristic of Drainage Above Monitoring Station: Undeveloped Drainages					
	Drainage Area		Stream Channel Length		Average Drainage Gradient	
Storm Flow Parameter	p (slope = 0)	R^2	p (slope = 0)	R^2	p (slope = 0)	R^2
Duration	0.04 (+)	0.31	0.04 (+)	0.31	0.04 (+)	0.31
Peak discharge	0.54	0.03	0.54	0.03	0.54	0.03
Mean discharge	0.25	0.11	0.25	0.11	0.25	0.11
Total flow volume	0.61	0.02	0.61	0.02	0.61	0.02
Flow weighted mean EC	0.01 (-)	0.49	0.01 (-)	0.49	0.01 (-)	0.49
Flow weighted mean TDS concentration	<0.01 (-)	0.52	<0.01 (-)	0.52	<0.01 (-)	0.52
Flow weighted mean pH	0.05	0.28	0.05 (+)	0.28	0.05 (+)	0.28
Flow weighted mean SAR	<0.01 (+)	0.70	<0.01 (+)	0.70	<0.01 (+)	0.70
Flow weighted mean sodium concentration	0.10	0.21	0.10	0.21	0.10	0.21
Flow weighted mean calcium concentration	<0.01 (-)	0.74	<0.01 (-)	0.74	<0.01 (-)	0.74
Flow weighted mean magnesium concentration	0.59	0.02	0.59	0.02	0.59	0.02
Flow weighted mean potassium concentration	0.28	0.10	0.28	0.10	0.28	0.10
Flow weighted mean bicarbonate concentration	0.57	0.03	0.57	0.03	0.57	0.03
Flow weighted mean sulfate concentration	<0.01 (-)	0.53	<0.01 (-)	0.53	<0.01 (-)	0.53
Flow weighted mean chloride concentration	0.75	0.01	0.75	0.01	0.75	0.01
Total event TDS load	0.63	0.02	0.63	0.02	0.63	0.02
Total event sodium load	0.05 (+)	0.28	0.05 (+)	0.28	0.05 (+)	0.28
Total event calcium load	0.44	0.05	0.44	0.05	0.44	0.05
Total event magnesium load	0.51	0.04	0.51	0.04	0.51	0.04
Total event potassium load	0.53	0.03	0.53	0.03	0.53	0.03
Total event bicarbonate load	0.38	0.06	0.38	0.06	0.38	0.06
Total event sulfate load	0.55	0.03	0.55	0.03	0.55	0.03
Total event chloride load	0.03 (+)	0.34	0.03 (+)	0.34	0.03 (+)	0.34

Table 5.4.2-3. Regression summaries for storm flow parameters versus drainage characteristics in all study drainages.

[Data are from 41 storm flow events in 9 drainages. Statistically significant (ά=0.05) regression slopes are indicated in red.]

	Characteristic of Drainage Above Monitoring Station: All Drainages					
	Drainage Area		Stream Channel Length		Average Drainage Gradient	
Storm Flow Parameter	**p (slope = 0)**	**R^2**	**p (slope = 0)**	**R^2**	**p (slope = 0)**	**R^2**
Duration	0.15	0.05	0.08	0.08	<0.01 (-)	0.24
Peak discharge	0.02 (+)	0.13	0.04 (+)	0.11	<0.01 (-)	0.19
Mean discharge	<0.01 (+)	0.26	<0.01 (+)	0.27	0.01 (-)	0.16
Total flow volume	0.02 (+)	0.13	0.01 (+)	0.18	<0.01 (-)	0.27
Flow weighted mean EC	0.66	0.01	0.96	<0.01	0.82	<0.01
Flow weighted mean TDS concentration	0.41	0.02	0.59	0.01	0.80	<0.01
Flow weighted mean pH	0.28	0.03	0.13	0.06	0.07	0.08
Flow weighted mean SAR	0.20	0.04	0.05 (+)	0.10	0.03 (-)	0.12
Flow weighted mean sodium concentration	0.22	0.04	0.06	0.09	0.05 (-)	0.10
Flow weighted mean calcium concentration	<0.01 (-)	0.27	<0.01 (-)	0.32	<0.01 (+)	0.26
Flow weighted mean magnesium concentration	0.25	0.03	0.44	0.02	0.58	0.01
Flow weighted mean potassium concentration	0.55	0.01	0.84	<0.01	0.40	0.02
Flow weighted mean bicarbonate concentration	0.52	0.01	0.14	0.06	0.16	0.05
Flow weighted mean sulfate concentration	0.29	0.03	0.34	0.02	0.55	0.01
Flow weighted mean chloride concentration	0.64	0.01	0.27	0.03	0.22	0.04
Total event TDS load	<0.01 (+)	0.22	<0.01 (+)	0.25	<0.01 (-)	0.34
Total event sodium load	<0.01 (+)	0.27	<0.01 (+)	0.28	<0.01 (-)	0.35
Total event calcium load	0.01 (+)	0.16	<0.01 (+)	0.19	<0.01 (-)	0.30
Total event magnesium load	0.06	0.09	<0.01 (+)	0.19	<0.01 (-)	0.32
Total event potassium load	0.01 (+)	0.16	<0.01 (+)	0.23	<0.01 (-)	0.28
Total event bicarbonate load	<0.01 (+)	0.25	<0.01 (+)	0.28	<0.01 (-)	0.33
Total event sulfate load	<0.01 (+)	0.20	<0.01 (+)	0.24	<0.01 (-)	0.34
Total event chloride load	<0.01 (+)	0.19	<0.01 (+)	0.30	<0.01 (-)	0.38

