REPORT ON STREAM ICE PROCESSES

Physical and Biological Effects and Relationship to Hydroelectric Projects

Federal Energy Regulatory Commission
Office of Hydropower Licensing
Washington, D.C.
Paper No. DPR-5
July 1992

This report was prepared by staff of the Office of Hydropower Licensing, Division of Project Review, and does not necessarily reflect the views of other members of the Federal Energy Regulatory Commission.

Report on Stream Ice Processes

The subject of this report is stream ice formation and its effects on the physical and biological environment of high mountain streams. The Federal Energy Regulatory Commission (FERC) is interested in this subject because of the potential effects of hydroelectric projects on stream ice conditions and the indirect effects on stream biota and ecology.

The purpose of this report is to provide a summary of information from the available literature on stream ice formation and its effects, and to document relationships that exist between stream icing and hydropower project operation that might cause biological impacts, such as fish mortality. Because this potential for biological impact due to stream icing and hydropower project operation exists, some preliminary guidance for evaluating the potential for project-related impact is provided in Section 2.

The report focuses on impacts on small high-gradient streams in the western United States, particularly California, Idaho, and Montana. Although the focus is on impacts in the western states, experience with ice processes and ecological effects in other areas of the country is considered, primarily to expand the limited information base.

Electronic databases were searched to find literature relevant to stream ice and its effects. Besides literature available in standard journal references and resource agency reports and study notes, individual scientists and managers experienced with the subject were contacted for their personal knowledge and observations. One video tape on stream icing was also reviewed.
As an aid to FERC and hydroelectric project applicants and owners, a list of questions was developed (Section 2) that could be posed and answered to gain insights into whether proposed or existing projects might negatively impact ice-related resources. Following these questions is discussion on how studies might be conducted and analyzed to further understanding of how a proposed hydroelectric project might affect ice processes and their impacts.

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Acknowledgements

The Office of Hydropower Licensing, Federal Energy Regulatory Commission would like to thank the many individuals of the firm of EBASCO Environmental Inc. for their dedicated research that brought this publication to fruition. We especially thank Mike Prewitt, the Task Manager, and Dennis Hanzlick, Tom Cannon, John Knutzen, Scott Urwick, and Leslie Smythe, who provided technical input and review.

Special thanks are extended to the following individuals who played important roles in the review and preparation of this document.

George D. Aston, U.S. Army Corps of Engineers
John M. Bartholow, U.S. Fish & Wildlife Service
John S. Blair, Federal Energy Regulatory Commission
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Thomas R. Payne, Thomas R. Payne & Associates
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Section 1. Ice and its Effects on the Physical and Biological Environment in Mountain Streams

This section focuses on the physical processes and biological effects of ice in small-to-medium sized, high-gradient mountain streams. Included are (1) a description of the types of ice found in streams, (2) details of their formation and the physical effects of ice, (3) a discussion of biological effects of ice, and (4) a discussion of the potential effects of hydropower projects on stream icing and subsequent impacts on physical and biological regimes.

1.1 Ice Types and Description of Formation

Commonly recognized types of stream ice include frazil ice, anchor ice, surface ice, and snow or slush ice. These are distinguishable by their characteristics and origins, and it is common to find all four types present in some combination along any mountain stream. Formation processes of these ice types are strongly interrelated and dependent upon each other.

1.1.1 Frazil Ice

Frazil ice can occur in flowing streams in winter when stream water temperature falls below 0°C. Frazil ice crystals are typically 0.1 to 1 mm in diameter and may be either discoid or needle-shaped (Ashton, 1986). Frazil disc concentrations may be up to one million discs per cubic meter of water (Osterkamp and Gosink, 1982). In high concentration, frazil ice may look like an underwater snowstorm.

The process of frazil ice formation and production is complex and depends upon stream characteristics and environmental conditions. An essential condition for formation is that the air temperature is approximately -10°C or colder, and water is supercooled. Supercooling occurs when an open water surface that has already been cooled to 0°C undergoes further heat loss by exposure to subfreezing air temperatures. Supercooling in streams has been measured to be about 0.01 to 0.1°C below the freezing point (Ashton, 1983). If the flow velocity is slow, the ice may form a thin surface sheet that evolves into a surface cover. Above a velocity of approximately 0.6 meters per second (m/s), the formation of a surface ice layer is prevented, and ice forms as frazil ice crystals within the water body rather than on top (Osterkamp, 1978; Ashton, 1988). Ice production continues as long as there is continued heat transfer out of the water. The production rate depends upon the rate of this heat transfer from the water to the air. Higher water velocities tend to keep frazil ice entrained. As velocity decreases, frazil ice will float upward and contribute to a surface cover of floating ice (Ashton, 1980). Production ceases in areas covered by a surface ice layer because of the insulating effect of the ice cover, but supercooled water may be carried beneath a surface ice layer and frazil production continued as the heat deficit of supercooling is converted to ice (Ashton, 1991).

Frazil ice contributes to the further accumulation of ice in streams in two ways: (1) by growth of individual frazil ice crystals and (2) by physical clumping together of frazil ice crystals. The most important characteristic of frazil ice crystals is their tendency to stick readily to anything they come in contact with as long as the water is supercooled. Frazil ice readily adheres to upstream faces of underwater structures such as rocks, boulders, submerged roots or branches, chains, or lines. Once a frazil ice crystal attaches to an underwater object, its growth rate, which is related positively to the speed of water past the crystal, accelerates (Osterkamp, 1978). In addition, other frazil ice crystals stick to the attached ice, leading to an accumulation of ice on underwater objects. At water velocities less than 0.9 m/s, frazil ice crystals tend to clump together and float upward. Such agglomerations may be carried downstream where they may collect in pools to freeze as surface ice. Where surface ice already exists, frazil ice may accumulate on the upstream edge of an ice sheet or the underside of surface ice.

1.1.2 Anchor Ice

The accumulation of frazil ice on underwater structures is known as anchor ice. On stream bottoms, it appears as smooth, white pillows. Anchor ice is typically a spongy, flocculent mass of ice crystals that is more porous than ice that forms on the surface. With time, patches of anchor ice may grow horizontally and join to form a continuous carpet of ice on a stream bottom. Maximum anchor ice thickness was about 30 centimeters and average thickness was about 8 centimeters in a Michigan trout stream (Benson, 1955). Anchor ice formation is usually highest during cold, clear nights, when heat loss from the water is greatest. In streams, anchor ice occurs most commonly on gravel and boulders in riffle areas where flow is most turbulent (Benson, 1955). Anchor ice seldom forms on substrates of fine sand, silt, or clay because (1) the anchor ice can lift free before attaining any significant size, or (2) streambed heat flow to the water may be effectively greater in these areas than gravel or rocky areas (Ashton, 1986). Wigle (1970) reported temperatures of 0.4 to 0.5°C at a depth of 10 to 20 centimeters below the bottom of the Niagara River, while temperatures of the water were supercooled, indicating the potential for surface heat transfer to water. Anchor ice may form on stream beds when turbulence is strong enough to transport supercooled water to the bottom, where ice crystals may attach to the bottom and further grow (Ashton, 1986). Anchor ice generally does not form when a surface ice cover is present (Brown *et al.*, 1953).

Anchor ice may grow when passing frazil crystals are trapped by the rough anchor ice surface (Osterkamp and Gosink, 1982) or when dislodged anchor ice masses moving along the bottom from upstream attach to the top of anchor ice patches.

Daily cycles with anchor ice formation at night and breakup during the day characterize anchor ice in streams. During the day anchor ice tends to break up and detach because of higher air temperatures and solar radiation (Brown *et al.*, 1953; Gilfilian *et al.*, 1972; Ashton, 1986).

Accumulation of anchor ice on the bottoms of streams often leads to formation of ice dams, an occurrence often mentioned in the literature (e.g., Gilfilian *et al.*, 1972; Brown *et al.*, 1953; Benson, 1955; Butler and Hawthorne, 1979; Flynn, 1984; Maciolek and Needham, 1952). This results in an increased stage upstream and decreased discharge downstream. Anchor ice growth patterns in streams may also form ice structures networked by small, interconnected water channels and caverns. Large buildups of anchor ice may be released abruptly after becoming detached from the bottom. Floating anchor ice often carries bits of substrate material, including sand, organic matter, and rocks.

1.1.3 Surface Ice

Ice covering the stream surface is termed surface ice. It forms on quiescent water in a thin, supercooled layer at the surface of the water cooled to the freezing point by heat loss to the atmosphere. The rate at which the thickness of surface ice increases is inversely proportional to ice thickness and directly proportional to air temperature less than 0°C. The thicker the ice, the greater the resistance to heat loss by water. The colder the air temperature, the greater the heat loss from water to atmosphere.

Surface ice formation in small streams is more complicated than on strictly quiescent water. Surface ice usually occurs in low-velocity regions such as pool areas or low gradient meadow sections of streams. This surface ice may be a combination of ice formed in place, frazil ice that has accumulated at the surface, and anchor ice that has lifted and entered a low-velocity region of a stream. This combination freezes and consolidates into an ice sheet as heat continues to be lost. Ice that has formed upstream and carried by the flow may be swept under the surface ice sheet and continue downstream or be captured by the rough underside and added to the thickness of the ice sheet. Accumulations of ice underneath an ice sheet form structures known as hanging dams (Osterkamp and Gosink, 1982). Ice may also accumulate at the upstream edge of an ice sheet and contribute to upstream ice cover. Ice dams and edges may further slow currents and thus contribute to additional surface ice formation.

One of the major influences on the formation of surface ice is water velocity. Below about 0.2 m/s, surface ice can bridge a stream and form an intact ice sheet (Ashton, 1988). Between about 0.2 and 0.6 m/s, ice forms as thin pieces of surface ice. Above about 0.6 m/s, the ice produced is frazil ice, and if the velocity is less than 0.9 m/s, the frazil ice tends to collect on the surface as a layered slush run. Surface ice will thus not be found in riffle areas, but in slow run areas and pool areas.

Another source of partial surface ice cover is growth from the sides of streams. Ice forms in the low-velocity boundaries at the edges of streams and may extend to the bottom. As the low-velocity boundary progresses toward the center of the stream, partial ice cover develops. Ice growth toward the center of the stream may cease if the ice edge encounters high velocities.

The presence of snow affects ice development in streams. When it snows, a snow cover may accumulate on surface ice, or snow banks adjacent to a stream may collapse onto the ice cover. As a result, the surface cover may break, be depressed, or become thicker with the addition of snow.

1.1.4 Snow or Slush Ice

Snow or slush ice is a slushy mixture of snow and streamwater. Its origin is snow that has fallen into a stream during snowfall or as a result of collapsing snow banks along a stream. Snow ice behaves much as frazil ice on the surface of a stream and may contribute to surface ice cover. It is also thought that snow may serve as seed crystals for the formation of frazil ice in streams (Osterkamp, 1978).

1.1.5 Aufeis

Aufeis is ice that has formed outside the main stream channel from water which has overflowed onto existing ice and subsequently frozen. This generally occurs when a stream has frozen to the bottom, and continuing flow from upstream overflows and freezes.

1.2 Physical Effects of Ice in Streams

1.2.1 Physical Effects of Frazil Ice

The effects of frazil ice are manifest primarily in its contributions to anchor ice and surface ice. However, some direct effects of frazil ice have been observed. Frazil ice that is dispersed throughout the water has been observed to increase the flow resistance of a stream, reducing maximum flow velocity from about 0.5 m/s to 0.4 m/s, and initially increasing the stage by 2 to 3 centimeters in a 2-meter deep stream reach (Osterkamp *et al.*, 1975).

Gilfilian *et al.* (1972) reported that growth of frazil ice particles resulted in rejection of impurities to the water phase, increasing the electrical conductivity of the stream water.

1.2.2 Physical Effects of Anchor Ice

Anchor ice directly disturbs the bottom of streams by dislodging and lifting substrate materials such as sand, gravel, insects, and organic matter when melting dislodges anchor ice. Freezing may penetrate 15 to 20 centimeters into the substrate, consolidating the substrate into an ice/rock mass and freezing anything contained in it, including fish eggs and fish (Reiser and Wesche, 1975; Walsh and Calkins, 1986). However, this would only occur to such depths due to complete freezing over the depth of anchor ice deposits and subsequent freezing penetration of the substrate. Direct connection via a solid mass to the cold air above is required for such deep-freezing penetrations (Ashton, 1991). Benson (1955) sampled floating ice and found sand, organic debris, insects, and one dead trout fry. Brown *et al.* (1953) observed bottom organisms floating with anchor ice slush mats, but concluded that bottom organism abundance was not affected by anchor ice. Anchor ice affects the stream by redistributing substrate materials, disturbing the bottom where the anchor ice is broken loose, and dispersing materials into the water column (Osterkamp and Gosink, 1982; Gilfilian *et al.*, 1972).

The formation of anchor ice dams also affects streams. Anchor ice dams may form over the course of one night. The immediate effect is an abrupt increase in the stage of a stream and reduction in discharge, due to instream storage. Needham and Jones (1959) observed increases in pool levels above riffles in Sagehen Creek, California of as much as 52 centimeters, averaging 40 centimeters for 20 episodes when anchor ice formed. Gilfilian *et al.* (1972) observed an increase in water level from 3 meters to 3.3 meters in Goldstream Creek, Alaska. The corresponding decrease in discharge was from 1.3 to 0.6 m^3/s.

The breakup of anchor ice on sunny days, and the subsequent collapse of anchor ice dams, leads to surges of water as normal stream flow is re-established. Previously flooded side channels are rapidly dewatered, and the streambed may be scoured by the surge of water and entrained ice chunks (Maciolek and Needham, 1952; Reimers, 1957, Butler and Hawthorne, 1979; Walsh and Calkins, 1986).

1.2.3 Physical Effects of Surface Ice

Surface ice inhibits local formation of frazil and anchor ice so that the stream bottom is not affected by in situ anchor ice. Surface ice also increases flow resistance resulting in reduced discharge associated with the increased stage. Tsang and Szucs (1972) reported a reduction of 25 percent in discharge of the Nottawasaga River in southwestern Ontario, Canada over approximately 3 weeks when surface ice cover formed. The corresponding velocity decrease was from 37 cm/s to 20 cm/s. The river study area was 80 feet wide. With locally reduced discharge and flow velocity, stage increases upstream because flow continues from upstream. The deposition of frazil ice beneath surface ice leads to the formation of hanging dams, which also impedes stream flow and increases the stage (Ashton 1986).

1.2.4 Physical Effects of Snow or Slush Ice

Snow or slush ice in streams is physically similar to the presence of heavy concentrations of frazil ice. Therefore the effects are similar to those exerted by frazil ice, namely the increase in resistance to flow, leading to reduction in flow-velocity and increase in stage.

The collapse of snow banks into a stream, which is one of the origins of snow ice, may have dramatic effects on the stream, even if the presence of snow ice generally appears to have minor effects. Nielson *et al.* (1956) reported several instances of snow bank collapse into Convict Creek in California. Collapses led to abrupt blockages of the stream and caused rapid increases in stage and flooding of the side channels. Blockage dissipated rapidly, leading to dewatering of the side channels, and encouraging water and ice surges in the stream. Needham *et al.* (1945) reported similar events and subsequent physical effects in earlier studies at Convict Creek.

1.3 Biological Effects of Ice in Streams

Detailing the biological effects of ice in streams is complicated because the occurrence of ice is accompanied by other environmental changes, including cold water temperatures, snow, potentially reduced food supply, and reduced stream flow relative to the warm season. Most published studies describe topics, such as migration, habitat selection, food abundance, feeding behavior, and food assimilation, that relate to fish behavior and survival during winter conditions. In this section, the focus will be on biological observations related to fish and stream biota that have been directly attributed to the presence of ice.

1.3.1 Summary of Effects

A variety of real and hypothesized effects occur to stream aquatic organisms from ice formation. Documented effects of anchor ice formation include fish and invertebrate stranding, fish egg displacement, and invertebrate displacement. Other effects that are thought to be caused by anchor ice formation include direct fish mortality, insect mortality, fish stress leading to poor condition, gravel displacement, and in situ egg mortality. Surface ice formation has been found to kill benthic insects at the point where the ice contacts the stream bottom.

1.3.2 Ice and Fish Mortality

Butler and Hawthorne (1979) observed daily cycles of formation and deterioration of anchor ice in Sagehen Creek, California, which caused flooding and subsequent dewatering of side channels. They reported that fish and other aquatic organisms that had entered flooded side channels were trapped as the disappearance of anchor ice allowed water to drain from the overflow areas. Direct fish mortality was not observed, but the report implied that the result was death of fish and aquatic insects. The authors stated that "heavy mortality may occur in the fish population as well as in the feed represented by aquatic insects" when conditions cause daily cycles of flooding and dewatering. Dead fish were shown being recovered in scenes from a film made by the authors documenting the occurrence and effects of anchor ice.

Maciolek and Needham (1952) conducted studies on the effects of winter conditions on trout and trout food in Convict Creek, California. They reported only one event where after three days of low temperatures, 63 trout were found stranded and dead on rocks in a flood-control bypass. Daily freezing and incomplete thawing of subsurface ice had progressively reduced water flow in the bypass. When water ceased to flow into the bypass due to ice blockage, fish were stranded as water in the bypass drained into the porous substrate. While this event was associated with artificial structures in the stream, the authors reported that other dead trout were observed several days later in similar situations, some in natural side channels as far as 1.5 miles upstream of the experiment station.

