EFFECTS OF FRAZIL ICE ON FISH

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ABSTRACT

During winter, frazil ice poses a threat to trout living in turbulent, high gradient streams both through direct physiological effects and by causing rapid and profound changes in habitat. The formation of frazil ice in turbulent, montane streams has a disjunct spatial distribution, varying with gradient, ground water input, and air temperatures.

As frazil ice crystals form and grow in supercooled water, they could directly affect the respiratory system of trout. When the ice crystals are small, they could abrade the gills leading to hemorrhage and as they grow and aggregate, they could plug gill rakers necessitating frequent coughing. At high enough densities, frazil ice could lead to suffocation.

Frazil ice may cause detrimental effects to habitat by aggregating on woody debris and on substrate to form anchor ice. The blanketing of these structures and plugging of interstices forces trout out of protective habitats that serve as cover during early fall. In some sections of the stream frazil and anchor ice may form ice dams which can lead to rapid localized fluctuations in water depth and habitat availability. The sudden break up of these dams can cause fish to be trapped, abraded, or crushed by ice.

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Whether trout populations can survive under conditions of frazil ice formation appears to depend on the presence of certain physical features and/or hydraulic regimes in the stream. Starting as early as September, trout in montane streams abandon their summer territorial behavior and aggregate in deep pools with a large amount of cover and low water velocity. As winter sets in, only a small portion of the total habitat in these systems may be suitable for overwintering. When frazil ice formation occurs, and anchor ice fills the pools which contain woody debris, trout are forced to move elsewhere. In ground water fed systems, trout find refuge from frazil ice near warm ground water inputs. Trout also avoid frazil ice by staying in stream sections with thick insulation provided by ice or snow cover. To avoid frazil ice or the sudden rush of ice and water during breakup of ice dams, fish also reside in pools with streaming flow or stay behind structures that deflect the current.

INTRODUCTION

During the winter, frazil ice poses a threat to trout living in turbulent, high gradient streams both through direct physiological effects and by causing rapid and profound changes in habitat. There are many valuable montane trout fisheries which may be affected by frazil ice formation and yet little is known about its effects on fish. In fact, the factors determining when and where frazil ice will form in a stream are not well understood (Lawson and Brockett, 1990). It is unlikely that trout can breath water containing frazil ice, since the spicule or discoid crystals would plug gill rakers and abrade delicate gill tissue leading to hemorrhage and frequent coughing by fish. Tack (1938) reported trout being suffocated when frazil ice formed in the upper layer of a German pond during a very windy, cold, clear night. Frazil ice formation also affects the spatial habitat quality and availability by displacing trout from favorable habitat through the formation of anchor ice.

Supercooling and consequently frazil and anchor ice formation routinely occur in turbulent, high gradient rivers subject to temperatures below $0^{o}C$. Frazil ice is formed when turbulent water at $0.0^{o}C$ undergoes further heat loss to the atmosphere (Ettma *et al.*, 1982; Lawson and Brockett, 1990; Shumway and Springer, 1992). When the water is supercooled, nucleation of small (0.1-1 mm) discoid or spicule shaped ice crystals (known as frazil ice) can occur in the water column (Andres, 1982; Ettma *et al.*, 1982; Lawson and Brockett, 1990; Shumway and Springer, 1992). While the water is supercooled, frazil ice crystals continue to grow and stick to one another forming aggregates or flocs (Lawson and Brockett, 1990). Frazil ice crystals also stick to any submerged object they come in contact with, forming anchor ice (Andres, 1982; Shumway and Springer, 1992). While being transported downstream, frazil ice may be deposited along the shorelines or at barriers in the river but after surface ice cover formation, it is also deposited at the leading edge of the ice and under it where flows are low (Lawson and Brockett, 1990; Shumway and Springer, 1992).

Trout gills may be effected by high concentration of frazil ice crystals just as they are by two harmful diatom species *Chaetoceros concavicornis* and *C. convolutus* which are much smaller than frazil ice. Yang and Albright (1992) described how the barbed spines of these diatoms became wedged in the gills of rainbow trout (*Oncorhynchus mykiss*) and penetrated the lamellar cells. This caused excess mucus production, hemorrhage, as well as hypertrophy and hyperplasia of respiratory epithelium which physically limited gill function.

