EFFECTS OF CBM WATER DISCHARGE ON WINTER FLUVIAL AND ICE PROCESSES IN THE POWDER RIVER BASIN

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ABSTRACT
The potential adverse geochemical impacts of discharging coalbed methane (CBM) product water into stream drainages are well recognized and reasonably well studied. However, not well recognized or understood are the impacts of heat commonly conveyed with CBM product water (pumped from underground coal beds) entering the Powder River and its tributary streams. The present study shows that heat transported with CBM product water has an annual visible impact on the thermal balance of the Powder River during winter. However, the long-term effects on the river and its 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 discharged was the frequent formation of lengthy open-water leads extending along a channel bank typically for several kilometers along the river. The observed leads, which persisted throughout the two winters, were three to seven meters in width. An analysis shows that, for constant values of air temperature and CBM water temperature discharged, the surface area of the open-water leads scales with the discharge rate of CBM water. The leads comprised a form of density or buoyancy current 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. Because the bed at one site scoured down to expose rock, it presently is unclear whether deeper bed scour would have occurred there. 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. Possible ecological aspects of lead formation are recommended as a topic of further research. The report additionally provides suggestions on how to manage lead formation, should further research on ecological influences indicate that lead extent should be minimized. Lead size can be reduced by several actions that decrease inflow water temperature and promoting greater transverse mixing across the river. In addition, the study provides insights into winter fluvial processes in Wyoming streams.

WRP Focus Category: Hydrology, geomorphological processes
Keywords: Coalbed methane, product water, ice, channel stability

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1. INTRODUCTION

The recovery of coalbed methane (CBM) requires the removal of groundwater to depressurize the coalbed aquifers. In the Powder River Basin (PRB) large amounts of groundwater are removed from coalbed aquifers during CBM production. These CBM-produced waters, which can be saline and sodic, are discharged into surface impoundments, used for irrigation (if salinity isn't too high), and discharged into perennial and ephemeral streams. Depending on its geochemistry, discharged CBM product water can increase salt content of soils, decrease soil porosity, harm riparian plants and crops, and change the chemistry of surface water features. Because of these potential problems, and the volume of water produced, Powder River CBM product water has been the subject of numerous geochemical studies (e.g., Frost and Brinck, 2005; Frost et al., 2002; Jackson and Reddy, 2007a; Jackson and Reddy, 2007b; Johnson, 2007; Mcbeth et al., 2003; Rice et al., 2002).

In addition to its geochemical load CBM product water carries one further quantity **–** *heat*. Evidently, no prior published work addresses how CBM heat affects fluvial processes in the PRB or similar rivers and streams.

Introducing heat into a stream may disrupt ice formation processes and potentially affect channel stability. This study shows that the continuous heat flux associated with CBM product water discharged into water ways impedes formation of a surface ice cover and changes the winter ice dynamics of the Powder River and its tributary streams. Instead of a more-or-less continuous ice cover, accumulations of frazil and anchor ice may form, causing rapid local changes in flow conditions resulting in flooding, increased bed and bank scour, and possibly adversly affecting winter stream habitat. Frazil ice comprises millimeter-sized discs of ice that form in supercooled, turbulent water. Anchor ice is ice that is attached to, and grows on, the river bottom.

1.1 Objectives

This project's principal objective was to determine if and how heat from CBM product water discharged into PRB streams impacts the winter flow and ice regime in the Powder River and PRB streams. Of practical interest is whether altered ice regimes affect channel stability and winter habitat. The study's results include:

- An overall evaluation of winter flow and ice processes in streams and the Powder River receiving CBM product water;
- Quantitative information including measurements of winter water temperatures along stream reaches with CBM product water discharge;
- Knowledge about frazil and anchor ice formation in the Powder River and similar Wyoming streams.

The project does not provide in-depth documentation of specific biologic impacts of CMB heat discharged into winter streams. Instead it focused on physical processes associated with CBM heat discharge and preliminarily delineated areas where this discharge has potential biological impacts. Such impacts associated with altered ice regimes should be the focus of future studies. The immediate direct need is better understanding of the effects CMB product water discharge exerts on winter flow processes and ice formation.

1.2 Ice Formation in Rivers

For rivers like the Powder River conveying turbulent flows, three different types of ice form as the water column losses heat to the atmosphere and starts freezing (Figure 1.1). The most visible ice type is border ice that grows at the water surface. The second ice type, frazil ice (usually termed frazil), consists of millimeter-sized ice disks that grow while suspended in turbulent, supercooled water (water cooled to below the freezing point). The third ice type, anchor ice, is ice that is attached to river bed. All of these ice types can form simultaneously in a given river reach. The relative abundance of each ice type depends on complex interactions between flow characteristics, heat loss to the atmosphere, number of seed-ice crystals, and bed materials (e.g., Tsang 1982, Ashton 1986).

Anchor ice formation is always associated with frazil formation. Frazil is a prevalent fluvial ice type, readily visible, when large areas of the river are open to the atmosphere (Daly, 1994). Frazil in supercooled water is ”sticky,” and exhibits strong cohesive tendencies between individual ice crystals and between ice crystals and bottom materials (Carstens, 1966). When frazil crystals stick to the bottom, they form initial anchor ice.

Environmental conditions leading to frazil and anchor ice formation have been studied in some detail, with the goal of minimizing the adverse effects of ice on engineering structures (Altberg, 1936; Arden and Wigle, 1972; Barnes, 1928; Daly, 1991; Daly, 1994; Daly and Ettema, 2006; Michel, 1971; Richard and Morse, 2008; Tsang, 1982). Tsang (1982, p.25) succinctly summarizes the conditions leading to frazil and anchor ice formation as: “. . .*requires zero solar radiation heat input, and large heat losses by long wave radiation, evaporation, and convection from a small water body. In common language, one says frazil and anchor ice are likely to form at night when the wind is strong, the humidity of the air is low and the river is at minimum flow, especially if such a night follows a cold, windy and cloudy day.*” Daly (1991) is more quantitative, reporting that frazil formation is associated with air temperatures less than about 6^{o}C, open water, and clear nights. Open water (lack of a surface ice cover) is critical for frazil and anchor ice formation. Daly (1991) states emphatically that frazil cannot form and, by extension, anchor ice will not form, where a continuous, stable ice cover is present. Water supercools at the surface; this supercooled water is mixed downward into the river by turbulence. Frazil crystals are mixed into the water column along with the supercooled water (Hammar and Shen, 1995). Supercooled water cools the riverbed and anything in the water column to below the freezing point. Once the bottom or an object in the flow is colder than the freezing point, frazil will adhere to it (Arden and Wigle, 1972; Daly and Ettema, 2006). This condition is often described as the frazil being “sticky” or “active” (Carstens, 1966; Michel, 1971; Tsang, 1982).

Anchor ice masses can grow to be quite large, covering hundreds of square meter of the riverbed, and stick tenaciously to the bottom for as long as the water remains supercooled. These large anchor-ice accumulations raise stage locally. In extreme cases, anchor-ice masses build up to the river surface, creating anchor-ice dams (Kempema and Konrad, 2004) that can create significant backwaters. Usually, incoming solar radiation during daylight hours warms the river water to the freezing point in the morning. When this occurs, anchor ice releases from the bottom and floats to the surface (Arden, 1970; Arden and Wigle, 1972; Wigle, 1970) carrying entrained sediment that can potentially be ice rafted long distances downstream (Kempema and Ettema, 2010). Although frazil ice usually forms at night, when weather conditions are particularly severe frazil can form in the water column at any time of the day, and anchor ice accumulations can stick to the bottom for several days (Daly and Ettema, 2006; Stickler and Alfredsen, 2009).

Fluvial anchor-ice formation depends on a number of factors working in combination (Kempema et al., 2008; Stickler and Alfredsen, 2009). The factors determine when and where anchor ice will form along a river reach, and can be grouped into three broad categories: heat flux from the water to the atmosphere; characteristics influencing flow mixing: channel morphology, gradient, bed material, water depth, and current velocity; and the availability of seed ice particles.

There is a consensus in the literature, extending back to Barnes (1906), that supercooling of the water column is necessary for the formation of “sticky” frazil ice and subsequent anchor ice formation. There is also a broad, though vague, consensus on the stream characteristics where anchor ice forms. Anchor ice forms in highly turbulent riffles (Tsang, 1982) on gravel or coarser beds (Arden and Wigle, 1972; Gilfilian et al., 1972; Tsang, 1982; Wigle, 1970). This consensus does not adequately delineate the details of flow associated with observed anchor ice. For example, Terada et al. (1999) studied anchor ice formation in a Hokkaido stream with water depths varying from 30 to 60cm. Anchor ice was hardly observed in the deeper portions of the stream, leading Terada et al. to conclude that flow depth was one of the controlling parameters for anchor ice formation. In contrast, Altberg (1936) reported a 1m-thick anchor ice accumulation at 20m depth in the Neva River. Similarly, reported limiting minimum water velocities for anchor ice formation range from $0.1 ms^{-1}$ (Stickler and Alfredsen, 2009) to $0.7 ms^{-1}$ (Hirayama et al., 2002). Stickler and Alfredsen (2009) discuss the range of values of stream characteristics associated with anchor ice formation. They conclude that anchor ice has a wider spatial distribution (in terms of stream characteristics) than previously recognized. Bisaillon and Bergeron (2009) modeled the presence/absence of anchor ice on three gravel-bed rivers in

Quebec. They found that water had to be supercooled for anchor ice production, and that fast and shallow conditions (as expressed by a Froude number[1]) favor anchor ice formation. In summary, the various observations about flow velocity and depth, and bed conditions, actually express information about mixing within the flow. Accordingly, conditions leading to anchor ice formation are best expressed in terms of parameters characterizing flow mixing (Kempema and Ettema, 2010.

Eventually, released anchor ice and frazil agglomerate and rise through the water column, forming drifting slush whose surface freezes over when exposed to the frigid air (Figure 1.1); a phenomenon frequently observed in the Powder River. As the consolidating slush drifts it accumulates as ice masses covering the channel which gradually freezes over. In sufficiently low velocity flows, drifting ice masses accumulate, along with border ice, to form a more-or-less uniform cover that thickens by thermal ice growth. In swifter flows, ice accumulates as non-uniform formations termed freeze-up jams and hanging dams, which develop under ice covers (Beltaos, 1995).

Stream flows shallower than the potential thickness of a thermally grown ice cover, and of low unit discharge (flow rate per unit width of channel), may become largely blocked by ice that extends down to the channel bed. The blocked flow then seeps over and freezes as laminations of ice (aufeis) on the ice cover. The resulting spreading and thickening ice growths are called aufeis formations. Aufeis formations commonly grow in areas of relatively steep topography (Carey, 1973; Harden et al., 1977; Kane, 1981), including steep streams feeding into the Powder River. Once formed, aufeis formations are notably resistant to decay and break-up, because they rest on the channel bottom, and usually are thick and strong. Spring and summer flows passing over aufeis formations erode down through them, exposing the channel bed, fragmenting the formations, and eventually washing them from the channel. During cooler and drier summers at some locations, aufeis formations may persist for more than a year. Aufeis presence retards flow, usually dispersing it laterally.

1.3 Powder River Basin Coalbed Methane Production and CBM Product Water

The Powder River Basin is known for its coal deposits, and indeed the basin is the largest coal mining region in the United States, though most of the coal is buried too deeply to be economically accessible. The region produces forty percent of the United States coal production. In 2007, Powder River Basin coal production was 436 million tons of coal, more than twice as much as the next largest coal region (Reddy, 2005). Coal production is an important commercial activity in the region. Because large extents of Powder River Basin coal beds are located at great depths challenging to physical excavation of the coal considerable attention is given to utilizing the coal by means of extracting its methane as CBM.

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[1] The Froude number is a dimensionless number relating a body's inertia to gravitational forces. It is defined as $Fr=U/(gY)^{-1/2}$, Fr: Froude number, U: velocity, g: gravitational acceleration, Y: water depth.

PRB coal seams contain an abundance of coal bed natural gas, predominantly coalbed methane (CBM), a substantial source of hydrocarbon energy that can be recovered by means of well systems constructed at numerous locations over PRB coal seams. These wells pump water from coal-bearing aquifers. Pumping from the aquifer allows CBM to desorb from the coal and be recovered at the well head. However, water pumped from the coal seam must also be disposed of. Options for disposal of CBM product water include storage in lined or unlined impoundments, water treatment with subsequent use of the treated water, managed surface irrigation, underground injection control (UIC) facilities, and direct or indirect discharge into surface streams. Disposal options depend on the quality of the recovered CBM product water.

In a 2009 report, the Wyoming Department of Environmental Quality (2009) estimated that 916 million barrels of CBM product water were extracted from Powder River Basin CBM wells during 2008. Of this volume, 20% (183 million barrels, consisting of a mix of treated and untreated water) was directly discharged into surface drainages. Most of this water was discharged into ephemeral tributaries of the Powder River (here termed “perennialized streams”) some distance upstream of respective Powder River/tributary confluences. This volume of CBM product water translates into an average annual discharge of 33cfs ($0.9m^3s^{-1}$). Based on available data, the average temperature of this product water at the wellhead is about 20^oC (Rice et al. 2002). This volume of water, at this temperature, adds a very large amount of heat to Powder River Basin drainages during the winter month. It is this water, and its entrained heat, that are the subject of this investigation.

1.4 The Powder River

The majority of the research effort for this study took place at and around two tributaries of the Powder River that discharge CBM product water into the River. This section contains a short description of the Powder River in this area.

The Powder River is a northward-flowing river with headwaters in the Bighorn Mountains of Wyoming. It flows northward out of Wyoming, eventually discharging into the Yellowstone River in Montana. CBM product water entering the River directly affects the water quality. At the gaging station nearest the study sites (Powder River upstream of Burger Draw, USGS station #06313590) for the water years 2003 to 2010, the average discharge for the winter season (defined here as November 1 through March 15) is about 100cfs ($2.8m^3s^{-1}$).

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 in close proximity to the Powder River consists of a flood plain and a series of alluvial terraces that grade into alluvial fans (Moody et al., 1999). These unconsolidated sediments are underlain by Tertiary sandstones, siltstones, and shales of the

Fort Union and Wasatch Formations. Away from the river, badlands topography rises to a high plain. These badlands are dissected by ephemeral tributary streams.

The annual hydrograph for the Powder River is twin-peaked, with a first peak that occurs 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 3000m. After this peak, discharge can be very low to non-existent in the middle Powder River (as defined by Hembree et al., 1952). The middle Powder River has a slope of ~0.001 and has an estimated average bedload discharge of 160,000 tons per year. All of the bedload sediment is sand-sized, with a median grain size of about 0.250mm (Hembree et al. 1952). Moody et al. studied river cross sections on the Powder River in Montana over a 17 year period after a large flood in 1978 (peak discharge of $930 m^3 s^{-1}$) severely eroded the river channel and floodplain. They report that the floodplain redeveloped by vertical accretion at an average annual rate of 2 to 8cm per year over the length of their study. Moody et al. also report that spring discharge peaks often cause ice jams to form, leading to local flooding.

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. Senecal cites Hubert (1993) as characterizing the river as having highly variable intermittent flow regimes that have unique prairie-river flow regimes and ecosystems. As such, the Powder River is an example of "a highly-evolved and increasingly-rare native fish assemblage." Senecal restricted her study to summer observations, and mostly considered the effects of increases in discharge caused by CBM product water flow into the Powder River. She concluded that alteration of summer flows caused CBM discharge affect both habitat and fish assemblages in the Powder River.

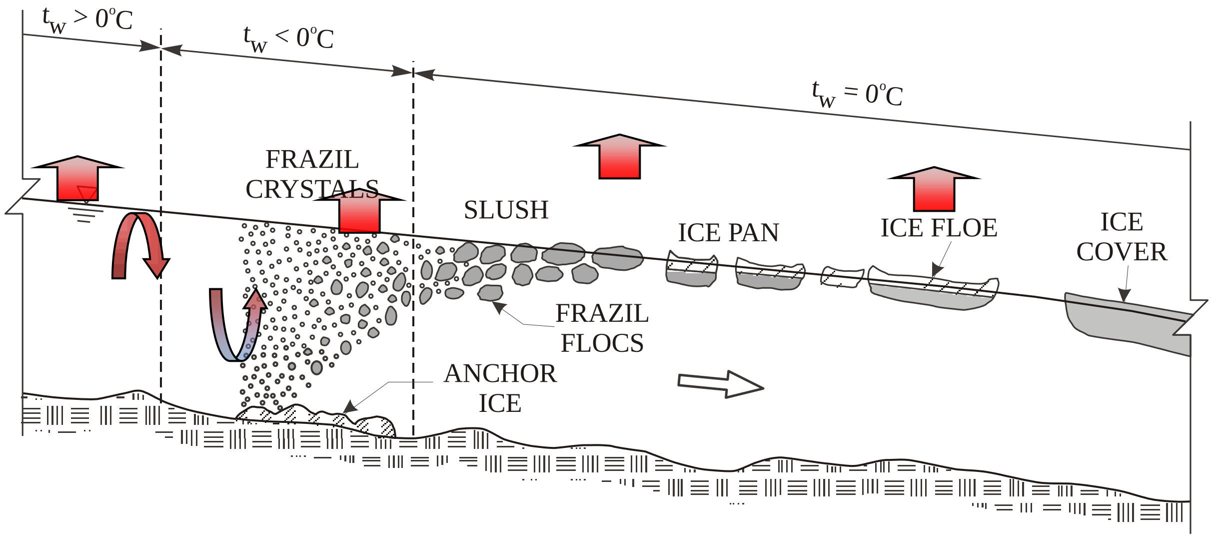

Figure 1.1 Sketch showing longitudinal river profile during ice formation. In turbulent river flow, the water becomes supercooled through heat loss to the atmosphere (red arrows); as a result the first ice to form is frazil and anchor ice. This frazil and anchor ice eventually rises to the surface and is incorporated into the growing thermal ice cover (right side of figure).

2. METHODS

The research for this project was carried out over two field seasons, the winters of 2009-2010 and 2010-2011. Winter is defined here as the period between November 1, when ice may begin forming on Powder River Basin streams, and March 15, when the ice cover has usually melted.[2]

Winter 2009-2010 studies entailed an initial reconnaissance of the Powder River Basin to identify suitable sites for more detailed survey. The investigators worked closely with hydrologists from the USGS office in Casper who regularly make water quality measurements in the PRB. In November 2009, they visited a number of sites along the Powder River (and minor tributaries): Crazy Woman Creek, Clear Creek, Prairie Dog Creek, and the Tongue River. Based on these visits, two sites were chosen for detailed study: *Prairie Dog Creek at Acme* (USGS Station 06306250; there was no CBM discharge at this site; note that logger sites are in italics through the rest of the report) and *Powder River below Burger Draw* (USGS Station 06313590). The locations of these study sites are shown on Figure 2.1. The *Powder River below Burger Draw* site included observations of the small creek that drains Burger Draw (referred to as "Burger Draw" through the rest of this report, USGS Station 06313604). Burger Draw's winter discharge consists entirely of CBM product water. Studies during the first year of the project consisted of instrumenting the study sites, and visiting the sites at three- to four-week intervals during the winter season. During visits, the investigators walked the study reaches, observed ice conditions, collected ice samples using methods outlined in Kempema and Ettema (2010), and serviced instruments. Since the USGS station Prairie Dog Creek at Wakeley (USGS Station 06306200) was on the road between the Prairie Dog Creek Acme and Burger Draw study reaches, the investigators often stopped at Wakeley to observe ice conditions and compare these conditions to the Acme site.

The instruments placed at *Prairie Dog Creek at Acme* consisted of two Onset Hobo U20 water level data loggers and one hobo TidbiT water temperature data logger. One water level logger and the TidbiT were mounted via stainless steel cable to a T-stake that was driven into the bed of Prairie Dog Creek 3m downstream of USGS gaging station. The second water level logger was placed under the USGS equipment shed, about 15m from the T-stake. The water level loggers were set to record temperature and pressure at 10-minute intervals. Placing a water level logger in air allowed the researchers to use Onset's Hoboware Pro software to compensate the stream data logger for atmospheric pressure variations, resulting in true water level measurements with a manufacturer-reported accuracy of 0.5cm and resolution of 0.2cm. The water level recorders also recorded temperature with an accuracy of 0.37°C and a

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[2] An ice season is a period that has a slightly different meaning than winter, in that it implies that ice, of some form, is present on the study reach. A winter season denotes the potential for ice formation, whereas ice season implies that potential is fulfilled. The two years of the research project nicely define the two phases of the project.

resolution of 0.1°C. The Tidbit, which also recorded every 10 minutes, had a reported accuracy of ±0.2°C and resolution of 0.02°C. In practice, the investigators found that the working accuracy is 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 how close recorded freezing points were to the actual freezing point. Temperature offsets observed in the zero-point calibration were removed from the data logger records during processing. There was no easy way to check the absolute calibration of the pressure sensors on the water level recorders. However, at the end of the field season all water level records were placed in the same location, in air, and allowed to record data for several days. The pressure logs were inter-compared, and no significant difference was found between recorders, so the pressure data was deemed acceptable.

The instrumentation at Burger Draw was similar to those at the Prairie Dog Creek reach: Hobo water level recorders and Tidbit temperature loggers. At the start of the field season water level loggers and Tidbits were placed in the Powder River about 100m upstream and downstream of Burger Draw (stations Powder River above Burger Draw and *Powder River below Burger Draw*). These loggers were attached to concrete-filled steel anchors, which in turn were attached to bedrock outcrops in the river with expansion bolts and stainless steel cable. These bedrock outcrops, which were first misidentified as boulders in the Powder River at Burger Draw, were later identified as concretionary outcrops of a bedrock sandstone outcrop that underlies the shallow alluvium below the Powder River at this location. Detailed cross section surveys during the 2010-2011 field seasons revealed that the river can scour down to this bedrock layer around Burger Draw. A Tidbit was also attached to a staff gage about 40 m from the mouth of Burger Draw, in a position where it could not be affected by inflow from the Powder River (*Burger Draw at mouth*). On December 16, 2009 it was discovered that the ice cover had thickened and encased the Powder River above Burger Draw data loggers. The water level logger was removed at this time, and the TidbiT was returned to the river for remainder of the winter season. Removing the water level logger served two purposes: it protected the logger from damage caused by freezing and it freed up the logger to be used as an air pressure recorder, so the downstream water level recorder could be corrected for atmospheric pressure. On March 5, 2010 two more TidbiTs were placed in Burger Draw: *Burger Draw at discharge* was placed in the run-out of a CBM product water discharge point to record water temperatures at the point where the CBM product water entered Burger Draw. This discharge was located 1000 m upstream of *Burger Draw at Mouth*. The second TidBit, *Burger Draw at Schoonover Road*, was placed just upstream of the Schoonover Road culvert, upstream of the *Burger Draw at discharge* location, about 1200m from the Burger Draw/Powder River confluence.