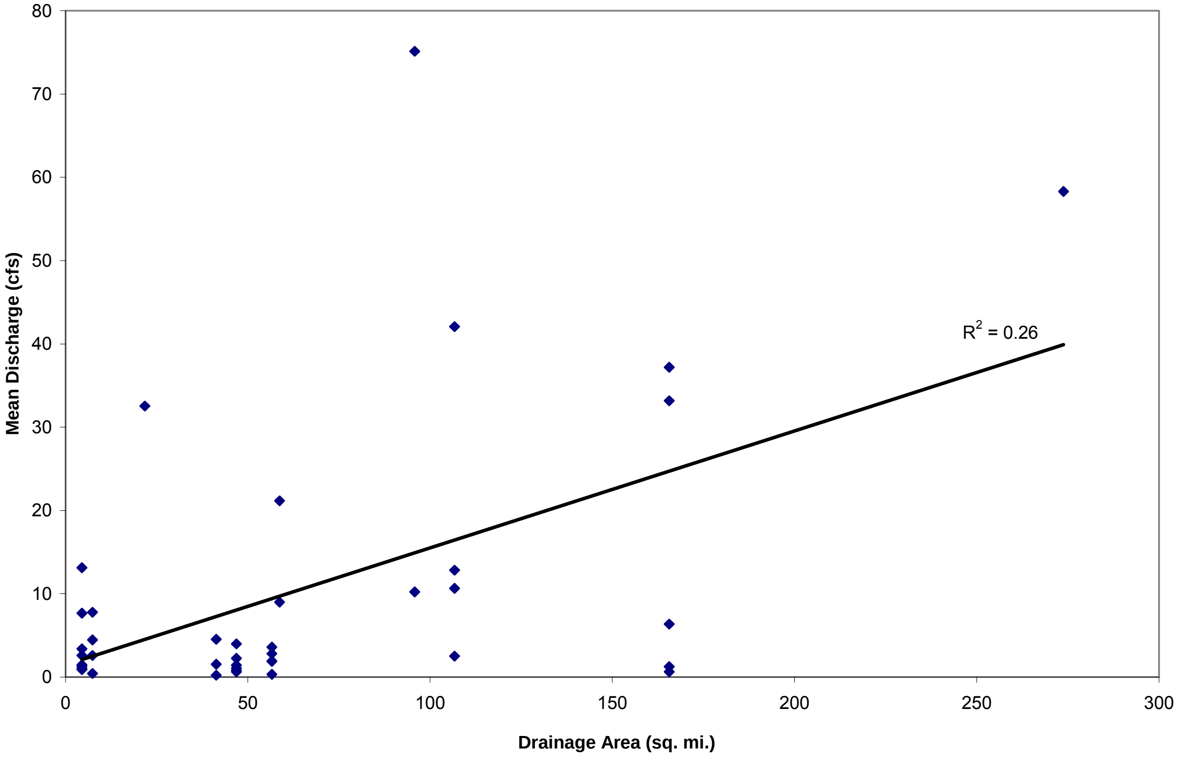


Figure 5.4.2-1. A typical regression result for Continuous Record station storm flow data. [The regression line is statistically significant (p=0.02), but fit to the data is relatively poor with an R^2 value of 0.13. This and similar results give insight into general storm flow trends, but offer little use as a predictive tool for storm flow characteristics.]

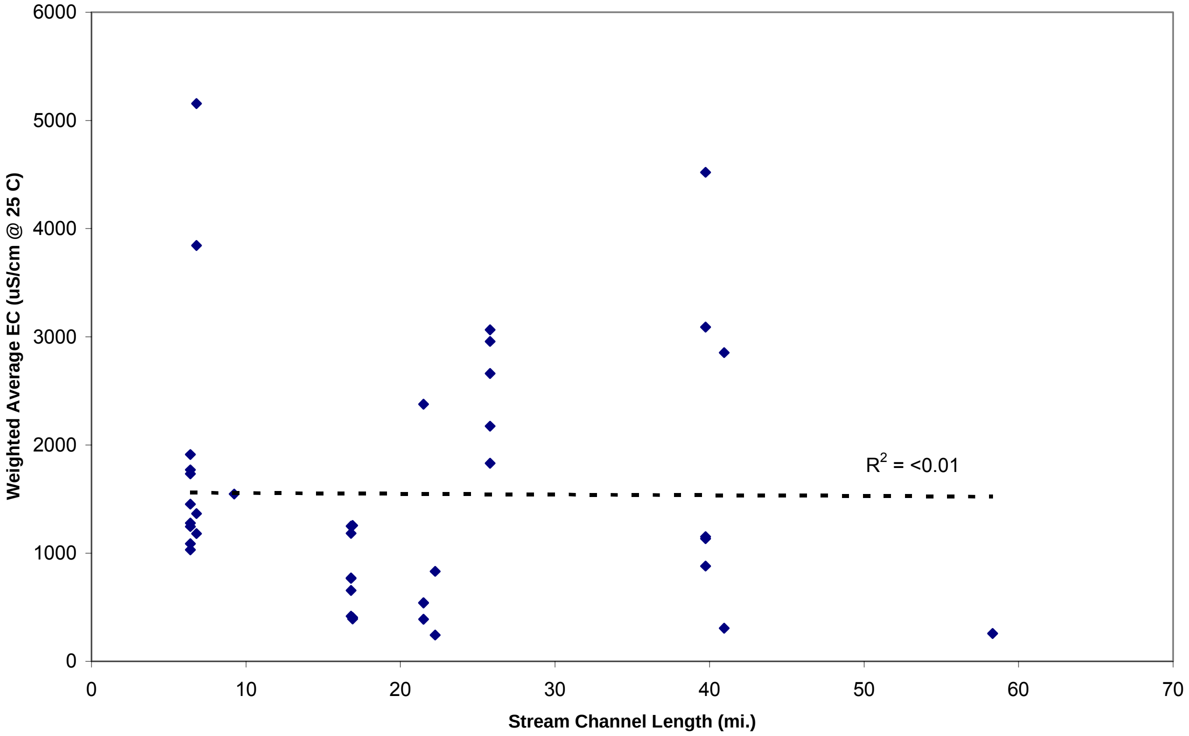


Figure 5.4.2-2. An example of a poor regression result for Continuous Record station storm flow data.
[No significant trend is present (p=0.97).]