Large fluctuations in water depth can occur in rivers and streams as a result of the formation and breakup of ice dams formed from the accumulation of frazil and anchor ice

(Maciolek and Needham, 1952; Shumway and Springer, 1992). Conditions related to ice damming have been reported to be a major cause of winter mortality in salmonid fish (Maciolek and Needham, 1952). Anchor ice can build to such heights that it dams rivers and streams. While dam formation is occurring, water depth increases upstream of the dam, and decreases below the dam, resulting in dewatering of some fish habitat. On one January day, in a high elevation (2200 m) California mountain stream, Maciolek and Needham (1952) found 63 trout lying on the rocks in dewatered pools and several other instances of this type were observed on other dates. Dewatering of some stream sections is also caused by a lowering of the water table due to a large percentage of the streams discharge being locked up as ice and a lack of run-off during winter. Other possible causes of ice related fish mortality are ice dam break-up, anchor ice filling the entire water column, and collapsing ice shelves and snow banks (Shumway and Springer, 1992). Incubating fish eggs of fall spawning species can also be damaged or displaced by anchor ice when it freezes the bottom, exposes eggs after detaching substrate materials, or dewaters the redds (Benson, 1955; Harvey and Ashwood-Smith, 1982; Calkins, 1989; Shumway and Springer, 1992).

Winter habitat use by trout has been studied in several geographical areas, but only a few studies have been done in areas where winter temperatures are sufficiently low that frazil and anchor ice formation occurs on a regular basis. Anchor ice was occasionally seen in two of three southern Ontario streams in which Cunjak and Power (1986) studied winter habitat use by trout. Eighty-six percent of the brook trout (*Salvelinus fontinalis*) and brown trout (*Salmo trutta*) they observed by snorkeling, were in winter aggregations. Of the 19 aggregations they found, 18 were found in locations where ground water discharge kept the areas 2-6°C warmer than the rest of the streams. The aggregations were in pools or glides which contained more cover than the habitat the fish used in summer. Snorkeling, however, is not a suitable method for data collection when ice cover is present in the study area, since one can not snorkel under ice cover. The only places snorkeling can be used to a large degree for winter studies is in mild climates or in areas where ground water input prevents surface ice formation.

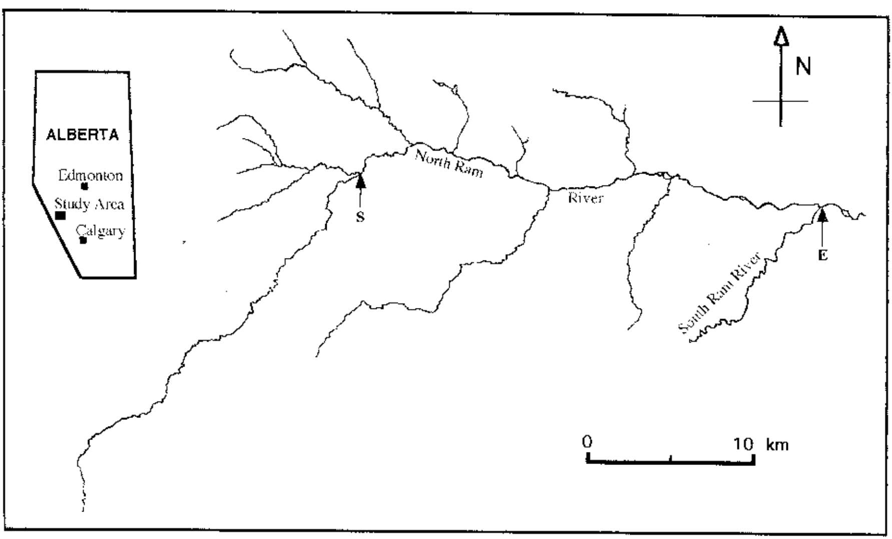
The use of radiotelemetry permits the evaluation of winter habitat use independent of ice cover. Using radiotelemetry, Chisholm and Hubert (1987) found that in winter, trout living in mountain streams used areas of low water velocity and cover in the low gradient sections of the stream where they were tagged. While some stream sections in their study area had severe stream conditions, including frazil and anchor ice, they only studied trout that resided above 2990 m where the streams where insulated from supercooling by snow bridging.

While trout have been studied in areas with severe winter conditions, they were all in low gradient areas and no direct effects of frazil or anchor ice were reported. We designed a study to evaluate habitat use by trout in a relatively high gradient mountain stream, where a variety of ice conditions exist during the winter. Radio telemetry was used to determine the responses of trout to frazil and anchor ice development.

