Simulation of Flow and Habitat Conditions Under Ice, Cache la Poudre River — January 2006

By Terry Waddle

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
square foot (ft^2)	0.0929	square meter (m^2)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

SI to Inch/Pound

Multiply	By	To obtain
meter (m)	3.281	foot (ft)
square meter (m^2)	10.76	square foot (ft^2)
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F=(1.8×°C)+32
Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C=(°F-32)/1.8
Vertical coordinate information is referenced to World GeodedicNorth American Vertical Datum of 1988 (NAVD 88).”
Horizontal coordinate information is referenced to the insert datum name (and abbreviation) here for instance, “North American Datum of 1983 (NAD 83).”
Altitude, as used in this report, refers to distance above the vertical datum.

Simulation of Flow and Habitat Conditions Under Ice, Cache la Poudre River — January 2006

By Terry Waddle[1]

Introduction

The U.S. Forest Service authorizes the occupancy and use of Forest Service lands by various projects, including water storage facilities, under the Federal Land Policy and Management Act. Federal Land Policy and Management Act permits can be renewed at the end of their term. The U.S. Forest Service analyzes the environmental effects for the initial issuance or renewal of a permit and the terms and conditions (for example, mitigations plans) contained in the permit for the facilities. The U.S. Forest Service is preparing an environmental impact statement (EIS) to determine the conditions for the occupancy and use for Long Draw Reservoir on National Forest System administered lands. The scope of the EIS includes evaluating current operations and effects to fish habitat of an ongoing winter release of 0.283 m^3/s (10 ft^3/s) from headwater reservoirs as part of a previously issued permit. The field conditions observed during this study included this release.

The U.S. Forest Service entered into an interagency agreement (05-IA-11021000-030) with the U.S. Geological Survey (USGS) Fort Collins Science Center to perform analysis of fish habitat and flow relationships in the Cache la Poudre River during winter ice-over conditions using a two-dimensional hydrodynamic model. The U.S. Forest Service selected the Fort Collins Science Center for this task because of their expertise in developing two-dimensional hydraulic models for habitat modeling applications. This report transmits model results to the U.S. Forest Service to analyze the effects of alternative flow scenarios at a site on the mainstem Cache la Poudre River in Larimer County, Colorado, near Kinikinik (40° 42' 44.16" N. lat, 105° 44' 30.70" W. log), as shown in figure 1. It will be used in pending environmental analyses and decisions for the occupancy and use of the Arapaho-Roosevelt National Forest by water storage facilities.

The water management scenarios of interest in this study are related to releasing water from Chambers and Barnes Meadows Reservoirs, based on the assumption that winter flow augmentation can increase potential fish habitat. Figure 2 shows the relationship between Chambers, Barnes Meadows, and Long Draw Reservoirs. At the time this study was proposed, existing flow simulation results showed that the channel constraints imposed by existing artificial low-head dikes would have little or no effect on the hydrodynamics of the river at the low flow levels that were to be evaluated. The Kinikinik study site contains deep pools, riffles, and runs. This diversity of habitat types made it ideal for assessing the effects of altered flow on fish habitat under ice in the main stem Cache la Poudre River. Thus, the Kinikinik site was selected for this study of winter habitat conditions.

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The preexisting topographic and hydrologic data collected at this site enabled data collection efforts for this study to focus on describing streamflow and ice cover during the winter months. A two-dimensional hydrodynamic model, River2D (Steffler and Blackburn, 2002), was used to simulate flow conditions under the ice cover that was observed January 24, 2006.

The objectives of this study are (1) to describe the extent and thickness of ice cover, (2) simulate depth and velocity under ice at the study site for observed and reduced flows, and (3) to quantify fish habitat in this portion of the mainstem Cache la Poudre River for the current winter release schedule as well as for similar conditions without the 0.283 m^3/s winter release.

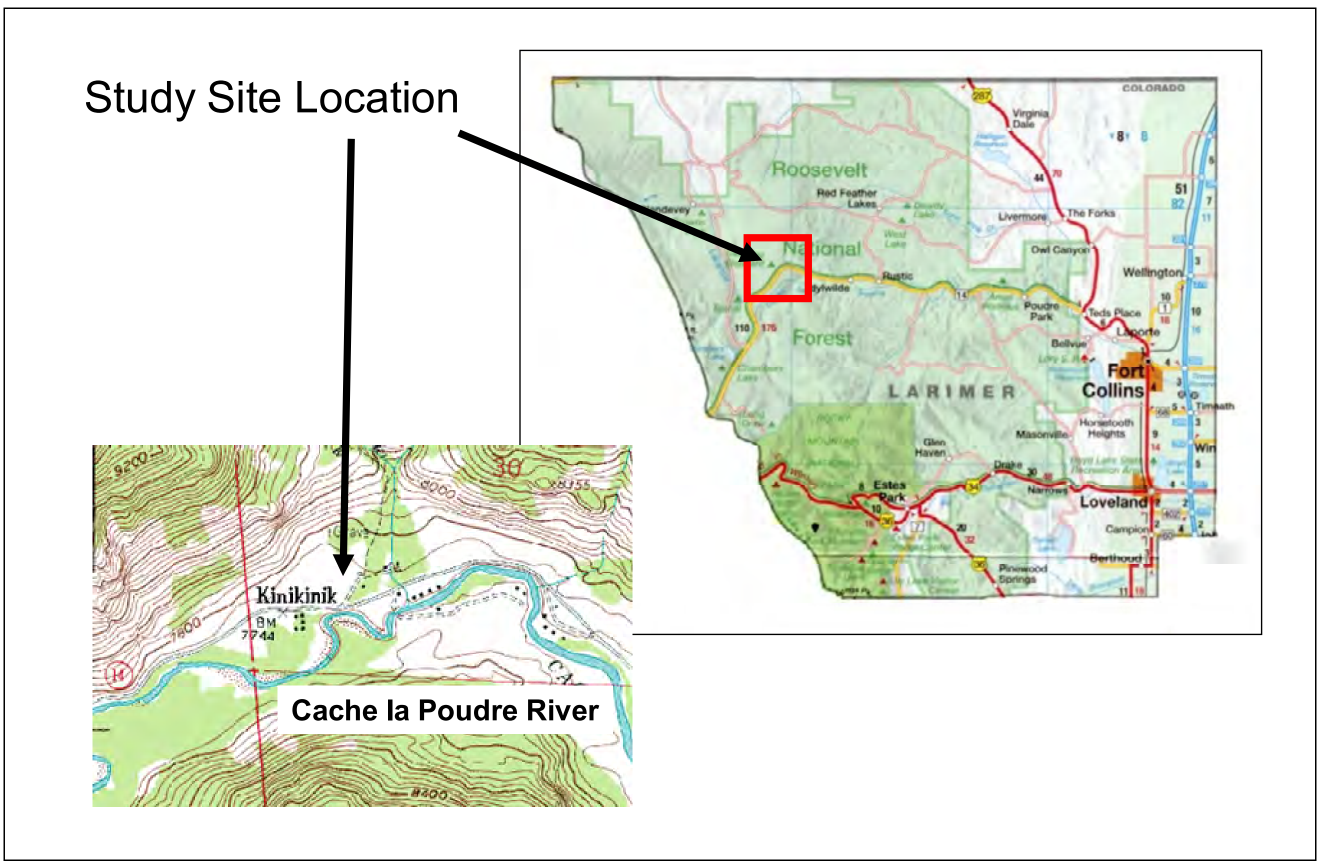

Figure 1. Location of Cache la Poudre River study site.

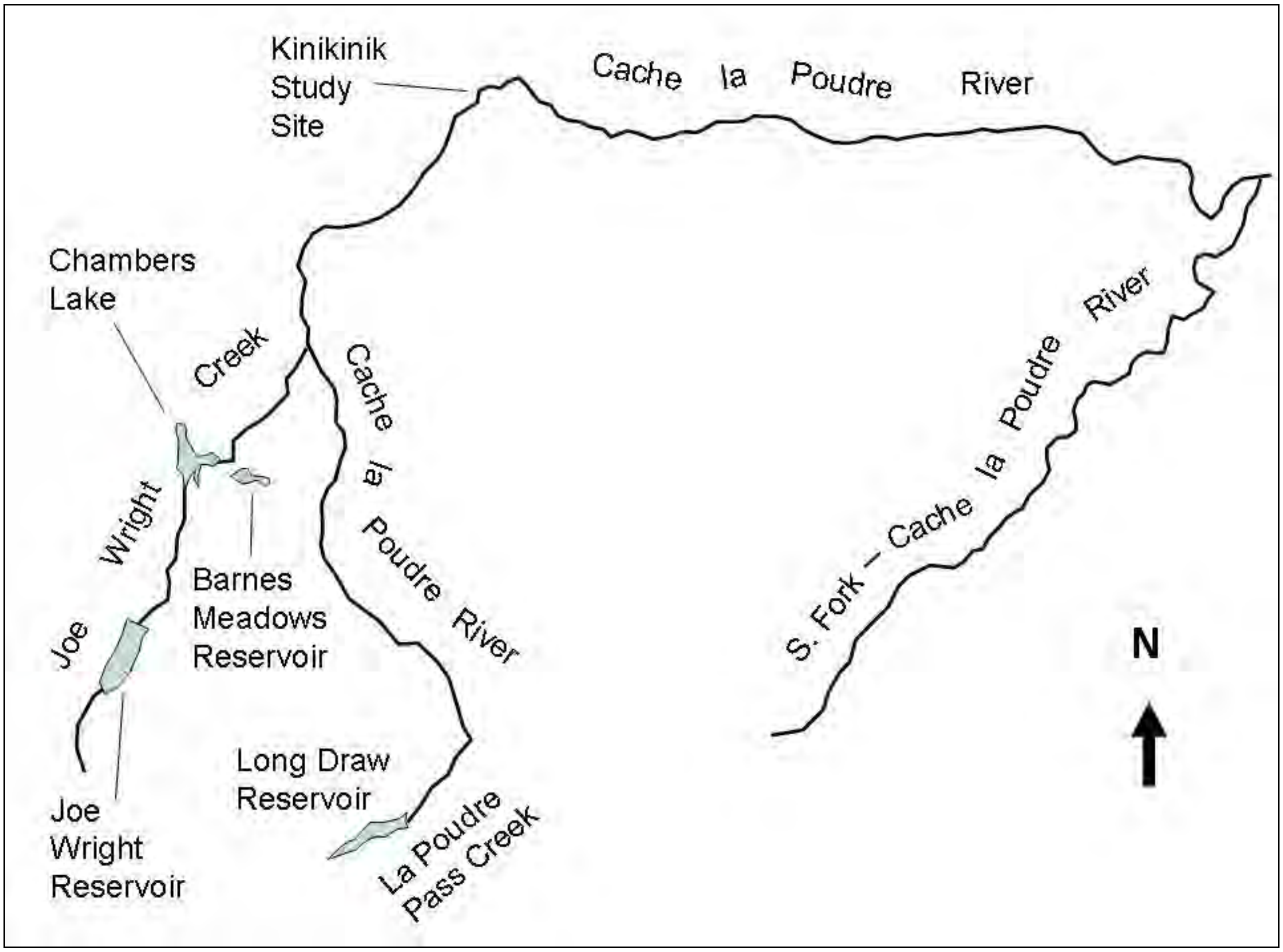

Figure 2. Diagram of Cache la Poudre River headwaters showing relationship between headwater reservoirs and Kinikinik study site.

Methods

An existing river flow and habitat model was applied to simulate flow and habitat conditions under ice. Model input requirements dictated the data collection, formatting, and modeling steps described below.

Field Data Collection

Two-dimensional models of open channel hydrodynamics require that a specific set of boundary conditions be supplied to the model. Among those boundary conditions are a three-dimensional digital elevation model, an outflow water surface elevation, and an inflow discharge rate. Data must be obtained from the study site for each of these required conditions.

Three-dimensional topographic data were obtained for the Kinikinik site using Trimble 4800 and 5800 survey grade global positioning system (GPS) receivers employing real time kinematic position recording and multi-path reduction (Trimble Navigation, Ltd., *http://www.trimble.com*). Both systems use carrier phase processing that enables centimeter accuracy in the field. Certain areas of the study site were occluded from GPS satellite reception by surrounding topography and trees. Survey of the occluded areas was conducted using a Leica 3-

second precision total station. All data were collected in Universal Transverse Mercator (UTM) coordinates (zone 13 north, datum WGS 1984).

A total of 3,426 topographic observations were obtained with the GPS and total station equipment from 2003 to 2006. A triangulated irregular network (TIN) was applied to the data to construct a digital elevation model of the study site. An additional 1,581 points were added to the topographic data set using linear interpolation to remove triangulation anomalies. The channel appears to have been quite stable from 2003 to the present, so the observed channel configuration was used without collection of additional topographic data.

Air and water temperature and pressure were recorded from November 22, 2005 to April 14, 2006, using Solinst Levelogger (*http://www.solinst.com*) recording pressure transducers. The Solinst system is capable of providing a continuous depth-of-flow record at a deployed location when both air and water pressure are recorded to allow correction for atmospheric conditions. The transducer deployed in the stream became encased in ice and did not yield a meaningful indication in changes in depth during this period, but both air temperature and temperature within the ice were recorded.

