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INTRODUCTION

The Region III Forest Practices Riparian Management Committee Literature Review and Annotated Bibliography compiles published research relevant to riparian management issues in interior Alaska. Region III covers the boreal forest in Alaska north of the Alaska Range. At present, most commercial forest activity in Region III occurs in the Tanana River basin, with a small amount of commercial harvesting in the Kuskokwim River basin. Commercial operations could occur in other areas in the future.

The Alaska Forest Resources and Practices Act (AS 41.17) governs forestry operations on state, municipal, and private land. The Act is designed to protect fish habitat and water quality, while ensuring that management standards are workable for landowners and operators. The Act sets standards for riparian area management. On public land in Region III, harvesting may not occur within 100 feet of an anadromous or high value resident fish water body unless adequate protection remains for the fish habitat. On private land, harvesting within 100 feet of an anadromous or high-value resident fish water body must be located and designed primarily to protect fish habitat and surface water quality from significant adverse effects. Regulations that accompany the Act (11 AAC 95) establish best management practices for harvesting, roading, and reforestation.

The Act also specifies that the management intent for riparian areas is to maintain ten habitat components:

- large woody debris,
- stream bank stability,
- channel morphology,
- water temperatures,
- stream flows,
- water quality,
- adequate nutrient cycling,
- food sources,
- clean spawning gravels, and
- sunlight.

In 1997, the Alaska Board of Forestry asked the Department of Natural Resources and the Department of Fish and Game to review the riparian management standards for Interior Alaska (Region III). The departments convened an interdisciplinary committee to do the science and technical review. The committee included fisheries biologists, hydrologists, and forest ecologists geomorphologists, foresters, soil scientists with scientific knowledge about Alaskan fisheries, riparian habitats, aquatic ecosystems, and interactions between forest practices, fish habitat, and water quality, and experienced field staff from the agencies. This group, the Region III Riparian Management Committee was charged with developing a waterbody classification system for interior Alaska, reviewing the existing riparian management standards, and if needed, recommending changes to the standards. The Board recognized that research from interior Alaska is scarce, and asked the Committee to review relevant literature from local research and from other areas as part of the review of riparian management standards.

The Committee identified seven key topics that merited literature review:

- Bank stability
- Large woody debris
- Permafrost and silty soils
- Winter fish use of glacial streams
- Fish use of upwellings
- Buffer function and design
- Ice Thickness and Ice Bridges

Volunteers from the Committee conducted a broad search of publications on each topic. References for publications relevant to conditions in Region III were collected and annotated, and an introduction compiled for each section. The bibliographies and introductions were submitted to the full committee for review and editing. This document compiles the seven review topics.

Questions about this document may be directed to the DNR Division of Forestry, Forest Practices Program Manager, 555 W 7th Avenue, Anchorage, AK 99501 (907-269-8473) or the ADF&G Habitat & Restoration Division, P.O. Box 25526, Juneau, AK 99802-5526 (907-465-4105).

BUFFER FUNCTION AND DESIGN

An Annotated Bibliography

Compiled for the
Region III Forest Practices Riparian Management Committee

by
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SUMMARY

Natural forests adjacent to water bodies can contribute all of the ten habitat components listed in the FRPA, AS 41.17.115, which were discussed in the Introduction. The relative importance of each component to maintaining fish habitat and water quality varies with differences in the physical and other characteristics of the water body, such as stream width (or lake size), gradient, incision depth, bank characteristics, and average, seasonal, and peak flow.

Research has demonstrated the importance of maintaining forested conditions along water bodies that are naturally forested. In the 1990s, this research began to be incorporated into forest practices-related laws and regulations. In Alaska, the FRPA, Tongass Timber Reform Act, and Tongass Land Management Plan (TLMP) revision each prescribe mandatory buffers for certain types of fish-bearing (and, in the case of TLMP, some non-fish-bearing) water bodies. Buffer widths vary, based on different water body classifications, which are in turn based on different physical stream characteristics, and the presence of anadromous fish. The TLMP standards use the classification of Paustian (1992). These buffers were designed for the relatively small stream systems found in Southeast Alaska. Murphy (1995) provides a good summary of buffer-related research conducted in Alaska, and riparian management recommendations that have been applied in Southeast Alaska. The Tongass Land Management Plan (1997) and the FRPA revisions of 1999 update Murphy's summary of existing buffer standards. Some of the Southeast Alaska (and Pacific Northwest) research is applicable to streams and lakes in Interior Alaska that share similar physical characteristics.

There are five primary fish habitat-related functions of riparian forests. First, trees entering the stream through natural mortality due to senescence, wind throw, or bank erosion provide large woody debris (LWD) to the water body. LWD forms stream and fish habitat features, controls the movement of gravel and sediment, contributes energy to streams, and provides a substrate for the growth of organisms. Second, energy input to the stream is derived from leaf litter, macro-invertebrates, and other energy sources that fall from trees into the water body. Third, the forest acts to control water temperature, by shading in warm conditions, and by heat retention and wind reduction in cold conditions. Fourth, for streams and other water bodies having banks held in place by vegetation, trees provide stability to stream banks and floodplains. Fifth, riparian vegetation has been shown to function as a filter for sediment and pollutants from adjacent sites.

Buffers are, by definition, natural vegetation left along the banks of a water body in the course of conducting a land-disturbing activity. This definition implies that the buffer has a finite width, starting at the water body, and ending at some point where the activity occurs. The alteration of the vegetation beyond the edge of the buffer means that the buffer boundary is exposed to conditions different from those in the natural forest. The edge of the buffer receives more sunlight, and is exposed to prevailing winds. From a design standpoint, then, in addition to the buffer width that is appropriate for the site conditions, buffer stability is an issue. If the objective of leaving a buffer is to maintain a rate of LWD input plus bank or flood plain stability not significantly different from the natural rate or conditions, then any factors that lead to premature loss of the buffer are undesirable. Buffer blowdown (or windthrow), tree mortality from engraver beetles (*Ips* spp.) around harvest units, and rapid bank erosion along dynamic stream reaches can reduce the number of trees in a buffer, and decrease the recruitment pool for LWD. Reid and Hilton (1998), Steinblums, et al (1984) and others discuss this aspect of buffer design. The Tongass National Forest Land Management Plan (U.S. Forest Service, 1997) requires both a no-cut buffer and an additional area to be managed "to provide for a reasonable assurance of windfirmness."

The utility of buffers for protecting fisheries habitat on reaches of larger river systems where banks are not held in place by vegetation, such as reaches of the Tanana, Kuskokwim, Yukon, and Porcupine Rivers in northern Alaska has not been studied as thoroughly as have smaller systems, where banks are either held in place by vegetation or controlled by bedrock. Two reasons for this lack of knowledge are that: 1) the role of LWD in larger rivers is not as well understood, and 2) LWD recruitment processes in these river systems are different from and more variable in both space and time than those in smaller, more stable streams.

To date, literature found by the Stream Classification Committee (SCC) suggests that LWD concentrations, such as jams, in large rivers may play an important role in stream morphology. This role contrasts with smaller, less dynamic streams, where wood often plays an important role in the area of the stream immediately adjacent to the point of input. For example, island, bar, and slough formation, and bank protection in larger rivers can all be initiated or maintained by concentrations of LWD. Therefore, the primary reason for leaving a buffer on such a system or reach may primarily be to provide wood to the stream system in general, rather than for the site where the tree enters the stream. For more information on the role of buffers in providing LWD to large rivers, see the SCC Large Woody Debris literature review, including the article by Abbe and Montgomery (1996), and Bryant and Sedell (1995).

The role of riparian forests (and buffers) and LWD in providing nutrients and other fish habitat-forming functions in large, dynamic river systems is also not well known. The articles by France et al. (1996), Wipfli (1997) and Piccolo and Wipfli (in press) discuss allochthonous input of nutrients such as leaf litter, macroinvertebrates, and wood from forest stands adjacent to streams.

The role of buffers in regulating stream temperature is well documented. Buffers for this purpose are routinely left in the Pacific Northwest and other areas of the continental U.S. Several references discuss this aspect of buffer function, including O'Laughlin and Belt (1995) and Johnson and Ryba (1992). Stream temperature regulation has been identified as an issue in the Interior with regard to low-gradient, slow flowing water bodies, such as backwater sloughs. Buffer width for temperature regulation is primarily a function of tree height, sun angle, and stream width.

Finally, the LWD recruitment processes along large rivers vary both spatially and temporally. Factors such as bank height, tree size, permafrost, channel complexity, seasonal flows, and natural rates of bank erosion make these processes both complex and dynamic. These factors make the proper prescription of buffers on larger, more dynamic stream systems more difficult, compared to smaller stream systems. The appropriate buffer prescription may vary over different reaches of a river, even though factors typically used for stream classification, such as width, depth, gradient, etc. may not change. Further, a prescription made at one point in time may only be appropriate for a limited period of time, as the stream or river characteristics often change.

In summary, while a “one size fits all” approach to buffers may work in many cases for smaller and more stable stream channel types, it is not likely that one riparian area management recommendation will be appropriate to all reaches of a larger, dynamic river system. Further, while there are some similarities, the reasons why buffers are appropriate on large river systems differ from those for smaller streams. In the short term, due to the lack of hard data on large rivers, these differences in buffer prescriptions will, to some extent, have to be inferred or deduced, based on what is known about natural processes on large, dynamic systems. The SCC has concluded that the most appropriate distinction to make in classifying stream systems for the purposes of applying buffers is whether the banks of the reach in question are held in place by vegetation and/or bedrock, or whether bank erosion by the stream is the dominant process. See the SCC Bank Stability literature review for more discussion of this point.

The following literature review includes references on the role and design of buffers on glacial and non-glacial, and large and small streams. However, most work that has been done on riverine systems has been on smaller non-glacial river systems, as the citations show. Bryant and Sedell (1995) provide additional references for work done on larger river systems.

The literature review used an on-line search by the Alaska Resources Library and Information Services (ARLIS). Additional articles came from the ADF&G files in Juneau, and from other members of the committee. Annotations are primarily authors' abstracts.

REFERENCES

Bren, L. J. 1993. Riparian zone, stream, and floodplain issues: a review. Journal of Hydrology 150:277-299.

In the last two decades, the effects of forest management on streams, riparian zones, and floodplains have become of much interest. In general, there is agreement that such areas should maintained in a state approximating naturalness, although it is recognized that definition of this state is usually difficult or impossible. A diversity of management effects has been recognized and , in some cases quantified. For upland catchments, issues particularly relate to direct disturbance of the zone, changes in the flow of woody debris into the stream, or disturbance to the environment by effects generated upstream or downstream. For many areas, a particularly important commercial aspect is the definition of a 'stream', as this can impose many expensive and severe restrictions on management of the land. For large rivers, a common issue is the effect of river management on flooding forests. In each case, the issues are complex, information is difficult to collect, and there are fundamental difficulties in going from anecdotal observation to data. Currently, most information appears to be at a relatively local level, and there is a very inadequate knowledge base to five a more holistic overview, although the concept of 'cumulative effects', with the effects accumulated over both space and time, has much potential value. There are many opportunities for work in this field.

Bren, L. J. 1998. The geometry of a constant buffer-loading design method for humid watersheds. Forest Ecology and Management 110:113-125.

Riparian buffer strips are used in forestry to protect streams from possible adverse effects of forest harvesting or other land uses. For any given stream reach, a buffer loading can be defined as the contributing watershed area per unit area of buffer. The study used a large (66 km^2) mountain watershed as a prototype. To allow accurate computation this was divided into facets by forming a flow net to the maximum accuracy of the 1:25,000 contour coverage. With fixed width buffers, the buffer loading was both highly variable and also independent of the Strahler order of the stream. Thus, the rationale of having larger buffers on larger streams does not seem justified. The study considered a buffer-strip design in which each element of stream buffer had exactly the same ration of upslope-to-buffer area, giving a constant buffer loading. Computation of the buffer for each facet used an iterative procedure to achieve a satisfactory shape and position of the buffer boundary within each facet. The method gave a much more substantial protection to (convergent) channel sources and less protection to divergent areas than a fixed-width buffer design. The buffers defined also were highly asymmetric and discontinuous. The buffers defined reflected the topography, and were strongly influenced by small facets close to the stream. In cases where flow lines run close to and approximately parallel to the streams, the buffers defined were also non-intuitive. The method is predicated on the subsurface hydrology flow paths being close to those given by surface flow lines and this is not always true. Of importance is the finding that, relative to the mean protection offered, fixed-width buffers tend to underprotect slope convergences at the heads of streams and overprotect divergent areas found along streams of increasing order.

Burckhardt, J. C., and B. L. Todd. 1998. Riparian forest effect on lateral stream channel migration in the glacial till plains. Journal of the American Water Resources Association 34:179-184.

Dendrochronology analyses of point bar complexes were used to quantify the effects of riparian forests on local lateral migration of bends in seven streams in the glacial till plains of north central Missouri. Stream bends were paired with similar bank height, midchannel radius of curvature, soil composition, and watershed size. In each pair, one concave bank was forested and one was unforested. Stream bends with unforested concave banks had an average local migration rate three times greater tan stream bends that had forested concave banks.

Davies, P. E., and M. Nelson. 1994. Relationships between riparian buffer widths and the effects of logging on stream habitat, invertebrate community composition and fish abundance. Australian Journal of Marine and Freshwater Research 45:1289-1305.

Impacts from the logging of Eucalyptus forest on stream habitat, macroinvertebrate abundance and diversity, and fish abundance were surveyed in Tasmania, Australia. Forty-five pairs of sites from 34 streams of greater than or equal to 2.5 km super (2) catchment area were each sampled once during summer in the period 1990-92. Each site pair consisted of an 'impacted' site downstream of a logging treatment and an upstream or closely matched 'paired control' site. Site pair treatments encompassed two logging methods (cable and conventional) with a range of riparian buffer strip widths (0-50 m) and included unlogged controls. Differences between site pair variables were used as test statistics for the detection of logging impacts. Logging significantly increased riffle sediment, length of open stream, periphytic algal cover, water temperature, and snag volume. Logging also significantly decreased riffle macroinvertebrate abundance, particularly of stoneflies and leptophlebiid mayflies, and brown trout abundance. All effects of logging were dependent on buffer strip width and were not significantly affected by coupe slope, soil erodibility or time (over one to five years) since logging. All impacts of logging were significant only at buffer widths of <30 m. Minimum buffer widths for eliminating logging impacts on stream habitats and biota are discussed.

Dwyer, J. P., D. Wallace, and D. R. Larsen. 1997. Value of woody river corridors in levee protection along the Missouri River in 1993. Journal of the American Water Resources Association 33:481-489.

Following the Midwest flood of 1993, a study was initiated along a 39-mile segment of the Missouri River to determine if there was an association between woody corridors and levee stability. A systematic sample of levee failures revealed that primary levees which did not fail had a significantly wider woody corridor than failed levees. Analysis of the total inventory of failed levees revealed that as the width of the woody corridor decreased, the length of the levee failure increased. Number of levee failures and their severity of damage could be reduced if woody corridors were at least 300 feet wide.

Fennessy, M. S., and J. K. Cronk. 1997. The effectiveness and restoration potential of riparian ecotones for the management of nonpoint source pollution, particularly nitrate. Critical Reviews in Environmental Science and Technology 27:285-317.

The interface found where rivers meet terrestrial systems is an ecotone that has a profound influence on the movement of water and waterborne contaminants. Maintaining or restoring ecotone functions and characteristics such as natural near stream vegetation and channel morphology are important means to safeguard water quality in agricultural landscapes. A riparian buffer zone of 20 to 30 m width can remove up to 100% of incoming nitrate. Denitrification is the major pathway of removal and rates depend on nitrate loadings, carbon availability, and hydrology. Denitrification occurs throughout the year as long as subsurface hydrology is intact, whereas plant uptake of nitrogen is limited to seasonal removal. Nitrate removal is favored in forested areas with subsurface flow and is less in grassed areas with surface flow. The balance between surface and subsurface flows and the redox conditions that result are critical to nitrate removal in riparian ecotones. Surface retention of nutrients and sediment is a function of slope length and gradient, vegetation density, and flow rates. Plant communities play a major role in nitrogen cycling by acting as a source of carbon for denitrifying bacteria, direct uptake of nutrients, and creating oxidized rhizospheres where nitrification can occur. Restoration of riparian zones requires knowledge of the area's hydrology and ecology, as well as clear goals for the project. Restoration of riparian zones for water quality improvement may provide higher economic benefits than allocating the same land to crops. While it is possible to restore the functions of natural floodplain systems, existing restoration techniques are in their infancy and success cannot be guaranteed, especially given the extent of hydrological modification that has occurred in most developed countries.

France, R. L. 1997. Potential for soil erosion from decreased litterfall due to riparian clearcutting: Implications for boreal forestry and warm- and cool-water fisheries. Journal of Soil and Water Conservation 52:452-455.

One of the most overt consequences of catchment clearcutting is increased soil erosion, which can seriously affect fish stocks. Riparian stands around 10 northwestern Ontario lakes, clearcut 4 to 10 years previously, were found to produce only 60% of the litterfall of nearby uncut riparian forests. As a result of this decrease in protective ground surface cover, the retention of organic duff within deployed mesh-bags, was significantly reduced in clearcut riparian zones. A rainfall simulation experiment further suggested that the erosion of sandy loam can be twice as great under litterfall conditions representative of clearcut, compared to forested shorelines. Due to the potential for increased soil erosion from clearcutting, Ontario should consider a return to its pre-1985 policy of preventing timber harvesting around "warm-" and "cool-water" lakes that contain percid and esocid sportfish and often support a lucrative commercial cyprinid baitfishery.

France, R., H. Culbert, and R. Peters. 1996. Decreased carbon and nutrient input to boreal lakes from particulate organic matter following riparian clear-cutting. Environmental Management 20:579-583.

The plankton communities of oligotrophic Canadian Shield lakes are strongly regulated by the allochthonous supply of total phosphorus (TP) and dissolved organic carbon (DOC), a proportion of both of which originate from particulate organic matter. Although decreased inputs of allochthonous leaf litter have been documented for small streams whose riparian forests have been removed, no such data exist for boreal lakes. Through estimates of airborne litter input from forested and clear-cut shorelines and laboratory measurements of concentrations released from leaf leachate, we determined that riparian deforestation resulted in reductions of DOC from 17.8 to 0.4 g/m shoreline/yr and of TP from 2.9 to 0.3g/m shoreline/yr. Previous predictive models indicate that such reductions may be substantial enough to decrease basic metabolic processes of lake plankton communities by as much as 9% in primary production and 17% in respiration.

France, R., R. Peters, and L. McCabe. 1998. Spatial relationships among boreal riparian trees, litterfall and soil erosion potential with reference to buffer strip management and coldwater fisheries. Annales Botanici Fennici 35:1-9.

Litter cover is known to protect ground surfaces from raindrop impact and therefore reduces soil erosion. Significant differences were found to exist in the abundance, composition and size of trees, in their litter production rates, and in the resulting potential for soil erosion of the foreshore (0-20 m from shorelines) compared with the backshore (20-50 m upslope) regions of riparian zones around four boreal lakes located in northwestern Ontario, Canada. These findings support a global pattern wherein litter production adjacent to waterbodies is often considerably reduced compared with that characteristic of upland forests. This study therefore raises questions of the presumed effectiveness of existing forestry guidelines concerning widths of protective buffer strips around boreal, coldwater lakes in Ontario, which are presently based on an erroneous assumption of uniform tree cover and litterfall throughout riparian zones.

Frissell C. A., W. J. Liss, C. E. Warren, and M. D. Hurley. 1986. A hierarchical framework for stream habitat classification: viewing streams in a watershed context. Environmental Management 10:199-214.

Classification of streams and stream habitats is useful for research involving establishment of monitoring stations, determination of local impacts of land-use practices, generalization from site-specific data, and assessment of basin-wide, cumulative impacts of human activities on streams and their biota. This article presents a framework for a hierarchical classification system, entailing an organized view of spatial and temporal variation among and within stream systems. Stream habitat systems, defined and classified on several spatiotemporal scales, are associated with watershed geomorphic features and events. Variables selected for classification define relative long-term capacities of systems, not simply short-term states. Streams and their watershed environments are classified within the context of a regional biogeoclimatic landscape classification. The framework is a perspective that should allow more systematic interpretation and description of watershed-stream relationships.

Gilliam, J. W. 1994. Riparian wetlands and water quality. Journal of Environmental Quality 23:896-900.

Because of wet soils adjacent to the streams, riparian buffers are frequently present between farming and urban activities on the uplands and small streams. These riparian areas have been shown to be very valuable for the removal of nonpoint-source pollution from drainage water. Several researchers have measured > 90% reductions in sediment and nitrate concentrations in water flowing through the riparian areas. The riparian buffers are less effective for P removal but may retain 50% of the surface-water P entering them. I consider riparian buffers to be the most important factor influencing nonpoint-source pollutants entering surface water in many areas of the USA and the most important wetlands for surface water quality protection.

Johnson, A.W. and D. M. Ryba. 1992. A literature review of recommended buffer widths to maintain various functions of stream riparian areas. Prepared for King County Surface Water Management Division. Aquatic Resource Consultants, Renton, WA. 29pp.

This paper examines available scientific literature on the function of riparian areas along streams. Specifically, we reviewed literature containing recommendations for buffer widths to maintain those functions, and various methodologies for setting buffer widths.

Some commonly recognized functions of stream riparian zones include:

1. stabilizing streambanks and preventing erosion;
2. filtering suspended solids, nutrients, and harmful or toxic substances;
3. moderating the microclimate of a riparian system; and
4. supporting and protecting fish and wildlife species and providing migration corridors.

In small and intermediate-sized streams in then Pacific Northwest, riparian vegetation directly influences the physical conditions of the stream environment. The roots of riparian vegetation stabilize streambanks, retard erosion, and create overhanging cover for fish. The above-ground portions of plants dissipate the energy of storm flows, obstruct the movement of sediment and detritus, and provide large organic debris to streams.

The effects of land uses on riparian areas can be multiple and varied. The effect depends on the type of land use, degree of disturbance to streamside vegetation, size of stream, physical setting, and succession after disturbance. While land use may vary, the resulting environmental alterations generally affect riparian systems in similar ways.

Buffer widths for stream and wetland habitats may be established using two general methods. These are fixed width to protect specific functions, or a variable width that considers specific site conditions. Fixed- or variable-width buffers each have advantages and drawbacks. An agency's available resources and constraints will figure strongly in the final choice of how buffers will be set.

Widths for vegetated buffers recommended by various investigators vary widely depending on the specific resource or function to be maintained. Buffer widths recommended by 38 separate investigators to maintain seven major riparian functions ranged from 3 to 200 meters (m). From our review, it appears buffers less than 10 m provide little if any maintenance of various riparian functions. Buffers of 15 to 30 m provide minimal maintenance for most functions; buffers greater than 30 m appear adequate for most functions. Despite whether a fixed or variable width buffer is to be established, we recommend a *minimum* buffer distance of 15 to 30 m. This distance will vary depending on the riparian function to be maintained.

Lisle, T. E., and M. B. Napolitano. 1998. Effects of recent logging on the main channel of North Fork Caspar Creek. Pages 81-86 *in* Ziemer, R.R., editor. Proceedings of the Conference on Coastal Watersheds: The Caspar Creek Story. USDA Forest Service, Pacific Southwest Research Station, PSW-GTR-168.

The response of the mainstem channel of North Fork Caspar Creek to recent logging is examined by time trends in bed load yield, scour and fill at resurveyed cross sections, and the volume and fine-sediment content of pools. Companion papers report that recent logging has increased streamflow during the summer and moderate winter rainfall events, and blowdowns from buffer strips have contributed more large woody debris. Changes in bed load yield were not detected despite a strong correlation between total scour and fill and annual effective discharge, perhaps because changes in stormflows were modest. The strongest responses are an increase in sediment storage and pool volume, particularly in the downstream portion of the channel along a buffer zone, where large woody debris (LWD) inputs are high. The association of high sediment storage and pool volume with large inputs of LWD is consistent with previous experiments in other watersheds. This suggests that improved habitat conditions after recent blowdowns will be followed in future decades by less favorable conditions as present LWD decays and input rates from depleted riparian sources in adjacent clearcuts and buffer zones decline.

Lowrance, R., L. S. Altier, J. D, Newbold, R. R. Schnabel, P. M. Groffman, J. M. Denver, D. L. Correll, J. W. Gilliam, J. L. Robinson, R. B. Brinsfield, K. W. Staver, W. Lucas, and A. H. Todd. 1997. Water quality functions of riparian forest buffers in Chesapeake Bay watersheds. Environmental Management 21:687-712.

Maryland, Virginia, and Pennsylvania, USA, have agreed to reduce nutrient loadings to Chesapeake Bay by 40% by the year 2000. This requires control of nonpoint sources of nutrients, much of which comes from agriculture. Riparian forest buffer systems (RFBS) provide effective control of nonpoint source (NPS) pollution in some types of agricultural watersheds. Control of NPS pollution is dependent on the type of pollutant and the hydrologic connection between pollution sources, the RFBS, and the stream. Water quality improvements are most likely in areas of where most of the excess precipitation moves across, in, or near the root zone of the RFBS. In areas such as the Inner Coastal Plain and Piedmont watersheds with thin soils, RFBS should retain 50%-90% of the total loading of nitrate in shallow groundwater, sediment in surface runoff, and total N in both surface runoff and groundwater. Retention of phosphorus is generally much less. In regions with deeper soils and /or greater regional groundwater recharge (such as parts of the Piedmont and the Valley and Ridge), RFBS water quality improvements are probably much less. The expected levels of pollutant control by RFBS are identified for each of nine physiographic provinces of the Chesapeake Bay Watershed. Issues related to establishment, sustainability, and management are also discussed.

Mann, D. H., C. L. Fastie, E. L. Rowland, and N. H. Bigelow. 1995. Spruce succession, disturbance, and geomorphology on the Tanana River floodplain, Alaska. Ecoscience 2:184-199.

A long-standing paradigm in the ecology of the Alaskan taiga states that black spruce (*Picea mariana* [Mill.] BSP) replaces white spruce (*Picea glauca* [Moench] Voss) after several centuries of primary succession on flooodplains. According to this Drury Hypothesis, autogenic thickening of organic horizons and shrinking of the active layer interact with the species' different physiological tolerances to cause black spruce dominance. We test the Drury Hypothesis on >200-year-old portions of the Tanana River floodplain near Fairbanks, Alaska, and reject it. In the meander belt portion of the study area, white spruce mixed with black spruce persists on geomorphic surfaces approximately 3,000 years old. Predictions of the Drury Hypothesis regarding active-layer and organize-horizon thicknesses are not substantiated. Neither of these variables correlates with the abundances of the different spruce species. Forest communities in the study area are distributed along geologically based environmental gradients and are shaped by secondary succession following fires and probably floods. Black spruce dominates in the poorly drained, permafrost-rich, and fire-prone backswamp and white spruce in the oppositely characterized meander belt. Although geological chronosequences can be identified along avulsion-prone rivers like the study reach of the Tanana River, superposition of a meander belt-backswamp plan and frequent fire and flood disturbances may negate any vegetation chronosequences older than several centuries.

Martin, D. J., M. E. Robinson, and R. A. Grotefendt. 1998. The effectiveness of riparian buffer zones for protection of salmonid habitat in Alaska Coastal Stream. Prepared for Sealaska Corporation, Juneau AK, and Alaska Forest Association, Ketchikan AK.

For this study, low-elevation aerial photographs were used to delineate potential LWD sources and these date were used to determine the effects of buffer zones on the short- and long-term supply of LWD. We used annual channel survey data from a four-year period (1994-197) to monitor changes in LWD recruitment and to examine the interaction between LWD, channel morphology, and fish habitat. The findings of this study concur with previous research and add new knowledge concerning the relative sensitivity of fish habitat to changes in LWD in different geomorphic channel types. The results show that LWD is most important for the formation of pools and contributes to the retention of gravel that forms spawning habitat. Increases in LWD loading can increase the frequency of small to medium pools, which improves the quantity and quality of salmonid rearing habitat. The relative effectiveness of LWD to form habitat is a function of channel type and the amount of LWD in the stream.

The analysis of 38 riparian zones and more than 11,000 trees indicates that nearly all (mean 94%) of the recruitable size trees in the riparian zone (i.e., tall enough to become LWS) occur within 20 m of the stream. Selective timber harvest in the standard buffer zones removed from 1% to 12% of the original stand. This harvest, in addition to windthrow following logging, did not significantly diminish the potential supply of LWD from the 0-10 m zone. The study shows that a 20-m buffer zone is more effective for providing LWD than a wide buffer (>20 m) or an unlogged area. Examination of tree densities at 15 standard 20-m buffer zones four to six years after logging indicated that the capacity of these buffers to maintain a future supply of LWD was directly related to the pre-harvest recruitable tree density.

The results of this study indicate that implementation of the current buffer regulation should include evaluation of stand composition for buffer zones adjacent to alluvial channels (Type A waters). The results also show that windthrow may reduce the potential long-term supply of LWD in a small percentage of the buffer zones. Planning buffer zones to increase the probability of LWD recruitment could improve the quantity and quality of fish habitat in streams that have a naturally low supply of LWD (e.g., channels formed in a mixture of alluvial and cobble/boulder bed materials, Type A and some Type B waters). In these channels LWD recruitment rates are minimized by the low frequency of bank erosion, landslides, and windthrow. Therefore, formation of fish habitat is limited by the ED recruitment rate, which will not improve without some type of buffer disturbance. Buffers wider than 20 m will maintain the natural recruitment rate, but a narrower buffer (e.g., 20-m wide) could increase the probability of LWD recruitment. In this case, designating buffers to take advantage of natural disturbances may provide more long-term benefits to fish habitat than might otherwise occur under natural conditions.

Mason, O. K., and J. E. Begét. 1991. Late Holocene flood history of the Tanana River, Alaska, U.S.A. Arctic and Alpine Research 23:392-403.

The Tanana River basin in central Alaska drains both the north slope of the Alaska Range and the south slope of the Yukon-Tanana upland. A sequence of historic and prehistoric flood deposits of the Tanana River is preserved in a small bedrock-sheltered slough near Fairbanks. Examination of these deposits using a suite of radiometric dates, microstratigraphic observation, and granulometric statistics suggests that large changes in flood frequency occurred during the late Holocene. Three major lithostratigraphic units are observed: (1) thick cross-bedded, pedogenically unaltered alluvial silty sands which were deposited between 3000 and 2000 yr BP, recording an interval of large floods; (2) a series of this silty beds and paleosols forms after 23000 yr BP during an interval when large floods were uncommon; and (3) a sequence of sand units recording large floods during the last several hundred years. Flood frequencies appear to have changed in response to regional climatic changes, with more frequent flooding occurring during times of widespread alpine glaciation and increase storminess.

Murphy, M. L. 1995. Forestry impacts on freshwater habitat of anadromous salmonids in the Pacific Northwest and Alaska--requirements for protection and restoration. NOAA Coastal Ocean Program Decision Analysis Series No. 7. NOAA Coastal Ocean Office, Silver Springs, MD.

This synthesis presents a science overview of the major forest management issues involved in the recovery of anadromous salmonids affected by timber harvest in the Pacific Northwest and Alaska. The issues involve the components of ecosystem-based watershed management and how best to implement them, including how to: Design buffer zones to protect fish habitat while enabling economic timber production; Implement effective Best Management Practices (BMPs) to prevent nonpoint-source pollution; Develop watershed-level procedures across property boundaries to prevent cumulative impacts; Develop restoration procedures to contribute to recovery of ecosystem processes; and Enlist support of private landowners in watershed planning, protection, and restoration. Buffer zones, BMPs, cumulative impact prevention, and restoration are essential elements of what must be a comprehensive approach to habitat protection and restoration applied at the watershed level within a larger context of resource concerns in the river basin, species status under the Endangered Species Act (ESA), and regional environmental and economic issues. This synthesis 1) reviews salmonid habitat requirements and potential effects of logging; 2) describes the technical foundation of forest practices and restoration; 3) analyzes current federal and non-federal forest practices; and 4) recommends required elements of comprehensive watershed management for recovery of anadromous salmonids.

Murphy, M. L., J. Heifetz, S. W. Johnson, K V. Koski, and J. F. Thedinga. 1986. Effects of clear-cut logging with and without buffer strips on juvenile salmonids in Alaskan streams. Canadian Journal of Fisheries and Aquatic Science 43:1521-1533.

This research paper reports the results of field studies conducted in southeastern Alaska that were designed to assess the short-term effects of logging on the density and habitat use of streams by juvenile coho salmon, steelhead, cutthroat trout, and Dolly Varden in old growth forest and in clearcuts with and without stream buffers. All streams were apparently nonglacial. Winter and summer habitat use was examined. Old growth forest contained Sitka spruce and western hemlock. Clearcuts were 1 to 12 years old with trees cut to both streambanks. Buffered reaches were on 3 to 10 year old clearcuts: one bank had a strip of uncut streamside trees 15 to 130 m wide; the other side had undisturbed forest.

Clearcut stream reaches had less undercut bank, canopy density, pool volume, and debris and more periphyton than old growth reaches. Clearcut reaches were less stable than old growth reaches, having significantly greater point bar formation, sediment packing, and scour and deposition. Buffered reaches had more debris than old growth reaches but did not differ consistently from old growth reaches in any other habitat variable. Most pools were formed by debris, and pool volume and debris volume were positively related. Periphyton biomass and benthos density were positively related.

Summer density of coho fry averaged more than two times greater in both buffered and clearcut reaches than in old growth reaches. Summer fry density was directly related to periphyton biomass and benthos. The more periphyton a reach had, the more fry it had, and the clearcut and buffered reaches with open canopy and abundant periphyton had the most fry. In winter, density of coho salmon fry was still greater in buffered than in old growth reaches. Clearcut reaches no longer had significantly more fry than old growth reaches. Both summer food abundance and debris appeared to influence winter density of coho fry. The more periphyton a reach had in summer and the more debris, the more fry it had in winter. Summer food abundance limited summer fry densities and quality of winter habitat (i.e., debris) determined winter survival.

Coho salmon parr were equally abundant in old growth, buffered, and clearcut reaches in summer, but significantly less abundant in clearcut than in old growth reaches in winter. If debris was left in clearcut reaches, or added in buffered reaches, coho salmon parr were abundant (10 to 22/100 m^2) in winter. If debris had been removed from clearcut reaches, parr were scarce (<2/100 m^2) in winter.

Nakamoto, R. J. 1998. Effects of timber harvest on aquatic vertebrates and habitat in the North Fork Caspar Creek. Pages 87-96 *in* Ziemer, R. R., editor. Proceedings of the Conference on Coastal Watersheds: The Caspar Creek Story. USDA Forest Service, Pacific Southwest Research Station, PSW-GTR-168.

[The author] examined the relationships between timber harvest, creek habitat, and vertebrate populations in the North and South forks of Caspar Creek. Habitat inventories suggested pool availability increased after the onset of timber harvest activities. Increased large woody debris in the channel was associated with an increase in the frequency of blowdown in the riparian buffer zone. This increase in large woody debris volume increased the availability of pools. No dramatic changes in the abundance of young-of-the-year steelhead, yearling steelhead, coho, or Pacific giant salamanders were directly related to logging. High interannual variation in the abundance of aquatic vertebrates made it difficult to contrast changes in abundance between pre-logging and post-logging periods. Changes in channel morphology associated with increased volume of large woody debris in the channel suggest that yearling steelhead, coho, and Pacific giant salamanders may benefit from logging in the short-term because of increased living space. However, over a longer time scale these conditions will probably not persist (Lisle and Napolitano, these proceedings).

O'Laughlin, J., and G. H. Belt. 1995. Functional approaches to riparian buffer strip design. Journal of Forestry 93(3):29-32.

The term buffer strip include functional descriptions such as filter, stabilization, or leave strips, and administrative designations such as Idaho's Stream Protection Zone, Oregon's Riparian Management Area, Washington's Riparian Management Zone, and the USDA Forest Service's Streamside Management Zone. This article summarizes the functions of buffer strips and describes three approaches to their design. These are FPA, the Forest Practices Act regulations for implementing the Clean Water Act in northwestern states; FEMAT/PACFISH, the closely related federal agency approaches for managing threatened and endangered species habitat; and CSE, the "bankfull channel width" buffer option developed by the Center for the Study of the Environment to manage salmon habitat in the Pacific Northwest.

Osborne, L. L., and D. A. Kovacic. 1993. Riparian vegetated buffer strips in water-quality restoration and stream management. Freshwater Biology 29:243-258.

A review is presented of the literature on riparian vegetated buffer strips (VBS) for use in stream-water-quality restoration and limitations associated with their use are discussed. The results are also presented of recent investigations on the effectiveness of a forested and a grass vegetated buffer strip for reducing shallow subsurface inputs of nutrients from agriculture to a stream in central Illinois, U.S.A. Both the forested and grass VBS reduced nitrate-N concentrations in shallow groundwater (up to 90% reduction). On an annual basis the forested VBS was more effective at reducing concentrations of nitrate-N than was the grass VBS, but was less efficient at retaining total and dissolved P. During the dormant season, both grass and forested buffer strips released dissolved and total P to the groundwater. The VBS apparently acted as a nutrient sink for much of the year, but also released accumulated nutrients during the remaining portion of the year.

Paustian, S. J., editor. 1992. A channel type users guide for the Tongass National Forest, southeast Alaska. USDA Forest Service, Alaska Region. R10 Technical Paper 26.

This User Guide is intended for forest resource planners, fisheries biologists, hydrologists, ecologists, or anyone involved with water resource management on the Tongass National Forest. It describes a stream classification system based on mapped stream reaches called channel types. Channel type mapping is a principal tool for managing aquatic and riparian resources of the Tongass National Forest. The purpose of this User Guide is to provide users with sufficient information to understand the characteristics of each channel type and to know what should considered when planning activities that may affect water and fisheries resources associated with each one.

Components of the Alaska Region Channel Type Classification System are defined within the context of nine basic fluvial process groups. These process groups describe the interrelationship between watershed runoff, landform relief, geology, and glacial or tidal influences on fluvial erosion and deposition processes. Individual channel type classification units within each process group are defined by physical attributes, such as channel gradient, channel pattern, stream bank incision and containment, and riparian plant community composition. Channel types are a means of distinguishing the various parts of a stream system. They allow us to define the characteristics of the channel and to predict, with a high degree of accuracy, probable responses to natural and human influence. However, channel types cannot be managed as isolated segments. Stream reach in one part of a watershed can be affected by activities taking place in a different part of the watershed, either upstream, downstream, or on adjacent land areas. Channel types help define the parts of a drainage basin and, as such, are tools intended to complement a holistic watershed management approach.