In early February 2010, the investigators received permission to access Beaver Creek, a CBM discharge stream that enters the Powder River about 6km upstream of Burger Draw (USGS

Station 06313585). On February 9, 2010, a TidbiT was placed in Beaver Creek (*Beaver Creek upstream of mouth*), and regular visits were made to this site to record ice conditions in the creek and the adjacent Powder River. Table 2.1 lists the geographic coordinates and durations of record for all of the data loggers placed during this study.

Discharge measurements were made when the Beaver Creek and Burger Draw study reaches were visited. The discharge measurements were made with a Marsh-McBirney Flowmate electromagnetic current meter attached to a top-set wading rod using the standard 0.4-depth technique. However, both of these creeks are very small, so usually on 10 to 12 verticals were used to determine the discharge.

For the second study season, 2010-2011, it was decided to concentrate efforts on Beaver Creek and Burger Draw. Anchor ice and frazil ice phenomena are best observed early in the day, and the long commute between Prairie Dog Creek Acme and Burger Draw made it impossible to visit both sites on the same morning. This consideration, combined with the fact that Prairie Dog Creek was not CBM impacted, drove the decision to concentrate on the two Powder River locations. However, the 2009-2010 Prairie Dog Creek observations provide a baseline for small stream freeze up processes in the Powder River Basin.

Water level loggers and TidbiT loggers were placed in the Powder River locations listed in Table 2.1 for the 2010-2011 seasons. The following changes in logger positions were made in the fall of 2010:

1. Abandoning the *Burger Draw at discharge* point because the discharge was no longer active (the authors later learned it had been moved upstream of Schoonover Road);
2. Abandoning the "Burger Powder River above Burger Draw logger station;
3. Placing a water level logger with the TidbiT at "Beaver Creek near mouth";
4. Establishing a station, "Powder River at mouth of Beaver Creek" in the Powder River 6m downstream of the Powder River/Beaver Creek confluence. Unfortunately, this site was downloaded once in January 2010, after that the station was covered with thick ice and could not be recovered. When the ice broke up, the logger was gone; and,
5. Establishing a TidbiT temperature logger at *Beaver Creek at Road*, about 1200 m upstream of the confluence with the Powder. This logger became encased in ice early in the ice season and did not record useful data.

It became apparent during the first observations at Burger Creek and Beaver Creek that there were consistent open-water leads (large areas of open water) in the Powder River below the confluences with these creeks. The extents of the leads were "mapped" on several occasions using a GPS and estimating the lead width at a number of geo-referenced points along the lead length. These positions and widths, along with the position of the end of the open water lead, were recorded in the field notes, and the areas and lengths of the leads were calculated in the office.

A major objective for the winter season 2010-2011 was to determine if the open water leads affected channel cross section shape over the course of the winter season. Seven cross-section lines were established in early September 2010, four on the Powder River at Burger Draw (named BD1 to BD4 from downstream to upstream) and three on the Powder River at Beaver Creek (BC1 to BC3). The cross sections were surveyed with a total station on September 9, 2010 (no ice) and December 15-16, 2010 (ice and open water lead present). Endpoint benchmarks consisting of three feet of 12mm rebar capped with a plastic cap were established on both sides of the river during the September visits. The positions of these benchmarks are shown in Figures 2.2 and 2.3. Surveys were made by stretching a Kevlar tape between the benchmarks marking the cross section lines, moving the rod in approximately 1m increments along the tape, and recording easting, northing, and vertical displacements with the total station.

The cross-section data were plotted in the office after field work. The sites were surveyed again on January 21-22, 2011 (ice cover and open water lead) and on March 15-16, 2011 (immediately after ice out at the study reaches). For these surveys, a Lasermark LMH laser level system was used to establish vertical displacements along the cross sections. This system has a stated precision of ±2.4mm over a 30m range. The system was used over ranges up to 100m; the accuracy at this range degrades to about ±1cm. Inter-comparison of relative benchmark elevations confirmed this accuracy. Horizontal control for the 2011 surveys was established by measuring distances from the river-left benchmarks on each survey line. This was accurate to an estimated ±5cm. The largest detriment to horizontal and vertical accuracy in all surveys was holding the survey rod (and rod man) in position in the sometimes strong currents. Maintaining position was much easier when ice was present. When ice was present, 150mm-diameter holes were drilled through the ice at 1m intervals before the surveys were started. Cross sections were then surveyed through these holes in the ice. Project personnel were very careful not to run the ice auger into the river bed during ice-hole drilling. Contacting the bed with the auger teeth instantly dulled the auger teeth to the point where they would no longer cut ice.

When ice was present, ice thicknesses at survey holes were measured with a shortened carpenter's square. The end of the square was rotated around the ice hole, and an average ice thickness value for the hole was recorded. In addition, current velocities were measured at 0.4 of the water depth with the Marsh McBirney current meter. These data were used to establish ice thickness profiles and velocity profiles under the ice and in open water leads.

Table 2.1: Data logger locations, deployment dates, and measured parameters.

Site	UTM Coordinates (Zone 13)		Timeline of Data		Instruments*
	Easting	Northing	Date Set	Date Pulled	Measuring
Burger Draw at Mouth	408618	4888914	1/21/2010	3/16/2011	T
Burger Draw at Discharge	409281	4888770	3/5/2010	10/29/2010	T
Burger Draw at Schoonover Road	409372	4888608	3/5/2010	3/16/2011	T
Powder River above Burger Draw	408737	4888769	11/17/2009	3/5/2010	T
Powder River below Buger Draw	408524	4888865	11/17/2009	3/16/2011	T,P
Powder River at Mouth of Beaver Creek	408991	4885675	9/8/2010	1/22/2011	T
Beaver Creek upstream of Mouth	409032	4885595	2/9/2010	3/16/2011	T,P
Beaver Creek at Road	409366	4885577	1/21/2011	3/16/2011	T
Powder River Air temperature and pressure	408897	4888555	11/17/2009	3/16/2011	T,P
Prairie Dog Creek at Acme	354937	4982814	11/18/2009	3/5/2010	T,P

*T=temperature P=pressure

Table 2.2: Bench mark locations for Burger Draw and Beaver Creek cross sections.

Location	UTM Easting	UTM Northing	UTM Elevation
BC1R	408994.08	4885660.93	1208.93
BC1L	408985.79	4885711.06	1208.48
BC2R	408974.38	4885651.41	1209.05
BC2R	408974.26	4885656.59	1208.94
BC2L	408972.73	4885708.83	1208.60
BC3R	408929.96	4885652.59	1209.22
BC3R	408929.64	4885660.23	1209.22
BC3L	408927.92	4885712.62	1208.63
BD1R	408540.44	4888876.78	1203.60
BD1L	408537.90	4888831.10	1202.26
BD2R	408587.35	4888866.75	1202.97
BD2L	408578.78	4888824.79	1202.46
BD3R	408612.73	4888863.33	1202.86
BD3L	408598.16	4888819.07	1202.56
BD4R	408632.94	4888855.34	1203.45
BD4L	408617.00	4888814.07	1202.73

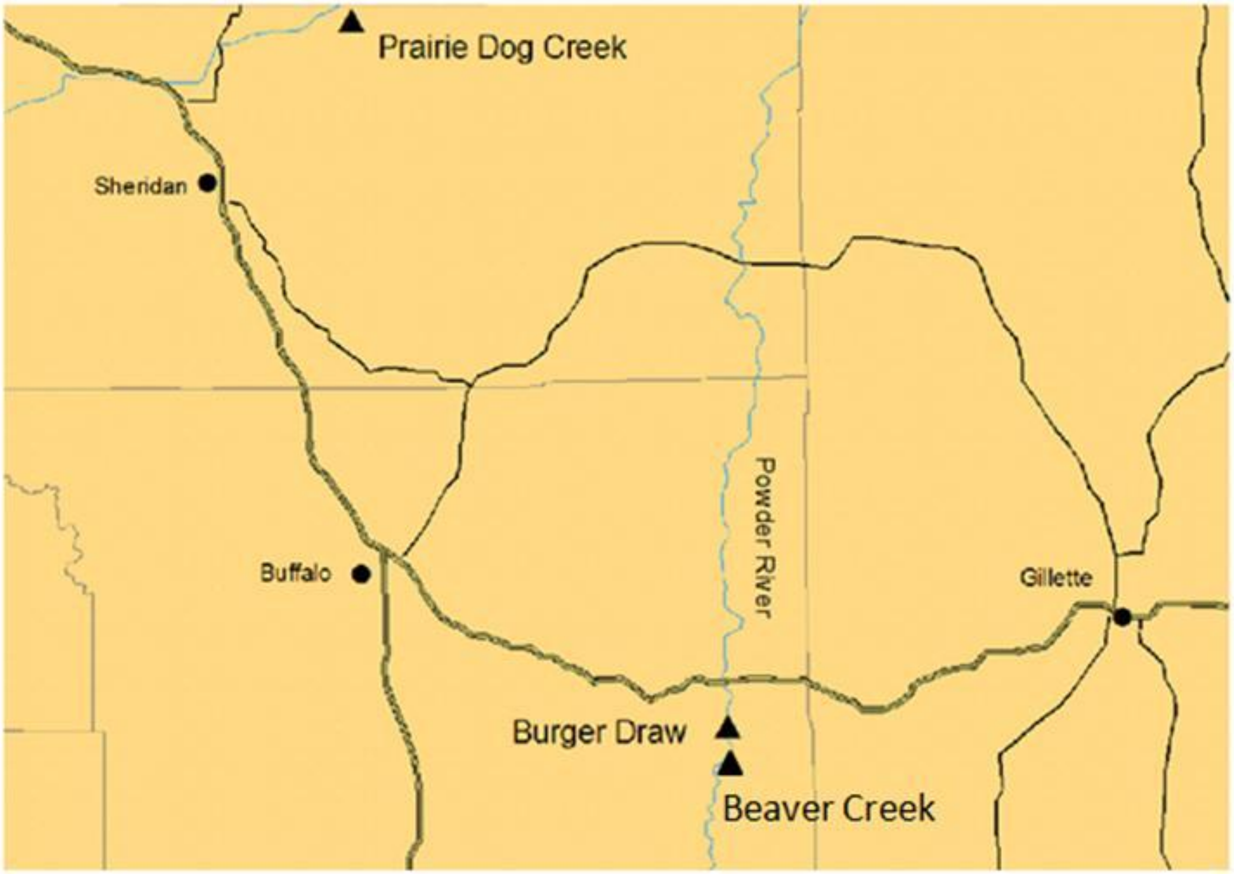

Figure 2.1. Map showing locations of study sites at Burger Draw, Beaver Creek, and Prairie Dog Creek.

Figure 2.2. Aerial image of the Beaver Creek—Powder River confluence showing the relative postions of the cross sections. Cross sections BC1 and BC2 are downstream of Beaver Creek while BC3 is upstream Beaver Creek. The arrow indicates flow direction of the Powder River. Distances (upstream or downstream) of the cross sections from the tributary confluence are: BC1: 30m, BC2: 10m, BC3: 40m.

Figure 2.3. Aerial image of the Burger Draw—Powder River confluence showing the relative positions of the Burger Draw cross sections. Cross sections BD1, BD2, and BD3 are downstream of Burger Draw while BD4 is upstream. The arrow indicates flow direction of the Powder River. Distances (upstream or downstream) of the cross sections from the tributary confluence are: BD1: 80m, BD2: 30m, BD3: 5m, BD4: 15m.

3. RESULTS

This chapter presents the principal findings from the field survey conducted over two winters. They comprise the following component aspects:

1. Water temperature and ice processes in response to air temperature variation;
2. Ice formation characteristics in the Powder River; and,
3. Powder River channel bathymetry responses to ice formation and the effects of CBM water.

The survey produced more data and observations than reported herein. Additional information is given by Stiver (2011).

3.1 Winter Water Temperatures and Ice Processes in Tributary Streams

This section presents the field survey's results regarding water flow and ice formation in the tributary streams to the Powder River – Prairie Dog Creek, Burger Draw, and Beaver Creek. The behavior of flow in these tributary streams bears upon ice conditions and flow in the Powder River over the reach studied. The wintertime behavior of Prairie Dog Creek was representative of streams that do not convey CBM water, whereas Burger Draw and Beaver Creek were CBM-water conveying streams. Prairie Dog Creek conveyed flow from 11 to 14cfs (0.28 to 0.40m^3s^{-1}) during the 2009-2010 ice season. Burger Draw conveyed a small amount of CBM water (0.19 to 1.6cfs; 0.005 to 0.5m^3s^{-1}) whereas Beaver Creek conveyed a much larger CBM flow (5 to 10cfs, 0.14 to 0.28m^3s^{-1}).

3.1.1 Prairie Dog Creek (No CBM Water Flow)

Prairie Dog Creek did not receive any CBM discharge water during the fall freeze up of 2009. As a result, the temperature record for *Prairie Dog Creek at Acme* (Figure 3.1) is typical for small Wyoming streams during freeze up. This sub-section of the report documents the main observations obtained from this site. The observations and associated data provide important, and relatively uncommon, insight into ice formation in small high-plains streams.

Cold air temperatures during late November lowered the water temperature to near freezing at night. However, during daylight hours, warmer air temperatures and incoming solar radiation warmed the water during daylight hours. During the night of November 29, the temperature record shows a short period of supercooling in Prairie Dog Creek; during this period ice was growing in the river, although daytime warming of the water to above 1^{o}C indicates that ice formed overnight probably melted during daylight hours. By the night of December 1, the water had cooled to very near the freezing point, and from December 2 onward daytime water temperatures did not exceed 0.3^{o}C. These small peaks in daytime temperature are indicative of a growing ice cover, and decreased in amplitude as the ice cover grew. Eventually they were no longer discernable in the temperature records. From early December until late February 2010, *Prairie Dog Creek at Acme* was completely covered by a continuous ice cover up to 30cm thick.

This ice cover was firmly attached to the Creek banks. The water beneath the ice cover remained stable at the freezing point during this period. As air temperatures warmed in February, the temperature record of is reversed; i.e. small temperature peaks show up in the water temperature record in mid-February during mid-day, and continue to increase in magnitude through early March. In addition, from March 1 to March 9, 2010, Prairie Dog Creek shows supercooling events at night (Figure 3.2), indicating that there was substantial open water upstream of the sampling site. The March 4 site visit confirmed that there was substantial open water, although significant portions of surface ice cover were still present. The large temperature spike on March 11, 2010, combined with the observation that water temperature never reached the freezing point after this date, suggests that there no more ice in the Creek after this date.

Weather conditions, particularly air temperatures and insolation, drive ice formation and melting on Wyoming streams. Depending on weather conditions, formation of a permanent ice cover may occur at any time between late October and late December. In addition, a cold snap followed by a warm spell may result intermittent formation and melting of the ice cover before the continuous ice cover is developed, as described above. This occurred at Prairie Dog Creek in late November 2009. Between November 18 and 24 there were four nights when creek water supercooled. This was followed by a five-day period when water temperatures never dropped below 0.2^{o}C, indicating there was no ice formation (and probably complete melting) of ice in the Creek. This warm spell soon transitioned into the cold snap that led to the seasonal ice cover development described above.

During the freeze up and ice-cover melt periods, when there is little or no floating ice cover and water supercools during the night, frazil and anchor ice form in the water column. Although frazil formation was not directly observed during this study, anchor ice (a derivative form of frazil) was observed in Prairie Dog Creek on three occasions. On November 18, 2009 there was a sparse anchor ice run in Prairie Dog Creek at Wakeley Siding (USGS sampling station 06306200, http://wy.water.usgs.gov/projects/qw/index.htm). Anchor ice covered 80% of the gravelly sand bed at this site at 7:38 AM. The anchor ice formed hard, sub-rounded masses up to 30 cm thick on the creek bed. Individual crystals in the anchor ice masses were sub-rounded to angular, flat plates 0.3 to 1.5cm in diameter. Two anchor ice samples were collected at this location, using the method described by Kempema et al. (2002). A floating anchor ice sample had a sediment concentration of 9.4gl^{-1}, while an anchor ice sample recovered from the Creek bed had a sediment concentration of 73.1gl^{-1} (Table 3.1). All of the sediment in both samples was sand sized (i.e. 0.062 to 2mm diameter). At 9:45 AM on the same day an anchor ice run on Prairie Dog Creek was sampled near Acme (USGS sampling station 06306250, http://wy.water.usgs.gov/projects/qw/index.htm). The ice crystals forming the floating anchor ice mass were similar to the Wakeley Siding samples collected earlier in the day. This sample contained 6.4gl^{-1} of sand-sized sediment. The largest sediment particle in this sample weighed 0.7g (Table 3.1). In addition, there was a 20cm high anchor ice dam located about 100m downstream of the USGS Acme gaging station at this time.

The last observed occurrence of anchor ice in *Prairie Dog Creek at Acme* occurred on March 4, 2010. This anchor ice formed a dam downstream of the USGS Acme sampling site (Figure 3.3). The dam developed on top of an inundated piece of the floating ice cover, and created a backwater effect extending approximately 100m upstream of the dam. Based on the water level record at the Acme gaging station, it appears that the anchor ice dam, along with increased discharge associated with runoff, raised the upstream water level by up to 60cm over a four day period from March 1 to March 4, 2010. The ice making up the anchor ice dam were flat, dendritic or "christmas-tree" shaped crystals and up to 5cm in diameter. The anchor ice dam, along with the ice crystals making up the dam, had morphologies remarkably similar to features reported from the Laramie River in southeast Wyoming (Kempema et al., 2008). In fact, all of the ice phenomena observed on Prairie Dog Creek have been observed at other Wyoming streams (Kempema and Ettema, 2009; Kempema and Ettema, 2010; Kempema and Konrad, 2004).

3.1.2 Burger Draw (Small Discharge of CBM Water)

The November through December, 2009 water temperature history of Burger Draw, whose small discharge (averaging about 0.75cfd, 0.02m^{3}s^{-1}, Table 3.2) consisted entirely of CBM discharge water, is markedly different than Prairie Dog Creek (Figure 3.1). Instead of the water temperature asymptotically approached the freezing point over several days as the average daily air temperature droped below freezing in the fall, it cooled to a point but warmed several degrees during daylight hours. It was found that Burger Draw water cooled to 0^{o}C, or even supercooled during night time. However, unless the air temperature became very low, the water temperature always rose during the daylight hours. This pattern continued throughout the winter (Figure 3.4); water temperatures often reached several degrees centigrade during daylight hours throughout the winter. As a result, a continuous ice cover was not maintained over Burger Draw. During the coldest winter weather, a continuous floating ice cover often formed over Burger Draw, but the continuous flux of warm CBM product water melted this ice when air temperatures increased. However, as there is a direct connection between the water and the atmosphere in Burger Draw (i.e., no insulating ice cover), cold weather conditions evidently led to supercooling with the consequence of frazil and anchor ice formation at any time during the winter.

Warm CBM discharge water was discharged into Burger Draw throughout the 2009-2011 ice seasons. This discharge was not continuously measured during the ice season. Instead, discharge was measured during each visit to the study site, and was augmented with USGS discharge measurements made during this study (Table 3.2).

Burger Draw water temperatures remained relatively warm (i.e., above the freezing temperature) for several extended periods during the 2010-2011 ice season (Figure 3.5), even though the first major CBM discharge point was moved 500m upstream during the summer of 2010. Discharge during the 2010-2011 season was also similar to the 2009-2010 season (Table 3.2). However, the water temperature record at the mouth of Burger Draw for 2010-2011 shows a marked difference from the 2009-2010 temperature record. This difference shows up as temperature dips of up to -2^{o}C during late November, late December through mid-February, and late February through early March. These sub-freezing temperatures were measured because aufeis grew in the shallow channel where the temperature logger was placed early in the season (Figure 3.6). This ice grew to the channel bed, encasing the logger in ice, and shifting Burger Draw flow about 1m to the left of the data logger position. As a result, for much of the 2010-2011 ice season, the *Burger Draw at mouth* data logger recorded ice temperatures, rather than water temperatures. The influence of the water flowing near the logger is seen in fact that the temperature record never falls far below the freezing point, but this station cannot be used to determine the temperature of water entering the Powder River at Burger Draw. The *Burger Draw at Schoonover Road* data logger, located 500m below a major discharge point, shows that stream temperatures were commonly 2^{o}C to 5^{o}C above freezing 1,200m above the confluence, but a significant (and unknown) amount of this heat was lost to the atmosphere before the water discharged into the Powder River.

Although the *Burger Draw at mouth* temperature logger record was not useable for the 2010-2011 ice season, the Burger Draw at Schoonover logger recorded maximum daily water temperatures of between 1 and 5^{o}C on most days during the winter season. However, qualitatively, much more ice was observed in the lower portions of Burger Draw during the 2010-2011 season compared to the previous season. Aufeis near Burger Draw mouth reached a thickness somewhat in excess of 30cm in early January 2011, forcing water out of the creek channel (Figure 3.6). Continued warm water flow under the aufeis melted the ice from below, creating an insulating ice and air layer that protected Burger Draw from warming.