Because the focus of this study is to describe flow under ice cover, free-surface water data collected when the channel was ice free were not applicable. During the winter of 2005–2006, discharge and ice cover data were collected in cooperation with U.S. Forest Service personnel. The conditions on January 24, 2006, were the most extensively sampled and are the conditions represented in this study.

On January 24, 2006, a discharge measurement (0.608 m^3/s, 21.43 ft^3/s) was obtained at a steep gradient section where there was an open lead (an area that was not completely covered by ice). In the portions of the discharge measurement cross section that were covered by ice, holes were drilled through the ice and a Marsh McBirney flow meter attached to a standard topset wading rod was inserted. Velocity observations were obtained at 0.2 and 0.8 times the depth in the areas covered by ice and at 0.6 times the depth in the open areas. The depth at all velocity measurement points did not exceed 0.2 m (1.7 ft) so it was deemed adequate to make the measurements at 0.6 times the depth in the open lead.

Ice Cover Construction

On January 24, 2006, ice thickness data were obtained for four cross sections including the discharge transect. The data were obtained by drilling through the ice and measuring thickness using a 0.015 m square stick ruled in both meters and feet with a 0.05 m angle bracket attached at the zero end of the stick. This allowed the measuring stick to be inserted into holes in the ice and hooked on the bottom of the ice, giving a direct reading of ice thickness at the surface. Depth from the ice surface to the bed was measured using the measuring stick or a standard level rod extended as necessary to reach the bottom in deep pools. Two cross sections were placed at known areas of high gradient, one in a pool and one in a transition from narrow channel to pool. Due to the thickness and hardness of the ice, a total of 47 observations were obtained. Each ice thickness observation was located using the GPS equipment by measuring XY coordinates, and ice surface elevation. Locations of ice and discharge measurement cross sections are shown in figure 3. See appendix 3 for the measured data.

The observed edge of the ice cover was found to correspond well to the water's edge derived from a simulated free-surface discharge of 2.83 m^3/s (100 ft^3/s). Thus the extent of ice surface for the entire study site was defined using the inundated area obtained from the 2.83 m^3/s free surface simulation.

The ice thickness cross section data indicated that ice froze to a uniform depth of approximately 60 cm in quiescent pools but formed a "flow tube" in areas of higher gradient. This "flow tube" effect appears to represent an equilibrium between thermal forces acting to solidify the water and the capacity of the stream to transport water at a sufficiently high velocity that ice crystals do not attach to the ice cover. Thus, lower velocity edges tended to freeze to the bed, forcing the flow toward the center of the channel.

Ice thickness was distributed over the entire domain of the study site by constructing similar cross sectional flow tubes in areas with gradients similar to the measured cross sections and interpolating between those approximated cross sections. A total of 75 cross sections were developed beginning with an upper ice surface derived from the 2.83 m^3/s flow simulation and adjusting ice thickness to produce cross sectional profiles that yielded discharge conveyance areas similar to those observed. The resulting ice cover is shown in figure 3. The gray lines indicate simulated 0.2 m ice thickness contours and the blue line indicates the simulated water's edge.

The average ice thickness observed over the pools was 0.60 m and was found to be consistent across both measured pools. Thus the ice thickness over all pools was set to 0.60 m or the depth from the estimated ice surface to the bed and adjusted where there was insufficient conveyance area between the bottom of the ice and the bed. Areas of steeper gradient required slightly less cross sectional area and areas of milder gradient required larger cross sectional area to convey the discharge. By contouring the conveyance areas to match observed areas, the estimated ice cover is believed to closely approximate the ice formation occurring over the unmeasured portions of the study site. Figure 3 illustrates the derived ice thickness and shows the areas measured on January 24, 2006.

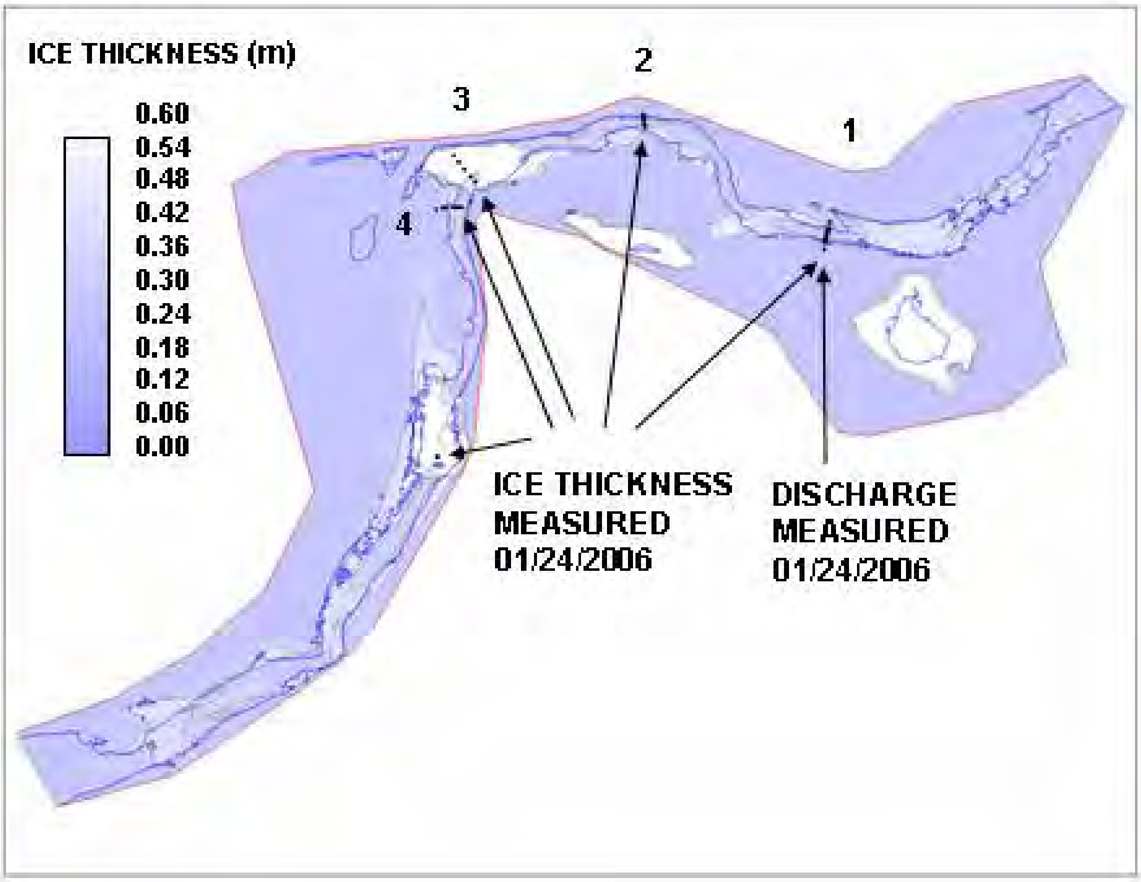

Figure 3. Study site schematic showing locations of measured cross sections and distribution of ice cover based on 2.83 m^3/s conveyance area and local gradient.

Hydrodynamic Modeling

The River2D model (Steffler and Blackburn, 2002) was selected for this study because of its capability to represent hydrodynamic conditions under ice cover. Numerous other two-dimensional hydrodynamic models are available; however, the ability to represent displacement and flotation of an ice cover is a unique feature of the model.

The River2D Model

The River2D model uses the finite element method to solve the "shallow water" equations. The following description of River2D is adapted from Steffler and Blackburn (2002).

Basic Governing Equations

The basic equations of two-dimensional models describe mass and momentum conservation in two dimensions. In River 2D, the differential equation of mass continuity is represented as,

$$\frac{\partial H}{\partial t}+\frac{\partial (HU)}{\partial x}+\frac{\partial (HV)}{\partial y}=0 \quad , \tag{1}$$

where: H is the depth of water, U and V are the velocity components in the x and y directions, respectively, and t is time.

The conservation of x momentum equation is represented as,

$$\begin{aligned}&\frac{\partial q_x}{\partial t}+\frac{\partial}{\partial x}(Uq_x)+\frac{\partial}{\partial y}(Vq_x)+\frac{g}{2}\frac{\partial}{\partial x}H^2\\&\quad = gH(S_{0x}-S_{fx})+\frac{1}{\rho}\left(\frac{\partial}{\partial x}(H\tau_{xx})\right)+\frac{1}{\rho}\left(\frac{\partial}{\partial y}(H\tau_{xy})\right)\end{aligned} \tag{2}$$

where: S_{0x} = bed slope in the x direction, $S_{fx} = \tau_{bx}/(\rho g H)$ is the friction slope in x, τ_{bx} is the bed shear in x, ρ is density and g is the gravitational constant. A similar equation describes the y component of momentum:

$$\begin{aligned}&\frac{\partial q_y}{\partial t}+\frac{\partial}{\partial x}(Uq_y)+\frac{\partial}{\partial y}(Vq_y)+\frac{g}{2}\frac{\partial}{\partial x}H^2\\&\quad = gH(S_{0y}-S_{fy})+\frac{1}{\rho}\left(\frac{\partial}{\partial x}(H\tau_{yx})\right)+\frac{1}{\rho}\left(\frac{\partial}{\partial y}(H\tau_{yy})\right)\end{aligned} \quad . \tag{3}$$

Relations for the bed and side shear stresses must be specified. Steffler and Blackburn (2002) point out (p 11): “Since these stresses arise primarily from turbulent flow interactions, there is considerable uncertainty in their evaluation. Typically, a two-dimensional form of Manning's equation is used for the friction slope,

$$S_{fx}=\frac{n^2U\sqrt{U^2+V^2}}{H^{4/3}}, \tag{4}$$

and a Bousinessq type eddy viscosity is used for the transverse shear,

$$\tau_{xy}=v_t\left(\frac{\partial U}{\partial y}+\frac{\partial V}{\partial x}\right).\text{”} \tag{5}$$

They further explain: “The parameters n and vt are not constants or fluid properties, but depend on the flow situation. As a result they become the “tuning” or calibration parameters that may be changed to bring a model prediction into agreement with measured data.” (Steffler and Blackburn, 2002, p 11) Note: v_t is commonly called the eddy viscosity and n is usually referred to as Manning’s n.

Due to the interdependence of terms, these coupled differential equations cannot be brought to a closed form solution using the tools of algebra and differential calculus. Thus, models that solve these or the full Navier-Stokes equations must rely on numerical techniques that are typically implemented on digital computers.

Incorporating Ice in River2D

River2D is equipped to model flow under a floating ice cover with known geometry. The ice thickness and roughness must be defined over the entire solution domain. When ice cover is present on a river, it affects the flow hydraulics in a number of ways: (1) roughness and shear stress operate on both the bed and the bottom of the ice cover, (2) velocity is redistributed due to the thickness of the ice cover, (3) average velocity may be reduced due to greater overall resistance or increased due to constraining the conveyance area of the flow, and (4) the calculated water surface elevation is increased to accommodate the submerged thickness of the ice cover. These conditions are accommodated in the River2D model by modifications to the *x* and *y* momentum equations to account for submerged depth of the ice cover (x equations shown here)

$$\frac{\partial q_x}{\partial t} + \frac{\partial}{\partial x}(Uq_x) + \frac{\partial}{\partial y}(Vq_x) + g\frac{\partial}{\partial x}\left(\frac{H^2}{2}\right) - gt_s\frac{\partial H}{\partial x}$$

$$= gD(S_{0x} - S_{fx}) + \frac{1}{\rho}\left(\frac{\partial}{\partial x}(D\tau_{xx})\right) + \frac{1}{\rho}\left(\frac{\partial}{\partial y}(D\tau_{xy})\right)$$

and by developing a combined ice and bed resistance model using an average shear stress

$$\tau_{fx} = \frac{\tau_{bx} + \tau_{ix}}{2}.$$

Then the friction slope incorporating ice becomes

$$S_{fx} = 2\frac{\tau_{fx}}{\rho g D} = \frac{2\sqrt{U^2 + V^2}}{gDC_s^2}U \quad .$$

In these equations, t_s is the submerged portion of the ice cover, *D* is the depth of flow from the bed to the bottom of the ice cover, *H* is the depth to the free surface, τ_{fx} is the average shear stress in *x*, τ_{bx} is the bed shear stress, τ_{ix} is the shear stress due to friction with the bottom of the ice cover, S_{fx} is the resulting friction slope in *x*, and C_s is the Chezy coefficient. See Steffler and Blackburn, 2002, for full development of the ice resistance model.

Execution of the River2D model with ice cover is accomplished by first running the desired discharge as a free surface (no ice) model and then adding ice cover and re-solving for the ice cover condition. Calibration and verification of the study site is required as it is with any free surface application of River2D.

Habitat Model

Two habitat model concepts were used in this application: a spatially explicit form of the Weighted Usable Area (WUA) model (Bovee, 1982; Bovee and others, 1998) and a habitat patch model such as used by Bowen, and others, (2003).

The fish habitat component contained in River2D is an implementation of the WUA concept similar to that used in the PHABSIM (Milhous, and others, 1989) family of riverine habitat models. WUA is calculated as an aggregate of individual habitat suitability indices (HSI, range 0.0 - 1.0) for depth, velocity and a channel descriptor that is evaluated at every point in the domain. WUA can be calculated by any method that integrates the individual HSI into a composite scaling value (composite suitability index, CSI) for each tributary area surrounding a point, multiplies that composite scalar times each tributary area and sums the result over the study site domain. The most commonly used form is a linear product that can be represented as:

$$WUA = \sum_i s_v * s_d * s_{ci} * a_i$$

where: s_v is the habitat suitability index for velocity, s_d is the habitat suitability index for depth, s_{ci} is the habitat suitability index for channel index, and a_i is the tributary area to node *i*. Here, the product of the three suitability indices is the CSI. Other forms of the WUA calculation use the composite suitability as a geometric mean of the suitability product or select the minimum suitability value as the scalar. In River2D, the nodes noted above are the computational nodes of the finite element mesh, and the tributary areas are the "Thiessen polygons", including the area closer to a particular node than all other nodes.