The Channel Type Classification System was developed with water resource management needs in mind. Propagation of anadromous fisheries is the major beneficial use of water resources in Southeast Alaska. Channel type inventories provide key information of fish habitat utilization, fish habitat capability, and fisheries enhancement options in survey area watersheds. Channel types also provide information on suitable stream crossing locations and design criteria for road drainage structures. Channel types are used to evaluate potential sediment delivery and retention for cumulative watershed effect analysis. Information of sport fishing potential and boat access is also included in the channel type descriptions.

This User Guide contains brief information for each of the 38 channel types currently mapped on the Tongass National Forest. There is a separate section, consisting of thee parts (Title, Physical Characteristics, and Management Considerations), for each channel type. Data used to describe the channel structure, riparian vegetation, and aquatic habitat have been obtained from channel typing verification and stream inventories conducted on watershed throughout Southeast Alaska.

Piccolo, J. J. and M. S. Wipfli. In press. Does alder (Alnus sp.) in upland riparian forests elevate macroinvertebrate and detritus export from headwater streams to downstream habitats in Southeast Alaska?

ABSTRACT: We assessed the effects of past timber management on macroinvertebrates and detritus export from headwater streams to downstream habitats in the Tongass National Forest, Southeast Alaska. Twenty-four fishless headwater streams (mean discharge = 3.5L / s, mean gradient 22%) were sampled across four riparian canopy types: old growth, clearcut (<5 years post-cut), young growth (35-40 years post-cut) alder, and young growth conifer. Export of each of six replicate streams per canopy type was sampled with a 250 m net for 96 h intervals, monthly from April-August 1998. Young-growth alder sites exported significantly more macroinvertebrates (mean = 10.9 vs. 2.6 individuals / m^3 water and mean = 3.5 vs. 1.0 mg dry mass / m^3 water) and detritus (mean = 46.8 vs. 10.1 mg dry mass / m^3) than did young-growth conifer sites. No significant differences were observed between other canopy types. Approximately 70% of the export was made up of aquatic macroinvertebrates; the remainder was terrestrial or unidentified. These results suggest that alder riparian canopies elevate macroinvertebrate and detritus export from headwater streams. We attribute elevated export to greater in-stream productivity associated with higher quality and quantity of allochthonous input. Maintaining an alder component in upland forests following timber harvest should increase the productivity of headwater streams, benefiting downstream, salmonid-bearing food webs that receive prey and detritus from these upland habitats.

Reid, L. M., and S. Hilton. 1998. Buffering the buffer. Pages 71-80 *in* Ziemer, R. R., editor. Proceedings of the Conference on Coastal Watersheds: The Caspar Creek Story; held May 6, 1998, in Ukiah, California. USDA Forest Service, Pacific Southwest Research Station, General Technical Report PSW-GTR-168.

Riparian buffer strips are a widely accepted tool for helping to sustain aquatic ecosystems and to protect downstream resources and values in forested areas, but controversy persists over how wide a buffer strip is necessary. The physical integrity of stream channels is expected to be sustained if the characteristics and rates of tree fall along buffered reaches are similar to those in undisturbed forests. Although most tree-fall-related sediment and woody debris inputs to Caspar Creek are generated by trees falling from within a tree's height of the channel, about 30% of those tree falls are triggered by trees falling from upslope of the contributing tree, suggesting that the core zone over which natural rates of tree fall would need to be sustain is wider than the one-tree-height's-width previously assumed. Furthermore, an additional width of "fringe" buffer is necessary to sustain appropriate tree-fall rates within the core buffer. Analysis of the distribution of tree falls in buffer strips and un-reentered streamside forests along the North Fork of Caspar reek suggests that rates of tree fall are abnormally high for a distance of al least 200 m from a clearcut edge, a distance equivalent to nearly four times the current canopy height. The appropriate width of fringe buffer needed to protect the core zone will need to be determined using an analysis of the long-term effects and significance of accelerated tree-fall rates after logging.

Steinblums, I. J., H. A. Froelich, and J. K. Lyons. 1984. Designing stable buffer strips for stream protection. Journal of Forestry 82(1):49-52.

On 40 streamside buffer strips in the Cascade Mountains of western Oregon, stability was a function of one vegetation and six topographic variables, and shading was related to three characteristics of buffer strips and one of adjacent clearcuts. Prediction equations were developed from these relationships to aid assessment of stream protection in proposed harvest designs and to aid rapid evaluation of design modification. Options can be quantified so that the most suitable design may be chosen.

Timoney, K. P., G. Peterson, and R. Wein. 1997. Vegetation development of riparian plan communities after flooding, fire, and logging, Peace River, Canada. Forest Ecology and Management 93:101-120.

In this study, we compare and contrast vegetation development following natural and logging disturbances in a major boreal river valley. Permanent sample plots and releves were establish and sampled for vegetation and landscape attributes in June and July of 1993 and 1994 in the Peace River Lowlands, Wood Buffalo National Park, Canada. In the Peace River Lowlands, primary succession is a flood-origin process. Secondary succession may be either autogenic through gap dynamics mediated by nursery logs, buried wood, and suckering, or allogenic, following fire or logging. Flood origin accounts for 72% and fire origin for 29% of the undisturbed forests. From 19561-1995, 24% of the forest land burned, yielding a fire return interval of 186 years. Forest successional trajectories are set soon after flood, logging, or fire, with little evidence of gradual replacement of one forest type by another. Vegetation composition and relative species abundance are strongly correlated with living moss depth, moss-lichen total cover, total tree cover, herb cover, and canopy height. Species with high indicator value are *Hylocomium splendens*, *Picea glauca*, *Pyrola chlorantha*, *Equisetum pratense*, and *Epilobium angustifolium*. Strong correlations exist between white spruce tree density and canopy height, total tree cover and canopy height, total tree cover and basal area per hectare, basal area and canopy height, and between canopy height and surface area. Clearcuts are initially dominated by rose-raspberry followed by balsam poplar (with lesser amounts of Alaska birch and aspen). After logging, temporal changes in composition and dominance occur more rapidly than during natural succession. There is no evidence of post-logging convergence toward the original white spruce and mixedwood forests; a long-term deciduous disclimax is predicted. Vegetation associations, successional pathways, landscape relationships, ad ecological benchmarks are identified.

U.S. Forest Service. 1997. Land and resource management plan, Tongass National Forest. USDA Forest Service. Alaska Region. R10-MB-338dd.

ABSTRACT: The Riparian forest-wide standards and guidelines discuss the management objectives and set the standards for buffers and other riparian management techniques for water bodies within the Tongass National Forest. The standards and guidelines for fish-bearing waters in the flood plain (FP) and glacial outwash (GO) channel type process groups state, in part: "No programmed commercial timber harvest in the Riparian Management Area (greatest of flood plain, riparian vegetation or soils, riparian associated wetland fens, or 130 feet (the height f one site-potential tree)). Manage an appropriate distance beyond the no-harvest zone to provide for a reasonable assurance of windfirmness of the Riparian Management Area (pay special attention to the area within one site-potential tree height of the Riparian Management Area)."

U.S. Forest Service. 1995. Report to Congress, synthesis: anadromous fish habitat assessment. USDA Forest Service. Alaska Region and Pacific Northwest Research Station. R10-MB-279.

ABSTRACT: The document, generally known as AFHA, includes a summary of the riparian management standards, including buffers, that were in place on the Tongass National Forest at the time of publication. The assessment includes three sections: a literature review, an evaluation of existing standards by a panel of experts, and a summary of three watershed analyses conducted on Game, Kadake, and Old Franks creeks. A synthesis of the three sections by an oversight team concluded that the existing riparian management standards, which included mandatory 100-foot no-cut buffers on anadromous fish streams and on resident fish streams that flow into anadromous streams, did not provide adequate long-term protection for salmon and steelhead habitats.

Welsch, D. J. 1991. Riparian forest buffers: function and design for protection and enhancement of water resources. USDA Forest Service, Northeast Area State and Private Forestry. NA-PR-07-91.

This relatively short publication is primarily directed at establishing riparian forest buffers for nonpoint source pollution control in agricultural and livestock grazing settings. As such, it provides a good primer on functional values of buffers other than the more usual shading, large woody debris, etc. Welsch provides a functional definition for riparian buffers, then a set of specifications for designing effective buffers to mitigate effects of upslope, upstream, and subsurface changes brought about the land management activities and uses. He notes in particular the need to control hillside erosion at the source for a riparian zone to effectively buffer fine sediment transport. Welsch describes a three-zone buffer prescription, with Zone 1 beginning at the water body's edge to create a stable ecosystem adjacent to the water's edge, Zone 2 mid-buffer to provide contact time and buffering processes for sheet flow toward the water body, and Zone 3 away from the water body to provide sediment filtering, nutrient uptake, and the space necessary to convert flows concentrated by land use activities into uniform shallow sheet flow. Zonal and total buffer width recommendations vary by local hydrology, soil capability, and the size of adjacent drainage areas and land use areas.

Wipfli, M.S. 1997. Terrestrial invertebrates as salmonid prey and nitrogen sources in streams: contrasting old-growth and young-growth riparian forests in southeastern Alaska, U.S.A. Can J. Fish. Aquat. Sci. 54: 1259-1269.

ABSTRACT: Terrestrial-derived invertebrate (TI) inputs into streams and predation on them by salmonids (40-180 mm fork length) were measured in six coastal Alaska stream reaches from April through October 1993-1994; riparian habitat of three stream reaches contained conifer-dominated old-growth (no timber harvesting) and three were alder-dominated young-growth (31 years postclearcutting). Data from pan traps placed on stream surfaces showed that TI biomass and nitrogen inputs averaged up to 66 and 6 mg/m/day, respectively, with no significant difference between habitats. Stomach contents from coho salmon (*Onchorhynchus kisutch*), cutthroat trout (*O. clarki*), and Dolly Varden (*Salvelinus malma*) revealed that TI and aquatic-derived invertebrates (AI) were equally important prey. Additionally, salmonids from young-growth systems ingested a greater TI proportion than those from old-growth systems. There were trends but no significant differences between habitats of TI and AI biomass ingested; however, statistical power was <0.30. These results showed that TI were important juvenile salmonid prey and that a riparian overstory with more alder and denser shrub understory may increase their abundance. Riparian vegetation management will likely have important consequences on trophic levels supporting predators, including but not limited to fishes.

Xiang, W. 1993. Application of a GIS-based stream buffer generation model to environmental policy evaluation. Environmental Management 17:817-827.

In this article, a GIS method is presented for riparian environmental buffer generation. It integrates a scientifically tested buffer width delineation model into a GIS framework. Using the generally available data sets, it determines buffer widths in terms of local physical conditions and expected effectiveness. Technical burdens of data management, computation, and result presentation are handled by the GIS. The case study in which the method was used to evaluated the stream buffer regulations in a North Carolina county demonstrates its capability as a decision support tool to facilitate environmental policy formulation and evaluation, and environmental dispute resolution.

FACTORS AFFECTING STREAM BANK AND RIVER BANK STABILITY, WITH AN EMPHASIS ON VEGETATION INFLUENCES

An Annotated Bibliography

Compiled for the
Region III Forest Practices Riparian Management Committee

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SUMMARY

In interior Alaska, concerns have been raised regarding the impact of forest management activities on fish habitat and water quality. The major concerns about the potential for timber harvest to affect fluvial systems seem to focus around riverbank erosion and large woody debris (LWD) recruitment. Vegetation has been shown to stabilize banks of rivers and streams in some systems, and LWD is known to be a critical component of anadromous and high value resident fish habitat, and to affect fluvial dynamics. It has been suggested that the harvest of riparian timber in interior Alaska can increase riverbank erosion rates with the result that productive spawning or rearing areas could be degraded through sedimentation processes or changes in channel morphology (e.g. simpler channels with fewer scour holes and fewer eddies and meanders). It has also been suggested that timber harvest near watercourses will decrease the supply of LWD that is recruited into a river through natural erosion processes. This literature review focuses on factors affecting stream bank and river bank stability, with an emphasis on vegetation influences. The role of LWD in fluvial systems is covered in another section of this report.

Although a formal definition of bank stability was not encountered in the literature, the context in which the term is used implies that a bank is stable if it does not change appreciably within a defined time frame. Bank stability is influenced by factors such as temperature regimes, composition of the bank material, hydraulic forces, presence or absence of permafrost, and vegetation (see Thorne (1982) for a description of bank erosion processes and mechanisms). Vegetation stabilizes banks primarily by increasing shear strength of the soil (Thorne and Lewin 1979, Gray and MacDonald 1989), reducing water velocity (Gray and MacDonald 1989), and armoring the bank (Thorne 1982). In arctic and subarctic regions where permafrost is present, vegetation also provides an insulating mat that helps protect frozen banks from erosion (Bray and Kellerhals 1979, Thorne 1982, Lawson 1983)—see the Permafrost and Silty Soils section of this report for additional discussion and references. The ability of vegetation to stabilize a bank is dependent upon factors such as plant vigor, density, and rooting depth (Heede 1980), interacting with the other bank stability variables mentioned above. Predicting bank erosion rates can be difficult because of the interaction of the many variables that influence the process.

Bank erosion rates can vary according to the type of riparian vegetation that is present. Different vegetation life forms (e.g. herbaceous, woody shrub, tree) and species can have different root-shoot architectures and biomass—both above and below ground—which influence the ability of vegetation to stabilize banks of streams and rivers (e.g. Mallik and Rasid 1993). For example, differences in relative erosion rates have been noted between forested and non-forested banks, but the trend is not consistent. Studies where erosion rates of forested banks were less than those of non-forested banks include Mackin (1956) and Burckhardt and Todd (1998). Conversely, studies where erosion rates of forested banks were greater than those of non-forested banks include Murgatroyd and Ternan (1983), Davies-Coley (1997), and Trimble (1997).

The ability of vegetation to stabilize stream or river banks is partly dependent upon scale, with both the size of vegetation relative to the watercourse and absolute size of the vegetation being important. Vegetation stabilization tends to be most effective along relatively small water courses (Thorne 1982, Gatto 1984, Nanson and Hickin 1986, Davies-Colley 1997). On relatively large rivers, fluvial processes tend to dominate (Gatto 1984, Nanson and Hickin 1986). Large uprooted trees can serve to stabilize banks along large rivers, but on smaller streams those same trees may cause acceleration of water flow that results in local bank erosion (Thorne 1982). One must note, however, that local bank erosion may also result in the formation of scour pools and backwater areas that often are necessary for high quality fish habitat. Large trees may locally increase mass failure of banks because the surcharge weight can overcome any additional increase in soil shear strength due to root systems (Thorne 1982, Gatto 1984).

Vegetation (including LWD) influences channel development and geometry through its influence on bank erosion processes. Narrow stable channels often are associated with relatively high levels of riparian vegetation, while wider, unstable channels are associated with relatively less riparian vegetation (Rowntree and Dollar 1999). For example, braided channels (relatively wide and unstable) tend to be associated with sparely vegetated banks (Leopold et al. 1964, Heede 1980). Cause and effect of this relationship, however, has not been proven (Leopold et al. 1964). Vegetation also influences the degree of channel sinuosity (Murgatroyd and Ternan 1983, Ebisemiju 1994). Removal of LWD from a stream can result in local bank erosion and channel widening (Smith et al. 1993)—see the Large Woody Debris section of this report for further discussion and references pertaining to LWD influences on channel morphology.

This literature review was conducted in two phases. First, a search was conducted using the electronic databases at the University of Alaska Fairbanks. Once relevant papers and books were located, additional references were located using the literature citation sections of those materials. Annotations are primarily authors' abstracts.

REFERENCES

Abernethy, B., and I. D. Rutherfurd. 1998. Where along a river's length will vegetation most effectively stabilise stream banks? Geomorphology 23: 55-75.

Riparian vegetation has different impacts on stream processes depending upon its position in a catchment. Native riparian vegetation is increasingly becoming the favored stream management tool but managers need to locate revegetation schemes where they will most effectively achieve ecological, geomorphological, or other project goals. Using the Latrobe River in SE Australia as an example, this paper illustrates a structured decision-making approach for assessing the role of vegetation in stream bank erosion at different points throughout a catchment. Three bank-erosion process groups are identified: subaerial preparation, fluvial entrainment, and mass failure. Although these processes act on banks throughout the catchment there exists spatial zoning in the dominance of each process group over the others. Bank erosion in upper reaches is dominated by subaerial preparation, in mid-basin reaches by fluvial entrainment, and in the lower reaches by mass failure. The authors found that in upper reaches, windthrown trees are responsible for most bank sediment transfer to the flow. Where direct fluvial entrainment of bank material is the dominant erosion process, flow resistance due to vegetation becomes crucial. In reaches where bank slumping is the dominant erosion process, increased bank shear strength due to root reinforcement is the major role of vegetation in stabilizing banks. Other effects, such as tree surcharge, and altered bank hydrology appear to exert only minor influences on the slumping process. Considering the above variables the authors were able to define a critical zone in which revegetation will be most effective in reducing bank erosion. On the Latrobe River, this zone occurs in that portion of the river where it first leaves the mountain front and meanders across a broad floodplain. This reach occupies the second quarter of the river's length. This information, combined with other scale analyses (e.g. ecological, hydrological), will assist river managers to plan physically based riparian revegetation strategies.

Beeson, C. E., and P. F. Doyle. 1995. Comparison of bank erosion at vegetated and non-vegetated channel bends. Water Resources Bulletin 31: 983-990.

Following major floods in 1990 which resulted in widespread bank erosion in southern British Columbia, four streams typical of the region were evaluated for the effect which riparian vegetation played in reducing erosion. A total of 748 bends in the four stream reaches were assessed by comparing pre- and post-flood aerial photography. Bends without riparian vegetation were found to be nearly five times as likely as vegetated bends to have undergone detectable erosion during the flood events. Major bank erosion was 30 times more prevalent on non-vegetated bends as on vegetated bends. The likelihood of erosion on semi-vegetated bends was between that of the vegetated and non-vegetated categories of bends.

Bradbury, J., P. Cullen, G. Dixon, and M. Pemberton. 1995. Monitoring and management of streambank erosion and natural revegetation on the lower Gordon River, Tasmanian Wilderness World Heritage Area, Australia. Environmental Management 19: 259-272.

The wash from high-speed tourist cruise launches causes erosion of the formerly stable banks of the lower Gordon River within the Tasmanian Wilderness World Heritage Area. Speed and access restrictions on the operation of commercial cruise vessels have considerably slowed, but not halted erosion, which continues on the now destabilized banks. To assess the effectiveness of restrictions, bank erosion and natural revegetation are monitored at 48 sites using erosion pins, survey transects, and vegetation quadrats. The subjectively chosen sites are grouped on the basis of geomorphology and bank materials. The mean measured rate of erosion of estuarine banks slowed from 210 to 19 mm/year with the introduction of a 9 knot speed limit. In areas where cruise vessels continue to operate, alluvial banks were eroded at a mean rate of 11 mm/yr during the three-year period of the current management regime. Very similar alluvial banks no longer subject to commercial cruise boat traffic eroded at the slower mean rate of 3 mm/yr. Sandy levee banks have retreated an estimated maximum 10 m during the last 10-15 years. The mean rate of bank retreat slowed from 112 to 13 mm/yr with the exclusion of cruise vessels from the leveed section of the river. Revegetation of the eroded banks is proceeding slowly; however, since the major bank colonizers are very slow growing tree species, it is likely to be decades until revegetation can contribute substantially to bank stability.

Bray, D. I., and R. Kellerhals. 1979. Some Canadian examples of the response of rivers to man-made changes. Pages 351-372 *in* D. D. Rhodes and G. P. Williams, editors. Adjustments of the fluvial system. Kendall/Hunt Publishing Company, Dubuque, Iowa.

This paper documents a few Canadian cases of known man-caused changes in fluvial systems. One of the cases summarizes a study by Cooper and Hollingshead (1973)[1], in which construction of a logging road resulted in accelerated bank erosion along the Liard River, near Watson Lake, Yukon Territory. The road was constructed on a bank of the river comprised of permafrost and possessing a southern exposure. Air photo analysis indicated that the banks were stable for 20 years before the vegetation was removed during construction of the road. After road construction, bank erosion increased in the section where vegetation was removed, but the banks remained stable where vegetation was not removed. The probable processes resulting in increased bank erosion after road construction are:

1.) Before road construction, the active layer—which is probably less resistant to erosion than permafrost—was located above the maximum height attained by water during annual flood events.
2.) Removal of the vegetation mat from the top of the river bank resulted in an increased depth of the active layer so that it extended below the maximum height attained by water during annual flood events.

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[1] Cooper, R. H., and A. B. Hollingshead. 1973. River bank erosion in regions of permafrost. Pages 272-283 *in* Fluvial processes and sedimentation. Hydrology Symposium Proceedings No. 9, University of Alberta, Edmonton.

3.) During annual flood events, the active layer can now be eroded more rapidly than the surrounding frozen soil, resulting in accelerated erosion where the vegetation mat was removed.

Burckhardt, J. C., and B. L. Todd. 1998. Riparian forest effect on lateral stream channel migration in the glacial till plains. Journal of the American Water Resources Association 34: 179-184.

Dendrochronology analyses of point bar complexes were used to quantify the effects of riparian forests on local lateral migration of bends in seven streams in the glacial till plains of north central Missouri. Stream bends were paired with similar bank height, midchannel radius of curvature, soil composition, and watershed size. In each pair, one concave bank was forested and one was unforested. Stream bends with unforested concave banks had an average local migration rate three times greater than stream bends that had forested concave banks.

Davies-Colley, R. J. 1997. Stream channels are narrower in pasture than in forest. New Zealand Journal of Marine and Freshwater Research 31: 599-608.

In the Hakarimata Range, west of Hamilton, New Zealand, second-order streams appear to be wider in native than in pasture catchments, whereas streams in pine plantations (18 years old) appear to be suffering active stream-bank erosion. A working hypothesis to explain these observations was that pasture vegetation replacing original forest encroaches on the stream channel, causing it to become narrower. To test the hypothesis, channel widths were measured up stream and down stream of "transitions" from native forest to pasture in 20 streams of different size in marginal ranges of the Waikato Basin. Small streams (catchment area <1 km^2, width in forest <2 m) were found to be half the width in pasture reaches as in forest. The degree of channel narrowing decreased as stream size increased and was minimal in large streams (catchment area >30 km^2, width in forest >10 m). This narrowing of stream channels implies that native forest clearance in New Zealand has reduced stream channel habitat. A concern regarding riparian planting for stream restoration is that sediment stored in pasture stream banks could be mobilized if grasses are extinguished by shading, resulting in turbid streamwater and sedimentation of fines in the channel.

Dwyer, J. P., D. Wallace, and D. R. Larsen. 1997. Value of woody river corridors in levee protection along the Missouri River in 1993. Journal of the American Water Resources Association 33: 481-489.

Following the Midwest flood of 1993, a study was initiated along a 39-mile segment of the Missouri River to determine if there was an association between woody corridors and levee stability. A systematic sample of levee failures revealed that primary levees which did not fail had a significantly wider woody corridor than failed levees. Analysis of the total inventory of failed levees revealed that as the width of the woody corridor decreased, the length of the levee failure increased. Number of levee failures and their severity of damage could be reduced if woody corridors were at least 300 feet wide.

Ebisemiju, F. S. 1994. The sinuosity of alluvial river channels in the seasonally wet tropical environment: case study of river Elemi, southwestern Nigeria. Catena 21: 13-25.

Investigations carried out in the Elemi river basin, southwestern Nigeria suggest that small intermittent streams in the seasonally wet humid tropics have a tendency to develop very sinuous channels characterized by compound and highly convoluted loops. Analysis of arc symmetry and the repetition of symmetry indicate that the 153 bends along the 39.3 km long river are not true meanders as objectively defined by Brice in 1964. The dominant factor controlling the degree of sinuosity is channel bank resistance to lateral erosion as influenced primarily by the nature of riparian vegetation and secondarily by the percentage silt/clay in channel bank sediment. The influence of bank vegetation is particularly pronounced in view of the preponderance of low flow discharges, high proportion of suspended sediment and gentle bed slope. The high density of riparian trees account for the relatively short length of the straight reaches and the high frequency of bends, compound and convoluted loops. The implications for river management of the inherent instability of small channels in seasonally wet humid tropical environments, and of the considerable channel bank erosion which occurs at the numerous bends are briefly highlighted.

Gatto, L. W. 1984. Tanana River monitoring and research program: relationships among bank erosion, vegetation, soils, sediments, and permafrost on the Tanana River near Fairbanks, Alaska. US Army Corps of Engineers, Cold Regions Research & Engineering Laboratory, Special Report 84-21.

The objective of the analysis was to determine if available data are useful in identifying characteristics that contribute to erodibility of the banks along two reaches of the Tanana River. Existing data on bank vegetation, soils, sediments and permafrost were used. The data were visually compared to the locations and estimated amounts of historical recession to evaluate if any relationships were obvious. The results of the analysis showed no useful relationships. Vegetation was similar in eroded and uneroded areas and its distribution did not show any obvious relationship to the locations of bank recession. Surface sediments and soils in the eroded areas had little, if any, effect on bank erodibility because the river erodes the bank over its entire depth, which is well below this surface zone. The subsurface sediment from eroded and uneroded wells and along transects with high and low measured recession was similar. Permafrost occurrences are about equal in eroded and uneroded sites, although it appears that recession can be higher where permafrost is common compared to where it is absent.

Additional comments

The author notes that results from other studies indicate that vegetation increases bank resistance to erosion. He also notes, however, that vegetation is unimportant in limiting erosion along large watercourses, because the rivers erode the bank to a depth that is well below the rooting zone of the vegetation. Once a river has eroded a bank to the point where riparian trees are unsupported, the unsupported trees will fall into the river, carrying with them, large amounts of bank sediment. Through this mechanism, vegetation can actually contribute to bank erosion. It has also been suggested, however, that collapsed trees may protect banks from further erosion if they lie against the subaqueous (below water) portion of the bank while remaining attached to the subaerial (above water) portion of the bank. It can be argued that attached, collapsed trees located at or below the water surface protect banks from erosion, because they serve to divert currents from the bank and to reduce near-bank current velocities. It is the author's opinion, however, that hydraulic forces of the river and not vegetation, soils, or surface sediments, are the important factors influencing bank erosion along the Tanana River.

Gatto, L. W. 1995. Soil freeze-thaw effects on bank erodibility and stability. US Army Corps of Engineers, Cold Regions Research & Engineering Laboratory, Special Report 95-24.

When air temperature is below ground temperature, a thermal gradient is established in the soil that causes the soil to lose heat to the atmosphere. When the soil has lost sufficient heat for soil water to freeze, the newly formed ice changes soil structure by disaggregating, separating, and reorienting soil particles. The suction set up within the freezing soil draws water to the freezing zone through the film of unfrozen water surrounding soil particles, supplying additional water for freezing, so the volume of ice increases. When appropriate thermal and water supply conditions are in place, disseminated ice lenses can form in the soil. As the ice lenses grow, the soil surface is heaved in the direction of heat flow from the soil. Soil particles can be displaced down a bank face when surface ice in heaved soil melts. The amount of ice in a frozen soil by the end of winter can be higher than its water content when unfrozen. Thus, upon thawing, the previously frozen soil temporarily has an excess of soil water and a disrupted soil structure, which significantly reduces internal friction and cohesion and reduces the soil's shear strength. In this weakened state, thawed bank soils are usually more easily eroded by raindrop impacts, overland flows, river and lake ice forces, currents and waves, and are highly susceptible to mass failures. In some instances newly thawed soils are weaker than at any other time of the year. Some studies show that processes related to bank soil freezing and thawing cause more bank recession annually than other processes in areas where seasonal frost forms. However, with time, the strength of the thawed soil returns as excess water drains from the soil, and soil particle packing and interlocking increase. Thus, frost-induced reductions in soil strength and soil particle displacements must be included in bank migration and bank erosion models to be applied in regions with seasonal soil frost.

Gray, D. H., and A. MacDonald. 1989. The role of vegetation in river bank erosion. Pages 218-223 *in* M. A. Ports, editor. Hydraulic engineering. Proceedings of the 1989 national conference on hydraulic engineering.

Vegetation modifies the interface region between flowing water and the stream bank. Hydraulic and mechanical properties near this interface will be modified in ways that affect the resistance of the bank to both surficial erosion and mass wasting respectively. With regard to mass stability, plant roots reinforce a soil and increase its shear strength. Vegetation also interacts with flowing water to influence bank erosion through disturbance of the flow field. Two distinct conceptual interpretations of this disturbance are proposed. The first views bank vegetation as a "carpet" of roughness elements akin to individual, albeit larger, grains of sediment. The second views vegetation in the form of single, isolated tree trunks which behave much as bridge pilings.

Harmel, R. D. 1997. Analysis of bank erosion on the Illinois River in northeast Oklahoma. Ph.D. thesis. Oklahoma State University. (Cited in Dissertation Abstracts International Part B: Science and Engineering, 1998, vol. 59(2))

The objectives of this research were: (1) to measure short-term bank erosion for selected sites, (2) to measure long- term erosion with aerial photographs, (3) to evaluate the impact of riparian vegetation on short- and long-term erosion, (4) to compare the short-term results of this study to similar work by D. L. Rosgen, and (5) to estimate the contribution of bank erosion to sedimentation of Lake Tenkiller. In July 1996, a bank characterization trip was made to gather data on eroding and stable banks. Characterized banks were grouped according to physical and vegetative conditions and hydrologic influence. At least one bank from each group was selected for detailed field study. Erosion was measured using bank pins and cross-sectional surveys from September 1996 through July 1997. Bank erosion was also measured from 1958, 1979, and 1991 aerial photographs. Erosion averaged 4.5 ft and ranged from -0.03 to 26.5 ft after four, 2.0 to 2.5 yr return period flow events from August 1996 to September 1997. An additional 0.40 ft average was measured for 14 sites after two at or near bankfull events in the spring and summer of 1997. The average annual flow for the study period exceeded the long-term average by 20%. In the aerial photograph analyses, lateral erosion averaged 3.6 ft/yr in the period 1979 to 1991 and averaged 1.7 ft/yr from 1958 to 1979. During the periods 1979 to 1991 and 1958 to 1979, the Illinois River eroded a total of 195 ac and 64 ac of land surface area, respectively. The long-term analyses showed that forest vegetation is important in reducing and preventing bank erosion. Major short- and long-term erosion did occur on banks with each vegetation type, so natural forest vegetation does not always prevent erosion but can lessen the likelihood of its occurrence. In general, the Rosgen Level III bank erosion potential evaluation was easy to understand and apply in the field; however, as it currently stands, it performed relatively poorly in predicting short-term bank erosion. Individually, the bank erosion potential and Pfankuch Channel Stability ratings did perform relatively well in relating ratings to short-term bank erosion, but the near bank stress estimates did not. The contribution of bank erosion to sedimentation of Lake Tenkiller was not successfully estimated.

Harwood, K., and A. G. Brown. 1993. Fluvial processes in a forested anastomosing river: flood partitioning and changing flow patterns. Earth Surface Processes and Landforms 18: 741-748.

In an effort to further understanding of multiple channel systems, this paper presents data on the flood response of channels in one of the last wooded, semi-natural anastomosed systems in Europe. The Gearagh, Ireland, is characterized by hundreds of small islands separated by interconnected channels of low slope. These include channels that cross islands at right angles to the main flow and blind anabranching channels. Islands are relatively stable and wooded, with evidence of division by channel erosion and growth by in-channel sedimentation. Four active zone cross-profiles were surveyed, each containing between seven and 13 channels. Velocities were measured in several channels before and during two separate floods. From these observations channels have been categorized into three types: fast (shallow and trapezoidal); slow (deep and more irregular); and flood channels. During the floods, interchannel flows were caused by variations in water surface elevations due to backing-up behind debris dams, and it is suggested that this is the origin of the anomalous cross-island channels and one cause of island division. Another potential cause of island division, blind anabranching channels, is the result of concentrated bank scour between root masses. Biotic components such as debris dams, tree root masses and tree-throw pits play a key role in the partitioning of flow, and cause variations in channel velocities and the overbank velocity distribution. The implications of these observations for channel pattern maintenance are briefly discussed.

Heede, B. H. 1980. Stream dynamics: an overview for land managers. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, General Technical Report RM-72.

This document provides a basic introduction to stream dynamics. Topics of discussion include: basic fluvial processes (subcritical and supercritical flow, laminar and turbulent flow, sediment transport), dynamic equilibrium, processes affecting channel pattern and shape, and processes affecting longitudinal profile.

Additional comments

Longitudinal profile, a measure of stream slope or gradient, is one of the major sources of channel pattern changes. Steeper streams have higher velocities and ,therefore, attack banks more strongly and carry higher sediment loads. For this reason, braided streams with their steeper profiles are more erosive than lower gradient meandering streams. Bank erosion, however, can only occur where erodible material is present. Braiding, for example, usually does not take place where banks are densely vegetated, but may occur where vegetation cover is sparse.

Bank stability is influenced by factors such temperature, chemistry of clay, and vegetation. The ability of vegetation to stabilize banks is dependent upon plant vigor, density, and rooting depth.

Hey, R. D., J. C. Bathurst, and C. R. Thorne. 1982. Gravel-bed rivers: fluvial processes, engineering and management. John Wiley & Sons Ltd., New York.

This book is a record of the proceedings of the International Workshop on ‘Engineering Problems in the Management of Gravel-bed Rivers’ held at Gregynog, Newtown, UK between 23 and 27 June 1980. Contributed papers deal with topics related to flow hydraulics, flow resistance, sediment transport, bank erosion, bar sedimentation, meander processes, hydraulics of mountain streams, dynamic modeling, regime equations, flow routing and river regulation, river stabilization and training, river regulation and channel stability, channel responses to changes in land use, and ecological implications of river regulation and training.

Huang, H. Q., and G. C. Nanson. 1997. Vegetation and channel variation; a case study of four small streams in southeastern Australia. Geomorphology 18: 237-249.

Channel vegetation of four small streams in southeastern Australia varies greatly in detail but it can be broadly categorized and even indexed for quantitative analysis. Such variations cause the hydraulic geometry of the study streams to differ significantly from each other and from patterns observed in most other geographical regions. Importantly, this study demonstrates that the impact of vegetation on channel form and velocity can be quantified in much the same way that other broadly based hydraulic geometry relations have been developed. Dense bank vegetation results in narrower channels whereas vegetation growing on the bed greatly increases flow resistance, causing channel widening, reduced flow velocity but no significant change in depth. The results obtained in this study, combined with those from other regions, permit an interpretation of the sensitivity of channel width to different forms of channel vegetation, information of use for river management.

Kondolf, G. M., and R. R. Curry. 1984. The role of riparian vegetation in channel bank stability: Carmel River, California. Pages 124-133 *in* R. E. Warner, and K. M. Hendrix, editors. California riparian systems: ecology, conservation, and management.

A narrow channel with well-vegetated banks developed on the lower 15 km. of the Carmel River by 1939, and by 1960 this condition had extended to the entire lower 24 km. of river channel. Noticeable die-off of riparian trees near water supply wells began in the 1960s and intensified during the 1976-1977 drought. Substantial bank erosion occurred during the winters of 1978 and 1980 along reaches which had suffered loss of bank-stabilizing riparian trees.

Kondolf, G. M., and R. R. Curry. 1986. Channel erosion along the Carmel River, Monterey County, California. Earth Surface Processes and Landforms 11: 307-319.

Historic maps, photographs, and channel cross-sections show that the channel of the Carmel River underwent massive bank erosion, channel migration, and aggradation in a major flood in 1911, then narrowed and incised by 1939. The channel was stable until 1978 and 1980, when bank erosion affected some reaches but not others. The narrowing and incision were in response to a lack of major floods after 1914 and construction in 1921 of a dam that cut off sediment supply from the most actively eroding half of the basin. Localized erosion in 1978 and 1980 occurred during low magnitude events along reaches whose bank strength had been reduced by devegetation. These events illustrate that the stability of a fluvial system can be disrupted either by application of a large erosive force in a high magnitude event (the 1911 flood) or in a low magnitude event, by reducing the resistance to erosion (bank devegetation). The Carmel River is a potentially unstable system. Its discharge and slope characteristics place it near the threshold between meandering and braided. On the Lower Carmel, the presence of bank vegetation can make the difference between a narrow, stable meandering channel and a wide shifting channel with braided reaches.

Lawson, D. E. 1983. Erosion of perennially frozen streambanks. US Army Corps of Engineers, Cold Regions Research & Engineering Laboratory, CRREL Report 83-29.

A literature review indicated that the effects of permafrost on streambank erodibility and stability are not yet understood because systematic and quantitative measurements are seriously lacking. Consequently, general controversy exists as to whether perennially frozen ground inhibits lateral erosion and bankline recession, or whether it increases bank recession rates. Perennially frozen streambanks erode because of modification of the bank's thermal regime by exposure to air and water, and because of various erosional processes. Factors that determine rates and locations of erosion include physical, thermal and structural properties of bank sediments, stream hydraulics and climate. Thermal and physical modification of streambanks may also induce accelerated erosion within permafrost terrain removed from the immediate river environment. Bankline or bluffline recession rates are highly variable, ranging from less than 1 m/year to over 30 m/year and, exceptionally, to over 60 m/year. Long-term observations of the physical and thermal erosion processes and systematic ground surveys and measurements of bankline-bluffline recession rates are needed.

Leopold, L. B., M. G. Wolman, and J. P. Miller. 1964. Fluvial processes in geomorphology. W.H. Freeman and Company, San Francisco.

This book deals primarily with landform development under processes associated with running water. The general subjects covered in the book include climate and denudational processes, weathering, the drainage basin as a geomorphic unit, water and sediment in channels, channel form and process, hillslope characteristics and processes, geochronology, drainage pattern evolution, channel changes with time, and evolution of hillslopes.

Mackin, J. H. 1956. Cause of braiding by a graded river. Bulletin of the Geological Society of America 67: 1717-1718.

South of Haley, Idaho, the Wood River meanders in a forest for many miles, braids in a 3-mile segment where the valley floor is prairie, and returns to a meandering habitat where the river re-enters a forest. The river is stable or slowly degrading in all three segments. The essential cause of the drastic difference in channel characteristics in adjoining segments is a difference in bank resistance due to presence or absence of bank vegetation.