STUDY AREA

The study was conducted on the North Ram River in west-central Alberta (Figure 1). The river originates at an elevation of 2130 m in the Ram Range of the Rocky Mountains and flows eastward as a tributary of the Ram River, which is part of the North Saskatchewan River drainage. The North Ram River has a drainage area of 736.6 square kilometers and an average gradient of 10.9 meters per kilometer over its entire length. The

Figure 1. Map of the North Ram River drainage showing the location of the start-S (latitude, 52°16'N; longitude, 116°03'W) and the end-E (latitude, 52°15'N; longitude, 115°39'W) of the study section.

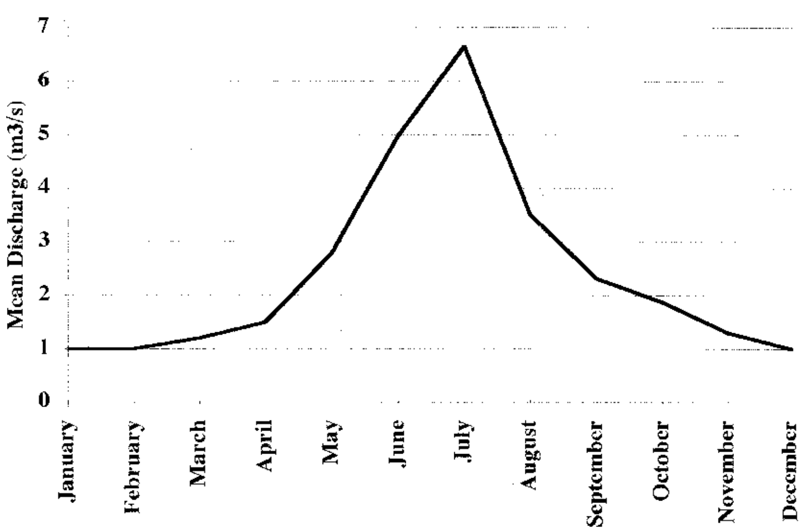


area is characterized by hilly to mountainous terrain with white spruce and lodgepole pine dominating the tree species. The exception is the river valley itself, where open areas provide suitable habitat for shrubs and grassy vegetation.

The 35 km study section was located on the lower half of the North Ram, starting at the confluence with Kiska Creek (latitude, 52°16'N; longitude, 116°03'W) and ending at its confluence with South Ram River (latitude, 52°15'N; longitude, 115°39'W) (Figure 1). The average gradient over the study section is 7.14 meters per kilometer. The study section is characterized by a naturally meandering stream bed with shallow gravely and cobbley riffles, deep pools that have little silting, and occasional log jams.

The North Ram River drainage has a substantial introduced population of cutthroat trout (*O. clarki*). Other fish species include longnose suckers (*Catostomus catostomus*), longnose dace (*Rhinichthys cataractae*), and brook stickleback (*Culaea inconstans*). Due to frequent fluctuations in water level, that are particularly evident in the spring and early summer (Figure 2), the quality of trout habitat also frequently changes both in a spatial and a temporal sense. Mean water discharge decreases from 6.65 m^3/sec. in July to 1.87 m^3/sec. in October. From year to year, erosion of banks, accumulation of woody debris,

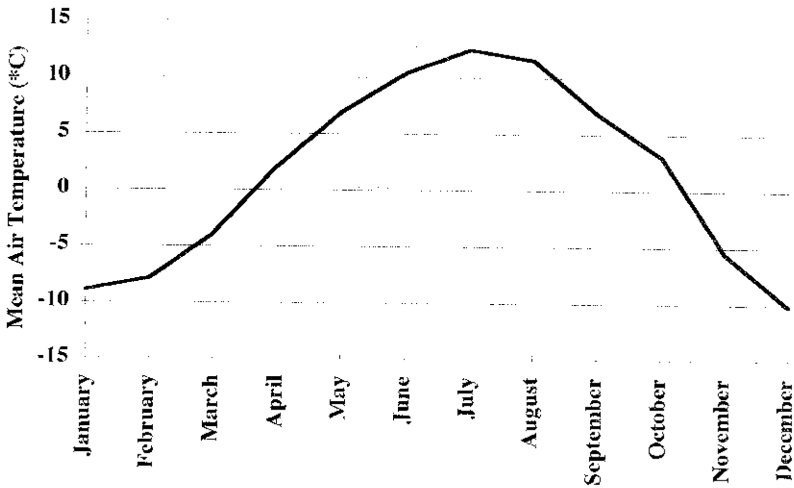
Figure 2. Mean monthly water discharge (m^3/s) in the North Ram River as measured by the Environment Canada water gauging station no.05DC011 located in the study section. The monthly means were calculated from 1981-1990 historic data from the gauging station.



and shifts in gravel bars during high flows in spring and early summer determine the habitat quality later in the fall and winter.