The habitat patch model used in this application is designed to select the area of the study site that classifies as pool habitat using various quantitative definitions of a pool. Here, pools are defined using binary criteria and calculated as the aggregate of all areas having (1) a depth greater than the defined threshold and (2) an average velocity less than the defined threshold. A range of binary threshold values are applied and reported to enable the Forest Service to select the most appropriate metric for defining trout habitat in the presence of ice.

Habitat Suitability Criteria

In the Weighted Usable Area concept, a set of habitat suitability indices (one index scale each for depth, velocity, and channel index) for a particular organism is often referred to as a set of habitat suitability criteria or simply habitat suitability criteria (HSC). The habitat suitability criteria used in this study are taken from Thomas and Bovee (1993). These criteria were developed independently from this investigation and were tested for transferability to the Cache la Poudre River. The habitat suitability criteria from Thomas and Bovee (1993) used herein are for adult rainbow trout (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*) in open channel conditions affected neither by ice nor low water temperatures near 0° C. The habitat suitability criteria used in this study are given in appendix 1.

The Thomas and Bovee (1993) study characterized channel index using a cover code based on combinations of visual isolation and velocity shelter. Such cover data were not collected at the Kinikinik study site due to ice cover. Hence, to facilitate calculation of habitat areas based on the Thomas and Bovee depth and velocity criteria, all channel index nodal values were set such that the resulting suitability index would be 1.0. This approach effectively removes channel index from the WUA calculation and focuses the results on depth and velocity.

The following general observations regarding over-winter habitat use and behavior are taken from Lindstrom and Hubert (2004), Simpkins and others (2000), Jakober, and others 1998, Cunjak 1996, Chisholm, and others 1985. One or more of these authors reported (1) fish locate in deep pools with low velocity areas to conserve energy during the winter, (2) fish actively feed during winter, (3) fish have strong site fidelity to a relatively small area, and (4) that deep slow areas afford protection from frazil ice events. Lindstrom and Hubert (2004) and Simpkins and others (2000) found trout in deep pools with low velocities and in stable areas during the winter under ice and in near freezing conditions. Simpkins and others (2000) found that wild trout in the Bighorn River below Boysen Dam moved to deeper (>1.49 m) and slower water (<30 cm/s) with the onset of winter. The preferred areas occurred near the bottom of the stream in deep pools with adjacent water velocities greater than 15 cm/s. Lindstrom and Hubert (2004) noted site fidelity during the winter because few fish moved once they had located in deeper areas of the stream. Simpkins and others (2000) reported, trout remain active in winter but they are not as active as during the other seasons. Harper and Farag (2004) reported disproportional use of off-channel pools, runs, and riffles. Yellowstone cutthroat trout (*O. clarki bouvieri*) were found in much higher proportions in pools and runs than the available proportion of those habitats and in lower proportions than available riffle habitat. Harper and Farag (2004) reported that only 3 percent of the observed Yellowstone cutthroat trout used riffles, yet riffles constituted from 40 to 60 percent of available habitat. The Yellowstone cutthroat trout were frequently found in deep run habitat. Overall, these observations suggest that habitat suitability criteria describing winter habitat use would rank deep pools with low velocities as better habitat than shallow pools with higher velocities.

The Forest Service provided a set of binary hydraulic criteria to the USGS to perform a habitat patch analysis of the amount of deep slow water. (R. Deibel, pers. comm.) The criteria require depths greater than 1 meter and velocities less than 0.3 m/s. Thus the patch-based habitat analysis during the winter focuses on identifying main channel pools and is based on assumed behavior of trout under ice such as cited above (R. Deibel, personal communication, 2007). There will be some fish that use microhabitats that may differ from the above criteria. The Forest Service criteria of depth >1 meter and velocity <0.3 m/s could also cause the model to select deep runs in the Kinikinik study site.

In addition to the binary pool patch criteria supplied by the Forest Service further combinations of minimum depth and maximum velocity were evaluated to better define the range of characteristics of the study site in winter. Each pair of pool limiting criteria was applied to the entire site for the 0.608 m^3/s and 0.325 m^3/s discharges to obtain the area of pool habitat derived from those limits. Table 1 summarizes the ten patch criteria threshold pairs evaluated:

Table 1. Pool patch criteria binary pairs.

Minimum depth (m)	Maximum velocity (m/s)
1.5	0.3
1.5	0.15
1.0	0.3
1.0	0.15
0.75	0.3
0.75	0.15
0.5	0.3
0.5	0.15
0.3	0.3
0.3	0.15

Results

Ice Cover Conditions

As noted above, ice thickness over low velocity areas and pools was found average 0.60 m. A thermal regime capable of producing this much ice over a pool can cause ice at the edge of the flowing stream to freeze to the bed. In areas of steeper gradient, the result is constriction of the flowing water into a tube-like cross section as shown in figures 4 and 5.

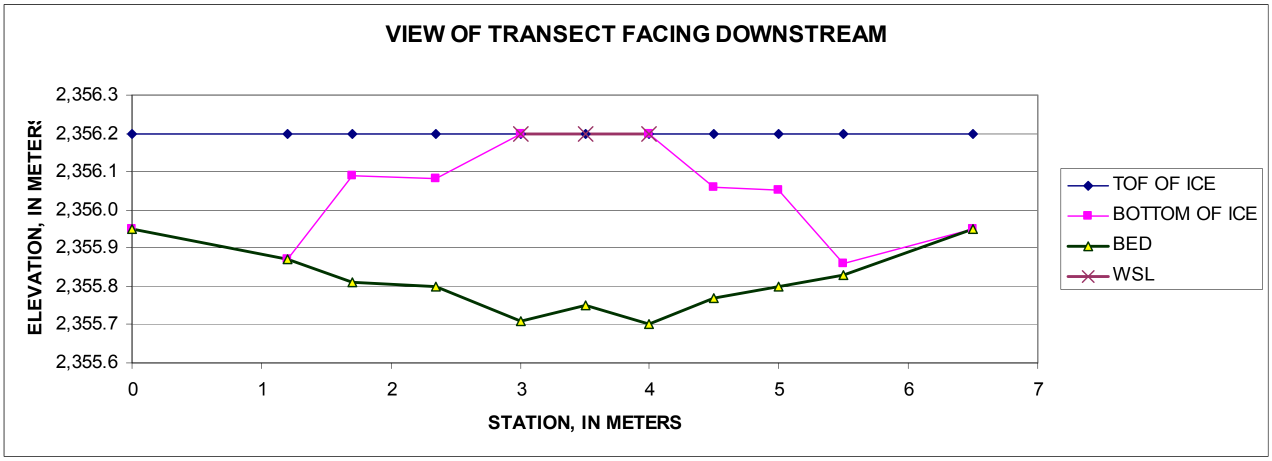

Figure 4. Discharge transect observed December 15, 2005, WSL = water surface elevation.

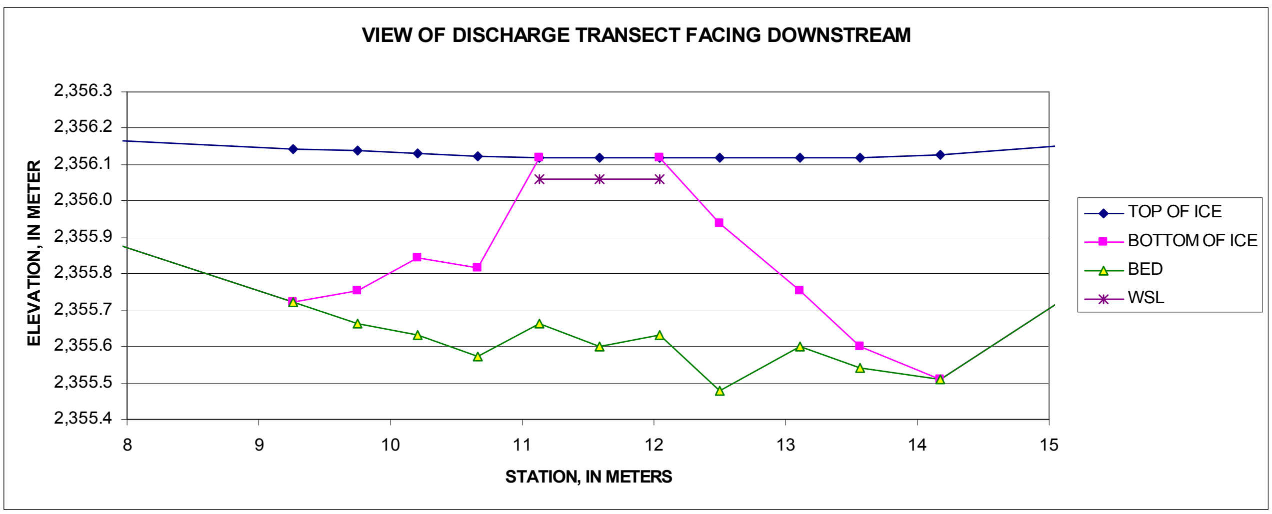

Figure 5. Discharge transect observed January 24, 2006, WSL = water surface elevation.

The cross sections in figures 4 and 5 were located within 5 m of each other in a relatively steep gradient section of the site. They were selected for discharge measurement because the open lead allowed the ice thickness near the edge to be readily observed so field crew members could move about with greater safety than in an area of unknown thickness. The location of the open lead in this portion of the channel had shifted between the two dates. Note that in both cases ice had frozen to the bed at the sides of the channel to thicknesses ranging from 0.3 to 0.6 m, confining the flow to the center of the channel. Midchannel velocities ranged from 0.6 to 1.0 m/s. Appendix 2 contains the observed ice and flow data that are summarized here.

In pools, the ice covered the water surface in a more uniform manner as shown in figure 6. The variation in measured thickness of the ice cover may be due to the ice breaking away when the digging bar broke through.

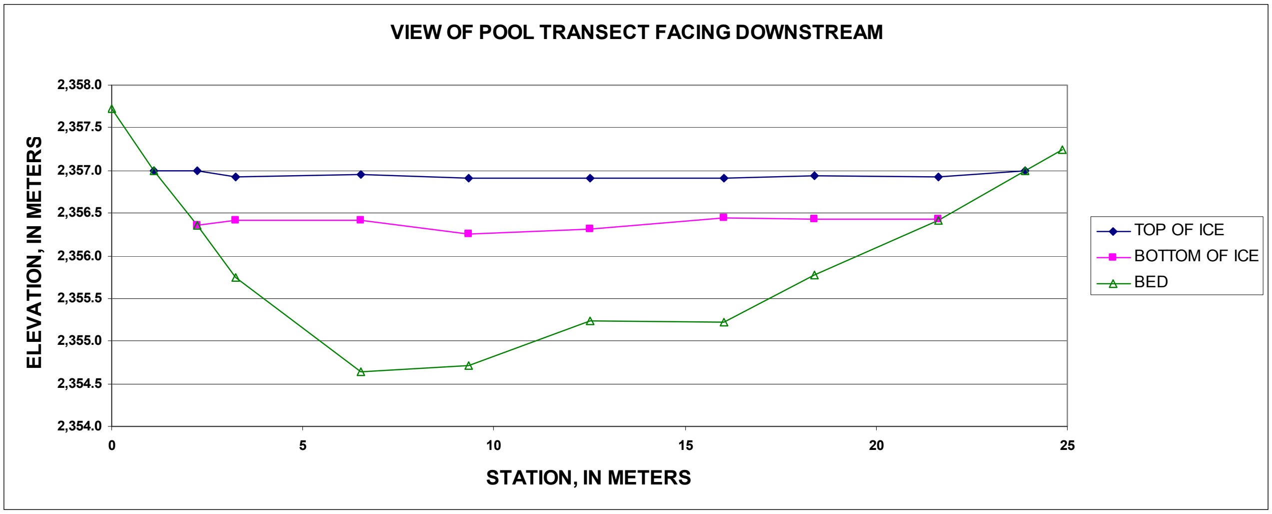

Figure 6. Pool transect showing average ice thickness of 0.6 m, edge ice thickness determined by extrapolation for illustration purposes.

Comparison of the bed elevations in the two deepest pools determined during open water surveys and those determined by measuring through the ice revealed differences as great as 0.3 m with the winter measurements resulting in lower bed elevations in those pools. Several factors may have influenced this result, including (1) measuring at near but different, XY locations; (2) penetration of softer bed sediments in winter, because the field crew could establish firmer footing on the ice than they could raft in summer, and possible scour or deposition of sediment in the bottom of the pools between measurements. Low flow dynamics in the pools are not significantly affected by these elevation differences. The pool bed elevation differences were assumed to have negligible effect on simulated habitat values.