Sinuosity of rivers is determined by width/depth of their channels. Ribbon-candy meanders develop only because, in a channel of low width/depth, factors which inhibit growth of bends are outweighed by a self-accelerating interplay in a set of factors which causes continued outgrowth. With high width/depth, a balance is struck between opposed sets of factors when bends attain a low curvature. Sinuosity is inversely proportional to width/depth.

Incidence of channel islands is also controlled by width/depth. Channel-island index (length of channel islands/length of channel) varies systematically from zero for channels with low width/depth to more than 2 for channels with high width/depth.

Width/depth is itself determined by (1) erosional force applied to the banks, and (2) bank resistance; it varies directly with (1) and inversely with (2). Erosional force is proportional to transporting force and is determined by discharge and load. Bank resistance is determined by the nature of the bank-forming material plus a vegetation factor.

Madej, M. A., W. E. Weaver, and D. K. Hagans. 1994. Analysis of bank erosion on the Merced River, Yosemite Valley, Yosemite National Park, California, USA. Environmental Management 18: 235-250.

Channel changes from 1919 to 1989 were documented in two study reaches of the Merced River in Yosemite National Park through a review of historical photographs and documents and a comparison of survey data. Bank erosion was prevalent and channel width increased an average of 27% in the upstream reach, where human use was concentrated. Here, trampling of the banks and riparian vegetation was common, and banks eroded on straight stretches as frequently as on meander bends. Six bridges in the upper reach constrict the channel by an average of 38% of the original width, causing severe erosion. In the downstream control reach, where human use was minimal, channel widths both decreased and increased, with a mean increase of only 4% since 1919. Bank erosion in the control reach occurred primarily on meander bends. The control reach also had denser stands of riparian vegetation and a higher frequency of large woody debris in channels. There is only one bridge in the lower reach, located at the downstream end. Since 1919, bank erosion in the impacted upstream reach contributed a significant amount of sediment (74,800 tons, equivalent to 2.0 t/km^2/yr) to the river. An analysis of 75 years of precipitation and hydrologic records showed no trends responsible for bank erosion in the upper reach. Sediment input to the upper reach has not changed significantly during the study period. Floodplain soils are sandy, with low cohesion and are easily detached by lateral erosion. The degree of channel widening was positively correlated with the percentage of bare ground on the streambanks and low bank stability ratings. Low bank stability ratings were, in turn, strongly associated with high human use areas. Channel widening and bank erosion in the upper reach were due primarily to destruction of riparian vegetation by human trampling and the effect of bridge constrictions on high flow, and secondarily to poorly installed channel revetments. Several specific recommendations for river restoration were provided to park management.

Mallik, A. U., and H. Rasid. 1993. Root-shoot characteristics of riparian plants in a flood control channel: implications for bank stabilization. Ecological Engineering 2: 149-158.

Root-shoot dimensions and dry biomass of samples of ten dominant species from the bank profiles of the Neebing-McIntyre Floodway, Thunder Bay, Ontario, Canada were significantly different from one micro-habitat to another. These differences were used as the basis of interpreting allocation of energy in different components of plants that helped them colonize specific micro-habitats along the bank profiles of the floodway. Thus, *Deschampsia flexuosa*, the dominant plant on the bank slope, allocates about 90% of its biomass in its shallow but dense root systems (compared to its shoots), which provides protection to the bank slope from surface runoff. *Alnus rugosa* and *Salix bebbiana*, dominant on erosional scarps, allocate about equal amounts of biomass in their above-ground and below-ground components, but have long tap roots, which help them colonize the steep scarp face. Plants on the bench and under-water shelf, such as *Juncus nodosus* and *Saggitaria latifolia*, allocate disproportionately large amounts of biomass to their above-ground components, which are exposed to the dynamics forces of waves and currents. Overall, the study indicates that root-shoot architecture and biomass can be used as biotechnical criteria in selecting riparian plants for bank stabilization of flood control channels.

Morisawa, M. 1968. Streams: their dynamics and morphology. McGraw-Hill Book Company, New York.

This book provides a good introduction to fluvial geomorphology. Topics include: hydrology, hydraulics of streams, sediment load transport, erosion, deposition, slope and channel morphology, the graded profile of the steady state, dynamic equilibrium, channel patterns, and basic concepts at the scale of the drainage basin (e.g. drainage patterns; drainage density and stream frequency)

Morisawa, M. 1985. Rivers: form and process. Longman Group Limited, New York.

This book discusses the morphology of rivers and their watersheds, and the mechanics by which rivers degrade landscapes, and transport and deposit sediments. Topics include: stream denudation, hydraulics of streamflow , entrainment and transport, mechanics and landforms of fluvial erosion, river morphology, river deposition and fluvial landforms, quantitative basin analysis, structural and lithological controls, and the impact of man on rivers.

Murgatroyd, A. L., and J. L. Ternan. 1983. The impact of afforestation on stream bank erosion and channel form. Earth Surface Processes and Landforms 8: 357-369.

Modification of the land use of a small catchment through coniferous afforestation is shown to have influenced stream bank erosion and channel form. Field mapping and erosion pin measurements over a 19-month period provides evidence of more active bank erosion along forested channel reaches than along non-forested. Extrapolation of downstream increases in bankfull width, bankfull depth, and channel capacity with increasing basin area for the non-forested catchment has demonstrated that afforestation of the lower part of the catchment has had a marked effect on channel form. Channel widths within the forest are up to three times greater than that predicted from the regression. These changes in bankfull width have led to stream bed aggradation and the development of wide shallow channels within the forest, and channel capacities within the forest are over two times that predicted from the basin area. The relationship between channel sinuosity and valley gradient for non-forested reaches of the river also indicated decreased sinuosity resulting from afforestation. These changes in channel form result from active bank erosion within the forest with coarse material being deposited within the channel as point-bars and mid-channel bars. Active bank erosion is largely attributed to the suppression by the forest of a thick grass turf and its associated dense network of fine roots, and secondly to the river attempting to bypass log jams and debris dams in the stream channel.

Nanson, G. C., and E. J. Hickin. 1986. A statistical analysis of bank erosion and channel migration in western Canada. Bulletin of the Geological Society of America 97: 497-504.

Mean lateral-migration rates of 18 meandering river channels in western Canada are explained statistically in terms of hydraulic and sedimentological variables. The volume of sediment eroded from the outer bank of a meander bend is shown to be largely a function of river size and grain size of sediment at the base of the outer bank. These variables explain almost 70% of the volumetric migration rate for these relatively large, sand- and gravel-bed streams. It would appear that bank erosion and channel migration are essentially problems of sediment entrainment which is dependent on total stream power and sediment size. Vegetation on the outer bank is seen to have little significant effect in controlling channel migration. Further refinements of the type of data used here should permit the development of an accurate predictive model of regional channel migration. To this effect, it is most important to develop a precise relationship between bank resistance and the size of sediment at the base of the outer bank.

Nanson, G. C., A. V. Krusenstierna, E. A. Bryant, and M. R. Renilson. 1994. Experimental measurements of river-bank erosion caused by boat-generated waves on the Gordon River, Tasmania. Regulated Rivers: Research & Management 9: 1-14.

Erosion of natural river banks by boat-generated waves is an increasingly serious problem on the navigable reaches of many rivers, particularly on the middle and estuarine reaches. An experiment designed to link bank erosion rates with easily measured wave characteristics, conducted on the scenic lower Gordon River in Tasmania, provides information useful for river management. Within a boat-generated wave train a number of characteristics were measured and most showed a high correlation with measured rates of bank retreat. Maximum wave height within the train is the simplest measure and is associated with a major threshold in erosive energy on unconsolidated sandy alluvium at wave heights of 30 to 35 cm. At maximum wave heights above 35 cm all but the most resistant bank sediments erode. Reducing maximum wave heights to < 30 cm by limiting boat speeds, and reducing the frequency of boat passages, caused a dramatic decline in bank erosion along the river.

National Technical Information Service. 1987. Soil erosion control: waterway embankments. January 1977-October 1986 (citations from the Selected Water Resources Abstracts database). National Technical Information Service, Springfield, Virginia. NTIS Order No.: PB88-850755/GAR.

This bibliography contains citations concerning the mechanisms of bank erosion and measures for erosion control. Land topography, river topography and currents, land use, weather factors, and waterway traffic are among the topics discussed. Retaining walls and vegetation renewal are considered as erosion control measures. Specific case studies are also included. (This updated bibliography contains 343 citations, none of which are new entries to the previous edition.) (Prepared in cooperation with Office of Water Research and Technology, Washington, DC (USA).)

National Technical Information Service. 1987. Soil erosion control: waterway embankments. November 1986 --October 1987 (citations from the Selected Water Resources Abstracts database). National Technical Information Service, Springfield, Virginia. NTIS Order No.: PB88-850763/GAR.

This bibliography contains citations concerning the mechanisms of bank erosion and measures for erosion control. Land topography, river topography and currents, land use, weather factors, and waterway traffic are among the topics discussed. Retaining walls and vegetation renewal are considered as erosion control measures. Specific case studies are also included. (This updated bibliography contains 56 citations, all of which are new entries to the previous edition.) (Prepared in cooperation with Office of Water Research and Technology, Washington, DC (USA).)

Rinaldi, M., and N. Casagli. 1999. Stability of streambanks formed in partially saturated soils and effects of negative pore water pressures: the Sieve River (Italy). Geomorphology 26: 253-277.

Streambanks of alluvial channels are usually composed of loose materials, which are unsaturated in ambient conditions. Unsaturated soils are subject to negative pre water pressures, which cause an apparent cohesion. The latter is the main factor in allowing the stability of near-vertical banks. Even during moderate in-bank flow events, the apparent cohesion can be strongly reduced as the material approaches full saturation; therefore, during the drawdown phase, as the confining pressure of the water in the channel disappears, a bank failure is likely to occur. Channel bed-level lowering along the Sieve River, Central Italy, has caused widespread bank instability. A geomorphological reconnaissance of forms and processes was followed by *in situ* tests to determine the shear strength of the banks. Interpretation of the tests and a streambank stability analysis were based on concepts of soil mechanics for unsaturated soils, in order to obtain relations between bank angle and height in limit equilibrium conditions. A stability chart was obtained with curves for different apparent cohesion values, and a stability analysis was performed taking into account the effects of flow events. In order to investigate the pore pressure effects, a series of piezo-tensiometers were installed in a streambank of the Sieve River. Data from a 1 year monitoring period show variations in pore water pressure and matric suction as a consequence of rainfall, evapotranspiration, and water stage variations. A planar failure with a tension crack occurred in the upper cohesive part of the bank during December 1996. The safety factor has been expressed as a function of the geometry of the bank and of the shear strength of the material. Safety factor variations through time are therefore shown as a function of seasonal variations in matric suction.

Rowntree, K. M., and E. S. J. Dollar. 1999. Vegetation controls on channel stability in the Bell River, Eastern Cape, South Africa. Earth Surface Processes and Landforms 24: 127-134.

Channel instability has occurred in the Bell River in the form of meander cutoffs, a number of which have occurred since 1952. Increased sediment loading from widespread gully erosion in the catchment has been proposed as the trigger for this instability. Willow species of the *Salix* family, in particular *S. caprea*, have been planted along the banks in an effort to prevent further channel shifting. This study reports the results of an investigation in to the effect of vegetation on channel form and stability over a 17 km stretch of channel. Results indicate that riparian vegetation has significant effects on channel form which have implications for channel stability. Riparian vegetation increases bank stability and reduces channel cross-sectional area, thereby inducing stability at flows less than bankfull. Evidence indicates that narrow stable stretches are associated with relatively high levels of riparian vegetation. Wider, unstable channels are associated with relatively less riparian vegetation. The effectiveness of riparian vegetation relative to bank sediments was investigated. A dense growth of willows was found to have an equivalent effect to banks with a silt-clay ratio of about 70 per cent. The channel narrowing induced by vegetation may contribute to channel shifting at high flows. The reduced channel capacity is thought to result in more frequent overbank flooding which may ultimately lead to avulsion. Thus where increased sediment loading is pushing the channel towards instability, vegetation may be effective in imparting local stability, but it is unable to prevent long-term channel shifts, and may rather help to push the system toward more frequent avulsions.

Smith, D. G. 1976. Effect of vegetation on lateral migration of anastomosed channels of a glacier meltwater river. Geological Society of America Bulletin 87: 857-860.

A series of experiments were performed on bank materials of anastomosed channels in flood-plain silt deposits in the Alexandra Valley in Banff Park, Alberta, to determine the effect of vegetation roots on bank erodibility and lateral migration of channels. Underground roots from the dense growth of meadow grass and scrub willow provide the reinforcement of bank sediment and a riprap-like protection of channel banks from river erosion. Results from the experiments suggest that in cool environments with aggrading river conditions where overbank deposition of silt, clay, and fine sand dominate the valley fill, vegetation roots are able to rapidly accumulate and decay very slowly, thus affording protection to banks from erosion in deeper parts of the channels.

Experiments were performed with a specially designed erosion box, used as a means to simulate natural erosion conditions and measure the influence of vegetation roots in reducing bank erosion. Results indicate that the bank sediment with 16 to 18 percent by volume of roots with a 5-cm root-mat for bank protection, typical of the area, had 20,000 times more resistance to erosion than comparable bank sediment without vegetation. Assuming five severe erosion days per year, potential lateral channel migration would amount to 4.2 cm per year. Such resistance, due to vegetation, accounts for the remarkable stability of channels during the last 2,500 yr in Alexandra Valley.

Smith, R. D., R. C. Sidle, P. E. Porter, and J. R. Noel. 1993. Effects of experimental removal of woody debris on the channel morphology of a forest, gravel-bed stream. Journal of Hydrology 152: 153-178.

Experimental removal of woody debris from a small, gravel-bed stream in a forested basin resulted in dramatic redistribution of bed sediment and changes in bed topography. Removal of debris changed the primary flow path, thereby altering the size and location of bars and pools and causing local bank erosion and channel widening. Marked bed adjustments occurred almost immediately following experimental treatment in May 1987 and continued through to the end of the study period in 1991.Increased bed material mobility was attributable to destabilization of sediment storage sites by removal of debris buttresses, elimination of low-energy, backwater environments related to debris, and an inferred increase in boundary shear stress resulting from the removal of debris-related flow resistance. In contrast to these changes, which favored sediment mobilization, deposition was favored by the elimination of debris-related scouring turbulence and by increased flow resistance from a developing sequence of alternate bars. A more regularly spaced sequence of alternate bars replaced the pretreatment bar sequence, whose location, size, and shape had been strongly influenced by large woody debris as well as by bank projections and channel curvature. Following initial readjustment of the stream bed during the first post-treatment year, loss of scouring turbulence and increased flow resistance from alternate bars resulted in deposition of approximately 44 m^3 of sediment within the 96 m study reach. The loss of 5.2 m^3 to bank erosion left a net increase in sediment storage of 39 m^3. Mean spacing of thalweg cross-overs and pools did not change measurably following debris removal, although variability of spacing between thalweg cross-overs tended to decrease with time as the location of bars stabilized. No consistent pattern of change in mean residual depth of pools or in distribution of depths occurred within the first 4 years following debris removal.

Stott, T. 1997. A comparison of stream bank erosion processes on forested and moorland streams in the Balquhidder catchments, Central Scotland. Earth Surface Processes and Landforms 22: 383-399.

Stream bank erosion rates measured over a two-year period on a moorland and a forested stream in the Institute of Hydrology's Balquhidder Paired Catchments in central Scotland were compared. Bank erosion rates are generally higher on the mainstream of the moorland catchment and highest in winter on both streams. Bank erosion is correlated with the incidence of frost: minimum temperatures measured on stream banks of the forested stream were an average of 3.7^{o} C higher than on stream banks both outside the forest and on the moorland stream. This makes the incidence of frost on forested stream banks half as frequent. Volumes of material eroded from the mainstreams were combined with bulk density measurements and it is estimated that erosion of the mainstream banks is contributing 1.5 and 7.3 % of the sediment yield of the forested and moorland catchments, respectively. Analysis of the vertical distribution of erosion on the banks of both streams suggests an undercutting mechanism which is more pronounced in the moorland stream. The influence of trees on bank erosion and possible implications for the management of forest streams are discussed.

Tatinclaux, J. -C. 1998. Recent progress in river ice engineering research at CRREL. Journal of Cold Regions Engineering: 114-37.

The author reviews and summarizes the results of the research and development efforts in river ice engineering conducted at the U.S. Army Cold Regions Research and Engineering Laboratory over the last 10 years and their applications to the Civil Works mission of the U.S. Corps of Engineers. Topics discussed include winter operation of navigation projects on the major northern U.S. waterways; river ice processes; ice jam documentation, prediction, and mitigation; and bed and bank erosion due to ice. In addition, future challenges and areas of needed research in river ice engineering are discussed.

Thorne, C. R. 1982. Processes and mechanisms of river bank erosion. Pages 227-271 *in* R. D. Hey, J. C. Bathurst, and C. R. Thorne, editors. Gravel-bed rivers: fluvial processes, engineering and management. John Wiley & Sons Ltd., New York.

The importance of bank erosion to channel hydraulics and sedimentary processes makes it appropriate that a review and investigation of the way in which a river erodes its banks should be undertaken. To do this it is necessary to consider the processes responsible for the erosion of material from a bank and the mechanisms of failure resulting from the instability created by those processes. Processes of erosion fall into two main groups: fluvial entrainment, and subaerial/subaqueous weakening and weathering. Usually it is particular combinations of processes which are most effective in causing erosion. Mechanisms of failure depend on the size, geometry and structure of the bank and the engineering properties of bank material. Mechanical bank failures supply material to the toe. Its removal from there depends on fluvial entrainment.

The balance between rates of supply and removal may be described by the state of basal endpoint control. This has important implications for the profile, stability and retreat rate of river banks and schemes to protect banks from erosion.

Additional comments

This paper is part of a proceedings of a workshop. In a discussion with the audience after the paper presentation, several comments were made that were relevant to this literature review. It was pointed out by N. G. Bhowmik that wind- and boat-generated waves also cause bank erosion, and in some cases can cause more bank retreat than fluvial erosion. It was also noted that vegetation influences on bank erosion can be positive or negative; the issue is a matter of scale. Large uprooted trees along the banks of large rivers protect banks against erosion. The same trees along smaller rivers can cause local acceleration of the flow, thereby causing bank erosion. The author agreed with the assessment. In addition, the author noted that absolute size of vegetation is also important. Large trees reduce bank stability with respect to mass failure because the additional weight of trees on steep banks is always more significant than the increased shear strength afforded by root reinforcement. On the other hand, smaller forms of vegetation such as small trees, shrubs, and deep-rooted grasses increase soil shear strength without significantly increasing the weight of a bank.

A detailed discussion by M. Church and M.J. Miles regarding riverbank stability in permafrost regions also is included. Types of riverbanks peculiar to arctic and subarctic regions, and erosional processes related to permafrost and river ice are described. Church and Miles note that vegetation roots may act as riprap to stabilize banks; stabilization is most effective along relatively small channels.

Thorne, C. R., and J. Lewin. 1979. Bank processes, bed material movement and planform development in a meandering river. Pages 117-137 *in* D. D. Rhodes, and G. P. Williams, editors. Adjustments of the fluvial system. Kendall/Hunt Publishing Company, Dubuque, Iowa.

Field observations of bank processes and bed material movement at a meander bend on the River Severn, U.K., are presented and discussed in the light of historical evidence for channel change in the past 150 years. Mechanisms of banks failure, in general dependent on bank structure and composition, are here dominated by fluvial undercutting and mechanical failure of cantilevers in the upper bank. Failed material accumulates at the bank foot from where it is removed by fluvial entrainment. Tracer experiments show that bank retreat rates are fluvially controlled though failure mechanisms are not. Measured retreat rates are around 0.5 m/yr comparing with up to 0.7 m/yr historically on the same reach.

Contrasting forms of planform development are apparent, including complex loop formation, neck and chute cut-offs, and the rapid abandonment of lengths of cut bank and deep channel. Upstream changes and large, but infrequent, discharge events have profound effects which are difficult to predict.

Channel change can be usefully regarded as a sediment transfer process involving bank failure, sediment entrainment, transport, and deposition. However, both field studies and documentary analysis are needed for a good understanding of the full range of contemporary channel change characteristics in space and time.

Additional comments

There was a large disparity in retreat rates between the lower portion of the bank where erosion was controlled by fluvial undercutting, and the upper portion of the bank where erosion was controlled by mechanical failure. This disparity of erosion rates resulted in the development of overhanging banks (cantilevers). The stability and dimension of these cantilevers was dependent upon the thickness of the upper bank material and its engineering properties. The mode of cantilever failure (shear, beam, or tensile failure) was also dependent upon the thickness of the upper bank material and its engineering properties. Developments of cracks in a cantilever was often the critical factor that brought about its failure. Roots and rhizomes of grasses enhanced the stability of the upper banks by reinforcing the soil, thereby inhibiting development of cracks.

Trimble, S. W. 1997. Stream channel erosion and change resulting from riparian forests. Geology 25: 467-469.

Forested stream banks, compared to grassed ones, can destabilize stream channels by promoting erosion. Four reaches of Coon Creek, Wisconsin, each with long-term grassed and forested subreaches were examined. Grassed reaches were narrower and had smaller channels (bankfull cross sections) than forested reaches, suggesting that grassed channel reaches stored about 2100 to 8800 m^3 more sediment per kilometer than forested reaches. Available evidence suggests that conversion of riparian forests to grass would allow storage of sediment along channels, possibly decreasing downstream sediment yields. These findings are important as many grassed riparian corridors are rapidly reverting to forest because of economic conditions and governmental policies.

Williams, J. R. 1952. Effect of wind-generated waves on migration of the Yukon River in the Yukon Flats, Alaska. Science 115: 519-520.

The author determined that summer wind-generated waves influence the migration of the Yukon River in east-central Alaska. Differences in soil development, vegetation, and alluvial features such as river islands and bars, between the north and south sides of the river suggest that the south bank has grown northward by deposition as the north bank has retreated by erosion. The strongest summer winds, which are from the southwest, produce choppy waves as they blow across the river. The waves attain their maximum height (up to three feet) and erosive power along the north bank of the river. In contrast, the south bank is protected from waves generated by the southwest summer winds. During winter, wind cannot form waves on the ice-covered river.

Wolman, M. G. 1959. Factors influencing erosion of a cohesive river bank. American Journal of Science 257: 204-216.

The sinuous channel of Watts Branch in Montgomery County, Maryland, traverses a grassy meadow nearly devoid of trees. The creek has a drainage area of four square miles and the river bank is composed primarily of cohesive silt. Resurveys of cross sections during the five years 1953-1957 have revealed as much as seven feet of lateral erosion. Over the past two years, additional measurements of the amount of erosion around rows of steel pins driven horizontally into the bank have been made at frequent intervals. These observations indicate several combinations of factors primarily responsible for the progressive recession.

Approximately 85 percent of the observed erosion occurred during the winter months of December, January, February, and March. A thickness of as much as 0.4 feet of sediment was eroded from the bank at specific points in a period of several hours during which a bankfull flow attacked banks which had previously been thoroughly wetted. Erosion was most severe at the water surface. Little or no erosion was observed during the summer despite the occurrence of the highest flood on record in July 1956.

Second in erosion effectiveness were cold periods during which wet banks, frost action, and low rises in stage combined to produce 0.6 foot of erosion in six weeks during the winter of 1955-56. Significant erosion also resulted from the combination of moist banks and low rises in stage. Lastly, crystallization of ice and subsequent thawing, without benefit of changes in stage, also produced some erosion as did flashy summer floods even on hard, dry banks. Inasmuch as such summer floods constitute the rare and “catastrophic” events on small drainage basins in this region, present observations suggest that the cumulative effect of more moderate climatic conditions on this process of erosion exceeds the effect of rarer events of much greater magnitude.

This preliminary analysis of several factors responsible for erosion of the cohesive river bank indicates that there is perhaps a crude correlation between precipitation and erosion during selected intervals of time. Precipitation exerts an affect both through increasing discharge in the channel and by increasing the moisture in the bank. Frost action acts similarly both to hold moisture in the soil and to comminute surface material, thus preparing it for erosion.

LARGE WOODY DEBRIS

An Annotated Bibliography

Compiled for the
Region III Forest Practices Riparian Management Committee

by
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SUMMARY

Much has been written the past few decades about the beneficial roles that wood, particularly large woody debris (LWD) can play in fish-bearing water bodies. Accordingly, the preservation of short- and long-term sources of LWD plays a central role in the statutory riparian standards of the Alaska Forest Resources and Practices Act. Few studies, however, have taken place on large rivers, on glacial rivers, or in interior Alaska; we found none published on a site with all three characteristics. The purpose of this literature review was to provide information on the roles of LWD using sources most applicable to large rivers, glacial rivers, and Region III.

In smaller or clearer water bodies, LWD plays a direct role in salmonid habitat, particularly for juvenile fish. This is largely related to the spawning and cover-use characteristics of this group of fishes (e.g., Lister and Genoe 1970, Lee 1985, Murphy et al. 1989, Hicks et al. 1991, Inoue and Nakano 1998). The review monograph by Murphy (1995) is the most applicable to Region III of the several volumes available documenting the effects of forestry-related activities on LWD and other aspects of fish habitat and water quality, although its focus is the Pacific Northwest and southeast Alaska. When ice (Jakober et al. 1998) or turbidity (Murphy et al. 1989) provide cover, the roles of LWD can shift from direct to indirect through effects on substrate size, island and side channel formation, and stream bed and bank roughness. The interaction of velocity, turbidity, and cover can result in small-scale differences in habitat suitability for both anadromous and resident fish.

In large streams in Region III, the role for LWD may be more indirect, because water velocities in mainstem channels are often high, and much of the LWD is on bars or jams above the free-flowing water during winter months. In large glacial streams, the chief role of LWD may well be in shaping stream morphology, adding hydraulic roughness to glacial streams, providing bank armoring, contributing to the formation of river bars and islands, and blocking side channels (Fetherston et al. 1995, Abbe and Montgomery 1996, Montgomery et al. 1996, Dudley et al. 1998). Removal of wood in many large rivers since European settlement of North America has resulted in altered channel structure even in large rivers, and the deleterious effects of such removal can be long-term (Maser and Sedell 1994). Because of its size, LWD in large rivers can be more stable than the relatively mobile bed load sediments, and can function as substrate for aquatic invertebrates used by fishes as food. Is has also been hypothesized that

LWD could play an important, but short-term, role during migration by providing eddies where upstream movement is easier and where fish can rest.

A number of data gaps were noted. The general lack LWD data for large, glacial rivers, especially those with seasonal ice cover, is striking when viewed against the large body of literature for smaller, clearer streams in more moderate climates. Basic information needs include data on wood budgets of large rivers, and optimal amounts of LWD in stream systems to provide fish habitat functions. Data on these direct and indirect roles of LWD as fish habitat in large rivers, glacial rivers, and during winter are also needed before we will be able to fully assess whether the status quo is above or below optimal, and how LWD can be a limiting factor for fish populations. Specific information on the role of LWD as cover or resting habitat for juvenile and adult anadromous and resident fish species could directly bear on the assessments and recommendations currently being developed by the SCC. A number of publications examined did not provide the size of the LWD being studied, or of the physical and chemical characteristics of the stream or river, and so the applicability of these publications to this review could not be determined.

Annotations in this review are primarily authors' abstracts. Citations and annotations came from a variety of sources, including an online search by the Alaska Resources Library and Information Services (ARLIS, key words "woody debris" and "log jams"), reviewers' personal libraries, and the 1998 report by A.G. Ott, et al.

REFERENCES

Abbe, T. B., and D. R. Montgomery. 1996. Large woody debris jams, channel hydraulics and habitat formation in large rivers. Proceedings of International Symposium on Habitat Hydraulics, Trondheim (Norway), 18-20 Aug 1994. Regulated Rivers: Research & Management 12:201-221.

Field surveys document the accumulation of large woody debris (LWD) into structurally distinctive jam types in the alluvial channel of the Queets River on the Olympic Peninsula of north west Washington. Calculations, field observations and historical evidence show that these jams can form stable structures controlling local channel hydraulics and providing refugia for riparian forest development over decades and possibly centuries. Distinctive spatial patterns of LWD, pools, bars and forested islands form in association with particular jam types. The deposition of 'key member' logs initiates the formation of stable bar apex and meander jams that alter the local flow hydraulics and thereby the spatial characteristics of scour and deposition leading to pool and bar formation. Historical evidence and the age structure of forest patches document the temporal development of alluvial topography associated with these jam types. Bar apex jams, for example, are associated with a crescentic pool, an upstream arcuate bar and a downstream central bar that is the focus of forest patch development. Experimental and empirical studies in hydraulic engineering accurately predict channel scour associated with jams. Individual jams can be remarkably stable, providing long-term bank protection that creates local refugia for mature forest patches within a valley floor environment characterized by rapid channel migration and frequent disturbance. Processes controlling the formation, structure and stability of naturally occurring LWD jams are fundamental to the dynamics of forested river ecosystems and provide insights into the design of both habitat restoration structures and ecosystem-based watershed management.

Assani, A. A., and F. Petit. 1995. Log-jam effects on bed-load mobility from experiments conducted in a small gravel-bed forest ditch. Pages 117-126 *in* Poesen, J., G. Govers, and D. Goossens, editors. Experimental Geomorphology and Landscape Ecosystem Changes. Proceedings of a Memorial Symposium for Prof. Jan de Ploey, 22-26 March 1993. Catena 25.

Bed-load transport experiments have been conducted in a steep gravel-bed open ditch. This initially straight ditch has been neglected for many years and looks at present like a second-order natural stream channel. The channel flows through a spruce forest and several log-jams have produced chutes and pools, creating supplementary roughness. The total shear stress has been evaluated using the slope-hydraulic radius product, and the ratio between grain and bed-form shear stresses has been calculated using different methods. The shear stress has also been evaluated from the shear velocities, and this gives a good evaluation of the grain shear stress. Additional experiments have been conducted with marked pebbles to estimate particle mobility and to improve the motion equations. Equations such as $\theta_c = a(D_i/D_{50})^b$, defined by Andrews, apply in these cases but the values of a and b are lower than those produced by this author. In a second stage of experimentation, we have destroyed the log-jams resulting in a diminution of the roughness and critical shear stress (when the total shear stress is used), an increase of the grain shear stress, and thus greater bed particle mobility for the same discharge. It emerges from these experiments that the log-jams contribute to the reduction of bed-load evacuation and explain the very weak bed-load discharge measured by a bed-load trap (0.3 $t/km^2/yr$).

Beschta, R. L., and E. G. Robison. 1990. Characteristics of coarse wood debris for several coastal streams of southeast Alaska, USA. Canadian Journal of Fisheries and Aquatic Sciences 47:1684-1693.

Coarse woody debris (>0.2 mm in diameter and 1.5 m long) was measured along five undisturbed low-gradient stream reaches; volume, decay class, and horizontal orientation in relation to channel flow of first-order, second-order, third-order, and fourth-order coastal streams were determined. Debris was also classified into four influence zones based on stream hydraulics and fish habitats. Average debris length, diameter and volume per piece increased with stream size. Eighty percent of debris volume of the first-order and the smaller second-order streams was suspended above or lying outside the bankfull channel, while less than 40% was similarly positioned in the fourth-order stream. Approximately one- third of all debris was oriented perpendicular to stream flow, regardless of stream size. First-order, second-order, and third-order streams had a higher proportion of recent debris in the channel than the fourth-order stream, most new debris being attributable to a major 1984 windstorm. Tree blowdown had a major influence on debris distribution along the smaller storm reaches. Debris jams and accumulations in the largest stream were formed from floated debris. These characterizations are useful for evaluating the distribution and amount of woody debris associated with land-management activities.

Bilby, R. E., and G. E. Likens. 1980. Importance of organic debris dams in the structure and function of stream ecosystems. Ecology 61:1107-1113.

Removal of all organic debris dams from a 175-m stretch of second-order stream at the Hubbard Brook Experimental Forest in New Hampshire led to a dramatic increase in the export of organic carbon from this ecosystem. Output of dissolved organic carbon (<0.50 ? m) increased 18%. Fine particulate organic carbon (0.50 ? m–1 mm) export increased 632% and coarse particulate organic matter (>1 mm) export increased 138%. Measurement of the standing stock of coarse particulate matter on streambeds of the Hubbard Brook Valley revealed that organic debris dams were very important in accumulating this material. In first-order streams, debris dams contain nearly 75% of the standing stock of organic matter. The proportion of organic mater held by dams drops to 58% in second-order streams and to 20% in third-order streams. Organic debris dams, therefore, are extremely important components of the small stream ecosystem. They retain organic matter within the system, thereby allowing it to be processed into finer size fractions in headwater tributaries rather than transported in a coarse particulate form.

Bragg, D. C., and J. L. Kershner. 1999. Coarse woody debris in riparian zones. Journal of Forestry 97:30-35.

Interdisciplinary cooperation is necessary to ensure long-term sustainability of our nation's forests and restore the processes and function associate with healthy ecosystems. Past models of forest management were often driven by narrow resource objectives and did not consider the variety of natural ecosystems. We believe that large-scale efforts, such as the Northwest Forest Plan and watershed analysis, provide new opportunities for cooperation among natural resource professionals. Prospects for interaction are considerable, since changes in forests have affected most of the riparian zones in North America.

Braudrick, C. A., G. E. Grant, Y. Ishikawa, and H. Ikeda. 1997. Dynamics of wood transport in streams: a flume experiment. Earth Surface Processes and Landforms 22:669-683.

The influence of woody debris on channel morphology and aquatic habitat has been recognized for many years. Unlike sediment, however, little is known about how wood moves through river systems. We examined some dynamics of wood transport in streams through a series of flume experiments and observed three distinct wood transport regimes: uncongested, congested and semi-congested. During uncongested transport, logs move without piece-to-piece interactions and generally occupy less than 10 per cent of the channel area. In congested transport, the logs move together as a single mass and occupy more than 33 per cent of the channel area. Semi-congested transport is intermediate between these two transport regimes. The type of transport regime was most sensitive to changes in a dimensionless input rate, defined as the ratio of log volume delivered to the channel per second (Q sub(log)) to discharge (Q sub(w)); this ratio varied between 0.015 for uncongested transport and 0.20 for congested transport. Depositional fabrics within stable log jams varied by transport type, with deposits derived from uncongested and semi-congested transport regimes having a higher proportion of pieces oriented normal to flow than those derived from congested transport. Because wood input rates are higher and channel dimensions decrease relative to piece size in low-order channels, we expect congested transport will be more common in low-order streams while uncongested transport will dominate higher-order streams. Single flotation models can be used to model the stability of individual pieces, especially in higher-order channels, but are insufficient for modeling the more complex interactions that occur in lower-order streams.

Bren, L. J. 1993. Riparian zone, stream, and floodplain issues: a review. Journal of Hydrology 150:277-299.

In the last two decades, the effects of forest management on streams, riparian zones, and floodplains have become of much interest. In general, there is agreement that such areas should be maintained in a state approximating naturalness, although it is recognized that definition of this state is usually difficult or impossible. A diversity of management effects has been recognized and, in some cases quantified. For upland catchments, issues particularly relate to direct disturbance of the zone, changes in the flow of woody debris into the stream, or disturbance to the environment by effects generated upstream or downstream. For many areas, a particularly important commercial aspect is the definition of a 'stream,' as this can impose many expensive and severe restrictions on management of the land. For large rivers, a common issue is the effect of river management on flooding forests. In each case, the issues are complex, information is difficult to collect, and there are fundamental difficulties in going from anecdotal observation to data. Currently, most information appears to be at a relatively local level, and there is a very inadequate knowledge base to give a more holistic overview, although the concept of 'cumulative effects.' with the effects accumulated over both space and time, has much potential value. There are many opportunities for work in this field.

Bryant, M. D., and J. R. Sedell. 1995. Riparian forests, wood in the water, and fish habitat complexity. Pages 202-224 *in* N.B. Armantrout, editor. Condition of the world's aquatic habitats. Proceedings of the World Fisheries Congress, Theme 1. Oxford & IBH Publishing Co. Pvt. Ltd., New Delhi.

Civilization has significantly removed or altered large tracts of riparian forest through agriculture, urbanization, and logging. The result has been a long-term (100 years+) loss of large wood in lotic ecosystems. This has changed the perspective in which rivers and large wood have been viewed. Historical records and undisturbed systems in the Pacific Northwest and Alaska have shown that large wood has been and is abundant in undisturbed streams. Large wood serves to connect the main stream to its floodplain, creates complex channel structure, and forms off-channel habitats and pools. All are in areas of high biological productivity, which is reflected in higher fish numbers. These trends appear to occur on a global basis over a diverse set of ecosystems. Given the continuing loss of riparian forests, management should promote retention of riparian forest. Rehabilitation and restoration of degraded riparian habitat is a long-term process and should re-establish riparian vegetation and reconnect rivers with floodplain processes.

NOTE: The authors provide a good discussion of the role of wood in large river systems, and provided extensive citations.

Bugosh, N., and S. G. Custer. 1989. Effect of a log-jam burst on bedload transport and channel characteristics in a headwaters stream. Pages 203-211 *in* Proceedings of the Symposium on Headwaters Hydrology, American Water Resources Association, Bethesda Maryland.

Hydraulic factors are commonly assumed to exercise primary control on sediment transport in high-gradient headwaters streams. Research in 1983 and 1984 on Squaw Creek, a tributary to the Gallatin River in Montana, has shown that other hydrologic and geomorphic factors are also important. One of these factors is log-jams. A log-jam functions as a sediment storage area and as a local base level. The catastrophic dispersal of an old-jam in the study reach was observed and recorded during 1983. The log-jam broke when discharge was 6.4 cu m/s. A pulse of sediment was released from storage. One side of the channel was filled and channel morphology was altered. As the stream adjusted to the new morphology, average bedload transport was as high as 0.4 kg/m/s. This rate is at least two times the bedload transport rate measured at similar and higher discharges during runoff in 1983 and 1984. Thirty percent of the measured bedload in 1983 moved in a three day period and is directly attributable to the burst of the log-jam. The dispersal of this log-jam and the resulting instantaneous changes in bedload transport parameters had a greater effect on bedload in Squaw Creek more than any other parameter studied. Log-jam breakage affects bedload availability, bedload transport and channel characteristics in headwater streams.

