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Effects of CBM Water Discharge on Winter Fluvial and Ice Processes in Powder River Basin, Wyoming

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The present study shows that heat transported with coal-bed methane (CBM) water has an annual visible impact on the thermal balance of the Powder River during winter. However, the long-term effects on the river's channel and its winter hydro-ecology are unclear. The study, conducted over two winters (2009-2010 and 2010-2011), entailed detailed surveys at two representative sites where CBM water was discharged into the river. Besides adding to river's flow, the most visible influence of CBM water discharge was the frequent formation of open-water leads extending along a channel bank typically for several kilometers along the river. The leads persisted throughout both winters. An analysis shows that the surface area of the leads scales with the discharge rate and temperature of CBM water. The leads comprised forms of density or buoyancy currents flowing in the river, cooling and eventually dissipating when exposed to frigid air. Lead presence altered flow distribution, concentrating flow along the lead, causing modest scour of the bed and, at some locations, accelerating bank erosion. The magnitudes of the measured channel changes were determined to be less than those typically caused by spring ice cover breakup and the larger spring flows conveyed by the river. Investigation of possible hydro-ecological aspects of lead formation is recommended as a topic for further research. The paper suggests how to manage lead formation, should further research on hydro-ecological influences indicate that lead extent should be minimized.

1. Introduction

The recovery of coalbed methane (CBM) requires the removal of groundwater to depressurize coalbed aquifers bearing CBM. In the Powder River Basin (PRB), Wyoming, large amounts of groundwater are removed from coalbed aquifers during CBM production. These CBM "product waters" are sometimes treated (CBM water can be saline and sodic to varying degrees) and then used for a variety of purposes, with a substantial flow of CBM water being discharged into natural waterways. Because of potential salinity problems and the volume of water produced, Powder River CBM water has been the subject of numerous geochemical studies (e.g., Frost and Brinck 2005, Rice et al. 2002). In addition to its geochemical load, however, CBM water usually conveys heat.

The present study shows that the continuous heat flux associated with CBM water discharge into waterways influences winter fluvial and ice dynamics of the Powder River and its tributary streams. Conducted over two winters, the study contributes early insight into processes whereby CBM water may affect channel bathymetry and winter hydro-ecology. The study, at this moment, does not document specific hydro-ecologic impacts of CMB heat discharge, but preliminarily delineates considerations possibly contributing to impacts. Kempema et al. (2011) fully document the study, the first to address how heat from CBM water affects winter fluvial and ice processes in the Powder River and its tributary streams.

2. Background

2.1 Powder River Basin Coalbed Methane Production and CBM Water

The Powder River Basin is the most productive coal mining region in the United States. Because extensive PRB coal deposits are too deep to be economically accessible via direct mining, considerable attention is given to utilizing the coal as a source of CBM, doing so by means of well systems constructed at numerous locations over the PRB. These wells pump water from coal-bearing aquifers, enabling CBM desorbed from the coal seams to be recovered at the well head. Water pumped from the coal seam must be disposed in various ways depending on CBM water quality. In a 2009 report, the Wyoming Department of Environmental Quality (2009) estimated that 916 million barrels of CBM water were extracted from the PRB during 2008. Of this volume, 20% (183 million barrels, consisting of a mix of treated and untreated water) was directly discharged into PRB surface drainages. Most CBM water discharges into ephemeral waterways, resulting in continuous flow or so-called "perennialized streams" draining to the Powder River. Some CBM water discharges directly into the Powder River. The overall volume of CBM water translates into an average annual discharge of 33cfs ($0.9m^3s^{-1}$) into PRB waterways. Based on available data, the average temperature of this product water at the wellhead is about 20^oC (Rice et al. 2002).

2.1 The Powder River

The study focused on a mid-reach of the Powder River, a northward-flowing river with headwaters in the Bighorn Mountains of Wyoming. The river merges with the Yellowstone River in Montana. Hembree et al. (1952) characterize the Powder River at the study area as a "wide, flat, meandering stream that flows over a sand-covered stream bed between predominantly low stream banks." The lowlands close to the Powder River consist of a flood plain and a series of alluvial terraces that grade into alluvial fans (Moody et al. 1999). Away from the river, badlands topography rises to a high plain. The badlands are dissected by ephemeral tributary streams that receive the majority of direct-discharge CBM water.