The warmest month of the year in the study area is July when mean air temperature reaches 12.4°C and the coldest month of the year in the study area is December when mean air temperature is only -10.2°C (Figure 3). Mean annual snowfall varies from 126-236 cm (over last 10 years). The entire discharge of the river in winter is from the ground water input since there is almost no run off from November to April of each year. Surface ice formation on the river usually starts in late October to early November and the minimum water temperature of 0.0°C is also reached at that time.

Figure 3. Mean monthly air temperature (°C) in the North Ram River area as determined from 1980-1989 data from Environment Canada weather stations at Ram Falls (30 km south of the study area) and Nordegg (30 km north of study area).



METHODS

Twenty-three trout for implantation of radio transmitters were captured by angling between October 2 to October 31, 1992. Fish were anaesthetized with 200 mg/liter solution of tricaine methane-sulfonate. A radio transmitter was surgically implanted in the body cavity of each fish using a procedure similar to Bidgood (1980) and Hop *et. al.* (1986). A 1-2 cm incision was made on the ventral side of the fish, anterior and slightly dorsal to either of the pelvic fins. The transmitters were dipped in beeswax before insertion to reduce irritation. The incision was closed with three individual sutures using OO silk.

Two types of transmitters were used to monitor fish movements. Advanced Telemetry Systems Inc. (ATS) Model 393 transmitter weighed 3 grams in air and had an estimated life of 50 days and ATS model 397 weighed 4 grams and had an estimated life of 100 days. Both types of transmitters had a pulse rate of about 1 pulse per second. An ATS Fieldmaster radio receiver was used to monitor the individual 150.000 to 150.160 MHz frequencies of transmitters. Trout locations were fixed with a three element YAGI antennae. The fish were located every second day until the end of the December. When each radiotagged fish was located, we recorded the type of habitat the trout used, ice conditions and water temperatures in the vicinity. We also surveyed the river for ground water input as revealed by thermal anomalies, ice conditions, and open water occurrence.

Daily maximum and minimum water temperature (^{o}C) and discharge (m^3/s) were also obtained. Water temperature was measured to the nearest 0.5^{o}C using a Ryan thermograph that was placed about 50 cm underwater in the upper portion of the study section. Thermal anomalies and localized temperatures were measured to the nearest 0.1^{o}C using a digital thermometer (Fisher Scientific) with a thermoresistor at the end of a 3 m cable. Water flow rate was supplied by Environment Canada, Water Survey Branch in Calgary from station no. 05DC011 which is located on the study section, 32 km upstream from the mouth of the North Ram River. Air temperature and precipitation data were obtained from Environment Canada weather stations at Ram Falls (30 km south of the study area) and at Nordegg (30 km north of the study area).

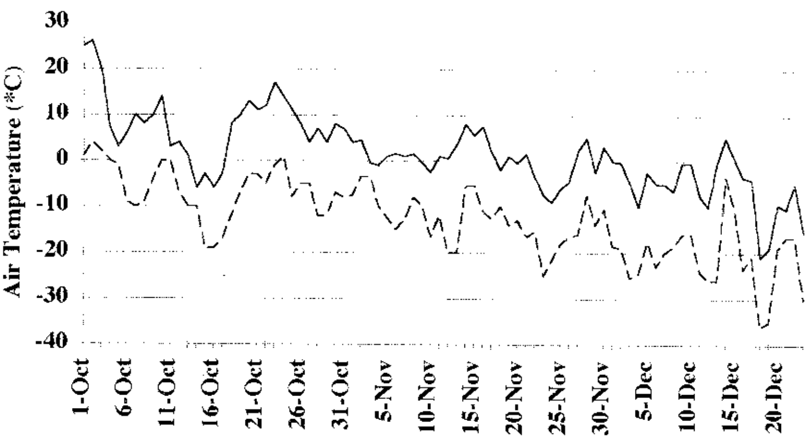
In the second and third week of December, six pools in the ice free section of the study area were surveyed for depth (m) and bottom water temperature (^{o}C). Three pools where trout were not overwintering, were randomly chosen for sampling. We also surveyed three more pools, where trout were found overwintering. Transects were run perpendicular to a baseline on the south shore of the stream. The baseline was parallel to the pool. At every meter along each transect, depth and bottom temperatures were recorded.