Diehl, T. H., and B. A. Bryan. 1993. Supply of large woody debris in a stream channel. ages 1055-1060 *in* Shen, H. W., S. T. Su, and Feng Wen, editors. Proceedings of Hydraulic Engineering '93 Conference, San Francisco. American Society of Civil Engineers.

The amount of large woody debris that potentially could be transported to bridge sites was assessed in the basin of the West Harpeth River in Tennessee in the fall of 1992. The assessment was based on inspections of study sites at 12 bridges and examination of channel reaches between bridges. It involved estimating the amount of woody material at least 1.5 meters long, stored in the channel, and not rooted in soil. Study of multiple sites allowed estimation of the amount, characteristics, and sources of debris stored in the channel, and identification of geomorphic features of the channel associated with debris production. Woody debris is plentiful in the channel network, and much of the debris could be transported by a large flood. Tree trunks with attached root masses are the dominant large debris type. Death of these trees is primarily the result of bank erosion. Bank instability seems to be the basin characteristic most useful in identifying basins with a high potential for abundant production of debris.

Dudley, S. J., J. C. Fischenich, and S. R. Abt. 1998. Effect of woody debris entrapment on flow resistance. Journal of the American Water Resources Association 34: 1189-1198.

Recent environmental concerns in floodplain management have stimulated research of the effect vegetation and debris have on flow conveyance, and their function in a productive riparian ecosystem. Although the effect of stable, in-channel woody debris formations on flow resistance has been noted by several authors, studies concerning entrapment of detrital debris in vegetation are lacking. Logs, limbs, branches, leaves and other debris transported during flooding often become lodged against bridges, hydraulic structures, trees and vegetation, and other obstacles, particularly in and near the overbank areas. Hydraulic measurements obtained in a channel prior to and following the removal of woody debris indicated that the average Manning's n value was 39 percent greater when woody debris was present. An examination of the drag-velocity relation for vegetation indicated that an increase in the frontal area of debris and/or vegetation results in a nearly proportional increase in Manning's n. The influence of debris on flow resistance decreased as flow depth increased.

Fetherston, K. L., R. J. Naiman, and R. E. Bilby. 1995. Large woody debris, physical process, and riparian forest development in montane river networks of the Pacific Northwest. Geomorphology 13:133-144.

The authors present a conceptual biogeomorphic model of riparian development in montane river networks. The role of physical process in driving the structure, composition, and spatial distribution of riparian forests is examined. The authors classify the drainage network into disturbance process-based segments including: (1) debris-flow and avalanche channels, (2) fluvial and debris-flow channels, and (3) fluvial channels. Riparian forests are shown to be significant in the development of channel morphology through stabilization of active floodplains and as a sources of large woody debris (LWD). LWD is operationally defined as wood >0.1 m diameter and > 1 m length. LWD plays a key role in the development on montane riparian forests. LWD deposited in the active channel and floodplain provides sites for vegetation colonization, forest island growth and coalescence, and forest floodplain development. Riparian forest patterns parallel the distribution of hillslope and fluvial processes through the network. Riparian forest structure, composition, and spatial distribution through the network are driven by the major disturbance processes including: (1) avalanches, (2) debris-flows, and (3) flooding. Riparian forest patterns also reflect the action of LWD in the organization and development of forested floodplains in gravel bedded montane river networks. The focus of the authors' examples are montane river networks of the Pacific Northwest, USA.

France, R. L. 1997. Macroinvertebrate colonization of woody debris in Canadian Shield lakes following riparian clearcutting. Conservation Biology 11: 513-521.

Deployment of litterfall traps revealed that clearcut logging of boreal riparian forests in northwestern Ontario, Canada resulted in a dramatic shift from once dominant conifers to regrowth composed largely of deciduous trees and reduced the allochthonous inputs of small woody debris to lake littoral zones by over 90%. Due to the rarity of macrophytes in these oligotrophic lakes, littoral macroinvertebrates were found to actively colonize woody debris placed within mesh litter bags. The recalcitrant nature of small woody debris in these lakes (average median persistence time of about 5 years estimated from mass loss data) indicates, however, that this important habitat resource will probably never completely disappear in relation to its projected rate of resupply during post-disturbance forest regeneration. Colonization rates of twigs and bark contained within the litter bags were not found to differ between coniferous and deciduous species. This indicates that macroinvertebrates in these boreal lakes are merely opportunistic colonizers of woody debris, probably for its use as either a biofilm substrate or a predation refuge. As a result, shifts in tree species composition following riparian clearcutting should not detrimentally affect the taxa richness or organism abundance of aquatic macroinvertebrates in these lakes.

Gregory, K. J., and R. J. Davis. 1992. Coarse woody debris in stream channels in relation to river channel management in woodland areas. Regulated Rivers: Research & Management 7:117-136.

Although river channel management now generally uses soft rather than hard engineering techniques the considerable research achieved for woodland river channels has not been completely collated with reference to management implications. Research results from 22 research papers show how debris dams have a significant influence upon the morphological, the process and the ecological aspects of channels, vary in their permanence, and differ in stability according to the overall organic matter budget. A summary diagram contrasts the impact of dams on river channel morphology, process and ecology before and after dam removal. Four major types of specific recommendations about the management of channels in woodland areas are identified from 29 research papers are that (1) management should be undertaken against a background knowledge of the behavior of coarse woody debris under natural conditions and that the organic matter budget should be disturbed as little as possible; (2) logging operations should minimize the amount of disturbance to, and disruption of, channel processes; (3) management should optimize the maintenance of habitat diversity and minimize the ecological disturbance to the channel; (4) in some areas specific management practices may require the introduction of new material into the channel. These recommendations were applied to the New Forest, southern U.K., which has a long history of clearance and management of coarse woody debris and where the requirements for clearance in relation to fish, drainage, and aesthetic impact can be achieved by minimizing the amount of removal of material from the river channel. In managing channels with debris dams in woodland areas, it is desirable to work with the river in a holistic basin context.

Gregory, K. J., A. M. Gurnell, and C. T. Hill. 1985. The permanence of debris dams related to river channel processes. Hydrological Sciences Journal 30:371-381.

Vegetation debris dams occur on average every 27 m of channel in a drainage basin in the New Forest, Hampshire, England, and within less than 12 months 36% changed position or were destroyed and 36% changed character. Such dams significantly affect the timing of flood peaks as they are routed through the channel network; their significance has been demonstrated by preliminary analysis of hydrograph travel times by measurements in a reach at different flow stages, and by measurements before and after dam clearance. There was a difference in travel time of over 100 minutes for the situation with and without dams for a discharge of 0.1 m^3/s but a difference of only 10 minutes for a discharge of 1.0 m^3/s along the same 4028 m channel reach.

Gurnell, A. M., K. J. Gregory, and G. E. Petts. 1995. The role of a coarse woody debris in forest aquatic habitats: Implications for management. Aquatic Conservation: Marine and Freshwater Ecosystems 5:143-166.

1. Throughout the Temperate Forest biogeographical zone, river valleys were once heavily wooded. Fallen trees had a major impact upon river systems by ponding water and storing sediments, and valley floors were characterized by extensive wetlands with networks of minor channels linking to the main channel. Concern for environmental conservation and for the

rehabilitation of damaged aquatic ecosystems has led to research on the links between river channel dynamics and vegetation, and an interest in the use of dead wood for environmentally sensitive engineering approaches to river management. 2. Accumulations of coarse woody debris (CWD) have an impact on the hydrological, hydraulic, sedimentological, morphological and biological characteristics of river channels. These impacts are very significant for the stability and biological productivity of river channels in forested catchments. 3. As a result of the geomorphological and ecological importance of CWD in river channels in forested catchments, such debris requires careful management. In particular indiscriminate removal of CWD should be avoided. 4. In the context of commercial forestry, a sequence of linked management options can be employed to control sediment and organic matter transport within river systems and to enhance channel stability and physical habitat diversity. These management options include selective removal of less stable debris, addition of debris to the river where the natural supply is inadequate, the maintenance of buffer strips of riparian trees which can act as a source of CWD, and the active management of woodland buffer strips to provide a wide range of physical habitat characteristics including light, temperature, flow, sediment transport and substrate conditions, thereby promoting high biological diversity within the river environment.

Gurnell, A. M., and R. Sweet. 1998. The distribution of large woody debris accumulations and pools in relation to woodland stream management in a small, low-gradient stream. Earth Surface Processes and Landforms 23:1101-1121.

This paper focuses upon the natural dynamics of large woody debris (LWD), the impact of management on LWD dynamics, and the impact of LWD removal and channelization on the distribution and size of pools in a British second to third order headwater catchment. The study stream is rather different from those subject to LWD accumulations which have been studied in North America. The most important contrast is that it is surrounded by predominantly deciduous rather than coniferous woodland. In terms of its width (1.8-4.5 m) and gradient (0.013 m/m), it falls within the lower range of channels studied in North America. Nevertheless, there are similarities in LWD dam and pool spacing with some North American studies. The information on LWD dynamics during a period without management and on recovery of LWD dams after clearance covers a 16 year period (1982-1997). The paper illustrates that seven to eight years after clearance the total number of LWD dams has recovered but the most hydraulically active dam type has not recovered to pre-clearance levels. An analysis of geomorphological maps of the channel surveyed in 1982 and 1996/97 shows an overall decrease in the number and size of pools along the section that was cleared of LWD dams. The magnitude of the decrease and the associated adjustments in pools through changes in their size and location differ according to location with respect to a section of the study stream which was channelized in *c*. 1966 and which has subsequently incised its bed.

Hicks, B. J., J. D. Hall, P. A. Bisson, and J. R. Sedell. 1991. Responses of salmonids to habitat changes. American Fisheries Society Special Publication 19:483-518.

In this review paper, the authors examined responses of salmonid populations to a variety of biotic and abiotic changes attributed to timber harvest and road building activities, including changes in the amount and kinds of LWD. LWD changes occur in all stream types and reaches, from small headwater streams to estuaries of large rivers. Important roles attributed to LWD include controlling stream channel morphology, regulating storage and routing of sediment and organic matter, and creating and maintaining fish habitat. The authors note that salmonid abundance is often closely linked to LWD abundance particularly in winter. The diversity of hydraulic gradients and hence microhabitats created by LWD supports greater diversity of coexistent species and age classes within the same stream reach. Removal of nearly all large trees from the riparian zone during logging has lead to long-term reductions in LWD in many larger rivers. The stumps, slash, and other smaller debris left from logging tends to deposit in fewer, larger jams than the larger typical riparian pieces. Unless large-scale events such as extensive blowdown occurs, LWD in the channel will decline until the next generation of trees becomes large enough. This was estimated at 50-100 years for most streams in the Pacific Northwest and southeast Alaska, with streams wider than about 15m requiring at least 60 years.

Hogan, D. L. 1987. The influence of large organic debris on channel recovery in the Queen Charlotte Islands, British Columbia, Canada. Pages 345-353 *in* Erosion and Sedimentation in the Pacific Rim. IAHS Publication No. 165. International Association of Hydrological Sciences, Washington, DC.

In-stream large organic debris (LOD) characteristics were evaluated in unlogged and logged coastal watersheds. The input, storage and output components of LOD budgets, how these are altered in logged and torrented channels and how these changes influence the recovery of disturbed channels were all examined. In small and medium sized watersheds, all components of the LOD budget are altered after logging and debris torrenting. Initially, the size and abundance of debris staged to enter the stream systems are reduced. Reduction in material size leads to a shift in the orientation of debris stored within the channel zone. Consequently, the scouring and trapping functions of debris pieces are altered. A less complex morphology results, including reduced depth, width and sediment texture variability and diminished pool area. The smaller debris is less stable causing an increased tendency for the material to cluster into major debris jams; this jam stores large volumes of clastic sediment upstream and leads to reduced channel stability. Because logging and debris torrenting can affect streambank vegetation for long periods of time, it is possible that the resultant channel disturbances will not be reversed over forest management time scales. (Author's abstract)

Inoue, M., and S. Nakano. 1998. Effects of woody debris on the habitat of juvenile masu salmon (*Oncorhynchus masou*) in northern Japanese streams. Freshwater Biology 40:1-16.

The effects of woody debris on stream habitat of juvenile masu salmon (*Oncorhynchus masou*) were examined at two spatial scales, stream reach and channel unit, for first- to third-order tributaries of the Teshio River in northern Hokkaido, Japan. The 48 study reaches were classified into three distinct types: Coarse-substrate step-pool (CSP), coarse-substrate pool-riffle (CPR) and fine-substrate pool-riffle (FPR) reaches. Each reach type included reaches with different riparian settings, broadly classified as forest (relatively undisturbed forest and secondary forest after fires) or grassland (bamboo bushland and pasture). The reach-scale analyses showed that neither total pool volume nor pool-to-pool spacing was correlated with woody debris abundance in any of the three reach types. Masu salmon density was positively correlated with both woody-debris cover area and total cover area, but not with total pool volume in the reaches. Channel-unit-scale analyses revealed that woody debris reduced non-pool velocity, increased pool depth and retained fine sediment in pools in FPR reaches, where the size of woody debris was very large relative to the substrate material size. However, woody debris did not influence any of the hydraulic variables (depth, velocity, substrate) in either non-pools or pools of CSP and CPR reaches. Habitat use by masu salmon in non-pools or pools was affected by woody-debris cover area or total cover area rather than by hydraulic variables in any of the reach types. The overall results suggest that woody debris in the study area contributed to masu salmon habitat by providing cover at the smaller, microhabitat scale.

Keller, E. A., and T. Tally. 1979. Effects of large organic debris on channel form and fluvial processes in the coastal redwood environment. Pages 169-197 *in* Rhodes, D. D., and G. P. Williams, editors. Adjustments of the Fluvial System. Kendall/Hunt Publishing Company, Dubuque, Iowa.

Large organic debris in streams flowing through old-growth redwood forest sin California significantly influence channel form and fluvial processes in small to intermediate size streams. The role of large organic debris is especially important in controlling the development of the long profile and in producing a diversity of channel morphologies and sediment storage sites. The residence times for the debris in the channel may exceed 200 years. The total debris loading along a particular reach represents a relation between rates of debris entering and leaving the reach. Loading is primarily a function of such interrelated variables as geology, valleyside slope, landslide activity, channel width, discharge, and upstream drainage area. Generally there is an inverse relationship between debris loading and stream size. Large organic debris in steep mountain streams may produce a stepped-bed profile where a large portion of the stream's potential energy loss for a particular reach is expended over short falls or cascades produced by the debris. Approximately 60% of the total drop in elevation over a several hundred meter second-order reach of Little Lost Man Creek is associated with large organic debris. The debris also provides numerous sites for sediment storage. Stored sediment covers up to about 40% of the entire area of the active channel in the study sections. The sediment storage sites or compartments provide an important buffer system that regulates the bedload discharge. The influence of large organic debris on channel form and process in low gradient stream reaches is less than in steeper channels. However, the debris still may affect development of pools and may help stabilize the channel banks. Root mats may armor banks and provide important fish habitats in the form of undercut banks. The stream channel of some low gradient reaches of Prairie Creek, California, may be quite stable. Lateral migration has only been one to two channel widths in the last several hundred years.

Lee, K. M. 1985. Resource partitioning and behavioral interactions among young-of-the-year salmonids, Chena River, Alaska. Master's thesis. University of Alaska, Fairbanks.

The partitioning of habitat and food and the behavioral interactions of young-of-the-year Arctic grayling (*Thymallus arcticus*), chinook salmon (*Oncorhynchus tshawytscha*), and round whitefish (*Prosopium cylindraceum*) were studied in the laboratory and in their natural habitat. Individuals of all three species defended territories. Arctic grayling were the most aggressive of the three and appear to displace round whitefish from their preferred habitat. In sympatry, these is a segregation of habitat use between Arctic grayling and chinook salmon. Stomach content analysis showed an overlap in diet among the three species. Larvae of the three species emerged at different times and sizes, resulting in a size divergence among coexisting species during their first summer. The three species were found to inhabit faster moving and deeper water as they grew, resulting in a spatial separation of the species and a reduced probability of interactions and competition among them. Juvenile chinook salmon readily utilized cover [LWD] when frightened; Arctic grayling and round whitefish did not.

Lisle, T. E., and M. B. Napolitano. 1998. Effects of recent logging on the main channel of North Fork Casper Creek. Pages 81-85 *in* Ziemer, R. R., editor. Proceedings of the Conference on Coastal Watersheds: The Caspar Creek Story, USDA Forest Service, Pacific Southwest Research Station, PSW-GTR-168.

The response of the mainstem channel of North Fork Caspar Creek to recent logging is examined by time trends in bed load yield, scour and fill at resurveyed cross sections, and the volume and fine-sediment content of pools. Companion papers report that recent logging has increase streamflow during the summer and moderate winter rainfall events, and blowdowns from buffer strips have contributed more large woody debris (LWD). Changes in bed load yield were not detected despite a strong correlation between total scour and fill and annual effective discharge, perhaps because changes in stormflows were modest. The strongest responses are an increase in sediment storage and pool volume, particularly in the downstream portion of the channel along a buffer zone, where LWD inputs are high. The association of high sediment storage and pool volume with large inputs of LWD is consistent with previous experiments in other watersheds. This suggests that improved habitat conditions after recent blowdowns will be followed in future decades by less favorable conditions as present LWD decays and input rates from depleted riparian sources in adjacent clearcuts and buffer zones decline.

Lister, D. B., and H. S. Genoe. 1970. Stream habitat utilization by cohabiting underyearlings of chinook (*Oncorhynchus tshawytscha*) and coho (*O. kisutch*) salmon in the Big Qualicum River, British Columbia. Journal of the Fisheries Research Board of Canada. 27:1215-1224.

This research paper reports the results of field research comparing the habitat distributions of juvenile coho and fall chinook salmon during the first three months of stream life in a river with stabilized flows in British Columbia. The smaller fry of both species occupied marginal areas in association with bank cover, particularly in back-eddies, behind fallen trees, undercut tree roots, and other well-protected areas. Both species preferred locations close to shelter, but adjacent to water of high velocity (40 cm/sec). The largest concentration of fish gradually shifted from marginal to midstream locations, with chinook preceding coho in the shift from margin to midstream. Chinook occupied higher velocity locations than coho, apparently because of their larger size at any given time.

Macdonald, A. and E. A. Keller. 1987. Stream channel response to the removal of large woody debris, Larry Damm Creek, Northwestern California. Pages 405-406 *in* Erosion and Sedimentation in the Pacific Rim. IAHS Publication No. 165. International Association of Hydrological Sciences, Washington, DC.

The removal of large woody debris (LWD) causes a channel form controlled by the remaining randomly distributed large roughness elements (LRE); these may be bends, exhumed or newly introduced woody debris, or bedrock outcrops. In Larry Damm Creek in California, the net result of removal of large woody debris (LWD) accumulations has been the evolution of the channel pattern towards a more 'alluvial' state, stabilized by bends at bedrock outcrops and woody-debris-defended banks. To examine the mechanisms by which LWD controls local energy expenditure ,and consequent patterns of water depth, velocity, and sediment storage, 70 cu m of LWD were removed from Larry Damm Creek, a third-order tributary in the Redwood Creek Watershed. The most notable effects of debris removal were (1) the local increase in water velocity through the vicinity of the debris jams at measured discharges as a result of displaced channel roughness and decreased sinuosity of the low flow thalweg, (2) approximately 100 cu m of sediment that was entrained solely from within the affected reach in the first year after debris removal, and (3) the creation or deepening of pools at bends above and below the two debris jams at the expense of numerous scour pools within the jam. A sediment routing model based on measured scour and fill was used to describe the movement of fine-grained, debris-stored sediment into new storage sites. Channel morphology has stabilized around the following LRE's: major bends in the channel above and below the former location of the debris jams, sediment deposits associated with these bends, and some of the original debris-stored sediment that was stabilized with vegetation prior to channel disturbance.

Maser, C., and J. R. Sedell. 1994. From the forest to the sea: the ecology of wood in streams, rivers, estuaries, and oceans. St. Lucie Press, Delray Beach, Florida.

This book provides a good nontechnical overview of the role and functions of wood in riverine, estuarine, and marine systems, and how humans have affected the roles and quantities of wood in those systems. Part One makes the case that the present situation is quite different from that found before European settlement of North America, and is largely a result of that settlement and the accompanying industrial activities. Chapters in Part Two, From the Forest to the Sea, discuss the sources, functions, and transport of wood along the stream order continuum, from headwaters to large rivers, to estuarine, beach, and open marine environments. The authors discuss the McKenzie, Columbia, and Willamette river systems as case studies, and provide insights into the roles of wood in the open ocean. Part Three, From the Sea to the Forest, follows the pattern of European settlement back upstream from the beaches to the upland forests, with concomitant reduction in woody debris. Historical records provide insights into the large volumes of wood initially at the mouths of large river systems, and removal and use of that wood to assist with construction, fuel needs, and increased navigation. As harvest turned more to live wood, streams and rivers were used as routes for log drives and splash dams were installed to create large enough flood flows to carry logs to mill or market. Each of these activities has left its mark on the abundance and functions of wood in these systems.

McFadden, T., M. Stallion, et al. 1976. Debris of the Chena River. U.S. Army Cold Regions Research and Engineering Laboratory, Technical Report.

Debris over a 44-mile stretch of the Chena River was studied. The study area extended from the first bridge on the Chena Hot Springs Road to the Chena River Flood Control damsite. The purpose of the study was to assess the potential danger to the Chena River Flood Control Dam outlet structure. Debris was catalogued, log jams were measured, and sources of debris were studied. The average size of logs was determined, as well as the number of logs present on the river. The authors concluded that a serious debris problem existed and would remain serious for the foreseeable future. Recommendations for debris handling were made.

Mchenry, M. L., E. Shott, R. H. Conrad, and G. B. Grette. 1998. Changes in the quantity and characteristics of large woody debris in streams of the Olympic Peninsula, Washington, U.S.A. (1982-1993). Canadian Journal of Fisheries and Aquatic Science 55:1395-1407.

The changes were assessed in large woody debris (LWD) abundance and composition at 28 sites in 27 low-gradient Olympic Peninsula streams between 1982 and 1993. The average number of pieces of debris was virtually identical in both years. A significant reduction was found in the total volume of LWD material in the stream sites surveyed. While the mean volume of second-growth derived LWD increased, the increase was insufficient to offset the loss of old-growth derived LWD. The mean volume of old-growth derived LWD for all sites decreased between sample years. The mean diameter of second-growth derived LWD was significantly larger in 1993 than in 1982, although still smaller than old-growth derived pieces. A significant increase was measured in the percentage of LWD pieces rated as highly decayed from 1982 to 1993. Results indicate that the loss of old-growth derived LWD following the removal of old growth riparian forests is initially very rapid, followed by a slower rate of depletion associated with watershed destabilization. Inputs of LWD from second-growth riparian forests up to 73 years old were characterized by small diameter, high mobility, and high decay rates.

Meehan, W. R., W. A. Farr, D. M. Bishop, and J. H. Patric. 1969. Some effects of clearcutting on salmon habitat in two southeast Alaska streams. Institute of Northern Forestry, Pacific Northwest Forest and Range Experiment Station. USDA Forest Service Research Paper PNW-82.

Evaluation of effect of clearcutting on streamflow, suspended sediment, stream temperature, log-debris jams, and indirectly on salmon populations, of two watersheds.

Montgomery, D. R., T. B. Abbe, J. M. Buffington, N. P. Peterson, K. M. Schmidt, and J. D. Stock. 1996. Distribution of bedrock and alluvial channels in forested mountain drainage basins. Nature 381:587-589.

Mountain river networks often consist of both bedrock and alluvial channels, the spatial distribution of which controls several fundamental geomorphological and ecological processes. The nature of river channels can influence the rates of river incision and landscape evolution, as well as the stream habitat characteristics affecting species abundance and aquatic ecosystem structure. Studies of the factors controlling the distribution of bedrock and alluvial channels have hitherto been limited to anthropogenic badlands. Here we investigate the distribution of channel types in forested mountain drainage basins, and show that the occurrence of bedrock and alluvial channels can be described by a threshold model relating local sediment transport capacity to sediment supply. In addition, we find that valley-spanning log jams create alluvial channels--hospitable to aquatic life--in what would otherwise be bedrock reaches. The formation of such jams depends critically on the stabilizing presence of logs derived from the largest trees in the riverside forests, suggesting that management strategies that allow harvesting of such trees can have a devastating influence on alluvial habitats in mountain drainage basins.

Morsell, J.. 1999. Pogo Project fish and aquatic habitat baseline investigations. Annual Report, 1999 Study Program. Prepared for Teck Resources, Inc., Fairbanks.

The author describes the substrate, and water depth and velocity, characteristics of chinook salmon spawning redds in the Goodpaster River near the Pogo mine project area. Suitable habitats were scattered throughout the area, although redds were also seen to occur in clusters or singly in small "pocket" habitats. The latter were often located against the bank on an outside curve or associated with a topographic anomaly such as a scour pool downstream from a log.

Murphy, M. L. 1995. Forestry impacts on freshwater habitat of anadromous salmonids in the Pacific Northwest and Alaska--requirements for protection and restoration. NOAA Coastal Ocean Program Decision Analysis Series No. 7. NOAA Coastal Ocean Office, Silver Springs, MD.

This synthesis presents a science overview of the major forest management issues involved in the recovery of anadromous salmonids affected by timber harvest in the Pacific Northwest and Alaska. The issues involve the components of ecosystem-based watershed management and how best to implement them, including how to: Design buffer zones to protect fish habitat while enabling economic timber production; Implement effective Best Management Practices (BMPs) to prevent nonpoint-source pollution; Develop watershed-level procedures across property boundaries to prevent cumulative impacts; Develop restoration procedures to contribute to recovery of ecosystem processes; and Enlist support of private landowners in watershed planning, protection, and restoration. Buffer zones, BMPs, cumulative impact prevention, and restoration are essential elements of what must be a comprehensive approach to habitat protection and restoration applied at the watershed level within a larger context of resource concerns in the river basin, species status under the Endangered Species Act (ESA), and regional environmental and economic issues. This synthesis 1) reviews salmonid habitat requirements and potential effects of logging; 2) describes the technical foundation of forest practices and restoration; 3) analyzes current federal and non-federal forest practices; and 4) recommends required elements of comprehensive watershed management for recovery of anadromous salmonids.

Murphy, M. L., J. Heifetz, J. F. Thedinga, S. W. Johnson, and K V. Koski. 1989. Habitat utilization by juvenile Pacific salmon (*Oncorhynchus*) in the glacial Taku River, southeast Alaska. Canadian Journal of Fisheries and Aquatic Science 46:1677-1685.

This research paper reports the results of field studies conducted to determine juvenile salmon use of the lower Taku River in southeast Alaska during summer 1986. Sockeye, coho, and chinook salmon were present within the study area. Chinook salmon were predominantly age 0 (99%) and ranged from 40 to 93 mm FL. Seining was used to estimate fish density. Habitat was classified into two broad categories: river habitats -- main channels, backwaters, braids, channel edges, and sloughs within the active river; and off-channel habitats -- beaver ponds, terrace tributaries, tributary mouths, and upland sloughs on the valley floor.

Mean water velocity was lowest (0-5 cm/s) in sloughs, backwaters, tributary mouths, upland sloughs, and beaver ponds; intermediate (10-21 cm/s) in braids, channel edges, and terrace tributaries; and highest (102 cm/s) in main channels. Main channels, except for channel edges, were assumed too swift (mean, 102 cm/s) to contain rearing salmon. Mean depth ranged from 0.3 m in braids to 1.0 m in beaver ponds and 2.9 m in main channels. Typically, river habitats were turbid (means, 240-400 JTU), whereas off-channel habitats were clear or humic (means, 20-208 JTU). Water temperatures were 2-4°C higher in beaver ponds and upland sloughs than in channel edges, braids, and terrace tributaries.

The distribution of salmon was most closely related to water velocity, and turbidity had a secondary influence. Sockeye and coho densities were highest in still or slow water (<11 cm/s), whereas chinook density was highest in slow-to-moderate current (1 to 20 cm/s). All species were virtually absent from areas with currents greater than 30 cm/s. Differences in water velocity may have masked effects of turbidity. Chinook density was similar in areas of different turbidity.

In the active channel of the lower Taku River, substrate is mostly compacted gravel, sand, and mud, providing little cover from the turbulent flow, and the only suitable habitat occurs along the channel edge. Other studies have shown juvenile chinook salmon can inhabit areas with current as fast as 70 cm/s where coarse substrate (20-40 cm diameter) provided cover from the fast current.

Mean salmon density in the habitat types corresponded to water velocity but also differed between the river and off-channel areas. Chinook primarily were in river habitats with mean velocities of 3 to 15 cm/s, particularly sloughs and channel edges (means, 6-8 fish/100 m^2), and off-channel terrace tributaries and tributary mouths (means, 5-8 fish/100 m^2). Chinook were virtually absent from beaver ponds and upland sloughs (<1 fish/100 m^2).

Nakamoto, R. J. 1998. Effects of timber harvest on aquatic vertebrates and habitat in the North Fork Caspar Creek. Pages 87-96 *in* Ziemer, R. R., editor. Proceedings of the Conference on Coastal Watersheds: The Caspar Creek Story, USDA Forest Service, Pacific Southwest Research Station, PSW-GTR-168.

[The author] examined the relationships between timber harvest, creek habitat, and vertebrate populations in the North and South forks of Caspar Creek. Habitat inventories suggested pool availability increased after the onset of timber harvest activities. Increased large woody debris in the channel was associated with an increase in the frequency of blowdown in the riparian buffer zone. This increase in large woody debris volume increased the availability of pools. No dramatic changes in the abundance of young-of-the-year steelhead, yearling steelhead, coho, or Pacific giant salamanders were directly related to logging. High interannual variation in the abundance of aquatic vertebrates made it difficult to contrast changes in abundance between pre-logging and post-logging periods. Changes in channel morphology associated with increased volume of large woody debris in the channel suggest that yearling steelhead, coho, and Pacific giant salamanders may benefit from logging in the short-term because of increased living space. However, over a longer time scale these conditions will probably not persist (Lisle and Napolitano, these proceedings).

Nakamura, F., and F. J. Swanson. 1993. Effects of coarse woody debris on morphology and sediment storage of a mountain stream system in western Oregon. Earth Surface Processes and Landforms 18:43-61.

Effects of coarse woody debris (CWD) on channel morphology and sediment storage were investigated at five sites, representative of first-order to fifth-order streams. In the steep and bedrock-confined stream (first-second order), interaction between the channel and CWD was limited, except where breakage upon falling produced CWD pieces shorter than channel width. Channel widening, steepening and sediment storage associated with CWD were observed predominantly in third- to fifth-order streams. Variation in channel width and gradient was regulated by CWD. In the fifth-order stream, most of the CWD pieces derived from the riparian forest interacted directly with the channel without being suspended by sideslopes. In this system CWD promoted lateral channel migration, but sediment storage was temporary, with annual release and capture.

Napolitano, M. B. 1998. Persistence of historical logging impacts on channel form in mainstem North Fork Caspar Creek. Pages 97-102 *in* Ziemer, R. R., editor. Proceedings of the Conference on Coastal Watersheds: The Caspar Creek Story, Ukiah, CA. USDA Pacific Southwest Research Station, Forest Service, PSW-GTR-168

The old-growth redwood forest of North Fork Caspar Creek was clearcut logged between 1860 and 1904. Transportation of logs involved construction of a splash dam in the headwaters of North Fork Caspar Creek. Water stored behind the dam was released during large storms to enable log drives. Before log drives could be conducted, the stream channel had to be prepared by removing all obstructions, including large woody debris jams, from the channel. Comparison of present-day woody debris loading on North Fork Caspar Creek (24 kg m^{-2}) to physically similar streams in old-growth redwood basins (49 to 268 kg m^{-2}) suggests that wood-loading and stability were greatly diminished by historical logging activities and change to second-growth cover. These changes are important, as woody debris creates large-volume, long-term sediment storage sites and diverse aquatic habitat conditions. Although historical logging appears to have caused lasting channel changes, including channel incision, simplification of form, and reduction in sediment storage capability, the significance of habitat-related changes remains unclear.

Piegay, H. 1993. Nature, mass and preferential sites of coarse woody debris deposits in the lower Ain Valley (Mollon reach), France. Regulated Rivers: Research & Management 8:359-372.

Coarse woody debris (CWD) has been examined in a section of the Ain, a sixth order piedmont river with an actively meandering channel and a wooded floodplain. The spatial distribution of CWD, its mass and forms of accumulation are controlled by the hydrodynamics and the retention capacity of the forest. A typology shows the relative importance of woody debris in the mosaic of patches and the essential role of the ecotonal zones. The mass of debris varies from 0.001 t/ha to more than 200 t/ha, but is lower than those observed in certain American rivers. Most of the material is deposited in the margins and forms a narrow debris line. The restocking in woody debris is recent in Europe and tends to diversify the environment. This affects the researcher and the planner. The first considers this transit of material as a useful hydromorphodynamic and biodynamic tool which is easy to evaluate, and the second considers it as a restoring and regenerative vector, the ecological functions of which are recognized. Its effect is stronger today as the watershed area tends to be subjected to a decrease in agricultural activity.

Piegay, H., and A. M. Gurnell. 1997. Large woody debris and river geomorphological pattern: examples from S.E. France and S. England. Geomorphology 19:99-116.

The study of accumulations of dead wood within the fluvial environment has been mainly undertaken in mountain streams and rivers within the Northwestern United States, and particularly in hydrosystems which have experienced little riparian vegetation cutting or disturbance by man. Appraisals of the spatial variability in the physical character of accumulations of dead wood has mainly highlighted the volumes of large woody debris (LWD) accumulations and the local channel morphological properties induced by their presence. The spatial variability in the accumulation and processing of organic material forms one of the central concepts of the River Continuum Concept, which characterizes the occurrence and processing of organic material, of which LWD is an important component, according to a longitudinal gradient along a river's course. Some studies have extended the concept by illustrating the importance of the lateral dimension, particularly in large rivers with extensive floodplains, and by relating the occurrence of dead wood to fluvial morphodynamics. However, to date there has been no synthesis of the relationship between LWD and the geomorphic pattern of the river channel.

Although the research literature shows that the routine clearance of wood from water courses is not an environmentally-sympathetic strategy, within Europe LWD accumulations are usually seen as a river management problem and are routinely cleared from river channels. This paper addresses these physical and applied aspects of the role of LWD. It presents an analysis based upon semi-natural hydrosystems in S.E. France and S. England. The forested corridors discussed are currently or have recently been maintained. They are essentially young and so produce relatively small amounts of woody debris in relatively small-sized individual pieces in comparison with the rivers studied in North America. Using observations from these example river corridors, the relationship between rivers of a particular size and geomorphic pattern and the dynamics of dead wood is described and evaluated. Major contrasts in the role of LWD are found between small, single thread rivers, and larger, piedmont, braided and wandering rivers. Some points of synthesis concerning the ecological, hydraulic and morphological impacts of dead wood are drawn from these examples, and are used as a basis for proposing some simple maintenance rules.

Richards, C., L. B. Johnson, and G. E. Host. 1996. Landscape-scale influences on stream habitats and biota. Conference Workshop on the Science and Management for Habitat Conservation and Restoration Strategies (HabCARES) in the Great Lakes, Kempenfelt, Barrie, ON (Canada). Canadian Journal of Fisheries and Aquatic Sciences 53(Supplement 1):295-311.

The relative influence of geologic versus anthropogenic attributes of catchments on stream ecosystems was examined in 45 catchments of a river basin in central Michigan. Each catchment was characterized by land use, surficial geology, elevation, and hydrography, and summaries of these data were related to physical habitat characteristics that had the greatest influence on macroinvertebrate assemblages. Partial redundancy analysis revealed that geologic and land-use variables had similar magnitudes of influence on stream habitats. Of the geologic variables, catchment area, proportion of lacustrine clays, and glacial outwash materials had the strongest influence on physical habitat, particularly on channel dimensions. Row-crop agriculture and the presence of wetlands were the most important land-use variables, particularly influencing amounts of woody debris. Stream buffers (100 m) were more important than whole catchment data for predicting sediment-related habitat variables; however, channel morphology was more strongly related to whole catchments. Results suggest that catchment-wide geology and land-use characteristics may be more important than stream buffers for maintaining or restoring stream ecosystems. These techniques can be used to develop biologic signatures of catchment condition that discriminate causal factors influencing the biodiversity and health of stream ecosystems.

Sedell, J. R. Undated. Report on salvage logging observations on the Chickamin and Unuk rivers, Misty Fiords National Monument, Tongass National Forest. USDA Forest Service Pacific Northwest Forest and Range Experiment Station, Forest Science Laboratory. Corvallis, Oregon.

This report documents observations on salvage logging effects on salmonid habitat made in the field in late July on the Unuk and Chickamin Rivers. Data from Alaska Department of Fish and Game has been examined and results summarized concerning fish utilization of habitats created by log jams, downed trees, and rootwads. Oblique air photos have been examined to attempt to determine the relative stability of downed trees versus root wads without boles. The results of the Chickamin and Unuk Rivers are related to other studies on rivers in the Pacific Coast region where large downed trees and fish habitat have been examined. An alternative to present salvage logging practices is presented.

Swanson, F.J., and G. W. Lienkaemper. 1978. Physical consequences of large organic debris in Pacific Northwest streams. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, General Technical Report PNW-69.

Large organic debris is a principal factor determining the biological and physical character of small and intermediate-sized streams in forested landscapes of the Pacific Northwest. Debris enters streams by blowdown, undercutting of streambeds, and mass movement processes on adjacent hillslopes. Water and sediment routing in channels is controlled by large debris which may create a stepped profile. Stream energy is thereby dissipated at the relatively short, steep sections of channel so that much of the stream area may have a gradient less than the overall gradient of the valley bottom. Debris in streams created habitat for aquatic organisms both by serving directly as a substrate and by modifying streamflow to form depositional areas. Large pieces of debris reside in streams for decades and even longer than a century. This long residence time results in a continuing concentration of debris in streams during the 100+ years of stand recovery following wildfire, except when debris torrents flush channels. Management activities directly alter debris loading by addition or removal of material and indirectly by increasing the probability of debris torrents and by removing standing streamside trees.