The annual hydrograph for the Powder River is twin-peaked, with a first peak occurring between late February and mid-April when lowland snows in the southern part of the basin melt (Moody et al. 1999). A second, larger-peaked flow occurs in mid-May to late June driven by snowmelt from elevations above about 3,000m. After this peak, discharge can be very low to non-existent in the middle Powder River (Hembree et al. 1952). The river has a natural discharge of around 100 to 200cfs (2.8 to 4.6m^3s^{-1}) during the winter months at the study sites.

Senecal (2009) studied the possible effects of energy development on fish assemblages in the Powder River. She notes (as do Moody et al. 1999) that the Powder River in Wyoming is one of the last relatively intact, unregulated prairie stream ecosystems in the United States. Hubert (1993) characterizes the river as having highly variable intermittent flows with unique prairie-river flow regimes and ecosystems. The Powder River is an example of "a highly-evolved and increasingly-rare native fish assemblage" (Hubert 1993). Senecal restricted her study to summer observations, and mostly considered the effects of increases in discharge caused by CBM water flow into the Powder River. She concluded that, by altering summer flows, CBM water affects habitat and fish assemblages in the Powder River. Possible winter effects of CBM water discharge have yet to be examined.

3. Methods

The study entailed field work at sites along a mid-reach stretch of the Powder River and two perennialized tributaries to the river – Burger Draw and Beaver Creek (Figure 1). It also involved qualitative observations of other tributary streams. Winter flow in the two tributaries consisted entirely of CBM water. The sites were visited at three- to four-week intervals throughout the 2009-2010 and 2010-2011 winters (November 1 through March 15). Discharge was measured at the tributaries' mouths during site visits using the standard technique of measuring several verticals with an electromagnetic current meter and a top-set wading rod. In addition, the U.S. Geological Survey measured discharges at these sites, and at the Powder River above Burger Draw, at monthly intervals throughout the study period (USGS data available from http://wy.water.usgs.gov/projects/qw/index.htm). Burger Draw discharges ranged from 0.19 to 1.60cfs (0.005 to 0.045m^3s^{-1}), with an average value of 0.7cfs (0.02m^3s^{-1}). Beaver Creek had larger discharges, ranging from 5.0 to 10.1cfs (0.14 to 0.29m^3s^{-1}), with an average value of 7.4cfs (0.21m^3s^{-1}).

The mouths of both tributary creeks were instrumented with Onset Tidbit data-loggers, which recorded water temperature every 10 minutes. The Tidbits had a reported accuracy of ±0.2^oC and resolution of 0.02^oC. In practice, the investigators found that the working accuracy was much better than the Onset reported accuracy. However, a zero-point calibration in an ice/water bath was performed on the loggers at the end of the field season to check the accuracy at the freezing point. Temperature offsets observed in the zero-point calibration were removed from the data-logger records during processing. Tidbit temperature loggers also were placed in the Powder River about 100m above and below its confluence with Burger Draw.

As the study also sought to determine whether CBM water discharge affected the channel bathymetry of the Powder River, seven bathymetric cross sections were established along the Powder River in early September 2010. Four were located within 120m of the Burger Draw confluence, and three within 50m of the Burger Creek confluence. These cross sections were surveyed with a total station, and were re-surveyed on December 15-16, 2010, January 21-22 2011, and March 15-16, 2011. Bathymetric surveys included measurement of the channel cross sections, ice thickness measurements, and flow speed and overall discharge.

4. Observations of Open-water Leads

As the study progressed it became clear that Burger Draw and Beaver Creek continuously delivered warm water to the Powder River throughout winter, not just during intermittent periods. A visible consequence of CBM water discharge was the persistent presence of open-water leads along the river downstream of the confluences of these streams with the Powder River (Figure 2). Leads also occurred at other locations where CBM water discharged into the Powder River. The leads were similar in appearance to leads observed in ice covers at rivers adjoining the cooling/blowdown water outlets of thermal power plants (Ashton 1986).