3.1.3 Beaver Creek (Substantial Flow of CBM Water)

Beaver Creek, like Burger Draw, is a perennialized stream consisting entirely of CBM water during the winter months. Measured discharges in Beaver Creek varied between 5 and 10cfs (0.142 to 0.283m^3s^{-1}, Table 3.2) during the two winter seasons of this study. Water temperatures measured near the creek mouth during the 2010-2011 ice season generally remained between 1^{o}C and 5^{o}C except for a week-long period near the end of February (Figure 3.7). Water temperatures at Beaver Creek were generally more stable that at Burger Draw (compare Figures 3.4, 3.5, and 3.7). This is attributed to the order-of-magnitude higher discharge of Beaver Creek (Table 3.2) and the deeper flow depth of Beaver Creek. Even though measured water temperatures remained well above freezing for most of the 2009-2010 ice season, ice covers still formed during cold snaps and melted during subsequent warmer periods. CBM water created open water leads in Beaver Creek during warm spells; these open water leads allowed water to cool rapidly when exposed to frigid air temperatures. As a result, a variety of ice types formed during frigid weather periods, including surface ice, anchor ice dams (Figure 3.8), and aufeis. Ice formation driven by cold air temperatures raised water levels significantly, at times completely filling the stream channel. When air temperatures warmed and ice melted, stage dropped, leaving hanging ice remnants (Figure 3.8). It is possible that dropping water levels left ice perched above the water surface, as was observed on Burger Draw. When this happens, it creates a dead air space that insulates the water from loosing heat to the atmosphere while at the same time insulating the perched ice from melting. The dynamic nature of ice formation in Burger Creek resulted in water level variations of up to 0.6m over the course of the winter. The water level tended to rise about 0.2m rather rapidly when temperatures dropped (Figure 3.7) and border ice and anchor ice dams retarded creek flow. Creek level would drop as air temperatures warmed and warm creek water thermally eroded the ice. The continuous flow of warm water down the creek created very dynamic changes in ice and flow conditions as weather conditions varied throughout the season.

3.1.4 Powder River (Recipient of CBM Inflow)

Powder River is a perennial (as opposed to perennialized) stream that has a natural discharge of around 100 to 200cfs (2.8 to 4.6m^3s^{-1}) at Burger Draw during the winter months (USGS, http://nwis.waterdata.usgs.gov/wy/nwis/measurements/?site_no=06313590; Table 3.2). As such, it should undergo a typical fall freeze up sequence consisting of cooling of river water to the freezing point and then initial formation of frazil, anchor ice, border ice, and congelation ice growth that amalgamate into a continuous surface ice layer that forms over several days. Once a continuous ice cover forms, it should continue to thicken as long as daily average air temperatures remain below freezing. However, perennialized CBM streams inject a significant quantity of heat into the Powder River. As a result, ice conditions below CBM-stream confluences are not fully natural for the Powder River below these discharge points. This sub-section assesses the quantity of heat injected into the Powder River at discrete CBM discharge points, and the effects that this heat has on ice conditions and cross section profiles in the Powder River.

Formation of Open-water Leads in the Powder River

A common consequence of warm water discharge into the Powder River was the formation of long, relatively narrow stretches of open-water flanking an incomplete ice cover in the river. Herein, these open-water stretches are termed “open water leads,” because their appearance has similarities to open-water leads observed in sea ice. The ice leads in the Powder River, however, formed by virtue of heat convected with tributary CBM flow entering the river, rather than by the action of wind or water current as is the case for sea ice.

During the two ice seasons, open-water leads developed at the confluences of Burger Creek and Beaver Creek with Powder River. They also were observed to occur at other locations where CBM water was discharged into the Powder River. Accordingly, they are a distinctive feature of CBM water discharge into the Powder River. Similar leads often develop in ice covers at rivers adjoining thermal power plants (Ashton 1986).

As described earlier in this report, Burger Draw and Beaver Creek discharge water above the freezing temperature at their confluence with the Powder River. The receiving flow in the Powder River at these confluences within 0.05^{o}C of the freezing temperature when the river is ice covered. On most winter days, the inflow temperature from the two streams varies 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 (Figures 3.4, 3.5 and 3.7). As a result, the Powder River at the confluences received a more-or-less cyclic input of heat on a daily basis. 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.

The influent discharges from Burger Draw and Beaver Creek flow as a form of density current along the Powder River, and do not immediately mix with water flow already in the river. Density currents maintain their form because gravity forces acting on the small difference in water density (between inflowing warmer water and Powder River water at 0^{o}C) inhibits instant dispersion of water. The streamwise flow of a density current in a river channel is greatly facilitated by gravity and drag from surrounding flow. CBM water at 4^{o}C is sufficiently denser (0.013%) than water at 0^{o}C that, bordered on one side by the channel bank, it can maintain itself as a thin density current in a lead extending over a very long distance. In contrast, CBM water introduced at 15^{o}C would be lighter (0.074%) than water at 0^{o}C, such that it would form a buoyant plume. Constrained on one side a channel bank (Figure 3.9 TOP and BOTTOM), 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, a density current or buoyant plume weakens and disperses in a river. Eventually, the leads disappear, unless augmented by additional inflow of relatively warm water.

The width and streamwise extent of the Burger Draw and Beaver Creek open-water leads scaled approximately with the magnitude of heat convected with tributary water flow into the Powder River. The relationship for lead size can be related to a balance of heat influxes in terms of the following heat balance relationship between heat inflow and heat loss to frigid air above the Powder River (e.g., Ashton 1986, Dingman et al. 1968):

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

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 air. The terms are expressed as relative 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 $1 ms^{-1}$, suggest that the flow is well mixed over their 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[3] associated with river flows during winter (Ashton, 1986).

The heat flux can be estimated from an energy budget analysis at the water surface. The budget is simply expressed as

$$\emptyset = H_{wa}(T_w - T_a) \quad (2)$$

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

$$\frac{dT_w}{dt} = -\frac{\emptyset}{\rho C_p Y} \quad (3)$$

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

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

If the average width of the open-water lead is taken into account, Eq. (4) adjust to

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

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

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[3] 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.

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:

1. The relative unit discharges (discharge per unit width) of the flows in Burger Draw and Beaver Creek;
2. The manner whereby the flow is introduced into the Powder River (e.g., angle between confluent channels, pipe discharge, manifold discharge); and,
3. The bathymetry of the channel at the discharge location and immediately downstream of it.

The open water lead below the Burger Draw confluence always had a relatively uniform width along its downstream length. In comparison, the open water lead in the Powder River below Beaver Creek tended hug the right river bank and to have a consistent width for about 800m downstream of the confluence. Downstream of this, the open water lead widened and filled the center of the channel. This change in lead character probably resulted from the presence of braided point bars that appear at this location.

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

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

In accordance with Eqs. (4) through (6), the surface area of downstream flow required to cool water from an initial relatively warm temperature of, say, 4^oC to 0^oC varies directly with the magnitude of the inflow rate. This tendency was reflected by the dimensions of the leads formed in the Powder River at Burger Draw and Beaver Creek, as summarized in Table 3.4. 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 10^4m^2. The corresponding open-water area for the lead produced by CBM water discharged from Burger Draw was about 3 x 10^3m^2. The surface areas of the leads scale reasonably well with the average discharges of the two CBM water discharges.

The formulation Eqs (1) through (6) is useful for identifying ways whereby the discharge of CBM water could be managed so as to reduce significantly the formation of open-water leads. Section 4.3 subsequently discusses possible management options that facilitate CBM water discharge, but with minimal effect on the Powder River, other than adding to its overall flow of water.

Influence on Powder River Ice Cover Profiles

Upstream of the Burger Draw and Beaver Creek confluences, the ice cover on the Powder River averaged about 0.4m in thickness in January and February. The ice cover was reasonably uniform upstream of each site, with thickness variations at locations where drifting anchor ice or frazil may have accumulated to differing extents as the cover initially formed. The formation of open-water leads below the confluences affected the ice cover primarily by impeding its development in the area occupied by the lead, except during especially frigid weather conditions when the ice cover expanded laterally to envelop portions of the lead (see Appendix 2 for ice profiles). The open water lead at Burger Draw, being smaller, was more readily enveloped by ice.

The measurements of cross sections of the ice cover produced profiles of ice cover thickness at the survey sites. The profiles show that the ice cover thickened rapidly with distance transversely away from each lead. Within about 2m from the lead's edge at each site, the cover was at its average thickness (Appendix 2). This thickness variation reflected the very limited lateral spreading of flow within each lead. Water discharged from Burger Draw and Beaver Creek did not affect the ice-cover thickness over much of the cross-section widths below the confluences (Appendix 2). At most locations the ice cover extended to the top of sand bar bars or to the river bed near the banks (Appendix 2). The covers maintained their thickness and strength, such that during the surveys it was possible to walk across the ice cover right up to the edge of the lead. During one site visit, cattle were observed standing on the ice cover and drinking from the open water lead, attesting to the strength of the ice all the way to the lead edge (Figure 3.10).

When a lead froze over during an especially cold period, ice over the lead readily melted out by heat convected from warm water flowing underneath. Lead freeze-over occurred as so-called border ice growth at the edges of the lead caused the lead to contract in a cross-stream direction and as frazil and released anchor ice collected and froze at the downstream boundary of the leads.

Responses of the Powder River Channel

The onset of frigid weather for rivers such as the Powder River typically cause the formation of an ice cover, which imposes a solid boundary across the top of the river, increasing flow resistance (and thereby usually producing a stage rise), and a decrease in flow as watershed runoff substantially diminishes. Frigid weather also affects the strength of channel banks by means of freeze-thaw action on bank soils and halting vegetation growth. The discharge of relatively warm CBM water into the channel of the Powder River affects ice cover formation (as described in the preceding sections) and increases wintertime flow.

Currently, it is only possible to describe in conceptual terms how ice influences alluvial-channel bathymetry (Ettema, 2002). No quantitative evidence exists that ice hastens or slows large-scale changes, such as the migration of a series of meander loops. Such evidence is hard to obtain, since ice is one of several factors influencing the dynamic balance between flow, slope, and sediment in an alluvial channel. Some evidence was obtained from the Power River survey sites suggests that slight adjustments in channel thalweg occurred, but the adjustments were of lesser magnitude than those observed to occur overnight during Spring break-up of the ice cover at the BC1 and BC2 survey sites (Appendix 1). This section describes the channel responses observed at all the sites.

The sets of channel bathymetry cross sections recorded for the Burger Draw and Beaver Creek sites are presented in Appendix 1. Figures A1.3 and A1.4 in Appendix 1 show the BC1 and BC2 cross section surveys for the 2010-2011 winter season. The site at these cross sections is illustrated in Figures 3.9.

The main responses observed were as follows:

1. Thalweg shift toward the open water lead when the thalweg was not entrenched along a channel bend;
2. The channel thalweg, which coincided with the open water lead, deepened slightly, typically by about 0.25m. Because bedrock underlies the Powder River at Burger Draw channel at shallow (and presently unknown) depth below the sandy alluvium, it is unclear whether this depth represents an equilibrium erosion depth in alluvium, or whether deepening was limited by the presence of the bedrock. The bed of the Powder River in the vicinity of the cross sections contains sandstone bedrock that was exposed in the channel below the open water lead during winter;
3. The deepened flow along the open water lead, in combination with weakening of bank soil, resulted in bank erosion and approximately a 2m lateral shift of the channel below the confluences of both Beaver Creek and Burger Draw.

The changes measured at the Beaver Creek and Burger Draw cross sections are summarized in Table 3.5. The responses are indexed in terms of the maximum vertical motion of the channel bed, and the widening of the channel owing to bank erosion. The vertical motions were scour (downward displacement) or fill (upward displacement) of the bed at points on the channel cross-section.

Heat flux to the Powder River and Ice suppression

Direct discharge of CBM water into ephemeral tributaries delivers a continuous flux of heat to the Powder River during the winter months. This heat flux varies on daily and longer time scales (Figures 3.4, 3.5 and 3.7). CBM tributary water temperatures (and hence heat flux) vary in a quasi-sinusoidal fashion with a day-long period (Figures 3.1 and 3.11), with highest water temperatures occurring in early afternoon and lowest temperatures occurring during the nighttime. The lowest temperature that CBM discharge water can reach (like any natural water) is a slight supercooling of $<0.1^{o}$C (Daly, 1994). The maximum possible water temperature of CBM discharge water is the temperature of the water at the discharge point. Average CBM water temperature at the well head is 20^{o}C (Rice et al., 2002). However, because CBM water is usually discharged into tributary channels, some distance upstream from the Powder River, the water cools as it flows down the channel. This effect can be seen in the last six days of the temperature record for Burger Draw in 2010 (Figure 3.4). During mid-March, average water temperatures in the Draw below a discharge point were 14-16^{o}C, while 1,200m downstream at *Burger Draw at mouth* the average water temperature was around 8^{o}C. A method for calculating cooling rate of a stream open to the atmosphere was discussed earlier. In this section a different approach, describing the amount of ice suppression caused by CBM tributary discharge into the Powder River, is discussed

The amount of heat delivered from Burger Draw for the 2009-2010 winter season, and for Beaver Creek during the 2010-2011 winter, to the Powder River can be can be determined with:

$$Q_h = C_p Q T_w t \qquad (7)$$

where Q_h is the total heat flux (kJ day^{-1}), C_p is the specific heat capacity of water (4187kJm^{-3o}C^{-1}), Q is discharge (flow of water from tributary to Powder River, m^{3}s^{-1}), T_w is the temperature of the incoming tributary water, measured near the mouth (^{o}C), and t is the time step. Water temperature was measured at 10 minute intervals, and discharge was measured at two to three week intervals (Table 3.2). By assuming constant discharge between discharge measurements, it was possible to calculate heat fluxes at 10-minute intervals. Summing the 10-minute intervals over the course of the day gave the daily CBM heat fluxes from Burger Draw and Beaver Creek into the Powder River. This daily heat flux was converted to an "ice suppression" value by dividing Q_h by the latent heat of fusion of ice (3.046X10^{5}kJm^{-3}). These daily ice suppression values are shown in Figure 3.12. Beaver Creek had consistently higher water temperatures and discharges compared to Burger Draw; as a result, the ice suppression values for Beaver Creek are consistently much higher than for Burger Draw. Beaver Creek ice suppression values ranged from 0 to 2450m^{3}day^{-1}, while Burger Draw had a maximum ice suppression value of 380m^{3}day^{-1}.

The term "ice suppression" is used herein to give a physical meaning to the heat that CBM-fed tributaries deliver to the Powder River. The term can be interpreted at least two ways: as the amount of excess heat that has to be removed by heat flux to air from the Powder River downstream of the tributaries before ice can form; and, as the amount of heat that is available to melt ice downstream of tributaries. Ice suppression applies only to excess heat delivered from CBM tributaries to the Powder River, and does not account for other heat fluxes to the river, for example, short wave solar radiation or conduction to the atmosphere on warm days. As noted earlier in this report, the temperatures of CBM tributary streams varies over several degrees on daily and longer cycles in response to air temperatures and insolation (Figures 3.4, 3.5 and 3.7). Ice suppression therefore varies on the same scale. However, the net flux of heat from Burger Draw and Beaver Creek maintains open water leads in the Powder River below these tributaries. For Burger Draw, the total potential ice suppression volume for the period of November 4, 2009 through March 15, 2010 was 20,800 m^3 of ice; for Beaver Creek between November 1, 2010 and March 15, 2011 the total potential ice suppression volume was 118,000

m^3. These numbers represent potential values, because air temperatures remained above freezing through mid-November during both seasons, and no ice formed until that time. However, as a result of the heat supplied by these tributaries, there were open water leads below both confluences in both the 2009-2010 and the 2010-2011 field seasons. The ice regimes in the Powder River were different below the confluences than above the confluences, as discussed below.

Effects of Open Water Lead on Ice Processes in the Powder River

The continuous flux of warm water from Burger Draw and Beaver Creek to the Powder River has a direct effect on Powder River water temperatures and ice regimes below these tributary confluences. The warm tributary water mixes with Powder River water. The *Powder River below Burger Draw* temperature logger was located 100m below the Burger Draw confluence and 6m from the right bank of the Powder River. During winter 2009-2010, the *Powder River below Burger Draw* recorded daytime warming less than 0.2^{o}C above the freezing point on most days (this shows up as a small saw tooth pattern in Figure 3.4). By contrast, during the 2010-2011 winter season, the same station shows repeated, long-term (up to 10 day) periods of temperatures of 0.2 to 0.4^{o}C above the freezing point. The warmest water temperatures measured at *Powder River below Burger Draw* correspond to the coldest air temperatures. In general, it appeared that the open water lead was less developed in 2010-2011 compared to 2009-2010. The authors interpret the long periods of relatively warm (0.2 ^{o}C to 0.4^{o}C) water observed in 2010-2011 to result from a thin ice cover forming over the Powder River between the confluence and the measuring site. This ice cover insulated the water from the atmosphere and allowed warm water temperatures to be maintained in the *Powder River below Burger Draw* for long relatively long time periods. Thus, the Powder River responded differently to the warm water flux from Burger Draw during the two seasons of this study. During 2009-2010, the Burger Draw heat flux maintained a relatively large open-water lead in the Powder River. As a result, the warm water from Burger Draw could be seen during the day, but at night, between mixing with Powder River water and heat loss to the atmosphere, the water cooled to the freezing point by the time it arrived at the logger location (~100m downstream of the confluence). By contrast, formation of even a thin ice cover between Burger Draw and the *Powder River below Burger Draw* logger site allowed the heat injected into the Powder River to be maintained for periods of up to 10 days (Figure 3.5). This heat was transported down steam under the ice, resulting in a thinning of the ice cover for some distance downstream. An important point highlighted by the temperature recordings in Beaver Creek, Burger Draw, and the Powder River during this study is that the presence of an ice cover on top of a stream does not necessarily mean that the water underneath is at the freezing point. The ice cover may act as an insulator, enabling warm water to move far downstream before it cools to the freezing point.

One consequence of maintaining an open water lead downstream of CBM tributaries is that there is a direct connection between the water surface and the atmosphere. This raises the possibility of frazil and anchor ice formation in the open water lead sections of the Powder River. As already noted, anchor ice was observed in Beaver Creek on several occasions during this project. Anchor ice was also observed in the open water leads below Burger Draw and Beaver Creek during this study. On February 9, 2010 and February 23, 2010 anchor ice was observed on boulders around the *Powder River below Burger Draw* logger station, and there was a moderate anchor ice run at the downstream end of the Burger Draw open water lead. This floating anchor ice was sampled on both occasions and found to have sediment concentrations less than $1gl^{-1}$ (Table 3.1).

February 9, 2010 was the first day of field work in and around Beaver Creek, which has about an order of magnitude greater flow than Burger Draw. Large accumulations of anchor ice, up to 50cm thick, composed of 2-3cm diameter crystals apparently formed regularly in the open water lead at distances of about 800 to 1600m from the Beaver Creek confluence. The large anchor ice masses at this site were unusual in that they formed on a sand bed (Kempema et al., 2008). On two occasions large volumes of anchor ice were observed (extending along 100m of the river, for the whole river width, with anchor ice 15-30cm thick) to rise to the water surface and drift downstream over about a 10-minute period. In addition, anchor-ice dams formed in this region.

Released anchor ice carried a noticeable amount of sediment, which consisted mainly of sand and pebbles. Sediment concentrations in collected, floating anchor ice sample ranged from 0.19 to $37.3gl^{-1}$ of sediment (Table 3.1). Two attached anchor ice samples contained 42.5 and 73.1g of sediment per liter. Both the absolute concentrations and the range of concentrations measured in Powder River anchor ice samples are similar to anchor ice concentrations reported from other rivers (Kempema and Konrad, 2004; Kempema and Ettema, 2009; Kempema and Ettema, 2010).

Even though the bed of the Powder River contains sediment ranging in size from fine sand to boulders, only relatively small sediment was observed in the collected anchor ice samples. The largest single sediment particle found in a Powder River anchor ice sample weighed 5 g and measured roughly 2.2cm by 1cm by 1cm (a pebble). Moody et al. (1999) studied the ontogeny of the Powder River floodplain near Moorhead, Montana over an 18-year period. They note the presence of ice rafted sand and gravel in fine-grained flood plain deposits. They attribute the presence of these coarse materials to ice rafting by blocks of ice that are carried downstream during breakup ice jams, and note that melting of the ice can deposit “decimeters” (1dm = 10cm) of sand and gravel on the floodplain. However, it is also possible that anchor ice is responsible for ice rafting this coarser material. Moody et al.’s (1999) observation suggests the possibility of anchor ice rafting of coarser material in the Powder River, but this was not confirmed in the present study. Kempema and Ettema (2010) note from the Laramie River that anchor ice rafting is capable of moving boulders weighing up to several kilograms.

At the *Powder River below Burger Draw*, it appears that frazil ice and anchor ice are not significant problems. No evidence of unusual ice thickening, hanging dams, or anchor ice dams were noted in the vicinity of the Burger Draw open water lead. This probably results from the fact that the Burger Draw open-water lead is relatively small, so there is not much chance for the water to supercool and underwater ice to form (Kempema et al., 2008).

By contrast, the open water lead below Beaver Creek appeared to be an anchor-ice factory. The open-water lead tended to hug the right river bank for about 800m downstream from the confluence with Beaver Creek as the Powder River made a large, left oxbow bend. Below this, the river straightens out. At this point, the lead melted the ice off the entire river surface for a distance of 300 to 500m (1,100 to 1,300m downstream of the Beaver Creek confluence). The large open water reach had the greatest the greatest volume of anchor ice. Anchor ice dams were seen in this area, along with hanging ice remnants up to 60cm above the normal water level that were indicative of larger dams in the past. Although these dams raised the water level for up to 150m upstream, they did not cause the water to rise out of the river channel.

Water above the freezing temperature maintains an open water lead, either in perennialized streams or in the main stem of the Powder River. If conditions get cold enough to form significant frazil and anchor ice, both the river and perennialized streams are subject to hanging dam formation, aufeis, and anchor ice. Although there is the potential for flooding when these ice types develop (Daly, 2002), there is relatively little risk posed by the flooding because of the undeveloped nature of the floodplain along the Powder River. However, relatively warm CBM water should probably not be discharged upstream of regions where the risk of flood damage to buildings or land exists.