Figure 3 presents the ice cover map developed for these simulations. To ensure that all flow margins produced realistic edge wetting, a 0.05 m ice thickness was assigned to all areas above the simulated water surface for the target discharge. Thus, the minimum thickness encountered over dry portions of the study site is 0.05 m. The ice cover is reduced to a zero thickness in the areas where narrow open leads (areas with no ice cover) were observed on January 24, 2006. This convention conforms to the observed increase in surface elevation of the ice at the stream edge obtained from the GPS measurements of January 24, 2006.

The recorded temperatures and pressures indicated that the ice cover broke up by March 29, 2006, because diurnal fluctuations of water temperature and pressure resumed on that day. Realistic depth values were reported from November 22 to November 29, 2005, after which ice influence or complete encasement occurred. Realistic depths were again recorded beginning March 29, 2006. Temperatures recorded by the ice-encased instrument did not exceed 0°C from December 04, 2005 – March 29, 2006 with significant periods substantially below 0°C from December 5 to December 23, 2005 and January 13 – March 5, 2006. The mean daily air temperature data (see fig. 7) show a significant cold period from December 2 to December 21, 2005, a warmer period from December 21, 2005 to January 15, 2006, and another cold period from January 16 to February 26, 2006. Measured discharge transects such as shown in Figures 4 and 5 do not show significant changes in the ice cover thickness between measurements. Lack of significant change in the measured transects suggests the warmer period was not sufficiently warm to change the ice cover. This assertion is further supported by the temperature recorded by the ice-encased transducer placed in the stream (fig. 7). Note that the temperature within the ice dropped significantly in response to periods of extremely cold air. The ice buffered the temperature variation of the instream transducer, but the extremely cold periods are likely to represent times when the erosion of ice from the bottom of the ice sheet was balanced by freezing from the sides. The ice cover observed on January 24, 2006 appears to have formed during the December cold period and was retained until at least mid-March. Thus, relatively stable channel and hydraulic conditions occurred from late November until ice break up after mid-March.

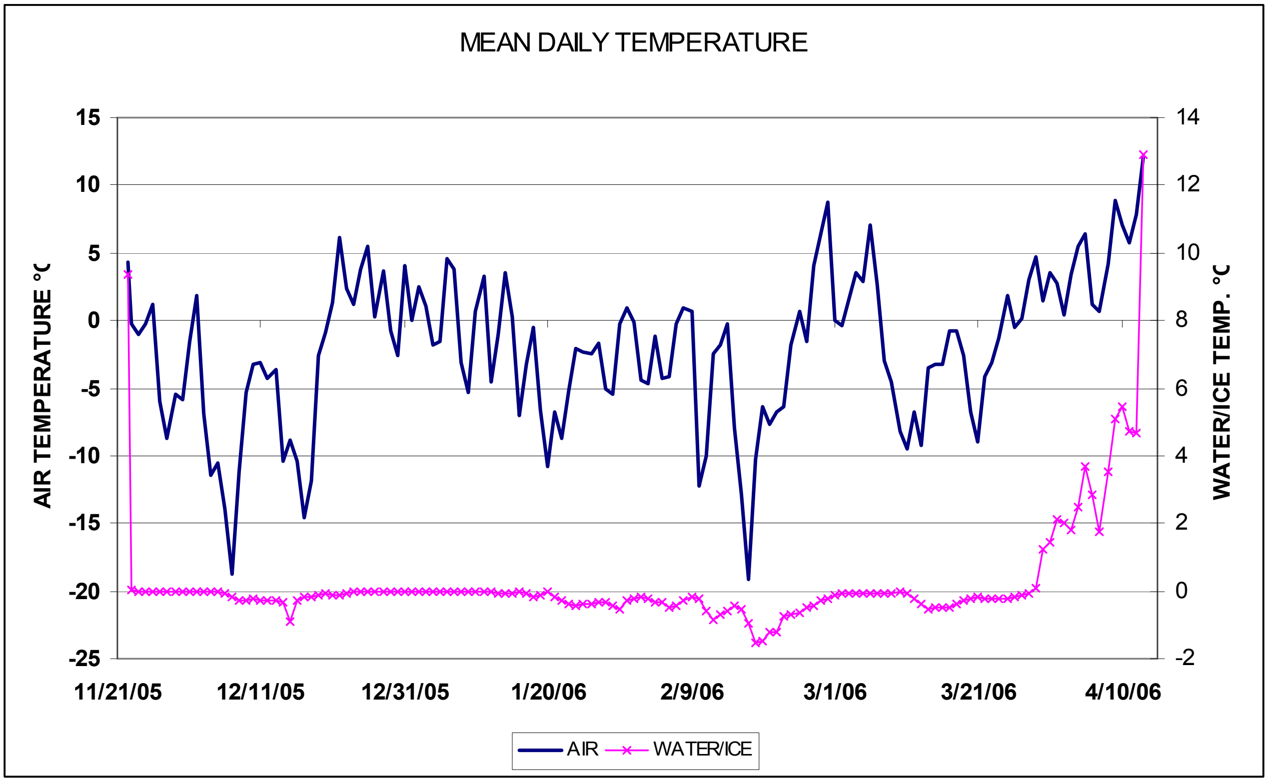

Figure 7. Mean daily air and water/ice temperature observed at the Kinikinik study site November 22, 2005 – April 14, 2006.

Depth and Velocity Under Ice

Due to the substantial difficulty encountered drilling large holes through the ice, velocity measurements were obtained for the discharge cross section only. Larger holes were required for insertion of velocity measuring apparatus than were required for measuring ice thickness. Due to this limitation, River2D was relied on to provide depth and velocity values for most of the study site. Depth and velocity values at the locations of the discharge transect, and depth and ice thickness at the other measured transects were compared with model results to verify model performance under the ice cover.

The empirical observations show surprisingly high velocity values in the high gradient areas. Confinement of the flowing channel by freezing-in from the sides as shown in figures 4 and 5 reduces the conveyance area, resulting in higher mid-channel velocities than would otherwise be encountered. The observed and simulated mid-channel velocities routinely exceed 0.6 m/s in high gradient areas. Figure 8 shows the observed and simulated velocity profile at the discharge measurement transect employed on January 24, 2006. See appendix 2 for measurement details.

Note that the higher edge velocities are partly an artifact of the model's current lack of a mechanism to freeze the ice to be bed. These "shoulder" velocities represent areas at the edge where the model floated the ice and allowed a portion of the discharge to pass through areas that were observed frozen to the bed. The smoothed nature of the simulated velocity profile and the higher velocities near the edges are also partly an artifact of the spatial averaging inherent in two-dimensional models.

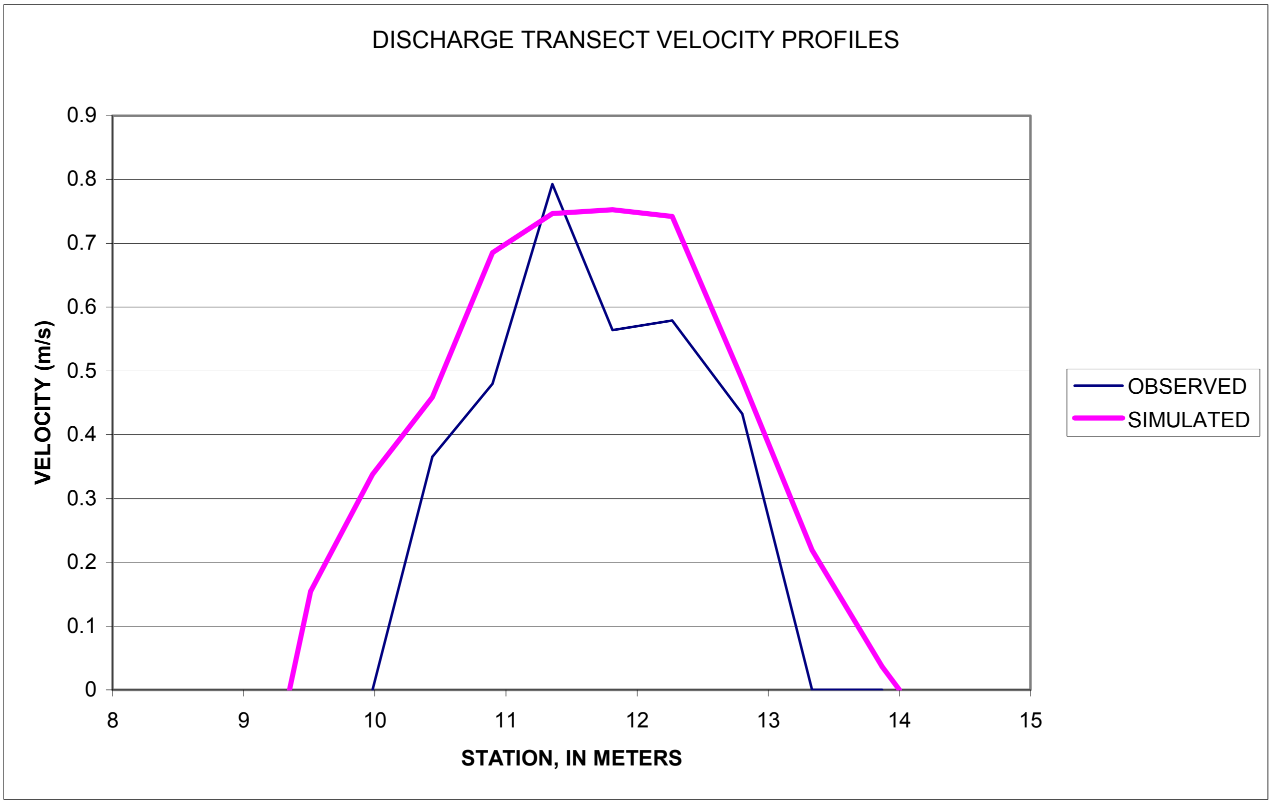

Figure 8. Observed and simulated velocity profile obtained for discharge of 0.608 m^3/s observed January 24, 2006.

Figures 9 and 10 show the spatial depth and velocity distribution simulated for the 0.608 m^3/s discharge (21.48 ft^3/s) encountered January 24, 2006. One of the backwater areas isolated by the constructed low dikes (indicated in fig. 9) has sufficient depth that approximately 0.4 m of water remain unfrozen under the 0.6 m ice cover.

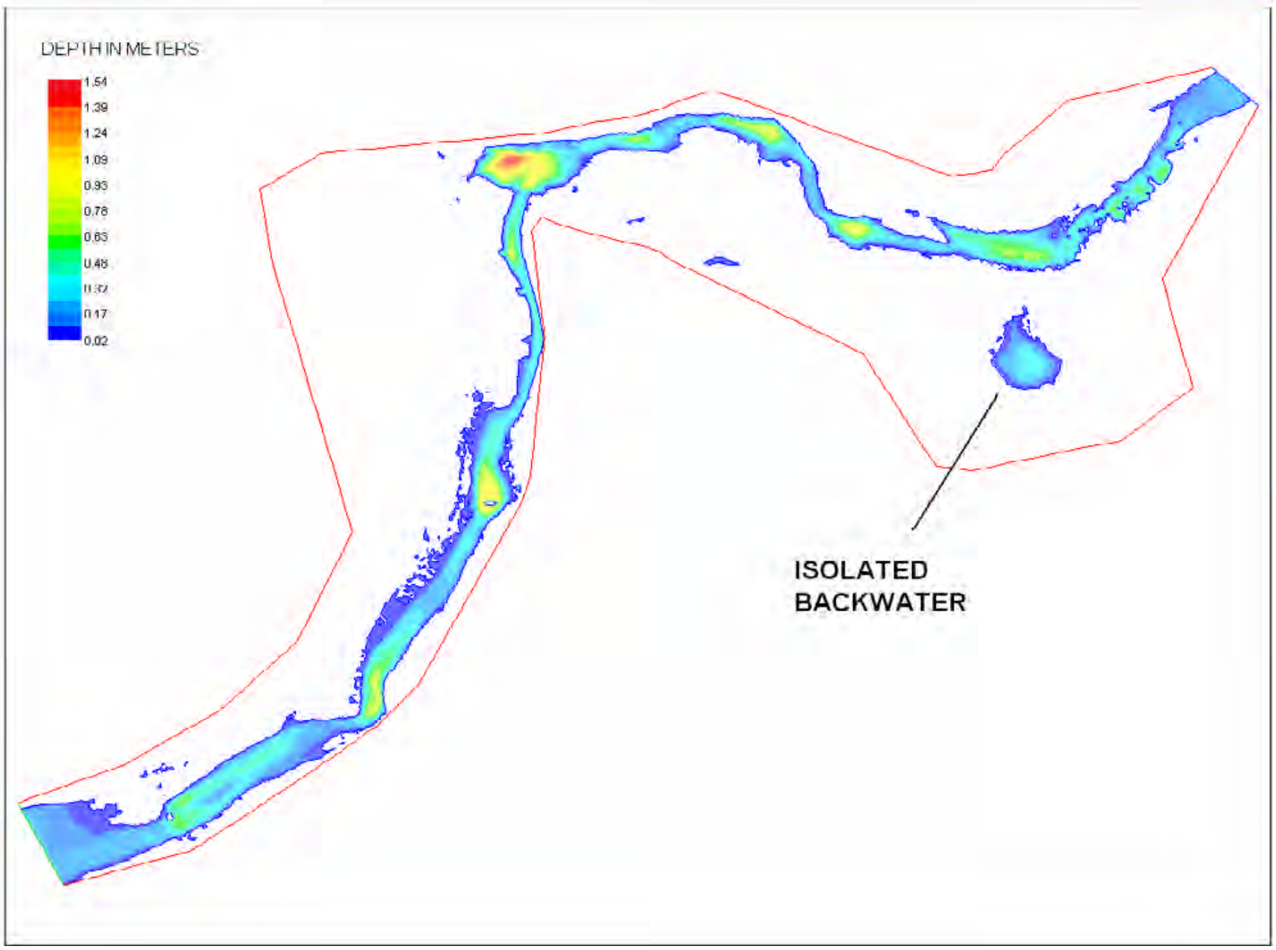

Figure 9. Depth distribution under ice cover for discharge of 0.608 m^3/s, January 24, 2006.