Tack (1938) reported about 100 of several thousand small rainbow trout in a hatchery pond in Germany died as a result of suffocation because of ice crystals in their mouths and gills. Larger fish in an adjacent pond suffered no corresponding mortality. The event was caused by frazil ice produced when very cold temperatures accompanied high winds causing water turbulence and preventing a stable surface ice layer from forming.

Calkins (1989) reported that salmonid species hide in the substrate during winter. This would make them vulnerable to accumulations of anchor ice over areas in which the fish are "hibernating" (Stalnaker, 1992).

1.3.3 Ice and Aquatic Insects

Stream ice may contribute to aquatic insect mortality. Logan (1963) observed dead insects frozen in ice at the edges of Bridger

Creek, Montana. Surface ice that began forming at the stream edges froze all the way to the bottom, entrapping and killing a small number of insects (9 were observed). Brown *et al.* (1953) also reported insect mortality when surface ice froze next to the shore. Logan concluded that surface ice cover, other than the small losses described above, had no significant effect on the abundance of bottom organisms.

Anchor ice indirectly causes dislodging of benthic organisms and dispersion in the water column. Maciolek and Needham (1952) observed that insects were dislodged and carried downstream when the collapse of anchor ice obstructions led to short-term events of increased flow of water and entrained ice that scoured the bottom. They noted that dislodged insects were generally alive and that the greatest numbers corresponded with high-flow events.

Benson (1955) found that insects collected in anchor ice, both frozen to the bottom and drifting in the flow were alive. The population densities of insects were approximately the same, an average of 10 organisms per square foot of ice, whether the anchor ice was collected from the bottom or was drifting. Two implications are that anchor ice released from the bottom directly transports insects into the water column and that insects survive being frozen in an anchor ice substrate.

Butler and Hawthorne (1979) surmised that insect mortality would accompany fish mortality due to stranding in side channels after collapse of anchor ice dams led to dewatering of side channels in Sagehen Creek. They did not actually report finding dead insects.

Reimers (1957) contended that snow bridging and/or surface ice cover affected bottom organisms and trout food abundance. His studies indicated that bottom organism abundance was 21.4 lbs/acre in mid-April 1952 in Convict Creek, California following a winter with harsher conditions than normal. The five-year average of 225 May-to-September samples was 109 lbs/acre of bottom organisms. An average of 12 bottom samples taken in late April 1952 a week after the steam had begun to clear yielded a value of 32.4 lb/acre of bottom organisms, a slight improvement on the value of 21.4 lb/acre obtained 12 days earlier. Reimers contended that extended periods of ice cover produced extended periods of reduced light, which in turn led to reduction in bottom organism abundance.

1.3.4 Ice and Fish Eggs

Fish eggs are deposited in the gravels of stream beds and may be susceptible to ice influences. Maciolek and Needham (1952) observed that two fish stomachs each contained two trout eggs. The authors speculated that the "action of ice in disturbing spawning gravels may have freed these eggs in the current," but suggested that the general scarcity of fish eggs in fish stomachs indicated only slight disturbance of spawning beds. Reiser and Wesche (1975) conducted experiments in the Laramie River, Wyoming. Boxes of 100 brown trout eggs were placed 15 to 18 cm deep in riffle areas with water depth of 6 to 36 cm. Upon removal in March, only 1 percent of the eggs were found to have survived. Three of 20 boxes were completely frozen, even though buried 15 cm in the substrate beneath 12 to 20 cm of flowing water. Reiser and Wesche concluded that extremely low water temperature and in situ freezing of redds were the two main factors contributing to egg mortality. Thus, eggs of all spawning salmonids may be jeopardized by ice in streams.

1.3.5 Ice and Fish Habitat

Direct effects of stream ice on fish were presented in Section 1.3.1. Ice in streams may affect fish survival indirectly by altering fish habitat. That is, if the result of ice presence in a stream is forcing fish into harsher environmental conditions than would be encountered in the absence of ice, then one potential consequence is relatively higher fish mortality. No studies were found that quantified or even isolated effects of habitat alteration by ice. However, it is possible that such effects do exist.

Bovee *et al.* (1978) presented figures showing surface ice cover profiles at three transects across the Tongue River in southeast Montana. In none of the figures was ice shown contacting the bottom. It is estimated (based on the figures) that surface ice excluded approximately 50 percent of the stream habitat. The authors hypothesized that presence of the ice cover would alter the flow velocity characteristics of the river, either creating, destroying, or simply re-distributing specific velocity habitat. There was no mention of direct effects on fish.

Johnson *et al.* (1982) found that surface ice contiguous with the shore excluded up to 60 percent of the cross-sectional area of Wagonhound Creek in Wyoming. Flow velocity and mean depth were subsequently affected. It follows that if brown trout were present and preferred areas of slow, deep water, then they would be forced to move or remain and endure less preferable habitat conditions.

Chisholm *et al.* (1987) similarly found that extensive surface ice excluded between 40 and 70 percent of the habitat in a stream in the Snowy Range in Wyoming. Tracking studies conducted by Chisholm *et al.* (1987) showed that brook trout generally selected low velocity conditions (less than 15 cm/s), deeper water (30 to 107 cm deep), but not substrate type. Presumably, these fish would migrate if habitat exclusion by surface ice (or by anchor ice) altered velocity and depth distributions in the stream.

Using underwater time-lapse photography, Butler and Hawthorne (1979) observed that fish habitat was obliterated by anchor ice, and fish appeared to lose orientation and swim aimlessly through caverns of anchor ice.

1.3.6 Snow Cover and Fish Mortality

Another source of winter fish mortality is the collapse of snow cover into streams. Such events are not caused by ice in streams, but may still be an important consideration in connection with overwinter fish survival. Needham *et al.* (1945) reported several hundred dead fish beneath a snow mass that had collapsed into the stream below a hatchery. Similarly, Nielson *et al.* (1956) attributed severe trout mortality (80 to 90 percent) in Convict Creek, California during winter to the periodic collapse of snow and ice overburden into the stream. Fish were said to have been killed in any of three ways: (1) crushed or suffocated directly beneath the collapsed mass; (2) suffocated throughout the length of stream dewatered downstream of a collapse; or (3) left stranded under the snow when the ponded area upstream of the snow barrier receded.

It is apparent from the literature that observations of direct effects of ice on fish are few. The published studies indicate that ice can kill fish directly and destroy fish habitat, but do not support hypotheses that ice represents a significant fish population limiting factor.

1.4 Effects of Hydropower Projects on Stream Ice and Subsequent Effect on Aquatic Biota

This section discusses the potential effects of hydropower projects on physical stream processes and stream biota. No known studies have directly assessed physical and biological conditions in mountain streams before and after hydropower projects were constructed. In the absence of specific studies, it is only possible to discuss potential, rather than observed, effects of hydropower projects on ice and its effects. The method used in the following discussion relies upon combining knowledge gained from studies and observations with information concerning the general nature of hydropower projects and the ways in which they are known to affect factors which relate to ice formation.

1.4.1 Physical Effects on Streams and Stream Icing

Ice characteristics are largely dependent on whether a hydropower project has a storage reservoir, or simply diverts water from a bypassed reach. In a project with a storage reservoir, water velocity in the reservoir is reduced relative to the stream, and water depth is increased. In reservoirs, the surface area to volume ratio is decreased, resulting in a reduced rate of heat loss. Because of this reduced rate of heat loss in a reservoir relative to the stream, heat will be retained. Wintertime reservoir water temperatures and their discharges are thus typically higher than those in uncontrolled streams. Since the average residence time of water in a run of river (R-O-R) project pool is less than that for a project which stores water for later release, the change in water temperature between inflow and outflow will be less for an R-O-R project.

Because of the quiescent nature of a reservoir, surface ice will likely form in cold, mountain settings. The surface ice serves as an insulating blanket for reservoir heat loss, especially if covered by snow. The exception is when a reservoir impounds a relatively warm spring, and pooling increases transit time and exposure to cold air, thus increasing heat loss to the atmosphere.

Stream discharge is affected through storage and release of water. High mountain stream flow normally decreases through the winter as precipitation is tied up as snow and ice. A store and release hydropower project with sufficient storage will always change the downstream discharge pattern, with seasonal shifts varying by the load characteristic, and yearly hydrology of the area. This is in contrast to a R-O-R project where operation does not alter stream discharge except in the bypassed reach, where present. Discharge changes may cause ice buildup in dewatered margins of the stream because of alternating cycles of increased and decreased discharge that cause stream stage to fluctuate. Ice may also form outside the main stream channel from overflow of water onto existing ice and subsequent freezing. This ice is called aufeis. No documentation of aufeis formation due to hydropower plant operation in small streams was found, although Gilfilian *et al.* (1972) reported stream ice and aufeis accumulation of about 2 meters due to anchor-ice-caused stage fluctuations in Goldstream Creek, Alaska.

In the case of hydropower projects with little or no storage, temperature is rarely affected when the diversion channel is open to the atmosphere. Heat may be retained to some degree if the diversion is a closed conduit, and, if it is underground, heat may be added to the water by conduction from the soil through the pipe walls.

Flow in the bypassed reach is reduced by the amount of water diverted through the diversion channel, and this reduced flow leads to reduced stage and velocity. If the bypassed reach has relatively vertical sides, little or no side-channel dewatering will occur. Because exposed stream surface area changes little in this scenario, heat flux will change little. However, the reduction in velocity that accompanies reduced discharge will likely lower the potential for frazil ice formation. If the reduction of velocity is to a value that is less than 0.6 m/s approximately, frazil ice production may cease entirely and surface ice may form.

If the bypassed reach is shallow with gently sloping bottom laterally, or if the channel is braided, then reduction in stage will cause dewatering of some of the streambed, exposing it to freezing air temperatures. In extreme cases of stage reduction, the depth of water remaining may be small enough that the stream may freeze to the bottom, and additional flow would spread on top of the ice and laterally, adding to the volume of the frozen stream. Gill and Kershaw (1979) observed this type of ice buildup at riffle points along the upper Tsichu River in northwest Canada.

If the hydropower project has a spillway exposed to the atmosphere, the increase in surface area and resultant increases in heat loss may cause the production of frazil ice.

1.4.2 Effects on Aquatic Biota

No documented studies of the effects of hydropower projects on aquatic biota in small, high-gradient mountain streams were found. Predicting biological effects becomes a matter of posing physical contingencies and determining the probable biological consequences. Since there is no source of specific studies of stream biology before and after hydropower project installation, predictions involve inference from published biological observations in mountain streams under winter icing conditions combined with potential physical effects of hydropower projects on ice conditions. Therefore, the following discussion draws upon observational biological information from Section 1.3 and projection of effects of hydropower projects on stream ice regimes.

In the case of a hydropower project with storage, effects on stream biota both in the reservoir and downstream can be beneficial at least in terms of water temperature and ice. In a reservoir in which water temperatures are increased relative to free stream flow, fish are not subjected to as low temperatures as in the free-flowing stream. In addition, water temperatures are more stable, and water velocities are lower than in free-flowing streams, which are desirable fish winter habitat features. Below the reservoir, the effects of increased temperature usually extend some distance downstream of the project, locally maintaining a greater amount of habitat by inhibiting ice formation and encroachment.

The overall effects are increases in the amount and desirability of fish habitat, and possibly increased survival rates.

When a hydropower project has a long buried pipe diversion, a relative temperature increase may occur in the stream below the powerhouse from the acquired ground heating or lack of heat loss to the atmosphere that can occur in the stream. This temperature increase would reduce the formation of ice in the reach below the powerhouse increasing available habitat. When the reservoir temperature is colder than free-flowing streams, such as when spring flows dominate the inflowing stream, there is the beneficial effect of quiescent water, stable temperatures, and surface ice formation in the reservoir. However, the colder reservoir water may increase local ice accumulation where it rejoins the stream channel and produce habitat loss comparable or worse than free-flowing conditions.

Since flow fluctuations from daily freezing and thawing of anchor ice have been observed to affect fish mortality in natural settings (Section 1.3), fluctuations in flow caused by hydropower project operation could affect fish as well. If the facility is operated so that extensive areas of solid ice form in and adjacent to the stream channel, fish mortality could be high. For example, peaking to meet variation in power demand can cause side channel areas to either dry up or freeze solid as flow levels drop causing mortality for fish residing in these areas. These low velocity areas may be used for overwintering fish, particularly for young-of-the-year fish. Gradually increasing flow during the winter can cause ice to form on top of ice. Extensive icing outside the main stream channel can damage riparian habitat adjacent to the stream (e.g., ice damage to bushes and trees), which may not directly affect fish, but might affect terrestrial animals that use that habitat either in cold or warm seasons.

Reduced water velocity and turbulence could result in less frazil ice production and, thus, less anchor ice accumulation on the bottom of the bypassed or downstream reach. Less anchor ice generally means reduced disruption of bottom substrate and less extreme fluctuations in stage, discharge, and velocity. Thus, flow reductions could result in winter habitat improvement for fish, their eggs, and insects that use the substrate for cover. Fish would be less likely to be stranded by rapid dewatering of side channels filled and drained by anchor ice dam formation and collapse. Reduction in flow surges caused by anchor ice dam collapse would also mean reduced scouring of the bottom substrate, which could wash out eggs, fish, and insects.

Hydropower projects would not be expected to have any additional effect on ice if the bypassed reach was narrow enough that the snow bridged and covered a significant portion of the stream. Snow bridging has been reported over streams 3 meters to 5 meters wide (Nielson *et al.*, 1956; Needham and Jones, 1959). In this case, snow cover would insulate the stream and prevent or slow down the cooling of water eliminating local formation of frazil and anchor ice. However, if stage in the bypassed reach fluctuated so that the snow cover collapsed, fish would be trapped and either suffocated or crushed (Needham *et al.*, 1945; Nielson *et al.*, 1956). Eggs and organisms in the substrate would not be directly affected by the collapse, but would likely be endangered by high speed scour that occurs when the water backed up by the collapse is suddenly released as the snow dam fails.

Predicting the effects of hydropower projects on aquatic biota will ultimately require combining observations of the physical and biological effects of stream ice in natural settings with projections of how the facility will modify stream conditions. Some suggestions for determining the potential physical and biological effects of hydropower projects related to stream icing and recommendations for potential studies follow in Section 2.

Section 2. Licensing Considerations

This section provides guidance for evaluating potential site-specific impacts of proposed hydroelectric projects on stream ice formation and aquatic organisms in small, high-gradient mountain streams. The information and guidance is provided to assist both applicants and FERC staff in evaluating the potential for project-related ice problems and in addressing those problems during the pre-filing period.

The section is presented in two sections. The first section presents a set of recommended questions to determine whether or not stream ice formation is a potential problem for a specific proposed project. The second section details additional studies which might be useful to evaluate the potential impact, if any, of a proposed hydropower project on stream ice formation and aquatic organisms.

As before, this section is focused on small, high-gradient mountain streams in the western United States. Different considerations would apply for larger streams or those at lower elevations or in other parts of the country. Physical and biological processes related to ice in those areas would be quite different from those in the regions described in this report.

2.1 Screening Criteria Questions

These questions are meant to identify whether ice might be problematic at a particular hydropower project. These questions can be answered with a minimum of on-site observational data and are proposed as initial screening criteria. It is recommended that the screening be applied during Stage I consultation to determine whether further studies might be necessary in Stage II. Questions are arranged in a dichotomous key with responses to each question level resulting in direction to a subsequent question (Figure 2-1).

QUESTION NO. 1

Is there currently a population of important fish in the stream reach in which flow will be reduced or augmented by project operations?

If NO, it can be concluded that project operation will not have negative biological effects even if stream icing conditions are made worse by the project.

If YES or UNKNOWN, continue to Question No. 2.