The USGS regularly measures water quality, including discharge and water temperature, on several CBM-impacted drainages in the Powder River Basin. Table 3.3 presents the USGS discharge and instantaneous water temperatures for Barber Creek (USGS Station #06313750) and Pumpkin Creek (USGS Station #06313560), located downstream of Burger Draw and upstream of Beaver Creek, respectively. Using the method outlined above, and assuming that discharge and water temperatures remain constant between consecutive discharge measurements (dubious at best, based on the fact that USGS personnel make discharge measurements during daylight hours, when water temperatures are at their warmest), it is possible to calculate the daily and winter season potential ice suppression for these streams. Pumpkin Creek had potential ice suppression of 160 to 920m^3day^{-1}, and a total potential seasonal (November 1 to March 15) ice suppression of 58,000 m^3. Barber Creek, by comparison, had much higher water temperatures of 18.8 to 21^oC throughout the winter. As a result, daily calculated ice suppression for Barber Creek ranged from 1,800 to 3,700m^3day^{-1}, with a seasonal total ice suppression estimated at 390,000m^3. Access to the Powder River at either of these sites was not available during the study, but USGS personnel reported that the Powder River stayed “completely open for several miles below Barber Creek” throughout the winter (Eric Blajszczak, USGS, personal communication). The observations for Beaver Creek and Barber Creek reported here most probably apply to the environs around Barber Creek, Pumpkin Creek, and other CBM water discharge points that discharge directly into ephemeral tributaries of the Powder River, i.e. all of these locations are sites of open-water leads, frazil, and anchor ice formation throughout the winter.

Table 3.1. Anchor ice samples collected in the Powder River Basin

Sample date	Sample Location	Sample type	Largest sediment* (g)	Sediment concentration (gl^{-1})
11/18/09	Prairie Dog Creek Wakeley Siding	Floating	1.8	9.42
11/18/09	Prairie Dog Creek Wakeley Siding	Attached	Sand	73.1
11/18/09	Prairie Dog Creek Acme	Floating	Sand	6.4
2/9/10	Powder River below Burger Draw	Floating	Sand	0.19
2/9/10	Powder River below Beaver Creek	Floating	Sand	37.2
2/9/10	Powder River below Beaver Creek	Search for largest sediment particle	16.4 g	n/a
2/23/10	Powder River below Burger Draw	Floating	Sand	0.45
2/23/11	Powder River below Beaver Creek	Floating	5.5	14.6
2/23/11	Powder River below Beaver Creek	Floating, but just released	Sand	42.5

*The largest sedimentary particle was hand-picked from each dried sample and then weighed. If the largest particles were sand-sized, the largest particle size is recorded as “sand” (<2mm diameter).

Table 3.2. Discharge measurements in Burger Draw, Beaver Creek, and the Powder River during this study.

Date	Burger Draw Discharge (cfs)	Beaver Creek Discharge (cfs)	Powder River above Burger Draw Discharge (cfs)	Measuring Agency*
11/04/2010	0.81	8.1	166	USGS
11/17/2009	0.98	--	--	UWYO
12/3/2010	.72	6.4	32	USGS
12/16/2009	0.83	--	--	UWYO
1/13/2010	.81	8.3	69	USGS
1/21/2010	0.77	--	--	UWYO
2/4/2010	.53	6.8	115	USGS
2/9/2010	0.93	9.03	--	UWYO
2/23/2010	0.47	7.8	--	UWYO
3/3/2010	1.1	8.7	183	USGS
3/04/2010	1.1	6.8	--	UWYO
3/30/2010	0.76	5.00	--	UWYO
10/29/2010	0.63	6.5	--	UWYO
11/09/2010	0.52	7.9	133	USGS
11/28/2010	0.64	7.1	--	UWYO
12/8/2010	0.56	7.2	122	USGS
12/14/2010	0.64	10.1	--	UWYO
1/5/2011	0.19	7.2	71	USGS
1/21/2011	0.45	5.3	--	UWYO
2/10/2011	0.35	5.9	122	USGS
2/23/10	0.47	7.8	--	UWYO
3/9/2011	1.60	8.1	308	USGS
3/16/10	0.42	8.58	456	UWYO

*USGS data taken from http://wy.water.usgs.gov/projects/qw/index.htm

Table 3.3. Heat flux and potential ice suppression for Barber Creek and Pumpkin Creek based on USGS discharge measurements during winter 2010-2011.

Date	Discharge Period (days)	Water Temperature (^{o}C)*	Discharge (cfs)*	Discharge (m^3s^{-1})	Heat Flux per Day (kJ day^{-1})	Ice Suppression (m^3day^{-1})
Barber Creek upstream of mouth						
2010/11/01 to 2010/11/22	22	20.5	3.9	0.11	8.19E+08	2700
2010/11/22 to 2010/12/20	28	19.5	2.8	0.079	5.59E+08	1800
2010/12/20 to 2011/01/09	20	18.8	5.1	0.14	9.82E+08	3200
2011/01/09 to 2011/02/22	38	21	5	0.14	1.08E+09	3500
2011/02/22 to 2011/03/15	21	21	5.3	0.15	1.14E+09	3700
Pumpkin Creek						
2010/11/01 to 2010/11/09	9	1.5	3.2	0.09	4.92E+07	160
2010/11/09 to 2010/12/08	29	9.4	2.9	0.082	2.79E+08	920
2010/12/08 to 2011/01/05	28	4.5	3.2	0.091	1.48E+08	480
2011/01/05 to 2011/02/10	33	3.1	2.3	0.065	7.30E+07	240
2/10/2011 to 2011/03/15	33	2.8	2.8	0.079	8.03E+07	260

*USGS data taken from http://wy.water.usgs.gov/projects/qw/index.htm

Table 3.4. Comparison of areas of open water to magnitudes of CBM water discharge

Confluence Site	Average Water Discharge (cfs)	Lead Length (km)	Average Width of Lead (m)	Approx. Area of Open-water (10^3m^2)
Burger Draw	0.75	Approx. 1	3	3
Beaver Creek	5.0	Approx. 3	7	21

Table 3.5. A summary of the maximum fill and scour depths, and change in width for all the cross sections over the two survey periods

Date:	**9/8/2010-12/14/2010**			**12/14/2010-1/21/11**			**1/21/11-3/15/11**		
Cross Section #*	**Max Fill Depth (m)**	**Max Scour Depth (m)**	**Δ Width (m)**	**Max Fill Depth (m)**	**Max Scour Depth (m)**	**Δ Width (m)**	**Max Fill Depth (m)**	**Max Scour Depth (m)**	**Δ Width (m)**
BC1	0.3	0.25	0.1	0.2	0.35	0.5	0.15	0.3	0.5
BC2	0.1	0.15	0	0.1	0.22	0.25	0.05	0.15	2
BC3	0.1	0.18	0	0.05	0.15	0	0.1	0.1	2
BD1	0.05	0.2	0.25	0.05	0.15	0.1	0	0.25	0
BD2	0.025	0.18	0	0.02	0.1	0.5	0.12	0.25	0
BD3	0.15	0.25	0.75	0.05	0	0.25	0.1	0.25	3
BD4	0.17	0.2	0	0.23	0.1	0.25	0.3	0.45	0.25

*BC is Beaver Creek, BD is Burger Draw

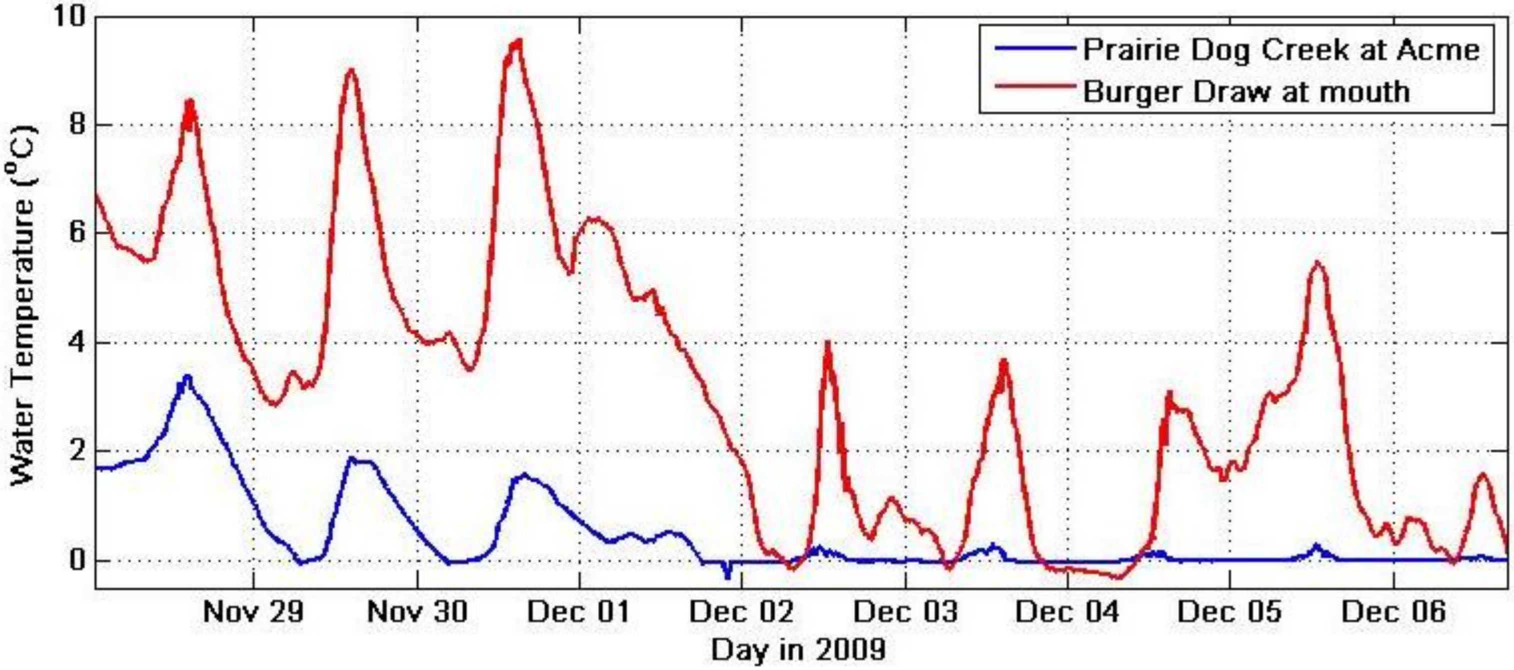

Figure 3.1. Plot of water temperatures in *Prairie Dog Creek at Acme* and *Burger Draw at mouth* during freeze-up in 2009. The Prairie Dog Creek temperature record is typical for the freeze up period for many small Wyoming streams. By contrast, the effect of warm CBM product water discharge into Burger Draw is indicated by the elevated temperatures in the temperature record for this stream.

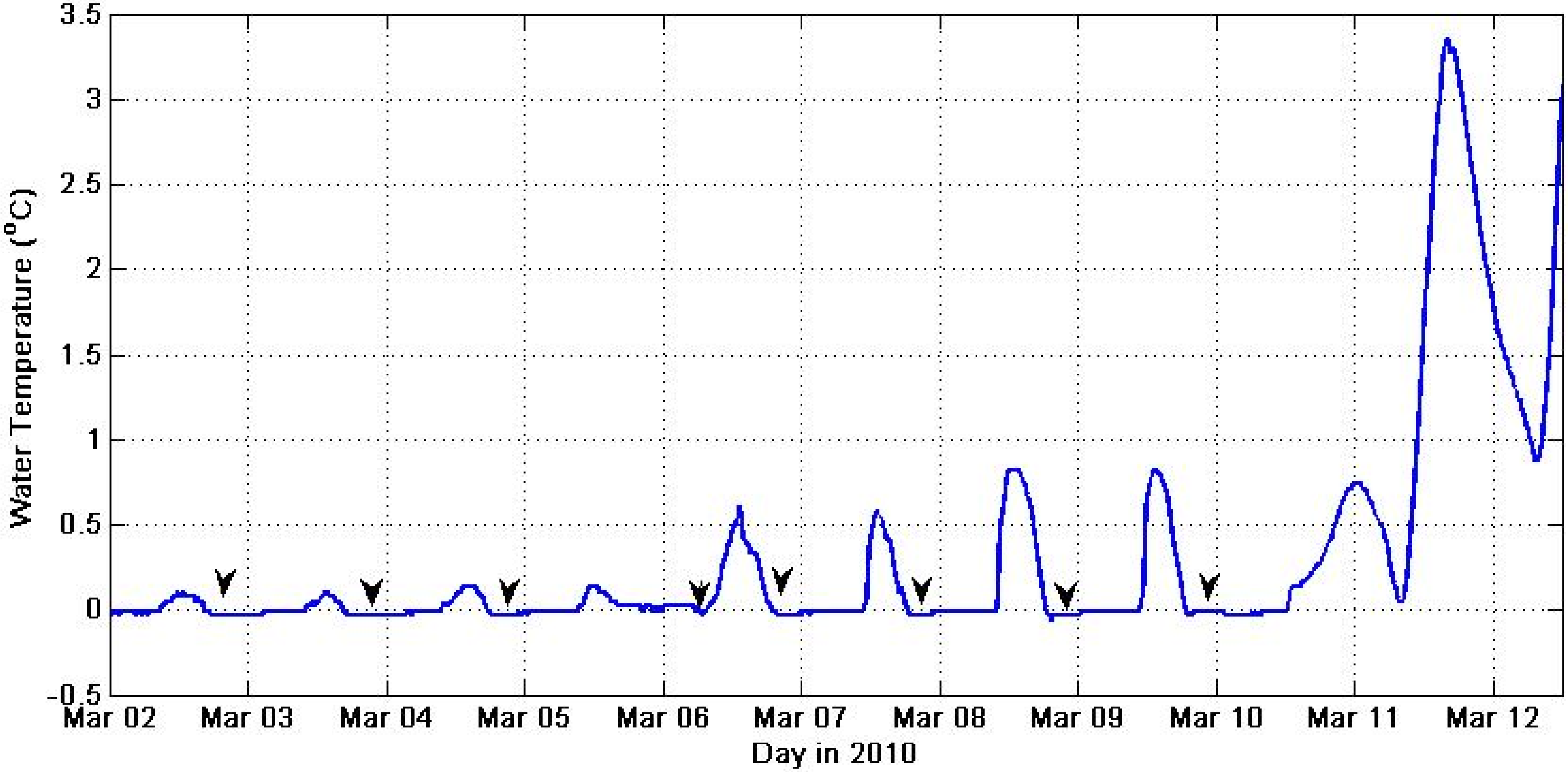

Figure 3.2. Temperature record for *Prairie Dog Creek at Acme* during the spring melt period. Water temperatures during the melt period are the mirror image of freeze-up temperatures; i.e., mid-day temperature peaks are small during the early part of the melt season, and increase in magnitude as air temperatures warm and ice melts. The black arrows mark supercooling periods, when the potential existed for frazil and anchor ice formation. Supercooling of the water column indicates significant amounts of open water and frigid night time air temperatures.

Figure 3.3. An anchor ice dam on Prairie Dog Creek, March 4, 2010. The vertical culvert pipe and cableway about 50 m in the background mark the position of the USGS gaging station, Prairie Dog Creek Acme (06306250). The anchor ice dam formed at night and was in place long enough for a thin layer of border ice to form on the backwater created by the dam.

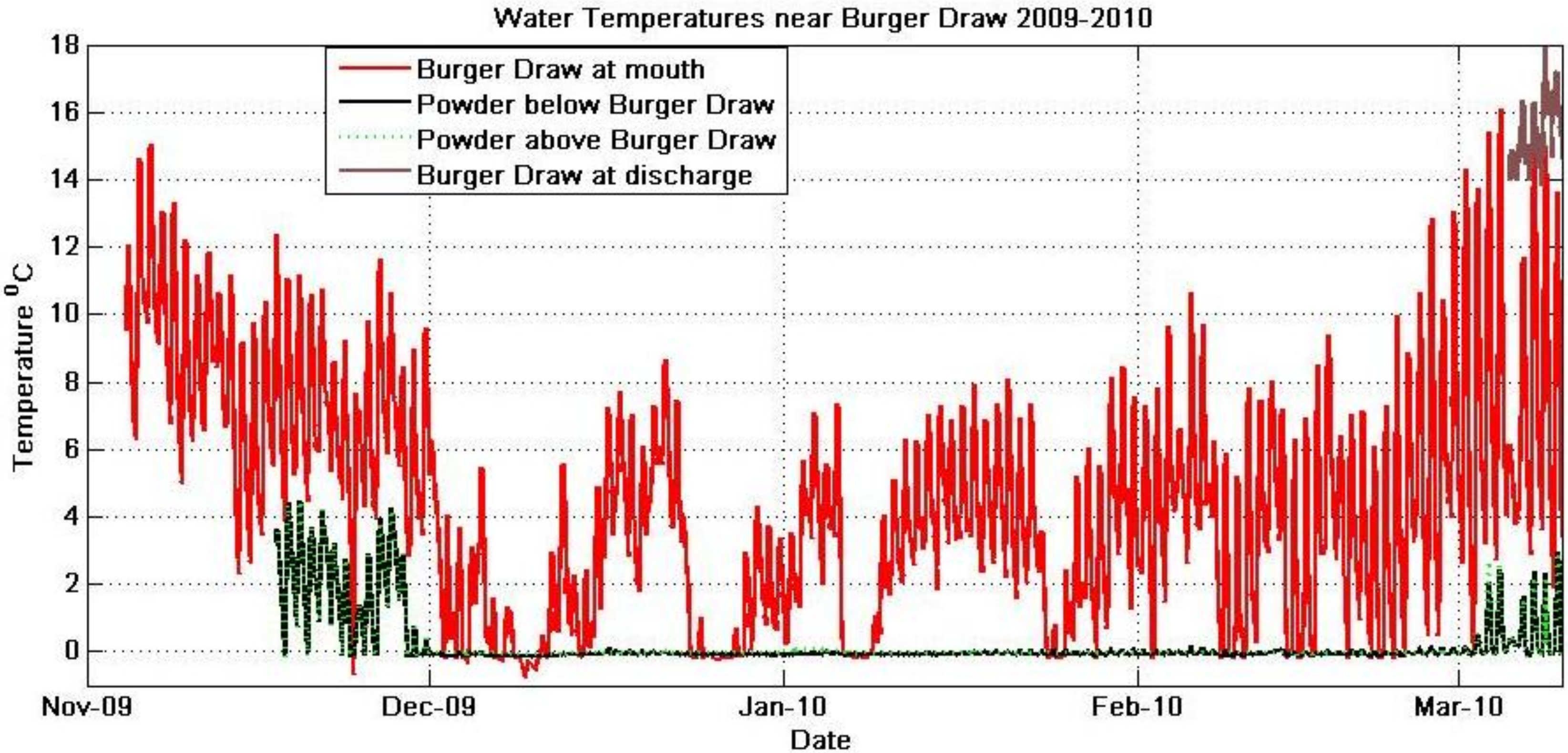

Figure 3.4. Water temperatures for Burger Draw and the Powder River near Burger Draw during the 2009-2010 ice season. The temperature record for *Burger Draw at mouth* (red) reached freezing several times during the winter, when air temperatures were very low. Generally, the Burger Draw water temperatures stayed well above freezing, and as a result this stream transmitted a significant amount of heat to the Powder River throughout the winter. Consequently, a series low-amplitude temperature spikes can be seen in the *Powder River below Burger Draw* temperature record from December through February, when ice was present on the Powder River. The *Burger Draw at discharge* temperature record, established on March 4, 2010, is a short record of the Burger Draw water temperature measured directly below a major discharge point, estimated to contribute >50% of the total flow to Burger Draw, located 1000m upstream of *Burger Draw at mouth*. Water temperatures at this discharge point remain well above 10°C, but the water cools substantially during passage down Burger Draw.

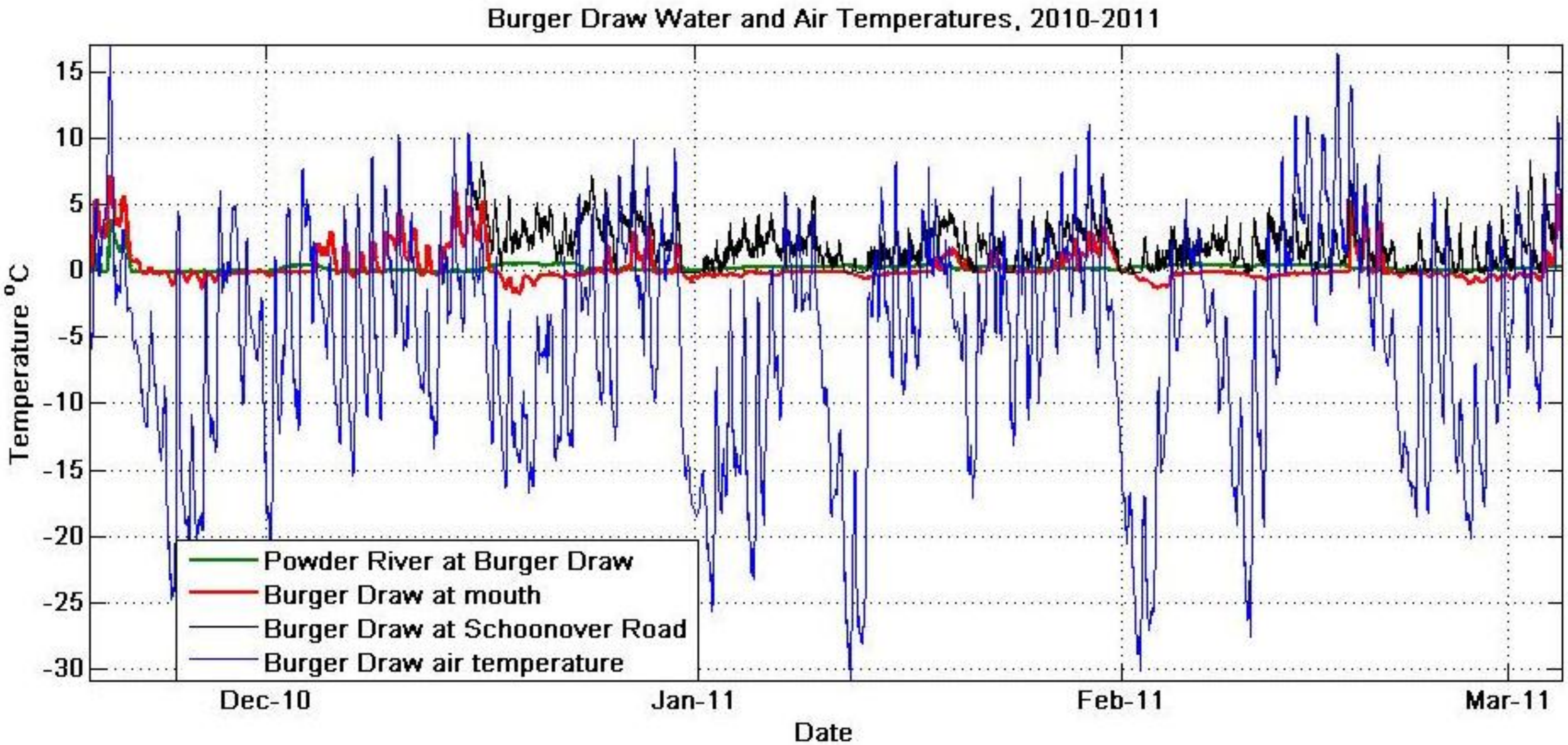

Figure 3.5. Winter water and air temperatures for Burger Draw and Powder River downstream of Burger Draw for the 2010-2011 ice season. During this season, the *Burger Draw at mouth* (red) data logger became encapsulated in ice near the start of the season. This ice grew to the stream bed at the data logger location, which caused the majority of Burger Draw flow to shift away from the data logger location, resulting in below-freezing temperature recordings during cold weather periods. As a result, it is not possible to calculate heat flux from Burger Draw to the Powder River for the 2009-2010 ice season. The *Burger Draw at Schoonover Road* sampling site is located 1200m above *Burger Draw at mouth*, and 500m below the first major discharge point on Burger Draw (which was moved during the summer of 2010).