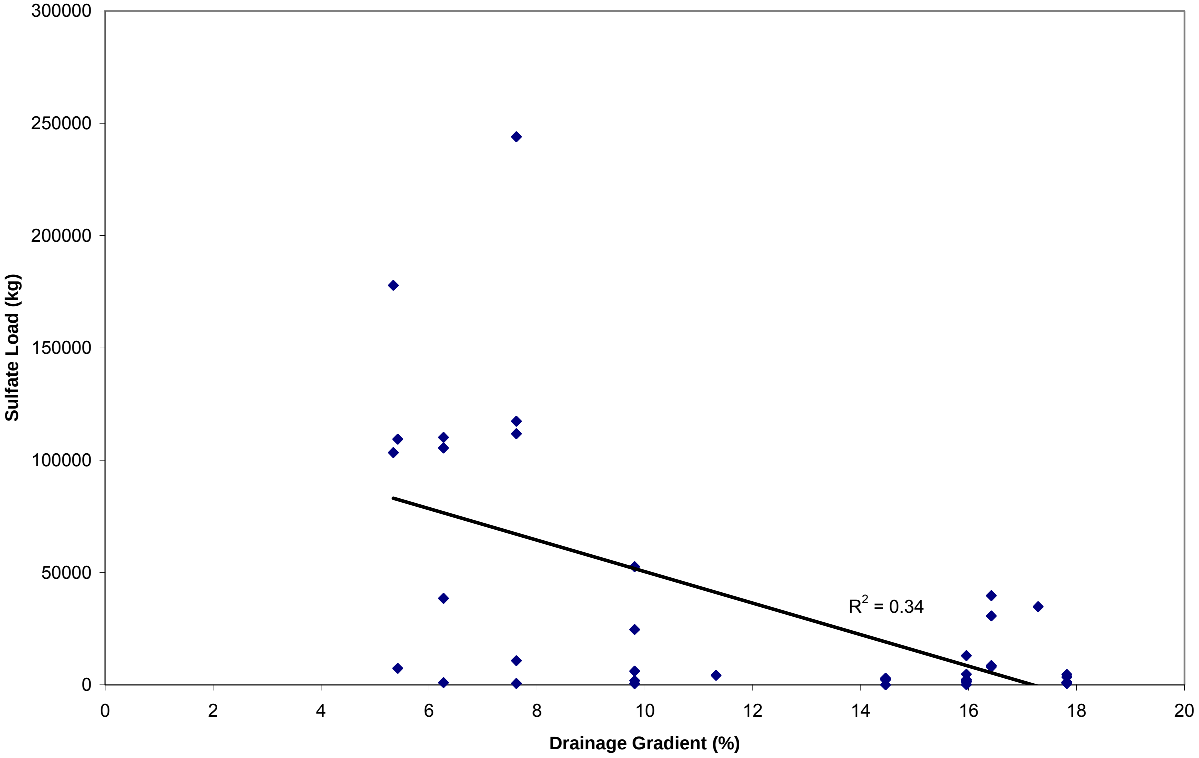


Figure 5.4.2-3. An example of a regression result for Continuous Record station storm flow data among the best observed.
[The regression line is statistically significant ($p<0.01$) and fit to the data is better than most of the comparisons made (R^2 value = 0.35), but the predictive usefulness of this relationship is still minimal.]

The large amount of unexplained residual variability in these regression analyses could result from several factors. As previously discussed, one likely source of variability is local heterogeneity in exposed members of the Wasatch and Fort Union Formations, which significantly affects the geochemistry of natural soluble materials on the landscape surface (Section 2.1). Another known source of variability in monitoring results is the frequency and spatial tracking of precipitation events that can differentially affect the between-storm buildup (time dependent) of soluble evaporites at the surface and their subsequent dilution while in transport during a given flow event. Most of the larger storm flow events observed in this study presumably were the result of convective thunderstorms, which commonly track west to east across the PR Basin. While a relatively large drainage (e.g., Pumpkin Creek) may have a higher probability of being affected by thunderstorms compared to a smaller drainage, the characteristics of observed storm discharges appear to be largely the result of chance related to the vagaries of weather systems, especially individual storm cells, passing through the study area. The observed precipitation events and their associated storm discharges at the monitoring gages appear to be relatively unique occurrences from a statistical perspective. Over the period of study to date, no two (2) events appear to represent the same pattern of precipitation, magnitude of precipitation, aerial coverage, and resulting surface flow. Thus, high variability in storm event data is evident.

One anomalous result should be noted about calcium concentrations versus drainage physical characteristics (see Figure 5.4.2-4). While R^2 values are relatively low, lower average calcium concentrations are significantly associated with flows in larger, longer, and less steep drainages. This pattern is evident when considering flows in undeveloped drainages only, flows in developed drainages only, or all storm flows combined. The smallest drainages in both the undeveloped (Headgate Draw) and developed (Barker Draw) groups had the highest calcium concentrations for those groups. The reason for this observed relationship is unclear but may be due in part to statistical bias associated with the small number of storms observed to date and the limited number of study watersheds.

Regression analyses also were performed to compare weighted average storm flow chemistries to total storm flow volumes. As before, these comparisons were made for CBM developed drainages, undeveloped drainages, and across all monitored drainages. Results from these analyses are summarized in Tables 5.4.2-4 through 5.4.2-6. Overall, storm flow volume was a poor predictor of weighted average flow chemistry. Other factors (discussed above) apparently are more important in determining the concentrations of dissolved constituents in storm flows than is the total volume of runoff observed at the gage sites.

A word of caution should be noted regarding comparisons between storm discharge volume over an entire event and associated total solute yield. Yield is the product of concentration times volume. Thus, chemical yield and volume are not independent measurements for a given event, and comparisons across events demonstrate strong autocorrelation among these variables. Lack of independence and presence of autocorrelation, in turn, result in false indications of significant relationships. For this reason, Tables 5.4.2-4 through 5.4.2-6, exclude comparisons between chemical yields and storm flow volumes. The low R^2 values seen in the comparisons between mean constituent concentrations and flow volumes are indicative of the high degree of variability in what amounts to flow-normalized event yields (which is another way of expressing mean constituent concentration).

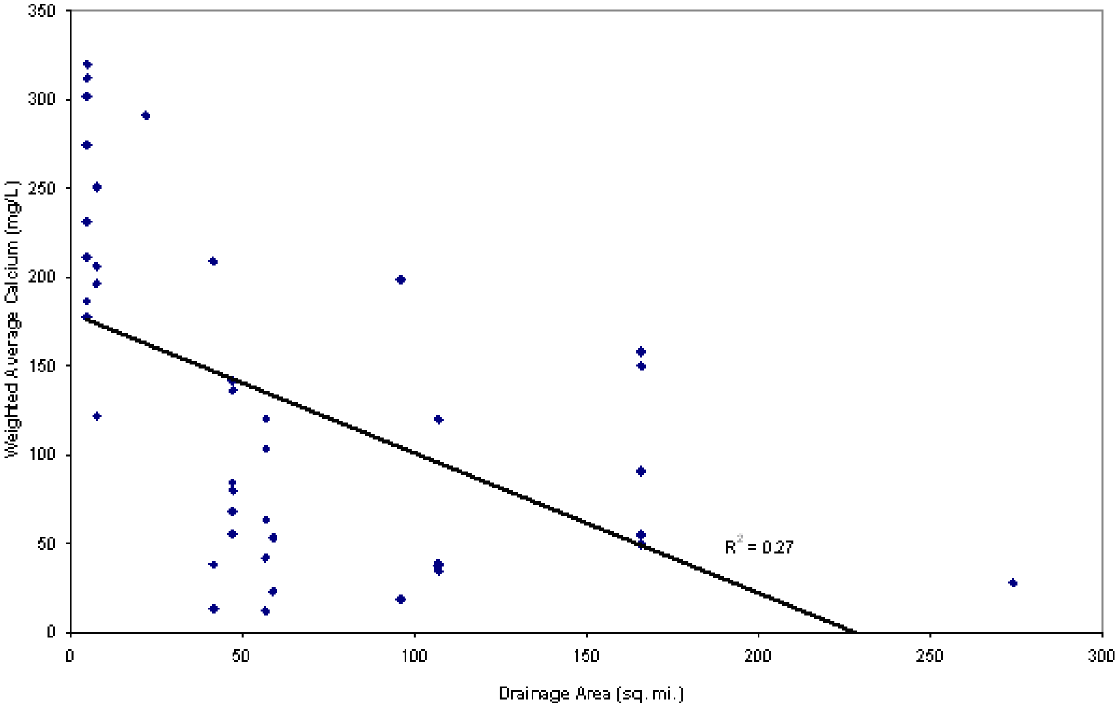


Figure 5.4.2-4. Example of anomalous relationship between average calcium concentrations and drainage physical characteristics for all drainages.
[Relationships for calcium were in the opposite direction of other storm flow parameters.]