QUESTION NO. 2

Does the location of the proposed project lie above 6,000 ft elevation in the Rocky Mountains or the Sierra Mountains, or

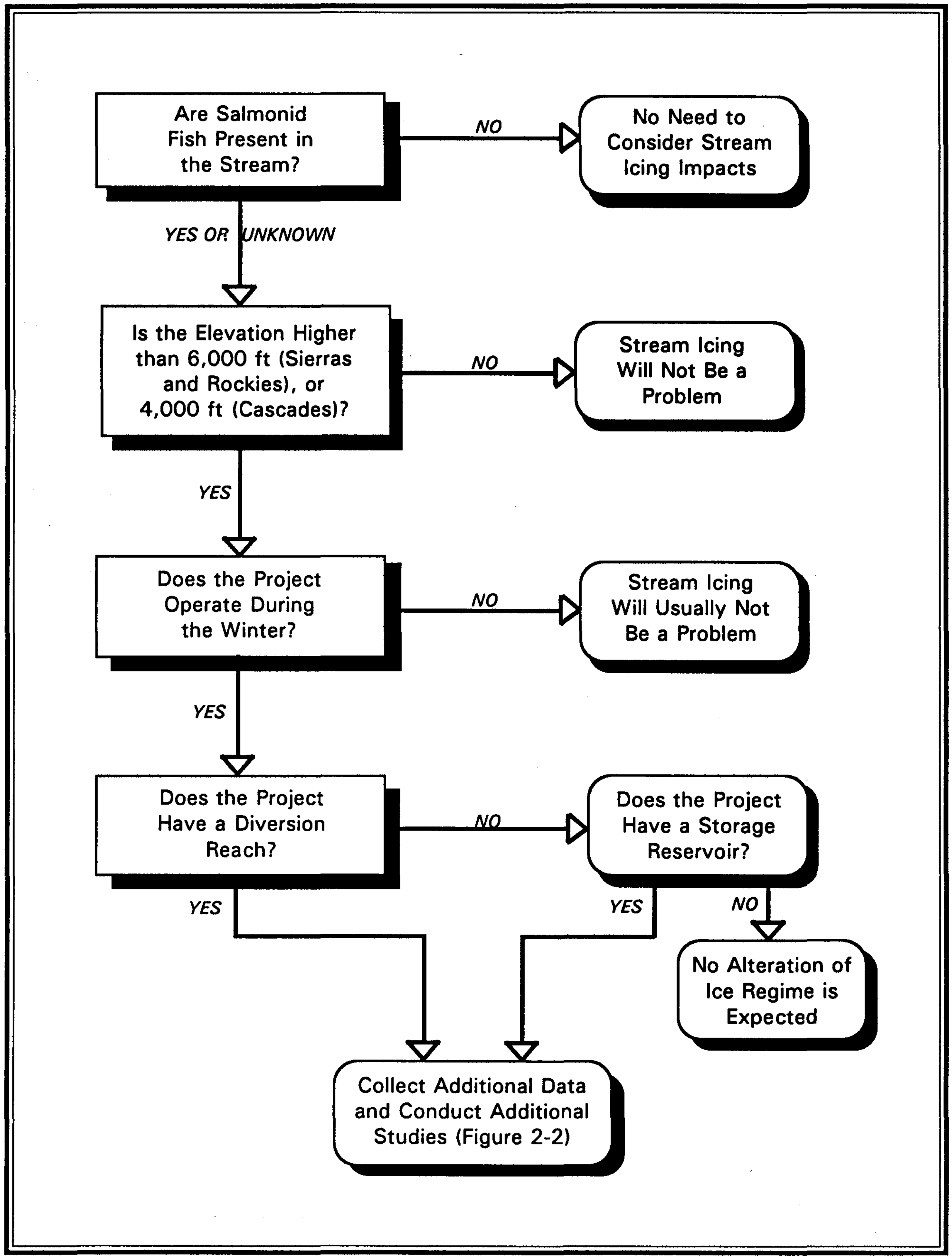

Figure 2-1 **Screening Criteria Questions**

above 4,000 ft elevation in the Cascade Mountains?

If NO, stream icing is not a potential consideration at this location.

If YES, continue to Question No. 3.

QUESTION NO. 3

Will the project operate during the winter months when stream icing may be expected to occur?

If NO, operation will not affect stream icing, except in rare or unforseen situations.

If YES, continue to Question No. 4.

QUESTION NO. 4

Will the project divert water from a reach of stream that provides overwintering habitat for important fish?

If NO, project design and operation still require consideration. Continue to Question No. 5.

If YES, there is a potential that the project might impact fish through alteration of the present stream icing patterns. Additional information is required to evaluate that possibility and to quantify the effects. Insights may be gained from additional studies.

QUESTION NO. 5

Does the project create storage in the form of a reservoir?

If NO, it can be concluded that, since there is no diversion and no storage, stream ice formation will not be significantly affected.

If YES, then there is the possibility that the project will modify the existing stream ice regime. Ice process changes may result either from reservoir effects on water temperature or from operations that create stream flow fluctuations. Additional information may be required to evaluate and quantify the possible effects.

2.2 Additional Studies

If answers to the foregoing questions indicate that studies might be required, this section provides guidance on such studies. It is important to note that extensive data collection efforts strictly to evaluate ice formation, unlike temperature simulations, may not provide answers at the level of confidence necessary for hydraulic evaluations or habitat. Figure 2-2 presents a schematic summary of recommended additional data and studies.

2.2.1 Physical

The primary objective of physical data collection is to obtain information which pertains to elements related to ice formation. Channel geometry data such as longitudinal distance, width, depth, average gradient, and substrate type all relate to ice formation, but provide little predictive value. Predictive capabilities may be obtained by conducting measurements at a series of transects across the stream channel, similar to those obtained for hydraulic simulation modeling. Such data are very often collected for conducting the U.S. Fish and Wildlife Service Instream Flow Incremental Methodology (IFIM) analyses. The IFIM is

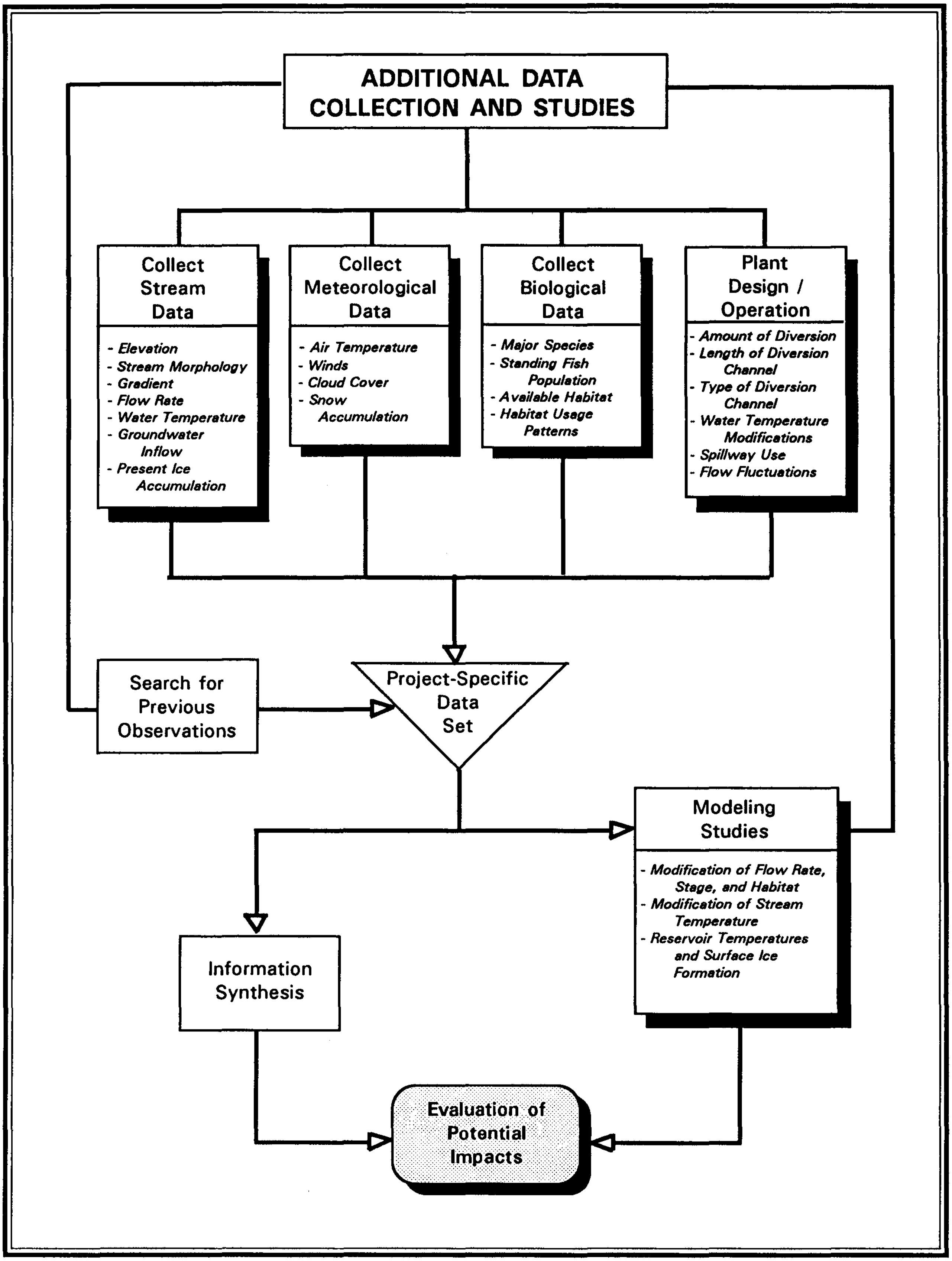

Figure 2-2 **Additional Data & Studies**

a simulation model-based assessment technique which combines predicted depth, velocity, and substrate conditions with fish preferences, to evaluate preferred fish habitat for flows associated with various project operations. The IFIM is routinely used on evaluations of proposed hydropower projects in the western states. It would be wise to evaluate any IFIM study plans in terms of both fishery and ice predictions in the many cases where IFIM is required. The IFIM analysis requires both pre- and with-project monthly discharge patterns, which will be valuable in ice simulations or evaluations.

In addition to IFIM hydraulic and habitat data bases, stream temperature data would be required for those winter periods when freezing might occur. As before, stream temperature data alone does not provide predictive capabilities, and a temperature simulation model or technique would probably be required to predict stream temperatures expected under project operations. Such models require, in addition to hydraulic data as needed for IFIM applications, water temperature measurements and meteorological data. These data should include daily air temperature time series with as short a sampling interval as possible. An effort should be made to correlate on-site temperature measurements with data from the nearest available permanent recording station, such as an airport. Local wind data should be collected because winds increase heat loss rates from water and blow snow into streams. Statistics regarding incidence and persistence of cloud cover should also be determined from existing local weather records. Data should include typical snow depths and seasonal patterns of snow accumulation in the project area. Site visits and documentation of field observations of ice conditions would be useful. Another useful statistic is the number of clear, sunny days during seasonal stream ice formation. Anchor ice forms at night, but often detaches from the substrate in response to sunshine the following day.

Groundwater inflows, if any, within and upstream of the affected reach should be identified. These data would most conveniently be gathered in conjunction with stream morphology surveys. Methods include physical observation of inflow or examination of temperature patterns along the stream channel.

Observations of existing winter ice and snow conditions on the stream are important for establishing baseline data. Such observations can be obtained by on-site observers or possibly by aircraft photographic overflights. These observations should be planned when ice formation is most likely to occur; however, direct observations may be expensive and hazardous to obtain, so these factors should be considered before proceeding with direct observations.

Ultimately, physical data would be used with hydraulic simulation techniques to determine at which discharges frazil and anchor ice might form, given the generally known water velocities which favor their development. The data from Ashton (1988) and repeated in Table 2-1 may be used as a general guide to how project-related velocity would relate to various ice processes given suitably cold climate conditions. In this way, model results would aid in characterizing the stream areas which meet certain ice formation standards or criteria. Use of computer simulations is discussed in

TABLE 2-1

Velocity Conditions Under Which Different Stream Ices May Form a/

Velocity	Ice That May Form
< 0.2	Intact Sheet Ice
0.2 - 0.6	Thin Pieces of Sheet Ice
> 0.6	Frazil
0.6 - 0.9	Layered Frazil and Slush
> 0.9	Well Mixed Frazil

a/ Given suitably cold climate conditions.

more detail in section 2.2.3. Detailed data and simulation models, however, should be used only to gain insights into the general directions of project-related ice changes. Predictive precision regarding ice formation and its subsequent effect is not at the level expected for hydraulic or stream temperature simulations.

2.2.2 Biological

Information about the fish populations is generally required of all applicants. At a minimum, species composition should be determined and fish populations estimated (see Figure 2-2). If possible, studies should be conducted to determine current overwinter fish mortality in the affected stream reach and approximately .25 mile upstream and downstream.

Biological surveys should determine the amount and types of habitat available to fish in summer and winter. In conjunction with any winter surveys, estimates of the amount of habitat excluded by ice should also be estimated. Additionally, the presence or absence of coarse substrate and evidence of fish overwintering in the substrate would be useful information.

2.2.3 Computer Modeling

As discussed previously, some insights may be gained into ice formation by use of computer simulations of stream hydraulics and temperatures. Frazil, surface, and anchor ice formation are products of three primary physical factors:

(1) **Water temperature** - obviously, ice cannot form if water temperature is above 0°C, so it is critical to know if and when that temperature is reached.

(2) **Water velocity and turbulence** - Frazil ice exists in or below areas of turbulence, surface ice forms in lower water velocity (less than 0.2 m/s), and anchor ice forms in higher velocity water.

(3) **Meteorology** - As discussed, cloud cover, windspeed, snow cover, and air temperature are related formations of the various ice types. Also, long- and short-wave radiation is a significant determinant of both stream water temperature and ice formation.

Ideally, a hydroelectric project applicant, given the potential for ice formation at the proposed project site, would want to determine whether the project operation would create or increase ice problems. Simulation modeling data could provide some insight into this question in the following fashion.

Three basic data or information sets would be developed. These would be:

(1) **Hydraulic data to predict stream velocity (for use in determining flow travel time), wetted width (for**

determining insolated area), and depth - These factors are used either directly to evaluate the ice formation potential or indirectly as inputs to the water temperature model described below.

(2) **Water temperature modeling** - In most instances, a water temperature model would be required to determine temperatures below a diversion or return point or below a storage reservoir release. In the former cases, the model would be used to determine changes in temperature resulting from dewatering the bypassed reach. Normally, during winter, such discharge decreases would not result in changes in either when, seasonally or where the 0°C would be reached. Use of a model in such situations would only be required if discharge reduction was large (greater than 70 percent relative to pre-project flows) and/or if the bypassed reach was exceptionally long (greater than 1 mile). In the latter case, temperature modeling relative to storage releases would be required, particularly if the storage reservoir were large enough to cause temperature stratification. Even with small reservoirs, however, enough thermal energy may be stored to cause significant changes from pre-project conditions.

Temperature models normally require hydraulic data (wetted width, travel time, depth) across the range of discharges to be simulated. They also require meteorologic data including cloud cover, shade factor, long- and short-wave radiation, air temperature, and day-length relative to canyon locations, if any. Stream temperature models are typically steady-state, that is, they predict temperature within stream reaches at time steps no shorter than the travel time of water through the stream reach. Temperatures can be predicted for steady conditions of all input factors except temperature and discharge, which would vary according to the need to simulate existing temperatures and discharges or those related to alternative project configurations or operations.

(3) **Climatic or weather-related information** - Some of the data in this area are the same as those collected for water temperature modeling, specifically, cloud cover, and air temperature. In addition, information on snow depth and frequency is required. These data are used to determine the frequency of periods when there are extremely cold temperatures (less than -15°C) with low snow accumulations and clear nights. Collectively, these situations would cause anchor icing if stream velocity were sufficient.

Generally, such simulation modeling results would be used to determine such conditions as the following:

(1) **When with-project discharges would be low enough to cause complete freezing** - Here, stream depth of less than 0.5 feet with low velocities (less than 0.1 fps), extremely cold air temperatures, and little snow cover could freeze the stream solid. However, such flows

would probably not be permitted initially because of their low fish habitat. Complete freezing of the entire stream is apparently a very rare occurrence in streams which naturally sustain fish populations.

(2) **When surface ice might form** - Surface ice forms when frazil ice is generated from very cold air temperatures (<-15°C) but water velocity is low (simple channel geometry and less than 0.2 m/s water velocity).

(3) **When anchor ice might form** - Here, project velocities would have to exceed 0.6 m/s and would be of concern only if velocities were significantly less in the existing condition. Also, in association with augmented winter flows, there would need to be clear nights and extremely cold air temperatures.

For non-storage hydro projects with diversions, the most reasonable outcome related to ice would be complete freezing or increased surface ice formation resulting from reduced depth and/or velocity. From a quantitative modeling perspective, these is no way to accountably predict whether a stream will or will not freeze completely or create surface ice due to the discharge changes associated with a hydroelectric project. Using hydraulic models in association with some climatic information, it is possible to generally evaluate whether the dewatering will be so extreme as to cause concern.

If the proposed project had storage, it would be necessary to model both the internal reservoir temperature regime and the resulting regime in the downstream affected reaches. If warmer water than pre-project were to be released, the stream temperature model could be used to determine the point downstream at which freezing might begin. The model would also be useful in simulating the stream temperature relative to the monthly discharges associated with the proposed operating alternatives. In all cases, one could determine the downstream point of potential freezing (0°C water temperature) and the water velocities associated with monthly discharges. Surface or anchor icing conditions could be generally predicted, again using the water velocity and temperature information derived from the hydraulic and temperature simulation models.

To summarize stream ice modeling approaches, effects of a hydroelectric project on stream icing regimes can only be predicted through a combination of stream temperature simulations, hydraulic modeling, and climatic information. Obviously, if the temperature simulations indicate that project releases would be warmer than 0°C, all modeling can be ceased and a "no-effect" conclusion reached. Therefore, temperature simulation modeling should be used as the primary tool for screening. If temperature simulation modeling predicts that stream temperatures will reach 0°C in a bypassed stream reach, in a diversion channel, or below a storage reservoir, then hydraulic modeling in combination with climate data should be used to predict whether stream velocities and temperatures will be suitable for ice formation and what type of ice would form.