Figure 3.6. The staff gage at *Burger Draw at mouth*, a water temperature logging station located 50 m from the mouth of Burger Draw. The ice accumulation (aufeis) shown here is exceeds 30cm in thickness, and extends outside the natural channel boundaries.

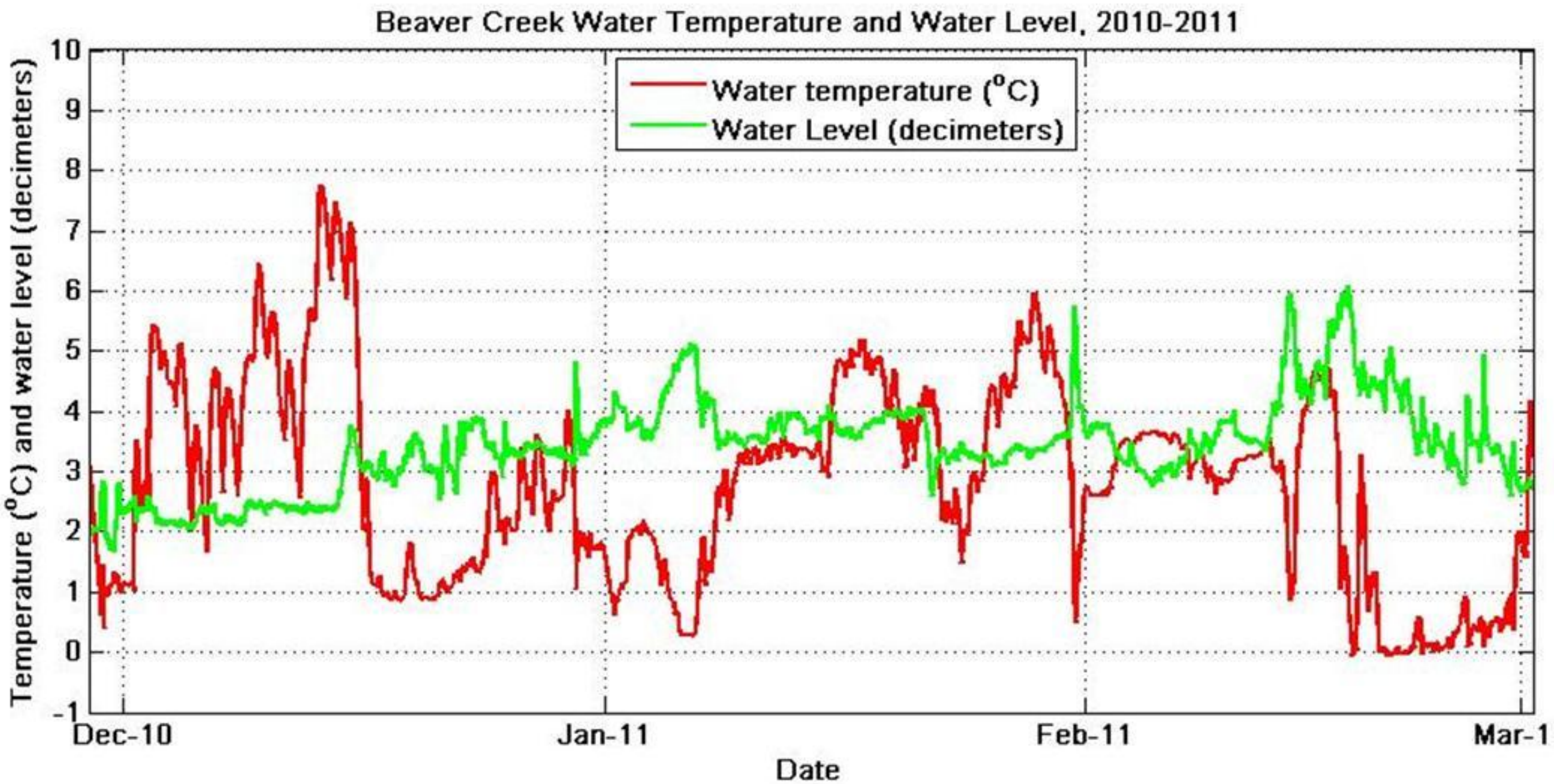

Figure 3.7. Beaver Creek water level and water temperature near the mouth of the Powder River during the 2010-2011 ice season. Water temperatures near the mouth of Beaver Creek stayed above freezing except for a 10-day cold snap at the end of February (see Figure 3.5 for local air temperatures). Water level generally rose during rapid temperature drops, indicating formation of surface ice covers and, potentially, anchor ice dams or over-flooding of the ice, which was observed during field visits in January and February.

Figure 3.8 TOP: Frozen surface of Beaver Creek on February 23, 2011. Water level along this stream section is reduced because of an anchor ice dam that formed by bluff in background of picture. BOTTOM: February 23, 2011 anchor ice dam about 50m upstream from the position where the top picture was taken. The anchor ice dam is creating a backwater. Evidence of water levels up to 25cm above the present water level is seen in the perched ice remnants along the right hand side of the creek. This higher water level completely filled the creek channel, as can be seen in the matted-down vegetation on the left side of the photograph. Flow is towards the viewer in both images.

Figure 3.9 TOP: Powder River below Beaver Creek January 21, 2011.The open-water lead visible along the (river) right bank of the Powder River is the result of warm CBM discharge from Beaver Creek, visible in the center of the picture. The researcher visible on the river ice is drilling holes for cross-section surveys, ice thickness measurements, and current meter measurements on cross section BC1. Cross sections BC1 and BC2 were located just downstream of the Beaver Creek/Powder River confluence (Figure A1.1), while BC3 was upstream of the confluence. The open water lead in this figure is about 6m wide; flow is toward the viewer.

Figure 3.9 BOTTOM: View of open water lead on Powder River downstream of Beaver Creek on January 21, 2011. This photograph was taken from the same positions 3.9 TOP, the photographer simply turned downstream to take this picture. This open water lead extended more than 1.1km downstream of the Beaver Creek confluence on this date.

Figure 3.10. Cattle using the open water lead on the Powder River below Burger Draw as a water source on February 23, 2010. The ice was thick enough right up to the edge of the lead to support the cattle.

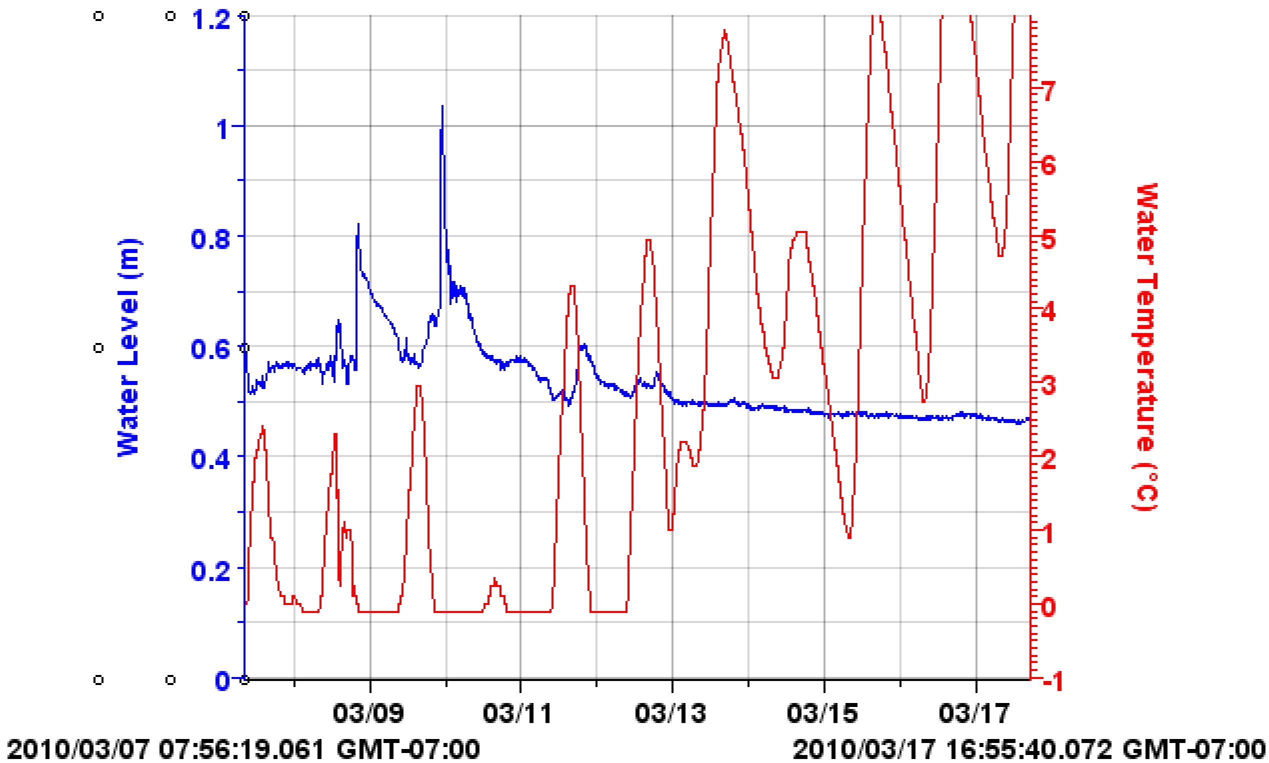

Figure 3.11. Water level and temperature for the *Powder River below Burger Draw* station, in early March, 2010. The steep rises in water level on during the nights of March 8 and 9 were probably driven by anchor-ice formation raising local stage or by formation of an anchor-ice dam downstream. By March 4 there was substantial melting of the ice cover from this location upstream to Beaver Creek, which would have enhanced night-time anchor ice formation. Powder River water at this site did not cool to freezing after the night of March 11, 2010, suggesting that all ice was off the river by this time.

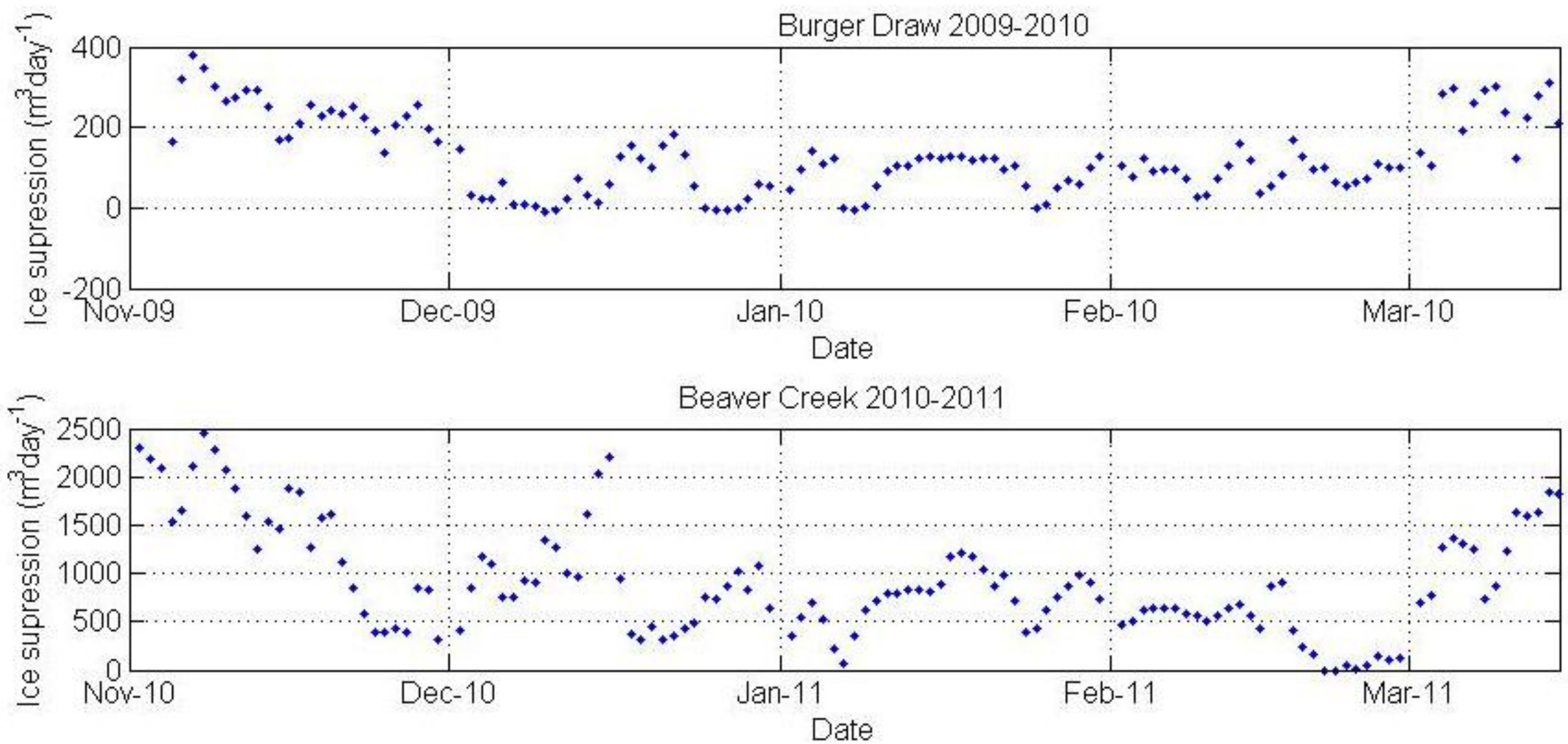

Figure 3.12. Daily ice suppression in Powder River caused by CBM product water heat delivered by Burger Draw (top) and Beaver Creek (bottom). The maximum ice suppression at Burger Draw was 380m^{3}day^{-1}, while Beaver Creek has a maximum ice suppression of 2450m^{3}day^{-1}. The large, almost continuous heat flux supplied by these drainages maintained open water leads downstream of confluences throughout the two winters of the study

4. DISCUSSION

To place the survey findings in an overall context of river ice formation in alluvial channels, it is useful to discuss them briefly in terms of ice effects on rivers and their banks, and relate the context to processes generally observed in the Powder River.

Channel response to ice-cover formation, and concomitantly with the inflow of relatively warm tributary water, soon becomes complicated, especially for a fully alluvial channel. Changes in channel thalweg alignment, channel width, the statistical properties of bedforms may occur in response to diverse changes in boundary resistance, flow rate and sediment supply. Some evidence exists that ice may influence mid-scale features of alluvial channels (e.g., Zabilansky et al. 2002). For example, ice jams may lead to meander-loop cutoffs. However, at this scale, ice effects are still subject to considerable hypothesis. At the local (or survey site) scale it is possible to identify several mechanisms whereby ice may hasten bank erosion and channel shifting. Two such mechanisms, for example, are flow concentration beneath an ice cover and bank/bed gouging by an ice run. Yet, questions remain as to whether these mechanisms prevail over other processes and conditions, and as to exactly how they work. Flow concentration was observed at the two study sites, especially along the open water leads (BC1, BC2, BD1, BD2 and BD3 cross sections, Appendix 1) when an open water lead was present. However, flow concentration was also seen on March 15, 2011 at cross section BC3, upstream of the Burger Draw confluence. This last flow concentration was caused by a rubble ice accumulation on the right portion of the river channel. All of these flow concentrations resulted in widening of the river channel at these locations through bank erosion.

The only prior study that examined how the seasonal appearance and disappearance of river ice perturbs the bathymetry, and thereby stability, of alluvial channels subject to frigid winters, is the survey study conducted by Zabilansky et al. (2002). It examined how the Missouri River downstream of Fort Peck Dam responded to the wintertime release of water from Fort Peck Dam. Their study reported similar observations to those noted for the present study. The literature regarding ice impacts on alluvial channels is sparse and rather inconclusive. A brief review of it ensues.

4.1 River Ice Effects on Channel Morphology

Several factors enable river ice to influence alluvial channel bathymetry. Most of them are explainable in terms of the ensuing functional relationship between a dependent variable, such as hydraulic radius of flow, R, and the typical set of independent variables for alluvial channels;

$$R = \mathrm{f}_R\left(Q, Q_s, \rho, \nu, d, \sigma_g, \rho_s, g\Delta\rho, B, S_o\right) \qquad (8)$$

Here, Q and Q_s are inflow rates of water and bed sediment, respectively; d, σ_g, ρ_s, and $g\Delta\rho$ are bed sediment diameter, geometric standard deviation (a measure of sediment-size distribution), density, and submerged unit weight, respectively; B is channel width; S_o is channel slope; and, ρ and ν are water density and kinematic viscosity, respectively. Other dependent variables of practical interest are channel width, average depth, shape, sinuosity (ζ), flow-energy gradient (S), and sediment-transport capacity (Q_{sc}). Significant changes in any of the independent variables in Eq. 8 may alter R, ζ, or Q_{sc}, and may destabilize the alluvial reach. The greatest natural disturbances typically result from changes in Q, or Q_s, which usually vary seasonally.

The seasonal appearance and disappearance of river ice expands and modifies the set of hydraulic variables in Eq. (8) in a somewhat periodic manner, with the annual cycle of winter. The extents to which ice affects important dependent variables, such as R, ζ, or Q_{sc}, are unclear for alluvial channels. Several qualitative aspects of river ice are clear, however. River ice modifies flow resistance. It exerts hydraulic and geomechanic influences that act over a range of scales in space and time. And, as to be expected, influence impact increases with decreasing channel stability under open water conditions.

A relatively long, level ice cover, for instance, practically doubles the wetted perimeter of flow in a channel, thereby significantly increasing the boundary resistance exerted on the flow. Ice accumulated as an ice jam increases flow resistance by locally constricting flow. Increased flow resistance typically results in increased flow depth, altered flow distribution, and reduced flow drag on the bed - at least for fixed-bed channels. For a given channel, ice impacts on channel bed and banks increase in significance as water discharge, Q, increases. Sediment entrainment and transport increase with increased flow in an ice-covered channel as with an open-water channel. Increased flow also increases the velocity of moving ice and increases the possibility of over-bank flow. River-ice influences likely become more significant when water discharge fluctuates appreciably; then, the prospects for other adverse ice influences increase, such as ice-cover break up followed by ice jamming.

The variables in Eq. (8) suggest that river ice may exert the following hydraulic influences on a channel reach:

1. Through its effects on lateral distribution of flow resistance and, thereby, flow and boundary drag, river ice may modify channel cross-sectional shape developed under open water-flow conditions. This channel response was observed for the cross sections at Beaver Creek and Burger Draw;

2. By imposing additional flow resistance, river ice diminishes the effective gradient of flow energy available for sediment transport and alluvial-channel shaping. It may consequently alter channel-thalweg alignment. This study indicated a thalweg change,

though further field work over a longer channel reach is needed to confirm this response. Also, it is not clear whether the observed thalweg change is the result of ice-cover formation or maintenance of an open water lead downstream of the tributary channels during the ice season.

3. By reducing the sediment-transport capacity of a reach, river ice redistributes bed sediment along the channel. Whatever local-scale effects river ice may exert in accentuating erosion, river ice reduces the channel's overall capacity to convey the eroded sediment a significant distance from the erosion location. Consequently, bars may develop in response to flow conditions under river ice, and then be washed out shortly after the cover breaks up. In situations where a significant load of bed sediment enters a long reach, river ice may tend to cause mild aggradation[4] of the channel it covers. Although there was limited fill in some portions of some of the cross sections during the ice survey (Appendix 1) little or no aggradation was evident. The largest fill volume occurred between the afternoon of March 15 and the morning of March 16, 2011 on the BC2 cross section. The ice had essentially all melted at this point, and stage had risen. The surveyed Powder River cross sections (Appendix 1) indicate no aggradation, likely because flow magnitudes along the river were not of sufficient magnitude to convey sediment, except along the open water lead and in the outer bends of the channel. Moreover, because the flow had scoured the channel to exposed rock in several locations, the river was not conveying bed sediment at its capacity.

4. At times of ice-cover formation and break-up, congestion or jamming of ice at one channel (or sub-channel) location may divert flow into an adjoining channel, which then enlarges (channel anabranching[5] and thalweg avulsion), or over-bank, which may result in a channel cutoff (avulson[6]). This phenomenon was not observed to fully occur at the survey sites, but the propensity for it was inferred by the ephemeral accumulations of ice (e.g., anchor ice congestion at the Beaver Creek site, and ice-cover break-up at both study reaches). A small ice jam was observed at the location of BC3 on the morning of March 15. This jam covered about three quarters of the river channel from the right bank, concentrating flow along the left bank. This jam was gone by late afternoon the same day. Another small ice jam was observed about 10km downstream of the Beaver Creek confluence on March 16, 2011. This jam created a riffle, but its effect on channel morphology is not known. Moody et al (2009) report significant ice jam formation along a study reach on the Powder River located near the Montana border.