Table 5.4.2-4. Regression summaries for storm flow chemical concentrations versus storm flow volume in developed drainages.
[Data are from 27 storm flow events in 7 drainages. No statistically significant (ά=0.05) relationships were present.]

Storm Flow Parameter	Total Storm Flow Volume: Developed Drainages	
	p (slope = 0)	R^2
Flow weighted mean EC	0.05 (-)	0.14
Flow weighted mean TDS concentration	0.05 (-)	0.14
Flow weighted mean pH	0.15	0.08
Flow weighted mean SAR	0.25	0.05
Flow weighted mean sodium concentration	0.12	0.10
Flow weighted mean calcium concentration	0.06	0.13
Flow weighted mean magnesium concentration	0.20	0.07
Flow weighted mean potassium concentration	0.04 (-)	0.16
Flow weighted mean bicarbonate concentration	0.16	0.08
Flow weighted mean sulfate concentration	0.09	0.11
Flow weighted mean chloride concentration	0.06	0.13

Table 5.4.2-5. Regression summaries for storm flow chemistry versus storm flow volume in undeveloped drainages.
[Data are from 14 storm flow events in 2 drainages. Statistically significant (ά=0.05) regression slopes are indicated in red.]

Storm Flow Parameter	Total Storm Flow Volume: Undeveloped Drainages	
	p (slope = 0)	R^2
Flow weighted mean EC	0.24	0.11
Flow weighted mean TDS concentration	0.25	0.11
Flow weighted mean pH	0.39	0.06
Flow weighted mean SAR	0.66	0.02
Flow weighted mean sodium concentration	0.25	0.11
Flow weighted mean calcium concentration	0.36	0.06
Flow weighted mean magnesium concentration	0.13	0.18
Flow weighted mean potassium concentration	0.11	0.20
Flow weighted mean bicarbonate concentration	0.38	0.06
Flow weighted mean sulfate concentration	0.26	0.11
Flow weighted mean chloride concentration	0.04 (-)	0.30

Table 5.4.2-6. Regression summaries for storm flow chemistry versus storm flow volume in all drainages.
[Data are from 41 storm flow events in 9 drainages. Statistically significant (ά=0.05) regression slopes are indicated in red.]

	Total Storm Flow Volume: All Drainages	
Storm Flow Parameter	**p (slope = 0)**	**R^2**
Flow weighted mean EC	0.09	0.07
Flow weighted mean TDS concentration	0.07	0.08
Flow weighted mean pH	0.53	0.01
Flow weighted mean SAR	0.62	0.01
Flow weighted mean sodium concentration	0.40	0.02
Flow weighted mean calcium concentration	0.02 (-)	0.14
Flow weighted mean magnesium concentration	0.26	0.03
Flow weighted mean potassium concentration	0.04 (-)	0.10
Flow weighted mean bicarbonate concentration	0.38	0.02
Flow weighted mean sulfate concentration	0.09	0.07
Flow weighted mean chloride concentration	0.28	0.03

5.4.3 Storm Flow Chemistry at Partial Record Stations

Partial Record stations use Troll instruments to monitor stage height and specific conductance (EC) on a continuous basis. The preferred metric for evaluation of total solutes entrained during the infrequent storm flows at the PR stations is total dissolved solids (TDS) which can be estimated using simple regression relationships between EC and TDS by station (see detailed analysis in Section 5.4.5; Table 5.4.5-1). Using this technique, TDS concentrations at PR stations during storm flow have been estimated for the undeveloped drainages of Mooney Draw, Squaw Creek, and Hood Draw.

Comparison of maximum derived TDS values (regression estimates) for combined flows in Mooney Draw (n=5), Squaw Creek (n=7), and Hood Draw (n=4) versus maximum TDS (from laboratory analyses) for flows in developed drainages (n=27) indicated a significant difference between the drainage types (t test, p<0.01), with maximum TDS values being higher in developed drainages. The mean ± standard deviation for undeveloped drainages was 683 ± 440 mg/L; for developed drainages these were 2,233 ±1,489 mg/L. The median value for undeveloped drainages was 648 mg/L and for developed drainages was 1,930 mg/L. As noted throughout this discussion, individual drainage characteristics were likely the source of this variation (see further discussion Section 5.4.4).

As was done for CR stations, discharge rates for monitored storm events were estimated for PR stations from gage height measurements. Estimated discharges by event were used to calculate total flow volumes, flow-weighted mean EC, flow-weighted mean TDS, and event TDS loads at PR stations.

Results of regression analyses comparing flow parameters to drainage characteristics are given in Table 5.4.3-1. Results of regression analyses comparing PR station flow volumes to average event EC and TDS are given in Table 5.4.3-2. As found with similar regression analyses for CR station data, correlations were poor. The maximum R^2 value for the PR station regressions was 0.28 and only one statistically significant relationship was observed. No apparent predictive relationships were observed between PR flow parameters and either flow volume or drainage characteristics.

Table 5.4.3-1. Regression summaries for storm flow parameters versus drainage characteristics at Partial Record stations in undeveloped drainages.
[Data are from 15 storm flow events in 3 drainages. Statistically significant (ά=0.05) regression slopes are indicated in red.]

	Characteristic of Drainage Above Monitoring Station: Partial Record Stations					
	Drainage Area		Stream Channel Length		Average Drainage Gradient	
Storm Flow Parameter	p (slope = 0)	R^2	p (slope = 0)	R^2	p (slope = 0)	R^2
Duration	0.57	0.03	0.57	0.03	0.52	0.03
Peak discharge	0.60	0.02	0.62	0.02	0.97	<0.01
Mean discharge	0.96	<0.01	0.99	<0.01	0.62	0.02
Total flow volume	0.52	0.03	0.54	0.03	0.92	<0.01
Flow weighted mean EC	0.50	0.04	0.47	0.04	0.16	0.15
Flow weighted mean TDS concentration	0.27	0.09	0.24	0.10	0.04 (+)	0.28
Total event TDS load	0.81	<0.01	0.85	<0.01	0.67	0.01

Table 5.4.3-2. Regression summaries for storm flow specific conductance (field measurement) and total dissolved solids (derived from specific conductance) concentrations versus storm flow volume at Partial Record stations in undeveloped drainages.
[Data are from 15 storm flow events in 3 drainages. No statistically significant (ά=0.05) relationships were present.]