The water temperature of the tributary creeks varied on diurnal and longer cycles. On most winter days, the inflow water temperature from the two streams ranged diurnally, peaking at up to 8^{o}C during early afternoon on sunny days, and then cooling to about the freezing temperature during the night time (Figure 3). As a result, the Powder River at the confluences received a more-or-less cyclic input of heat on a daily basis; when ice covered, the Powder River water at these confluences was within 0.05^{o}C of the freezing temperature. The temperature of CBM water entering the Powder River was influenced by the distance between the discharge points in the tributaries and the confluences with the Powder River. Burger Draw, with a much lower flow than Beaver Creek, showed much stronger diurnal temperature variations than Beaver Creek. Longer temperature cycles were driven by weather systems passing through the study area, although correlation between air temperature and tributary water temperature is not always straight forward, as shown in the January temperature record for Beaver Creek (Figure 3). A result of these high water temperatures was that a complete ice cover rarely formed in the CBM-supplied tributary streams. Ice did form in back eddies, and occasionally covered entire stream reaches during cold snaps, but it quickly melted when the weather warmed. The constant heat flux from Beaver Creek and Burger Draw maintained open-water leads in the Powder River below the tributary confluences. Similar open-water leads were observed in other perennialized streams during the field work.

It was observed that, at some locations where the river's thalweg crosses from one side of the channel to another, the current generating a lead passed under a short distance of ice cover, emerging a short distance downstream. This feature occurred when the channel was especially sinuous, and was most notable when the thalweg switched from one outer bend to another in the river's winding channel. Also, when an open water lead passed by a bank irregularity such as a rock outcrop or bar, the local flow structure at the irregularity created secondary currents that disrupted and dispersed the lead, which caused widening of the lead.

The open-water area of each lead varied with passing cold fronts. During the coldest periods, the lead below Burger Creek would completely freeze over, although it would open quickly after air temperatures warmed. This lead averaged about 3-5m and 1km in width and length, respectively, throughout winter and hugged the right bank of the river. The lead below Beaver Creek, in comparison, averaged about 7m and 3km in width and length. Frazil and anchor ice formed frequently in both leads throughout winter.

The influent discharges from Burger Draw and Beaver Creek formed a plume or density current along the Powder River, and did not immediately mix with water flow already in the river. CBM water at, say, 4^oC is sufficiently denser (0.013%) than water at 0^oC that, bounded by the channel bank and bed, it could maintain itself as a thin density current in a lead extending over a very long distance. In contrast, CBM water introduced at, say, 15^oC is lighter (0.074%) than water at 0^oC, such that it would form a buoyant plume. Constrained on one side by a channel bank (Figure 2), such a plume also would form an open-water lead. In due course, through the effects of heat loss to air and turbulent mixing generated by channel bed and bank features, the density current or plume weakens and disperses, as observed for the Powder River. Eventually, the leads ended, unless augmented by additional inflow of CBM water.

The width and streamwise extent of the leads formed by CBM water discharging from Burger Draw and Beaver Creek scaled approximately with the magnitude of heat convected with CBM inflow. A relationship for lead size can be related to a balance of heat influxes (e.g., Ashton 1986, Dingman et al. 1968):

$$\frac{\partial(\rho C_p T_w)}{\partial t} + U\frac{\partial(\rho C_p T_w)}{\partial x} = \frac{\partial}{\partial z}\left[E_z \frac{\partial(\rho C_p T_w)}{\partial z}\right] - \frac{\emptyset}{Y} \qquad [1]$$

in which ρ = water density, C_p = specific heat capacity, T_w = water temperature, t = time, U = mean velocity, x = streamwise position, z = transverse position, E_z = transverse dispersion coefficient, Y = flow depth, and ϕ = heat flux from the water surface to air above. The terms in Eq. [1] are (left to right of the page): rate of heat loss from the flow, convection of heat in the flow, transverse dispersion of heat, and heat flux to frigid air above the river. The terms are expressed relative to unit volume of flow.

Equation [1] is written using the assumption that the water is fully mixed over its depth and that there is no transverse mixing due to transverse velocities generated by large-scale turbulence structures in the flow. Measurement of flow velocities through the leads, estimated as about $1ms^{-1}$, suggest that the flow is well-mixed over its depth, thereby impeding thermal stratification, which could enable ice-cover growth over stationary water. The assumptions normally are sound for values of densimetric Froude number[1] associated with river flows during winter (Ashton 1986).