[4] Aggradation refers to deposition of bed sediment in a manner that elevates the channel bed and steepens its overall slope.
[5] Anabranching refers to a sub-channel that diverts away from the main channel then merges with it.
[6] Avulsion refers to the cut-off of a tight channel loop or a meander bend.

4.2 River Ice and Thermal Effects on Channel Banks

River ice may influence channel bathymetry through several geotechnical influences it potentially exerts on channel riverbanks:

1. Freeze-thaw thermal weakening of riverbank soils. This was observed during the two winters of site survey as vertical cracks forming on the floodplain and on bluffs flanking the river. The riverbanks would later fail along the cracks, sloughing sediment into the river. No quantitative measurements were taken to document weakening, however;

2. Reduce riverbank strength by increasing pore-water pressure or by producing rapid drawdown of the riverbank water-table during dynamic ice-cover or ice-jam breakup. Survey measurements documented changes in stage associated with ice-cover formation and break-up. Relatively large stage changes occurred at the *Beaver Creek upstream of mouth* site, with rapid stage changes of up to 25cm (Figure 3.7) recorded during cold spells throughout the winter, but no evidence of bank failure was seen in this portion of Beaver Creek. At *Powder River below Burger Draw* water rose nightly over several days in early March, 2010, and dropped down again during daylight hours. These nightly rises peaked on the night of March 10, 2010, with a water level increase of 0.47m (Figure 3.11). The rapid rise at night, followed by drop during the daytime, suggests anchor ice formation backed up the flow in this region. Field notes for the March 6 visit indicate that there was already continuous open water channel about 10m wide from Beaver Creek to an unknown distance past Burger Draw on this day. This channel was bordered by ice attached to the banks. The fact that water no longer reached the freezing point after the night of March 11 suggests that all the ice was off the river by this date. The rapid rises and falls may have affected bank stability. However, it is important to note that this ice-associated water level rise is not directly associated with the discharge of warm CBM water from Beaver Creek 100m upstream. Anchor ice formation and ice jams both occur regularly in rivers without CBM input, so the water level rises seen here probably would have occurred regardless of warm-water input;

3. Tear and dislodge riverbank material and vegetation during collapse of channel-bank-fast ice. It was observed that ice cover break-up sometimes resulted in the removal of grass-cover along the channel bank;

4. Gouge and abrade channel-bank material and vegetation during an ice run. Ice break-up along the Powder River occurred fairly gradually over a several day period for the two winters of survey. Therefore, no significant gouging or abrasion of the channel banks was observed.

In general terms, the foregoing influences reduce channel-bank resistance to erosion, increase the local supply of sediment entering a channel, and can promote lateral shifting of channel. The first two influences are not well studied. The third and fourth have received a little attention, but the extents to which they affect channel morphology is unclear. The observations at the survey sites augment those reported by Zabilansky et al. (2002) for the Missouri River. For both studies, the channel banks flanking the river were formed of relatively weak, easily erodible sedimentary rock.

4.3 Approaches to Management of CBM Water Discharge

Besides augmenting water flow in the Powder River, the principal visible effect of CBM product water discharge into the river at the two sites surveyed, and at other sites informally observed, was the formation of open water leads immediately downstream of locations where CBM product water discharged into the Powder River. The surface area associated with each lead was found to scale in proportion to the magnitude of CBM water discharged into the river, for the same prevailing values of initial CBM water temperature and air temperatures; larger CBM water discharges result in larger open water leads. In a similar fashion, increased water temperatures at constant discharge also increases open water lead areas. Important questions to be considered are the significance of lead formation, and, if the effects are determined to be adverse, the options for minimizing lead formation.

The study shows that the formation of open water leads may influence the following aspects of the Powder River at the sites:

1. The formation and stability of the river's ice cover;
2. The alignment and stability of the river's largely alluvial channel (the channel is not fully alluvial in some reaches, because exposed sandstone bedrock is encountered at in some bed and bank locations); and,
3. The wintertime ecology of the river.

For the sites studied during the winters 2009-2010 and 2010-2011, the present study showed that lead presence locally affected ice-cover formation and channel bathymetry, but did not greatly disrupt them. The present study did not examine how an open water lead might influence the wintertime ecology of the sites, or river as a whole. The similar study by Zabilansky et al. (2002) also did not consider ecological effects resulting from the formation of open water regions along the Fort Peck reach of the Missouri River, but anecdotally noted that such regions seemed to attract fish and birds during winter.

The ecological effects associate with the thermal aspects of CBM product water discharge, lead formation, or mixing with river flow are largely unknown, or analytically substantiated. There appears to be no prior study that has examined these effects. Observations during the two winters noted that the open water leads served as places for animals (both domestic and wild) to drink. Geese and ducks were observed on the leads in February of both years, when the rest of the Powder River was frozen. Finally, small fish were regularly observed right at the confluence of Burger Draw throughout both ice seasons of this study. These admittedly anecdotal observations suggest wildlife might concentrate around leads during the winter months.

Should further consideration indicate the need to decrease the extent or number of open-water leads in the Powder River, Eqs (1) through (6) provide a theoretical framework for determining how to do so. These equations indicate that the following straightforward actions reduce lead size:

1. The length and width of the lead reduce in direct relationship with reductions in the amount of heat entering the river. Eq. (5) directly shows that the amount of heat diminishes when the initial water temperature (T_{wo}) of CBM water at the location of discharge into the river decrease. In frigid winter weather, two methods would decrease T_{wo}:

    a) Lengthen the flow path between the originating source for CBM water (e.g., a CBM discharge point) and the location of eventual discharge into the river.

    b) If feasible, release more CBM water during night time, when air temperatures are normally colder, there is no short wave radiation warming the water (insolation), and water cooling is enhanced by black-body radiation. As shown by Figures 3.4 and 3.5, air temperatures from late afternoon through early morning typically are especially cold (other factors that enhance cooling are also optimal at this time), and therefore cause greatest cooling of CBM water in tributary streams. If this strategy is adopted to control water temperatures entering the Powder River, careful monitoring will be required. It is possible that increased warm water flow at night would increase the potential for ice jams (caused by anchor ice dams or hanging frazil dams) that could increase the flooding potential. The situation in Flat Creek though Jackson, Wyoming as related by Daly (2002) is a cautionary tale in this regard. Warm groundwater was pumped from wells and discharged into Flat Creek to reduce frazil and anchor ice formation thorough the town. The well water did not supply enough heat to Flat Creek to protect the town; instead it just moved the freezing problem downstream.

    c) Increasing the heat flux to air for CBM water while it is flowing from the discharge point to the river. This enhanced cooling of CBM water can be achieved by aerating the flow in a manner that causes it to flow over a small drop-structure or a man-made rock riffle. The increased exposure to air increases the heat transfer coefficient, ϕ, and thereby causes more rapid cooling of CBM water. Some CBM product water is already discharged through a system like this to precipitate solids, increasing the length of the system would allow more heat to be lost to the atmosphere.

d) A combination of actions a) through c).

2. Enhanced transverse dispersion of discharged CBM water across the Powder River channel will result in more rapid mixing of CBM water with the river's flow, and thereby reduce lead size. The formulation of Eq. (1) indicates two ways for increasing mixing and dilution of CBM water:

   a) Increase the transverse-dispersion coefficient, E, in Eq. (1). The results of various laboratory and numerical studies (e.g., Fischer et al. 1979, Rutherford 1994, and Boxall et al. 2002) show that carefully locating discharge locations can maximize the mixing rates in rivers. A discharge located on the outside of a bend produces a faster rate of transverse mixing than does a discharge on the inside of a bend.

   b) Introduce transverse velocities, by means of secondary currents and large-scale turbulence structures. Inclusion of local structure in the channel can promote secondary currents and mixing across the channel.

There is a fine point to consider with option 2. The mixing of two streams of relatively hot and cold water changes the temperature of the combined water mass, but not the heat content. So, heat introduced at a CBM-influenced tributary must still be removed before ice can form. The result of mixing water is to spread the heat out over a larger volume. If the river is ice-free, the larger open water area will efficiently lose heat to the atmosphere. However, if CBM-water supplied heat mixes and spreads out over a large area under the ice cover, the result will be slight melting of the bottom side of the ice cover that comes in contact with the heat-laden water. The Beaver Creek open water lead apparently shows that mixing can have unexpected effects. On most days when surveying the Beaver Creek site during the ice season, a uniformly wide open water lead hugged the right side of the channel. The lead extended about 800m downstream of the creek's confluence with the Powder River. Depending on weather conditions, the lead was 2m to 7m wide and remarkable for its uniform width. Between 800 and 1,000m downstream of the confluence, where the river transitioned from a long-radius left hand meander bend through a short straight reach, the open water lead consistently widened to cover most of the channel width. The straight section of the channel has several large bars that apparently enhance cross-channel mixing and widen the open channel lead. However, the influence of warm Beaver Creek water at this point is still enough to melt essentially all of the ice in the channel for several hundred meters more downstream. This wide open channel area is the zone where the greatest accumulations of anchor ice occurred; it had the greatest amount of anchor-ice rafting and the largest anchor ice dams observed in the study area. Other streams with comparable discharges and heat fluxes, like Barber Creek or Pumpkin Creek (Table 3.3) probably have similar large, wide open water reaches that act as anchor ice factories throughout the winter.

4.4 Impact of Open Water on Winter Fluvial and Ice Processes

The most important outcome of this study is the documentation of long, continuous open-water reaches of water in perennialized tributary streams and in the main stem of the Powder River during winter. This open water is associated with CBM product water discharge points. Considered here are the impacts of such leads.

River reaches without a floating ice cover respond differently to freezing air temperatures than do reaches with an ice cover. Ice-covered river reaches respond by slow thickening of the ice cover. As the ice cover thickens, its insulation value increases, so eventually an equilibrium ice thickness forms on the river surface, ice growth stops, and conditions under the ice become stable. In contrast, when there is a direct connection between the river water and atmosphere (i.e., no ice cover), river water supercools causing frazil and anchor ice form. These ice types can create anchor ice dams (Figures 3.3 and 3.8), raise stage significantly (Figures 3.7 and 3.11), and increase ice-rafting erosion of coarse-grained sediment from the reach's channel bed (Table 3.1). In addition, in small, shallow perennialized streams cold snaps can lead to aufeis formation and local flooding (Figure 3.6). In short, formation of a floating ice cover leads to stable conditions in a river, whereas inhibiting ice cover formation creates very dynamic conditions. The present study documents two types of dynamic conditions observed in the Powder River and its tributaries.

1. The formation of frazil and anchor ice; and,
2. The dynamic nature of the ice cover forming on both the Powder River and its tributary streams.

The dynamic nature of the surface ice cover is seen in the expansion and contraction of open water leads with fluctuating weather conditions (primarily air temperature). Very cold conditions eventually result in closing of open water leads and even growth of ice covers in tributary streams (possibly with local flooding when the ice cover forms). Ironically, the same conditions that close leads also promote dynamic ice frazil and anchor ice formation that result increased stage and ice rafting. When the weather warms, the flux of CBM-supplied heat quickly re-establishes large open water areas, resulting once again in dynamic frazil and anchor ice formation. It should be stressed that CBM-generated open-water leads do not create un-natural ice types. Frazil and anchor ice occur commonly in many Wyoming streams, as illustrated by Prairie Dog Creek. Instead, the maintenance of substantial open water leads throughout the winter creates conditions that cause frazil and anchor ice to form through the entire winter, rather than their normal occurrence during a few days in the spring and fall.

This study focused on ice conditions and channel responses around Burger Draw and Beaver Creek. However, there are at least five CBM discharge points between Pumpkin Creek and Barber Creek, a distance of about 40 river kilometers, encompassing the four creeks and a direct discharge point about 9km below Burger Draw that maintains an open water lead for more than 1km downstream. Table 3.4 shows measured discharges and water temperatures for Barber Creek and Pumpkin Creek during the 2010-2011 winter season. Both creeks contribute significant heat to the Powder River. Barber Creek, in particular, with measured temperature near the mouth consistently above 18^{o}C (Table 3.4) transports significant heat to the Powder River throughout the entire winter season. Based on the scaling laws discussed in Section 3 (Formation of open water leads in the Powder River), the open water lead downstream of the Powder River/Barber Creek confluence should be significantly larger than the one observed on Beaver Creek, with a concomitant increase in persistent frazil and anchor ice formation. The large size of the Barber Creek open water lead was confirmed by observations from USGS personnel (Eric Blajszczak, USGS, personal communication). The presence of so many warm water discharge points over a relatively short river stretch may have multiplicative effects not recognized in this study.

This study documented changes to the channel bathymetry associated with open-water leads, and finds that the changes are hard to distinguish from effects attributable to ice jams and large, ice-free flows in the channel. It is noted, though, that flooding caused by anchor ice formation can be a serious problem in developed areas (Daly 2002).

It was beyond the scope of this study to address biological impacts. However, 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 (Brown et al. 2011, Lindstrom and Hubert 2004, Simkins et al. 2000, Stickler et al., 2008). (The authors highly recommend Brown et. al., 2011 for an informative review ice processes and stream-dwelling fish.) Based on the unique assembly of fish found in the Powder River and the environmental stresses they are exposed to in summer (Senecal 2009), the results of the present study strongly indicate the need for further study of the effects of CBM-product-water generated open-water leads on the biological community in the Powder River.

5. CONCLUSIONS AND RECOMMENDATIONS

The present study examined the extent to which the discharge of warm CBM water into the Powder River drainage during winter flow conditions influenced the Powder River. Its principal objectives were to:

1. Determine if discharge or relatively warm CBM product water had any effect on ice conditions in the Powder River Basin
2. Determine the effects of CBM water discharge on local ice conditions in the Powder River at two representative sites during winter; and,
3. Evaluate if CBM water discharge, by virtue of influencing ice conditions, affects channel morphology in the Powder River.

The first year of the study was entailed a preliminary survey of the area and ice conditions. Two streams, Burger Draw, which consisted entirely of CBM product water discharge, and Prairie Dog Creek, which had no CBM influence, were chosen for the first year of the study. Prairie Dog Creek was examined to gain insight into the winter regime of small, natural stream in the

Powder River basin. These streams were relatively far apart (about a 1.5 hour commute), making it very difficult to visit both sites in one morning. During the second year of the study, two streams were again chosen for more detailed study. The Burger Draw and Beaver Creek sites were chosen because they were located accessibly close to each other, flows in both creeks consisted of CBM product discharge water, and they differed in discharge by about one order of magnitude.

5.1 Conclusions

The study's conclusions provide useful information addressing its objectives. Though limited to site surveys conducted at three sites during two winters, 2009-2010 and 2010-2011, they provide information of use to agencies and industries involved in CBM recovery and managing CBM water discharge. The insights have direct relevance to all rivers subject to frigid winter conditions.

The study's main conclusions are:

1. Besides adding to the flow of water in the Powder River, the most visible influence of CBM product water discharge is the formation of open water leads extending along a channel bank typically for the order of one or more 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 water temperature discharged, the surface area of the open water leads scales with the discharge rate and temperature of CBM water.
2. The open water leads comprise a form of density current when the discharging CBM water has greater density 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. 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.
4. The presence of an open-water lead caused small adjustments in the Powder River channel bed that eroded the bed and at times also resulted in channel bank failure. The maximum depth of winter bed scour was about 0.25m, and bank erosion at most caused a 2m lateral shift of the channel. Presently, it is unclear whether deeper bed scour

would have occurred had flow in the Beaver Creek open water lead not eroded the bed down to the sandstone bedrock. The banks directly downstream of the Burger Draw and Beaver Creek confluences are did not have plant covers, indicating recent deposition of the sediment. These unvegetated banks experienced the greatest erosion measured in the cross section surveys.

5. With the upstream movement of the lower-most Burger Draw discharge point during the summer of 2010, the amount of time CBM product water had to cool down effected the amount of open water it created on the Powder River. A possible approach to control the amount of open water that direct CBM water discharges have on the Powder River (or any other river) would be to increase the time CBM product water is exposed to the atmosphere before it is discharged into the main river. This approach could be achieved by increasing CBM product water transit time in tributary drainages or by holding water in settling ponds before discharging in the perennialized drain channels.
6. The discharge of CBM water predominantly along the observed open water leads resulted in an incomplete ice cover formation over the Powder River at the survey sites. The cross-channel ice cover thickness was little affected by flow along the lead, though some thinning occurred very close to the lead. The cover did end abruptly at the edge of the lead. This finding adds credence to the supposition that the leads comprise a density or buoyancy current that undergoes little transverse mixing. The CBM discharge did not affect the overall thickness of the ice cover; the ice cover near the lead was as thick as upstream of the lead. Saraaf (1990), for example, modeled thermal effluent discharged into a river. The model results, confirmed with field studies in the Mississippi River, showed that warm water can be transported long distances under an existing ice cover at the downstream ends of open water lead, resulting in thinning of the ice in this region.
7. The open water leads were observed to be places where wildlife drink and feed during winter.
8. The influences of warm CBM water discharge into small tributary drainages in the Powder River basin is striking. The CBM water provides a warm perennial flow to many such streams, and thereby dramatically alters ice formation in them. CBM product water also significantly increases the total average Powder River discharge during winter months.
9. 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) through (6). Lead size can be reduced by several actions that decrease inflow water temperature and promoting greater transverse mixing across the river.

5.2 Recommendations for Further Research

The present study, essentially an exploratory survey, prompts several recommendations for further research:

1. An effect only casually observed during the site surveys concerns the biological aspects of warm CBM water discharge into the Powder River. The open water leads formed by CBM discharge evidently attracted animals for drinking and possibly feeding. As CBM-induced open water leads appear to be a major wintertime ecological feature of the Powder River, a useful further research will be to ascertain the ecological implications of such leads;
2. It will be useful to determine the overall extent and frequency of open-water lead formation along the Powder River during winter. The present study focused particularly on two sites having CBM discharge. Casual observation of the river at other sites indicated that leads consequent to CBM-water discharge are frequent features of the middle portion of the Powder River during winter and are a significant feature of winter fluvial and ice processes along the river. If CBM water discharge adds about 33cfs to the rivers erstwhile flow of 100cfs, open water lead formation is likely to be substantial;
3. Casual observations of CBM water discharge at a few sites identified late in the present study indicate larger lead formation than observed at the two survey sites. Useful additional research will be to more closely study CBM water discharge at those sites; and,
4. At a site where CBM water is currently is quite warm (say about 10^{o}C or warmer) when entering the Powder River, it will be useful to implement a simple pilot test to confirm the performance of one or more methods this report proposes for reducing CBM water temperature or enhance mixing with flow in the Powder River.
5. A growing body of literature suggests that frazil and anchor ice stress fish. Extending frazil and anchor ice formation events through the entire winter in CBM-heat-impacted reaches of the Powder River may have negative impacts of native fish populations. A combined, detailed physical/biological study of processes in Powder River is warranted.

6. PUBLICATIONS

- Stiver, J.J., (in preparation, expected completion in Summer 2011), Effects of CBM Water Discharge on Fluvial and Ice Processes in Powder River Basin, Wyoming Streams, M.S. Thesis, Civil and Architectural Engineering, University of Wyoming, Laramie, WY.
- Kempema, E.W., Stiver, J.J. and Ettema, R., (accepted, in preparation), Effects of CBM water discharge on fluvial and ice processes in Powder River Basin, Wyoming Streams; in: Conference Proceedings, CRIPE 2011 Workshop on River Ice, Winnipeg, Canada, September 2011.
- Ettema, R. and Kempema, E.W., (invited, in press), Ice effects on gravel-bedded channels, 7th Gravel-Bedded River Conference 2010, Tadoussac, Quebec, Canada, September 6-10 ,2010, 22 p.
- Kempema, E.W. and Ettema, R., 2011. Anchor ice rafting: observations from the Laramie River. River Research and Applications: doi:10.1002/rra.1450 (published online in 2010).

7. PRESENTATIONS

- Kempema, E.W., Stiver, J.J. and Ettema, R., (September, 2011), Effects of CBM water discharge on fluvial and ice processes in Powder River Basin, Wyoming Streams; at: CRIPE 2011 Workshop on River Ice, Winnipeg, Canada, September 2011.
- Stiver, J.J., April 7 2011, Presentation to Class: Water Resources Seminar, REWM 5250, Instructor: KJ Reddy.
- Stiver, J.J April 20 2011, Presentation to Class: Spatial Analysis, RNEW 5200, Instructor: Scott Miller.
- Kempema, E.W., Ettema, R, and Stiver, J. May 25, 2010. Effects of Coalbed Methane Product Water on Winter Flow in the Powder River; Energy Resources and Produced Waters Conference: Laramie, WY.
- Stiver, J.J., April 7, 2010, Presentation to Class: Watershed H_20 Quality, REWM 5710, Instructor: KJ Reddy.
- Stiver, Jared, March 5, 2010. Effects of CBM waters in the Powder River Basin, invited presentation to RNEW 5710 class taught by KJ Reddy.
- Kempema, E.W. and Ettema, R. November 2009. Progress Report to the Wyoming Water Development Commission, Cheyenne, WY.
- Stiver, J.J., October 6 2009, Presentation to Class: Principles of Water Quality, REWM 5640, Instructor: KJ Reddy.

8. STUDENT SUPPORT

- Jared Stiver, a Civil Engineering student, worked on this projected since it started. Mr. Stiver worked on this project as an undergraduate during the Fall Semester 2009. In January 2009, Mr. Stiver enrolled as a graduate student in Civil Engineering. He plans to finish his thesis on CBM heat impacts on Powder River sstreams during winter during summer, 2011.

- Casey Valkenburg, an undergraduate in Mechanical Engineering, worked with the project during the 2010-2011 winter season as a field helper. Mr. Valkenburg received training in laser-level surveying techniques and discharge measurement techniques, and learned how to drill holes in river ice on this project.