Ward, G. M., and N. G. Aumen. 1986. Woody debris as a source of fine particulate organic matter in coniferous forest stream ecosystems. Canadian Journal of Fisheries and Aquatic Sciences 43:1635-1642.

The potential contribution of woody debris to fine particulate organic matter pools (0.45 mu m less than or equal to FPOM < 1 mm) was investigated in a coniferous forest stream ecosystem in western Oregon. Studies of vertical distribution indicated that most fine wood is concentrated within 0.3 m of the stream bottom, while large wood is more evenly distributed up to 0.7 m. Lignin concentrations of large wood, soil, and FPOM were very similar. Erosion rates of wood surfaces ranged between 0.5 and 11 $mm \cdot yr^{-1}$ depending on decay state of the log. Using conservative estimates of processing rates, woody debris could be a source for approximately 90 $g \cdot m^{-2} \cdot yr^{-1}$ of FPOM.

Young, W. J. 1991. Flume study of the hydraulic effects of large woody debris in lowland rivers. Regulated Rivers: Research & Management 6:203-211.

As part of a study investigating the hydraulic effects of large woody debris (LWD) in lowland rivers, a series of small-scale experiments were conducted in a rectangular glass-walled recirculating flume. These experiments were undertaken to determine the order of magnitude of the increase in flood levels caused by LWD at different positions within a channel cross-section. Position variables considered in these experiments were height above bed, angle to flow direction, and separation distance in the direction of flow. This study was undertaken to quantify the hydraulic benefits (primarily reduced flood levels) gained by the removal of LWD from lowland rivers, which is a common practice in several countries. From an integrated river management perspective it is necessary to weigh any hydraulic benefits of LWD removal up against the environmental costs of faunal habitat, and possible geomorphic instability. The results of these experiments indicate the levels of LWD commonly occurring in the lowland rivers of southeastern Australia seldom cause any significant effect on flood levels. However, where LWD occur at channel constrictions, or where unusually high densities of LWD are present, the effect on flood levels will be significant.

PERMAFROST AND SILTY SOILS

An Annotated Bibliography

Compiled for the
Region III Forest Practices Riparian Management Committee

by

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SUMMARY

Alaska forest management practices in Region III present a unique challenge not generally encountered in management areas south of the Alaska Range. The presence of perenially frozen ground, or permafrost, must be addressed as a critical factor in achieving responsible stewardship of fish-bearing streams in forest management areas in Interior Alaska. Permafrost may be of relatively small significance within many harvest areas, but it can be a major factor in virtually all access roads or trails. It is especially critical to bear in mind that the only way to confirm the presence or absence of permafrost at any given location is by geotechnical drilling or targeted geophysical surveys.

There is a commonly-held belief that large trees are indicators that an area is permafrost-free, and that there is therefore no need to consider permafrost an issue in tree harvest areas. Permafrost is a controlling factor in the distribution patterns of trees and shrub vegetation only when it occurs at a depth shallow enough to influence subsurface drainage, soil stability, and soil temperature within the zone of root growth. It is important to recognize that large ice bodies may be present at depth in areas that support large trees. There is evidence to suggest that there may be a correlation between the height of white spruce with the depth of the active zone using the relationship that the height of the spruce stand in feet indicates the minimum depth of the active zone in inches (Stoeckeler, 1952**)**. Studies by Hopkins and others (1955) show that a pure stand of (harvestable?) white spruce in interior Alaska could have permafrost as shallow as 2 ft below the surface. Birch or black spruce in bottomlands usually indicates the soil is permanently frozen within four or five feet, although stunted birch can survive where the upper surface of the permafrost layer is within two feet of the surface.

The primary reason for concern regarding permafrost in fish-bearing stream habitat management is the danger of melting the frozen substrate, triggering subsidence, erosion, and increased sediment load in runoff waters. Essentially, any disturbance which eliminates or greatly reduces plant cover in an area shallowly underlain by permafrost will result in an increased thaw. If the vegetative cover is physically damaged and mineral soil is exposed the increased thaw may be accompanied by erosion, especially in sloping sites. Effects of vegetation

disturbance may include both short-term and/or point sources of sedimentation and erosion and longer-term, nonpoint source effects such as surface alterations and sheet flows. Many studies show that removal of the vegetation leads to the most extensive modifications, but the subsequent response to disturbance varies with primarily four factors: 1) ground ice volume; 2) distribution and size of massive ground ice; 3) material properties during thaw; and 4) relief, including progressive changes during thaw subsidence. Terrain underlain by ice-poor sediments that are stable upon thawing are altered only by thaw subsidence and consolidation, while ice-rich sediments that are unstable at thaw are extensively modified by a complex interaction of slumping, sediment flow, and thermal and mechanical erosion. Drainage promotes meltwater erosion, whereas undrained areas will be modified significantly less and attain stability (that is, regain an equilibrium state with respect to permafrost conditions) more rapidly.

General controversy exists as to whether perenially frozen ground inhibits lateral erosion and bankline recession, or whether it increases bank recession rates. Studies show that the effects of permafrost will vary depending on local conditions. Perenially frozen streambanks erode because of modification of the bank's thermal regime by exposure to air and water, and because of various erosional processes. Factors that determine rates and locations of erosion may include: 1) exposure to currents and wind waves; 2) texture and stratigraphy of the bank sediments; 3) ice content, distribution and type; 4) slope aspect; 5) Coriolis force; 6) timing and depth of thaw; 7) water level and temperature; 8) vegetation; 9) ice and snow cover; and 10) groundwater. The response of channels ranges from total permafrost control of channel processes, including bed scour and lateral erosion, to only brief restriction of channel behavior in the early stages of flood rise. Permafrost has been cited both as the cause of extreme stability and the cause of unusual instability in arctic streams as compared to those elsewhere, although no detailed studies have identified whether these conclusions are valid in the subarctic as well. The net effect of the permafrost environment seems to be to create greater channel stability than is found in unregulated streams of similar size in nonpermafrost environments. Combinations of factors, particularly those that encourage high rates of thermo-erosional niching, can nevertheless cause extreme rates of erosion.

An additional potential concern with permafrost is its effect on stream hydrology. The presence of permafrost exerts a major influence on the behavior of streams, but this influence is rather indirect. Its most important roles are in: 1) supporting a shallow or perched water table beneath the valley bottom area, so that overland flow derived from standing water in this area dominates the hydrograph rise and peak; 2) restricting deep groundwater flow from reaching the stream if no thaw buld exists around channels; and 3) providing an impermeable surface beneath the moss on the north-facing slopes, over which water infiltrating the moss flows to the stream to dominate the hydrographic recession. Permafrost-underlain terrain is much more responsive to precipitation inputs than is permafrost-free terrain, and proportion of permafrost, with concomitant cold, thick organic layers overlying mineral soil, is the primary determinant of differing streamflow characteristics in headwaters catchments. A permafrost-dominated first-order stream generally has higher peak streamflow, higher storm-flow suspended sediment concentration, lower base (non-storm) streamflow, and lower base-flow suspended sediment concentrations than do nearby, virtually permafrost-free first-order streams (Slaughter et al, 1983). Although comparisons of spot discharge measurements of predominantly permafrost and non-permafrost subwatersheds generally show that permafrost-dominated watersheds have a much “flashier” response to precipitation than non-permafrost watersheds (Haugen et al, 1982), several studies have indicated extremely long hydrograph recessions for streams draining permafrost areas, and some large basins have a high proportion of their runoff occurring as groundwater outflow (Dingman, 1975).

REFERENCES

Abele, G. 1990. Snow roads and runways: CRREL Monograph 90-3.

Discusses snow characteristics and presents detailed snow pavement construction techniques, evaluation, and design criteria. Includes lots of testing data.

Benninghoff, W. S. 1952. Interaction of vegetation and soil frost phenomena. Arctic 5(1):34-44.

Basic discussion of the interactions between vegetation and soil frost, and how each can affect the character of the other.

Benninghoff, W. S. 1966. Relationships between vegetation and frost in soils. Pages 9-13 in National Academy of Sciences, National Research Council, Proceedings of Permafrost: International Conference.

Examines the effects of vegetation on permafrost and discusses calculations of thermal energy in soils. The total effect of vegetation is to: 1) reduce the quantity of radiant energy that escapes either directly (by reflection) or indirectly to the atmosphere; 2) increase the long wave length infrared component in the energy that does escape to the atmosphere; 3) increase the energy diverted to work as in metabolism of organisms, physical and chemical weathering of rock materials, etc.; and 4) increase the store of energy on the earth in short-term forms as in vaporized water and in long-term forms as in humus and coal. The significance of vegetation in governing the occurrence of permafrost decreases the more the earth surface mean annual temperature is depressed below the freezing point. Where the surface mean annual temperature is not more than 2° or 3° C below 0°C, the kind and condition of the vegetation cover will be critical to the development and duration of permafrost, but where the surface mean annual temperature is more than several degrees below 0°C, the vegetation cover exercises little control. Vegetation does exert an influence, however, on the occurrence, extent, and effects of seasonal frost in the upper layers of the soil, wherever the climate will produce such freezing.

Brown, J., W. Rickard, and D. Vietor. 1969. The effect of disturbance on permafrost terrain. CRREL Special Report 138.

Reemphasizes the importance of the surface layer in preserving permafrost terrain. Essentially, any disturbance which eliminates or greatly reduces plant growth will result in an increased thaw. If the vegetative cover is physically damaged and mineral soil is exposed the increased thaw will be accompanied by erosion.

Brown, J., and N. A.Grave. 1979. Physical and thermal disturbance and protection of permafrost. CRREL Special Report 79-5.

A review of the major findings of site and regional investigations dealing with human-induced and natural disturbances of permafrost terrain throughout the world. Excellent summary tables of terrain disturbances of permafrost in North America and the U.S.S.R.

Crory, F. E. 1991. Construction guidelines for oil and gas exploration in northern Alaska. CRREL Report 91-21.

This report presents construction guidelines for activities associated with petroleum exploration in northern Alaska. Examples of both new and old ways of constructing and operating on snow, ice and frozen ground are presented. The guidelines address how to construct winter trails, drill pads, roads and airfields, and includes information on how each is to be abandoned and the natural environment restored. Includes a general discussion of permafrost and thermal regimes.

Delaney, A. J., S. A. Arcone, and E. F. Chacho, Jr., 1990. Winter short-pulse radar studies on the Tanana River, Alaska. Arctic 43(3):244-250.

Subsurface profiles were obtained during airborne and surface short-pulse radar surveys along a winter roadway over the Tanana River near Fairbanks. The airborne profiles were intended for ice thickness profiling but also revealed sporadic reflections from a deeper horizon beneath the bars. The study shows that airborne radar surveys are capable of detecting open channels beneath an ice cover and measuring depth of frost beneath bars in a braided river. The airborne technique may be an effective way to determine the position of significant anomalies, such as local thaw zones. A surface profile confirmed the unfrozen horizon detected by the airborne survey.

Dingman, S. L. 1973. Effects of permafrost on stream flow characteristics in the discontinuous permafrost zone of central Alaska. Pages 447-453 in National Academy of Sciences, National Research Council. Proceedings of Permafrost: North American contribution to the Second International Conference.

Looks at the effects of permafrost in the watershed of Glen Creek, 13 km NNE of Fairbanks. The presence of permafrost is shown to be a major influence on the behavior of the stream, but this influence is rather indirect. Its most important roles are in supporting a high water table beneath the valley bottom area, so that overland flow derived from standing water in this area dominates the hydrograph rise and peak; restricting groundwater flow to the stream; and providing an impermeable surface beneath the moss on the north-facing slopes, over which water infiltrating the moss flows to the stream to dominate the hydrographic recession.

Dingman, S. L. 1975. Hydrologic effects of frozen ground: Literature review and synthesis. CRREL Special Report 218.

Summarizes the hydrologic effects of frozen ground and describes the general characteristics of seasonally frozen ground and its geographical distribution. The hydrologic effects of permafrost are profound, but these effects can be considered static unless one is concerned with long-term climatic changes. Permafrost acts as an aquiclude, restricting the movement and recharge of groundwater. The effects of this on streamflow are not necessarily the expected straightforward ones of increased runoff and flashier streamflow. Several studies have indicated extremely long hydrograph recessions for streams draining permafrost areas, and some large basins have a high proportion of their runoff occurring as groundwater outflow. Although runoff percentages estimated for small central and northern Alaskan watersheds are moderately high (around 50%), most of this is snowmelt, and the thaw season runoff percentages are much lower (as low as 5% at Barrow). The susceptibility of frozen ground to erosion by running water has a profound effect on the geomorphology of permafrost areas.

Ferrians, Jr., O. J., R. Kachadoorian, and G. W. Greene. 1969. Permafrost and related engineering problems in Alaska. U.S. Geological Survey Professional Paper 678.

Discusses the problems of construction and maintenance of structures underlain by frozen ground and gives guidelines to minimize the adverse effects of permafrost and frost action upon structures. Also provides a very good summary of permafrost, its origin and thermal regime, its areal distribution and thickness, and related geomorphic features.

Gatto, L.W. 1984. Tanana River monitoring and research program, relationships among bank recession, vegetation, soils, sediments and permafrost on the Tanana River near Fairbanks, Alaska. CRREL Special Report 84.

The report evaluated whether data on vegetation, soils, sediments, and permafrost could be used to assess their relative contribution to bank erosion on two reaches of the Tanana River. The data were visually compared to the locations and estimated amounts of historical recession to evaluate if any relationships were obvious. Results indicate no useful relationships. Vegetation was similar in eroded and uneroded areas and its distribution did not show any obvious relationship to the locations of bank recession. Surface sediments and soils in the eroded areas had little, if any, effect on bank erodibility because the river erodes the bank over its entire depth, which is well below the surface zone. Permafrost occurrences are about equal in eroded and uneroded sites, although it appears that recession can be higher where permafrost is common than where its is absent.

Haugen, R. K., C. W. Slaughter, K. E. Howe, and S. L. Dingman. 1982. Hydrology and climatology of the Caribou-Poker Creeks Research Watershed, Alaska. CRREL Report 82-26.

Comparisons of spot discharge measurements of predominantly permafrost and non-permafrost subwatersheds showed that permafrost-dominated watersheds have a much “flashier” response to precipitation than non-permafrost watersheds.

Heginbottom, J. A. 1973. Some effects of surface disturbance on the permafrost active layer at Inuvik, N.W.T., Canada. Pages 649-657 in National Academy of Sciences, National Research Council. Proceedings of Permafrost: North American contribution to the Second International Conference, p. 649-657.

Assesses the effects of disturbance on permafrost terrain by grouping the disturbances into the following categories, ranked by the intensity of their initial impact: compaction of ground surface; mechanical damage to vegetation; destruction of vegetation; removal of vegetation; removal of vegetation-peat mat; and removal of surface vegetation and soil.

Higgins, C. G., D. R. Coates, T. L. Péwé, R. A. M. Schmidt, and C. E. Sloan. 1990. Permafrost and thermokarst: Geomorphic effects of subsurface water on landforms of cold regions. Pages 211-218 in C. G. Higgins and D. R. Coates, editors. Groundwater geomorphology: The role of subsurface water in Earth-surface processes and landforms. Geological Society of America Special Paper 252.

A brief summary of permafrost and permafrost-related landforms.

Hopkins, D. M., and six coauthors. 1955. Permafrost and ground water in Alaska. Pages 113-146 in U.S. Geological Survey Professional Paper 264-F.

A study of the interrelations of permafrost and ground water, and a discussion of the role of aerial photography in the mapping of permafrost conditions. The distribution of ground water in Alaska affects and is affected by the distribution of permafrost. Knowledge of permafrost and ground-water conditions is summarized for the following representative areas of Alaska: the Arctic slope and northern Seward Peninsula in the continuous-permafrost zone; southern Seward Peninsula, the Yukon Flats, the middle Tanana River valley, and the upper Kuskokwim River valley in the discontinuous-permafrost zone; the Bristol Bay region in the sporadic-permafrost zone; and the Kenai lowland in the no-permafrost zone. The application and limitations of aerial-photograph interpretation in permafrost studies are discussed.

Of particular note is a discussion of the use of vegetation types as an indicator of permafrost depth. The authors state that permafrost is a controlling factor in the distribution patterns of trees and shrub vegetation only when it occurs at a depth shallow enough to influence subsurface drainage, soil stability, and soil temperature within the zone of root growth. The following table indicates the **minimum depth to permafrost**, if it is present, beneath some vegetation assemblages that are widespread in Alaska. It does not indicate maximum possible depth.

Tall willows on flood plains	8 ft
Pure stands of mature aspen or white birch	4 ft
Mixed willow, alder, and white birch	3-4 ft
Pure stands of balsam poplar	3-4 ft
Mixed white spruce and balsam poplar	3 ft
Pure stands of white spruce	2-3 ft
Mixed stands of white birch and white spruce	2-3 ft
Mixed white and black spruce	1-2 ft
Black spruce in wet tundra or muskeg	1 ft

In other words, a pure stand of (harvestable?) white spruce in interior Alaska could have permafrost as shallow as 2 ft below the surface.

Johnson, P. R., and C. M. Collins. 1980. Snow pads used for pipeline construction in Alaska, 1976: Construction, use and breakup. CRREL Report 80-17.

Describes construction methods for three snow pads used by Alyeska Pipeline Service Company during the winter of 1975-1976, which were deemed generally successful in providing a surface for construction while protecting the underlying vegetation and permafrost.

Jorgenson, M. T, C. H. Racine, J. C. Walters, and T. E. Osterkamp. In press. Permafrost degradation and ecological changes associate with a warming climate in central Alaska: Climatic Change 38.

Studies from 1994–1998 on the Tanana Flats in central Alaska reveal that permafrost degradation is widespread and rapid, causing large shifts in ecosystems from birch forests to fens and bogs. Fine-grained soils under the birch forest are ice-rich and thaw settlement typically is 1–2.5 m after the permafrost thaws. The collapsed areas are rapidly colonized by aquatic herbaceous plants, leading to the development of a thick, floating organic mat. Based on field sampling of soils, permafrost and vegetation, and the construction of a GIS database, the authors estimate that 17% of the study area (263,964 ha) is unfrozen with no previous permafrost, 48% has stable permafrost, 31% is partially degraded, and 4% has totally degraded. For that portion that currently has, or recently had, permafrost (83% of area), ~42% has been affected by thermokarst development. Based on airphoto analysis, birch forests have decreased 35% and fens have increased 29% from 1949 to 1995. Overall, the area with totally degraded permafrost (collapse-scar fens and bogs) has increased from 39 to 47% in 46 y. Based on rates of change from airphoto analysis and radiocarbon dating, the authors estimate 83% of the degradation occurred before 1949. Evidence indicates this permafrost degradation began in the mid-1700s and is associated with periods of relatively warm climate during the mid-late 1700s and 1900s. If current conditions persist, the remaining lowland birch forests will be eliminated by the end of the next century.

Jorgenson, M. T., Y. Shur, and H. J. Walker. 1998. Factors affecting evolution of a permafrost dominated landscape on the Colville River Delta, northern Alaska. Pages 523-530 in Lewkowicz, A. G. and M. Allard, eds., Proceedings of Permafrost: Seventh International Conference. Universite Laval, Sainte-Foy, Quebec, Collection Nordicana, No. 57.

To help provide information essential for engineering design and evaluation of potential environmental impacts in preparation for oil development on the Colville River Delta, studies on soil stratigraphy and permafrost development were conducted during 1992–1996 to investigate the nature and distribution of surficial deposits in the delta. The studies involved investigation of stratigraphy of near-surface materials along numerous toposequences in the delta, classification and mapping of terrain units, classification and description of cryostructures, dating and analysis of material accumulation rates, and determination of erosion rates. After detailed classification and analysis of the microscale and macroscale differences in soil properties across this complex landscape, the patterns and processes that were observed were synthesized into a simplified conceptual model of the evolution of the deltaic landscape.

Kreig, R. A., and R. D. Reger. 1982. Air-photo analysis and summary of landform soil properties along the route of the Trans-Alaska Pipeline System. Alaska Division of Geological & Geophysical Surveys, Geologic Report 66.

The results of a compilation of detailed subsurface information on soils, bedrock, ground water, permafrost, and other environmental factors along the Trans-Alaska Pipeline System (TAPS) are summarized. Includes a collection of aerial photographs that illustrate the broad diversity of landforms crossed by the TAPS route, and discussions of subsurface data from soil borings. Many good examples of permafrost-related features in interior Alaska and elsewhere.

Lawson, D. E. 1983. Erosion of perennially frozen streambanks. CRREL Report 83-29.

General controversy exists as to whether perenially frozen ground inhibits lateral erosion and bankline recession, or whether it increases bank recession rates. This report concludes that the effects of permafrost will vary depending on local conditions. Perenially frozen streambanks erode because of modification of the bank's thermal regime by exposure to air and water, and because of various erosional processes. Factors that determine rates and locations of erosion include: exposure to currents and wind waves; texture and stratigraphy of the bank sediments; ice content, distribution and type; slope aspect; Coriolis force; timing and depth of thaw; water level and temperature; vegetation; ice and snow cover; and groundwater. Thermal and physical modification of streambanks may also induce accelerated erosion within permafrost terrain removed from the immediate river environment. Bankline or bluffline recession rates are highly variable, ranging from less than 1 m/year to over 30 m/year and, exceptionally, to over 60 m/year.

Lawson, D. E. 1986. Response of permafrost terrain to disturbance: A synthesis of observations from northern Alaska, U.S.A. Arctic and Alpine Research.18(1):1-17.

Examines disturbances of perenially frozen terrain in the National Petroleum Reserve-Alaska that resulted from activities in the late 1940s and early 1950s. The disturbances were grouped into trampling of vegetation, killing of vegetative cover, removal of the vegetative mat, and removal of the vegetation and soil. Removal of the vegetation led to the most extensive modifications at all sites, but the subsequent response to disturbance varied with primarily four factors: ground ice volume; distribution and size of massive ground ice; material properties during thaw; and relief, including progressive changes during thaw subsidence. Terrain underlain by ice-poor sediments that are stable upon thawing was altered only by thaw subsidence and consolidation, while ice-rich sediments that are unstable at thaw were extensively modified by a complex interaction of slumping, sediment flow, and thermal and mechanical erosion. Drainage promoted meltwater erosion, whereas undrained areas were modified significantly less and attained stability more rapidly. Physical stability is required for growth of vegetation and thermal equilibrium, and has taken over 30 years to attain in ice-rich, thaw-unstable areas. Ice-poor, thaw-stable materials in undrained or low relief areas required an estimated five to ten years for stability. Thaw depth measurements suggest that certain of these areas have also equilibrated thermally.

Linell, K. A. 1973. Long-term effects of vegetative cover on permafrost stability in an area of discontinuous permafrost. Pages 688-693 in National Academy of Sciences, National Research Council. Proceedings of Permafrost: North American contribution to the Second International Conference.

In 1946, the U.S. Army Corps of Engineers started a long-term experiment at its Farmers Loop Road Field Station near Fairbanks, Alaska, to investigate the effects of climatics and surface conditions on ground temperature. This paper presents information obtained as part of these studies, on the relationship between vegetative cover and permafrost degradation. The data extend through 1972, 26 years after the start of the experiment. A comparison of three 61-m square test sections – one kept in its natural tree-covered condition, a second cleared of trees but not stripped, and a third section stripped of all vegetative cover to a depth of about 0.4 m – has shown that only the original densely tree-covered section has remained free from permafrost degradation over the observation period of 26 years. In both the cleared and stripped sections permafrost degradation was still continuing, but at a much slower rate. It was concluded that in an environment like that of Fairbanks the maintenance or re-establishment of a random, mixed-type low vegetative cover can not be counted on to stop or prevent permafrost degradation in an area subjected to surface disturbance.

Lobacz, E. F. 1986. Arctic and subarctic construction: General provisions. CRREL Special Report 86-17.

A manual that provides basic background data for and detailed criteria pertaining to arctic and subarctic facility design, including information for considering frost action and permafrost.

Lotspeich, F. B., and A. E. Helmers. 1974. Environmental guidelines for development roads in the subarctic. Environmental Protection Agency report EPA-660/3-74-009.

A set of guidelines based on Federal and State regulations that set standards to protect the total environment when constructing roads in the subarctic, with many examples from the Fairbanks area. Basically a collection and summary of road-related practices, with emphasis on resource development roads which meet environmental protection requirements. Includes brief sections on ice bridges and reclaiming temporary roads.

Mann, D. H., C. L. Fastie, E. L. Rowland, and N. H. Bigelow. 1995. Spruce succession, disturbance, and geomorphology on the Tanana River floodplain, Alaska. Ecoscience 2:184-199.

A long-standing paradigm in the ecology of the Alaskan taiga states that black spruce replace white spruce after several centuries of primary succession on floodplains. According to this Drury Hypothesis, autogenic thickening of organic horizons and shrinking of the active layer interact with the species' different physiological tolerances to cause black spruce dominance. The authors test the Drury Hypothesis on >200-year-old portions of the Tanana River floodplain near Fairbanks, Alaska, and reject it. In the meander belt portion of the study area, white spruce mixed with black spruce persists on geomorphic surfaces approximately 3000 years old. Predictions of the Drury Hypothesis regarding active-layer and organic-horizon thicknesses are not substantiated. Neither of these variables correlates with the abundances of the different spruce species. Forest communities in the study area are distributed along geologically based environmental gradients and are shaped by secondary succession following fires and probably floods. Black spruce dominates in the poorly drained, permafrost-rich, and fire-prone backswamp and white spruce in the oppositely characterized meander belt. Although geological chronosequences can be identified along avulsion-prone rivers like the study reach of the Tanana River, superposition of a meander belt-backswamp plan and frequent fire and flood disturbances may negate any vegetation chronosequences older than several centuries.

Mason, O. K., and J. E. Begét. 1991. Late Holocene flood history of the Tanana River, Alaska, U.S.A. Arctic and Alpine Research 23:392-403.

A sequence of historic and prehistoric flood deposits of the Tanana River is preserved in a small bedrock-sheltered slough near Fairbanks. Examination of these deposits using a suite of radiometric dates, microstratigraphic observations, and granulometric statistics suggests that large changes in flood frequency occurred during the late Holocene. Three major litho-stratigraphic units are observed: (1) thick cross-bedded, pedogenically unaltered alluvial silty sands which were deposited between 3000 and 2000 yr BP, recording an interval of large floods: (2) a series of thin silty beds and paleosols formed after 2000 yr BP during an interval when large floods were uncommon: and (3) a sequence of sand units recording large floods during the last several hundred years. Flood frequencies appear to have changed in response to regional climate changes, with more frequent flooding occurring during times of widespread alpine glaciation and increased storminess.

McVee, C. V. 1973. Permafrost considerations in land use planning management. Pages 146-151 in National Academy of Sciences, National Research Council. Proceedings of Permafrost: North American contribution to the Second International Conference.

A very brief summary of permafrost effects as they relate to land use planning management, including new townsites and village expansion, rights-of-way, mineral and oil development, timber harvest, farming, recreation activities, control of wildfires, and military activities.

Ott, R. A. 1998. The impact of winter logging roads on vegetation, ground cover, permafrost, and water movement on the Tanana River floodplain in Interior Alaska: Alaska Department of Natural Resources Division of Forestry, Cooperative Agreement AK-DF-A97-RN0006, 10-97-052.

A study of active layer depths and vegetation and ground cover patterns on two winter roads and adjacent undisturbed areas in eight plant communities underlain by permafrost. Surface permafrost receded in the roadbeds of six sampled plant communities, with the greatest increase in active layer thickness occurring in two communities characterized by black spruce. The author notes that the entire organic mat on this roadbed had been removed, perhaps accounting for these sites being the most influenced. The four other plant communities where permafrost receded (paper birch forest, tamarack woodland, shrub birch-alder, and cottongrass tussock) were located in roadbeds which retained an insulating mat of organic material. Mean active layer depths indicate that permafrost aggraded in the roadbeds of the shrub birch-leatherleaf-Labrador tea and leatherleaf communities.

Péwé, T. L. 1954. Effect of permafrost on cultivated fields, Fairbanks area, Alaska. U.S. Geological Survey Bulletin 989-F, p. 315-351.

Describes the destructive effect of permafrost on cultivated fields and delineates the parts of the Fairbanks area which are least suitable for agriculture because of the character of the underlying permafrost.

Scott, K. M. 1978. Effects of permafrost on stream channel behavior in arctic Alaska. U.S. Geological Survey Professional Paper 1068.

A study of five streams in northern Alaska to assess the effects of frozen bed and bank material on channel behavior and the importance of the annual breakup flood in forming the channels of arctic streams. The response of channels ranged from total permafrost control of channel processes, including bed scour and lateral erosion, to only brief restriction of channel behavior early in the rise of early flooding. Permafrost has been cited both as the cause of extreme stability and the cause of unusual instability in arctic streams as compared to those elsewhere. While comparison of absolute rates of lateral erosion were not deemed feasible, the author concludes that the net effect of the permafrost environment is to create greater channel stability than is found in unregulated streams of similar size in nonpermafrost environments. He goes on to note, however, that combinations of factors, particularly those that encourage high rates of thermo-erosional niching, can nevertheless cause extreme rates of erosion.

Sigafoos, R. S., and D. M. Hopkins. 1952. Soil instability on slopes in regions of perenially-frozen ground. Pages 176-192 in National Academy of Sciences, National Research Council. Frost action in soils: A symposium. Highway Research Board Special Report No. 2.

A good summary paper describing soil-instability features in permafrost areas. Roads are often preferably built on hill slopes in regions of perenially frozen ground because the hill slopes are subject to less heaving and less severe subsidence than the marshy lowlands. However, because of poor drainage, wet soils, disturbances caused by repeated cycles of freezing and thawing, and the presence of a glide plane at the surface of the perenially-frozen ground, slopes subject to rapid creep are much more common in northern latitudes than in more temperate regions. Recognition of micro-relief features can assist in selecting the best of several routes when building access roads.

Slaughter, C. W., J. W. Hilgert, and E. H. Culp. 1983. Summer streamflow and sediment yield from discontinuous-permafrost headwaters catchments. Pages 1172-1177 in National Academy of Sciences, National Research Council. Proceedings of Permafrost: Fourth International Conference.

Examines how the presence of permafrost in a catchment system affects the hydrology and water quality of streamflow in the discontinuous-permafrost taiga of central Alaska. Permafrost-underlain terrain is much more responsive to precipitation inputs than is permafrost-free terrain, and proportion of permafrost, with concomitant cold, thick organic layers overlying mineral soil, is the primary determinant of differing streamflow characteristics in headwaters catchments. A permafrost-dominated first-order stream has higher peak streamflow, higher storm-flow suspended sediment concentration, lower base (non-storm) streamflow, and lower base-flow suspended sediment concentrations than does a nearby, virtually permafrost-free first-order stream.

Stoeckeler, E. G. 1952. Trees of interior Alaska: Their significance as soil and permafrost indicators. U.S. Army Corps of Engineers investigation of military construction in Artic [sic] and Subartic [sic] regions. 25 p.

A discussion of the habitats and growth characteristics of eight species of trees in interior Alaska and implications for predicting permafrost depth. The author correlates the height of white spruce with the depth of the active zone using the relationship that the height of the spruce stand in feet indicates the minimum depth of the active zone in inches. Other observations of note: black spruce occurs principally in soils permanently frozen within three feet of the surface; tamarack nearly always grows in cold ground which is permanently frozen two to three feet below the surface; balsam poplar requires substrate in which permafrost lies at least six feet below the surface; quaking aspen grows best on unfrozen, deep soils on warm slopes; Alaska birch in bottomlands usually indicates the soil is permanently frozen within four or five feet, although stunted birch can survive where the upper surface of the permafrost layer is within two feet of the surface.

Viereck, L. A. 1965. Relationship of white spruce to lenses of perenially frozen ground, Mount McKinley National Park, Alaska. Arctic 18(4):262-267.

This study reports an investigation of ice lenses beneath white spruce trees and suggests ways in which permafrost may form under vegetation where it has previously been absent. The frozen lenses are thought to result from the insulating effect in summer of a thickened moss mat and from soil cooling in winter as a result of a thin snow layer under the trees.

Viereck, L. A. 1970. Forest succession and soil development adjacent to the Chena River in interior Alaska. Arctic and Alpine Research 2(1):1-26.

Compares four forest stands on varying aged river deposits with a climax stand on a higher and older terrace to show changes in soil and vegetation with time on the floodplain of the Chena River. The succession proceeds from the near xeric conditions of the gravel bar to the mesic balsam poplar and white spruce stands. Autogenic changes brought about by the development of a thick organic layer and interaction with the cold climate result in the development of a permafrost layer. Succession then proceeds from the mesic conditions of the poplar and white spruce stands to the hydric conditions of a slow-growing black spruce stand with a thick, saturated sphagnum mat on a permafrost table only 20 to 30 cm below the moss surface.

Viereck, L. A. 1973. Ecological effects of river flooding and forest fires on permafrost in the taiga of Alaska. Pages 60-67 in National Academy of Sciences, National Research Council. Proceedings of Permafrost: North American contribution to the Second International Conference.

Examines the effects of flooding and fire on thermal regime of permafrost in the Fairbanks area. Observations of flooding effects include: 1) flooding and water-table rise by warm water can quickly thaw existing permafrost or cause higher soil temperatures over at least the upper 150 cm of the substrate; 2) siltation during flooding results in the compaction and death of the moss layers, thus reducing their insulating value in summer which results in higher soil temperatures and an increase in thickness of the active layer; 3) the result of thawing of frozen layers heavily laden with ice can be surface subsidence, tipping of trees, and eventually the formation of thaw ponds; 4) in some cases, flooding over permafrost results in the separation of the organic layer at the permafrost boundary and a compression and rolling of the organic layer into peat mounds. Fire in forests underlain by permafrost results in a temporary thickening of the active layer. For the first 15 years after fire, thaw is more than 1 m; return to preburn thaw levels takes about 50 years.

Walker, D. A., D. Cate, J. Brown, and C. Racine. 1987. Disturbance and recovery of arctic Alaska tundra terrain: A review of recent investigations. CRREL Report 87-11.

This is a summary of over a decade of CRREL-managed research regarding disturbance and recovery in northern Alaska. The impacts that are discussed include bladed trails, off-road vehicle trails, winter trails, ice roads, gravel pads and roads, borrow pits, roadside impoundments, road dust, hydrocarbon spills and seawater spills. The main themes to come out of the report are: most anthropogenic disturbances have natural analogs, which can provide information that can be related to modern disturbances and their rates of recovery; most single-event disturbances will heal and develop a functioning ecosystem within a human life span, but a return to the original ecosystem can rarely be expected for major impacts; and, in permafrost regions with massive ground ice, recovery of the vegetation is limited by alterations to the permafrost regime.

Walters, J. C., C. H. Racine, and M. T. Jorgenson. 1998. Characteristics of permafrost in the Tanana Flats, interior Alaska. Pages 1109-1116 in Lewkowicz, A.G. and M. Allard, eds., Proceedings of Permafrost: Seventh International Conference. Universite Laval, Sainte-Foy, Quebec, Collection Nordicana, vol. 57.

The Tanana Flats is a wetland region located on the distal slopes of an extensive alluvial fan complex built out of the Alaska Range. Vegetation in the Flats consists of a mosaic of fen, birch forest, black spruce forest, shrub, and bog. Permafrost is not present in the fen and bog areas, but it exists on the bordering forested and shrub areas 0.5 to 2 m above water level. The studies show that permafrost in the Flats is relatively warm at –0.2 to –0.7°C, and that the distribution and characteristics of permafrost are related to the geobotanical conditions at the specific site. In general, permafrost is more ice rich and shows higher secondary porosity where finer-grained sediments (silts) are abundant. These are environments characterized by birch forest vegetation. Permafrost in areas of birch forest appears more susceptible to thaw and is currently showing signs of extensive degradation.

Williams, J. R. 1970. Ground water in the permafrost regions of Alaska. U.S. Geological Survey Professional Paper 696.

The presence of permafrost imposes certain unique limitations on ground-water occurrence, including: 1) Permafrost acts as an impermeable barrier to the movement of ground water, because the pore spaces are generally filled with ice within the zone of saturation. Recharge and discharge of water to and from aquifers beneath permafrost are therefore limited to the unfrozen zones that perforate the permafrost. 2) Permafrost limits the number of sites from which water can be produced from shallow wells. It commonly is necessary to drill to greater depths in permafrost regions than in comparable geologic environments in temperate regions. The near-surface unconsolidated deposits that provide abundant water in some parts of the temperate regions are commonly frozen, and utilization of aquifers of lower yield or poorer quality beneath the permafrost may be necessary. 3) The ground-water temperature ranges from 0° to 4.5°C because of low ground temperature above and below permafrost. In this temperature range, ground water is more viscous and moves more slowly than in temperate regions.

WINTER FISH USE OF GLACIAL STREAMS

An Annotated Bibliography

Compiled for the
Region III Forest Practices Riparian Management Committee

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SUMMARY

Glacial streams (water bodies that are fed seasonally by sediment-laden glacial meltwater) are a significant feature of interior Alaska. The use of glacial rivers and streams by salmonids (salmon, char and whitefish) for summer and fall spawning migrations is well known and documented. These migrations are vital for effective harvest in commercial, subsistence, and recreational fisheries. Winter is much less important as a time for fisheries harvest but is a critical period for arctic and subarctic fishes that use glacially-fed waters to survive this difficult period. The purposes of this literature review were to better understand and document the use of glacial streams by fish during winter months, to assist with assessment of vulnerability of overwintering fish use to land use activities, and to provide a background for the development of effective best management practices.

Rivers fed only by glaciers (e.g., braided rivers in Denali National Park) cease to flow during winter and are not viable winter fish habitat. Large glacial rivers with substantial base flows of groundwater (e.g., Tanana River) are essential fish habitat and play a critical role for fish in winter. In these rivers, the onset of winter fish use occurs when cooler fall temperatures cause glacial flow contributions to cease, and water turbidity drops from a summer high of 1000-2000 NTU, to about 150 NTU in October, and finally to about 10 NTU after freeze-up. The amount of DO can decrease in winter with time and distance downstream of open water patches, sometimes reaching minimums that threaten fish survival in March and April just before breakup. The "sealed" nature of some glacial river and stream reaches in winter also gives rise for concerns about the ecological effects of waste discharge in these rivers (Reynolds 1997).