RESULTS

The major effect frazil and anchor ice formation had on trout habitat use in late fall, and early winter was to cause fish to shift from relatively deep pools containing large amounts of cover, in the form of woody debris, to areas with ground water input or areas having large, ice covered pools, which lacked woody debris.

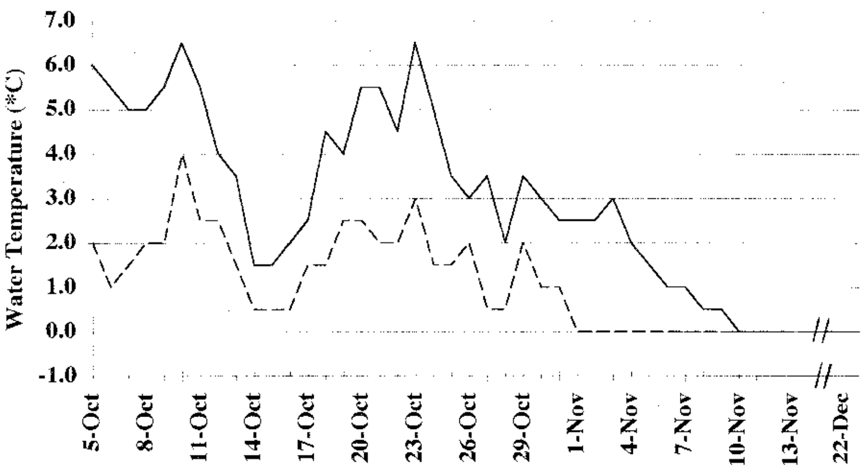
In early fall, cutthroat trout were found in large, deep pools which contain large amounts of cover in the form of woody debris composed of log jams and beaver caches. Although, there were no beaver dams on the mainstream of the North Ram River, most of the pools had beaver caches. The woody debris in these pools was dense, providing good cover from predators during early fall. Ironically, the presence of woody debris which the trout preferred in early fall, made these pools unsuitable for overwintering. As air temperatures decreased, frazil and consequently anchor ice regularly formed. Frazil and anchor ice was first observed on November 6, 1992 when the minimum air temperatures reached -15^{o}C, this was the third consecutive night that the minimum air temperature was at or below -10^{o}C (Figure 4). The minimum water temperature dropped to 0.0^{o}C on November 1 and the maximum water temperature on November 6 was only 1.0^{o}C (Figure 5). When frazil ice formed during the night, it stuck to woody debris and the substrate to form anchor ice. Early in November, anchor ice melted with increasing morning temperatures. Later in November, increasingly colder daytime temperatures kept anchor ice from melting, allowing large accumulations in some stream sections.

Figure 4. Maximum (–) and minimum (- -) daily air temperature (^{o}C) in the North Ram River area from October 1, 1992 to December 23, 1992. The temperatures were obtained by averaging the daily maximum and minimum air temperatures from Environment Canada weather stations at Ram Falls (30 km south of the study area) and Nordegg (30 km north