	Total Storm Flow Volume: Partial Record Stations	
Storm Flow Parameter	p (slope = 0)	R^2
Flow weighted mean EC	0.07	0.24
Flow weighted mean TDS concentration	0.13	0.16

5.4.4 Undeveloped versus Developed Study Drainages

An important part of this study is comparison of storm discharge characteristics observed in undeveloped and CBM developed drainages. Of the 41 storm flows recorded at CR stations, 14 occurred in the two (2) undeveloped drainages (Bloom Creek and Headgate Draw). The remaining 27 events occurred in a total of nine (9) CR stations located in seven (7) drainages with CBM development. Importantly, it is required for statistical inference that comparisons among the resulting data account for the over-weighting of observations (number of replicates) in just two (2) undeveloped watersheds for which we have no measure of their representativeness among the population of all possible baseline stations, compared to observations in nine (9) developed watersheds. This issue is further discussed below where appropriate.

Storm flow parameters recorded for events in undeveloped drainages were compared to those from developed drainages using Student's t tests. Results for these comparisons are presented in Table 5.4.4-1. Note that the presented group means are arithmetic means of flow-weighted averages from each individual storm flow. The values within a group for each test have not been weighted based on the size of the individual total storm discharge within that group (doing so would skew the t distribution for the tests and test results by artificially inflating the sample size). As such, the group means listed in Table 5.4.4-1 represent a different summary statistic for water chemistry than the flow-weighted group averages presented in Table 4.1-2.

Table 5.4.4-1. Summary of multiple Student's t tests comparing storm flow parameters and drainage characteristics in developed versus undeveloped drainages. [Statistically significant (ά=0.05) differences between developed and undeveloped drainages are indicated in red. See the text for explanations regarding the source of these differences.]

	DEVELOPED DRAINAGES		UNDEVELOPED DRAINAGES		
Storm Flow Parameter	**MEAN (μ_D)**	**Standard Deviation**	**MEAN (μ_B)**	**Standard Deviation**	**p (μ_D=μ_B)**
Duration (hours)	94.6	87.3	24.9	34.0	0.01
Peak discharge (cfs)	234.1	410.2	44.0	66.3	0.09
Mean discharge (cfs)	14.3	19.6	3.0	3.5	0.04
Total flow volume (acre-feet)	129.3	231.2	4.5	5.0	0.05
Flow weighted mean EC (μS/cm)	1739.1	1377.9	1182.9	439.2	0.15
Flow weighted mean TDS (mg/l)	1366.5	1190.9	1003.8	449.5	0.28
Flow weighted mean pH (standard units)	7.7	0.7	7.3	0.2	0.01
Flow weighted mean SAR	4.5	5.4	0.6	0.3	0.01
Flow weighted mean sodium (mg/l)	218.1	234.8	30.2	13.5	0.01
Flow weighted mean calcium (mg/l)	100.8	80.6	184.3	94.0	0.01
Flow weighted mean magnesium (mg/l)	66.2	91.2	35.7	14.7	0.22
Flow weighted mean potassium (mg/l)	11.2	4.7	10.5	3.1	0.62
Flow weighted mean bicarbonate (mg/l)	310.1	329.5	101.8	19.6	0.02
Flow weighted mean sulfate (mg/l)	725.1	722.5	580.3	286.3	0.54
Flow weighted mean chloride (mg/l)	7.6	6.0	2.5	1.2	<0.01
DRAINAGE CHARACTERISTICS					
Drainage area above station (sq. mi.)	85.1	64.9	22.7	21.8	<0.01
Stream length above station (mi.)	25.4	13.2	10.9	5.3	<0.01
Drainage slope (%)	10.1	4.2	16.8	1.0	<0.01

Table 5.4.4-1 also includes comparisons of drainage physical characteristics (drainage area, stream channel length, and drainage gradient above the monitoring stations) between the undeveloped and developed drainages. The results show that the undeveloped study drainages are significantly smaller and steeper than developed drainages. This situation represents real-world constraints on the study design regarding: the initiation phase of this study when the presence of and access to undeveloped drainages were limited; and the short time period of the study with regard to precipitation frequency. As previously discussed, some study drainages appear to be associated with higher-precipitation-frequency storm tracks (e.g., Headgate Draw) than others.

Representative examples for different physical characteristics of study watersheds versus flow frequency are Headgate Draw, Bloom Creek, and Nine Mile Creek. Headgate Draw, a undeveloped drainage with an area of only 4.5 square miles, is the smallest drainage in the study area; yet this drainage experienced a relatively high number of storm flows averaging several flows per year (Section 5.1), which suggests a spatial association with storms tracking eastward from the Bighorn Mountains during summer and early fall. Bloom Creek is an undeveloped, medium-sized watershed covering 46.9 square miles with six (6) recorded storm flows during the study period. A local landowner, Mr. Glenn Gay, has observed a small lateral catchment area discharging into Bloom Creek immediately upstream of the gage site; this lateral may tend to discharge at a higher frequency compared to the larger ephemeral drainage further upstream. This lateral has physical drainage characteristics suggestive of Headgate Draw (relatively short and steep), which also suggests that some similarities between Headgate Draw and Bloom Creek may be evident in the observed storm discharge chemistry data. This appears to be the case given that both drainages exhibit relatively low sodium in storm discharge. Nine Mile Creek is a large undeveloped drainage covering more than 149 square miles, but no storm flow was recorded during the study. This observation may be related in part to large on-channel structures present along Nine Mile Creek above the gage site.

Eight (8) of the 14 storm flows in undeveloped watersheds occurred in Headgate Draw. Consequently, results for the undeveloped group are biased towards the small flows and calcium sulfate rich waters of this small drainage. Results shown in Table 5.4.4-1 indicate no statistical difference in TDS and EC of flows in undeveloped and developed drainages. However, differences in the concentrations of individual solutes contributing to TDS were found. Sodium and bicarbonate concentrations were both significantly lower in undeveloped drainages. At the same time, calcium concentrations in undeveloped drainages were significantly higher, which resulted in significantly lower SAR in these drainages. All of these differences reflect statistical bias introduced by the relatively high frequency of flows in Headgate Draw.

Significant differences in flow volumes were observed between the developed and undeveloped drainage groups. Thus, dissolved constituent yields (which are the product of flow volume and mean concentration) from developed and undeveloped drainages cannot be compared unequivocally. Significant results for such comparisons may reflect differences in rainfall patterns that occurred across study drainages rather than inherent differences in discharge chemistry between developed and undeveloped drainages.

Selected comparisons of results for PR stations to those from CR stations in developed drainages are shown in Table 5.4.4-2. Although the comparisons were similar to those described above for CR stations in developed and undeveloped drainages, it must be noted that the data were collected and analyzed using different methods for CR versus PR stations. Therefore, caution should be used in interpreting statistical results. The findings for PR stations versus CR stations are generally consistent with comparisons of flow-weighted mean dissolved solids concentrations from CR stations in developed versus undeveloped drainages as described above and presented in Table 5.4.4-1.