The heat flux can be estimated from an energy budget analysis at the water surface:

$$\emptyset = H_{wa}(T_w - T_a) \qquad [2]$$

[1] Densimetric Froude number = $U/(\Delta\rho/\rho[gY])^{0.5}$, where $\Delta\rho/\rho$ = normalized density difference of density current relative to river flow density, g = gravity acceleration, and Y = flow depth.

here, H_{wa} = heat transfer coefficient stemming from the heat-budget analysis, T_a = air temperature, and T_w = water temperature. If warm tributary water is fully mixed across the river depth when it enters the Powder River and a Lagrangian approach is used (i.e., follow a parcel of water at Udt = dx), Eq. [1] simplifies to

$$\frac{dT_w}{dt} = -\frac{\emptyset}{\rho C_p Y} \qquad [3]$$

This equation can be integrated to yield relationships for the length and area of open water lead; i.e.,

$$L = x - x_{(T_w = 0^oC)} = -\frac{\rho C_p q}{H_{wa}}\left[ln\left(\frac{-T_a}{T_{wo} - T_a}\right)\right] \qquad [4]$$

If the average width of the open-water lead is taken into account, Eq. [4] adjusts to

$$A = B(x - x_{(T_w = 0^oC)}) = -\frac{\rho C_p q B}{H_{wa}}\left[ln\left(\frac{-T_a}{T_{wo} - T_a}\right)\right] \qquad [5]$$

in which unit discharge q = UY, B = average width of open water lead, and T_{wo} = the initial value of T_w at x = 0 and t = 0. The downstream end of the lead approximately corresponds to the location where water in the lead has cooled to the freezing temperature as prevails in the Powder River. Values of B at the survey sites were influenced by several factors: the relative unit discharges (discharge per unit width) of the flows in Burger Draw and Beaver Creek; the manner whereby the flow is introduced into the Powder River (e.g., angle between confluent channels, pipe discharge, manifold discharge); and, the bathymetry of the channel at the discharge location and immediately downstream of it. The lead below Burger Draw confluence always had a relatively uniform width along its length. In comparison, the lead below Beaver Creek hugged the right river bank and had a fairly uniform width for about 800m downstream of the confluence. Thereafter, the lead widened and filled the center of the channel, owing to the dispersive effects of the channel's subsequent braided morphology.

If the same values of T_a and T_{wo} were assumed,

$$\frac{A_{Beaver\ Creek}}{A_{Burger\ Draw}} = \frac{(qB)_{Beaver\ Creek}}{(qB)_{Burger\ Draw}} = \frac{Q_{Beaver\ Creek}}{Q_{Burger\ Draw}} = 6.5 \qquad [6]$$

Eqs. [4] - [6] infer that the surface area of downstream flow required to cool water from an initial relatively warm temperature, say 4^oC, to 0^oC varies directly with the magnitude of the inflow rate. This observation was confirmed by the dimensions of the leads formed below Burger Draw and Beaver Creek (Table 1). The greater discharge and heat input from Beaver Creek resulted in an open-water lead just over 3km in length and on average 7m wide; and open-water surface are of approximately 2 x $10^4 m^2$. The corresponding open-water area for the lead produced by CBM water discharged from Burger Draw was about 3 x $10^3 m^2$. The surface areas of the leads scale reasonably well with the average discharges of the two CBM water discharges.

Eqs. [1] - [6] suggest ways whereby CBM water could be discharged with reduced lead formation, if leads are undesirable (for eco-hydrologic reasons). Pre-cooling of CBM water and greater lateral dispersion and mixing at the discharge location reduce lead length (Kempema et al. 2011).

5. Scale and Impacts of CBM Water Discharge

Burger Draw and Beaver Creek are representative "small" and "large" CBM-water discharges delivering heat to the Powder River. The study identified five locations of CBM water inflow between Pumpkin Creek and Barber Creek. Figure 4 is a pictograph of CBM-water flow and heat inputs from these locations in December 2010. Measurements for Pumpkin Creek, Beaver Creek, and Burger Draw were made by the USGS on December 8, 2010. The Barber Creek measurements were made on December 20, 2010, and the Direct Discharge values represent average flow and temperature measurements for the discharge reported to the Wyoming Department of Environmental Quality by the CBM producer. Except for the Direct Discharge point, all of the reported values are "instantaneous," representing conditions when the measurements were taken. However, a comparison of all discharge measurements throughout the two-year study period indicates the relative values remain the same throughout the winter, that is, for example, Barber Creek and Beaver Creek have similar discharge magnitudes throughout the winter, but Barber Creek water temperatures are always much warmer than Beaver Creek (Kempema et al. 2011).