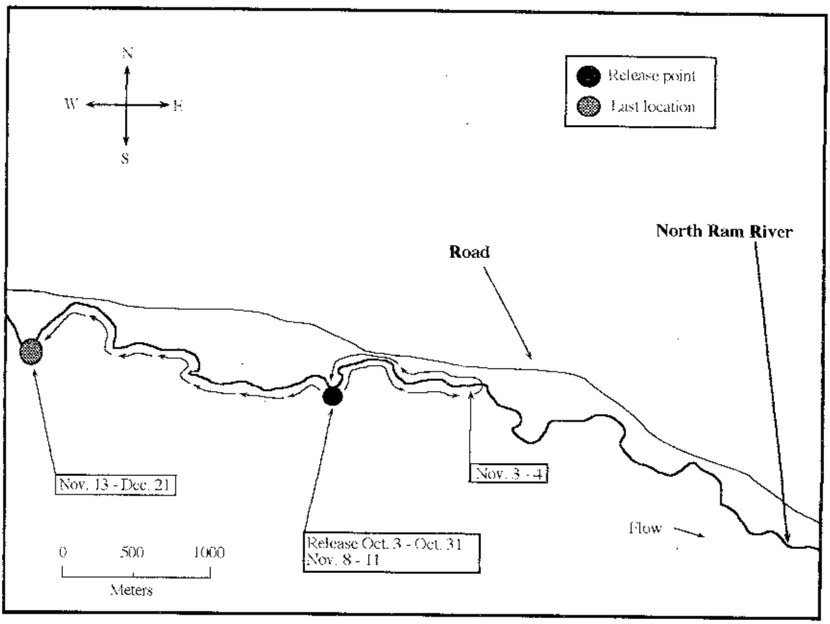
When frazil ice formed, it accumulated on submerged objects and the stream bottom as anchor ice, this coincided with changes in fish behavior. Areas with a large number of submerged objects accumulated more anchor ice than areas without. Large amounts of anchor ice were observed in the pools where trout aggregated in early fall, these pools contained large quantities of submerged woody objects (whole trees, logs, branches, etc.). As these pools filled with anchor ice, the trout were forced to find alternative habitat in other areas. Therefore, fish were forced to overwinter elsewhere and there was a net movement of trout out of these pools coinciding with increased accumulation of anchor ice in November.

Figure 5. Maximum (–) and minimum (- -) daily water temperature (°C) in the study section of the North Ram River from October 5, 1992 to December 23, 1992. Note, the Ryan thermograph was placed in an area not influenced by ground water input.



The movement of trout occurred over a one month period between mid October and mid November, because the time of formation and amount of anchor ice formed varied throughout the study area. Some areas were filled by anchor ice later than others due to the influence of warm ground water discharge nearby. The distance downstream of a warm goundwater discharge, where water reached supercooling temperatures, was also a function of air temperatures. If the pool was not within a stream section which was influenced by warm ground water discharge, the trout were excluded from that pool by anchor ice relatively early. In areas where ground water influx was present and open water existed, the first place where anchor ice accumulated and excluded trout habitat was furthest downstream from the ground water source. As anchor ice accumulations reached the air-water interface, the water velocity decreased promoting surface ice formation and damming. With continuing cold temperatures, the front of accumulating anchor ice and surface freeze-up traveled upstream towards the ground water source. As the front passed through the pools that were closer to warm water influx, the fish were forced out of these pools. This happened as late as mid November (Figure 6). Upstream movement of the ice front would continue until the warm ground water upstream would prevent the formation of frazil ice. In some river sections with ground water influx, there existed a transition zone, where the front of accumulated anchor ice and surface ice would travel up and down the river periodically freezing over and breaking up depending on fluctuating air temperatures. In one area of the river, ice was present above and below a warm ground water source leaving only an approximately 100 m transition zone around the ground water source. This area would have anchor and surface ice present when air temperatures cooled

Figure 6. Individual movement behaviour of one cutthroat trout (*Oncorhynchus clarki*) in the North Ram River. The fish was implanted with a radio transmitter on October 2, 1992 and tracked until December 20, 1992. The arrowed lines follow movements of the fish between locations labeled in boxes.



and would open as air temperatures warmed. This was one of the overwintering areas for an aggregation of trout which included two radiotagged fish.

After trout were excluded from the pools where they aggregated during early fall, they moved to habitats where they could avoid frazil and anchor ice. Frazil and anchor ice was not observed in areas covered by surface ice and snow or in areas where warm water influx kept water temperature above 0.0°C. Therefore, trout overwintered in either large deep pools which were covered with surface ice and lacked woody debris or areas where water temperatures were kept above 0.0°C by ground water. Where ground water input was present, fish were able to use pools and glides that contained woody debris and with maximum water depths as low as 8 cm. However, even when ground water input was present and areas were kept free of surface ice, overwintering trout used deeper and warmer pools (Table 1). There was a significant difference between the sums of temperatures and depths for pools used by overwintering fish and pools that were not utilized by overwintering fish ($p<.05$, t-Test: Two-Sample Assuming Unequal Variances). By the end of December 1992, most (77%) radiotagged trout were in areas influenced by warm ground water discharge. The remaining (23%) fish were in pools covered with surface ice. In these areas, surface ice acted as an insulating blanket reducing radiant heat loss, thus the water did not become supercooled and frazil ice did not form. Despite the presence of ice cover, none of the trout in these areas used pools which contained woody debris as cover, only a few (1%) trout in areas of ground water input used woody debris as cover. Occasionally, in areas of ground water input, trout were seen using ice shelves extending from the banks as cover.