In all cases, as stated earlier, ice processes and conditions are not as predictable and quantifiable as stream temperatures, depths, and velocities. Hydroelectric project applicants may gain insights into the directions of ice changes, but only through careful project operation and monitoring will the exact effects of ice be known. Generally, however, studies and case histories indicate that the usual project operations licensed in small, high-gradient western streams, would not create physical change great enough to warrant concern for ice problems other than the initial concerns for fish habitat preservation.

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KEYWORDS

ANCHOR ICE,
FRAZIL ICE,
ICE FORMATION

LOCATION OF STUDY:

Upper Niagara River between Lake Erie and Niagara Falls, New York.

STREAM CHARACTERISTICS:

0.8 to 3.0 m/s velocity; no others given.

HYDROELECTRIC PROJECT EFFECTS:

Reduction of flow in the 24 kilometer-long bypass reach.

PHYSICAL EFFECTS OF ICE:

A stationary ice cover could not develop because of high velocities that prevent initiation of the bridging process, ice control procedures, and a boom that eliminates ice inflow from Lake Erie. Frazil ice forms rapidly in supercooled water near the surface under clear skies. Surface ice production increases as the water column cools, and the area of surface ice increases. Surface ice continuously moves with the river flow. Formation of anchor ice causes a sudden flow reduction of 20 to 30 percent during night hours. Flow slowly increases during daylight hours. The prime condition for anchor ice formation is a rocky or gravelly bottom.

BIOLOGICAL EFFECTS OF ICE:

None discussed.

COMMENTS:

None.

Ashton, G.D. 1989. Effect of Toston dam on upstream ice conditions. Special Report 89-16. U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

KEYWORDS
ICE MODELING, RIVER ICE

LOCATION OF STUDY:

Missouri River upstream of Toston Dam in Montana; elevation approximately 3,950 feet.

STREAM CHARACTERISTICS:

2,000 to 5,000 cfs.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

This report presents results of a modeling study to predict effects of ice after raising the height of Toston Dam. In general, ice will increase water levels upstream slightly higher than if ice were not present. The physical setting is not applicable to the present project concerning small, high-gradient streams.

BIOLOGICAL EFFECTS OF ICE: N/A

COMMENTS:

None.

Ashton, G.D. 1988. Falls river anchor ice study. Letter report to Mr. Grant Durtschi, Environmental Energy Company, Driggs, Idaho. April 7, 1988. 6 pp.

KEYWORDS

ANCHOR ICE

LOCATION OF STUDY:

Falls River; Eastern Idaho, east of Marysville.

STREAM CHARACTERISTICS:

300-400 cfs in winter; 200 feet wide; 1.1 feet deep; slopes of 0.004 to 0.008.

HYDROELECTRIC PROJECT EFFECTS:

Diversions of flow through power generation facilities will reduce flow to 160 cfs in the reach between diversion and return points. There is no anticipated effect on the hydroelectric project by ice.

PHYSICAL EFFECTS OF ICE:

It is unlikely that frazil ice or anchor ice formation rate will be significantly affected in the diverted reach as long as the open water area remains approximately constant. There is an increased tendency for formation of floating ice cover at reduced flow rates.

BIOLOGICAL EFFECTS OF ICE:

Not discussed.

COMMENTS:

This paper discusses characteristics of frazil and anchor ice and factors that influence their production. It informally assesses the effects of river diversion on frazil and anchor ice production in the diverted reach.

Ashton, G.D. 1987. River ice problems, where are we? A review. International Union of Geodesy and Geophysics. Vancouver, British Columbia, Canada. August 12, 1987.

KEYWORDS
RIVER ICE

LOCATION OF STUDY: N/A

STREAM CHARACTERISTICS: N/A

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE: N/A

BIOLOGICAL EFFECTS OF ICE: N/A

COMMENTS:

This paper summarizes major problems associated with river ice and discusses the state of knowledge of the various processes and phenomena that are involved with those problems. There is general discussion of ice formation, evolution, and deterioration and relation of ice to environmental and ecological systems, in-river structures, navigation, and hydropower. No specific study site is discussed.

Ashton, G.D. 1986. River and lake ice engineering. Water Resources Publications. Littleton, Colorado. 504 pp.

KEYWORDS

RIVER ICE,
LAKE ICE

LOCATION OF STUDY: N/A

STREAM CHARACTERISTICS: N/A

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE: N/A

BIOLOGICAL EFFECTS OF ICE: N/A

COMMENTS:

This is a general reference text for ice on rivers and lakes. It presents technical discussions of ice types and processes. It is not site oriented. Presentations are often theoretical, and the text covers a wide variety of topics associated with ice in rivers and lakes.

Ashton, G.D. 1983. Frazil ice. *In:* Theory of Dispersed Multiphase Flow. Academic Press, New York. pp. 271-289.

KEYWORDS
FRAZIL ICE

LOCATION OF STUDY: N/A

STREAM CHARACTERISTICS: N/A

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE: N/A

BIOLOGICAL EFFECTS OF ICE: N/A

COMMENTS:

This is an informational paper that discusses physical characteristics of frazil ice and processes associated with its formation and transport in rivers and streams. No specific studies are included and it is not oriented toward evaluation of effects of frazil ice on streams.

Ashton, G.D. 1980. Freshwater ice growth, motion, and decay. *In:* Dynamics of Snow and Ice Masses (S.C. Colbeck, Ed.), Academic Press, New York. pp. 261-304.

KEYWORDS

RIVER ICE,
LAKE ICE

LOCATION OF STUDY: N/A

STREAM CHARACTERISTICS: N/A

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE: N/A

BIOLOGICAL EFFECTS OF ICE: N/A

COMMENTS:

This paper gives a general review of freshwater ice growth, motion, and decay for river and lake ice. The emphasis is on river ice. It presents equations governing energy budgets for ice formation, growth, and decay. In addition, it discusses ice jams and physical break-up of ice cover. This paper does not discuss aspects of a particular river or stream.

Ashton, G.D. 1979. River ice. American Scientist. 67:38-45.

KEYWORDS

RIVER ICE

LOCATION OF STUDY: N/A

STREAM CHARACTERISTICS: N/A

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE: N/A

BIOLOGICAL EFFECTS OF ICE: N/A

COMMENTS:

This is a general reference paper on river ice. It does not concern a particular study or location. It describes physical processes of ice formation, growth, and deterioration on rivers. It does not include specific discussions of surface ice, anchor ice, or frazil ice.

Barnes, H.T. 1928. Ice Engineering. Renouf Publishing Co., Montreal, Canada. April 1928. 366 pp.

KEYWORDS
ICE FORMATION

LOCATION OF STUDY: N/A

STREAM CHARACTERISTICS: N/A

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE: N/A

BIOLOGICAL EFFECTS OF ICE: N/A

COMMENTS:

This is one of the early references that discusses various aspects of ice formation in streams, river, and lakes. Much of the content has been either confirmed or superseded by more recent studies. It is included for completeness.

Barton, D.R., and W.D. Taylor. 1985. Dimensions of riparian buffer strips required to maintain trout habitat in southern Ontario streams. North American journal of Fisheries Management. 5:364-378.

KEYWORDS

TROUT
TEMPERATURE

LOCATION OF STUDY:

Thirty eight streams in southern Ontario, Canada.

STREAM CHARACTERISTICS:

All but one of the streams had typical weekly maximum temperatures less than 22°C. All the streams had stable flow regimes and low concentrations of fine suspended solids.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE: N/A

BIOLOGICAL EFFECTS OF ICE:

The paper describes the relationships between riparian land use, fish composition (mainly trout), and stream parameters such as: temperature, suspended solids, and discharge variability. Results indicated that temperature is indeed the most significant factor determining the presence or absence of resident trout in southern Ontario streams. Turbidity and discharge stability also contribute but to a lesser degree. It was concluded that these stream parameters can be controlled to a certain extent by establishing or maintaining forested riparian buffer strips along stream banks.

COMMENTS:

Benson, N.G. 1955. Observations of anchor ice in a Michigan trout stream. Ecology. 36:529-530.

KEYWORDS

ANCHOR ICE

LOCATION OF STUDY:

Pidgeon River, Otsego County, Michigan.

STREAM CHARACTERISTICS:

Average winter flow is 40 cfs; depth 6 to 24 inches; contains brown trout, rainbow trout.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

Anchor ice formed during clear nights when air temperature fell below -15.6°C and was observed on 5 days during the study interval. Anchor ice formed primarily in fast-flowing, turbulent stream bed sections. The mean thickness of anchor ice was about 2 inches, reaching a maximum of 7 inches. Usually, anchor ice lifted by 10 a.m. and floated downstream. Stream flow decreased gradually during anchor ice formation. When ice loosened, large amounts of stored water were released, abruptly increasing flow volume. These flow surges produced no observable stream bed scouring. Samples of lifted ice contained sand, gravel, organic debris, and organisms.

BIOLOGICAL EFFECTS OF ICE:

All insects found in the drifting ice were alive. One egg sac trout fry was found dead. It was speculated that the fry could have been vulnerable during emergence if ice scour occurred, but that eggs would not be affected because of the short duration of the ice on the stream bottom, usually less than 12 hours. Surface ice prevented formation of anchor ice during much of the year. Observed flooding effects were much less than normal spring flows. Trout that were observed were not feeding and were in poor condition. Ice could apparently dislodge benthic insects, but the number was too small to depopulate the stream bottom.

COMMENTS:

No direct harmful effects of anchor ice on fish were observed. All insects that were drifting in the ice were alive, and the ice only carried small amounts of sand from the bottom. Number of insects lost from drift would be small. Only minor flooding was observed due to ice formation.

Bjornn, T.C. 1971. Trout and salmon movements up two Idaho streams related to temperature, food, stream flows, cover and population density. Transactions of the American Fisheries Management. 5:364-378.

KEYWORDS

SALMONID
MIGRATION
FACTORS

LOCATION OF STUDY:

Lemhi River and Big Springs Cree, eastern Idaho.

STREAM CHARACTERISTICS:

The Lemhi River falls an average of 6.7 m/km, is 90.3 km long, has a maximum water level fluctuation of 0.61 m, and discharges 3.4 to 4.0 m3/s. Big Springs Creek is 8 km long, has a maximum water level fluctuation of 0.85 m, and discharges 0.8-1.0 m3/s. Daily water temperature fluctuations ranged from none to more than 14°C in the summer. During the summer, daily temperatures ranged from a minimum of 7-13°C to a maximum of 23.9°C.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

Ice was present in the streams during the winter. Effects were not discussed.

BIOLOGICAL EFFECTS OF ICE:

The study concluded that age I chinook salmon and age II or III steelhead trout migrate seaward in the spring. Downstream migration also occurred during the fall, winter and spring by pre-smolt and non anadromous fish.

COMMENTS:

In this study, both field experiments and laboratory experiments were conducted and them compared in an effort to determine which factors cause or influence fish migratory movements.

Bjornn, T.D., and J. Mallet. 1964. Movements of planted and wild trout in an Idaho river system. Transactions of the American Fisheries Society. 93:70-76.

KEYWORDS

SLUSH ICE,
ICE JAMS

LOCATION OF STUDY:

Upper Salmon River and Middle Fork of the Salmon River, Idaho.

STREAM CHARACTERISTICS:

Both streams are found in the mountains at elevations of up to 11,000 feet. These streams mostly flow through steepsided canyons and occasionally through narrow valleys. Mean discharge of the upper Salmon River is 1881 cfs and 1484 cfs for the Middle Fork of the Salmon River.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

Not discussed.

BIOLOGICAL EFFECTS OF ICE:

Both cutthroat trout and Dolly Varden followed the same movement patterns, upstream in the spring and early summer, and downstream in the fall and winter.

COMMENTS:

During the winter it is not uncommon to find slush ice and ice jams extending for many miles along both streams.

Bovee, K., J. Gore, and Dr. A. Silverman. 1978. Field testing and adaptation of a methodology to measure "in-stream" values in the Tongue River, Northern Great Plains (NGP) region. Montana University, Missoula, Montana.

KEYWORDS

RIVER ICE,
ICE THICKNESS vs.
FLOW

LOCATION OF STUDY:

Tongue River, southeast Montana.

STREAM CHARACTERISTICS:

Medium size river, average width 50 meters, average discharge 45 m3/s with a width to depth ratio of 50 to 1, contains cool water fisheries.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

The paper first presents a general background of ice types and their formation. In the discussion of observations, a regression relation between current velocity and ice thickness was given, and the relation was quoted as significant at the 1 percent level. During early stages of surface ice formation, thickness of the ice sheet was fairly uniform. As thickening continued, the rate was faster in low velocity areas than in high velocity areas. Frazil ice and anchor ice were not observed.

BIOLOGICAL EFFECTS OF ICE:

The authors hypothesized that the formation of surface ice would have its greatest impact on organisms, particularly insects, living in shallow water areas that are susceptible to freezing all the way to the bottom. A change in velocity is characteristic in certain areas of the increased roughness of the ice, which may affect organisms that are tied to a specific velocity. Generally, velocity would decrease in the shallowest areas and increase in the thalweg areas as ice formation progressed, given that discharge would not change appreciably with freeze-up. Application of the regression relation developed by the authors indicated that the greater the flow, the smaller the amount of bottom that would be frozen.

COMMENTS:

None.

Brown, C.J.D., W.D. Clothier, and W. Alvord. 1953. Observations of ice conditions and bottom organisms in the West Gallatin river, Montana. Proceedings of the Montana Academy of Sciences. 13:21-27.

KEYWORDS

ANCHOR ICE,
BOTTOM ORGANISMS

LOCATION OF STUDY:

West Gallatin River, Gallatin County, Montana.

STREAM CHARACTERISTICS:

150-300 feet wide.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

Both anchor ice and surface ice were observed at three stations in the study area. Observations indicated that anchor ice first seeded on upstream faces of rocks in riffle areas and was thickest and most extensive in riffle areas. Anchor ice formed during nighttime at subfreezing air temperatures and generally broke free and floated downstream during daytime, when incident solar radiation penetrated to the stream bottom. Aquatic organisms were seen floating along with the ice on several occasions, but no large stones were observed being lifted and carried away by the ice. Where surface ice formed, no anchor ice was found below except at the extreme outer edge. Floating slush ice often packed below the surface ice and froze to the underside.

BIOLOGICAL EFFECTS OF ICE:

Bottom organisms were observed floating with the anchor ice slush mats. Bottom organism abundance did not appear affected by anchor ice. Areas not observed to have anchor ice had a density of 3.43 m/s per sample. Areas with anchor ice observed on different occasions had densities from 3.47 m/s per sample to 4.75 m/s per sample. Organisms were found dead in sheet ice near the shore. They tested the ability of organisms to survive in freezing water in a can. They found that if any water at all were present in the can, most organisms would remain alive.

COMMENTS:

They found no apparent detrimental effect of anchor ice on bottom organisms. This was apparently because water in which organisms can live fills space between ice crystals. Apparently shore ice is the most damaging to benthic insects as they freeze in the ice when it contacts the bottom.

Butler, R.L., and V.M. Hawthorne. 1979. Anchor ice, its formation and effects on aquatic life. Science in Agriculture. 26(2).

KEYWORDS

ANCHOR ICE

LOCATION OF STUDY:

Pennsylvania (unidentified) and a film from Sagehen Creek, California.

STREAM CHARACTERISTICS: N/A

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

This article presents findings of a study of formation and biological effects of anchor ice in Sagehen Creek near Truckee, California. Anchor ice formation may temporarily alter stream bed configuration, form subsurface dams, and affect stream bed conditions. It repeats statements in the source document to the effect that anchor ice can be "very destructive to aquatic organisms".

BIOLOGICAL EFFECTS OF ICE:

Fish were observed swimming "aimlessly" through caverns of ice when anchor ice formed and the stream flooded. Fish and insects were caught in off-channel areas where they were trapped by the nightly flooding. Referred to a film "Trout Streams in Winter" that could be obtained. Greatest risks were due to low snow cover and very cold temperatures.

COMMENTS:

Calkins, D.J. 1989. Winter habitats of Atlantic salmon, brook trout, brown trout and rainbow trout. A literature review. Special Report 89-34. U.S. Army Corps Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

KEYWORDS
FLOATING ICE, ANCHOR ICE

LOCATION OF STUDY: N/A

STREAM CHARACTERISTICS: N/A

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

Paper summarizes winter ice effect on streams. In streams that had floating ice, temperatures were near 0°C, and if the temperature rose to 0.2° or 0.3°C the ice would melt in the stream. Supercooled water in rivers with ice cover may enter gravel beds, but is less likely to enter river beds with fine sediment. Also noted was how flow depth in a stream will increase as ice cover occurs on the stream due to the resulting roughness increase, even occurring with floating ice cover. Anchor and slush ice may occupy 60 to 80 percent of a stream cross-section in small streams. This may ultimately develop into surface ice.

BIOLOGICAL EFFECTS OF ICE:

This is a literature summary of winter habitat uses by several species of salmon and trout relating specifically to velocity, depth, and substrate. Presented is a summary of literature on habitat uses by life stage.

COMMENTS:

The paper presents little specific discussion of the effects of ice on fish other than citing past general literature about its importance. Concentrated on focal point habitat uses in the winter by various species.

Carstens, T. 1966. Experiments with supercooling and ice formation in flowing water. Geophysical Publications. 26:1-18.