The USGS measurements used for Figure 4 indicate that, although Barber Creek, Pumpkin Creek, and the Direct Discharge site each have smaller CBM water discharges than does Beaver Creek, each delivers more heat to the Powder River and probably produces a larger lead. Based on the analysis of lead size presented above, the lead downstream of Barber Creek likely is an order of magnitude larger than the Beaver Creek lead. Also, frazil and anchor ice formation were commensurately much greater in the Beaver Creek lead relative to the Burger Draw site (Kempema et al. 2011). The observations indicate that frazil and anchor ice occur commonly in the CBM-generated open-water leads in the Powder River. Their consequences have yet to be determined.

Water temperatures at the confluences of the different input streams shown in Figure 4 vary considerably. The USGS measurements for December 8, 2010 indicate no heat flowed into the Powder River below the Burger Draw confluence at this time (i.e., Burger Draw measured water temperature was 0^{o}C). However, Burger Draw flow did deliver heat to the Powder River though most of the winter, as evident from the continuous open-water lead maintained below the confluence. The different water temperatures at the confluences observed for similar weather conditions result from the varying residence time of CBM water in the perennialized stream channels. For example, CBM water enters Beaver Creek at more than 2km upstream of the Powder River confluence. By the time it reached the Powder River, it was relatively cool. In contrast, the much smaller discharge of the Direct Discharge flows through a channel about 15m long before entering the Powder River. As a result, it delivers a larger heat flux to the Powder River (Figure 4).

Two potential impacts of lead formation were identified during the study, though each needs further investigation: channel morphology, and hydro-ecology. Preliminary observations indicate that the leads may affect thalweg position and bank erosion in winter, perhaps with relatively little effect on long term physical processes or morphology in the river, though more definitive study is needed (Kempema et al. 2011). The prior biological studies by Senecal (2009) and Hubert (1993) suggest that more needs to be understood about winter hydro-ecologic conditions, and lead formation, in the Powder River. It was beyond the scope of this study to address hyro-ecology impacts. There is a growing body of literature indicating that the dynamic conditions associated with frazil and anchor ice create harsh conditions for fish that may lead to increased mortality (e.g. Brown et al. 2011). If it is determined that lead size needs to be reduced in the Powder River, Eqs [1] - [6] can be used as a framework to manage lead formation.

6. Concluding Comments

This study, entailing field work at two sites on the Powder River during two winters, 2009-2010 and 2010-2011, provides useful insights for agencies and industries managing CBM product water discharge. Moreover, the insights have a broader relevance for other cold-region rivers subject to lateral, point-source inflow of relatively warm water.

The main findings are as follow:

1. Besides adding to the flow of water in the Powder River, the most visible influence of CBM water discharge is the formation of open-water leads extending along a channel bank typically for the order of kilometers along the Powder River. The observed leads were, on average, three to seven meters in width, and formed because of heat conveyed by CBM water entering the river. For constant values of air temperature and CBM discharge water temperature the surface area of the open water leads scales with the discharge rate and temperature of CBM water.

2. The leads contain a form of density or buoyancy current when the discharging CBM water has greater or lesser density, respectively, than the water flowing in the Powder River. For example, this situation prevails when CBM water is at 4^{o}C. The leads comprised essentially a buoyant current when CBM water is lighter than water flowing in the river. For example, this situation prevails when CBM water is at 15^{o}C. For both currents, the leads maintain their form in part because the leads are flanked by a channel bank. At some locations along the river where the channel thalweg crosses from one side of the channel to another, notably when the thalweg switches from one outer bend to another, the current may pass under an ice cover, emerging a short distance downstream.

3. Substantial quantities of anchor and frazil ice formed in the leads throughout winter.

4. A framework for identifying how to manage lead formation readily is evident from the formulation of heat loss in open-water flow, as indicated by Eqs [1] – [6]. Lead size can be reduced by several actions that decrease inflow water temperature and promote greater transverse mixing across the river.