Table 1. Summary of depth (m) and temperature (°C) for six pools in a section of the North Ram River which was free of surface ice, conducted from December 10 to December 22. Pools 1-3 were randomly selected and were not used by overwintering trout. Pools 4-6 were used by overwintering trout.

Pool	Mean Depth (m)	Max. Depth (m)	Mean Temp. (*C)	Max. Temp. (*C)	Sum
1	0.50	1.40	0.00	0.00	1.9
2	0.40	1.00	0.76	1.50	3.7
3	0.31	0.81	0.54	0.60	2.3
4	0.70	2.00	0.46	0.60	3.8
5	0.50	1.20	0.79	2.30	4.8
6	0.48	1.04	1.95	2.60	6.1

We observed mortality of trout due to harsh winter conditions during a preliminary survey in 1991 as well as in 1992. We found a total of ten dead trout which were killed in two separate events. The first occurrence was in October 1991. In this instance, 9 fish were found, 7 in a 50 m long glide downstream of a large plunge pool, and 2 were found in the riffle upstream of the same pool. One dead trout was found on December 19, 1992. This trout was found in a long riffle which was upstream of a plunge pool which was used by a large aggregation of overwintering trout. In all cases, there was no evidence of physical damage to the exterior of the fish. We also examined the gills and saw no visible damage. All of the fish were juveniles (less than 10 cm) and were found dead after cold spells during which minimum air temperature dropped below minus 25°C (Figure 4).

We also noted other winter related injuries to one radio tagged fish (296 mm long, 268 g) which was trapped in a riffle about 50 m long, where a small amount of 2.6°C ground water was upwelling. The water temperature in this riffle varied from 1.0°C to 2.6°C depending on air temperature. The stream was dammed and frozen to the bottom, both upstream and downstream of the warm water input. This area had ice shelves extending 20-50 cm from the stream banks and completely covering the stream in one section. The fish used these ice shelves for cover, even though they frequently collapsed. When water level dropped to only a few centimeters, we noticed scratch marks on the lateral surface of the radiotagged fish.

DISCUSSION

In the North Ram River, trout made a distinct shift in habitat use during early winter. This occurred when frazil and anchor ice first appeared in the areas where trout had earlier aggregated. The formation of frazil and anchor ice in trout streams has been reported by others (Maciolek and Needham, 1952; Needham and Jones, 1959), but direct shifts in habitat use associated with frazil and anchor ice formation have not been documented. The appearance of these ice forms in our study excluded fish from overwintering habitat that had a relatively large amount of cover in the form of woody debris. Instead, the trout in our study used habitat which was often devoid of cover. This is in contrast to the great importance of cover use in winter found by other workers (Cunjak and Power, 1986, 1987; Heggenes *et. al.,* 1991; Meyers *et. al.,* 1992).

Trout moved to overwintering areas in direct response to the formation of frazil and anchor ice in their local environment. Since the timing of frazil and anchor ice formation varied over the study section as a result of differential ground water input, the timing of movements to overwintering areas also varied. In areas where warm water influx kept surface ice from forming there was a transition zone between ice covered and ice free areas. This situation may be common during winter below man made dams and weirs on high gradient rivers. In these areas, the turbulent water released from dams is typically above zero, often at 4°C and may produce massive amounts of frazil ice downstream as it supercools. In transition areas between open water and ice cover, fish survival could be very tenuous and just enough warm water may be available to keep the fish from being overcome by ice.

We found a majority (77%) of trout using areas of ground water influx during winter. The importance of this habitat is also supported by Cunjak and Power (1986) who found 18 of 19 aggregations of brook and brown trout in water 2.0-6.0°C warmer than the rest of the stream. The trout in our study were able to use water depths of only 8 cm when ground water influx was present. Cunjak and Power (1987) also argued that water depth is not a primary criterion for winter habitat selection. However, they said that it becomes important where it provides cover or is associated with reduced flows.

Some (23%) of the trout overwintered in pools covered with surface ice. All of these fish were in the lower part of the study sections where surface ice cover was dominant. This is similar to the habitat that brook trout used in Wyoming streams (Chisholm and Hubert, 1987), where trout overwintered in beaver dams and stream sections covered with snow. In areas with surface ice or snow cover, trout are protected from supercooled water temperatures and predators.