KEYWORDS

ICE FORMATION,
HEAT TRANSPORT

LOCATION OF STUDY: N/A

STREAM CHARACTERISTICS: N/A

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

See comments.

BIOLOGICAL EFFECTS OF ICE: N/A

COMMENTS:

The paper describes cold-room experiments to investigate supercooling of water as a function of heat flux across the water/air interface and heat transport from the interior of the water mass to the surface. The experiments were made in response to the practical problem of icing of intakes in rivers with an ice regime. No study location or specific river was mentioned. Experimental results were compared with theoretical predictions or were used to formulate empirical parameterization of processes involved in frazil ice production and fate. The paper provides a good laboratory reference for examining frazil ice in natural settings.

Chisholm, I.M. 1985. Winter stream conditions and brook trout habitat use on the snowy range, Wyoming. Master's Thesis, University of Wyoming, Laramie, Wyoming. 113 pp.

KEYWORDS

STREAM ICE,
TROUT WINTER
HABITAT

LOCATION OF STUDY:

Albany County, Wyoming, tributaries to the Little Laramie River; two streams elevation 2,993 to 3,205 meters and reaches below this elevation, nine reaches at 2,280 to 2,068 meters.

STREAM CHARACTERISTICS:

Of the upper sites, most are second order with gradients ranging from 0.39 to 1.35 percent. Average daily flow during the winter ranges from 0.01 to 0.11 m3/s. One stream had an average of 0.58 m3/s. Minimum winter flow was less than 0.01 m3/s. The nine additional lower elevation sites had gradients ranging from 0.2 to 4.3 percent. These streams were third to fifth order.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

Surface ice physically excluded little stream habitat. No ice was observed at 3,205 meters elevation, and little at 3,150 and 3,120 meters. Maximum thickness of ice at these elevations was 16 centimeters, and it occurred only near the bank at pool edges. Ice was most extensive at 2,993 meters elevation, where the maximum thickness was 24 centimeters. Generally, the deepest snow was found at the highest elevations. Ice thickness was inversely correlated with snow depth. Riffles had the highest proportion of depth covered with ice. Surface ice diminished through the winter, persisting at edges of the stream and often separated from the water by an air gap. Habitat exclusion by surface ice increased with decreasing elevation. Surface ice covered from 40 percent to about 70 percent of the total cross-sectional area at elevations below 2,800 meters. Anchor and frazil ice were observed at only 3 of 13 sites. At elevations greater than 2,990 meters, anchor ice, slush, or surface ice did not impede the flow.

BIOLOGICAL EFFECTS OF ICE:

Five of seven tagged fish moved downstream in 1983-84 with an average distance of 0 to 306 meters. During 1984-85, fish movement ranged from 33 to 342 meters, the mean of 163 meters. Fish generally moved to low gradient habitats in pools, typically with velocities less than 15 centimeters per second. During 1984-85, six fish moved from high gradient areas (1.6 to 6.8 percent) to a beaver pond. Most fish selected water 30 to 46 centimeters and 60 to 76 centimeters deep.

Chisholm, I.M., W.A. Hubert, and T.A. Wesche. 1987. Winter stream conditions and use of habitat by brook trout in high-elevation Wyoming streams. Transactions of the American Fisheries Society. 116:176-184.

KEYWORDS

STREAM ICE,
TROUT WINTER
HABITAT

LOCATION OF STUDY:

Several tributaries to the Laramie River, Albany County, Wyoming; on the east slope of the snowy range. Four study reaches at high elevation; 2,993 to 3,205 meters and nine study reaches at low elevation at 2,280 to 2,868 meters.

STREAM CHARACTERISTICS:

Most low slope at 1.5 percent, some up to 4 percent; mean width 2.2 to 5.1 meters; winter flow less than 0.5 m3/s. Stream order mostly two and some three, mostly brook trout.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

Surface ice physically excluded little stream habitat. No ice was observed at 3,205 meters elevation, and little at 3,150 and 3,120 meters. Maximum thickness of ice at these elevations was 16 centimeters, and it occurred only near the bank at pool edges. Ice was most extensive at 2,993 meters elevation, where the maximum thickness was 24 centimeters. Generally, the deepest snow was found at the highest elevations. Ice thickness was inversely correlated with snow depth. Riffles had the highest proportion of depth covered with ice. Surface ice diminished through the winter, persisting at edges of the stream and often separated from the water by an air gap. Habitat exclusion by surface ice increased with decreasing elevation. Surface ice covered from 40 percent to about 70 percent of the total cross-sectional area at elevations below 2,800 meters. Anchor and frazil ice were observed at only 3 of 13 sites. At elevations greater than 2,990 meters, anchor ice, slush, or surface ice did not impede the flow.

BIOLOGICAL EFFECTS OF ICE:

Seven brook trout were monitored with radio tags. In streams with elevations greater than 2,900 meters, fish actively moved between pools. Net movement distance averaged 96 meters, and ranged from 0 to 206 meters. Five of the fish moved downstream to low gradient reaches. The next year, six of eight fish moved downstream an average distance of 163 meters. Preferred winter habitats were primarily pools with velocities less than 15 centimeters per second, often beaver ponds. Fish were usually found in water 30 to 107 centimeters deep. The authors concluded that in the region of elevations greater than 2,900 meters, water withdrawal would not compound the loss of habitat from freezing or surface ice.

However, at lower elevations, habitat loss would be worse from withdrawal because of the exclusion of habitat by surface ice.

COMMENTS:

The article suggests that snow cover and channel shape play a major role in the ice formation and potential loss of winter habitat for trout. The major loss of habitat was in riffle areas, and pools were the most selected habitat area by fish. There was no determination of whether or not changes in flow would increase the proportion of habitat loss. In areas with snow, loss is proportional to flow change. In ice areas, habitat loss is greater than the reduction of flow would suggest.

Cunjak, R.A. 1988. Physiological consequences of overwintering in streams: the cost of acclimatization? Canadian Journal of Fisheries Aquatic Sciences. 45:443-452.

KEYWORDS

TROUT
ACCLIMATIZATION

LOCATION OF STUDY:

Credit River, Ontario, Canada.

STREAM CHARACTERISTICS:

Five separate reaches were studied: three characterized as main channel and two smaller tributaries as spring creek tributaries. Spring creeks had 0 to 9 percent ice cover during the year, while the main channel sections had ice cover ranging from 22 to 39 percent of the surface. Winter discharge ranged from 0.4 to 2.2 m3/s in the main channel sections and 0.7 to 0.4 m3/s in the tributary sections. One of the spring creeks had a fairly low slope and sand and gravel as the main substrate, while some of the main channel sections had high gradient with boulder substrates.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

Not discussed.

BIOLOGICAL EFFECTS OF ICE:

In two types of trout habitat, spring creeks and main channels, trout energy reserves were depleted rapidly from late summer to early winter, with the general depletion in biological characteristics of the brook trout being similar in both the springs creeks and the main channel reaches. Condition factors of all fish decreased significantly from August to the November/December period. In the coldest streams, there was also a decrease in the number of fish in March. The implication is that a decrease in temperature from fall to winter was more stressful to the fish than the rising spring temperature.

COMMENTS:

While anchor ice was not mentioned, there was significant surface ice on the main channel streams. There was no significant difference in condition factor between fish in spring creeks with little surface ice and those in colder main channel sections with heavy ice cover. This suggests that ice conditions may not play a major role in winter survival of trout in streams.

Cunjak, R.A., R.A. Curry, and G. Power. 1987. Seasonal energy budget of brook trout in streams: implications of a possible deficit in early winter. Transactions of the American Fisheries Society. 116:817-828.

KEYWORDS
TROUT METABOLISM

LOCATION OF STUDY:

Credit River, 30 km west of Toronto; Calendon site, gradient 0.31 percent; Spring Tributary, gradient not measured; Black Creek, gradient 0.67 percent.

STREAM CHARACTERISTICS:

Calendon, 2.2 cfs in winter; Spring Tributary, 0.08 cfs in winter; Black Creek, 0.39 cfs in winter.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE: N/A

BIOLOGICAL EFFECTS OF ICE:

See comments.

COMMENTS:

This study mentions no ice or ice effects; it presents the results of studies of fish metabolism. Although brook trout continued to feed throughout the winter, their condition declined markedly from late summer to early winter, and remained low until spring. It appeared that low winter temperatures restricted the rate of food intake, which thereby limited energy intake. This restriction was believed to be responsible for the metabolic deficit condition when minimal costs of maintenance metabolism could not be offset by energy intake. Where groundwater minimized temperature fluctuations, winter deficits only occurred in reproductively spent brook trout.

Cunjak, R.A., and G. Power. 1987. The feeding and energetics of stream-resident trout in winter. Journal of Fisheries Biology. 31:493-511.

KEYWORDS

TROUT WINTER
FEEDING

LOCATION OF STUDY:

Credit River, Ontario, Canada.

STREAM CHARACTERISTICS:

This main river is a fifth order stream that drains directly into Lake Ontario. Two tributaries to this stream were studied: the North Branch, which has a gradient of 1.6 percent and discharge of 1.6 to 2.2 cubic meters per second, and the West Branch which has a discharge of 0.4 to 0.6 cubic meters per second. Brook and brown trout are the dominant species.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

The North Branch has anchor ice forming infrequently and has average surface ice cover of 22 percent. The West Branch is cooler and has a surface ice cover of 39 percent. It generally freezes sooner and thaws later than the North Branch.

BIOLOGICAL EFFECTS OF ICE:

Active feeding was observed in the winter as indicated by fish stomachs greater than 70 percent full. North Branch stomachs were fuller than those of the West Branch, which had more severe ice conditions in the winter. Brown and brook trout had similar diets in all areas. The condition factor of fish decreased from late summer to early winter, including immature fish of both species. Consumption of food was similar among all seasons studied; late summer, early winter, late winter and spring, indicating that fish actively feed in the winter. Lower feeding in West Branch was a function of lesser quantity of food available. Even though fish actually take in food in the winter, food assimilation may not be sufficient for requirements in the colder part of the year, resulting in poor condition factor. Fish were not able to digest enough food, even if their stomachs were full, to meet the energy needs in the early winter (November). The colder stream, West Branch, had a greater early winter deficiency in food intake. It also had a greater deficiency in later winter (March), possibly because of lower food availability. Colder winter climate in the West Branch retarded insect emergence, which reduced food supply.

COMMENTS:

Direct effect of ice was not discussed. Colder temperatures in the lower productivity stream appeared to increase winter energy deficiencies for trout. Although trout actively fed through the winter, they continued to lose condition factor. Because of the cold temperature, they could not assimilate the quantity of food needed. The implications are that even with sufficient food supply, fish in cold streams cannot obtain energy requirements needed to maintain condition factor.

Cunjak, R.A., and G. Power. 1986. Winter habitat utilization by stream resident brook trout and brown trout. Canadian Journal of Fisheries and Aquatic Sciences. 43:1970-1981.

KEYWORDS

TROUT WINTER
HABITAT
UTILIZATION

LOCATION OF STUDY:

Upper Credit River, Ontario, Canada; drains into Lake Ontario.

STREAM CHARACTERISTICS:

The mainstream is a fifth order stream. Shoreline vegetation includes cedar, hardwoods, and hemlock. Major species are brook trout and brown trout with some rainbow. Three streams were sampled. Calendon, with a winter discharge of 1.6 to 2.2 m3/sec, and having surface ice along its edges from November to mid-March, was the first stream. Anchor ice forms in exposed riffles and runs, but is not common. The surface ice covers about 24 percent of the stream surface mostly occurring along the shallow margins and regions less than 20 centimeters deep. The mean width is 12 meters. The second stream sampled was Spring Tributary, which is a second order stream. It has groundwater inflow of .07 cubic meters per second, no ice formations, and a mean width of 5 meters. The third stream was North Branch, which is just below the spring tributary. It has a high gradient of 16 meters per kilometer and similar discharge to Calendon. It has a mean width of 9 meters. It has more frequent anchor ice than Calendon, and surface ice covers about 22 percent of the stream.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

None described.

BIOLOGICAL EFFECTS OF ICE:

Fish were more commonly found in aggregations in the winter than in the summer. Aggregation behavior increased as the temperature dropped from 5.5 to 0.1°C. The majority of these aggregations of fish, 18 of 19, were facing or in tributaries with groundwater flow having temperatures of 2 to 6°C. Aggregations of fish were found in deeper, slower water more often in the winter than in the summer. Some of the trout were found in the bottom rubble when the temperature was less than 5°C. Fish fed less in the winter than in the summer. During the winter, fish were rarely observed in the high velocity areas. Most were found in pools, runs, and margins. Most fish, 50 to 60 percent, were found resting on the bottom in the winter. Generally, fish were not found over-wintering within the substrate. Fish may have migrated to more suitable pool habitat as winter commenced. Aggregation increased with reduced temperature because feeding occurred less. Optimal habitat may become more limited with reduced flow and increased ice cover. Large trout still stayed in the deep pools.

COMMENTS:

Direct ice effects on fish were not discussed. These streams apparently did not have extensive ice conditions. Fish were observed to aggregate in the winter, using low velocity areas as temperature decreased. It was speculated that low-velocity cover habitat may be the major habitat requirement in the winter, and food becomes less important.

Ettema, R., M.F. Karim, and J.F. Kennedy. 1984. Frazil ice formation. CRREL Report 84-18. U.S. Army Corps of Engineers. Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

KEYWORDS
FRAZIL ICE

LOCATION OF STUDY: N/A

STREAM CHARACTERISTICS: N/A

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE: N/A

BIOLOGICAL EFFECTS OF ICE: N/A

COMMENTS:

This paper discusses frazil ice formation, particularly in relation to turbulence and water temperature. It presents both analytical and experimental investigations and associated findings with respect to frazil ice formation. Rate and quantity of frazil ice formation increases with both increasing turbulence intensity and decreasing water temperature. The extent of initial supercooling of water is also an important factor.

Ferguson, H.L., and H.F. Cork. 1972. Regression equations relating ice conditions in the upper Niagara river to meteorological variables. The role of snow and ice in hydrology. Proceedings of the Banff Symposium, Alberta, Canada. September 1972. World Meteorological Organization; Geneva. 2:1314-1327.

KEYWORDS
RIVER ICE, ICE MODELING

LOCATION OF STUDY:

Upper Niagara River between Lake Erie and Niagara Falls, New York.

STREAM CHARACTERISTICS:

None given, but flow retardation of 30,000 cfs is mentioned. This is a large river.

HYDROELECTRIC PROJECT EFFECTS:

Ice production affects the amount of water available for power generation.

PHYSICAL EFFECTS OF ICE:

The work involved relating water temperature and meteorological variability to ice formation on the river. As much as 85 percent of the variance in ice flow and 80 percent of the variance in stream flow retardation by anchor ice formation were explained.

BIOLOGICAL EFFECTS OF ICE:

Not discussed.

COMMENTS:

This paper is useful for its investigation of individual terms of the thermal energy balance equation for the river expressed in a simple manner. The equation is applicable to icing of streams of all sizes, even though the importance of individual terms may vary.

Flynn, J.W. 1984. Authority, background and guidelines for department recommendations on winter flows for small hydro development. Montana Department of Fish, Wildlife and Parks.

KEYWORDS

STREAM ICE,
FISH MORTALITY

LOCATION OF STUDY: N/A

STREAM CHARACTERISTICS: N/A

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE: N/A

BIOLOGICAL EFFECTS OF ICE: N/A

COMMENTS:

This document presents a literature review of the ice effects on fish, particularly in Montana streams, where stream flow is 76 percent snow melt. The stream flow typically averages 1.4 to 2.1 percent of the annual flow during November to March. No flow withdrawals were recommended during the winter months for protection of fisheries. Fish mortality in the Gallatin River was 53 percent in the winter and 17 percent in the summer. Mortality for the Madison River was 9 to 50 percent in the winter and 9 to 33 percent in the summer. Cited literature indicated that the primary causes of winter mortality were the collapse of snow banks and bridges and the dewatering of side channels. Fish may be active in the winter but do not feed as extensively as in warmer seasons. Habitat uses are different in the winter than summer. Major conclusions presented, but not substantiated or quantified by specific studies are (1) anchor ice is a severe detriment to fish survival in winter, (2) flow reductions will lead to the worsening of stream ice conditions, in particular, the increased formation of anchor ice, and (3) increased flow will provide protection against freeze-ups. Many of the conclusions regarding cause-and-effect of ice conditions and biological and physical aspects of the stream appear to be speculative.

Gilfilian, R.E., W.L. Kline, T.E. Osterklamp, and C.S. Benson. 1972. Ice formation in a small Alaskan stream. The role of snow and ice in hydrology, Proceedings of the Banff Symposium, September 1972. 1:505-513.

KEYWORDS

ICE FORMATION,
FRAZIL ICE,
ANCHOR ICE

LOCATION OF STUDY:

Goldstream Creek, near Fairbanks, Alaska; elevation not given.

STREAM CHARACTERISTICS:

0.6 m/s mean velocity; 8 m wide; 0.6 m deep; gradient 0.12 percent.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

The presence of frazil ice and the subsequent formation of anchor ice modified the streamflow and changed the physical characteristics of the stream. Lifting and transport of anchor ice resulted in rapid redistribution of sediment. Supercooling of the stream led to immediate frazil ice formation, and if sustained for a few hours or more, abundant anchor ice formed on the bottom. Border ice also formed and grew slowly toward the center of the stream. Flow discharge decreased and stream level increased in response to anchor ice formation.