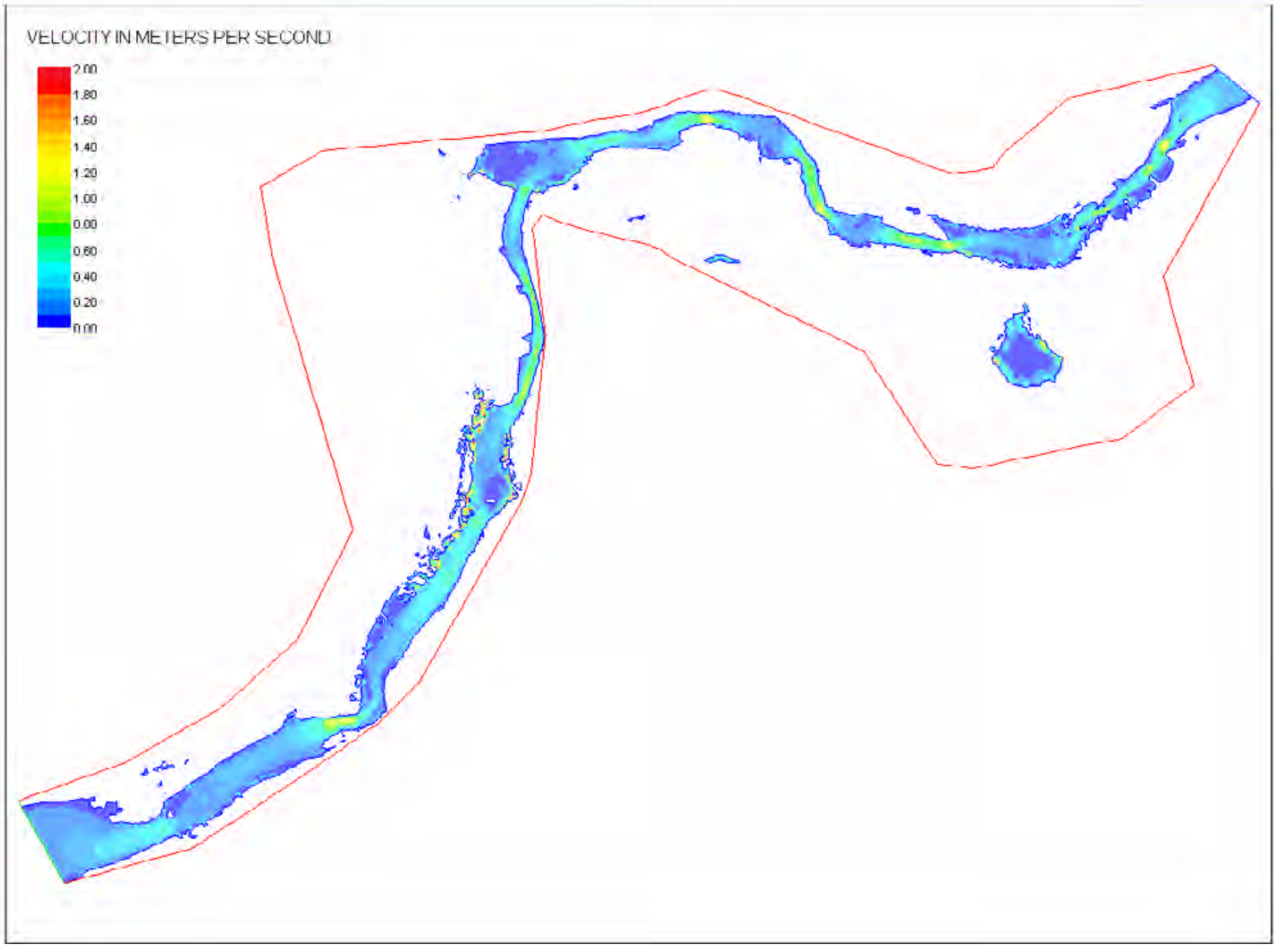

Figure 10. Velocity distribution under ice cover for discharge of 0.608 m^3/s, January 24, 2006; Qin = inflow discharge, Qout = simulated outflow discharge.

River2D Performance With Ice Cover

Addition of ice cover increases the computational burden for the River2D model. In particular, edges of the wetted area appear to have two varieties of computational difficulties that must be accommodated when applying the model. First, convoluted edges and large time steps are difficult for the model to handle as presently formulated. The north bank of the river bend near the middle of the site is riprapped to protect the adjacent highway. The original computational mesh follows the riprap contours in great detail. This detail produced locally infeasible results when ice cover was added. To remedy this problem, the riprap contours were smoothed and a new mesh was developed for that area. Second, it was also necessary to limit the time step attempted in the model to prevent numerical infeasibilities, so the maximum time step was constrained by switching from the direct solver to the iterative Generalized Minimal Residual solver. (Steffler and Blackburn, 2002 p 40-41) With these changes the model ran without encountering infeasible conditions.

As currently formulated, the River2D model does not have the ability to attach the ice cover to the river bed. As a result, the mode may predict that ice floats in some edge areas where the ice is actually frozen to the bed. This phenomena results in a thin film of water (often less than 0.03 m in depth) occurring in some edge areas and in calculation of unrealistically high velocities for those areas. The areas subject to this phenomenon are unstable, such that the computational elements with such shallow depths and unrealistic velocities change with each iteration of the solution procedure. Because of the very small depths involved, the mass flux of these areas was deemed to be insignificant to the overall solution. Further, areas of such depths are rated as zero habitat value and excluded from the habitat sum due to being too shallow to satisfy the suitability criteria. Therefore, the unusual edge behavior did not influence the predicted amount of habitat.

Effects of Ice Cover on Flow Characteristics

To evaluate the overall effects of ice cover, the River2d model was run at 0.566 m^3/s (20 ft^3/s) for both open water and ice covered conditions. Recall that depth in the presence of ice cover is defined as the distance from the bed to the bottom of the ice. Figure 11 shows reductions in the total area occupied by all but one of eleven depth bins due to the presence of ice. Figure 12 shows that the area occupied by the lowest velocity bin decreases substantially in the presence of ice and increases in areas occupied by velocities greater than 0.5 m/s. These results are consistent with the observed ice formation from the sides toward the middle of the channel noted earlier. That is, as the ice became thicker and more of the channel edge became frozen to the bed, more low-velocity areas were occupied by ice, forcing the flow into the remaining conveyance area at higher velocities. In summary, ice produced less flow area and higher velocities.

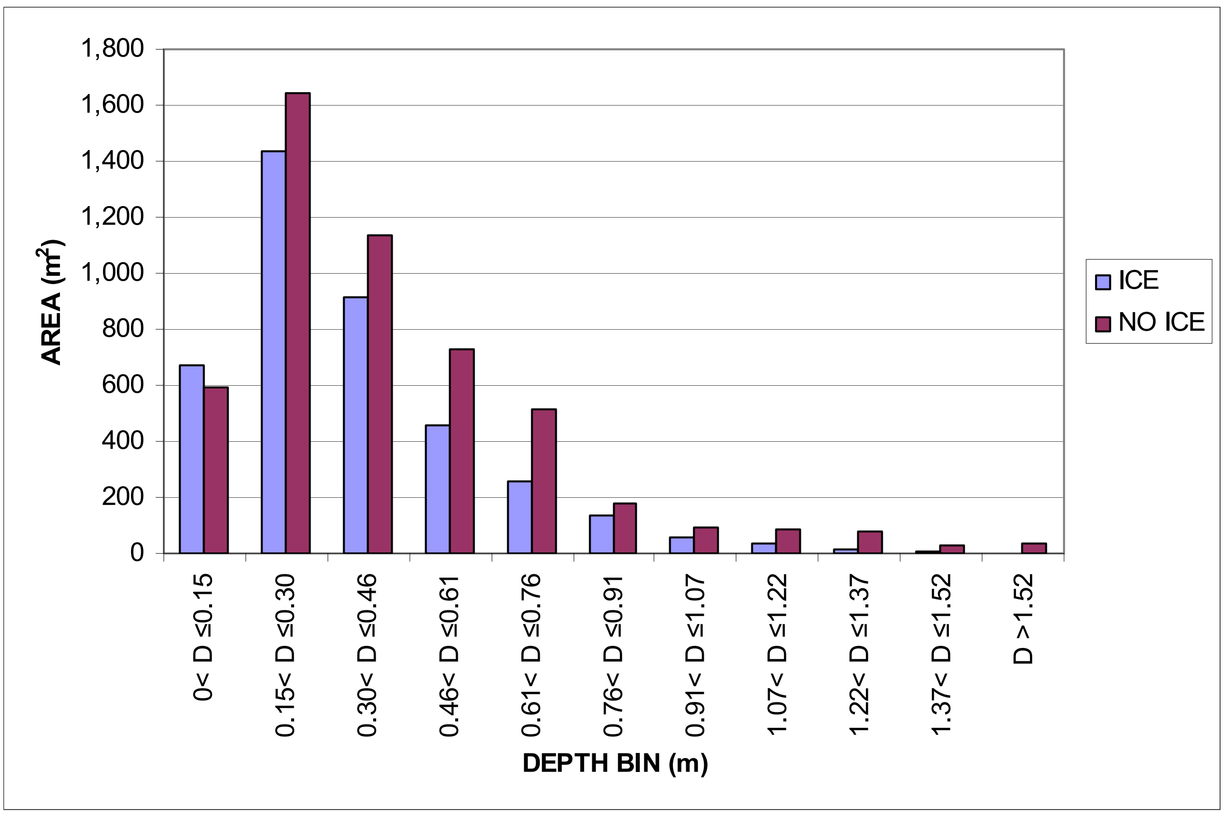

Figure 11. Area occupied by depth increments with and without ice at 0.566 m^3/s; D = depth.

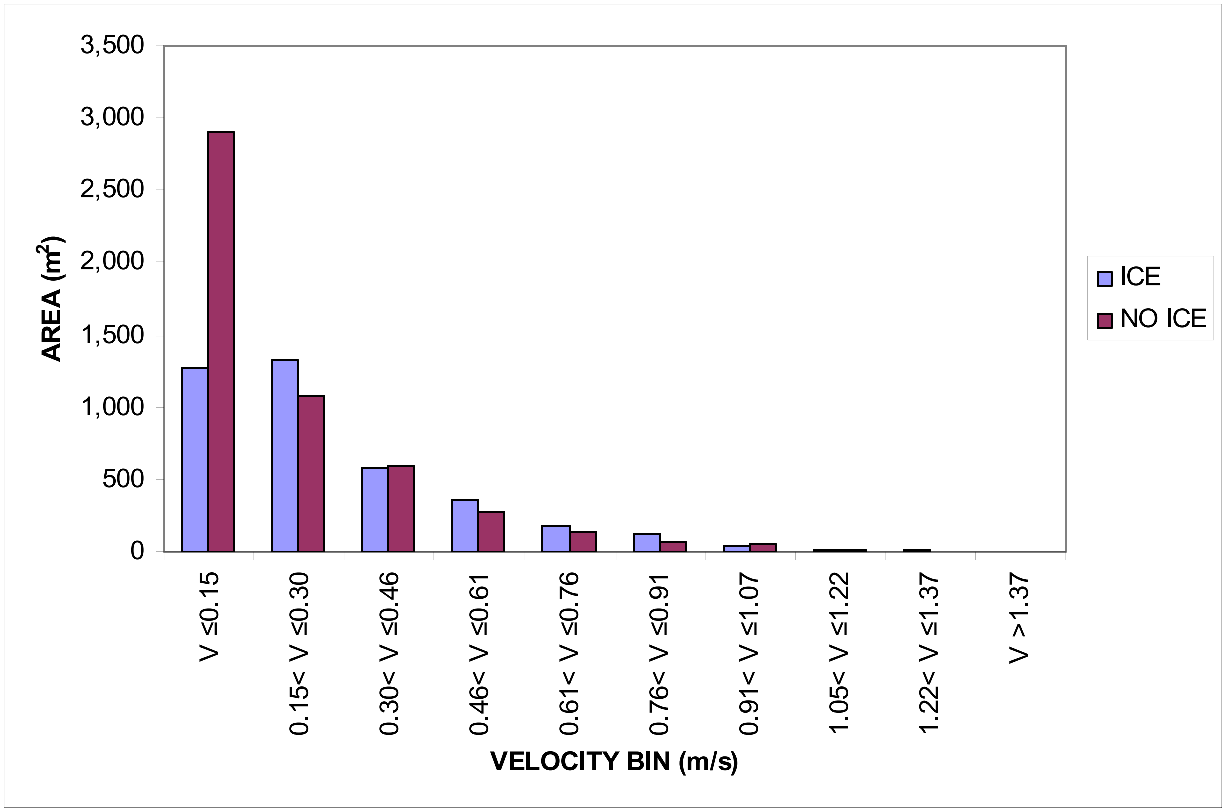

Figure 12. Area occupied by velocity increments with and without ice at 0.566 m^3/s; V = velocity.