There are three general groups, or life stages, of fish that use glacial streams as overwintering habitat: eggs, alevins (sac fry), and fingerlings of salmonids that spawned during summer and fall; adults of resident species inhabiting clearwater and non-glacial tributaries of glacial streams in other seasons; and all life stages of other resident species that occupy glacial streams year round.

Among salmonids whose eggs or young overwinter in interior Alaska glacial streams, fall chum salmon are best known and most common. For example, radio-tagging studies of fall chum salmon (Barton 1992) documented 18 distinct spawning areas in the mainstem Tanana River between the upper end of Salchaket Slough and the Little Gerstle River. These relatively small spawning areas are collectively more important to chum salmon production in the Tanana River in some years than previously realized. Chum salmon fry migrate to sea during spring discharge and do not spend a second winter in freshwater. King salmon generally spawn in non-glacial tributaries of glacial rivers (e.g., Chena and Goodpaster rivers). Their young usually remain in these tributaries for two winters, first as eggs and alevins, then as fingerlings. A third winter may be spent in a tributary, or in sloughs and other flowing backwaters of glacial rivers before these fish migrate down river as smolts. Dolly Varden, whitefish, and inconnu (sheefish) spawn in the fall and may use braided reaches, or other areas with gravel substrate, in mainstem glacial rivers for spawning (e.g., Brown 2000). Thus, the dependence of early life stages of salmonids on glacial streams for wintering habitat is common. Spawning areas are characterized by gravel with significant interflow for egg incubation. Groundwater or hyporheic upwelling areas and winter ice cover affect flow, temperature, and ice pattern. Fish use ice as cover in areas where there are open leads (Jakober et al. 1998).

Certain resident fish species (e.g., Arctic grayling, northern pike) spend most of the year in clearwater tributaries including their spawning periods. However, adults of these species, having attained enough size to provide them with energy reserves for migration and protection from predation, may seek glacial waters downstream for overwintering habitat. For example, some stocks of adult Arctic grayling spend the winter in the Tanana River before gathering near the mouths of non-glacial tributaries (e.g., Shaw Creek, Goodpaster River) in April, just prior to an upstream spawning migration into the tributary (Clark and Ridder 1988). During autumn, northern pike from sections of Minto Flats move into the mainstem Tanana River to spend the winter in areas between the Tolovana and Kantishna rivers (Burkholder and Bernard 1994). The habitat of these larger fish is not well documented but seems to be “holes” and other deep areas on outer bends where cut banks and bluffs are prevalent.

Some species reside in glacial waters year round. The most common and well known is burbot. Some burbot may enter tributaries for long-distance spawning migrations during winter (Breeser et al. 1988), while others may use various reaches of the mainstem Tanana at different life stages (Evenson 1989). The habitat use of other year-round residents, such as lake chub, longnose sucker and slimy sculpin, is poorly described except during summer (Mecum 1984) but is assumed to include various mainstem and side channel habitats during winter. Small species and life stages have the advantage of burrowing in the substrate or using large woody debris for protection during winter (Reynolds 1997), but larger individuals must move to deeper areas that have adequate flowing water during severe freezing periods (Cunjak 1984).

Two major data gaps were present in the sources we evaluated for this review: the role of woody debris in overwintering habitat (e.g., cover for fish, nutrients and substrate for insect larvae, alterations of depth and flow), and an understanding of the microhabitat needs of overwintering fish.

Annotations in this review are primarily author's abstracts. Citations and annotations came from a variety of sources, including an online search by the Alaska Resources Library and Information Services (ARLIS, key word "glacial"), reviewers' personal libraries, and the 1998 report by A. G. Ott, et al.

REFERENCES

Barton, L. H. 1992. Tanana River, Alaska, fall chum salmon radio telemetry study. Alaska Department of Fish and Game. Fisheries Research Bulletin No. 92-01. Juneau.

A total of 210 Tanana River fall chum salmon was radio tagged in fall 1989 about 11 km below Fairbanks. Previous surveys documented fall chum spawning areas only in those areas where visual surveys could be conducted.

Specific spawning areas were identified for 131 fish. Ninety-seven (74%) of these fish spawned in the floodplain of the Tanana River between upper Salchaket Slough and the mouth of the Little Gerstle River. Six different spawning areas were identified in the mainstem Tanana River between upper Salchaket Slough and the Little Delta River. Specific spawning sites were observed in mainstem channels or sloughs near Salchaket Slough, the mouths of the Little Salcha and Salcha Rivers, Flag Hill, Silver Fox Lodge, and about 5 km below the Little Delta River. Four spawning areas were found between the Little Delta River and Delta Creek.

About 18% of the 131 fish for which spawning areas were determined used the Delta River for spawning. Only three tagged fish (2%) were believed to have spawned above the Gerstle River. The furthest upstream spawner was near the mouth of George Creek. Overall, about 82% of the spawners were tracked to areas upstream of the Little Delta River.

In Barton’s concluding remarks he states that at least in some years, the numerous and relatively smaller spawning areas in the mainstem Tanana River, when taken collectively, contribute more substantially to total Tanana River fall chum salmon spawning escapement than previously realized.

Breeser, S. W., F. D. Stearns, M. W. Smith, R. L. West, and J. B. Reynolds. 1988. Observations of movements and habitat preferences of burbot in an Alaskan glacial river system. Transactions of the American Fisheries Society 117:506-509.

Movements of 21 radio-tagged burbot in the upper Tanana River drainage from the Northway area to Tetlin were recorded from October 1983 to December 1984. The tagged burbot ranged from 50 to 95 cm long. The fish were tracked at three-week intervals. Burbot were relocated up to 68 km downstream and 84 km upstream from release sites. The longest combined upstream and downstream movement of an individual fish was 125 km. The longest upstream movements occurred from November to March, although burbot moved during all seasons. Most tagged burbot apparently preferred the main channels; those fish that moved into clear tributaries did so in late summer after water velocities had dropped and turbidity had decreased.

Brown, R. J. 2000. Migratory patterns of Yukon River inconnu as determined with otolith microchemistry and radio telemetry. Master's thesis. University of Alaska, Fairbanks.

Migratory patterns of Yukon River inconnu *Stenodus leucichthys* were evaluated using otolith aging and microchemical techniques and radio telemetry. Research was conducted each fall between 1997 and 1999, on inconnu captured at a study site 1,200 river km from the Bering Sea. Biological data were collected to establish maturity and spawning condition. Sagittal otoliths were analyzed optically to determine age distribution, and microchemically to determine amphidromy. Inconnu were tagged with radio transmitters and located in upstream spawning destinations. Inconnu captured at the study site were uniformly large, mature fish preparing to spawn. Age estimates ranged from 7 to 28 years. Microchemical analyses suggested that the population was amphidromous rather than freshwater only. Preliminary testing of radio transmitter attachment methods showed that the internal method (pushed through the esophagus into the stomach) was superior to the external method (attached behind the dorsal fin) for use with migrating inconnu. Most radio-tagged inconnu were located during their spawning time in a common region of the Yukon River. Inconnu captured at the study site each fall were mature fish engaged in a spawning migration that originated in the lower Yukon River or associated estuary regions, and continued towards a common spawning destination in the Yukon River, approximately 1,700 river km from the sea.

Buklis, L. S., and L. H. Barton. 1984. Yukon River fall chum salmon biology and stock status. Alaska Department of Fish and Game Division of Commercial Fisheries, Information Leaflet No. 239.

Increasing exploitation by commercial and subsistence fisheries during the period 1974-1983, combined with declining escapement indices, leads the authors to recommend conservative harvest regulation of Yukon fall chum salmon (*Oncorhynchus keta*). While total return showed a moderate increase of 10% for the recent 4-year period (1980-1983) over the previous 4-year period (1976-1979), commercial harvest increased by 30%, subsistence harvest increased by 36%, while the escapement index decreased by 42% and 58% for the Porcupine and Tanana River stocks, respectively. A comprehensive review of information available on the life history, stock composition, exploitation, escapement, and stock status of Yukon River fall chum salmon is presented. Deficiencies in the present data bas are discussed, and recommendations are made for future research.

Burkholder, A., and D. R. Bernard. 1994. Movements and distribution of radio-tagged northern pike in Minto Flats. Alaska Department of Fish and Game, Division of Sport Fish. Fishery Manuscript No. 94-1, Anchorage.

Radio telemetry was used to study the movements of northern pike *Esox lucius* in Minto Flats. Ninety-eight northern pike were surgically implanted with high frequency (150-152 MHz) transmitters during the fall of 1987. Tracking was conducted with a fixed-wing aircraft during 10 tracking periods between September, 1987 and September, 1988. Northern pike radio-tagged throughout Minto Flats during the fall of 1987 segregated into four overwintering groups. About 70% of the radio tags implanted in the fall of 1987 were assumed to have failed prematurely and unexpectedly by April 1988. The highest median velocities for most northern pike for each overwintering group were achieved prior to December, 1987. In general, median velocities progressively decreased throughout the winter (December through April). No differences between the velocities of male and female or small and large radio-tagged northern pike for a given overwintering group were detected. Differences between the velocity of male and female northern pike for a given tracking period were only detected in three of 28 comparisons. Differences between the velocity of small and large northern pike for a given tracking period were only detected in two of 25 comparisons. An additional 20 northern pike were radio-tagged at one of the overwintering sites in March, 1988. Dispersal from this overwintering site was not detected until May. Northern pike located throughout the remaining tracking periods (after May) moved very little.

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

Reviews winter habitat studies of overwintering salmonids in ice-covered streams providing general information on substrate conditions and focal point velocities and depths. Draws attention to various areas as yet inadequately addressed. A review of winter habitat studies in ice-covered streams for four species of salmonid provided some general information on substrate conditions and focal point velocities and depths. All species of fry are found at depths less than 40 cm and at velocities of 10 cm/s or less; juveniles of all species are found at velocities of less than 15 cm/s. A lack of continuous physical, chemical and biological measurements throughout the ice-covered season was a common deficiency of the studies reviewed. The interaction of the ice cover with other physical processes in the stream was rarely addressed.

Chen, L. C. 1968. The biology and taxonomy of the burbot, Lota lota leptura, in interior Alaska. Biological Papers of the University of Alaska No 11.

This study was done on burbot in the Yukon and Tanana Rivers. Taxonomic data on burbot, length and age and length and weight relationships, and reproductive and food habits are presented. Young-of-the-year burbot were seined during high water on flooded grassy beaches in the upper Yukon River. Young-of-the-year burbot were also found in an isolated pond in the upper Chena River. Young-of-the-year burbot were caught in the Tanana River using seines in late July. Small burbot feed primarily on benthic invertebrates, mainly Plecoptera, but change to a diet of fish as they grow. The most abundant species in both the Yukon and Tanana Rivers are longnose suckers, lake chub, and slimy sculpin.

Clark, R. A., and W. P. Ridder. 1988. Stock assessment of Arctic grayling in the Tanana River drainage. Alaska Department of Fish and Game, Division of Sport Fish, Fishery Data Series No. 54. Juneau.

This report describes field studies conducted during 1987 on stocks of Arctic grayling in the Delta Clearwater, Richardson Clearwater, Goodpaster, Chena, Chatanika, and Salcha rivers, Caribou and Shaw creeks, and Fielding and Tangle lakes.

Sampling in the Richardson Clearwater River was conducted between 7 July and 3 August. The Arctic grayling population was estimated to be 2,775 fish larger than 250 mm in the lower 12.8 km of the river. Seventy five of the Arctic grayling sampled in the Richardson Clearwater River were tagged previously in other waterbodies in other years (54 from Caribou Creek, 18 from the mouth of Shaw Creek, and 3 from the Goodpaster River).

The post-spawning migration of Arctic grayling out of Caribou Creek was sampled with a weir from 3 to 11 June. A total of 932 Arctic grayling, of which 315 were considered sexually mature, was captured. Tag returns included 77 Arctic grayling tagged at Caribou Creek in previous years, one Arctic grayling tagged at Clear Creek in 1984, and 4 Arctic grayling tagged 1.5 months earlier at the mouth of Shaw Creek.

Electrofishing at the mouth of Shaw Creek before breakup from April 15 to 23 found Arctic grayling consistently only in two small areas. One area was located 0.8 km above the mouth in a backwater slough approximately 50 m wide, 300 m long, and 3 m deep. The other area was 0.8 km below the mouth in the main channel of the Tanana River. Arctic grayling were holding in a 100 m long and 1 m deep section of water adjacent to the main current. Two hundred eighty eight Arctic grayling were captured during this sampling. Thirty nine Arctic grayling were initially tagged in previous years: 37 at the Caribou Creek weir, 1 tagged at the mouth of Caribou Creek in 1979, and 1 tagged in Clear Creek in 1984. Population estimates for Arctic grayling in Shaw Creek are provided and discussed.

Craig, P. C. 1989. An introduction to anadromous fishes in the Alaskan Arctic. University of Alaska Biological Papers 24:27-54

Overview of Arctic anadromous fishes and of their adaptation to key environmental features. Examines commonly held beliefs that Arctic fish are regulated by limited availability of overwintering habitats and that life history pattern of anadromy allows fish access to abundant food supply in marine environment

Cunjak, R. A. 1984. Habitat utilization by stream fishes overwintering. Paper presented to Ontario Ethology Colloquium, April 18, 1984. University of Waterloo.

A comparison of overwintering strategies used by fish in subarctic rivers and those used in temperate streams showed contrasts. In northern streams, juvenile fish moved into the substrate in autumn and remained buried until the following spring. Larger fish depended on deeper pools in large rivers or lakes to provide overwintering habitat. In temperate areas, there was extensive use of ground water refugia in tributary streams or in the main river channel. These areas provided protection against ice and critically low temperatures and allowed the fish to remain mobile. In both areas, early winter was the period of greatest depletion of body reserves. Data collection involved three field trips to the Koksoak River in northern Quebec. An autumn (late Sept.) sampling period gave data on the start of the winter while a late May visit provided data on the condition of the fish at the end of the winter. A mid-March attempt to get winter data failed because the conditions were too difficult for sampling (6-8 feet of ice and temp. of -40 degrees C). However, considerable experience was gained attempting winter work which may be useful in future projects.

Cunjak, R. A. 1996. Winter habitat of selected stream fishes and potential impacts from land-use activity. Canadian Journal of Fisheries and Aquatic Sciences 53Supplement:267–282.

This paper reviews the habitat characteristics and the behavior of selected stream fishes during winter in temperate–boreal ecosystems. Emphasis is placed on the salmonid fishes upon which most winter research has been directed. As space is the primary factor regulating stream fish populations in winter, aspects of winter habitat are considered at various spatial scales from microhabitat to stream reach to river basin. Choice of winter habitat is governed by the need to minimize energy expenditure, with the main criterion being protection from adverse physicochemical conditions (e.g., ice, spates, low oxygen). The distance moved to wintering habitats, and the continued activity by many fishes during winter, need to be considered when making management decisions regarding fish habitat. How habitat is affected by land-use activity in stream catchments is discussed with reference to impacts from water withdrawal, varying discharge regimes, and erosion or sedimentation. Even stream “enhancement” practices can deleteriously affect fish habitat if project managers are unaware of winter habitat requirements and stream conditions. Maintenance of habitat complexity, at least at the scale of stream sub-basin, is recommended to ensure the diversity of winter habitats for fish communities.

Dinneford, W. B. 1978. Final report of the commercial fish--technical evaluation study: Tanana and Delta Rivers. Joint State/Federal Fish and Wildlife Advisory Team. Special Report No. 20.

Fall chum salmon escapement, distribution, timing, age class and length trends, fecundity and egg retention were measured in the Delta and Tanana rivers in 1977 as part of studies associated with the construction of the Trans-Alaska Pipeline. Limited data concerning development of chum salmon eggs and juveniles are presented. Fry in the Delta River emerged in early-to-mid April with peak outmigration occurring in early-to-mid May.

Rip rap bank protection on the south bank of the Tanana River at Big Delta caused at least a short term avoidance of the area by spawning chum salmon. Spawner distribution in 1976, the year of construction, indicated that only 20 to 25% of the traditional number of spawners used the disturbed area. The distribution of spawners in 1974 and 1977 was similar, suggesting the cause of the low count in 1976 was sediment-choked spawning gravel from construction activities that was eliminated by normal high water flows before the 1977 run reached the spawning grounds.

It was estimated that a break in the pipeline at Jarvis Creek could kill the entire Delta River chum population of spawners or pre-smolt, while a break over the Tanana River could similarly affect an entire class of migrant adults (fall) and/or pre-smolt juveniles (spring) found below the line for an undetermined distance downstream.

Eiler, J. H., B. D. Nelson, and R. F. Bradshaw. 1992. Riverine spawning by sockeye salmon in the Taku River, Alaska and British Columbia. Transactions of the American Fisheries Society 121:701-708.

Radio telemetry was used to determine the distribution of sockeye salmon *Oncorhynchus nerka* returning to spawn in the glacial Taku River in 1984 and 1986, and to locate and characterize spawning areas used by this species. During the study, 253 sockeye salmon were tracked as they moved upriver; 204 of these were followed to spawning areas. Only 37% of the 204 fish traveled to areas associated with lakes; the remaining 63% returned to "riverine" areas—river areas without lakes (42% to the Taku River main stem, 17% to the Nakina River, and 4% to other rivers). Sockeye salmon spawning in riverine areas used a variety of habitat types, including main-river channels, side channels, tributary streams, and upland sloughs. Most (55%) of the radio-tagged fish that returned to the Taku River main stem were tracked to side-channel spawning areas. Half of the 471 adult sockeye salmon sampled in the main-stem spawning areas had migrated to sea as juveniles before their first winter. This study showed that many sockeye salmon returning to the Taku River do not depend on lakes, and that riverine sockeye salmon make up a major portion of the run in some river systems.

Evenson, M. J. 1988. Movement, abundance and length composition of Tanana River burbot stocks during 1987. Alaska Department of Fish and Game, Division of Sport Fish. Fishery Data Series No. 56. Juneau.

This paper reports the results of field studies conducted in 1987 in the Tanana River from Manley Hot Springs upstream to its headwaters near Northway. In 1987, 4,516 burbot (greater than or equal to 300 mm total length) were captured in hoop traps and tagged. Length frequency, growth, age, and movement data are presented. Population estimates are provided for sections of the Tanana River near Rosie Creek and near Healy Lake.

Tag returns indicated 72% of burbot were recaptured within 8 km of tagging sites, 25% moved upstream greater than 8 km, and 3% moved downstream 8 km or more. The median distance traveled was 27 km, with a maximum distance of 265 km. A greater percentage of movement was documented during summer (June, July, August) and winter (December, January, February) than in fall or spring. Of fish captured in winter, almost 70% had made significant movements (usually in an upstream direction). The winter movements are probably associated with spawning and summer movements may be correlated with feeding.

Evenson, M. J. 1989. Biological characteristics of burbot in rivers of interior Alaska during 1988. Alaska Department of Fish and Game, Division of Sport Fish. Fishery Data Series No. 109. Juneau.

This paper reports the results of field studies conducted in 1988 in six sections of the Tanana River from Manley Hot Springs upstream to near Tok, in one section of the Yukon River, in one section of the Tolovana River, and in one section of the Chena River. In 1988, 2,305 burbot were captured in hoop traps and tagged in the Tanana, Chena, and Tolovana rivers. Length frequency, age, movement, catch per unit effort, and gear selectivity data are presented.

Movement information from tag recoveries indicate burbot are 76% resident (captured within 8 km of the tagging site) to a given area up to a period of 1.5 years. The percentage of burbot remaining resident to an area is lower (48%) after a period of 1.5 years, indicating burbot are not completely resident to an area throughout their lifetime. Movements are predominantly upstream. Downstream movements are infrequent and short ranging. Movements were most frequent in the fall and winter and were likely feeding migrations (fall) in response to prey outmigrations from tributary systems or spawning migrations (winter).

Movement of burbot between the Tanana River and the Tolovana, Goodpaster, and Chena rivers indicated stocks of burbot in these systems are not isolated. Few small (300-449 mm) burbot were captured in the Tolovana River, suggesting that spawning and rearing of burbot may not occur in this system. Migrations of burbot into the Chena River in the fall may be related to feeding, spawning, or both. Tag returns also indicate the Goodpaster River may be used for spawning.

Tag returns also indicated that at least two isolated stocks of burbot exist in the mainstem Tanana River with the boundary lying near the mouth of George Creek (river km 594). The boundary area is characterized by swift current, which may act as a barrier to burbot migration, and relatively low burbot densities.

Evenson, M. J. 1993. Seasonal movements of radio-implanted burbot in the Tanana River drainage. Alaska Department of Fish and Game. Fishery Data Series No. 93-47. Anchorage.

Radio-transmitters were surgically implanted in 40 large (greater than 650 mm) and 15 small (less than 450 mm) burbot in the Tanana and Chena rivers in the vicinity of Fairbanks from 24 August to 4 September 1992. Radio-tracking occurred from September 1992 to July 1993.

Small burbot moved shorter distances than did large burbot between all consecutive tracking periods. Total ranges of small burbot averaged 17 km and were all less than 40 km. Ranges of large burbot averaged 57 km and were between 5 and 255 km. The largest movement downstream from the point of release was 224 km, whereas the largest upstream movement was 85 km.

The high frequency of downstream movements documented in this study were at odds with previously recorded tag returns, which indicated movements, tended to be upstream. This discrepancy may be related to recovery from transmitter implantation, mortality or expulsion of transmitters, or biased tag return data from unequal distribution of sampling effort among river areas.

Mean movements of large burbot were greatest during periods coinciding with river freeze-up and breakup, and were smallest during periods coinciding with spawning. There was substantial interchange of burbot between the Tanana and Chena rivers.

Fourteen general spawning locations were identified in the Tanana and Chena rivers for 33 large burbot. The largest concentration of large burbot was near Whiskey Island where six fish were located throughout the spawning period.

Francisco, K. 1976. First interim report of the commercial fish - technical evaluation study. Joint State/Federal Fish and Wildlife Advisory Team. Special Report No. 4.

The objectives of this study were to determine the distribution, abundance and timing of fall chum and coho salmon spawning above and below the Trans-Alaska Pipeline crossing of the Tanana River at Big Delta that could be affected by the construction and operation of the pipeline, sample chum and coho salmon escapement for age-sex-size information, and to obtain early life history information for Delta River chum salmon (development, emergence, and outmigration timing). The time period of the early life history studies was from November 1974 through May 1975. Distribution studies of adult salmon were conducted from September to December 1975. Studies of chinook and chum salmon juveniles and adults in the Salcha River also were described.

Water temperatures, dissolved oxygen content, flow, and ice conditions were reported for the lower Delta River. Limited data regarding chum salmon fry growth and development and emergence are presented. The distribution and abundance of fall chum and coho adult salmon was incompletely determined because of poor survey conditions.

King salmon fry in the Salcha River were most common in the deep holes, around the brush piles and beaver houses, and in the sloughs. Fry also were found in riffle areas but were not very abundant. The number of fry using beaver food caches increased dramatically in September and were speculated to be important potential overwintering areas. King salmon fry use of tributary streams seemed to be concentrated in the lower mile of the tributaries. Some limited growth data for king salmon fry are presented.

Limited limnological data are presented for the Salcha River and several of its tributaries. Adult king and chum salmon distributions, and age and sex distribution were presented. The peak smolt outmigration for both chum and king salmon occurred during a high water event from May 10 through 15.

Francisco, K. 1977. Second interim report of the commercial fish--technical evaluation study. Joint State/Federal Fish and Wildlife Advisory Team. Special Report No. 9.

This paper reports the results of studies conducted from October 1975 to June 1976 on the early life history of chum salmon in the Delta River. Chum salmon spawning occurred from mid October through November. Hatching began in early February and continued until mid March. Emergence from the gravels began in early April and continued through the third week in April. Downstream migration of the chum smolt began in early April, with very few remaining in the river for rearing before moving downstream. Outmigration peaked on April 28 and on May 17 following increased river flows. Survival to smolt outmigration was estimated to be 2.9 to 4.9% of the potential egg deposition. Total smolt production in the Delta River in spring 1975 was estimated at 72,500 to 191,900 smolts.

A small number of king salmon juveniles, young-of-the-year and age 1 fish, were captured in the Delta River. King salmon are not known to spawn in the Delta River. A small number of coho smolt, age 1, also were caught in the lower Delta River. Limnological data are presented for April and May 1976.

Hallberg, J. E., R. A. Holmes, and R. D. Peckham. 1987. Movement, abundance, and length composition of 1986 Tanana River burbot stocks. Alaska Department of Fish and Game, Division of Sport Fish. Fishery Data Series No. 13. Juneau.

This paper reports the results of field studies conducted in 1986 in the Tanana River from Manley Hot Springs upstream to its headwaters near Northway. [Sections not sampled included the area from Moose Creek upstream to Big Delta]. In 1986, 3,541 burbot (greater than or equal to 300 mm total length) were captured in hoop traps and tagged. Length frequency and age data are presented. A population estimate of burbot in a 6.4 km section of the Tanana River near Rosie Creek near Fairbanks provided an estimate of 2,892 burbot greater than 300 mm.

Tag returns obtained from area anglers and continued sampling indicate that burbot move upstream more than downstream after release. The greatest recorded movement was by a burbot that moved 256 km upstream over a period of 1,244 days. Three burbot were recaptured in the Goodpaster River during winter, suggesting that these fish may have moved into this river to spawn.

Hillman, T. W., J. S. Griffith, and W. S. Platts. 1987. Summer and winter habitat selection by juvenile chinook salmon in a highly-sedimented Idaho stream. Transactions of the American Fisheries Society 16:185-195.

Summer and winter habitat used by age 0 spring chinook salmon was assessed in the Red River, an Idaho stream heavily imbedded with fine sediment. Chinook salmon used habitats with water velocities less than 20 cm/sec, depths of 20 to 80 cm, and close associations with cover (undercut banks). During summer, 95% of the age 0 chinook salmon were concentrated in pool and glide habitat, predominantly along the sides and tail-ends of this habitat. About 5% of the chinook salmon were in riffles, and these fish were found behind boulders greater than 25 cm in diameter, where water velocities were comparable to velocities used by juveniles in glides and pools. As fish became larger, they selected faster, deeper water. Fish that remained in the study area during winter selected areas where submerged sedges and grasses overhanging undercut banks provided cover and where water velocities were less than 12 cm/sec.

Cobble (mean maximum diameter, 19 cm; range 9 to 37 cm) was piled 26 cm deep on the streambed to evaluate the relationship between sediment and winter habitat selection by juvenile chinook salmon. After cobble substrate was added to the streambed beneath undercut banks and in midchannel in a glide and a riffle habitat, eight times more chinook salmon used the cobble substrate (in November) than in the previous year. Significantly more chinook salmon used cobble placed under banks than any other area.

Jakober, M. J., T. E. McMahon, R. F. Thurow, and C. G. Clancy. 1998. Role of stream ice on fall and winter movements and habitat use by bull trout and cutthroat trout in Montana headwater streams. Transactions of the American Fisheries Society 127(2):223-235.

We used radiotelemetry and underwater observation to assess fall and winter movements and habitat use by bull trout *Salvelinus confluentus* and westslope cutthroat trout *Oncorhynchus clarki lewisi* in two headwater streams in the Bitterroot River drainage, Montana, that varied markedly in habitat availability and stream ice conditions. Bull trout and cutthroat trout made extensive (>1 km) downstream overwintering movements with declining temperature in the fall. Most fish remained stationary for the remainder of the study (until late February), but some fish made additional downstream movements (1.1–1.7 km) in winter during a low-temperature (1°C) period marked by anchor ice formation. Winter movement was more extensive in the mid-elevation stream where frequent freezing and thawing led to variable surface ice cover and frequent supercooling (<0°C). Habitat use of both species varied with availability; beaver ponds and pools with large woody debris were preferred in one stream, and pools with boulders were preferred in the other. Trout overwintered in beaver ponds in large (*N* = 80–120), mixed aggregations. In both streams, both species decreased use of submerged cover following the formation of surface ice. Our results indicate that (1) continued activity by trout during winter is common in streams with dynamic ice conditions and (2) complex mixes of habitat are needed to provide suitable fall and winter habitat for these species.

Jordan, J. L. 1998. Riparian rehabilitation along the north fork of the Bradfield River, stand 29. Prescription for Certification. Wrangell Ranger District, Wrangell, Alaska.

This report presents the abiotic and biotic background data, and management prescription, for restoring and enhancing riparian conditions beside Stand 29 along a glacial outwash channel (North Fork Bradfield River) in southeast Alaska. It is one of the few written references to discuss use of glacial mainstem habitat by juvenile coho and chinook salmon. The objectives for the selected stand were to improve fish habitat and stream and/or riverbank stability, increase the size of snags and crown competition factor for wildlife habitat, maintain or increase aquatic and terrestrial invertebrate populations, and minimize costs of implementation.

Mainstem habitat is used by overwintering coho and chinook salmon, and becomes increasingly important as temperatures and flows drop in winter, dewatering side channels. Large accumulations of wood are associated with greater depth and are important factors in overwintering habitat. Coho juveniles overwinter within these complex debris jams, while juvenile chinook used the less complex margins of these jams, and surrounding rubble.

Off-channel overwintering habitat consists primarily of historic and current beaver ponds, which are used by coho salmon, cutthroat trout, Dolly Varden, and perhaps sockeye salmon. The report suggests that the importance of these areas as overwintering habitat depends on depth and the presence of upwellings.

Lorenz, J. M., and J. H. Eiler. 1989. Spawning habitat and redd characteristics of sockeye salmon in the glacial Taku River, British Columbia and Alaska. Transactions of the American Fisheries Society 118:495-502.

Spawning habitats of sockeye salmon *Oncorhynchus nerka* in the Taku River and its tributaries in British Columbia and Alaska were studied to determine habitat use and redd characteristics in a glacial river system. We used radiotelemetry to track adult sockeye salmon to 26 spawning reaches, and 63 spawning sites were sampled for habitat characteristics. Over 40% of the sockeye salmon in the sampling area had a freshwater age of zero, and most of these spawned in main channels or off-channel areas. The availability of upwelling groundwater influenced habitat use in the main stem of the river; upwelling groundwater was detected in nearly 60% of the sites sampled in main-stem areas. Spawning sites with upwelling groundwater had lower water velocities and more variable substrate compositions than sites without upwelling groundwater. Redds had two to four times more fine sediment than previously reported. The probability of use was greatest when substrate had less than 15% fine sediment, water velocity was between 10 and 15 cm/s, and intragravel temperature was between 4.5 and 6.0C.

Mecum, R. D. 1984. Habitat utilization by fishes in the Tanana River near Fairbanks, Alaska. Master's thesis. University of Alaska, Fairbanks.

This study evaluated summer habitat utilization of fishes and the effects of floodplain developments on fish and aquatic habitat in the glacially-fed Tanana River near Fairbanks, Alaska. Aquatic habitats were quantitatively described on the basis of water velocity, depth, and clarity, and substrate, cover and vegetation. Lake chub and longnose sucker were abundant in all habitats. Whitefishes, juvenile salmon, and northern pike were captured most frequently in areas with high water clarity. Burbot preferred deeper, turbid waters. Young-of-the-year of lake chub and longnose sucker preferred shallow, silty backwaters; juvenile lake chub demonstrated no habitat preferences; and adult lake chub, juvenile longnose sucker, and juvenile/adult slimy sculpin preferred gravel riffles. Bank stabilization activities have significantly modified aquatic habitat and fish communities of Tanana River backwaters. In general, free-flowing sidechannels have become blocked-off sloughs resulting in reduced turbidities and lower flows.

Murphy, M. L., J. Heifetz, J. F. Thedinga, S. W. Johnson, and K V. Koski. 1989. Habitat utilization by juvenile Pacific salmon (*Oncorhynchus*) in the glacial Taku River, southeast Alaska. Canadian Journal of Fisheries and Aquatic Science 46:1677-1685.

This research paper reports the results of field studies conducted to determine juvenile salmon use of the lower Taku River in southeast Alaska during summer 1986. Sockeye, coho, and chinook salmon were present within the study area. Chinook salmon were predominantly age 0 (99%) and ranged from 40 to 93 mm FL. Seining was used to estimate fish density. Habitat was classified into two broad categories: river habitats -- main channels, backwaters, braids, channel edges, and sloughs within the active river; and off-channel habitats -- beaver ponds, terrace tributaries, tributary mouths, and upland sloughs on the valley floor.

Mean water velocity was lowest (0-5 cm/s) in sloughs, backwaters, tributary mouths, upland sloughs, and beaver ponds; intermediate (10-21 cm/s) in braids, channel edges, and terrace tributaries; and highest (102 cm/s) in main channels. Main channels, except for channel edges, were assumed too swift (mean, 102 cm/s) to contain rearing salmon. Mean depth ranged from 0.3 m in braids to 1.0 m in beaver ponds and 2.9 m in main channels. Typically, river habitats were turbid (means, 240-400 JTU), whereas off-channel habitats were clear or humic (means, 20-208 JTU). Water temperatures were 2-4°C higher in beaver ponds and upland sloughs than in channel edges, braids, and terrace tributaries.

The distribution of salmon was most closely related to water velocity, and turbidity had a secondary influence. Sockeye and coho densities were highest in still or slow water (<11 cm/s), whereas chinook density was highest in slow-to-moderate current (1 to 20 cm/s). All species were virtually absent from areas with currents greater than 30 cm/s. Differences in water velocity may have masked effects of turbidity. Chinook density was similar in areas of different turbidity.

In the active channel of the lower Taku River, substrate is mostly compacted gravel, sand, and mud, providing little cover from the turbulent flow, and the only suitable habitat occurs along the channel edge. Other studies have shown juvenile chinook salmon can inhabit areas with current as fast as 70 cm/s where coarse substrate (20-40 cm diameter) provided cover from the fast current.

Mean salmon density in the habitat types corresponded to water velocity but also differed between the river and off-channel areas. Chinook primarily were in river habitats with mean velocities of 3 to 15 cm/s, particularly sloughs and channel edges (means, 6-8 fish/100 m^2), and off-channel terrace tributaries and tributary mouths (means, 5-8 fish/100 m^2). Chinook were virtually absent from beaver ponds and upland sloughs (<1 fish/100 m^2).

Murphy, M. L., K V. Koski, J. M. Lorenz, and J. F. Thedinga. 1997. Downstream migrations of juvenile Pacific salmon (*Oncorhynchus* spp.) in a glacial transboundary river. Canadian Journal of Fisheries and Aquatic Science 54:2837-2846.

Migrations of juvenile Pacific salmon (*Oncorhynchus* spp.) in the glacial Taku River (seventh order) were studied to assess movement from upriver spawning areas (in British Columbia) into lower-river rearing areas (in Alaska). Differences between fyke-net catches in the river and seine catches in the river's estuary indicated that many downstream migrants remained in the lower river instead of migrating to sea. In particular, age-0 coho salmon (*O. kisutch*) and chinook salmon (*O. tshawytscha*) moved downriver from May to November but were not caught in the estuary. Age-0 sockeye salmon (*O. nerka*), coho presmolts, and other groups delayed entry into the estuary after moving downriver. We tagged groups of juvenile coho (ages 0-2) from the fyke net with coded-wire to determine when they left the river. One-third of all tags recovered from sport and commercial fisheries occurred 2-3 years later, showing that many coho remained in fresh water for 1-2 years after moving to the lower river. Lower-river areas of large glacial rivers like the Taku River can provide essential rearing habitat for juvenile salmon spawned upriver and are important to consider in integrated whole-river management of transboundary rivers.

Peckham, R. D. 1980. Evaluation of interior Alaska waters and sport fish with emphasis on managed waters, Delta district. Annual performance report. Alaska Department of Fish and Game, Federal Aid in Fisheries Restoration Volume 21 Project F-9-12, Job G-III-I.

This report describes field studies conducted in 1979 that included estimates of angler harvest of Arctic grayling on the Tanana River and Shaw Creek, stream surveys on Shaw Creek and two of its tributaries, and sampling on the Goodpaster River.

An early spring fishery for Arctic grayling and round whitefish occurs in open water on the Tanana River at Big Delta from late March through mid April. An estimated 1,029 angler hours of effort during a 15 day sampling period caught an estimated 309 Arctic grayling and 134 round whitefish. Sampled Arctic grayling averaged 266 mm in length with a range of 203 to 365 mm. Round whitefish averaged 326 mm with a range of 250 to 405 mm.

Highway reconstruction in 1976 altered the Tanana River downstream of Shaw Creek, eliminating the pool that in the past attracted Arctic grayling for a period of two to three weeks before breakup on Shaw Creek. Since highway reconstruction, the concentration of Arctic grayling and the resulting sport fishery have not occurred.

Arctic grayling were observed spawning in the lower four miles of Rapids Creek, a tributary of Shaw Creek, on May 17 and 18. Spawning was observed over sandy-silt bottom and organic debris, usually in flowing water just below beaver dams. No Arctic grayling were seen in the upper four miles of Rapids Creek.

A small downstream weir was installed on September 10 and operated for four days on Caribou Creek, a tributary to Shaw Creek. Eight species were captured: Arctic grayling, humpback whitefish, longnose sucker, slimy sculpin, round whitefish, lake chub, coho salmon, and northern pike. Mean lengths and ranges are provided for each species.

Reynolds, J. B. 1997. Ecology of overwintering fishes in Alaskan freshwaters. Pages 281-302 *in* Milner, A. M. and M. W. Oswood, editors. Freshwaters of Alaska—Ecological Syntheses. Ecological Studies, Vol. 119. Springer-Verlag New York, Inc., New York.

Sixty years have passed since Hubbs and Trautman (1935) made their plea for winter studies of freshwater fishes. They perceived a serious neglect of such investigation and concluded that the state of affairs had resulted because of lack of winter-trained personnel, limited funding for winter research, and--probably most importantly--a preference among biologist for summer field work. The reasons for concern are the same now as they were then: winter may be a critical period controlling or limiting freshwater fish production. Many of the questions posed by Hubbs and Trautman are framed in an ecological context: Do fish experience food shortages during winter? Is ice formation an important factor in fish mortality? Are habitat requirements similar between winter and summer?

Hubbs and Trautman would be pleased to know that winter research in fisheries and freshwater ecology has significantly increased since the 1970s, particularly in Alaska and Canada, where the severity of winter has long been regarded as a significant factor in freshwater fish ecology. In Alaska, this increase occurred because of increased State funds (oil development), changes in priorities (environmental concerns) and improved technology (e.g., biotelemetry). Alaskan winter fisheries studies have centered in three areas of the state: northern or arctic Alaska, including the North Slope and Brooks Range, where winter extractions of gravel and water from streams are needed for site development by the oil and gas industry; central Alaska including the interior and Alaska Range, due to human population growth and its related impacts (e.g., proposed hydroelectric dams on the Susitna River); and southeast Alaska, the coastal rain forest, spurred by potential impacts of mining and timber harvest on salmonid production in coastal streams.