Finally, while caution must be used in making inferences from data analyses for PR stations, results do suggest the same biases occur in drainage physical characteristics for undeveloped PR drainages as were previously discussed for comparisons of CR station data in developed versus undeveloped drainages. Results indicate that the undeveloped PR station drainages are smaller, shorter, and steeper than the developed drainages containing CR stations.

Table 5.4.4-2. Summary of multiple Student's t tests comparing storm flow parameters and drainage characteristics in undeveloped Partial Record drainages versus developed Continuous Record station drainages.
[Statistically significant (ά=0.05) differences were observed for all comparisons. Data collection and calculation methods differ between the station types, so caution should be used in making inferences from these results.]

	CONTINUOUS RECORD DEVELOPED DRAINAGES		PARTIAL RECORD UNDEVELOPED DRAINAGES		
Storm Flow Parameter	**Mean (μ_D)**	**Standard Deviation**	**Mean (μ_B)**	**Standard Deviation**	**p (μ_D=μ_B)**
Duration (hours)	94.6	87.3	10.6	6.5	<0.01
Peak discharge (cfs)	234.1	410.2	7.5	10.9	0.05
Mean discharge (cfs)	14.3	19.6	0.7	0.9	0.01
Total flow volume (acre-feet)	129.3	231.2	0.9	1.4	0.05
Flow weighted mean EC (μS/cm)	1739.1	1377.9	644.3	347.5	0.01
Flow weighted mean TDS (mg/l)	1366.5	1190.9	497.2	289.4	0.01
DRAINAGE CHARACTERISTICS					
Drainage area above station (sq. mi.)	85.1	64.9	8.9	5.6	<0.01
Stream length above station (mi.)	25.4	13.2	7.4	3.2	<0.01
Drainage slope (%)	10.1	4.2	15.8	4.6	<0.01

5.4.5 Total Dissolved Solids versus Specific Conductance Regressions for Partial Record Stations

In addition to monitoring gage height of channel flow, PR stations monitor discharge EC as a surrogate for TDS. Although fixed generic conversions are commonly applied for converting measured EC to estimated TDS values, the exact conversion appropriate for a given water sample is dependent on the mixture of solutes present in that particular sample. Relationships between EC and TDS are slightly curvilinear, although linear approximations work well for field data and may be acceptable within the ranges typical of natural waters (Hem, 1985). The appropriate multiplier for natural waters may range from less than 0.50 to greater than 1.0 depending upon the chemical composition of the sample. High sulfate concentrations, in particular, tend to raise TDS:EC ratios (Hem, 1985). Using a generic multiplier to convert EC to TDS can introduce substantial error, so a site-specific approximation procedure that directly compares laboratory values for both EC and TDS from the water type being considered is preferred. Accordingly, storm discharge samples where both EC and TDS were determined by laboratory analyses were used to empirically estimate the appropriate conversion multiplier for study watersheds. Linear regression was used to evaluate chemical data from single-stage samples collected during storm flows in three (3) undeveloped PR drainages (Hood Draw, Squaw Creek, and Mooney Draw). Results of regression analyses comparing measured TDS to measured EC are summarized in Figure 5.4.5-1 and Table 5.4.5-1.

Conversion multipliers for the three (3) drainages ranged from 0.66 to 0.84. Sample sizes for this analysis were small, but linear fits were quite good. These examples demonstrate that storm flow EC collected at PR stations are a useful surrogate measure for TDS and possibly other water chemistry values so long as drainage-specific conversion factors were derived from direct laboratory measurements.

Table 5.4.5-1. Empirically derived total dissolved solids:specific conductance ratios for storm flow samples from three undeveloped drainages.

Drainage	Samples	Mean TDS/EC Ratio	Standard Deviation
Hood Draw	3	0.66	0.14
Mooney Draw	11	0.84	0.12
Squaw Creek	5	0.73	0.04
Combined	**19**	**0.78**	**0.12**