BIOLOGICAL EFFECTS OF ICE:

Not discussed.

COMMENTS:

Gill, D., and G.P. Kershaw. 1979. Ecological role of river icings in the Tsichu river valley, Northwest Territories, Canada. *In:* Snow and Ice Symposium on the Camberra Assembly, International Union of Geology and Geophysics, Canberra, Australia.

KEYWORDS

TOTAL FREEZE-UP

LOCATION OF STUDY:

Upper Tsichu River, NW Canada, 15 to 20 km east of Macmillan Pass, on the border between Northwest Territories and the Yukon; elevation 1,300 to 1,400 m.

STREAM CHARACTERISTICS:

None are given, other than it being described as a high-gradient stream with numerous riffles over bedrock outcrops.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

Total freeze-up of the stream forces water to overflow outside the stream channel and freeze. Snow cover is incorporated into the ice, creating a virtually snow-free corridor. This type of icing only occurs in regions of very long cold winters. This is an extreme example of stream icing and may not be directly applicable to the present scope.

BIOLOGICAL EFFECTS OF ICE:

Willows line the banks and moose use the clear river channel from icing as a route for feeding on the willows. Moose were not found to over-winter in the area unless icing occurred. They noted moose kills by wolves that had forced the moose out of the river channel into the higher snow where they could not escape.

COMMENTS:

This relates to larger, colder streams but it does imply that surface ice can provide habitat for some important terrestrial species.

Hoyt, W.G. 1913. The effects of ice on stream flow. Water Supply Paper 337, U.S. Geological Survey. 77 pp.

KEYWORDS
STREAM ICE, STREAM FLOW

LOCATION OF STUDY: N/A

STREAM CHARACTERISTICS: N/A

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE: N/A

BIOLOGICAL EFFECTS OF ICE: N/A

COMMENTS:

This is one of the earliest published manuscripts that concerns ice in streams. It draws upon observations of ice at many different locations, and provides descriptions of the effects of ice on stream flow characteristics. It includes brief descriptions of frazil and anchor ice and details of their formation as understood at the time. It also discusses the effects of surface ice cover on flow velocity. In general, the presence of ice increases the river stage. The documentation of ice and flow conditions at several locations makes this paper an important source of historical information. The technical content has been greatly supplemented by subsequent studies, so that more recent literature should be consulted for details of ice types and processes in streams.

Hillman, T.W., and J.S. Griffith. 1987. Summer and winter habitat selection by juvenile chinook salmon in a highly sedimented Idaho stream. Transactions of the American Fisheries Society. 116:185-1195.

KEYWORDS

FISH WINTER
HABITAT

LOCATION OF STUDY:

Red River, which is tributary to the south fork of the Clearwater River in Idaho.

STREAM CHARACTERISTICS:

The study area is a low gradient stream of 1 to 2 percent meandering through a meadow, major species include chinook and steelhead.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

No winter studies were conducted beyond November.

BIOLOGICAL EFFECTS OF ICE:

Fish migrated out of the region in fall and winter with density declining approximately 80 percent from August to November. With the inclusion of cobble into these reaches and selected areas, the population only declined 57 percent. Summer habitat used by chinook was pools and glides. They are often found over sand and gravel. Fish were often found in aggregations. In the winter, fish moved to the lateral scour pools and into shallower water than used during the summer and were usually not found in pools. They used bank sedges for cover. Trout migration occurred in the late fall when temperatures dropped from 8° to 4°C. They suggested that the major cause of out migration was lack of suitable habitat in the reach.

COMMENTS:

There was no discussion of ice in this region. The results indicate a large out-migration of chinook in the fall as temperature approach 4°C or about 80 percent of those typically rearing in the stream. Large cobble improved habitat quality and reduced out-migration of chinook.

Hunt, R.L. 1969. Overwinter survival of wild fingerling brook trout in Lawrence Creek, Wisconsin, Journal of Fisheries Research Board of Canada. 26:1473-1483.

KEYWORDS

TROUT WINTER
SURVIVAL

LOCATION OF STUDY:

Lawrence Creek, Wisconsin.

STREAM CHARACTERISTICS:

Not indicated, but stream temperature typically decreases to 0°C between 5 and 10 days per year.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

Not discussed.

BIOLOGICAL EFFECTS OF ICE:

Over-winter survival ranged from 35 to 73 percent, with a mean of 54 percent for fingerling brook trout. Two factors significantly correlated with survival were fish size and air temperature. Generally, survival rate increased with increasing fish size and decreased with decreasing air temperature. Generally, the larger the number of days during December, January, and February with air temperatures greater than 4.5°C, the greater the survival of over-wintering fingerling brook trout.

COMMENTS:

This paper does not discuss ice effects directly. It reports that low air temperatures are directly correlated with winter mortality.

Johnson, L.S., T.A. Wesche, D.L. Wichers, and J.A. Gore. 1982. Instream salmonid habitat exclusion by ice cover. Project No. B-038-WYO. Water Resources Research Institute, University of Wyoming, Laramie, Wyoming.

KEYWORDS

STREAM ICE,
HABITAT EXCLUSION

LOCATION OF STUDY:

Wagon Home Creek, Carbon County, Wyoming

STREAM CHARACTERISTICS:

Fifteen to 45 feet wide; elevation 7,420 feet; typical riffle-pool-run; mean velocity of 0.254 ft/s in September. September mean discharge ranges from 2.59 to 7.7 cfs; it contains ice cover after November. Riparian vegetation is willow, rose, cottonwood, and adjacent grazed land.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

Regression formulas were developed that related percent habitat excluded by ice with length of day, degree days of frost, mean water depth, and mean water velocity for riffle, run and pool areas. No specific physical effects of ice formation at the study area were described. In riffle areas, percent habitat excluded was positively correlated with length of day and negatively with degree days of frost, average depth, and average velocity. In run areas, percent habitat excluded was positively correlated with degree days of frost and negatively with length of day, average depth, and average velocity. In pool areas, percent habitat was positively correlated with degree days of frost and average depth, and negatively with length of day and average velocity. Measurements began on January 15 and continued to March 25. Ice thickness decreased as the study progressed. At the start of the study, about 60 to 70 percent of all three stream habitats were excluded, including runs, riffles, and pools. The greatest percentage increase in habitat over time was in riffles and runs, while pools were the last to regain most of their habitat. Velocity was not correlated with ice thickness, because surface ice formed from the shore out and not from frazil ice.

BIOLOGICAL EFFECTS OF ICE:

Not discussed.

COMMENTS:

These regression formulas did not produce accurate predictions when tested in another stream (Chisholm et al. 1987).

List, R., and L.A. Barrie. 1972. Heat losses and synoptic patterns relating to frazil ice production in the Niagara river. The role of snow and ice in hydrology, Proceedings of the Banff Symposium, Alberta, Canada. September 1972. World Meteorological Organization, Geneva. 2:1328-1338.

KEYWORDS
FRAZIL ICE

LOCATION OF STUDY:

Upper Niagara River, New York.

STREAM CHARACTERISTICS:

None mentioned; this is a large river.

HYDROELECTRIC PROJECT EFFECTS:

Not discussed.

PHYSICAL EFFECTS OF ICE:

This paper describes relationships between frazil ice production and synoptic weather patterns and investigates the heat exchange between the river and the atmosphere. Empirical heat transfer equations were developed. A surface ice cover did not form because of high turbulence intensities, and no ice advents in from Lake Erie. Therefore, virtually all ice production was due to frazil ice.

BIOLOGICAL EFFECTS OF ICE:

Not discussed.

COMMENTS:

Logan, S.M. 1963. Winter observations of bottom organisms and trout in Bridger Creek, Montana. Transactions of American Fisheries Society. 92:140-145.

KEYWORDS

STREAM WINTER
BIOLOGY

LOCATION OF STUDY:

Bridger Creek, Southwest Montana. Five miles northeast of Bozeman.

STREAM CHARACTERISTICS:

Seventeen feet wide with a mean depth of 15 inches, numerous riffles and a few deep pools, 14 inches of snow in the winter. Bank conditions of willow and brush associated with fir and aspen. Rainbow is the most abundant trout.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

Only surface and anchor ice were found in this study. Surface ice ranged from 2.5 to 4.5 inches thick. Surface ice disturbed the stream bed at edges of the channel, killing some limnephilids. Anchor ice dams did not form because of the presence of surface ice cover. Therefore, the study area did not experience sudden changes because of water surges released by collapsing anchor ice dams.

BIOLOGICAL EFFECTS OF ICE:

Water temperature had no effect on benthic organism abundance (November:285 organisms per square foot; May:104). Surface ice was common from November through March. There was no difference in the abundance of benthic insects under the ice cover and in open water. They noted that dead insects were observed where ice froze all the way to the bottom. Ice cover appeared to have no effect on abundance of bottom organisms, and bottom organisms only decreased during the high spring flows. No increase in drift was correlated with surface ice formation. Trout abundance from October 21 to April decreased to 9.6 percent. Approximately 62 percent were left on November 21. Greater than 50 percent of all marked fish recovered were within 150 feet of their original location. Downstream and upstream movements were similar; 38 percent upstream and 27 percent downstream. In spring, summer, and fall, fish were mostly in the pools, while in the winter, fish were under ice near the edges of the stream.

COMMENTS:

The only impact from ice was the freezing of insects along the shore where ice had frozen to the bank. Little anchor ice was found, and no increase in insect drift occurred where ice drift was observed. Greater than 90 percent of the fish moved less than 400 feet during the winter. Apparently, mortalities greater than 90 percent occurred in the original marked population of rainbows that were more than 7 inches long.

Maciolek, J.A., and P.R. Needham. 1952. Ecological effect of winter conditions on trout and trout foods in Convict Creek, California. Transactions of the American Fisheries Society. 18:202-217.

KEYWORDS

STREAM ICE,
STREAM WINTER
BIOLOGY

LOCATION OF STUDY:

Convict Creek, Mono County, California. On the east slope of the Sierra Nevada mountains. Elevation 7,200 feet.

STREAM CHARACTERISTICS:

Natural stream is 10 feet wide. This stream is divided into four 1/4-mile-long channels. Willows and meadows grow along the stream. Snow usually is present in the area from 2-4 feet deep in the winter. Flow during the period was 8-23 cfs for the whole stream. During the study, only two cold periods occurred during which ice formed on the stream. The stream contains mostly wild brown trout, with a few rainbow.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

Surface ice formed over quiescent pools and along stream edges in riffle areas. Frazil ice and anchor ice formation were also observed at the edges. Surface ice indirectly caused disturbance of stream banks and bottom when water surges broke it loose. Frazil ice contributed to clogging the main channel. Anchor ice formed during cold, cloudless nights, appearing first at the downstream ends of pools, second in riffles, and lastly on the bottoms of pools. Anchor ice blocked water flow into side channels and caused gradual decreases in flow volume through the nighttime hours. Subsequent breaking free of anchor ice with increased incident solar radiation on the following days liberated water and scoured the stream. Only small amounts of bottom material were lifted by anchor ice.

BIOLOGICAL EFFECTS OF ICE:

Sheet ice was used for cover by trout in the creek. On one occasion when frazil ice formed because high winds blew ice into the stream, the stream left its banks, but no adverse effect on trout was observed. The surge of water from melting anchor ice caused stream bed scour, dislodging benthic organisms. This dislodging of benthic organisms supplied food to the fish. Trout were seen to be active during the daytime. Biomass of insects in the riffles was higher in the winter than in the summer. Trout were observed feeding only during periods following peak flows when insect drift was highest. During drift net studies only infrequently were trout eggs observed, indicating little disturbance of the bottom from anchor ice, particularly red areas. Sixty-three fish were found stranded in side channels after three days of cold weather, which caused reduced flows from freezing. This was the only direct source of winter mortality observed. Some fish were observed in poor and dying conditions (7 brown trout and 4 rainbow trout) but never during freezing weather. Trout generally did well in the winter after some initial detriments occurred. Later, ice provided cover and dislodgement of food sources.

COMMENTS:

The only observed direct mortality was from stranding of fish in the side channel. Some fish eggs may have been dislodged during scour from anchor ice. Ice provided cover, and melting dislodged benthic insects that fish could feed upon. Anchor ice commonly formed at night and melted daily.

Marcus, M.D., L.E. Noel, and M.K. Young. 1990. Rating salmonid habitat research needs in the central Rocky Mountains. Fisheries. 15(5):14-18.

KEYWORDS
SALMONID HABITAT

<u>LOCATION OF STUDY</u>: N/A

<u>STREAM CHARACTERISTICS</u>: N/A

<u>HYDROELECTRIC PROJECT EFFECTS</u>: N/A

<u>PHYSICAL EFFECTS OF ICE</u>: N/A

<u>BIOLOGICAL EFFECTS OF ICE</u>: N/A

<u>COMMENTS</u>:

This article, through a survey, evaluated the research needs for streams in the central Rocky Mountains. State and federal agencies in this region were asked to rank 50 specific questions concerning the importance of fisheries habitat for future management research needs. The second highest ranked question was: "Define the determinates of winter habitat that are critical to the over-winter survival of some salmonid fisheries." This indicates that winter habitat area is of major interest to resource managers. It also suggests very little information is currently available on cold winter habitat uses by salmonids in the Rocky Mountains.

Marsh, P., and T.D. Prowse. 1987. Water temperature and heat flux at the base of river ice covers. Cold Regions Science & Technology. 14:33-50.

KEYWORDS

RIVER ICE,
ICE MODELING

LOCATION OF STUDY:

Laird River near its confluence with the Mackenzie River near Fort Simpson, N.W.T., Canada; no elevation given.

STREAM CHARACTERISTICS:

Annual mean 9,200 cfs; 700 m wide; 2 m deep; 0.037 percent slope.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE: N/A

BIOLOGICAL EFFECTS OF ICE: N/A

COMMENTS:

This study does not concern small high-gradient streams. It is useful as a reference comparison of methods for calculating heat transfer coefficients, and thus heat flux, at the base of river ice covers. Comparisons showed it is essential to consider ice roughness and to measure water temperature to a high degree of accuracy. The Colburn analogy method for calculating heat transfer coefficients agreed best with that using a temperature decay approach.

Martin, S. 1981. Frazil ice in rivers and oceans. Annual Review of Fluid Mechanics. 13:379-397.

KEYWORDS
FRAZIL ICE

LOCATION OF STUDY: N/A

STREAM CHARACTERISTICS: N/A

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE: N/A

BIOLOGICAL EFFECTS OF ICE: N/A

COMMENTS:

This is a review paper concerning frazil ice and describes general aspects of frazil ice formation, characteristics, and fate. It also provides several references for previous models of frazil ice production. No specific studies are included.

Morrill, C.F., and T.C. Bjornn. 1972. Migration response of juvenile chinook salmon to substrates and temperatures. Research Sediment Completion Report, Project A-028-IDA. Water Resources Research Institute. University of Idaho, Moscow, Idaho.

KEYWORDS
SALMON MIGRATION

LOCATION OF STUDY:

Hayden Creek, an artificial stream channel on the Lemhi River, Idaho.

STREAM CHARACTERISTICS:

None given.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE: N/A

BIOLOGICAL EFFECTS OF ICE: N/A

COMMENTS:

Ice was not discussed. However, the results regarding fish movements during periods of declining water temperature may be peripherally related to fish condition and distribution in streams that are subject to icing.

Studies were conducted to assess the effects of temperature and substrate size on out-migration of zero-age spring chinook. It was found that few fish left the artificial channels of suitable substrate, that is, large rocks 15 to 45 centimeters in diameter, and were present independent of temperature. Generally, more fish out-migrated in streams of poor substrate than in streams with good substrate; poor substrates being rocks of 1.6 centimeters or smaller in size. Out-migration began as temperatures dropped from 10° to 5°C. In some cases with poor substrate, out-migration increased as temperature dropped below 5°C. In studies with constant temperature and poor substrate, fewer fish out-migrated, but as temperature dropped, out-migration increased. It was concluded that suitable substrate in the fall reduced out-migration, but that some out-migration will still occur even when suitable substrate is present for zero-age chinook. Fish tended to go into the substrate when temperatures were less than 5 to 7°C.

Needham, P.R., J.W. Moffett, and D.W. Slater. 1945. Fluctuations in wild brown trout populations in Convict Creek, California. Journal of Wildlife Management. 9:9-25.

KEYWORDS

TROUT WINTER SURVIVAL

LOCATION OF STUDY:

Convict Creek, Mono County, California. East slope of the Sierra Nevada mountains. Elevation 7,200 feet.

STREAM CHARACTERISTICS:

Twelve feet wide with willows, aspen, and grass.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

Not discussed.

BIOLOGICAL EFFECTS OF ICE:

The only biological effect of ice or snow was the collapse of a hanging snow bank below a nearby hatchery. Several hundred first-year fish were found dead beneath the snow mass. The authors stated that smaller losses were "common," but did not elaborate. Regarding first-year trout mortality, the authors believed that severe winter conditions exert the primary influence on growth and survival. According to their observations, overwinter losses of all trout, regardless of size, were 60 percent.