This chapter describes Alaskan freshwaters as winter habitat for fish, and summarizes the results of Alaskan studies of freshwater fish populations during winter. Scientific and common names of fishes referenced in this chapter are listed in Table 11.1. Much of the work by government agencies is excellent, but the resulting reports remain part of the "gray" literature; these sources have been used only when no published source was available to support a particular point. Fortunately, a number of key studies have been published in the peer-reviewed literature; these serve as the primary source of information for this chapter. In addition, relevant studies in Canada, the continental United States, and elsewhere are cited, not as an exhaustive review, but as needed to support and complement the purpose of this review (i.e., to synthesize what is known about overwintering fishes in Alaskan freshwaters).

Rickman, R. L. 1998. Effect of ice formation on hydrology and water quality in the lower Bradley River, Alaska—implications for salmon incubation habitat. U.S. Geological Survey, Water-Resources Investigations Report 98-4191. Prepared in cooperation with the Alaska Energy Authority.

Previous studies of streamflow in the lower Bradley River near Homer, Alaska, have shown that a minimum flow of 50 cfs is required from November 2 to April 20 to ensure adequate habitat for salmon incubation. The flow regime of the lower Bradley River was reevaluated in a U.S. Geological Survey study to determine the effects of ice formation on salmon habitat. The limiting factor for determining the minimal acceptable flow in the lower Bradley River appears to be stream-water velocity. The minimum short-term flow needed to ensure adequate salmon incubation habitat when ice is present is about 30 cfs. For long-term flows, 40 cfs is adequate when ice is present. Long-term minimum discharge needed to ensure adequate incubation habitat--which is based on mean velocity alone--is as follows: 40 cfs when ice is forming; 35 cfs for stable and eroding ice conditions; and 30 cfs for ice-free conditions. The effects of long-term streamflow <40 cfs on fine-sediment deposition and DO interchange could not be extrapolated from the data. Hydrologic properties and water quality data were measured in winter only from March 1993 - April 1998 at 6 transects in the lower Bradley River under three phase of icing: forming, stable, and eroding. Discharge in the lower Bradley River ranged from 33 to 73 cfs during all phased of ice formation and ice conditions, which ranged from ice-free to 100% ice cover. Hydrostatic head was adequate for habitat protection for all ice phases and discharges. Mean stream velocity was adequate for all but one ice-forming episode. Velocity distribution within each transect varied significantly from one sampling period to the next. No relation was found between ice phase, discharge, and wetted perimeter. Intragravel-water temperature was slightly warmer than surface-water temperature. Surface- and intragravel-water DO levels were adequate for all ice phases and discharges. No apparent relation was found between DO levels and streamflow or ice conditions. Fine-sediment deposition was greatest at the downstream end of the study reach because of low shear velocities and tide-induced deposition. DO interchange was adequate for all discharges and ice conditions. Stranding potential of salmon fry was found to be low throughout the study reach. Minimum flows from the fish-water bypass needed to maintain 40 cfs in the lower Bradley River are estimated.

Ridder, W. P. 1994. Arctic grayling investigations in the Tok River drainage during 1993. Alaska Department of Fish and Game, Fishery Data Series No. 94-19. Anchorage.

This study was conducted in April, May, June, and September 1993 to determine the age and size composition of Arctic grayling larger than 149 mm in the Tok Overflow for an initial assessment of the population in this system. Sampling was expanded to include other locations within 21 km of the Tok Overflow when few fish were found in the Tok Overflow. Other areas sampled included the Tok Overflow #2, the Little Tok River, the Tok River, and Mineral Lake Outlet. Stream descriptions and descriptions of each fishery are provided. Length and age composition data are provided.

The Tok River below the Tok Overflow was found to be an overwintering area for Arctic grayling that disperse upstream to at least Mineral Lake Outlet. Water temperatures indicated the Tok Overflow to be the coldest stream in the study area and likely inhospitable as a summer feeding area for Arctic grayling. Daily high stream temperatures ranged from 2.7 to 4.8°C between 15 April and 6 August. Arctic grayling (56 fish between 200 and 300 mm) were found at the mouth of the Tok Overflow only on 22 June (five other surveys were conducted) when the stream temperature at the mouth was 5.9°C.

The Tok River drainage is the only locale in the Tanana River drainage that supports a significant Dolly Varden fishery. Dolly Varden were captured in the Tok Overflow and the Tok Overflow #2. Two Dolly Varden were active on a redd in the Tok Overflow on 13 September. Eighteen Dolly Varden in the Tok Overflow #2 in June averaged 142 mm in length (range = 101 to 191 mm; SD = 20). Five Dolly Varden captured in the Tok Overflow #2 averaged 159 mm (range = 115 to 212 mm; SD = 32).

Ridder, W. P. 1998. Radio telemetry of Arctic grayling in the Delta Clearwater River 1995 to 1997. Alaska Department of Fish and Game, Fishery Data Series No. 98-37.

In 1995 and 1996, 110 adult Arctic grayling *Thymallus arcticus* with implanted radio transmitters were released at their summer feeding area in the Delta Clearwater River, a spring-fed tributary to the Tanana River in interior Alaska. The fish were tracked from aircraft and by boat for one year after implanting to locate overwintering and spawning areas and to estimate fidelity to the Delta Clearwater River for summer feeding. The majority of fish overwintered within a 115 mile reach of the Tanana River. Spawning areas were found in eight streams up to 72 mile distant from release. The greatest proportion of radio tagged fish spawning in the Goodpaster (59%, SE = 7%) and Volkmar (20%, SE = 6%) rivers. After spawning, 98%)SE = 3%) of live fish returned to the Delta Clearwater River for summer feeding. A radio tag shedding rate of 25% (SE = 9%) is estimated from recaptures of 24 radio-tagged fish one to two years after release.

Schallock, E. 1966. Investigations of the Tanana River and Tangle Lakes fisheries: migratory and population study. Annual report of progress. Alaska Department of Fish and Game Federal Aid in Fisheries Restoration Project No. F-5-R-7, Job 16-B.

This paper describes field work conducted in summer 1965 on Arctic grayling in the Delta Clearwater, Fielding Lake, and the Tangle Lakes systems. Field work included migration, growth, fecundity, spawning, parasite, and overwintering, and tag loss studies.

Limited data from work conducted in the Delta Clearwater indicated similar results to that described in Schallock (1965). Delta Clearwater Arctic grayling tag recoveries indicated some upstream and downstream movement, and for short tag to tag-recovery intervals, no movement phenomena during the summer. Tag recoveries also indicated immigration from Clearwater Lake and the Goodpaster River.

Netting in the Delta Clearwater - Tanana Slough area in mid October produced 22 Arctic grayling, all of which were located downstream of chum salmon redds. Sixty nine percent of the retained Arctic grayling contained salmon eggs in their stomach contents. One short sampling effort in mid December in the campground area revealed one large school of about 200 fish (several were tentatively identified as Arctic grayling; the remainder were considered whitefish). Several other small schools of unidentified fish also were seen.

Tack, S. L. 1980. Migrations and distributions of Arctic grayling, *Thymallus arcticus* (Pallus), in Interior and Arctic Alaska. Annual performance report. Alaska Department of Fish and Game Federal Aid in Fisheries Restoration Volume 21. Project R-I, Job R-I.

This report describes in detail seasonal migrations and distributions of Arctic grayling for five basic river types in Interior and Arctic Alaska. River types included: unsilted rapid runoff streams (Chena, Salcha); silted rapid runoff streams (Tanana, Yukon); spring-fed streams (Delta Clearwater); bog-fed streams (Shaw Creek, Little Salcha River); and glacier-fed streams (heavy silt load in summer only; generally have little or no fish life). Information presented includes overwintering distribution, prespawning migration, spawning distribution, postspawning migration, summer distribution, fall migration, and miscellaneous short-term movements.

Whalen, K. G., D. L. Parrish, and M. E. Mather. 1999. Effect of ice formation on selection of habitats and winter distribution of post-young-of-the-year Atlantic salmon parr. Canadian Journal of Fisheries and Aquatic Science 56:87-96.

We determined how ice affects selection of habitats and distribution of post-young-of-the-year Atlantic salmon (*Salmo salar*) parr during winter. Night snorkeling surveys were completed between November and April to evaluate parr habitat use and movements. Systematic measurements of water depth and velocity were recorded during ice-free and 55% iced conditions to quantify habitat availability. Ice formation altered the distribution and reduced the abundance of habitats commonly used by parr; differences between parr habitat use and habitat availability were greatest when ice was present. Edge ice formation resulted in the concentration of flows, and areas of high flow were formed in midchannel; few parr were observed in midchannel after ice had formed. Through the winter, most parr were found lateral to high flows on the ice edge boundary or in the post-ice period lateral to the stream midchannel. The correspondence of parr movements during winter to changes in the physical habitat associated with ice formation indicates that movements and redistributions may be important for survival in streams affected by ice.

FISH USE OF UPWELLINGS

An Annotated Bibliography

Compiled for the
Region III Forest Practices Riparian Management Committee

by
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SUMMARY

Several water bodies in the Tanana River Basin exhibit areas of upwelling—localized or widespread areas where water flows from the bed up into the water column. These upwelling areas can appear as gravel-bedded springs, pockmarked areas in sandy or silty areas, or generalized flow up through gravel substrate. More than one water source feeds upwelling areas. Some waters are hyporheic, part of the river or stream water column that moves down into and rises up out of porous bed materials. These flows have chemical characteristics very close to those of the surface flow. Other upwellings are true groundwater, which has been subsurface for extended time (years to millennia), and has have conductivity and very low dissolved oxygen (DO) relative to surface flows. Recent field work along the Tanana River suggests that a third water source may also supply upwelling areas, with a subsurface time of perhaps months to a few years, exhibiting similar chemical and DO characteristics to that of hyporheic flow but being relatively independent of channel flow stage or season. This literature review was undertaken to better understand fish use of upwelling areas, and to assist with evaluating potential risks to such use by land use activities including timber harvest and access road construction.

Preferential use by fish of upwelling areas has been widely reported. Baxter and McPhail (1999) found that bull trout females preferentially spawned in upwelling locations, which had warmer water temperatures. Garrett et al. (1998) found that kokanee (landlocked sockeye salmon) preferred to spawn in upwelling areas in the North Fork Payette River, Idaho, and that the warmer water temperatures accelerated development, protected eggs from freezing, and perhaps increased survival. Lorenz and Eiler (1989) examined sockeye salmon spawning areas in the glacial Taku River near Juneau, and its tributaries. They found that upwelling groundwater was an important component of spawning habitat in the main stem of the Taku, and that redd characteristics were different in such areas. Kogl (1965) looked at the interactions of groundwater and chum salmon spawning in the mid-Chena River, and noted the complex interplay between overwinter water temperatures, DO, spawning sites, and upwelling areas. Barton's (1992) radiotelemetry work in 1989 catalyzed much of the ADF&G interest in upwelling areas by documenting fall chum spawning in the main stem of the glacial Tanana River, and similar patterns have been observed during subsequent annual aerial surveys of spawning chum salmon in the area. ADF&G Division of Sport Fisheries biologists have noted use of upwelling areas by spawning fall chum salmon in the Nenana River basin as well.

The key attributes of fish habitat in upwelling areas are warmer winter water temperatures, and increased or consistent intergravel flow. The warmer water provides thermal units needed for hatching and prevents freezing of eggs. The flow provides oxygen and carries away waste products and may prevent freezing. Fish preferentially use areas with warm upwelling sources that contain adequate DO or that have been oxygenated by mixing with air or with cooler water that contains abundant DO. Fish survival may also benefit from the stability of environmental conditions in groundwater upwelling areas; these areas tend to have more stable temperatures, water levels, and intergravel flow rates.

In general, authors were concerned that the importance of upwelling areas to maintenance of healthy fish populations has not been fully appreciated by fisheries and land managers. Barton (1992, page 15) notes that the relatively numerous and small spawning areas in the main stem of the Tanana River cumulatively contribute significantly to the total available spawning area for Tanana Basin fall chum salmon. Garrett et al. (1998, page 929) agree that use of upwelling areas by fish can have population level effects, and suggest that managers consider affording special consideration to upwelling areas used by spawning salmonids. However, no studies were found that provided data on linkage between upwelling areas used by fish and potential effects from land use activities. Before it can be determined whether or not dispersed timber harvest and road building activities, or cumulative effects of more regional harvesting efforts, could affect upwelling areas and the fish species that use them, we need a better understanding of where the upwelling water is coming from; why upwellings, as such, occur where they do; and what the fish use of the upwellings areas is. First steps could include (1) monitoring the temperature and water chemistry of upwellings and winter open water areas, and (2) documenting the year-round presence and abundance of fish, by species and life stage, in these upwelling areas.

Annotations in this review are primarily author's abstracts. Citations and annotations came from a variety of sources, including an online search by the Alaska Resources Library and Information Services (ARLIS, key word "upwelling"), reviewers' personal libraries, and the 1998 report by A. G. Ott, et al.

REFERENCES

Barton, L. H. 1992. Tanana River, Alaska, fall chum salmon radio telemetry study. Alaska Department of Fish and Game. Fisheries Research Bulletin No. 92-01. Juneau.

A total of 210 Tanana River fall chum salmon was radio tagged in fall 1989 about 11 km below Fairbanks. Previous surveys documented fall chum spawning areas only in those areas where visual surveys could be conducted.

Specific spawning areas were identified for 131 fish. Ninety-seven (74%) of these fish spawned in the floodplain of the Tanana River between upper Salchaket Slough and the mouth of the Little Gerstle River. Six different spawning areas were identified in the mainstem Tanana River between upper Salchaket Slough and the Little Delta River. Specific spawning sites were observed in mainstem channels or sloughs near Salchaket Slough, the mouths of the Little Salcha and Salcha Rivers, Flag Hill, Silver Fox Lodge, and about 5 km below the Little Delta River. Four spawning areas were found between the Little Delta River and Delta Creek.

About 18% of the 131 fish for which spawning areas were determined used the Delta River for spawning. Only three tagged fish (2%) were believed to have spawned above the Gerstle River. The furthest upstream spawner was near the mouth of George Creek. Overall, about 82% of the spawners were tracked to areas upstream of the Little Delta River.

In Barton's concluding remarks he states that at least in some years, the numerous and relatively smaller spawning areas in the mainstem Tanana River, when taken collectively, contribute more substantially to total Tanana River fall chum salmon spawning escapement than previously realized.

Baxter, J. S., and J. D. McPhail. 1999. The influence of redd site selection, groundwater upwelling, and over-winter incubation temperature on survival of bull trout (*Salvelinus confluentus*) from egg to alevin. Canadian Journal of Zoology 77:1233-1239.

Bull trout females generally selected spawning areas of groundwater discharge that had higher water temperatures during the incubation period. Fertilized eggs were placed in locations selected and not selected by females for redds. Eggs in selected areas had significantly higher, and less variable, survival rates that eggs in nonselected areas, although alevin lengths did not significantly differ. The authors suggest that preferred redd locations may be limiting in bull trout systems.

Clark, R. A., and W. P. Ridder. 1987. Abundance and length composition of selected grayling stocks in the Tanana Drainage during 1986. Alaska Department of Fish and Game, Division of Sport Fish. Fishery Data Series No. 26. Juneau.

This report describes field studies conducted during 1986 on stocks of Arctic grayling in the Delta Clearwater, Richardson Clearwater, Goodpaster, Chena, Chatanika, and Salcha rivers, One Mile Slough, Caribou and Shaw creeks, and Fielding and Tangle lakes.

Sampling in the Richardson Clearwater River was conducted between 21 and 30 July. The Arctic grayling population was estimated to be 1,418 fish larger than 150 mm. Twenty seven of the Arctic grayling sampled in the Richardson Clearwater River were tagged previously in other waterbodies in other years (24 from Caribou Creek, 1 from Rapids Creek, and 2 from the Goodpaster River).

The post-spawning migration of Arctic grayling out of Caribou Creek was sampled with a weir from 2 to 18 June. A total of 817 Arctic grayling, of which 320 were considered adults, was captured.

Dingman, S. L., H. R. Samide, D. L. Saboe, M. J. Lynch, and C. W. Slaughter. 1971. Hydrologic reconnaissance of the Delta River and its drainage basin, Alaska. Cold Regions Research and Engineering Laboratory, Research Report v. 262, Hanover, NH.

A one-year reconnaissance study was made of a large braided glacial river and its drainage basin (drainage area 1665 m2; elevation range 1000 - 10,000 ft) for which a minimum of hydrometric and meterologic data existed. The report includes estimates of the water balance, flow-duration curves, and sediment characteristics, and descriptions of stream response to glacial melt and rain, channel geometry and channel processes. Mean annual basin precipitation is estimated at 40.4 in. and mean annual loss of permanent glacial storage is about 1 in. About 30%

of this leaves the basin as evapotranspiration, 50% as stream flow, and 20% as groundwater flow. Characteristics of response to glacial melt are outlined. Flow peaks near the mouth occur with 24 hours of rainfall greater than 0.5 in./day at foothills meterological stations; rains of less than that amount do not generally produce discernible stream response. Stream channel geometry is described in detail. Most channels on the lower floodplain are asymmetrical and are roughly triangular or parabolic, and have high width/depth ratios. At-a-station hydraulic geometry is described. Surveys and ground and aerial photography are used to describe channel changes.

Eiler, J. H., B. D. Nelson, and R. F. Bradshaw. 1992. Riverine spawning by sockeye salmon in the Taku River, Alaska and British Columbia. Transactions of the American Fisheries Society 121:701-708.

Radio telemetry was used to determine the distribution of sockeye salmon *Oncorhynchus nerka* returning to spawn in the glacial Taku River in 1984 and 1986, and to locate and characterize spawning areas used by this species. During the study, 253 sockeye salmon were tracked as they moved upriver; 204 of these were followed to spawning areas. Only 37% of the 204 fish traveled to areas associated with lakes; the remaining 63% returned to "riverine" areas—river areas without lakes (42% to the Taku River main stem, 17% to the Nakina River, and 4% to other rivers). Sockeye salmon spawning in riverine areas used a variety of habitat types, including main-river channels, side channels, tributary streams, and upland sloughs. Most (55%) of the radio-tagged fish that returned to the Taku River main stem were tracked to side-channel spawning areas. Half of the 471 adult sockeye salmon sampled in the main-stem spawning areas had migrated to sea as juveniles before their first winter. This study showed that many sockeye salmon returning to the Taku River do not depend on lakes, and that riverine sockeye salmon make up a major portion of the run in some river systems.

Francisco, K., and W. B. Dinneford. 1977. Fourth interim report of the commercial fish - technical evaluation study: Tanana and Delta Rivers. Joint State/Federal Fish and Wildlife Advisory Team. Special Report No. 19.

This paper reports the results of studies conducted from September 1976 through May 1977. The distribution and abundance of chum and coho salmon were determined through test gillnet fishing, aerial surveys and ground surveys. Carcass sampling was used to determine the age and sex composition of chum and coho salmon. Early life history information and the timing of smolt outmigration was recorded for chum salmon in the Delta River.

An estimated 39 to 43 chum salmon spawned in 1976 in the Tanana River next to riprap installed as part of the Trans-Alaska Pipeline crossing. In 1974, before construction, an estimated 247 chum salmon spawned in the area. Fish distribution in 1974 and 1976 was similar, and the estimated escapement for the area was higher in 1976 than in 1974.

Delta River chum salmon hatched after about 122 days of incubation (October 7 to February 3). The first emerged fry were seen on April 6, which indicates about 185 days from spawning to emergence. Outmigration peaked in the two weeks from April 8 to April 21. Water chemistry data are presented for the Delta River chum salmon spawning area for April through May 1977.

Garrett, J. W., D. H. Bennett, F. O. Frost, and R. F. Thurow. 1998. Enhanced incubation success for kokanee spawning in groundwater upwelling sites in a small Idaho stream. North American Journal of Fisheries Management 18:925-930.

Kokanee (*Oncorhynchus nerka* lacustrine sockeye salmon) spawned in groundwater upwelling in the North Fork of the Payette River, Idaho. Intragravel water temperatures in groundwater-influenced redds exceeded surface flow water temperature by 2.4-2.6°C. In redds without groundwater influence, intragravel and water column temperatures did not differ by more than 0.2°C. Although redds constructed in upwelling sites contained significantly more fine sediments (<0.83 mm) and were constructed in areas of significantly lower surface water velocities than redds not influenced by upwelling, preemergent survival of fry from redds in upwelling sites (84%) significantly exceeded that from redds in other areas (66%). Higher incubation temperatures at upwelling sites accelerated rates of development, protected embryos from freezing, and my increase survival of fry recruiting to Payette Lake.

Kogl, D. R. 1965. Springs and ground-water as factors affecting survival of chum salmon spawn in a sub-arctic stream. Master's thesis. University of Alaska, Fairbanks.

The distribution of spawning chum salmon in relation to springs and ground-water seepage, and the survival of chum salmon eggs in these areas, was studied in the Chena River in 1963-1965. The study area was located on the Chena River, about 64 miles upstream from its mouth and immediately upstream of the mouth of Horner Creek. Temperature and water quality information (dissolved oxygen concentrations, pH, iron, alkalinity, and hardness) were recorded. Plastic standpipes were used to obtain in-river groundwater temperature and water quality measurements. Egg survival, and survival and growth of embryos were recorded.

All seepage water analyzed during the summer and winter had (1) a pH of 6.5, (2) a temperature lower than the main river in summer and higher in winter, (3) an iron content of about 0.1 to 0.3 mg/l, and (4) a lower dissolved oxygen content than surface waters of the main river. Intragravel water temperatures generally were 1 to 2°C higher than the study area surface water. Surface dissolved oxygen concentration was 5.7 mg/l in late October and declined to about 2.0 mg/l by March. Average dissolved oxygen concentrations of intragravel water at the estimated time of egg hatching (December 1) was about 3.8 mg/l. Intragravel water dissolved oxygen concentrations were usually lower than that of the surface, but in those cases where temperatures were lower, dissolved oxygen was higher. Intragravel water hardness increased from about 86 mg/l during incubation to about 103 mg/l about one month after hatching began. Alkalinity initially was 69 mg/l and increased to 86 mg/l during the same period.

Chum salmon chose well defined spawning sites that were directly or indirectly affected by groundwater seepages. Chum salmon spawned at depths ranging from 0.05 to 1.2 m and in water velocities of 0.0 to 0.6 mps. Chinook salmon spawned at water depths of 1.2 to 1.8 m and velocities of 0.5 to 0.8 mps. Average survival of eggs was 84.2%. Alevins hatching from eggs incubated at higher dissolved oxygen concentrations were larger in size (dry weight) than those incubated at lower dissolved oxygen concentrations.

Lorenz, J. M., and J. H. Eiler. 1989. Spawning habitat and redd characteristics of sockeye salmon in the glacial Taku River, British Columbia and Alaska. Transactions of the American Fisheries Society 118:495-502.

Spawning habitats of sockeye salmon (Oncorhynchus nerka) in the Taku River and its tributaries in British Columbia and Alaska were studied to determine habitat use and redd characteristics in a glacial river stream. Radiotelemetry was used to track adult sockeye salmon to 26 spawning reaches, and 63 spawning sites were sampled for habitat characteristics. Over 40% of the salmon in the sampling area had a freshwater age of zero, and most of these spawned in main channels or off-channel areas. The availability of upwelling groundwater influenced habitat use in the main stem of the river; upwelling groundwater was detected in nearly 60% of the sites sampled in main-stem areas. Spawning sites with upwelling groundwater had lower water velocities and more variable substrate compositions than sites without upwelling groundwater. Redds had 2-4 times more fine sediment than previously reported. The probability of use was greatest when substrate had less than 15% fine sediment, water velocity was between 10-15 cm/s, and intragravel temperature was between 4.5 and 6.0 C. (Author 's abstract)

Murphy, M. L., J. Heifetz, J. F. Thedinga, S. W. Johnson, and K V. Koski. 1989. Habitat utilization by juvenile Pacific salmon (*Oncorhynchus*) in the glacial Taku River, southeast Alaska. Canadian Journal of Fisheries and Aquatic Science 46:1677-1685.

This research paper reports the results of field studies conducted to determine juvenile salmon use of the lower Taku River in southeast Alaska during summer 1986. Sockeye, coho, and chinook salmon were present within the study area. Chinook salmon were predominantly age 0 (99%) and ranged from 40 to 93 mm FL. Seining was used to estimate fish density.

Habitat was classified into two broad categories: river habitats -- main channels, backwaters, braids, channel edges, and sloughs within the active river; and off-channel habitats -- beaver ponds, terrace tributaries, tributary mouths, and upland sloughs on the valley floor.

Mean water velocity was lowest (0-5 cm/s) in sloughs, backwaters, tributary mouths, upland sloughs, and beaver ponds; intermediate (10-21 cm/s) in braids, channel edges, and terrace tributaries; and highest (102 cm/s) in main channels. Main channels, except for channel edges, were assumed too swift (mean, 102 cm/s) to contain rearing salmon. Mean depth ranged from 0.3 m in braids to 1.0 m in beaver ponds and 2.9 m in main channels. Typically, river habitats were turbid (means, 240-400 JTU), whereas off-channel habitats were clear or humic (means, 20-208 JTU). Water temperatures were 2-4°C higher in beaver ponds and upland sloughs than in channel edges, braids, and terrace tributaries.

The distribution of salmon was most closely related to water velocity, and turbidity had a secondary influence. Sockeye and coho densities were highest in still or slow water (<11 cm/s), whereas chinook density was highest in slow-to-moderate current (1 to 20 cm/s). All species were virtually absent from areas with currents greater than 30 cm/s. Differences in water velocity may have masked effects of turbidity. Chinook density was similar in areas of different turbidity.

In the active channel of the lower Taku River, substrate is mostly compacted gravel, sand, and mud, providing little cover from the turbulent flow, and the only suitable habitat occurs along the channel edge. Other studies have shown juvenile chinook salmon can inhabit areas with current as fast as 70 cm/s where coarse substrate (20-40 cm diameter) provided cover from the fast current.

Mean salmon density in the habitat types corresponded to water velocity but also differed between the river and off-channel areas. Chinook primarily were in river habitats with mean velocities of 3 to 15 cm/s, particularly sloughs and channel edges (means, 6-8 fish/100 m^2), and off-channel terrace tributaries and tributary mouths (means, 5-8 fish/100 m^2). Chinook were virtually absent from beaver ponds and upland sloughs (<1 fish/100 m^2).

Pearse, G. A. 1974. A study of a typical spring fed stream of interior Alaska. Annual report of progress. Alaska Department of Fish and Game, Federal Aid in Fisheries Restoration, Volume 15. Project F-9-6, Job G-III-G.

This paper reports the results of field work conducted on the Delta and Richardson Clearwater rivers in 1972 and 1973 examining the distribution, movements, abundance, life history information, and food habits of Arctic grayling and round whitefish, and certain aspects of coho salmon life history. Water quality values for temperature, pH, alkalinity, hardness, dissolved oxygen, and carbon dioxide are presented.

Smaller (<300 mm) Arctic grayling entered the Delta Clearwater in early April, with larger Arctic grayling entering the river in mid May and June. Most of the fish moved downstream in fall; a few remained through mid winter. All were absent in March 1973. No ripe pre-spawning Arctic grayling were collected in the Delta Clearwater; however, nine young-of-the-year were captured in the lower river in late July 1973, indicating a few Arctic grayling do spawn in the system. Rearing grayling emigrate from spawning rivers such as the Goodpaster River and Shaw Creek, and migrate to summer feeding areas such as the Delta and Richardson Clearwater rivers.

Arctic grayling tagged in the Goodpaster River in May were recaptured in the Delta Clearwater later in the summer. Arctic grayling tagged in the Goodpaster River in late summer were captured the following year in the Richardson Clearwater and Clearwater Lake. Arctic grayling tagged in the Delta Clearwater in May and June were captured later in the summer in Clearwater Lake and the Goodpaster River.

Round whitefish tagged in the Tanana River between the mouths of the Delta Clearwater and Goodpaster rivers, and near the mouth of the Delta River in late March were recaptured in the Delta Clearwater, Richardson Clearwater, Tanana River, and Clearwater Lake. No young-of-the-year round whitefish were captured in the Delta Clearwater, which suggests spawning does not occur in this system. Few round whitefish were seen in early September in the Delta Clearwater. Two round whitefish tagged in the Delta Clearwater were observed in a large school of pre-spawning round whitefish in the Goodpaster River in mid September.

Pre-spawning coho salmon were first observed in the Delta Clearwater in 1973 on September 24. Peak spawning occurred around mid October. About 350 to 400 coho salmon were observed in the Richardson Clearwater. Coho and chum salmon were observed in the lower seven miles of the Richardson Clearwater. Young-of-the-year and age 1 coho salmon were observed and captured along the stream margins in cover areas during summer. Some also were captured in spring areas. Rearing fish were absent from the stream margins in fall but were captured in greater numbers in spring areas at this time. Springs are the preferred overwintering habitat for these age classes of salmon. The majority of coho smolt had outmigrated before May 25; some were captured in the Tanana River near the mouth of the Delta River in March.

Ridder, W. P. 1994. Arctic grayling investigations in the Tok River drainage during 1993. Alaska Department of Fish and Game. Fishery Data Series No. 94-19. Anchorage.

This study was conducted in April, May, June, and September 1993 to determine the age and size composition of Arctic grayling larger than 149 mm in the Tok Overflow for an initial assessment of the population in this system. Sampling was expanded to include other locations within 21 km of the Tok Overflow when few fish were found in the Tok Overflow. Other areas sampled included the Tok Overflow #2, the Little Tok River, the Tok River, and Mineral Lake Outlet. Stream descriptions and descriptions of each fishery are provided. Length and age composition data are provided.

The Tok River below the Tok Overflow was found to be an overwintering area for Arctic grayling that disperse upstream to at least Mineral Lake Outlet. Water temperatures indicated the Tok Overflow to be the coldest stream in the study area and likely inhospitable as a summer feeding area for Arctic grayling. Daily high stream temperatures ranged from 2.7 to 4.8°C between 15 April and 6 August. Arctic grayling (56 fish between 200 and 300 mm) were found at the mouth of the Tok Overflow only on 22 June (five other surveys were conducted) when the stream temperature at the mouth was 5.9°C.

The Tok River drainage is the only locale in the Tanana River drainage that supports a significant Dolly Varden fishery. Dolly Varden were captured in the Tok Overflow and the Tok Overflow #2. Two Dolly Varden were active on a redd in the Tok Overflow on 13 September. Eighteen Dolly Varden in the Tok Overflow #2 in June averaged 142 mm in length (range = 101 to 191 mm; SD = 20). Five Dolly Varden captured in the Tok Overflow #2 averaged 159 mm (range = 115 to 212 mm; SD = 32).

Schallock, E. 1965. Investigations of the Tanana River grayling fisheries, migratory studies. Annual report of progress. Alaska Department of Fish and Game, Federal Aid in Fisheries Restoration Project No. F-5-R-6, Job 16-B. 12.

This annual report describes results of studies conducted in 1964 of movements, growth rates, and tag loss in Arctic grayling in the Delta Clearwater, Richardson Clearwater, and the Goodpaster River.

The Arctic grayling of the Delta Clearwater move upstream during the summer months (June to September) whereas the fish in the Goodpaster River exhibit both upstream and downstream tendencies with the majority of the fish showing no movement. It is suspected the intrastream movement pattern found in the Goodpaster River is the result of the upstream migration occurring earlier in the season and being masked by the high water of breakup. By the time conditions allow sampling, fish generally have established residency and little net change occurs thereafter.

Inter-stream system movement trends that appeared in 1964 were tendencies for Arctic grayling to move from the Goodpaster River and the Clearwater Lake area into the Delta Clearwater. The absence of ripe fish and young-of-the-year in the Delta Clearwater, the presence of these two groups in the Goodpaster River, and a documented emigration of Goodpaster River fish and immigration of fish into the Delta Clearwater, supports the conclusion that the Goodpaster River is supplying the Delta Clearwater with some of its fish.

Adult Arctic grayling probably spawn in the Goodpaster River and some move to the Delta and Richardson Clearwaters. The Goodpaster River then may serve as a rearing area for the offspring of the adults that take summer residency in the Delta and Richardson Clearwaters. Tag recoveries of inter-system moving fish were made in the summer following tagging and suggest fish may congregate in the Tanana River in winter. Information on growth rates is presented for Goodpaster River and Delta Clearwater Arctic grayling.

West, R. L., M. W. Smith, W. E. Barber, J. B. Reynolds, and H. Hop. 1992. Autumn migration and overwintering of Arctic grayling in coastal streams of the Arctic National Wildlife Refuge, Alaska. Transactions of the American Fisheries Society 121:709-715.

During 1984 and 1985, 67 adult Arctic grayling *Thymallus arcticus* with surgically implanted radio transmitters were released at their summer feeding areas in three river systems of the Arctic National Wildlife Refuge, Alaska. We tracked the fish from aircraft to determine patterns of autumn migration to overwintering locations. During August or September in each area, fish left the small tundra streams where they were tagged and migrated into larger streams. Migration rates peaked at 5-6 km/d about 1 September and averaged 1 km/d. Fish in two river systems moved into adjacent rivers after passage through estuarine waters. Migration distances from spawning or summer feeding areas to overwintering sites were as great as 101 km. Potential overwintering areas determined from transmitter relocations included deep pools, spring-fed areas, and lakes. Management problems associated with these extensive seasonal migrations may include the maintenance of the species migratory circuit in a region that may face future development.

Wilcox, D. E. 1980. Geohydrology of the Delta-Clearwater area, Alaska. U.S. Geological Survey, Water-Resources Investigations 80-92.

The Delta Agricultural Project is developing more than 93 square miles of land in the Delta-Clearwater area. Geohydrologic information can help planners, farmers, and environmentalists evaluate ground-water supplies and potential effects of development on ground and surface water.

The alluvial aquifer system underlying the Delta-Clearwater area is composed of lenticular, interbedded deposits of silt, sand, and gravel. Ground water here occurs under both confined and unconfined conditions. The potentiometric surface across the area slopes approximately northward at gradients ranging from about 1 to 25 feet per mile. Well yields are as high as 1,500 gallons per minute from a well at Fort Greely. Water discharges from the alluvial aquifer into the Clearwater Creek network and Clearwater Lake, into the mouth of the Delta River, and into the Tanana River along the northern boundary of the study area. The discharge rate from the aquifer shows little variation; from May 977 to July 1979 flow at a gaging station on spring-fed Clearwater Creek ranged from 650 to 773 cubic feet per second. Average annual ground-water discharge is estimated to be greater than 1,200 cubic feet per second. The aquifer is recharged by seepage through the streambeds of rives and creeks in the area and by infiltration of precipitation. Reaches of many rivers and creeks are perched above the aquifer and lose water to it. Hydrographs from observation wells in the area reflect seasonal recharge pulses.

The following ground-water flow system is hypothesized: Losses from the Gerstle River, losses from several small creeks draining the Alaska Range, and losses from the Tanana River east of Clearwater Creek recharge the sections of the aquifer that discharge at the Clearwater Creek network. Losses from the Delta River and Jarvis Creek are the main sources of recharge to the sections of the aquifer that discharge in the vicinities of Clearwater Lake and Big Delta. Additional work is needed to verify these hypotheses.

ICE THICKNESS AND ICE BRIDGES

An Annotated Bibliography

Compiled for the
Region III Forest Practices Riparian Management Committee

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SUMMARY

The purpose of this literature review was to document our knowledge and lack of knowledge on 2 related topics: ice thickness regimes of Region III lakes, streams, and rivers; and ice-bridge construction. The focal point for this review was to better understand the potential impacts of river ice and ice-bridges on fish and fish habitat. Therefore, some redundancy may exist in citations found below and in the bibliographies on "Fish Use of Upwellings" and "Winter Fish Use of Glacial Streams".

A considerable amount of data and data analysis has been published by the U.S. Army, Cold Regions Research and Engineering Laboratory (CRREL), regarding ice-thickness regimes. These and other data indicate the range of cumulative seasonal ice thickness for interior Alaska to be from 75 to 160 cm (30 to 63 inches). There exists considerable variation in the date of ice initiation and date of ice breakup as well as ice thickness growth as a function of air temperatures and water body characteristics. Aldrich (1981) gives the 1, 2, 5, 10, 20, 50, and 100 year return period ice thickness values for many Alaskan and Canadian locations. Many theoretical studies exist that analyze and attempt to model the ice growth and decay processes. Simpler methods correlating ice thickness with freezing degree-days provide a more accessible guideline for estimating ice thickness under given conditions. Some methods include the effects of snow depth on the ice cover. Frazil ice and submerged frazil slush can accelerate the initiation and early season growth rates of ice thickness. Of great concern to the Region III Forest Practices Stream Classification Committee (SCC) was the location and frequency of open water (leads or polynas) in rivers with a general ice cover. Although widely recognized, little scientific attention has been given to this phenomenon in the literature reviewed. One author speculated that polynas are related to island frequency (Gerard, 1989).