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10. APPENDICES

Appendix 1 contains cross sections of the Powder River collected at Beaver Creek and Burger Draw during the 2010-2011 field season.

Appendix 2 contains the ice thickness profiles collected at Beaver Creek and Burger Draw during the 2010-2011 field seasons.

10.1 Appendix 1: Powder River Cross Sections, 2010-2011

Figure A1.1. Aerial image of the Beaver Creek—Powder River confluence showing the relative positions of the cross sections in the Powder River. Cross sections BC1 and BC2 are downstream of Beaver Creek while BC3 is upstream Beaver Creek. The arrow indicates flow direction of the Powder River. Distances (upstream or downstream) of the cross sections from the tributary confluence are: BC1: 30m, BC2: 10m, BC3: 40m.

Figure A1.2. Aerial image of the Burger Draw—Powder River confluence showing the relative positions of the cross sections in the Powder River. Cross sections BD1, BD2, and BD3 are downstream of Burger Draw while BD4 is upstream. The arrow indicates flow direction of the Powder River. Distances (upstream or downstream) of the cross sections from the tributary confluence are: BD1: 80m, BD2: 30m, BD3: 5m, BD4: 15m

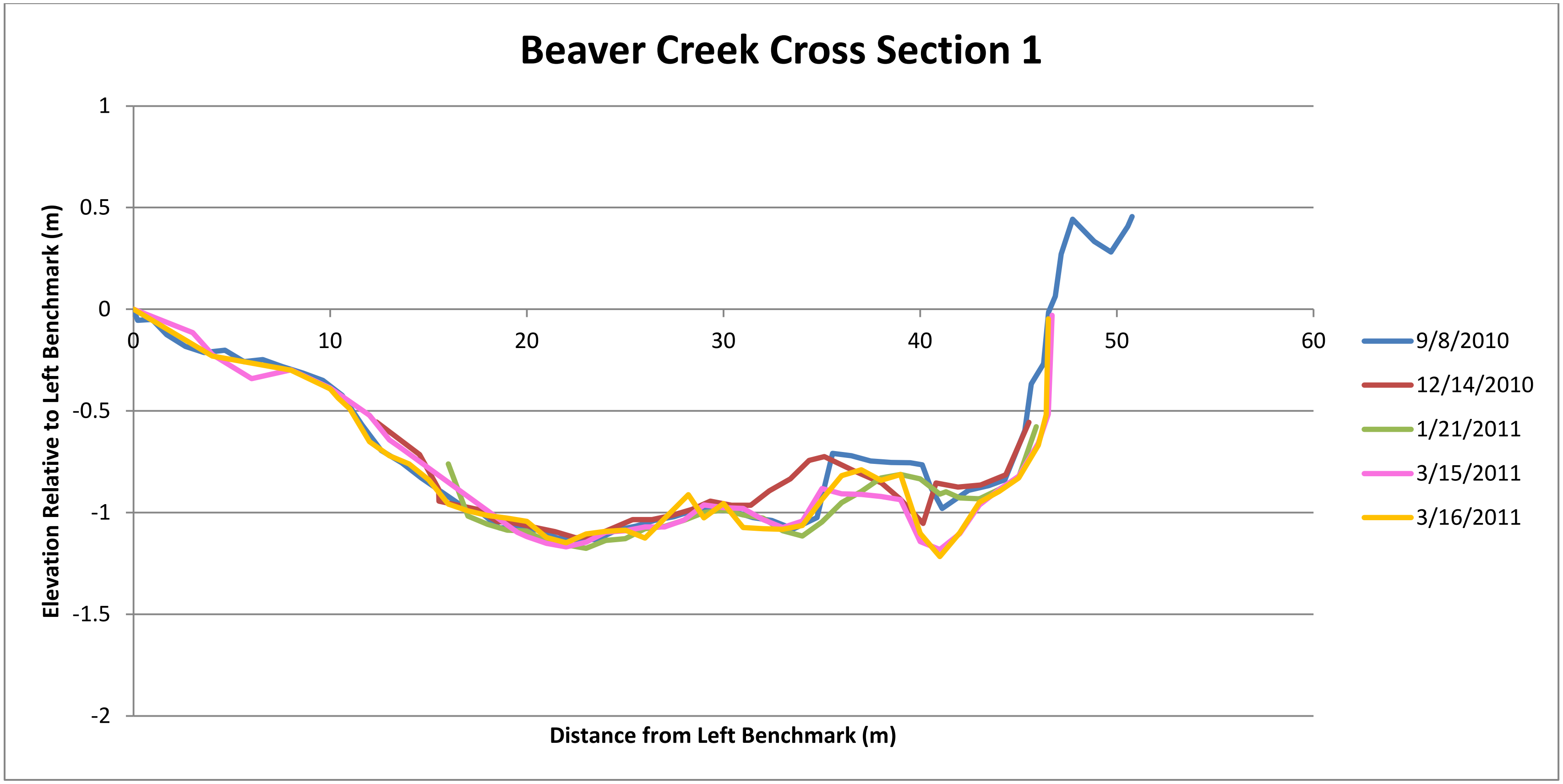


Figure A1.3. Beaver Creek Cross Section 1 (BC1).

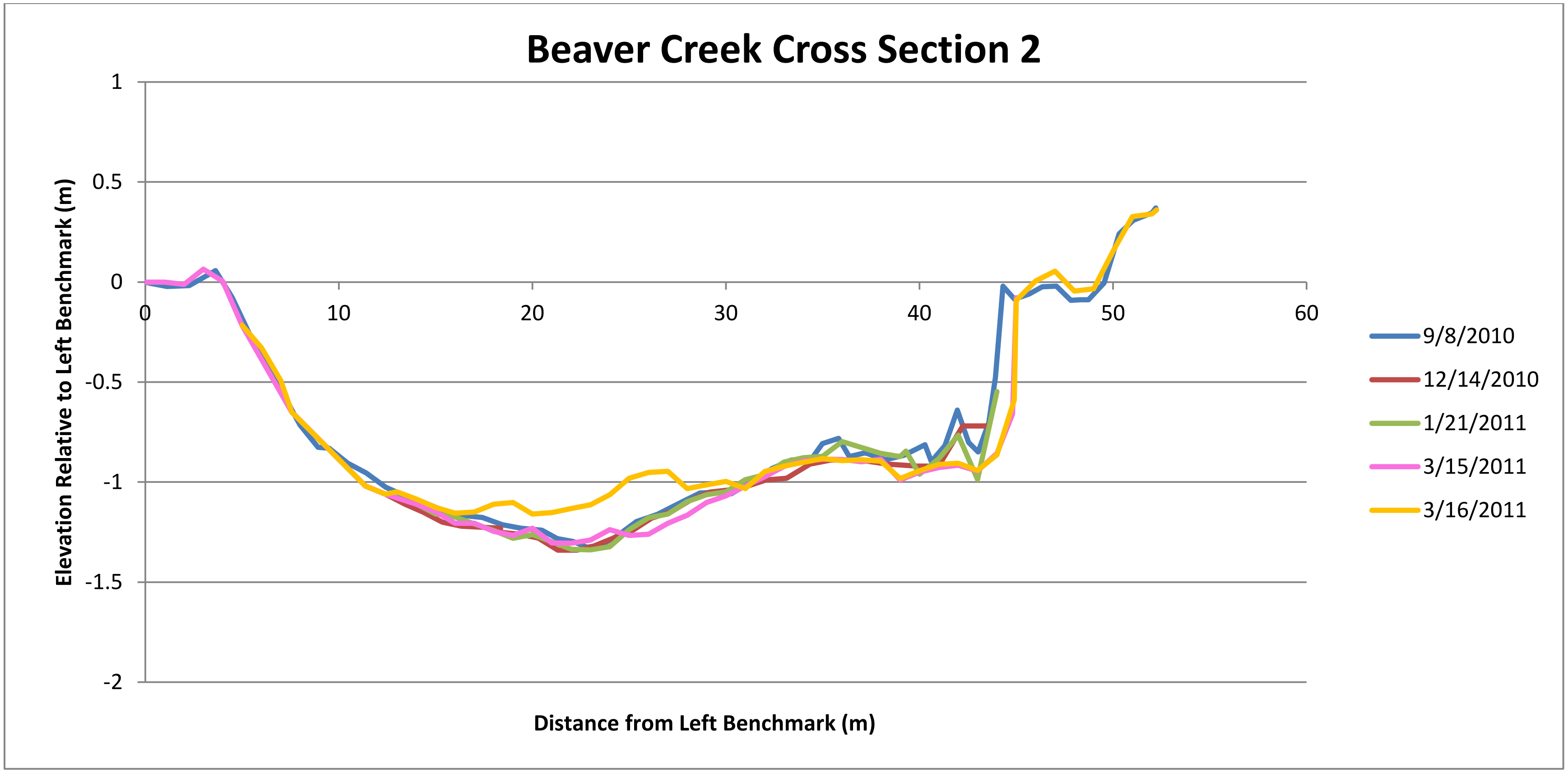


Figure A1.4. Beaver Creek Cross Section 1 (BC2).

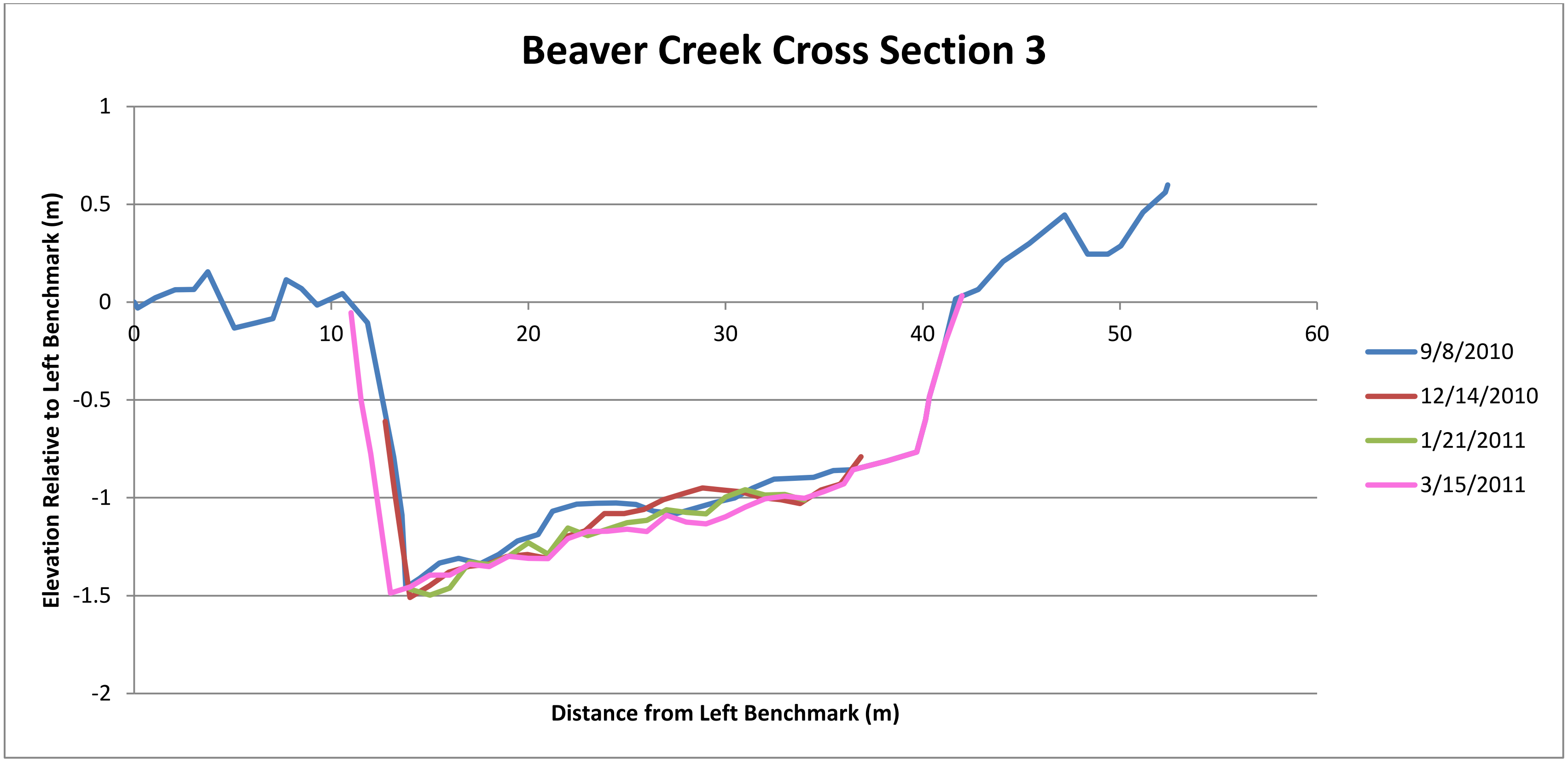


Figure A1.5. Beaver Creek Cross Section 3 (BC3).

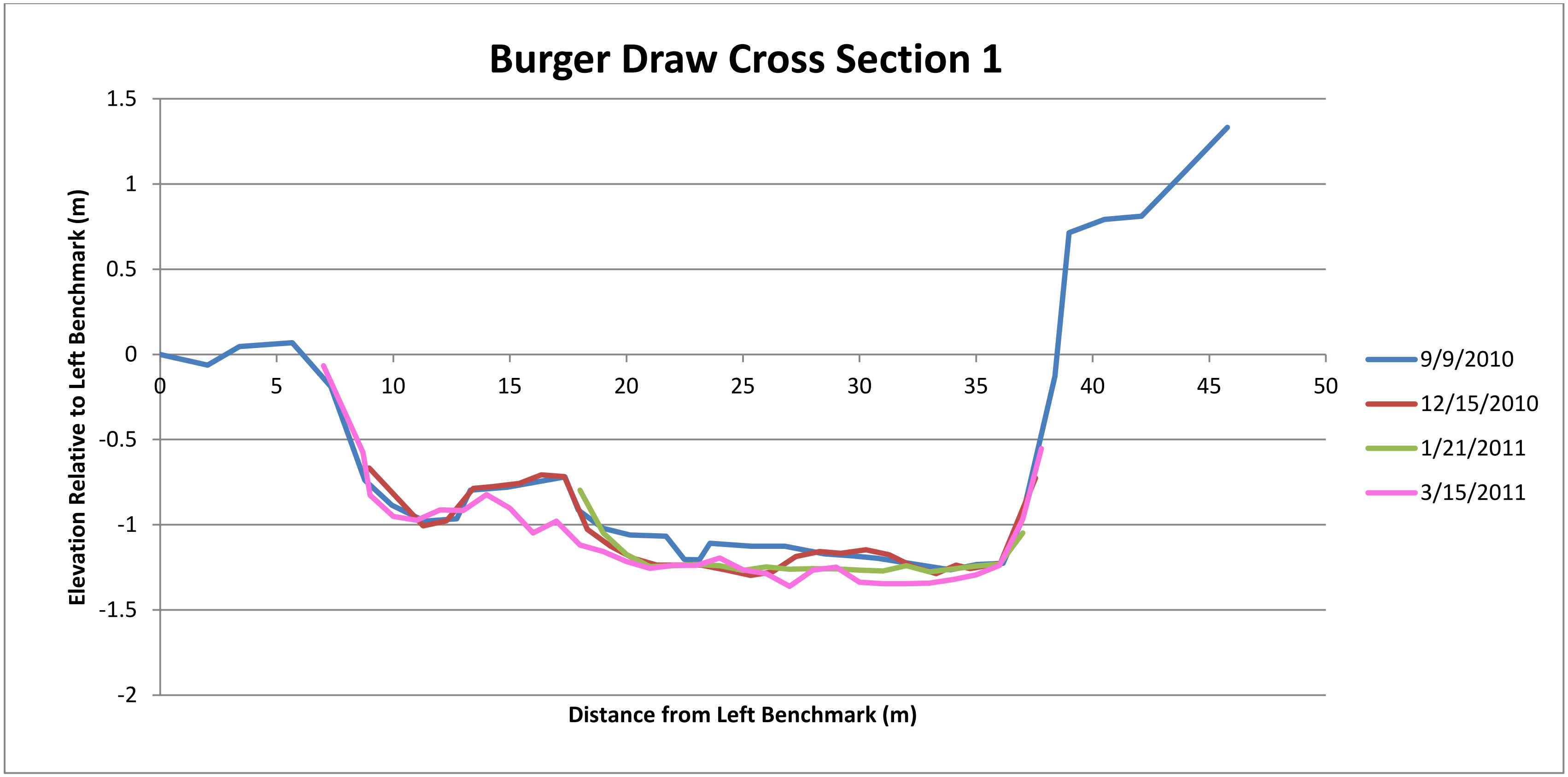


Figure A1.6. Burger Draw Cross Section 1 (BD1).

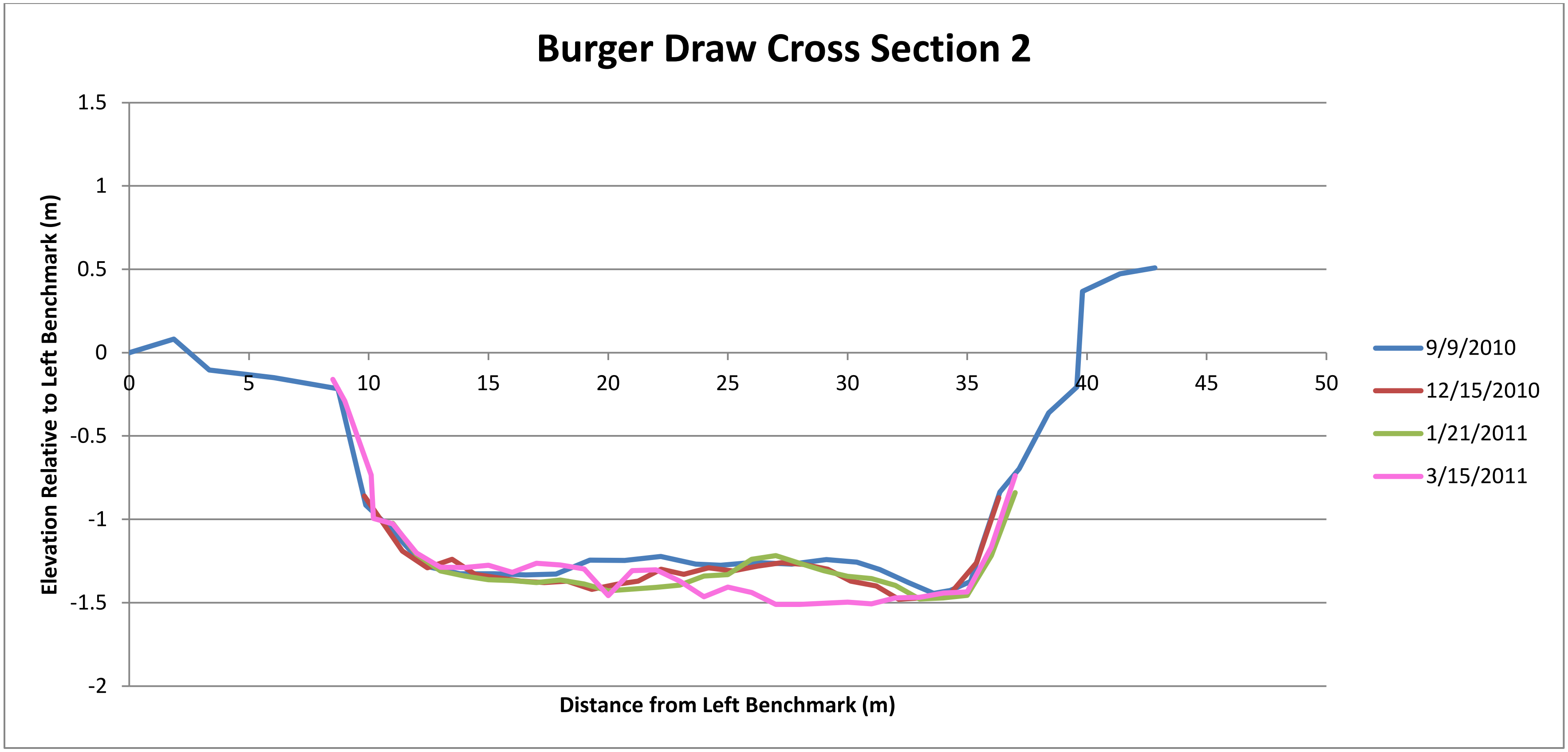


Figure A1.7. Burger Draw Cross Section 2 (BD2).