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Table 1. Comparison of areas of open water to magnitudes of CBM water discharge.

Confluence Site	Average Water Discharge (cfs)	Approx. Lead Length (km)	Average Width of Lead (m)	Approx. Area of Open-water ($10^3 m^2$)
Burger Draw	0.7	1	3	3
Beaver Creek	7.4	3	7	21

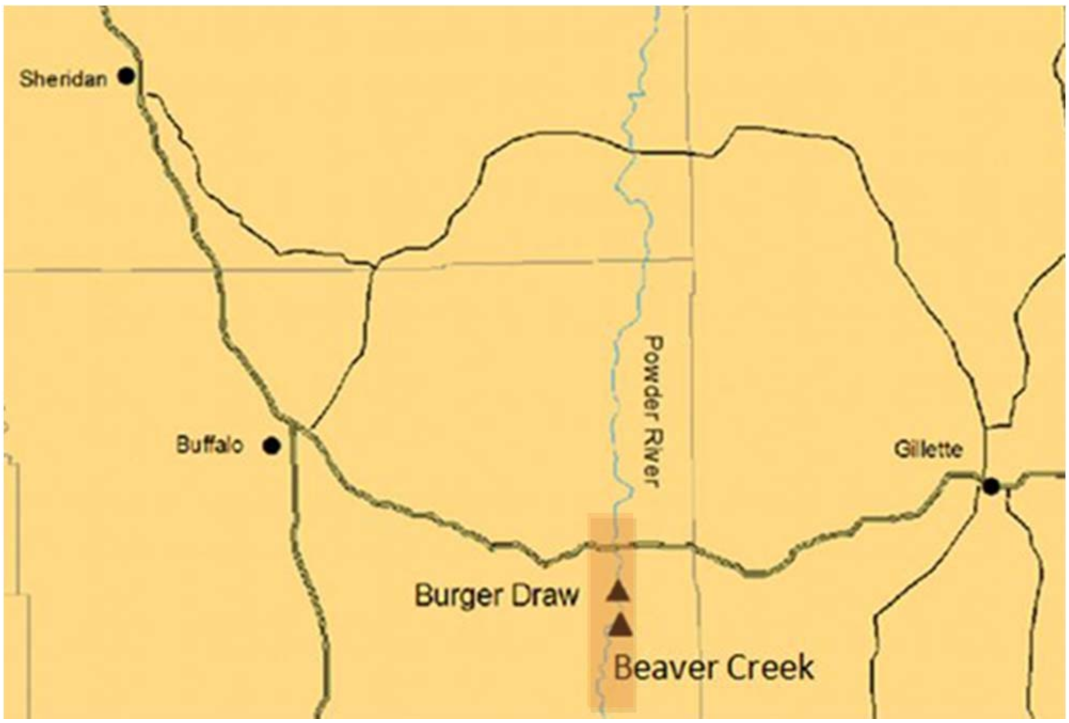

Figure 1. A location map indicating the field sites on the Powder River in northeast Wyoming. The primary study sites of Burger Draw and Beaver Creek are marked by triangles; the orange rectangle marks the 70-km long stretch where five major CBM water inputs enter the Powder River between Pumpkin Creek and Barber Creek.