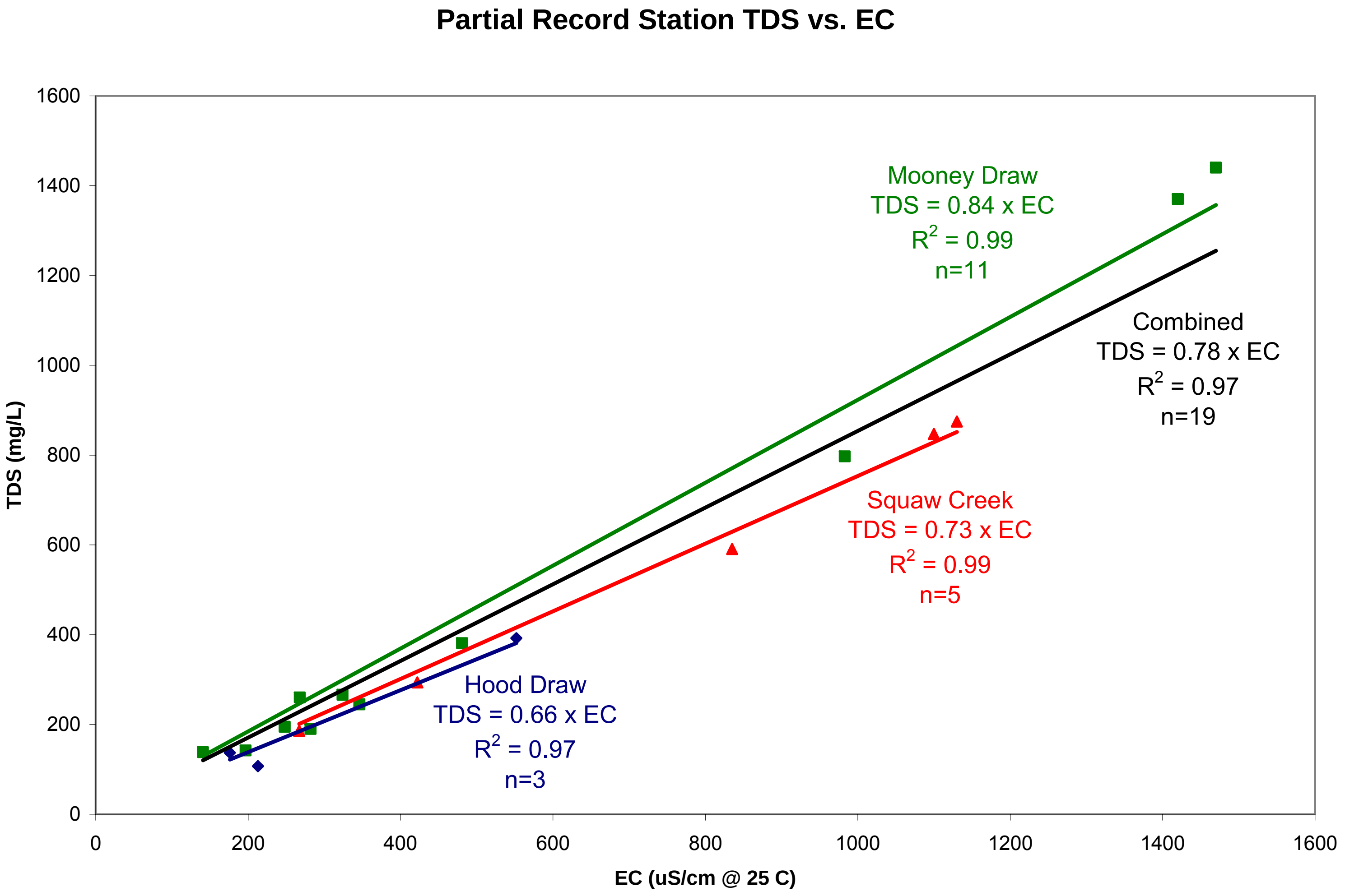


Figure 5.4.5-1. Results of regression analyses comparing laboratory specific conductance and total dissolved solids measurements for discrete storm flow samples collected in three undeveloped drainages.
[Partial Record station TDS vs. EC]

6.0 SUMMARY AND CONCLUSIONS

A study of storm discharge hydrology and geochemistry was conducted in the middle Powder River Basin on 12 watersheds tributary to the Powder River and on one (1) watershed tributary to the Belle Fourche River. The study is ongoing and is focused on observations of streamflows and chemistry in relation to CBM development. Emphasis was placed on significant spring through fall runoff originating from rain storms; channel flow resulting from snowmelt during early spring is not considered in this report. A previous report (Sanders et al., 2003) summarizes study data obtained from the 2001 through 2002 water years. This report summarizes data obtained from the 2003 through 2006 water years and presents an analysis of all data obtained from the 2001 through 2006 water years.

Effort has been made to include both CBM-developed and undeveloped drainages in the study design to facilitate comparisons of monitoring data between these watershed types. Selection of monitored gage sites was constrained by field conditions, including landowner access to preferred monitoring locations, but a representative, broadly distributed monitoring network of study watersheds was achieved. The study was started after CBM development in the study area began. Only limited pre-CBM development data are available for some of the watersheds. The period of study has coincided with a severe drought in NE Wyoming that undoubtedly has effected study results.

Significant storm discharges in most of the ephemeral watersheds monitored during the study have been infrequent. Most of the runoff observed resulted from short duration, intense precipitation events from storms tracking along relatively narrow spatial bands within the study area (in contrast to large regional precipitation events) during late spring through early fall. Time intervals between significant consecutive storm events for individual study watersheds commonly exceed one (1) year. Separate analysis of a long-term flow record (19 years) on Dead Horse Creek, a relatively large tributary of the Powder River in the study area, demonstrated that mean-daily discharges exceeding 1.0 cfs occurred only 5% of the time. Available data indicate that overbank discharges that constitute natural surface irrigation for flood plain agricultural zones occur very infrequently for ephemeral streams in the PR Basin.

Field observations show that far-field, downgradient runout of storm flows that begin in headwater areas of ephemeral tributaries are significantly truncated by channel storage processes and by on-channel reservoirs. Storm events that occur in headwater reaches may not flow to lower reaches where irrigable flood plains are common.

Observations on the geochemistry of significant storm discharges in the study watersheds indicate that storm chemistry varies widely among individual events. The high observed variability likely results from a blend of background causal factors. For example, significant spatial heterogeneity is evident: in the relative surface exposures of different geologic strata of the Wasatch and Fort Union Formations whose weathering and subsequent release and transport of dissolved minerals significantly effects the geochemistry of associated surface waters; and the apparent intensity, size, and frequency of significant precipitation events among the study watersheds, which may either cause relatively continual flushing of a given watershed or lead to prolonged dry periods during which time soluble evaporate salts can accumulate on the landscape surface. The results of this background heterogeneity, which is poorly quantified at present, are that observations on the hydrology and geochemistry of significant storm discharges to date are widely variable among the study watersheds.

In summary, major observations and conclusions based on monitoring data collected during the 2001 through 2006 water years are as follows.

- A high degree of variability was observed in the hydrology and associated chemistry of storm discharges, both within and across drainages and drainage types (CBM developed and undeveloped watersheds).

- The observed variability in storm discharge flow and chemistry in the study watersheds is likely the result of: the relative surface area and differential weathering rates of exposed geologic strata, which provide a natural source for high annual yields of salts from ephemeral drainages; and the highly variable and unpredictable spatial tracking of rainstorm cells that infrequently cause surface runoff in individual drainages, resulting in high seasonal and year-to-year variability in storm discharges among ephemeral drainages. The spatial heterogeneity of these physical characteristics and processes results in high variability among the study watersheds in yield of soluble ions, including sodium, during storm discharge.

- Only limited analysis of time trends in developed drainages (early CBM development to later more intensive development occurring during the study period) was possible due to the low frequency of storm events; however, no significant trends in storm discharge chemistry were observed at Continuous Record gages for three significantly CBM-developed watersheds (Pumpkin Creek, LX Bar Creek near Mouth, and Barker Draw near Mouth).

- Some differences in storm flow characteristics were observed between CBM-developed and undeveloped drainages, but results are confounded by physical and geochemical differences in study drainages. The undeveloped group is heavily biased by frequent storms in one small drainage (Headgate Draw) with high calcium concentrations in storm discharge. Overall, no meaningful statistical differences between developed and non-developed watersheds could be discerned from the study data concerning storm discharge geochemistry.

- Beginning with the low ionic strength of direct precipitation (meteoric water input) and the relatively homogenous and well characterized CBM-produced water chemistry (dominance of Na and HCO_3 and the near absence of SO_4), geochemical comparisons were made to other surface water types (including potholes, shallow alluvial groundwater, and storm discharge) to evaluate potential effects of CBM-produced water discharges on individual study watersheds. To form the basis for a simple comparison, the commonly observed geochemistry of natural waters combining near-surface alluvial groundwater, potholes, and storm flows may be characterized as follows: the Na:Ca:Mg ratio was on the order of 5:2.5:2.5 and the SO_4:HCO_3:Cl ratio was on the order of 6:3.5:0.5. These ratios demonstrate considerable change from meteoric water and from CBM discharge chemistry.

- In comparison to the low ionic strength of meteoric water, the considerable increase in dissolved solutes observed in naturally occurring pothole water, shallow alluvial groundwater, and landscape-dominated storm discharge (i.e., characterized by high sulfate concentrations) indicate that the natural landscape provides considerable solute yield during storm flow. Naturally occurring high solute yield results from: (1) constant mineral weathering of exposed geologic strata (containing high background concentrations of sodium, calcium, magnesium, sulfate, bicarbonate and other salts); (2) surface accumulation of many weathering products as soluble evaporites during time intervals between significant storm flushing events; (3) subsequent dissolution and transport of evaporite salts during significant storm flushing; and (4) entrainment of high salt-content pothole water during channel flow. Thus, any effect of CBM discharges on natural salt yield during storm flows must be evaluated in this context.