Physical Effects of Winter Release

A release of 0.283 m^3/s (10 ft^3/s) from reservoirs upstream of the Kinikinik study site was maintained during winter 2005–2006. To evaluate the effects on the stream of this release, the calibrated River2D model was run for the observed January 24, 2006, condition (0.608 m^3/s) and an assumed condition of 0.325 m^3/s; the observed condition less 0.283 m^3/s.

Reducing the discharge at the study site from 0.608 m^3/s to 0.325 m^3/s when subject to the same ice cover reduces the wetted area from 4,092 m^2 to 3,559 m^2. Figures 13 and 14 show the changes in depth and velocity bin area. Note that reducing the discharge reduces the area occupied by all depth bins and the area occupied by all but the lowest velocity bin. Thus, in general, reducing the discharge by 0.283 m^3/s produces across the board reductions in the depths and velocities.

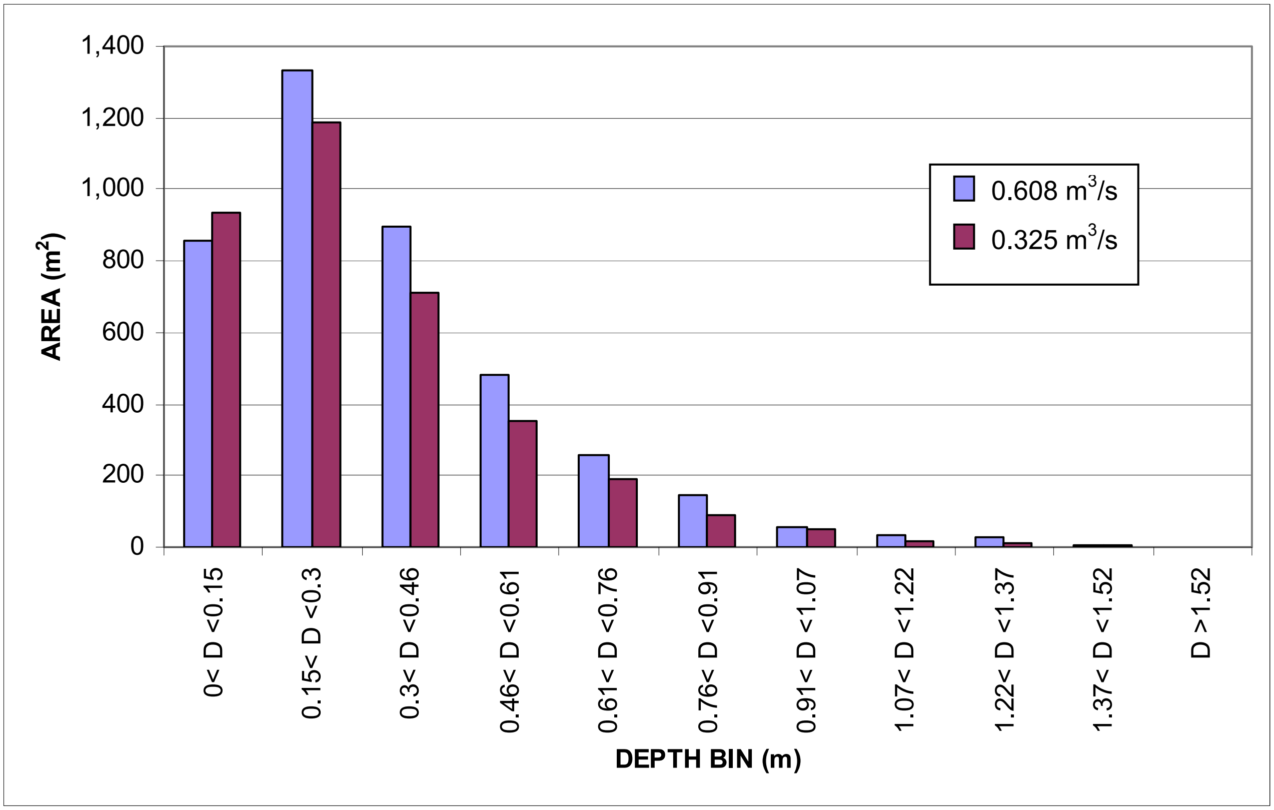

Figure 13. Area occupied by depth increments at 0.608 m^3/s and 0.325 m^3/s.

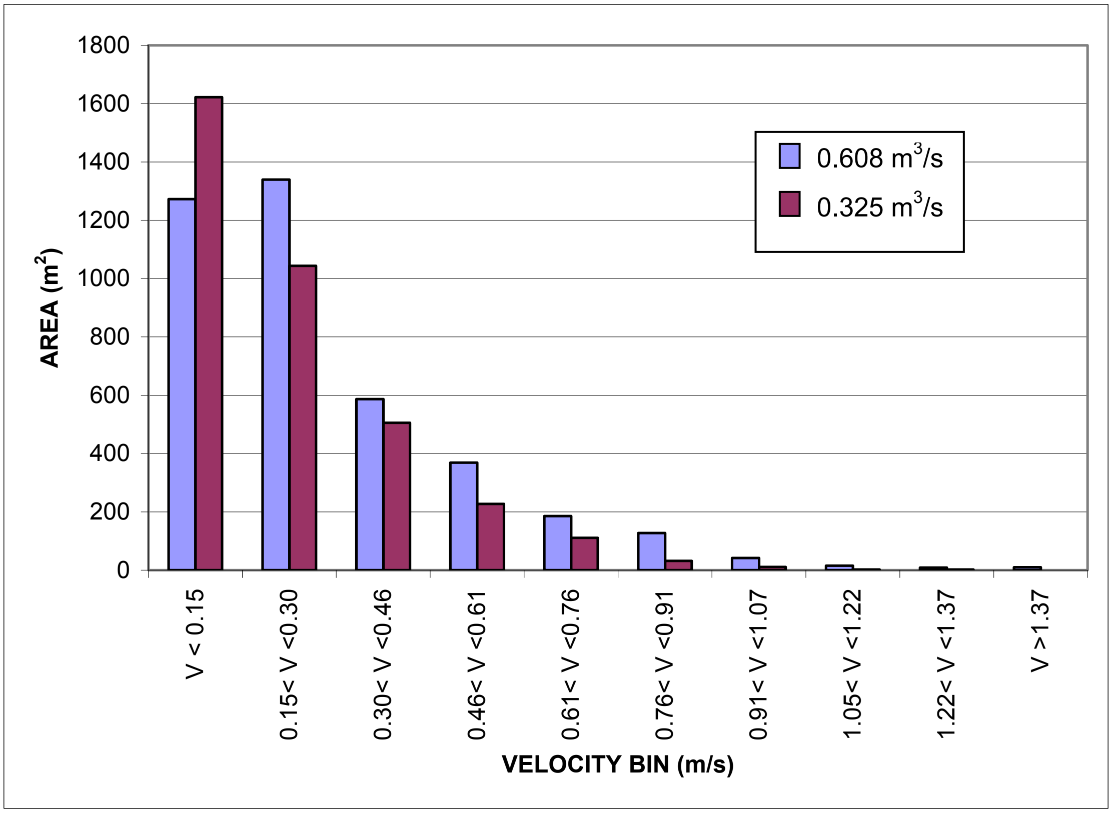

Figure 14. Area occupied by velocity increments at 0.608 m^3/s and 0.325 m^3/s.

Winter Habitat

Freshwater salmonids exhibit a wide range of behaviors in response to winter conditions. Some have been observed maintaining active feeding and migration behavior in winter. (Cunjak and Power, 1986; Cunjak, 1996; Jakober, and others 1998; Simpkins and others 2000; Lindstrom and Hubert, 2004) However, winter conditions are also known to produce high fish mortality. (Annear, and others 2002) Other authors observed fish entering pools created by beaver dams and preferring those pools throughout winter. (Chisholm, and others, 1985; Cunjak, 1996; Jakober, and others, 1998,) Harper and Farag (2004) observed that cutthroat trout used pools during periods of cold temperatures and runs when water temperatures exceeded 1° C. Cunjak (1996, p. 273) points out “winter habitat selection often differs from that in summer, generally involving movement to areas with lower water velocity (day and night).” Due to the wide range of reported behaviors, it is difficult to predict the specific behavioral responses to temperature and winter ice cover of brown and rainbow trout in the Cache la Poudre River. Cunjak (1996) provides some guidance when he states that areas of lower velocity will be selected to minimize energy expenditure when exposed to lower winter temperatures.

Few habitat suitability criteria (HSC) have been developed specifically for winter conditions, particularly under ice cover, due to the rigor of obtaining significant samples. Cunjak and Power (1986, p. 1975) observe: “In temperate latitude streams subject to freezing conditions for considerable periods (months) over the winter, there exists no published record of salmonid behaviour based on underwater observations.” In the same article, Cunjak and Power describe winter fish observations, but they worked in a stream that did not freeze over. Thus, a quantitative evaluation of habitat with ice cover in the Poudre River requires analysis of the physical conditions present in the stream and inference from relative differences in calculated habitat derived from summer or at least open water HSC.

Thomas and Bovee (1993) developed habitat suitability for adult brown trout (*Salmo trutta*) and rainbow trout (*Oncorhyncus mykiss*) for the South Platte River and found the criteria to be transferable to the Cache la Poudre River. Applying those criteria to the Kinikinik study site, and assuming that all substrate in the study site are fully suitable for over-wintering adult trout, yields the following habitat results (table 2):

Table 2. Habitat area (Weighted Usable Area) for two discharges at the Kinikinik site for ice conditions equivalent to those observed January 24, 2006 and for open channel conditions.

Ice condition	Simulated discharge m^3/s	Brown trout adults m^2	Rainbow trout adults m^2
Ice	0.608	660.66	532.25
Ice	0.325	422.87	346.18
No ice	0.608	831.93	728.46
No ice	0.325	565.67	507.41

When using Weighted Usable Area based on the Thomas and Bovee (1993) HSC as the habitat metric, reducing flow without ice cover by approximately one-half of the discharge observed on January 24, 2006 produces a reduction of about 32 percent in the calculated habitat metric. When flow under ice cover is reduced by the same amount, habitat is reduced by about 35 percent. As noted earlier, this example applies summer criteria to winter conditions. It serves as an illustration of the relative habitat changes occurring when winter flows are reduced. That is, overall an approximate 47 percent reduction in flow produces an approximate 33 percent reduction in habitat area, with or without ice. Definitive description of winter HSC and therefore habitat use under ice cover would require development of criteria specifically designed for that purpose.

Cunjak (1996) and Lindstrom and Hubert (2004) note that winter habitat selection involves movement into areas with lower velocity and(or) greater depth. These observations (though qualitative in nature) suggest that a patch-type habitat metric may apply to the Kinikinik site in winter. The calculated velocity bins shown in figure 14 suggest that reducing the discharge may increase the area of the stream that contains velocities less than 0.15 m/s. However, as delineated, the velocity bins do not differentiate between the narrow band that can occur at the edge, between the bottom of the ice and the bed, and the areas that would be classified as pools.[2] Therefore, pool habitat was evaluated using the pool habitat criteria defined in table 1.

Using these pool patch criteria results in total pool areas shown in table 3, when evaluated for the observed January 24, 2006, condition (0.608 m^3/s) and a reduced flow of 0.325 m^3/s. Note that for a maximum velocity threshold of 0.15 m/s the total pool area increases with decreasing discharge when the depth limit is relaxed to 0.5 or 0.3 meters (rows 4 and 5), as illustrated in figure

[2] In this application, “pool” refers to an area of adequate depth and lower velocities that provides resting shelter during extreme low temperature conditions. Pool patches are defined as areas with $v<V$ and $d>D$, where V and D are defined pool velocity and depth thresholds and v and d are calculated velocity and depth for a patch.

15. This increase is due to an increase in mid-channel velocity at the higher discharge exceeding the 0.15 m/s threshold without sufficient increase in slow area to offset the loss of mid-channel slow habitat. For all other cases, a decrease in discharge of 0.283 m^3/s from the observed condition results in a decrease in pool area, as defined by the depth and velocity thresholds.

Table 3. Area of low velocity and increased depth based on different pool criteria, results derived from criteria provided by U.S. Forest Service are shown in bold.