COMMENTS:

This study is directed toward gathering information regarding patterns and causes of changes in trout populations, and ice effects are not discussed directly, but mentioned in "severe winter conditions." This article is useful in combination with other studies at Convict Creek.

Needham, P.R., and A.C. Jones, 1959. Flow, temperature, solar radiation, and ice in relation to activities of fishes in Sagehen Creek, California. Ecology. 40:465-474.

KEYWORDS

STREAM ICE,
WINTER FISH
ACTIVITY

LOCATION OF STUDY:

Sagehen Creek, California. Tributary to Little Truckee river located on the California-Nevada line. Elevation 6,337 feet.

STREAM CHARACTERISTICS:

Fifteen feet wide; flow ranging from 50 cfs in the spring to 2 cfs in September; forested along the banks with pine and fir. Average snow is 44 inches deep. Severe winter from mid-December to the end of March. Contains rainbow, cutthroat, and brown trout.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

Physical factors (temperature) leading to ice formation were discussed. Groundwater inflow moderates temperature in the winter. When the weather is stormy, the creek temperature may be well below groundwater temperature. Anchor ice first appeared in riffles and sometimes accumulated, creating ice dams. The influence of the slightly elevated temperatures of groundwater inflow prohibited anchor ice formation within 500 yards downstream of the groundwater entrance. Anchor ice was found in the open regions of meadows where no trees or groundwater upwelling occurred. Anchor ice formed between -9°F and 12°F. It occurred once at 26°F after a high windstorm blew snow into the stream. Anchor ice was more prevalent in December than in January through March, possibly because of increased insulation from snow during the latter period. Whenever the temperature was less than 0°F, anchor ice formed. Formation of anchor ice caused the stream level to rise an average 1.3 feet at a gaged pool. The average flow at this time was 3.5 cfs.

BIOLOGICAL EFFECTS OF ICE:

Trout were observed to feed at 32° and 33°F in the winter when frazil ice was floating down the stream. There was no directly observed mortality of fish. In the daytime, fish were observed near shelter (overhanging banks, root wads), and more were seen out in the stream at night. At night, trout maintained close contact with the substrate, often with fins touching the bottom. Bottom organisms were apparently abundant and active in the winter.

COMMENTS:

No loss of fish due to ice was documented, although substantial periods of anchor ice occurred. Anchor ice caused substantial increase in stream elevation and some drop of flow, (not quantified). Anchor ice dislodged benthic organisms that were thought to increase food for fish. Fish actively fed in the winter even at 32°F with frazil ice in the water. Speculation was that dewatering of streambed areas due to ice jams and ice in riffle areas could affect fish, but no such effects were actually observed. Frazil ice can form in streams although the temperature is not very cold if high winds blow in substantial quantities of snow.

Needham, P.R., and D.W. Slater. 1944. Survival of hatchery-reared brown and rainbow trout as affected by wild trout populations. Journal of Wildlife Management. 8(5):22-36.

KEYWORDS
ANCHOR ICE

LOCATION OF STUDY:

Convict Creek, north of Bishop, California; elevation 7,200 ft.

STREAM CHARACTERISTICS:

2 cfs; 12 ft. wide; 2 percent grades.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

Anchor ice formed on the bottom of riffle areas, and snow blown into the water drifted against the anchor ice, forming dams. Water levels rose up to 2 or 3 feet, forming pools upstream of the dams. Pools would freeze over. Sunlight on following days caused melting and breakup, usually removing all ice formed the previous night. Snow banks broke off into the water occasionally, covering bottom and fish.

BIOLOGICAL EFFECTS OF ICE:

COMMENTS:

Nielson, R.S., N. Reimers, and H.D. Kennedy. 1956. A six-year study of the survival and vitality of hatchery-reared rainbow trout of catchable size in Convict Creek, California. California Fish and Game. 42:5-6.

KEYWORDS

TROUT WINTER
SURVIVAL

LOCATION OF STUDY:

Convict Creek, Mono County, 35 miles north of Bishop, California.

STREAM CHARACTERISTICS: N/A

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

Heavy snow collapsed into the stream: (1) crushing/suffocating fish; (2) suffocating fish throughout the dewatered length of the stream; and (3) stranding fish when elevated water levels receded. Snow cover inhibited formation of anchor ice.

BIOLOGICAL EFFECTS OF ICE:

Mortality is high in small streams for wild trout as well as for hatchery trout. In winters when conditions are extreme and protracted, mortality is exceptionally high and more drastic among hatchery-reared trout than among wild trout.

COMMENTS:

None.

Osterkamp, T.E. 1978. Frazil ice formation: A review. Journal of the Hydraulic Division, American Society of Civil Engineers. 104:1239-1255.

KEYWORDS
FRAZIL ICE

LOCATION OF STUDY: N/A

STREAM CHARACTERISTICS: N/A

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

See comments.

BIOLOGICAL EFFECTS OF ICE: N/A

COMMENTS:

As the title indicates, this is a review article; no specific study or study location is mentioned. The article covers supercooling of water leading to frazil ice formation, the nucleation process that initiates formation, physical properties of frazil ice, the growth rate of frazil ice crystals, and the quantification of frazil ice production. It combines information from previous sources with basic mathematical descriptions of thermodynamic processes. One notable result is that frazil ice crystal growth rate is proportional to the square root of velocity of supercooled water flowing past it. Thus, the relative velocity between suspended ice crystals and water may only be a few centimeters per second. However, the relative velocity becomes equal to the mean flow velocity as soon as the crystal becomes attached to some stationary point, and the result is a striking increase in growth rate of the crystal. Accumulation and growth of frazil ice on submerged objects may thus occur rapidly once the process has begun.

Osterkamp, T.E., R.E. Gilfilian, and C.S. Benson. 1975. Observations of stage, discharge, Ph, and electrical conductivity during periods of ice formation in a small sub-arctic stream. Water Resources Research. 2:268-272.

KEYWORDS

FRAZIL ICE,
ANCHOR ICE

LOCATION OF STUDY:

Goldstream Creek near Fairbanks, Alaska.

STREAM CHARACTERISTICS:

0.5 cfs; 8 m wide; 0.6 m deep; gradient is 0.12 percent.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

Frazil ice suspended in the stream flow reduced velocity profiles and increased the stage. Anchor ice and border ice formation decreased discharge during two episodes of underwater ice production by 31 and 55 percent, respectively. Ice formation reduced flow by storing water in the form of ice and causing upstream water storage by flow obstruction.

BIOLOGICAL EFFECTS OF ICE: N/A

COMMENTS:

None.

Osterkamp, T.E., and J.P. Gosink. 1982. Ice cover development on interior Alaska streams. Geophysical Institute, University of Alaska, Fairbanks, Alaska.

KEYWORDS
STREAM ICE

LOCATION OF STUDY:

Yukon River, Goldstream Creek, Tanana River.

STREAM CHARACTERISTICS:

None included.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

See comments.

BIOLOGICAL EFFECTS OF ICE:

Not discussed.

COMMENTS:

This is a very good background paper on ice in streams. It presents a thorough discussion of ice types, the physical processes associated with their formation and growth, and factors that influence their formation and growth. This paper also includes photographs illustrating various observations concerning stream ice. It does not present results of particular studies, but reviews and clarifies physical aspects of ice in streams and the associated processes.

Pariset, E., and R. Hausser. 1961. Frazil ice and flow temperature under ice covers. The Engineering Journal (Canada) EIC. January 1961. pp. 46-49.

KEYWORDS
FRAZIL ICE

LOCATION OF STUDY: N/A

STREAM CHARACTERISTICS: N/A

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

See comments.

BIOLOGICAL EFFECTS OF ICE: N/A

COMMENTS:

This paper is a combination of theoretical and empirical investigations into alleviating the problem of frazil ice accumulation on intakes in rivers subject to icing. There is no specific, related field study. It examines frazil ice formation, transport, deposition, and sticking properties as well as water temperature variations under river ice covers. While some general physical parameters and descriptions of ice processes may apply to any type of supercooled flow, the work and results presented are primarily aimed at very large river systems.

Pariset, E., R. Hausser, and A. Gagnon. 1966. Formation of ice covers and ice jams in rivers. Journal of the Hydraulics Division, American Society of Civil Engineers, pp. 1-23.

KEYWORDS
SURFACE ICE, ICE JAMS

LOCATION OF STUDY: N/A

STREAM CHARACTERISTICS: N/A

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE: N/A

BIOLOGICAL EFFECTS OF ICE:

Not discussed.

COMMENTS:

This paper presents a theoretical analysis of ice cover formation and thickening on large rivers. It may be a useful source of parameters that relate to ice freeze-up processes.

Platts, W.S., and R.L. Nelson. 1989. Stream canopy and its relationship to salmonid biomass in the intermountain west. North American Journal of Fisheries Management. 9:446-457.

KEYWORDS

SALMONID
PRODUCTIVITY

LOCATION OF STUDY:

Seventeen study areas were selected in the northern Rocky Mountains and the Great Basin of the western U.S., specifically Idaho, Nevada, and Utah.

STREAM CHARACTERISTICS:

All streams studied generally had high temperatures during the summer and cold temperatures (high potential for heavy icing) during the winter.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

Not discussed.

BIOLOGICAL EFFECTS OF ICE:

Stream canopy conditions studied were: canopy density, light intensity, unobstructed sun arc, and average daily thermal input in both grazed and ungrazed habitat. Results showed that thermal input can be a potential measurement index of salmonid productivity in some riparian habitats.

COMMENTS:

Purpose of study was to investigate possible relationships between stream (riparian overstory) canopy conditions, salmonid biomass, and livestock grazing.

Reichmuth, D.R., D.D. Findorff, and M.J. Leaverton. 1988. Evaluation of the potential for anchor ice formation along a reach of the Falls River, Idaho. Revised April 22, 1988. Geomax. P.C. Bozeman, Montana.

KEYWORDS

FRAZIL ICE,
ANCHOR ICE

LOCATION OF STUDY:

Falls River, Eastern Idaho, Fremont County, east of Marysville.

STREAM CHARACTERISTICS:

300-400 cfs in winter; 200 feet wide; 1.1 feet deep; slopes of 0.004 to 0.008.

HYDROELECTRIC PROJECT EFFECTS:

Proposed diversion would reduce winter flows in the bypassed reach to approximately 160 cfs. Ice formation will not affect hydro project.

PHYSICAL EFFECTS OF ICE:

As long as the area of open water remains approximately constant, the formation rate of frazil ice and anchor ice will not increase due to reduced flow in the bypassed reach. Reduced flow may increase production of surface ice cover and reduce production of frazil ice and anchor ice.

BIOLOGICAL EFFECTS OF ICE:

Not discussed.

COMMENTS:

None.

Reimers, N. 1963. Body condition, water temperature, and over-winter survival of hatchery-reared trout in Convict Creek, California. Transactions of the American Fisheries Society. 92:39-46.

KEYWORDS
TROUT MORTALITY

LOCATION OF STUDY:

Convict Creek, California; elevation 7,200 feet; discharge 5 to 15 cfs.

STREAM CHARACTERISTICS: N/A

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

Not discussed.

BIOLOGICAL EFFECTS OF ICE:

The summer survival of catchable size, hatchery trout from August to November averaged 87 percent, ranging from 70 to 97 percent. Winter survival (November through May) of these hatchery trout ranged from 2.8 to 69 percent, with an average of 27 percent. Mortality generally increased by month through the winter as fish condition factors decreased. No sudden increase in mortality occurred that would indicate catastrophic events. The author mentioned that the same mortality was not observed in wild fish, but did not provide references or study results.

COMMENTS:

This article does not directly address causes of winter mortality other than the loss of condition factor. No catastrophic mortalities were observed during the winter. However, winter conditions were average or better than average in this region during the study. Catastrophic events such as side channel dewatering and snow bridge collapse may not generally occur under these environmental conditions.

Reimers, N. 1957. Some aspects of the relation between stream foods and trout survival. California Fish and Game. 43-69.

KEYWORDS

TROUT WINTER
SURVIVAL,
STREAM ICE

LOCATION OF STUDY:

Convict Creek, Mono County, California; elevation 7,200 feet.

STREAM CHARACTERISTICS:

6 to 15 feet wide; bottom gravel and rubble; long riffles; few deep pools; about 2 percent grade.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

Anchor ice and slush ice were observed. Slush ice was likely a combination of wetted snow, frazil ice, and refloated anchor ice. Anchor ice formation produced ice dams that caused fluctuations in flow by water backing up behind dams and then being released suddenly as the dams collapsed. The result was deterioration of stream bottom habitat by exposing areas to partial drying, freezing, and rewatering. Snow and ice bridged the creek, and occasional collapses due to weight of the cover filled the channel, forming backwaters. Snow bridges also caused periods of darkness up to 4 months long in the stream bed below. Surges of refloated anchor ice, slush ice, and released water scoured the bottom of the creek episodically. Radical changes in flow were judged more harmful to bottom dwelling populations than partial snow and ice cover. The importance of physical abrasion of fish by slush and ice was noted.

BIOLOGICAL EFFECTS OF ICE:

In the darkness under snow bridges, the stream bottom became devoid of algal growth, which reduced the population of larger bottom organisms that serve as food for fish. Scouring of the bottom by surges of water and slush and disruption of the bottom by formation and dissipation of anchor ice also reduced bottom-dwelling populations. Formation and dissipation of anchor ice set bottom-dwelling organisms adrift in the stream, where they became more accessible to fish for food. Comparison of observations from two different years with different snow and ice conditions led the author to surmise (recognizing the statistical limitations of observations) that "populations of bottom-dwelling organisms are apparently harmed less by partial snow and ice cover than by repeated exposure to the radical changes in flow that accompany subsurface ice action." The total effect of ice and snow is a gradual depletion of available trout food through the winter.

Controlled starvation experiments were conducted in a hatchery trough exposed to the gamut of winter ice conditions versus one subjected only to surface ice formation, and in open stream versus pond environment. The results suggested that physical factors such as abrasion by slush and ice, crushing or suffocation beneath collapsed snow and ice bridges, and stranding by fluctuations in flow were major influences on winter trout survival. Of secondary effect was quantity of food, and experiments indicated that assimilation rate rather than food quantity controls trout nourishment in water near the freezing point. The overall conclusion is that the physical effects of water conditions are more important than food regarding overwinter losses of catchable-size trout.

COMMENTS:

This paper is based upon direct observations and a sequence of controlled exposure and starvation experiments. Results are presented in a detailed and straightforward manner, making this a useful information source concerning trout survival in small streams that are subject to snow and ice effects in winter.

Reiser, D.W., and T.A. Wesche. 1975. In situ freezing as a cause of mortality in brown trout eggs. The Progressive Fish-Culturist 41(2):58-60.

KEYWORDS

TROUT EGG
MORTALITY

LOCATION OF STUDY:

Laramie River, Wyoming; 35 km west of Laramie.

STREAM CHARACTERISTICS:

Transition zone between steep gradient and low gradient meandering section. Average discharge is 2.8 m3/s, during the study it was 1.4 m3/s.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

In an 80-ft.-long study area of the river, sheet ice completely covered the pool area and anchor ice covered the substrate in the riffle area. No frazil ice was observed. Intra-gravel ice formed and contributed to trout egg mortality is a controlled experiment.

BIOLOGICAL EFFECTS OF ICE:

Brown trout eggs were placed 15 to 18 centimeters deep in riffle areas in water depth of 6 to 36 centimeters, with a 31 centimeter mean depth. Upon removal in March, only one percent of the eggs survived. Three of the twenty samples were completely frozen. The author suggested that gravel freezes due to the slow movement of supercooled water through the substrate. These results suggest that freezing of the substrate occurs to a depth of 12 to 20 centimeters even in the absence of frazil ice. This freezing may cause high mortality among fish eggs buried in the substrate.

COMMENTS:

Assuming that temperatures increase enough that substrate freezing does not occur after approximately March or April, then it can be inferred that egg/sac fry of fall/winter spawning salmonids may face greater risk of freezing mortality than for spring-spawning salmonids.

Santeford, H.S., G.R. Alger, and J.A. Stark. 1986. Ice in streams--its formation and effects on flow. US Geological Survey Report 86-4209. Lansing, Michigan.

KEYWORDS

STREAM ICE,
ICE MODELING

LOCATION OF STUDY:

Sturgeon River near Sidnew, Sturgeon River near Nahma Junction, Red Cedar River near Williamston, all in Michigan.

STREAM CHARACTERISTICS:

30 to 100 cfs; 65 to 100 ft. wide; 1 to 10 ft. deep; moderate slope.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

Formation of surface ice cover over an open channel changed the water-surface profile and the stage-discharge relation. Extent of the change depended upon the nature and location of the ice cover relative to the measurement site. Where elevation controlled stage and discharge, floating ice cover had no effect on the flow. Elevation controls include those features that generally act as weirs. Other such features are inlets or outlets from lakes or reservoirs, adverse slopes, and major channel constrictions. Where resistance dominated, the stage-discharge relation was a function of geometry, ice roughness, and buoyant displacement of ice. Resistance controls are features, such as channel roughness or an ice cover, that produce frictional resistance to flow. No frazil ice or anchor ice were observed in the study or considered in the development of an analytical model relating ice-covered profile to open-water profile and stage to discharge.