- Based on an evaluation of storm flow chemical data collected during the study period, observations indicate that baseline conditions are variable among the study sites, and CBM-related influences on storm discharge geochemistry are not easy to discern within the high background variances observed.

- Because of the ubiquity of Na in the surficial geology of the PR Basin and the near absence of SO_4 in CBM produced water, potentially useful indicators of the influence of CBM discharges on the chemistry of natural waters are the abundance of SO_4 and, specifically, the correlations of Na to SO_4. When correlations of sodium and sulfate concentrations for all individual storm flows across all drainages were considered, a median R^2 value of 0.804 was calculated. The relatively high median correlation coefficient between sodium and sulfate across all events provides considerable evidence that the sodium observed in storm flows is derived primarily from natural landscape materials and not from CBM-related discharges. However, some storm data are equivocal, and further review of the detailed geochemistries of such events is required to evaluate the potential for CBM discharge-related effects in these discharge events. While the sodium-sulfate statistical comparison may be useful for evaluating sources of solutes found in storm discharge from individual watersheds, this comparison apparently cannot be universally used without site-specific study.

- Based on study data collected to date, CBM development has had little, if any, discernable influence on storm discharge chemistry among and within the study drainages. The primary exception to this general finding is the superimposition of storm discharge on WYPDES-permitted perennialized flow at one CR station, LX Bar Creek near Mouth.

- Streamflow at the LX Bar Creek near Mouth gage (a naturally ephemeral reach) has been perennialized from upstream WYPDES-permitted direct discharges of CBM-produced water (generally less than 2 cfs sustained flow) since July 2005. Here, the geochemistries of several modest storm runoff events, having apparent landscape-dominated chemical signatures, were superimposed over the CBM-dominated perennial flow. The storm-runoff/CBM-discharge mixture was characterized by a dominance of sodium and bicarbonate. Larger storm discharge volumes may dilute the chemistry of the relatively small CBM-discharges and revert to a combined chemistry that reflects predominance of landscape-level influences on total and individual solute transport.

The present study is an observational study that does not include experimental releases of CBM produced water in selected drainages nor has the study period allowed before-and-after CBM-development data sets to be obtained for representative watersheds. Available observations cannot rule out all possibilities of CBM-related changes on storm water chemistry in the set of watersheds monitored to date. However, in the broad context of the study, both spatially and temporally, little direct evidence has been found that suggests that CBM-discharges have significantly affected storm flow chemistry, with the exception of perennialized flow in the lower section of one study watershed.

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GLOSSARY

Bank – The sloping ground that borders a stream and confines the water in the natural channel when the water level or flow is normal.

Bankfull discharge – Maximum discharge that can be accommodated within a channel. Discharges greater than bankfull cause the stream to overtop the banks and spread onto the flood plain.

Bed material – Sediment composing the streambed.

Bed sediment – The material that temporarily is stationary in the bottom of a stream or other watercourse.

Channelization – The straightening and deepening of a stream channel to permit the water to move faster or to drain a wet area for farming.

Cubic foot per second (cfs) – Rate of water discharge representing a volume of 1 cubic foot passing a given point during 1 second, equivalent to approximately 7.48 gallons per second or 448.8 gallons per minute or 0.02832 cubic meter per second. In a stream channel, a discharge of 1 cubic foot per second is equal to the discharge at a rectangular cross section, 1 foot wide and 1 foot deep, flowing at an average velocity of 1 foot per second.

Discharge – The volume of fluid passing a point per unit of time, commonly expressed in cubic ft per second, million gallons per day, gallons per minute, or seconds per minute per day.

Drainage area – The drainage area of a stream at a specified location is that area, measured in a horizontal plane, which is enclosed by a drainage divide.

Ephemeral stream – A stream or part of a stream that flows only in direct response to precipitation; it receives little or no water from springs, melting snow, or other sources; its channel is at all times above the water table.

Evapotranspiration – The process by which water is discharged to the atmosphere because of evaporation from the soil and surface-water bodies, and transpiration by plants.

Flood – Any relatively high streamflow that overflows the natural or artificial banks of a stream.

Flood attenuation - A weakening or reduction in the force or intensity of a flood.

Flood plain – A strip of relatively flat land bordering a stream channel that is inundated at times of high water.

Fluvial – Pertaining to a river or stream.

Fluvial deposit – A sedimentary deposit consisting of material transported by suspension or laid down by a river or stream.

Full gully discharge – In some streams, the main or low-water channel is incised within a larger channel or gully. The full gully discharge is the maximum discharge that can be accommodated within the gully. Greater discharge causes the stream to overtop the gully banks and spread onto the flood plain.

Groundwater –In the broadest sense, all subsurface water; more commonly that part of the subsurface water in the saturated zone.

Headwaters – The source and upper part of a stream.

Historical flood – Large flood that has occurred sometime in the past, serving as a source of streamflow history. Floods leave high-water marks, composed of debris such as wood and seeds. The high-water marks can be used to provide information concerning the maximum elevation and discharge of a flood at a site.

Irrigation – Controlled application of water to arable land to supply requirements of crops not satisfied by rainfall.

Overland flow – The flow of rainwater or snowmelt over the land surface toward stream channels.

Peak stage – Maximum height of a water surface above an established datum plane. Same as peak gage height.

Precipitation – Any or all forms of water particles that fall from the atmosphere, such as rain, snow, hail, and sleet. The act or process of producing a solid phase within a liquid medium.
Reach – A continuous part of a stream between two specified points.
Runoff – That part of precipitation or snowmelt that appears in streams or surface-water bodies.
Sediment – Particles, derived from rocks or biological materials, which have been transported by a fluid or other natural process, suspended or settled in water.
Sedimentation – The act or process of forming or accumulating sediment in layers; the process of deposition of sediment.
Stage – Height of the water surface above an established datum plane, such as in a river above a predetermined point that may (or may not) be at the channel floor.
Stream mile – A distance of 1 mile along a line connecting the midpoints of the channel of a stream.
Stream reach – A continuous part of a stream between two specified points.
Streamflow – The discharge of water in a natural channel.
Swale – A slight depression, sometimes filled with water, in the midst of generally level land. A stream course that does not have well-defined banks.
Water year – A water year occurs from October 1 to September 30 of the following year.

Appendix A – Maps of Study Watersheds 2003-2006 Water Years

Appendix B – Individual Storm Data 2003-2006 Water Years

Appendix C – Summary Storm Hydrographs 2003-2006 Water Years

Appendix D – Storm Chemistry Tables 2003-2006 Water Years