Case	Minimum depth (m)	Maximum velocity (m/s)	Pool area at 0.608 m^3/s (m^2)	Pool area at 0.325 m^3/s (m^2)
1	1.5	0.15	4.51	0.0
2	1.0	0.15	81.63	59.43
3	0.75	0.15	209.01	197.72
4	0.5	0.15	463.04	499.23
5	0.3	0.15	756.47	983.26
6	1.5	0.3	4.51	0.0
7	**1.0**	**0.3**	**83.9**	**59.43**
8	0.75	0.3	277.65	202.28
9	0.5	0.3	753.47	591.98
10	0.3	0.3	1,464.8	1,341.5

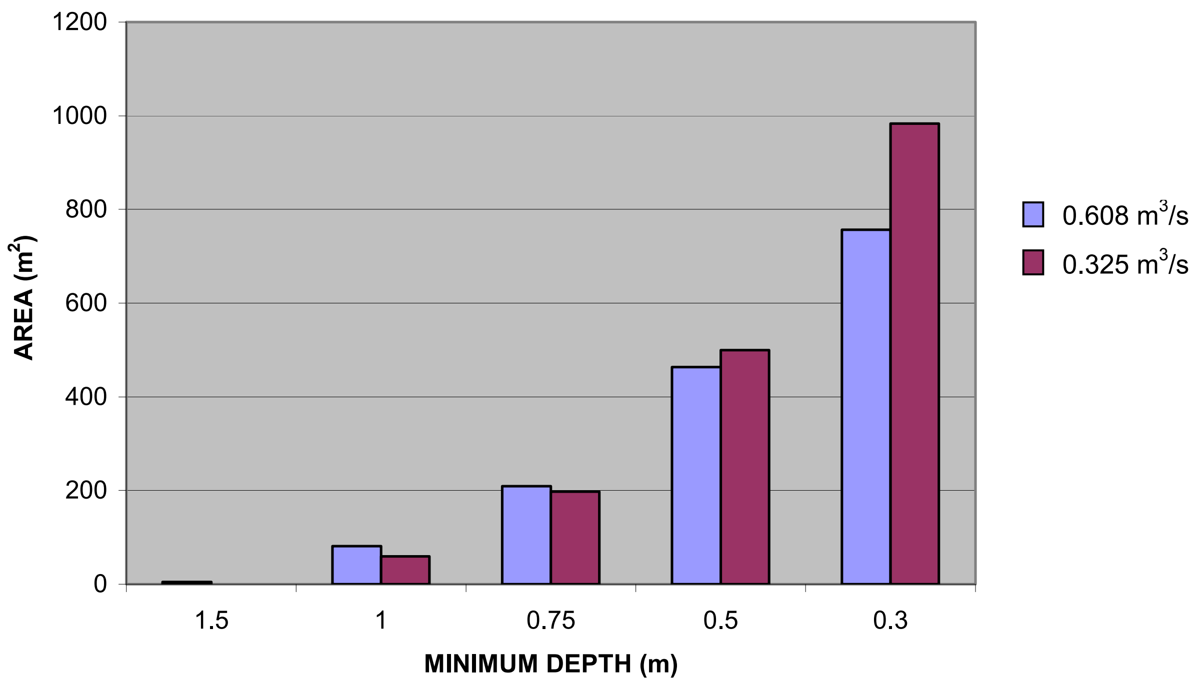

Figure 15. Habitat area under ice for V<0.15 m/s.

The change in pool habitat occurs in the two deep pools in the study area (see figure 16). The reduction in pool area occurring from 0.608 m^3/s to 0.325 m^3/s for all but the two shallow pool definitions (cases 4 and 5, table 3; fig. 15) illustrate an overall tendency for sheltered pool areas to change in concert with discharge regardless of the exact pool criteria. Based on the Cunjak (1996) and Lindstrom and Hubert (2004) results, it would appear that the two deep pools provide the most reliable winter habitat in the Kinikinik study site. Under-ice observations of fish in this study area, the exact kind of data that is missing, would be required to confirm the actual degree of habitat usage.

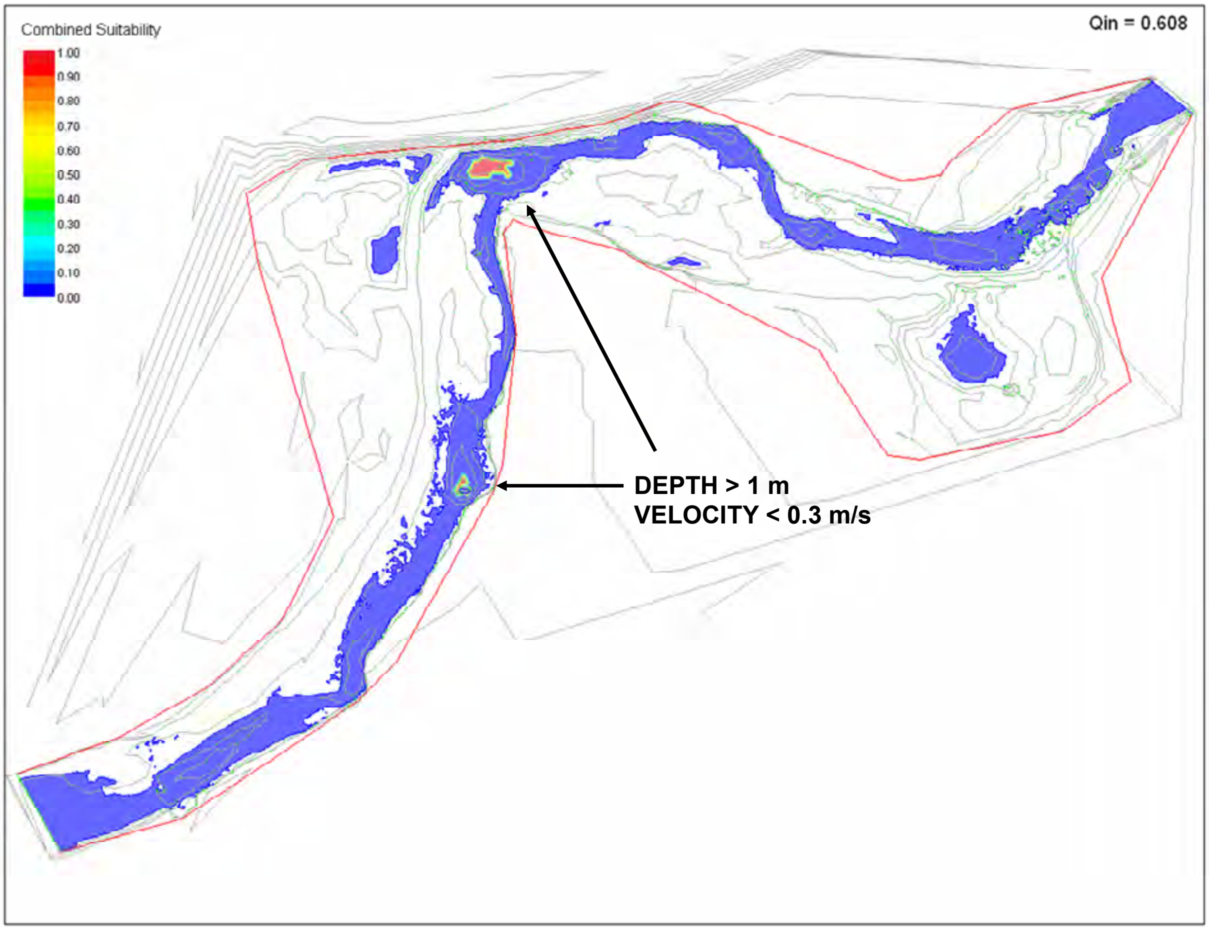

Figure 16. Pool areas at 0.608 m^3/s using the Forest Service criteria; gray lines are topographic contours.

Discussion

Chisholm, and others, (1985) did not observe anchor or frazil ice in a study in the Snowy Range, Wyo. (approximately 100 km north of the Cache la Poudre River study site), in areas where the stream was covered with ice or snow. Neither frazil nor anchor ice was observed in the open leads measured during this study. The form of the habitat model used in this study inherently assumes the water column is free of obstructions not included in the topographic data. In the present context, it inherently assumes frazil ice is not present. The hydrodynamic model formulation does deal with ice cover over the stream and thus appears to be consistent with the conditions observed in the field.

At the current state of development, the River2D model requires the ice cover to be defined as input to the hydrodynamic modeling process. In this situation, the ice cover developed from January 24, 2006, observations (0.608 m^3/s discharge) was assumed to be representative of the ice cover present at 0.325 m^3/s. The extent and thickness of the actual ice cover without a winter release from upstream reservoirs would, of course, be different. The degree of difference can only be determined empirically. For the purposes of this study using the ice cover generated from January 24, 2006 observations was judged to be adequate to illustrate the overall magnitude and location of depth and velocity conditions at the lower discharge.

The 0.283 m^3/s release from headwater reservoirs is currently maintained throughout the winter. The ice cover observed on January 24, 2006, appears to be the result of cold periods that occurred in December and January. Similar cold temperatures continued with a few interruptions until the last third of March 2006. Because the current management practice is based on a fixed release from upstream reservoirs, and because the cold conditions continued from mid-December through mid-March, the assumption that the Jananuary 24, 2006 condition is representative of overall winter hydrodynamics seems justified.

This analysis of fish habitat under winter conditions does not consider stream discharge needed to maintain connectivity between pools. Observation of ice formation during winter 2005–2006 suggests that the flowing stream will maintain adequate space between the ice and the bed to convey the streamflow. Abrupt increases in discharge are likely to result in flow over the surface of the ice. When drilling through the ice we encountered areas of over-ice where 3–5 cm of ice had formed on top of the consolidated ice cover resulting in distinct layers. It appears likely that a larger sustained discharge would result in freezing and erosion of the bottom of the ice until equilibrium between the discharge and ice thickness was reached. Thus flow of water between the pools is likely to be maintained; however, thorough evaluation of the capacity of fish to move through the high velocities and low temperatures encountered under the ice would require more information.

In addition to low water velocities requiring less energy expenditure, a portion of the definition of a "pool" common in fisheries science is based on having sufficient depth that fish are less subject to avian predation. With complete ice cover, that portion of the definition may be removed for this study site. Redefining "pool" as "pool under ice" may allow depths as shallow as 0.3 m with slow velocities to be classified as pools. Applying such a definition will increase the amount of pool habitat calculated for both discharges. For some "pool" criteria definitions, reduction of velocities in shallow pools may result in increased area with a decrease in discharge. However, overall there is an apparent increase in pool habitat obtained by increasing the discharge.

Due to the process of freezing-in from the stream margins, shallow edge habitat is reduced in winter regardless of flow. Therefore, because of the nature of freezing dynamics, neither increasing nor decreasing the flow will enhance edge habitats in a stream with stable winter flow, such as the stream observed in this study,.

Using a Weighted Usable Area metric leads to the conclusion that, within the range of conditions simulated, increased winter flow increases the habitat area for both brown and rainbow trout. With the exception of combinations of shallow depth and low velocity threshold, the same conclusion is borne out for pool habitats. An extensive study of brown and rainbow trout subjected to ice cover such as was observed at the Kinikinik site would be necessary to objectively determine the actual occupancy of different habitats by over-wintering trout in the Cache la Poudre River.

A survey of channel types for the substantial portion of the Cache la Poudre River influenced by the winter release was not conducted as part of this study. Thus, the precise length of the river represented by the Kinikinik study site is unknown. The Kinikinik site is in a portion of the Poudre River Valley that was glaciated and is representative of the channel characteristics observed upstream of the terminal moraine known as Home Moraine. A study of ice formation and break-up in steeper gradient sections of the river would provide a more representative description of those sections. However, the general occlusion of the stream margins by ice formation would occur in all portions of the river subject to extended periods of sub-zero temperatures such as those that occurred in December 2005, and January and February 2006.

Products of this Study

River2D files containing the solutions for 0.608 and 0.325 m^3/s; the ice cover generated for January 24, 2006; the habitat suitability criteria based on the Thomas and Bovee (1993) study; and the pool criteria used herein are products of this study. These files and brief instructions about loading them to River2D are provided to the U.S. Forest Service with this report. The Forest Service may then use these files to reevaluate weighted usable area for the flow-under-ice conditions described herein with alternative habitat suitability criteria.

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Appendix 1. Habitat Suitability Criteria from Thomas and Bovee (1993)

Table 1-1. Brown Trout adults active. (Data from South Platte River, Colorado.)

[Continuous criteria from exponential polynomial curves, English units translated to metric, 1 = no cover, 2 = visual isolation, 3 = velocity shelter, 4 = combination: velocity shelter + visual isolation.]

Mean velocity (m/s)	SI	Depth (m)	SI	Cover	SI
0.000	0.33	0.000	0.00	1	0.72
0.250	0.81	0.201	0.04	2	0.72
0.326	0.92	0.290	0.10	3	1.00
0.402	1.00	0.357	0.19	4	1.00
0.497	1.00	0.686	0.80		
0.591	0.92	0.817	0.94		
0.914	0.44	0.905	1.00		
1.064	0.26	1.036	1.00		
1.140	0.19	1.149	0.92		
1.274	0.11	1.411	0.58		
1.426	0.06	1.588	0.34		
1.692	0.02	1.698	0.22		
1.768	0.00	1.829	0.12		
100.000	0.00	2.103	0.00		
		100.000	0.00		

Appendix 1. Concluded

Table 1-2. Rainbow Trout adults active. (Data from South Platte River, Colorado.)

[Continuous criteria from exponential polynomial curves, English units translated to metric, 1 = no cover, 2 = visual isolation, 3 = velocity shelter, 4 = combination: velocity shelter + visual isolation.]

Mean velocity (m/s)	SI	Depth (m)	SI	Cover	SI
000	0.31	0.000	0.00	1	1
0.171	0.55	0.238	0.07	2	1
0.357	0.86	0.393	0.19	3	1
0.433	0.95	0.588	0.44	4	1
0.488	1.00	0.820	0.81		
0.579	1.00	1.015	1.00		
0.655	0.94	1.134	1.00		
0.747	0.81	1.250	0.93		
0.972	0.37	1.561	0.59		
1.064	0.22	1.756	0.38		
1.195	0.09	1.951	0.23		
1.308	0.03	2.222	0.11		
1.494	0.00	2.536	0.05		
100.000	0.00	2.847	0.03		
		3.048	0.00		
		100.000	0.00		

Appendix 2. Discharge and Ice Thickness Measurements November 2005–February 2006, Transcribed Field Notes

Table 2-1. Discharge measurement November 22, 2005.