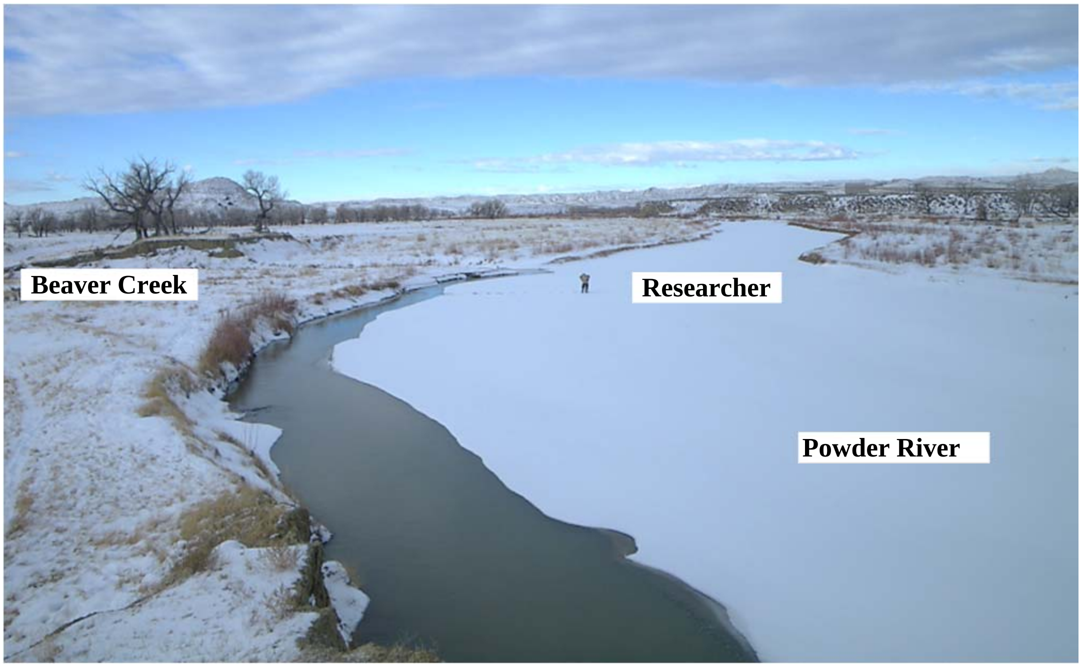

Figure 2. View of the Powder River below its confluence with Beaver Creek, January 21, 2011. The open-water lead visible along the river's right bank resulted from CBM-water discharge from Beaver Creek. The researcher on the river ice is drilling holes for cross-section surveys, ice thickness measurements, and flow measurements in the Powder River.

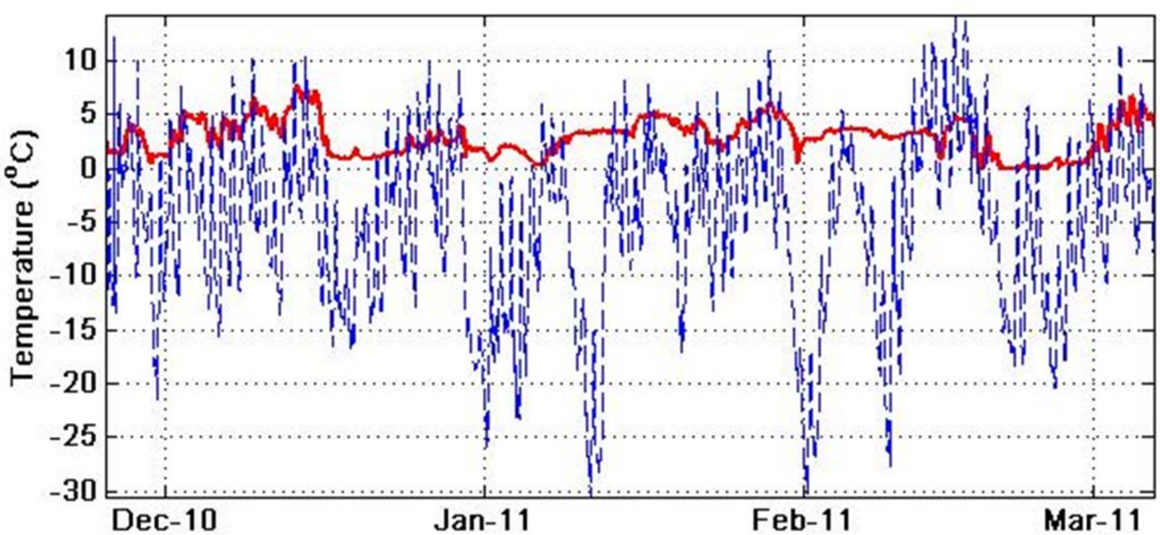

Figure 3. Water (heavy red) and air (dashed blue) temperatures at the mouth of Beaver Creek for the period when the Powder River was ice covered during 2010-2011 winter. Heat input from Beaver Creek to the Powder River remained high throughout the winter except for a short period in late February.