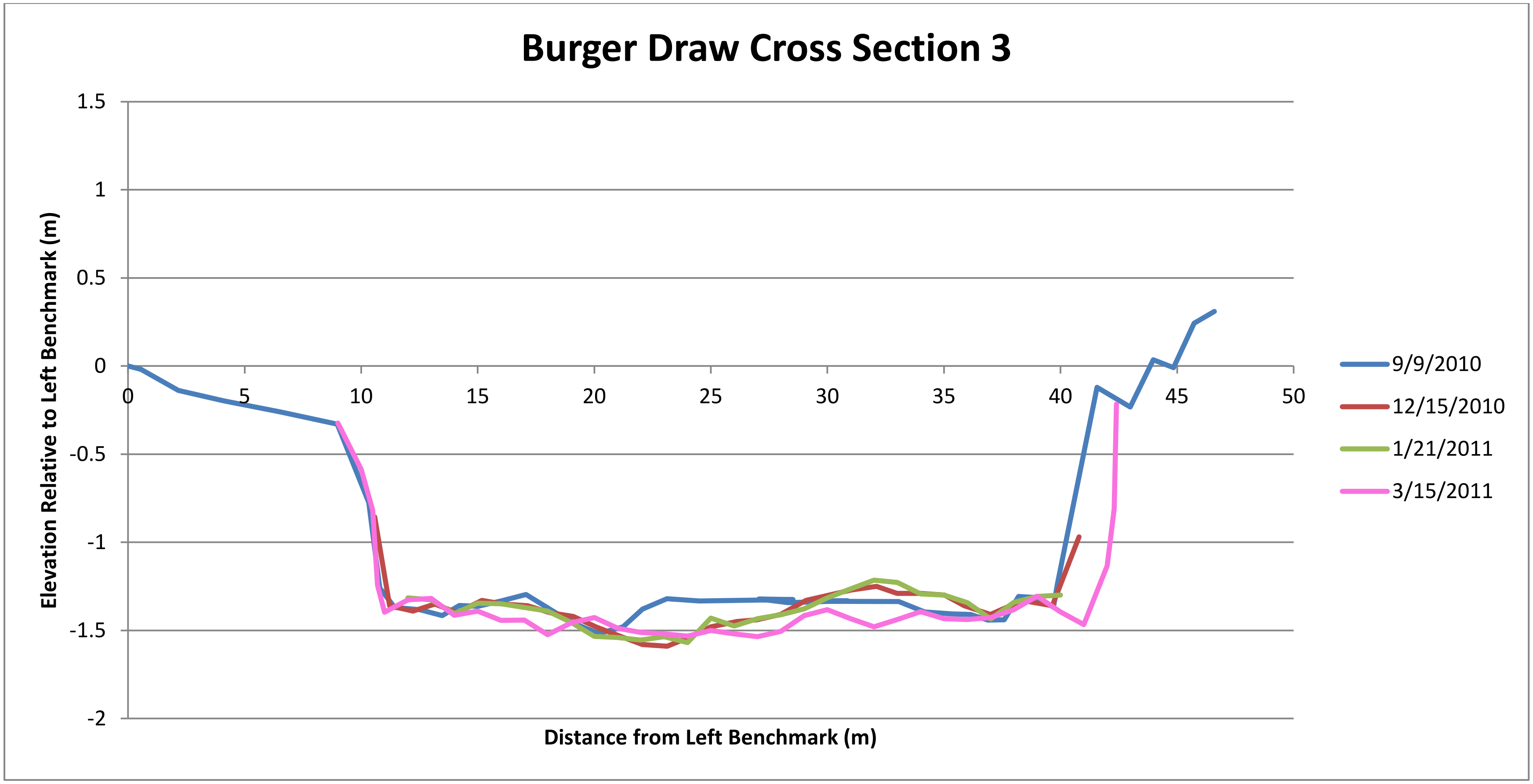


Figure A1.8. Burger Draw Cross Section 3 (BD3).

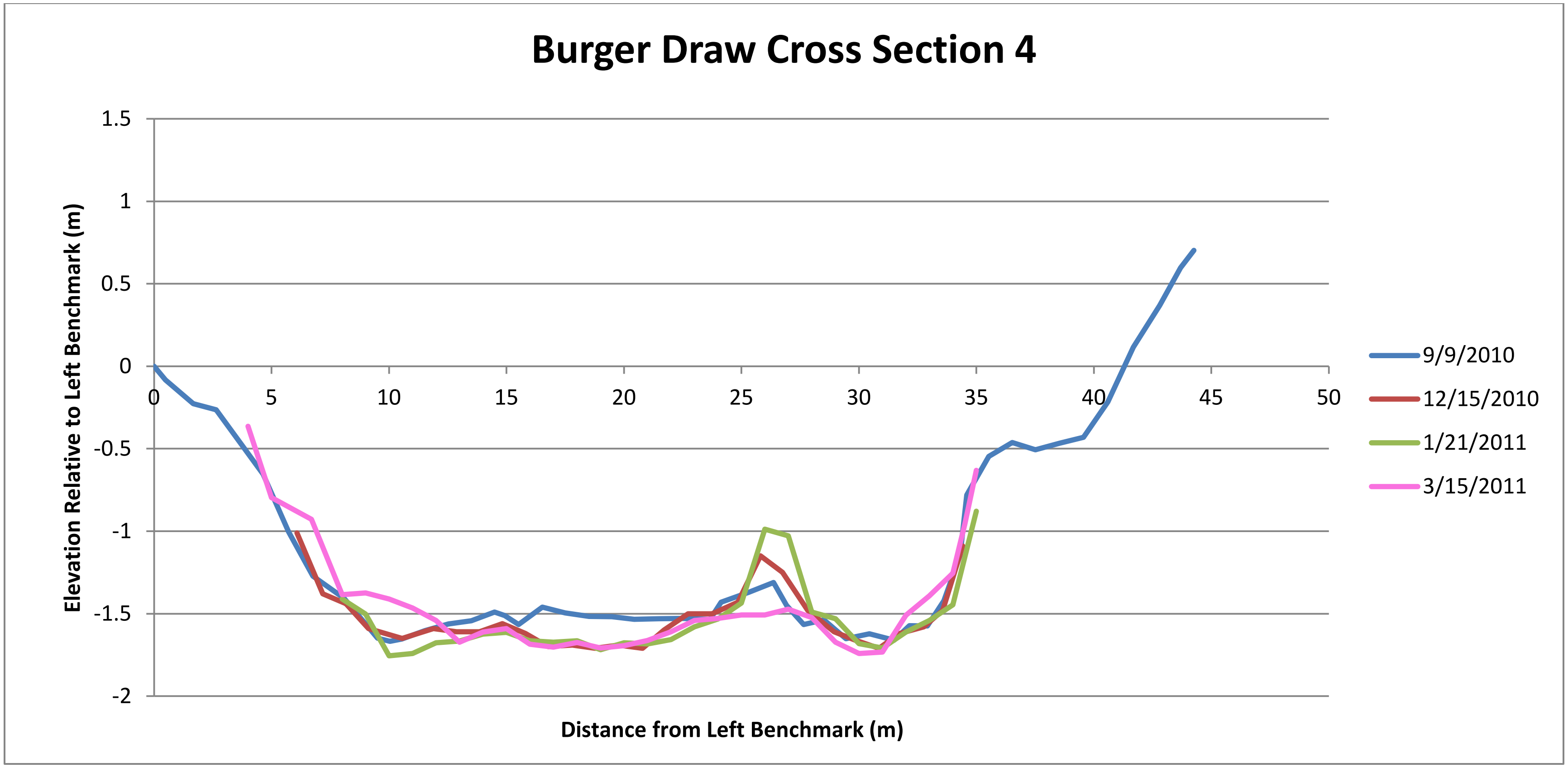
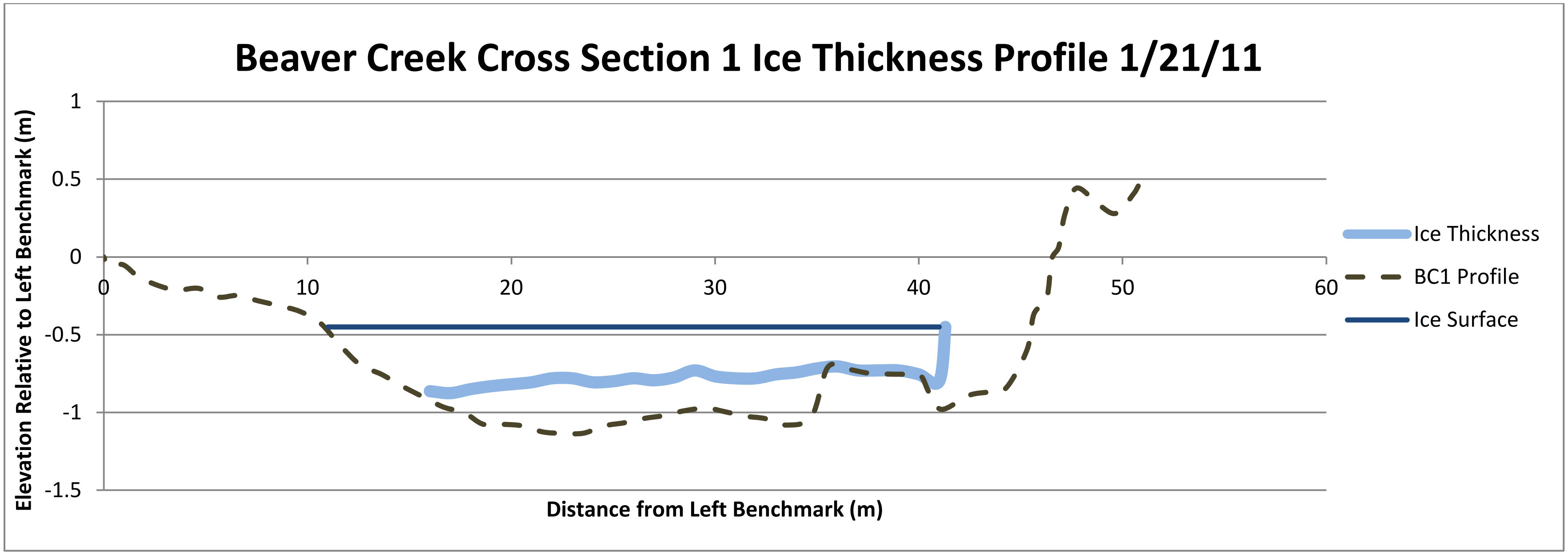


Figure A1.9. Burger Draw Cross Section #4 (BD4)

10.2 Appendix 2. Powder River Ice Thickness Profiles



FigureA2.1: Beaver Creek Cross Section 1 Ice Thickness Profile, surveyed on January 21, 2011. BC1 has an open water lead on the right end of the profile that is roughly 5 meters wide. The Ice thickness is continuous throughout the profile till the open water lead. BD1 is 25 meters downstream of the mouth of Beaver Creek.

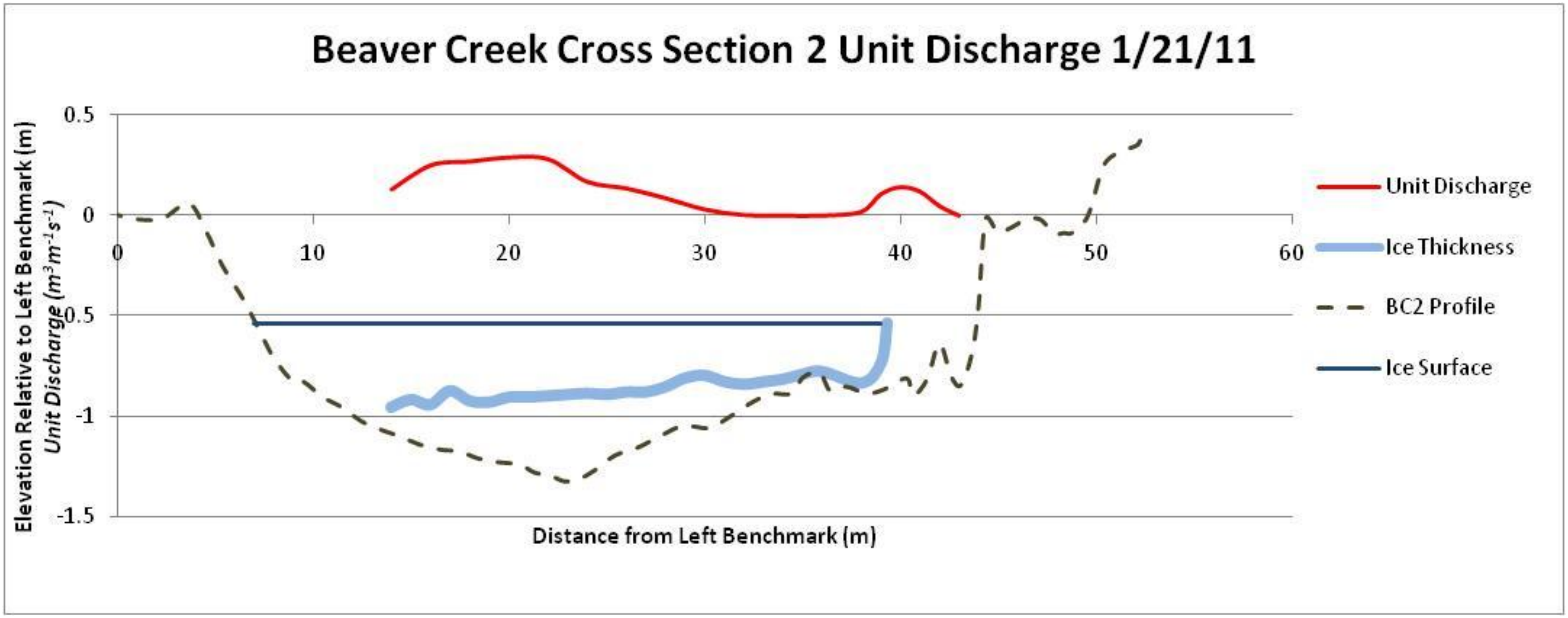


Figure A2.2: Beaver Creek Cross Section 2 Ice Thickness Profile was surveyed on January 21, 2011. BC2 is the cross section closest to the mouth of Beaver Creek and directly downstream of Beaver Creek. There is an open water lead that has formed on the right side of the Powder River. In addition to the cross section and ice-thickness profile, this figure shows the unit discharge per cross sectional area on January 21. Highest unit discharges are concentrated in the profile thalweg and in the open water lead.

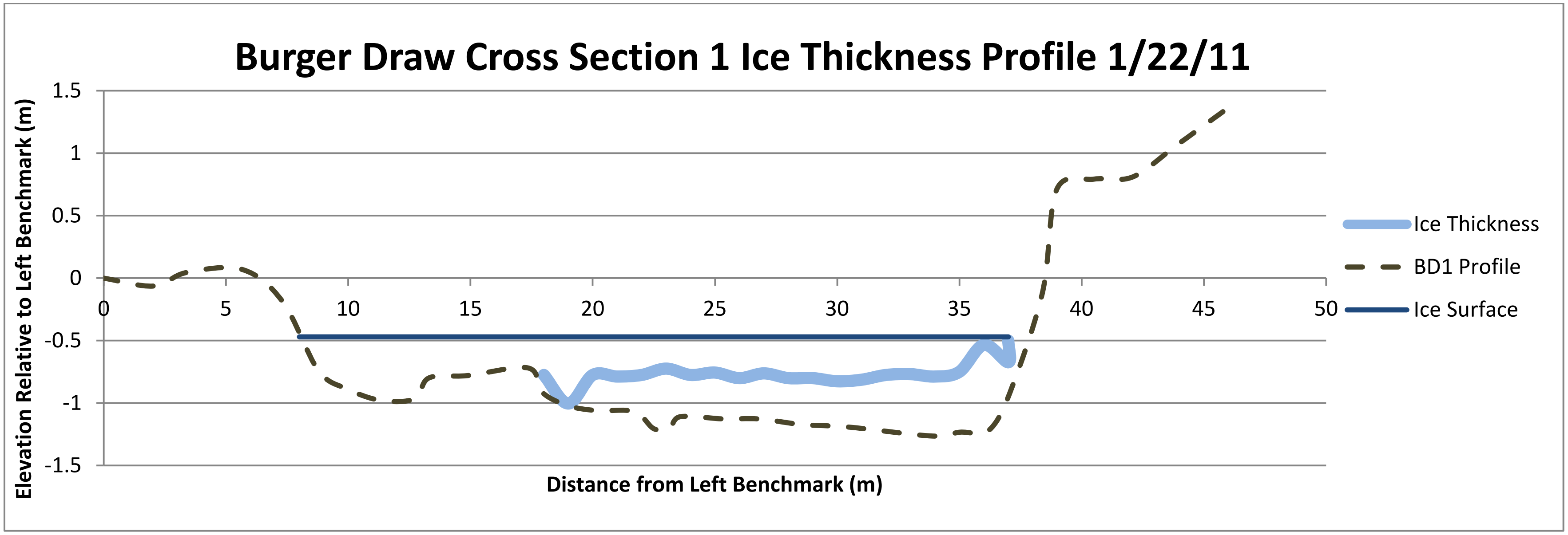


Figure A2.3. Burger Draw Cross Section 1 Ice Thickness Profile was surveyed on January 21, 2011. BD1 has a 1 meter wide open water lead on the right end of the profile. BD1 is 80 meters downstream the mouth of Burger Draw. Ice froze to the bed from left water edge to about 17 meters from the left benchmark.

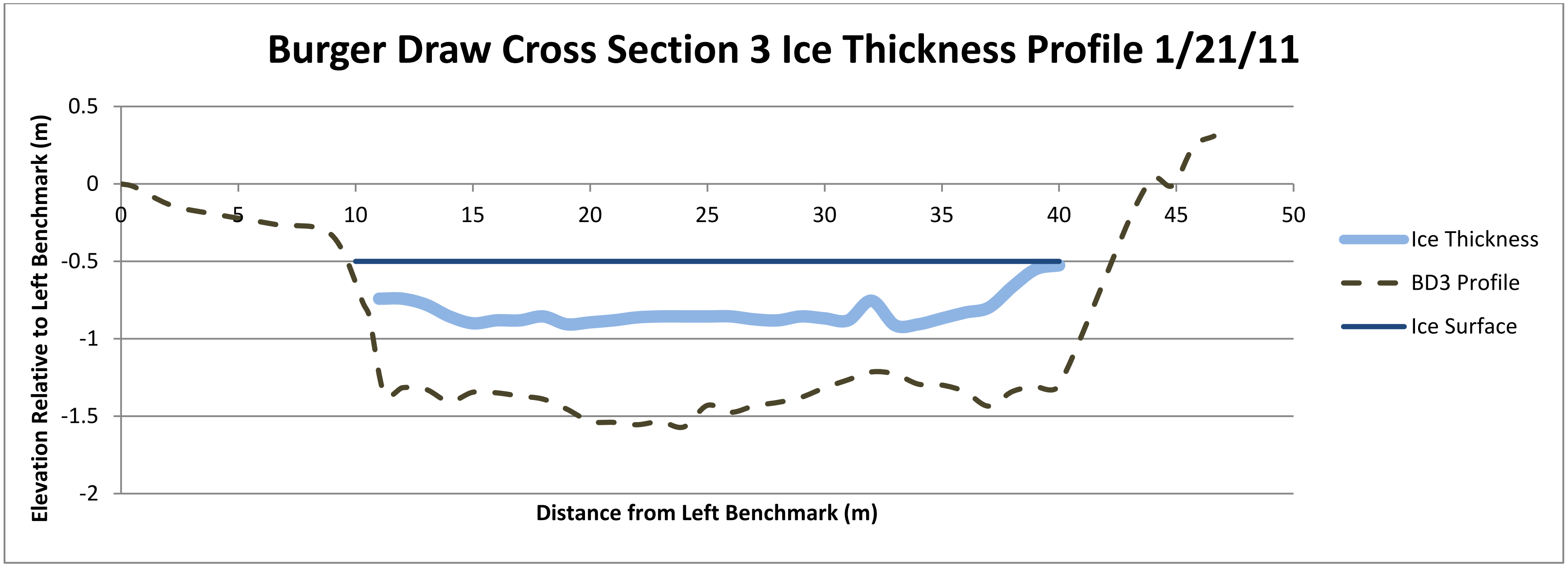
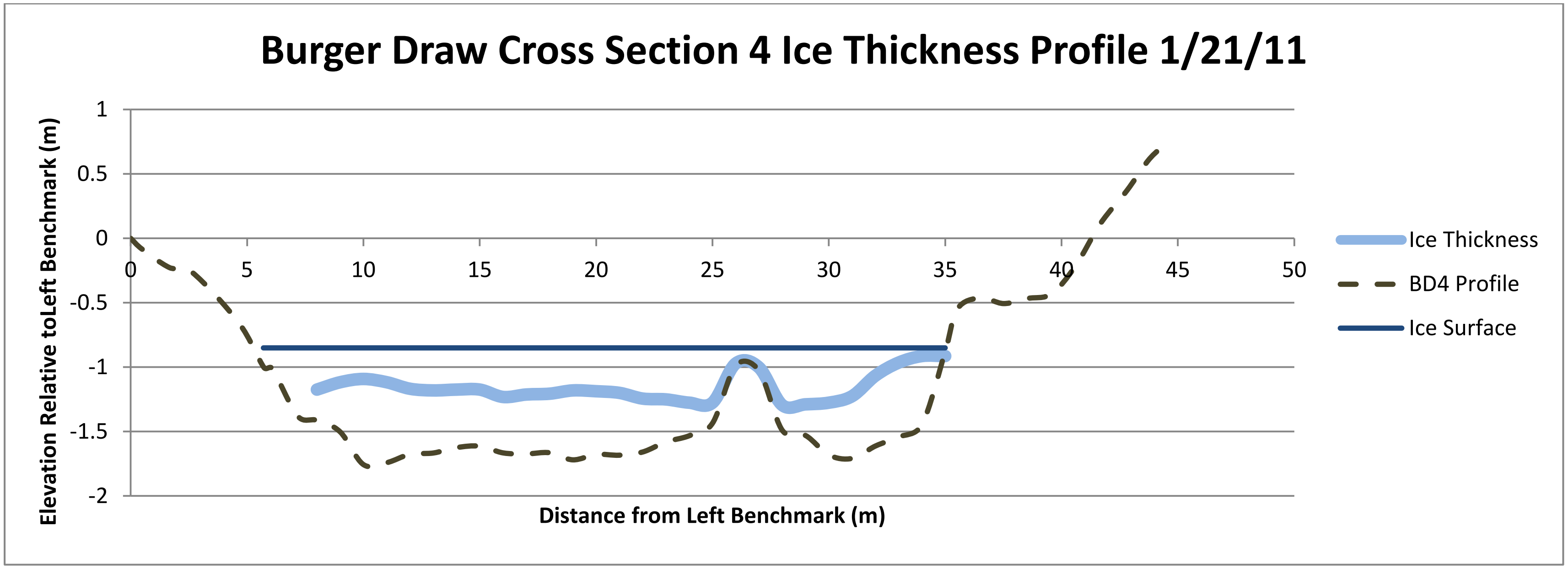


Figure A2.4: Burger Draw Cross Section 3 Ice Thickness Profile, surveyed on January 21, 2011. BD3 is the cross section closest to the mouth of Burger Draw and is directly downstream of the confluence. A small open water lead formed on the right side of the river. The ice thickness is fairly consistent throughout the profile till it draws near the open water lead end and thins rapidly.



FigureA2.5: Burger Draw Cross Section 4 Ice Thickness Profile; surveyed on January 21, 2011. BD4 is upstream of Burger Draw on the Powder River, and has a continuous ice cover. The underside of the ice profile ends before the left end of the ice cover because field personnel feared driving the ice auger into the bed at that location.