In the lower half of the study section, we found little anchor ice because the river was mostly covered with surface ice, however, anchor ice did occur in riffles where flow was fast enough to prevent surface ice formation. Frazil ice can form in these open riffles and get carried downstream where it can accumulate under surface ice covering pools and glides. In the ice covered river sections, frazil ice can adhere to the bottom of the surface ice and thick layers of ice build downward into the pool forming a hanging dam (Tsang, 1982). The fish in such a pool would be forced to search for new habitat while the water column is filled with frazil ice. The effects of this phenomenon on fish should be examined since it could be a major cause of winter mortality. Although we did not observe hanging dams in our study due to surface ice cover, we think that mortalities related to hanging dams could be avoided if fish overwintered in pools which were not near open riffles, or in pools which did not have submerged woody debris present. The presence of woody debris in pools should increase the buildup of hanging dams. Frazil ice should coat the submerged woody debris in these pools, just as it did in the pools which trout used in early fall. The coating of woody debris with frazil and consequently anchor ice would accelerate the hanging dam buildup and this may be the reason why the ice covered pools which trout used during winter were devoid of submerged woody debris.

The presence of frazil ice may have caused direct mortality. Ten trout were found dead on the bottom of the river. Since there were no signs of crushing or epidermal damage, we suspect they were either directly suffocated by frazil ice, as Tack (1938) found, or froze in the cold air when they were trapped in dewatered pockets caused by the formation or break up of the dams. There was no evidence that the stream was dewatered in the immediate vicinity causing mortalities as Maciolek and Needham (1952) found. However, the dead fish we found could have been carried some distance downstream after their death. Fry and juvenile fish may be more vulnerable to suffocation by frazil ice since their mouth are smaller and are probably more easily plugged with ice crystals than those of larger fish. Trout gill function may be adversely affected by frazil ice crystals between 0.1 to 1 mm in diameter. Yang and Albright (1992) described how the barbed spines of two diatom species (*C. concavicornis* and *C. convolutus*), which are much smaller than frazil ice crystals, became wedged in the gills of rainbow trout (*O. mykiss*) and penetrated the lamellar cells. This caused excess mucus production, hemorrhage, as well as hypertrophy and hyperplasia of respiratory epithelium. Any sort of abrasions or punctures of the epithelial tissue of gills might also promote the intracellular freezing of fish when trout gills encounter supercooled water and have contact with ice (Valerio *et. al.*, 1992). However, this can only occur in saltwater dwelling salmonids and no freshwater populations of fish would be affected since the freezing temperature of freshwater is very close to 0.0°C. Incubating fish eggs of fall spawning species can also be damaged or displaced by anchor ice. As anchor ice breaks up and lifts from the bottom, it detaches substrate materials and exposes the eggs. The build up and brake up of ice dams can dewater the redds and scour the stream bed crushing eggs in the process (Benson, 1955; Harvey and Ashwood-Smith, 1982; Calkins, 1989; Shumway and Springer, 1992).

We observed epidermal injuries on one radiotagged cutthroat trout and suspect they were caused by ice damming and dewatering. When anchor ice accumulates in riffles it can form dams which cause water depth to increase above the dam and decrease below the dam (Shumway and Springer, 1992). Trout that are below the dam can be trapped in dewatered areas and die from exposure to freezing air temperatures. It is also possible that as the one radiotagged trout was presented with smaller and smaller habitat to use, it was forced to move to seek some better holding areas. As the fish was struggling to move through the shallow riffle, the sharp ice and rock edges could have caused the visible damage to its epidermis. Other possible causes include being trapped under the collapsing ice shelves which we observed to be used as cover.

The presence of frazil and anchor ice in high gradient mountain streams is probably more prevalent than previously realized. The type of habitat improvement work done on a stream should be planned in light of the ice conditions in the area, and location of ground water inputs and levels. The way that riparian zones are managed could also have a large affect on frazil ice formation. Removal of trees in the riparian zone could cause increases in the amount of radiant heat loss from streams increasing frazil production and decreasing suitability of fish habitat in these areas.

The number of montane streams affected by frazil and anchor ice is probably very large, and some of North America's most valuable trout streams are found in such areas. Frazil ice formation and warm water input may be major factors determining habitat suitability and carrying capacity in montane streams. The effects which frazil ice have on fish warrants much further research.

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DISCUSSION

Rick Cunjak:

How would fish know to move upstream?

Reply:

They followed one another during movement; spawned upstream in spring.