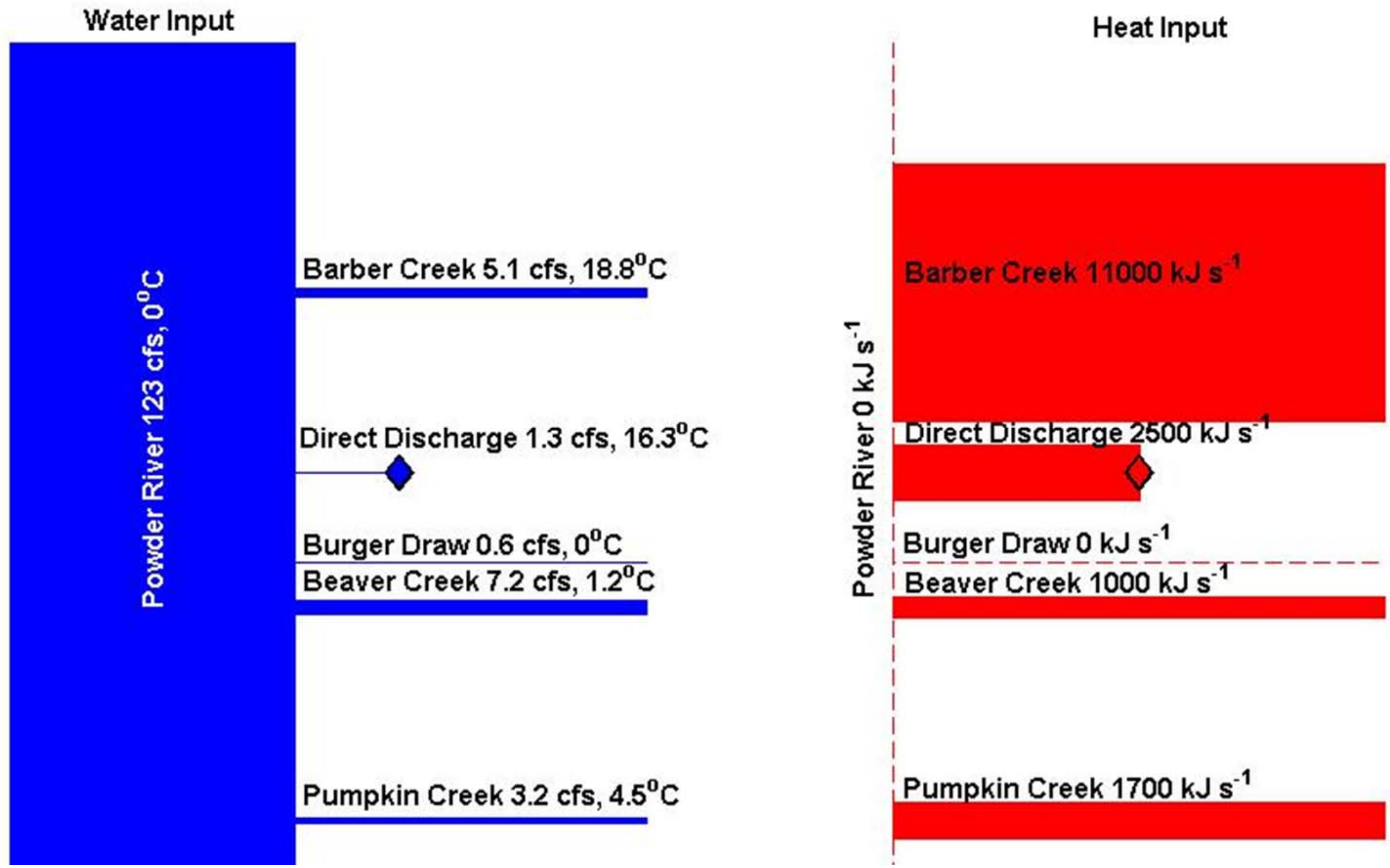

Figure 4. Pictographs of water and heat inputs into the Powder River in early December 2010. The perennialized streams and direct discharge point have small discharges but deliver large heat fluxes to the Powder River during the ice season. Even though the USGS data used to construct this figure recorded an instantaneous water temperature of 0^oC for Burger Draw, and thus no heat flux, over the course of the winter Burger Draw CBM product water flow delivered enough heat to maintain the open water lead in the Powder River downstream of the Burger Draw confluence.