[Discharge measurement notes transcribed from field book, note: English units translated to metric, RB = right bank, LEW = left edge of water.]

Stage influenced by ice
Ice broken to facilitate discharge measurement
Bridge Pier NW to bank perpendicular to flow
Marsh # s/n 2003632
Pygmy #
Start time: 11:40 a.m.
End time: 12:22 p.m.

Station (m)	Depth (m)	Pygmy velocity (m/s)	Marsh velocity (m/s)	Note
0.3	0.305	0.00	0.00	Pier edge RB
0.7	0.564	0.01	0.01	
0.9	1.189	0.08	0.08	
1.3	1.128	0.155	0.19	
2.0	0.914	0.29	0.25	
2.5	0.823	0.40	0.4	
3.0	0.732	0.37	0.32	
3.5	0.610	0.53	0.54	
4.0	0.561	0.44	0.43	
4.5	0.518	0.37	0.41	
5.0	0.472	0.34	0.3	
5.5	0.411	0.24	0.27	
6.0	0.366	0.26	0.25	
6.5	0.335	0.19	0.19	
7.0	0.305	0.07	0.07	
7.5	0.244	0.03	0.05	
8.0	0.091	0.02	0.01	
9.5	0.000	0.00	0.00	LEW

Table 2-2. Discharge measurement December 12, 2005.

[Discharge measurement notes transcribed from field book, note: English units translated to metric, frzn = frozen, WSL = water surface level, xsec = transect, UTM = universal transverse Mercator.]

Start Time 10:18 a.m.
End Time 10:50 a.m.
Marsh # s/n 2003632
Q xsec located in partially open water from approximate UTM locations
437666 4507048
to 437664.5 4507041.5
width: 6.67 meters
Area adjusted for ice, measured through chopped holes where covered
Station 0 solid ice N. side

Station (m)	Depth (m)	Velocity (m/s)	Distance from stream bed to bottom of ice (m)	Velocity depth	Calculated ice thickness (m)	Notes
0.00	-	-			0.25	frzn to bed
1.20	0.00	-			0.33	frzn to bed
1.70	0.39	0.00	0.28	0.5d	0.11	
2.35	0.40	0.57	0.28	0.5d	0.12	
3.00	0.49	1.05		0.6d		open
3.50	0.45	0.95		0.6d		open, WSL = top of ice
4.00	0.50	0.65		0.6d		open
4.50	0.43	0.60	0.29	0.5d	0.14	
5.00	0.40	0.28	0.25	0.5d	0.15	
5.50	0.37	0.05	0.03	0.5d	0.34	
6.50	0.25	-			0.25	frzn to bed

Table 2-3. Discharge measurement January 24, 2005.

[Discharge measurement notes transcribed from field book, note: English units translated to metric, velocity depth as fraction of active depth (to bottom of ice), frzn = frozen, L. Pin @ Root = left bank zero location at a root near the top of the bank.]

Start Time: 11:40 a.m.
End Time: 12:25 p.m.
Marsh McBirney # 2003632
Note; water depth under ice is the distance between bottom of ice and bed
Depth of ice is measured to top of water
(1) L. Edge of channel before ice was removed
(2) R. Edge of channel before ice was removed
Clarification: these references are to edges of open lead

Station (m)	Depth of flow(m)	Velocity (m/s)	Measured ice thickness (m)	Velocity depth	Notes
0.000					L.Pin @ root
0.305					edge of ice
4.572					edge of bar
5.913					edge of bar/ice
9.266					frzn to bed
9.754	0.091	0.000	0.366	0.5d	under ice
10.211	0.213	0.366	0.274	0.2d	"
				0.8d	
10.668	0.244	0.480	0.305	0.2d	"
				0.8d	
11.125	0.457	0.792		0.6d	open water (1)
11.582	0.518	0.564		0.6d	open
12.040	0.488	0.579		0.6d	open water (2)
12.497	0.457	0.433	0.183	0.6d	under ice
13.106	0.152	0.000	0.366	0.2d	"
				0.8d	
13.564	0.061	0.000	0.518	0.5d	"
14.173	0.000		0.610	0.5d	frzn to bed
16.764					edge of ice

Table 2-4. Discharge measurement February 23, 2005.

[Discharge measurement notes transcribed from field book, note: English units translated to metric, Velocity depth as fraction of active depth (to bottom of ice), L. Edge = left edge, R. edge = right edge, Est = estimated, over ice = ice that has formed after water flowed over the established ice surface.]

Start Time: 12:15 p.m.
End Time: 12:48 p.m.
Marsh McBirney #2003632
stationing faces upstream

Station (m)	Depth (m)	Velocity (m/s)	Measured ice thickness (m)	Velocity depth	Notes
0					L. edge ice at bank
0.5		0	0.34		ice to bed
0.75	0.400	0	0.31		edge of water
1.05	0.427	0.56	0.15	0.6d	4 cm over ice
1.55	0.518	0.86	0.08	0.6d	2 cm over ice
2.05	0.518	0.88	0.22	0.6d	2 cm over ice
2.55	0.488	0.76	0.11	0.6d	2 cm over ice - edge open water
3.05	0.488	0.74		0.6d	open water
3.9	0.579	0.5	0.31	0.6d	3 cm over ice - edge open water
4.35	0.518	0.02	0.44	0.6d	2 cm over ice
4.85	0.430	0	0.33		3 cm over ice
5.5					est ice to bed
9.3					R. edge of ice at bar

Appendix 3. Ice Thickness Measurements January 24, 2006

Table 3-1. Cross Section 1 from survey grade Global Positioning System (GPS).

[GPS: UTM Zone 13 N, Datum: WGS 1984, UTM = universal transverse Mercator, WGS 1984 = world geodetic system 1984 standard ellipsoid, Stationing adjusted to match tagline measurements, point names and controller notes as logged in field, xsl = transect line, lie = left edge of ice, rie = right edge of ice, mid chl = mid–channel, wsl = water surface elevation.]

Point	X	Y	Z (m)	Controller notes	Station (m)
012406p1	437663.577	4507049.964	2356.221	xs1 lie	7.500
012406p13	437663.544	4507049.858	2356.172	xs1 lie 23	7.611
012406p2	437662.989	4507047.905	2356.138	xs1 top ice	9.641
012406p6	437662.641	4507046.424	2356.123	xs1 top ice	11.162
012406p9	437662.147	4507044.194	2356.119	xs1 top ice	13.445
012406p11	437661.956	4507042.659	2356.149	xs1 ice to bed	14.983
012406p12	437661.672	4507040.353	2356.197	xs1 rie	17.298
012406p5	437662.845	4507046.620	2355.926	xs1 bot ice	10.923
012406p8	437662.167	4507044.095	2355.848	xs1 bot ice	13.536
012406p4	437663.158	4507047.745	2355.631	xs1 bed	9.758
012406p7	437662.465	4507045.363	2355.507	xs1 mid chl	12.233
012406p10	437662.056	4507042.647	2355.673	xs1 bed	14.973
012406p3	437663.009	4507047.903	2356.060	xs1 wsl	9.638
012406p14	437662.561	4507046.152	2356.027	xs1 wsl	11.445

Table 3-2. Cross Section 1 from tag line.

[Top of Ice elevations obtained by calculating best fit to GPS data, bottom of ice by subtracting thickness, L. Pin @ Root = left bank zero location at a root near the top of the bank, frzn = frozen, edge of ice = location where earth, sand or gravel bank intersected with ice cover.]

Station (m)	Depth (m)	Calculated elevation (m)	Ice thickness (m)	Top of ice (m)	Point notes	Bottom of ice (m)	WSL (m)
0.000					L.Pin @ root		
0.305		2356.120	0.000		edge of ice		
4.572		2356.220			edge of bar		
5.913		2356.120	0.000	2356.220	edge of bar/ice	2356.120	
9.266		2355.721	0.399	2356.142	frzn to bed	2355.721	
9.754	0.091	2355.663	0.366	2356.137	under ice	2355.754	
10.211	0.213	2355.632	0.274	2356.131	"	2355.846	
10.668	0.244	2355.571	0.305	2356.125	"	2355.815	
11.125	0.457	2355.663		2356.120	open	2356.120	2356.059
11.582	0.518	2355.602		2356.120	open		2356.059
12.040	0.488	2355.632		2356.120	open	2356.120	2356.059
12.497	0.457	2355.480	0.183	2356.120	under ice	2355.937	
13.106	0.152	2355.602	0.366	2356.120	"	2355.754	
13.564	0.061	2355.541	0.518	2356.120	"	2355.602	
14.173	0.000	2355.510	0.610	2356.128	frzn to bed	2355.510	
16.764		2356.120	0.000	2356.197	edge of ice	2356.120	

Table 3-3. Cross Section 2 from survey grade Global Positioning System (GPS).

[GPS: UTM Zone 13 N, Datum: WGS 1984, UTM = universal transverse Mercator, WGS 1984 = world geodetic system 1984 standard ellipsoid Stationing adjusted to match tagline measurements, point names and controller notes as logged in field, xs 2 = transect 2 , i = ice thickness in cm, d = depth from ice surface to bottom in cm, ice bottom and bed elevations obtained by subtracting thickness and depth from ice top elevation.]

Point	X	Y	Ice top (m)	Controller notes	Station (m)	Ice bottom by subtraction (m)	Bed by subtraction (m)
012406p26	437598.364	4507088.309	2356.581	xs 2 i24 d 0	1.562	2356.341	2356.341
012406p25	437598.407	4507087.536	2356.581	xs 2 i47 d 93	2.334	2356.111	2355.651
012406p24	437598.427	4507087.540	2356.581	xs 2 i47 d 93	2.336	2356.111	2355.651
012406p23	437598.382	4507087.156	2356.574	xs 2 i28 d 93	2.711	2356.294	2355.644
012406p22	437598.362	4507086.554	2356.596	xs 2 i20 d101	3.305	2356.396	2355.586
012406p21	437598.730	4507085.150	2356.581	xs 2 i20 d 98	4.745	2356.381	2355.601
012406p20	437598.657	4507085.212	2356.577	xs 2 i20 d 98	4.816	2356.377	2355.597
012406p19	437598.722	4507085.142	2356.577	xs 2 i38 d 88	4.893	2356.197	2355.697
012406p18	437598.748	4507084.800	2356.576	xs 2 i36 d 83	5.236	2356.216	2355.746
012406p17	437598.776	4507084.381	2356.583	xs 2 i50 d 77	5.655	2356.083	2355.813
012406p16	437598.848	4507083.906	2356.590	xs 2 i50 d64	6.135	2356.090	2355.950

Table 3-4. Cross Section 3 from survey grade Global Positioning System (GPS).

[GPS: UTM Zone 13 N, Datum: WGS 1984, UTM = universal transverse Mercator, WGS 1984 = world geodetic system 1984 standard ellipsoid Stationing adjusted to match tagline measurements, point names and controller notes as logged in field, xs 2 = transect 2 , i = ice thickness in cm, d = depth from ice surface to bottom in cm, ice bottom and bed elevations obtained by subtracting thickness and depth from ice top elevation.]

Point	X	Y	Ice top (m)	Controller notes	Station (m)	Ice bot by subtraction (m)	Bed by subtraction (m)
012406p38	437532.084	4507073.649	2356.954	xs3i54d 7.6f	6.515	2356.414	2354.638
012406p37	437533.741	4507071.367	2356.910	xs3i66d 7.2f	9.334	2356.250	2354.715
012406p36	437535.665	4507068.832	2356.913	xs3i60d 5.5f	12.517	2356.313	2355.237
012406p35	437537.932	4507066.173	2356.902	xs3i46d 5.5f	16.007	2356.442	2355.226
012406p34	437539.362	4507064.292	2356.934	xs3i51d 3.8f	18.369	2356.424	2355.776

Table 3-5. Cross Section 4 from survey grade Global Positioning System (GPS).

[GPS: UTM Zone 13 N, Datum: WGS 1984, UTM = universal transverse Mercator, WGS 1984 = world geodetic system 1984 standard ellipsoid Stationing adjusted to match tagline measurements, point names and controller notes as logged in field, xs 2 = transect 2 , i = ice thickness in cm, d = depth from ice surface to bottom in cm, ice bottom and bed elevations obtained by subtracting thickness and depth from ice top elevation.]

Point	X	Y	Ice top (m)	Controller notes	Station (m)	Ice bot by subtraction (m)	Bed by subtraction (m)
012406p27	437525.741	4507054.530	2357.067	xs 4 lie	0.000	2356.950	2356.950
012406p28	437528.352	4507055.054	2357.018	xs 4 icetobed	2.614	2356.830	2356.830
012406p29	437529.292	4507055.324	2356.934	x4icetobed37	3.556	2356.564	2356.564
012406p30	437531.950	4507055.204	2357.002	xs4 i44 d59	6.213	2356.562	2356.412
012406p31	437533.116	4507055.241	2356.974	xs4 i37 d89	7.379	2356.604	2356.084
012406p32	437533.761	4507055.273	2356.952	xs4 i38 d88	8.024	2356.572	2356.072
012406p33	437534.707	4507055.183	2357.013	xs4 i2 d92	8.970	2356.813	2356.093