BIOLOGICAL EFFECTS OF ICE:

Not discussed.

COMMENTS:

None.

Scarnecchia, D.L., and E.P. Bergersen. 1987. Trout production and standing crop in Colorado's small streams, as related to environmental features. North American Journal of Fisheries Management. 7:315-330.

KEYWORDS
TROUT PRODUCTION

LOCATION OF STUDY:

Ten small streams in northern Colorado; elevations ranging from 2,146 to 3,139 m.

STREAM CHARACTERISTICS:

Stream order one to three; width 1.5 to 4.7 m; containing brook, brown, and mostly cutthroat trout; discharges ranges from 0.01 to 0.14 m3/s in the summer.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE: N/A

BIOLOGICAL EFFECTS OF ICE:

The studies correlated specific factors to trout production and biomass. Elevation had the highest single correlation to trout production and biomass, that is, the greater the elevation, the lower the trout production and biomass. The next most important factors were conductivity, alkalinity, hardness, and substrate diversity. It was concluded that elevation had the best correlation with production because only streams with good habitat were included. Lower elevation streams that may have had less suitable trout habitat were not used. The step-wise model, after elevation was entered, found that stream width-to-depth ratio was the most important in predicting trout production.

COMMENTS:

Stream ice effects were not assessed. The fact that lower production occurs at the higher elevations suggests that longer, colder winters, independent of the possibility of increased snow cover, which reduces ice cover (as indicated in other articles), may result in poor production. Although not stated, it is expected that the winters would be longer at higher elevations than at the lower elevations.

Schaefer, V.J. 1950. The formation of frazil and anchor ice in cold water. Transactions of the American Geophysical Union. 31:885-893.

KEYWORDS

FRAZIL ICE,
ANCHOR ICE

LOCATION OF STUDY:

No formal study was made, although informal observations were made at North Creek, Mohawk River, and Cutler River in New York; elevation was not given.

STREAM CHARACTERISTICS:

None given.

HYDROELECTRIC PROJECT EFFECTS:

Frazil ice collected on intake trash racks, with potential to shut down the powerplant within an interval of about 1 hour.

PHYSICAL EFFECTS OF ICE:

The author describes observations of frazil and anchor ice formation. Frazil ice formed in supercooled water in turbulent areas. It collected on underwater objects such as rocks, chains, bars, or plants. The author distinguished between accumulations of frazil ice on the bottom and the formation of anchor ice. This distinction is no longer held in more recent literature.

BIOLOGICAL EFFECTS OF ICE:

None presented.

COMMENTS:

This is largely anecdotal information in which the observations are generally consistent with contemporary studies.

Schrader, W.C. 1989. Trout mortality, movements, and habitat selection during winter in south Willow Creek, Montana. Master's Thesis, Montana State University, Bozeman, Montana.

KEYWORDS

STREAM ICE,
TROUT WINTER
BEHAVIOR

LOCATION OF STUDY:

South Willow Creek, Gallatin County, Montana. Tributary to Jeffery River southwest Montana.

STREAM CHARACTERISTICS:

Average slope 4 percent; elevation 1,829 meters; third order stream; small high gradient. There were three study sections. The lower had a width of 6.9 meters, the middle had a width of 6.6 meters and both had a slope of 4 percent, consisting of rapids and cascades. The upper section had an average width of 6.9 meters and a low gradient of 1.2 percent, mostly riffles and some pools. Substrate was mostly boulders greater than 256 millimeters, and the lower and middle sections were cobble from 65 to 256 millimeters in the upper section. The banks consisted mainly of willows and alders with some pine and fir. Mostly rainbow trout were present. Discharge during the year ranged from 0.4 to 11 m3/s. Winter discharge was less than 0.5 m3/s.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

Anchor ice was common in the upper and lower sections when air temperatures were less than -18°C. It never occurred in the middle section. Surface ice was common in the middle section from October to April, although this was not quantified.

BIOLOGICAL EFFECTS OF ICE:

Average winter abundance of rainbow trout decreased 32 percent and standing crop 30 percent from fall to spring. Fifteen rainbow trout longer than 225 millimeters were radio tagged. Movement during the winter averaged 114 meters but was 65 meters when adjusted for direction. Lowest section had some fish movement upstream, while movement in the others was both directions along the streams. Of five fish released in pools greater than 1 meter deep, four remained in these pools all winter. Of fish released into pools less than 0.5 meters deep no number given in the thesis, probably 5 or 6, only one remained. Fish preferred the deepest water with cover habitat. Fifty percent of the fish in the upper section and 80 percent of the fish in the lower and middle sections used pools, particularly high-quality pools. Ice was only observed being used for cover twice. The thesis presented a summary of winter mortality from other studies, in which mortality ranged from 46 to 97 percent. Condition of fish remained good, and fish were observed feeding in the winter on insects dislodged by anchor ice. Absolute and relative mortalities of fish were similar in the upper and lower sections, which had sporadic and extensive anchor ice, to mortalities in the middle section, which did not have anchor ice presumably because of the presence of surface ice. Catastrophic mortality from snow and ice events may not be as important as earlier thought, and that snow and ice disturbance may in fact be beneficial. Greater than 90 percent of all tagged fish recovered were in the original marked section of the stream, indicating little winter movement.

COMMENTS:

This study was designed to determine winter habitat use in a future small-hydro diversion reach. Ice conditions were not quantified, but there were no differences in winter mortality between regions with extensive anchor ice and those areas without anchor ice. Movement of large rainbow trout was limited in the winter, with preferred habitat being pools greater than 0.5 meters deep with cover. Ice was rarely used as cover. Mortality in this study was low, at 32 percent, relative to other winter mortality studies quoted in the thesis.

Smith, R., and Dr. J. Griffith. Researchers find greatest enemy of Idaho fish: it's winter.

KEYWORDS

TROUT WINTER
BEHAVIOR

LOCATION OF STUDY:

Henry's Fork River, Idaho.

STREAM CHARACTERISTICS:

None provided.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

Not discussed.

BIOLOGICAL EFFECTS OF ICE:

Concealment cover is needed in the winter. Rainbow trout select habitat with a velocity range of 0 to 6 centimeters per second near high-velocity areas. As concealment cover decreases in the winter (loss of macrophytes), juvenile rainbow abundance decreased. Fish moved from 1.5 kilometers downstream to .85 kilometers upstream in winter, in response to the loss of shoreline habitat as water level dropped. Caged fish studies showed that fish condition and water temperature were major factors influencing fish survival. Generally, the colder the water in the winter, the greater the condition factor that fish needed in the fall for them to survive through winter.

COMMENTS:

This article was received from FERC with insufficient information to identify the source citation details.

Tack, E. 1938. Trout mortality from the formation of suspended ice crystals. Fisherei-Zeitung. 41:42 (Reviewed in Progressive Fish-Culturist 1937-38).

KEYWORDS

TROUT MORTALITY

LOCATION OF STUDY:

Hatchery Pond, Germany.

STREAM CHARACTERISTICS: N/A

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

High wind coupled with freezing temperatures caused ice crystals to be mixed homogeneously in the water of a hatchery pond. Surface ice could not form.

BIOLOGICAL EFFECTS OF ICE:

Out of several thousand rainbow trout fingerlings in a pond beset by an overnight freeze accompanied by high winds, about 100 died. Fish examined immediately after death showed mouths and gills plugged with small masses of ice sufficient to cause asphyxiation. Larger fish (no size quoted) in a neighboring pond subject to the same conditions experienced no difficulty from the ice crystals.

COMMENTS:

Study indicates fish can die directly from ice crystals in water.

Tsang, G., and L. Szucs. 1972. Field experiments of winter flow in natural rivers. The role of snow and ice in hydrology. Proceedings of the Banff Symposium, Alberta, Canada, September 1972. World Meteorological Organization; Geneva. 1:772-785.

KEYWORDS

RIVER ICE,
FRAZIL ICE,
ANCHOR ICE

LOCATION OF STUDY:

Nottawasaga River, southwestern Ontario, Canada and Peace River, Alberta, Canada.

STREAM CHARACTERISTICS:

230 cfs. minimum; 80 ft. wide.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

Channel resistance increased as surface ice cover increased. The result was an increase in stage and decrease in flow velocity and volume. Ice formed first at the edges of the rivers and progressed toward the center. Decreasing water temperatures led to frazil ice production, which then froze onto the border ice and contributed to ice coverage. Most frazil ice formed during night and in early morning. No anchor ice was observed. Ice cover thickened through accretion of frazil ice produced upstream, accumulation and freezing of precipitation on top of the ice, and continued freezing of water to the bottom surface of the ice. Development of the ice cover caused very active lateral sediment transport as a result of changing velocity profiles. Ice cover breakup began with moderating temperature and progressed quickly over the course of a week. Discharge increased from 230 cfs to 700 cfs.

BIOLOGICAL EFFECTS OF ICE:

Not discussed.

COMMENTS:

None.

Walsh, M., and D. Calkins. 1986. River ice and salmonids. 4th workshop on hydraulics of river ice, Montreal. U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

KEYWORDS

RIVER ICE,
SALMONID WINTER
MORTALITY

LOCATION OF STUDY: N/A

STREAM CHARACTERISTICS: N/A

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

This is a review article that draws upon previously published studies. It presents a useful qualitative/quantitative discussion of stages of ice formation and growth in streams. Major points are that freeze-up may lead to ice occupying up to 70 percent of the stream cross section; frazil ice deposited underneath an ice cover appears to accelerate growth of the solid ice sheet; fraziling may extend approximately into the bottom substrate; and ice jams can cause the stage in shallow streams to rise up to 1 m.

BIOLOGICAL EFFECTS OF ICE:

See comments.

COMMENTS:

This article presents a literature summary of the effects of river ice on habitat of Atlantic salmon. The authors indicate four factors that were detrimental to over-winter survival: (1) crowding of juveniles from ice reduced habitat areas, (2) migration caused from overcrowding, (3) solid ice growth into the substrate, and (4) high velocity during ice cover breakup. Atlantic salmon juveniles move into the substrate in the winter below cobble and boulders up to 15 centimeters deep in the substrate. Low winter air temperatures and low winter discharge reduce egg-to-fry survival of Atlantic salmon. Frazil ice, in combination with surface ice, will increase freezing to the bottom. Freezing to the bottom may be the major problem for survival. Factors that inhibit ice growth into the substrate include snow cover and air voids from water level drops, geothermal heat, and high friction energy. Snow bridging is a form of insulation that is more common on narrow streams. For over-wintering Atlantic salmon, cover such as boulders is of primary importance, as these fish often penetrate into the substrate. Exact mechanisms of over-winter mortalities have not been defined, but key factors are stream depth and flow volume.

Wankiewicz, A. 1984. Analysis of winter heat flow in an ice-covered Arctic stream. Canadian Journal of Civil Engineering. 11:430-443.

KEYWORDS
ICE MODELING

LOCATION OF STUDY:

Caribou Creek near Inuvik, N.W.T., Canada; elevation not given.

STREAM CHARACTERISTICS:

0.5 cfs; width typically 6 m; depth typically 0.4 m; gradient not given.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE: N/A

BIOLOGICAL EFFECTS OF ICE: N/A

COMMENTS:

This paper is not directly applicable to small high-gradient streams. It also contains no discussion of biological effects. The paper presents a model of channel ice growth in the stream and a comparison of model results with observations. It may be useful as a source of modeling techniques and parameters for heat transfer processes associated with ice formation in flowing streams.

Wichers, D.L. 1978. Telemetric determination of salmonid winter microhabitat occupation and movement in ice-covered streams. Master's Thesis, University of Wyoming, Laramie, Wyoming.

KEYWORDS

SALMONID WINTER
BEHAVIOR

LOCATION OF STUDY:

Albany County, Laramie River near Jehn, Wyoming.

STREAM CHARACTERISTICS:

Discharge range from a maximum daily discharge of 4,200 cfs to a minimum of 5.6 cfs and in the winter, is near 32 cfs. Ice cover persists from late November through February. Elevation is 7,739 feet, banks contain willow, alder and grass, and hayfields are common. Contains good brown trout populations.

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE:

Details of ice formation were not recorded during this study. Relative to ice-free conditions, the presence of ice reduced volume flow by about 4 percent, decreased water depth by 17 percent, and increased flow speed by 25 percent.

BIOLOGICAL EFFECTS OF ICE:

Sixteen brown trout, in excess of 11.5 inches long, were tagged and tracked from late fall into the winter for a period of no more than three months. Of all brown trout studied during the summer, 36 percent used water greater than 1.5 ft. deep, preferring low velocity regions less than 0.5 feet per second. After ice cover, the fish used low velocity regions, but preferred shallower water 0.55 to 0.99 feet deep. The fish apparently used ice as cover in the winter. Average ice thickness where most fish were often found was 1.34 feet. Majority of movement in September, October, and November was upstream, possibly based on spawning runs. As temperature cooled, movement decreased. Fish that were collected from other regions and moved tended to migrate back to their original region. Average distance moved by fish was 700 feet, with a maximum of 1,900 feet. The fish used rubble and ice for cover during the winter.

COMMENTS:

This study was done on a stream of medium size, moderate slope, and mostly covered with ice. It did not address anchor ice, as it was not a problem in this area.

Wichers, D.L., T.A. Wesche, L.S., and Johnson, J.A. Gore. 1982. Two techniques for locating and sampling brown trout microhabitat under complete ice cover. Water Resources Research Institute Report 83. University of Idaho, Moscow, Idaho.

KEYWORDS
COMPLETE ICE COVER

LOCATION OF STUDY:

STREAM CHARACTERISTICS:

HYDROELECTRIC PROJECT EFFECTS:

PHYSICAL EFFECTS OF ICE:

BIOLOGICAL EFFECTS OF ICE:

COMMENTS:

The information contained in this paper re-iterates the findings presented in Wichers, D.L. 1978. Telemetric determination of salmonid winter microhabitat occupation and movement in ice covered streams. Masters Thesis, University of Wyoming, Laramie, Wyoming. Refer to that citation for annotations.

Wigle, J.E. 1970. Investigations into frazil, bottom ice, and surface ice formation in the Niagara River. Proceedings of the International Association for Hydraulic Research Ice Symposium 1970, Reykjavik, Iceland.

KEYWORDS

FRAZIL ICE,
ANCHOR ICE

LOCATION OF STUDY:

Upper Niagara River between Lake Erie and Niagara Falls.

STREAM CHARACTERISTICS:

190,000 cfs; average depth is 12 feet; no other data were given.

HYDROELECTRIC PROJECT EFFECTS: None

PHYSICAL EFFECTS OF ICE:

This river is definitely not a small, high-gradient system. However, the paper does present results of observations which showed that frazil and anchor ice did not form on sandy bottom, but only on rocky substrate. Frazil ice formation and flocculation were also observed.

BIOLOGICAL EFFECTS OF ICE: N/A

COMMENTS:

None.

Williams, G.P. 1972. A case history of forecasting frazil ice. The role of snow and ice in hydrology. Proceedings of the Banff Symposium, Alberta, Canada. September 1972. World Meteorological Organization; Geneva. 2:1212-1223.

KEYWORDS
FRAZIL ICE, ICE FORECASTING

LOCATION OF STUDY:

Ottawa River, between Ottawa, Ontario and Hull, Quebec, Canada.

STREAM CHARACTERISTICS:

None given, this is a large river system.

HYDROELECTRIC PROJECT EFFECTS:

Frazil ice collection on intakes affects operation.

PHYSICAL EFFECTS OF ICE:

Rate of heat loss at a given site gives an indication of potential magnitude of frazil ice formation. For this study, frazil ice was a problem when water was at or very near the freezing point and heat loss averaged more than 30 cal/cm^2 per hour over the preceding 12-hour period. Convective heat loss was the most important factor affecting frazil ice formation, but long-wave and short-wave radiation and evaporation exerted strong influence, depending on weather conditions. Heat exchanges were greater in early fall, when the area of open water was greater relative to spring breakup. This meant that in fall, the winter temperature decreased faster than it increased in spring. Water temperatures in early fall were still above freezing.

BIOLOGICAL EFFECTS OF ICE:

Not discussed.

COMMENTS:

None.

No author listed. No date, but literature as recent as 1984 is cited. Effects of winter conditions on fish life of eastern sierra streams of Inyo and Mono Counties. California Department of Fish and Game.

KEYWORDS

STREAM ICE,
WINTER FISH
MORTALITY

LOCATION OF STUDY:

No study was made.

STREAM CHARACTERISTICS: N/A

HYDROELECTRIC PROJECT EFFECTS: N/A

PHYSICAL EFFECTS OF ICE: N/A

BIOLOGICAL EFFECTS OF ICE: N/A

COMMENTS:

This is a literature review concerning effects of winter conditions on streams and associated biological populations. It does not describe studies actually carried out in streams in Inyo and Mono counties, California, but rather infers probable effects on the basis of published findings from other studies. Major causes of winter mortality were speculated to be snow bank/bridge collapse and scouring and dewatering caused by anchor ice. The data presented did not support directly that anchor ice is the direct cause of mortality. This document is a good summary of the behavior of trout in winter and the alleged effects that occur in trout populations during winter.

This article is Attachment A of a document originated by the California Department of Fish and Game. The article was received from FERC with insufficient information to identify the source citation details.