Several references from CRREL and others offer guidelines for ice-bridge construction. The ideal site has the following characteristics: deep, narrow, slow flow in a single straight channel with gradual approaches to the ice; no tributary streams, creeks or lakes immediately upstream; and it is located near an existing road network. The site should also be free of warm springs and sand bars and not subject to major snow drifting. Being downstream of riffles/rapids may be

conducive to supercooling and frazil ice formation that might accelerate ice formation and growth at the bridge site. One reference suggested sites with low flow rates, thick ice over flowing water or dry channels during winter. Booms have been used to trap or collect frazil ice at the bridge site. Once natural ice cover has progressed across the channel thick enough to bear the weight of personnel and light equipment, existing snow cover is removed to accelerate ice growth at the bottom of the ice sheet. Variation exists in whether snow is removed or just compacted. Snow removal is recommended on upstream and downstream sides of the road for a distance of 23-30 meters (75-100 feet) as well as on the road itself. Subsequent to ice growth in response to snow removal, surface flooding is recommended to build up ice thickness on the road surface. Some references indicate initiating this flooding stage immediately after deep snow removal. Removal of shallow snow cover is often ignored prior to the flooding process. Lateral barriers of snow, logs or boards are used to contain floodwater on the road surface. Water should be applied by layering, allowing full freezing of previous water applications before the next. Conflicting recommendations exist as to whether brush or logs should be incorporated into the ice. One study did document the increase in ice strength after incorporating geo-grid material during the ice buildup process. A regular regime of ice drilling and monitoring of ice thickness is recommended. Snow packing is commonly used to grade approaches to the ice bridge. Steep exit grades may result in trucks losing power and rolling backward onto the ice. The number of freezing degree-days possible in a region places a physical limit to ice thickness under conditions of no snow cover. Therefore, if one does not wish to freeze the whole water column or the streambed, one should have enough water depth and winter flow to allow the desired unfrozen water depth to be maintained. One may also need to allow for deflection (elastic sagging of large ice sheets under vertical load) of the ice bridge, and for the increased draft of floating ice bridges under loads due to surface ice buildup and traffic. While much anecdotal experience and some documentation exists for the complete freezing of natural cross-sections of small streams (Haugen et.al., 1982), little documentation of complete water-column freezing under ice bridges was found. An interagency correspondence was found (Ott, 1990) discussing the “grounding” of an ice-bridge and subsequent overflow on an interior Alaska river.

The final, but motivating focus of this review, is also the realm of sparsest data and greatest uncertainty. While there is evidence of heightened awareness of possible interactions between ice and fish, there are few data sets and little documentation of the occurrence, direction, or magnitude of such impacts either under natural ice-cover regimes or those affected by humans. Logic and theory may allow the forecasting of physical and hydraulic effects of ice cover occurrence, thickness and duration on cross-sectional or longitudinal channel form and water flow characteristics. However, the direct or secondary effects on individual fish survival (various life stages), fish behavior, or population dynamics rests on more speculative grounds. Two main dimensions of this problem are (1) the logistic and technical difficulties of conducting such studies and (2) the lack of communication between hydrologists (broadly defined) and biologists (broadly defined). However, there are encouraging signs of advances on both fronts including the new generation of digital sensors and recorders, and the increase in multi-disciplinary research and management teams and “cross-trained” graduate students. Citations by Chacho(1992), Scrimgeour et.al.(1992), Calkins (1989, 1990), Prowse (1992) and Rundquist and Baldrige (1990), as well as discussion by members of the SCC, point out some areas of concern and convey some anecdotal and general observations. Fish habitat requirements differ from species to species and change from one life stage to another. For example, the range of water velocities that a fish can use increases with the fish size and swimming capabilities. In addition to water flowing over the surface of a streambed, groundwater also can be important. In winter, living space can be restricted due to ice cover and low stream flow. Cold water temperatures and limited oxygen supply in conjunction with limited space can stress fish. Upwelling groundwater is usually warmer than surface water during winter months and may contain oxygen (the source of which seems enigmatic). These areas are also less likely to freeze and therefore may be important for incubating embryos as well as overwintering resident species or juvenile anadromous species requiring more than one year in freshwater. Warmer water temperatures may also be significant for Fall spawners in terms of physiological thresholds or behavioral triggers based on thermal time (cumulative degree-days or degree-hours).

Research needs specific to ice thickness and ice bridges include: (1) measurement of ice thickness growth and hydraulic conditions upstream, downstream and immediately under ice bridges; (2) the use of models to explore the reduction in habitat space associated with ice bridge construction under various conditions of original water depth, freezing degree-days, and patterns of snow removal and surface flooding; (3) monitoring the annual variation in the occurrence of leads in important fish streams in winter. Research needs related to ice and ice-bridge effects on fish and fish habitat are found under the literature reviews on fish use of upwellings and winter use of glacial streams.

REFERENCES

Note: All library call numbers are from the University of Alaska Fairbanks libraries: “Geophy. Inst.” refers to the Geophysical Institute Library on UAF campus, “Alaska” refers to the Alaska Collection in the UAF Rasmuson Library, “Doc” refers to the government document collection in the Rasmuson Library, and all others refer to the general collection in the Rasmuson Library.

Abele, G. 1990. Snow roads and runways. US Army Corps of Engineers, Cold Regions Research & Engineering Laboratory, Monograph 90-3.

Snow characteristics are discussed. These characteristics include snow strength, grain size, effects of time and temperature on snow strength, interrelationship between snow properties, and behavior under load. Methods of measuring snow strength, and snow pavement construction techniques are described.

Adam, Kenneth M. 1978. Building and operating winter roads in Canada and Alaska. Published under contract for Environment Division, Northern Environmental Protection and Renewable Resources Branch, Department of Indian and Northern Affairs, Ottawa, Canada.

This is a useful reference that includes sections on building and operating winter roads, planning winter roads, and experience with winter roads. Within the section on building and operating winter roads there is a chapter on ice bridges that reviews the general considerations of site selection, construction, operation, maintenance, and closure. Appendixes include maps of permafrost, date of cumulative freezing degree-days > 550 F, date of snow depth > 4 inches, and general vegetation cover for Canada. Appendixes also include guidelines on the bearing capacity of ice, descriptions of testing equipment, and recommendations for safety. (Alaska TE 175 A33 1983, Microform, in French; English version was borrowed from ABR, Inc. for review.)

Alaska Dept. of Fish & Game. (undated). Tips on the weight-bearing capacity of ice. One page hand-out obtained from CRREL files, Fort. Wainwright , AK

Contains 10 guidelines for travel on ice covered waters, including maximum loads for given ice thickness:

Minimum Ice Thickness (inches)	Max. Load
02	1 man on foot
03	Group, single file
08	Automobile (2 tons GVW)
12	Heavy truck
25	45 tons
36	110 tons

Aldrich, J. W. 1981. A stochastic analysis of some existing ice thickness data. The Northern Engineer 13(1):4-10.

The author utilizes data reported by CRREL on average date ice was first observed, the ice sheet was continuous across the water body, the earliest maximum ice thickness occurred, water was first observed within the ice sheet, and the water body was ice free, to test three distributions , the Gumbel I, the Log Normal, and the Log Pearson Type III. He found the Pearson Type III distribution to fit the data best. He then presents tables of recurrence intervals for ice thickness for selected Alaskan and Canadian rivers and lakes.

Allen, W.T.R. 1977. Freeze-up, break-up and ice thickness in Canada. Fisheries and Environment Canada. Report CLI-1-77.

This is a valuable compilation of river ice data across Canada from 1974 and earlier; in some cases dating back to the turn of the century. May be of limited utility for specifics of interior Alaska rivers except as comparative opportunities and as a base for general data analysis. (Geophy.Inst. GB 2429 A44 1977)

Anonymous.1986. Squad leaders guide for constructing ice bridges. Dept. of the Army, 6th Infantry Division (Light) Pamphlet No. 350-11.

This pamphlet briefly describes how to (1) conduct a site reconnaissance for locating an ice bridge; (2) construct an ice bridge profile; (3) classify a bridge based on ice thickness, color, and strength; (4) strengthen a bridge; (5) maintain a bridge; and (6) cross an ice bridge.

Anonymous. (undated). Construction of an ice bridge across the Imjin river in Korea. (obtained from CRREL files, Fort. Wainwright , AK)

Five pages of typed notes describing the ice bridge construction.

Anonymous. (undated). Ice bridge construction : 1978-1979. (obtained from CRREL files, Fort. Wainwright , AK)

One and one-half pages of typed notes describing ice bridge construction on the Tanana River, Alaska.

Anonymous. (date unknown). Ice bridge construction briefing outline. (obtained from CRREL files, Fort. Wainwright , AK)

Five typed pages of ice bridge construction guidelines.

Anonymous. (undated). Workshop on ice-bridging. Notes. (obtained from CRREL files, Fort. Wainwright , AK)

Four typed pages of notes.

Arctic Environmental Information and Data Center. 1984a. Assessment of the effects of the proposed Susitna Hydroelectric Project on instream temperature and fishery resources in the Watana to Talkeetna reach. Final Report for Harza-Ebasco for the Alaska Power Authority. Volume 1.

This report presents the results of weekly instream temperature simulations for the Susitna River comparing Watana-only and Watana/Devil Canyon project configurations with natural condition temperature simulations. These simulations were run using historic hydrometeorological data covering four summers and five winters. The effect of these temperatures on anadromous fish species is assessed by comparison with life stage-specific temperature tolerance criteria established from the literature, field studies, and lab studies. The model SNTEMP was used to simulate instream temperatures at various locations. Simulated stream temperatures were then used as input to the ICECAL model used to calculate ice conditions in the river. While this report notes the need for information on ice effects on fish resources it foresee that work as subject of some future report. (Alaska SH 177 T45 A87 1984 v.1)

Arctic Environmental Information and Data Center. 1984b. Assessment of the effects of the proposed Susitna Hydroelectric Project on instream temperature and fishery resources in the Watana to Talkeetna reach. Final Report for Harza-Ebasco for the Alaska Power Authority. Volume 2. APPENDICES A-H.

Contains details of simulated weekly water temperatures at selected middle Susitna River locations, isotherm plots of temperature simulation results, stream width functions, observed vs. predicted air temperatures for water years 1981-1983, observed vertical air temperature profiles,

basin weekly wind speeds, residual errors, and temperature histories at selected locations in relation to the five Pacific salmon life phase activities for all simulation scenarios. (Alaska SH 177 T45 A87 1984 v.2)

Ashton, G.D. 1980. Freshwater ice growth, motion, and decay. Pages 261-304 in S.C. Colbeck , editor. Dynamics of Snow and Ice masses. Academic Press, NY

This chapter in Colbeck's edited volume is an overview of the general processes involved in river ice phenomenon. Review the energy balance of ice growth, deals with frazil ice formation, floes, breakup and ice jams. (Geophy. Inst. GB 2403.2 D95).

Ashton, G.D. 1990. Ice Effects on Hydraulics and Fish Habitat. Cold Regions Research & Engineering Laboratory Special Report 90-8, U.S. Army, CRREL, Hanover, New Hampshire.

One of the only reports on ice that mentions possible effects on fish habitat. However, there is actually little discussion of fish habitat per se, beyond the opening statement that since ice cover affects water velocities and depths, and water velocities and depths are attributes of fish habitat, then ice cover must affect fish habitat. The rest of the report presents a mathematical analysis of the effect of ice cover on depth of flow, stage, and velocity. Other effects are briefly discussed qualitatively. Application is made to the Platte River in Nebraska. (Alaska GB 2401 U533 no. 90-8).

Ashton, G.D. and J.F. Kennedy. 1970. Temperature and flow conditions during the formation of river ice. IAHR Ice Symposium, Reykjavik, Iceland, 2.4.

This is a detailed investigation of the velocities and temperatures characteristic of flow in rivers during the onset and occurrence of ice covers. Vertical and lateral temperature and velocity distributions, and ice thickness and configuration were measured in an Iowa river at frequent intervals during the period of ice cover. (Alaska TC 163 I5 1970).

Barthelemy, J.L. 1975. Snow-road construction - a summary of technology from past to present. Tech. Report R 831, Civil Engineering Lab., Naval Construction Battalion Center, Port Hueneme, California.

Mainly reviews snow-road construction techniques and is not particularly useful with respect to ice-bridge construction. Discusses two methods: layered-compaction and depth-processing. This report documents the evolution of vehicle road systems on snow and presents a synoptic overview, summarizing all aspects of snow-road technology.

Bates, R.E. and D Saboe. 1968. Ice conditions and prediction of freeze-over on streams in the vicinity of Ft. Greely, Alaska. Cold Regions Research & Engineering Laboratory Special Report 121 Part *I*, U.S. Army, CRREL, Hanover, New Hampshire.

Descriptions of the events leading to freeze-over of the Delta River, near Ft. Greely, including ground and aerial photos and diagrams showing the changes in river ice conditions, are given. Curves that can be used to forecast ice formation at three river locations near Ft. Greely, Alaska, were developed. (Alaska GB 2401 U533 no. 121).

Bergman, G. R. and B. V. Proskuriakov. 1954. Ice Crossings. Original publication in Russian, Moscow 1943. translated by SIPRE Bibliography Project, Library of Congress for U.S. Army, Corps of Engineers.

Translated from the Russian book (chapter 1,2 &5 with Appendices 1-6,&8). Includes introduction to problem of determining safe loads on an ice cover and construction of ice crossings. Briefly describes conditions of water bodies and properties of ice and snow, and discusses “Natural Ice Bridges” and reinforcement of the ice cover. Appendices are tabulated values of math functions used in formulas in text and table for calculating the supporting power of an ice cover. (note: first authors name may be spelled Bregman). (Alaska TE 247 B74 1954).

Bilello, M. A. 1964. Method for predicting river and lake ice formation. Journal of Applied Meteorology 3(1):38-44.

Two sets of curves are developed which can be used to forecast the dates of first appearance of ice in the Fall, and ice formation from shore to shore on the Mackenzie River at Fort Good Hope, Canada. Similar curves could be developed for other locations based on relationships between mean daily air temperature and previously observed dates of ice formation. To apply the curves, an adjusted temperature record is maintained starting in early summer. Subsequently, this daily-adjusted temperature is applied to the family of curves to provide a day-to-day forecast of the date of ice formation.

Bilello, M. A. 1968. Ice conditions and prediction of freeze-over on streams in the vicinity of Ft. Greely, Alaska. Cold Regions Research & Engineering Laboratory Special Report 121 Part II, U.S. Army, CRREL, Hanover, New Hampshire.

Develops a site specific temperature accounting method and curves to reproduce observed freeze-over dates on the Delta River near Ft. Greely, Alaska. (Alaska GB 2401 U533 no. 121).

Bilello, M. A. 1980. Maximum thickness and subsequent decay of lake, river and fast sea ice in Canada and Alaska. Cold Regions Research & Engineering Laboratory Report 80-6, U.S. Army, CRREL, Hanover, New Hampshire.

This report analyzes weekly ice thickness data collected over a period of 10-15 years with particular attention to ice decay and its relation to accumulated thawing degree-days . Ice decay curves are presented for various locations. (Alaska GB 2401 U53 no. 80-6).

Bilello, M. A. and V.J. Lunardini. 1961,1964,1966,1969,1971,1972,1975,1991,1996. Icethickness observations, North American Arctic and Subarctic, 1974-75, 1975-76 and 1976-77. Cold Regions Research & Engineering Laboratory Special Report 43 part *s I-IX*, U.S. Army, CRREL, Hanover, New Hampshire.

Most detailed record of ice thickness data for Canada and Alaska. First 2 or 3 reports have only sparse data for Alaska, but subsequent reports have many more Alaskan river measurement sites. Measurements reported are maximum ice thickness for the season, weekly ice thickness and snow depth measurements at select cross-sections throughout the winter ice cover period. Generally, the least end-of-season ice thickness values range from near 60 cm. in the southern part of the state (excluding the Aleutian Chain and the southeast panhandle regions) to 170 cm on the west coast. The range of maximum ice thickness in Alaska ranges from 100 cm. in the southern part to 180 cm. on the North Slope. (Alaska GB 2401 U533 no. 43 pt. 1-9).

Blinn, C. 1998. Ice bridges. Forest management practices fact sheet: crossing options. Series #*4*, Univ. of Minnesota Extension Service, FS-7004-GO.

Describes ice bridges as used for temporary use in streams with low flow rates, thick ice, or dry channels during winter. Bridges made by pushing and packing snow into streams and applying water to freeze the structures solid. He suggests state permits may be required; choose a period when night temperatures below 0 F.; choose a site that has low flow, is completely frozen or dry, or has a layer of ice on top of flowing water; approaches should be level or nearly level. Recommends against adding brush or other vegetation to the snow-ice-water mix, claiming it will weaken structure and can dam the stream when the bridge melts. Build up ice for level approach and load-bearing capacity.

Blinn, C. R., R. Dahlman, L. Hislop, and M. A. Thompson. 1998. Temporary stream and wetland crossing options for forest management. USDA, Forest Service, North Central Res. Sta., General Technical Rpt. NC-202, 127 pp.

A comprehensive general review of the topic of temporary stream crossings. Only one page and one reference cited with regards to ice bridges. A good literature review for non-winter and non-ice bridge concerns. (Docs. [microform] A13. 88: NC-202).

Bouzoun, John. 1985. Review of Ice Bridging – Appendix C. Disposition Form, Cold Regions Research & Engineering Laboratory, AK.

Contains notes and suggestions for changes in Appendix C of Ice Engineering manual based on personal observations and experience of the reviewer.

Calkins, D. J. 1979. Accelerated ice growth in rivers. Cold Regions Research & Engineering Laboratory Report 79-14, U.S. Army, CRREL, Hanover, New Hampshire.

Reports on and calculates the effect of frazil slush beneath the ice cover on increasing the solid ice growth rates by as much as 50–90 %. (Alaska GB 2401 U53 no. 79-14).

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

This review, citing 44 references, concluded that a lack of continuous physical, chemical and biological measurements throughout the ice-covered season was a common deficiency of the studies. He found that the interaction of the ice cover with other physical processes in the stream was rarely addressed. All species of fry were found at depths less than 40 cm and at velocities of 10 cm/s or less. Juveniles of all species were found at velocities of less than 15 cm/s. Information in this citation overlaps with information in the next citation. (Alaska GB 2401 U533 no. 89-34).

Calkins, D. J. 1990. Winter habitats of Atlantic salmon and brook trout in small ice-covered streams. Pages 113-126 in Proceedings IAHR Symposium on Ice 1990, vol. 3. Espoo, Finland.

This is a review of winter habitat studies conducted in ice-covered streams for two species of salmonids gives some general information on substrate conditions, flow velocities and depths. Brook trout were usually found at depths of <40 cm and at focal velocities of 5 cm/s or less. Juveniles were found at velocities < 17 cm/s but at slightly greater depths. Atlantic salmon young-of-the-year and parr (age 1) were found in the substrate. The velocities at 0.6 depth in 40-45 cm of water were 40-45 cm/s. The size of substrate used by all salmonids is a function of fish size, with both preferring a combination of sand, gravel and rubble. A lack of continuous physical, chemical and biological measurements throughout the ice-covered season was a common deficiency of the studies reviewed. Some duplication of information exists between this citation and the previous one. This review cited 34 references. (Geophy. Inst. GB 2401.2 I57 1990 vol. 3)

Carlson, R. F. 1981. Ice formation on rivers and lakes. The Northern Engineer 13(4): 4-9

This is a good overview of the energy balance components of a river reach or lake and the linkage to the ice formation and ice growth processes.

Chacho, E.W. ,Jr., 1993. Rapporteur report: Northern research basins workshop #4 on Environmental effects of river ice. Pages 701-704 in T. D. Prowse, C.S.L. Ommanney, and K. Ulmer, editors, Proceedings of the Ninth International Northern Research Basins Symposium/Workshop , Yukon Territory to Inuvik, NWT. National Hydrology Research Institute, NHRI Symposium Series no. 10.

This report summarizes a workshop on the environmental effects of river ice. It recognizes that while the effects of the growth and breakup of river ice should be a major event in the physical and biological environment of river systems, only recently has its ecological significance been recognized. Accordingly, there are few studies and little relevant data. This workshop provided a framework for considering these effects. Some examples of significant effects include river channels rerouted around ice jams, scour holes developed beneath ice jams, buried contaminants released from a scoured streambed and subsequently transported with sediment and meander bend cutoffs. The difficulty of collecting relevant data during winter and the historical lack of interaction and communication between biologists and hydrologists were cited as problems that should be addressed. (Geophy. Inst. GB 2401 N572 vol. 2).

Chacho, E., W. Traub, and J. Gosink. 1987. Frazil ice characteristics on the Tanana River as related to siting ice bridges. Technical Note, U.S. Army Cold Regions Research and Engineering Laboratory, Ft. Wainwright, Alaska. (An informal, unofficial memorandum for limited distribution only).

Case study of recon information on frazil ice formation relative to the Goose Island ice bridge on the Tanana river. Discusses the role of frazil ice flows and jams in initiating early ice cover as a base for ice bridge construction. Discusses use of ice booms to create frazil dams for ice bridge formation.

Dean, Jr., Arnold M. (undated). Evaluation of ice-covered water crossings. U.S. Army, Cold Regions Research & Engineering Laboratory, Hanover, New Hampshire. Pages 443-453 of unknown document. No detailed citation information available. (Obtained from CRREL files, Fort. Wainwright , AK)

Makes reference to using radar unit to obtain ice thickness data for an ice bridge on the Tanana river near Fairbanks, AK. Makes note of difficulties encountered and mentions several pieces of equipment lost through the ice.

Delaney, A. J., S. A. Arcone, and E. F. Chacho, Jr. 1990. Winter Short-pulse radar studies on the Tanana River, Alaska. Arctic 43(3):244-250.

Subsurface profiles were obtained during airborne and surface short-pulse radar surveys along a winter roadway over the Tanana River near Fairbanks, AK. The roadway crossed ice-covered channels and intervening frozen channel bars. This paper, while indicating the utility in ice-thickness profiling, concentrated on locating unfrozen channels and measuring the depth of frost penetration beneath bars in a braided river.

DenHartog, S.L., T. McFadden, and L. Crook. 1976. Failure of an ice bridge. Cold Regions Research & Engineering Laboratory Report 76-29, U.S. Army, CRREL, Hanover, New Hampshire.

Reports on experiment where a heavily loaded truck was used to make successive passes over two ice bridges in order to verify current theoretical equations on ice bearing capacity. Breakthrough occurred on one bridge with a vehicle weight of 53,630 lb (24,327 kg). The ice thickness as 17.5 in. (44.5 cm). This one test was in good agreement with the theoretical equations. (Alaska GB 2401 U53 no. 76-29).

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

Reports the results of laboratory studies on the influence of turbulence and water temperature on frazil ice formation. The rate and the quantity of frazil ice formed in a specified volume of supercooled water increase with both increasing turbulence intensity and decreasing water temperature. Larger particle sizes were found with lower supercooled water temperatures while particle size decreased with increasing turbulence. (Alaska GB 2401 U53 no.84-18).

Ettema, R. and Hung-Pin Huang. 1990. Ice formation in frequently transited navigation channels. Cold Regions Research & Engineering Laboratory Special Report 90-40, U.S. Army, CRREL, Hanover, New Hampshire.

Deals with the problem of greater ice growth in channels where ice is frequently broken by ships. Reviews general math and physics of river ice growth. Reports on experiments in flumes and on rivers to minimize the re-growth of ice on frequently traveled river routes by careful scheduling of ships. Only a convoy strategy seemed to mitigate the re-freezing problem. (Alaska GB 2401 U533 no. 90-40).

Fox, J. D. 1992. Incorporation freeze-thaw calculations into a water balance model. Water Resources Research 28(9):2229-2224.

Combines a soil water balance accounting model with the St. Paul (MN) equations (layered Stephan equations) to predict soil freezing and thawing based on cumulative freezing degree-days and accounting for variable snow depth throughout the winter. Presents a sensitivity analysis of the model and tests against field measurements.

Frey, Paul J. 1969. Ecological changes in the Chena river. Federal Water Quality Administration, U.S. Dept. of Interior, Northwest Region, Alaska Water Lab., College, Alaska

Describes and documents changes in the Chena river physical, chemical and biological conditions in response to 10-15 years of change in human population and activity in the watershed. (Geophy.Inst., GB 1227 C48 F7).

Frey, Paul J., Ernst W. Mueller, Edward C. Berry. 1970. The Chena River, A study of a subarctic stream. Federal Water Quality Administration, U.S. Dept. of Interior Northwest Region, Alaska Water Lab, Project No. 1610—10/70, College, Alaska

Classic study of the Chena river limnology including documentation of low DO in winter and high Coliform bacteria counts in the lower reaches of the river. Includes weekly temperature data at 4 stations on the river. Also includes water chemistry data and stream benthic survey data. (Geophy.Inst., GB 1227 C48 F7).

Gerard. R. 1989. Ice formation on northern rivers: summary of presentation. Page 23 in Mackay, W.C., editor, Northern lakes and rivers. Occasional Publ. no. 22, The Boreal Institute for Northern Studies.

Brief one page summary of presentation. Makes interesting discussion of frazil ice, ice dam effects, and open water polynas. Relates speculation that fish could suffocate on frazil ice crystals. Also mentions that the number of natural polynas (areas that stay open during winter) is a function of island frequency (0.2 x island frequency). (Alaska GB 1629 N67 1989).

Gerding, Richard L. 1990. U.S. Dept. of the Army Memorandum for Director of Engineering and Housing, ATTN: Bill Peake. SUBJECT: Arctic Warrior 91 Ice Bridges – Tanana river and tributaries. (Obtained from CRREL files, Fort. Wainwright , AK).

Memo describes results of meeting with ADF&G regarding ice bridges, permits, problems of overflow and upwellings at bridge sites, as well as concerns about retrieving a bulldozer.

Ginzburg, B.M. 1969. Probability characteristics of the freeze-up and break-up dates of rivers. Soviet Hydrology: Selected Papers, no.1:64-78.

This paper reports a study of the probability distribution of ice phenomenon for the former USSR. Twenty to seventy years of observational data were available from a large number of gaging stations across European and Asiatic USSR. Small-scale maps of the former USSR with lines of equal probability of ice appearance, beginning of freeze-up, and beginning of ice run are presented. The statistical distributions found most useful were of the Pearson type III, binomial. A discussion of the geographic variation of parameters is included.

Gold, L.W. 1971. Use of ice covers for transportation. Canadian Geotech. J. 8:170-181.

Reports observations on the failure and use of freshwater ice covers for vehicular traffic. Experience in the construction and use of ice roads and parking areas in included. The study suggests that good quality ice covers can support loads 250 h^2 pounds where h is the ice thickness in inches. (volume missing from UAF Rasmuson Library).

Green, G. M. and S.I. Outcalt. 1985. A simulation model of river ice cover thermodynamics. Cold Regions Science and Technology 10:251-262.

A numerical model of ice growth and decay along the international section of the St. Lawrence River for winter 1980-81. The model calculates a surface equilibrium surface temperature at the air-ice interface using surface characteristics and meteorological data. At the lower boundary, an empirical algorithm simulates turbulent transfer of heat from the water. Within the ice an implicit numerical solution to the general heat diffusion equation is used. Five river sites were simulated. The model represented ice growth rates well but produced decay rates slower than those observed. During the growth period, the model was more sensitive to the values assigned to ice properties than it was to the error range in the meteorological variables. During breakup, the most sensitive boundary variable was water temperature.

Gow, A. J. and J. W. Govoni. 1983. Ice growth on Post Pond, 1973-1982. Cold Regions Research & Engineering Laboratory Report 83-4, U.S. Army, CRREL, Hanover, New Hampshire.

Describes the analysis of ice thickness measurements on Post Pond, New Hampshire and results of using Stefan formula to calculate ice growth and decay. Includes a good description of the progression of events at this one site and the utility of freezing and thawing degree-day methods. (Alaska GB 2401 U53 no. 83-4).

Gulliver, J. S., and H. G. Stefan. 1986. Wind function for a sheltered stream. J. Environ. Engineering 112(2):1-14.

Tests various empirical wind functions to be used in air-water transfers of heat and mass. These wind functions while derived for use primarily over large lakes were fitted to data for a sheltered stream. All functions performed well but one suggested as best in terms of simplicity.

Haggag, M. R. I. 1976. Hydraulics of ice covered channels. Master of Applied Science thesis, University of Windsor, Ontario, Canada.

Primarily a theoretical and laboratory study aimed at the problem of estimating the composite roughness of a channel with an ice cover and subsequently the discharge. (Alaska GB 1398.2 H34 1976a, [microform]).

Harza-Ebasco Susitna Joint Venture. 1984. Instream ice, calibration of computer model. Susitna hydroelectric project, document no. 1122, Alaska Power Authority.

Reports on the calibration of the ICECAL model for the Susitna River reach from the confluence at Talkeetna to Gold Creek. The model was only used for freeze-up calculations and not for break-up. A brief description of the model is given followed by a description of the data available for the calibration task. The model would require "post-project" simulated stream temperature data from the SNTEMP model operated by AEIDC, for post-project ice effects. This calibration is for pre-project conditions. Computed ice-free water surface profiles within 0.5 ft of observed values for flow rates of 3000 and 9700 cfs were realized. Maximum water/ice elevations were generally within ± 2 ft. of observed values although there were some locations where differences of 3-8 ft. resulted. Computed ice thickness agreed very well with observed following the 1982 freeze-up. Observed thickness were considerably higher than calculated thickness following the 1983 freeze-up. Mixed results were also found for simulations of the leading edge progression of ice, with better results in 1982 than in 1983. (Alaska TK 1424 A4 S834 1984).

Harza-Ebasco Susitna Joint Venture. 1984. Instream ice simulation study. Susitna hydroelectric project, final report, document no. 1986, Alaska Power Authority.

This report presents the results of the instream ice simulation studies for the Susitna Hydroelectric Project. The objective of these studies was to determine the effect of the proposed

Watana and Devil Canyon Dams on river ice processes and the corresponding water surface elevations during the winter season in the Susitna River downstream of the dams. The studies are limited to the middle reach of the Susitna River (upstream from the confluence with the Chulitna River). The study results are based on the use of 3 models : a Dynamic Reservoir Simulation Model (DYRESM), a stream temperature simulation model, (SNTEMP), which computes longitudinal stream temperature profiles on a weekly basis, and a model for the simulation of instream hydraulic and ice conditions (ICECAL). Exhibits A through T are provide the graphical portrayal of results for both natural conditions, and post-project conditions. (Alaska GB 1398.4 A4 I57 1984).

Harza-Ebasco Susitna Joint Venture. 1985. Instream ice simulations [microform]: supplementary studies for middle Susitna River. Susitna hydroelectric project, document no. 2845, Alaska Power Authority.

This is a follow-up study of the "Instream Ice Simulation Study", to report the results of supplementary simulations to evaluate the sensitivity of the ice processes to alternative instream flow requirements, alternative operating policies for multi-level power intakes, alternative low levels for Watana power intake, and alternative levels for Devil Canyon cone valves. (Alaska TC 425 S9 I584 1985a Microform).

Harza-Ebasco Susitna Joint Venture. 1985. Instream ice simulations [microform]:supplementary studies for middle Susitna River. Susitna hydroelectric project, document no. 3524, Alaska Power Authority.

This is a follow-up study of the "Instream Ice Simulation Study", to report the results of supplementary simulations to evaluate the sensitivity of the ice processes to a revised three-stage construction of the project, alternative instream flow requirements, alternative operating policies for multi-level power intakes, alternative low levels for Watana power intake, and alternative levels for Devil Canyon outlet works. (Alaska TC 425 S9 I585 1985a Microform).

Haugen, R.K., C.W. Slaughter, K. E. Howe, and S.L. Dingman. 1982. Hydrology and climatology of the Caribou-Poker Creeks research watershed, Alaska. Cold Regions Research & Engineering Laboratory Report 82-26, U.S. Army, CRREL, Hanover, New Hampshire.

This general report on the hydrology and climatology of the Caribou-Poker Creeks watershed area does include interesting observations of the lack of flow in Caribou Creek during the period from 11 Dec. 1975 to 4 April 1976. The conditions thought to cause the stream to completely freeze that winter were a combination of low precipitation the preceding fall and extremely low temperatures. Heavy aufeis formed downstream from the gaging station that winter. (Alaska GB 2401 U53 no. 82-26).

Haynes, F. Donald, Charles M. Collins, and Walter W. Olson. 1992. Bearing capacity tests on ice reinforced with geogrid. Cold Regions Research & Engineering Laboratory Special Report 92-28, U.S. Army, CRREL, Hanover, New Hampshire.

Laboratory tests were conducted on floating freshwater ice sheets, reinforced with a high-strength polymeric mesh (Geogrid). Geogrid reinforced ice sheets increased the bearing capacity of thin ice(49 mm) up to 38% and of thicker ice(96 mm) about 10-15 %. In a field test, the Geogrid reinforced ice also reduced deflection of the ice sheet under load. (Alaska GB 24012 U533 no. 92-28).

Hoffman, C.R. 1967. Ice construction – methods of surface flooding. Technical Report R-511, Naval Facilities Engineering Command, U.S. Naval Civil Eng. Lab., Port Hueneme, CA.

Two surface-flooding techniques for improving natural ice areas have been developed by the U.S. Naval Civil Engineering Laboratory. Confined flooding, in which the flood is contained by natural barriers or man-made dikes, is used principally for filling and leveling ice areas where deflection of the natural ice is not a problem. Free flooding, in which the outward flow of water is governed by natural forces such as gravity and freezing of the flood perimeter, is generally used for the accelerated buildup of thinner natural ice areas where deflection is encountered. Adequate method have been developed for surface flooding a relatively small area with a maximum dimension of 1,200 feet and for increasing ice thickness by as much as 5 feet. Continued investigation is required for the multi-pump flooding of areas 5,000 feet long, the flooding of deep snow, and the construction of ice roadways through tidal and pressure-ice areas.

Hough, A., J. King, and A. Bailey. Report on the use of snowmaking machine for ice bridge construction. U.S. Army, 47th Engineer Company, Fort Wainwright, AK. (Obtained from CRREL files, Fort. Wainwright , AK)

This reports on tests of a snowmaking machine as an alternative to flooding in ice bridge construction. Results indicated both snowmaking and spraying results in faster freezing than flooding and that although the ice created was air-entrained, it had higher compression strength.

Irons, J.G. and M. W. Oswood. 1992 Seasonal temperature patterns in an arctic and two subarctic headwater streams. Hydrobiologia 237:147-157.

The thermal regime of three Alaska streams were studied: Monument Creek and Little Poker Creek, in interior Alaska, and Imnavait Creek in the arctic tundra. Although it is about 450 km north of the other streams, the tundra steam accumulated more degree-days, had higher maximum and mean temperatures, greater daily temperature amplitudes, and steeper slopes of vernal and autumnal temperature rises and declines. The absence of a canopy of riparian plants, channel morphology, and continuous sunlight during summer accounted for these results. Useful background data from two subarctic Alaskan streams.

Johnson, Phil. 1980. A guide for operating cars and light trucks on a floating ice sheet.: using thin plate analytical solutions. Report prepared by Phil Johnson Engineering, Fairbanks, AK. (Obtained from CRREL files, Fort. Wainwright , AK)

The author used the "Thin Plate" method to investigate the reaction of floating ice sheets to cars and light trucks. He developed a general solution and technique that makes it possible to predict the reaction of an ice sheet to any car or light truck without resorting to a computer solution. He discusses factors other than tensile stress that affect the behavior of ice under load.

Johnson, Phil. 1980. An ice thickness-tensile stress relationship for load-bearing ice. Cold Regions Research & Engineering Laboratory Special Report 80-*9*, U.S. Army, CRREL, Hanover, New Hampshire.

The "bearing capacity" of a floating ice sheet is of considerable interest. The pattern of ice thickness versus tensile stress for a fixed load and fixed ice properties was examined and showed some constant relationships. It proved possible to completely describe the ice thickness-tensile stress pattern in terms of a single number. When the load was changed by increasing the payload but not altering the geometry of the load pattern, other relationships were found that described the tensile stress in the ice sheet for any combination of payload and ice thickness. This provides a simple method of finding tensile stress in the ice that can be used in the field.

Joslin, S. J. 1999. Tanana River ice formation study: Surprise Side timber sale. Delta Junction, Alaska, October 1998 to March 1999. (unpublished report, State of Alaska, Division of Forestry).

A brief report with photographs documenting the rise in river water and ice between October 1998 and March 1999 on the Tanana River between the Delta and Little Delta Rivers.

Kerr, A. D. 1975. The bearing capacity of floating ice plates subjected to static or quasi static loads: a critical survey. US Army Corps of Engineers, Cold Regions Research & Engineering Laboratory, Research Report 333. 43 pp.

This report contains a critical survey of the literature on the bearing capacity of floating ice plates. It consists of a discussion of general questions, a critical survey of analytical attempts to determine the bearing capacity of floating ice plates, and a survey of field and laboratory tests on floating ice plates and their relation to the analytical results. The paper concluded with a systematic summary of the results, a discussion of observed shortcomings, and suggestions for needed investigations.

Kivisild, H. R., G. D. Rose, and D. M. Masterson. 1975. Salvage of heavy construction equipment by a floating ice bridge. Can. Geotech. J., 12:58-69.

Describes the construction and operational results of an ice-bridge built to access a grounded barge carrying a load of heavy equipment for the James Bay Project. Following completion of the 100 ft wide and 74 inch thick bridge, the ice bridge was instrumented and tested prior to and during the unloading process. Parameters measured were thickness, width, temperature, ice soundness, and deflections. Loads of 70 tons and heavy trucks were removed with no problem. Deflections were very small. Ice was built up by flooding and freezing in layers not greater than 1.5 in. Fifty-eight inches of ice was built up in 2 week.

Lal, A., M. Wasantha, and H. T. Shen. 1993. A mathematical model for river ice processes. Cold Regions Research & Engineering Laboratory Report 93-4, U.S. Army, CRREL, Hanover, New Hampshire.

This publication describes a detailed mathematical model of river ice growth and decay applicable to composite ice covers consisting of snow, ice and frazil layers. The model has been applied to the St. Lawrence River and the Ohio River system, with simulated results comparing favorably with field observations. It is a one-dimensional model called RICE. While somewhat obtuse for the lay person, this publication does include a nice flow-chart of river ice processes in its brief introduction. (Alaska GB 2401 U53 no. 93-4).

Lindgren, S. and J. Neumann. 1982. Crossings of ice-bound sea surfaces in history. Climatic Change 4:71-97.

Seven documented cases of the use made of ice-bound sea areas in winter for the purposes of warfare are reviewed. These crossings took place in 1495, 1577, 1581, 1658, 1809, 1940, and 1943. The early crossings took place in the Gulf of Finland and the Gulf of Bothnia and were thought to have been fairly common during what is called “the little ice age”.

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

Detailed measurements of water temperature and velocity were made in the Liard River prior to and during breakup. Comparison of four different techniques for calculating heat transfer coefficients showed that it is essential to consider ice roughness and to measure water temperature to a high degree of accuracy. The water temperatures had large spatial and temporal variations. The highest temperatures and heat fluxes tended to occur in the high velocity sections of the channel which had a thin ice cover. Heat transfer coefficients calculated from the Colburn analogy method were in closest agreement to those using a temperature decay approach. A standard empirical technique derived from laboratory data seriously under-predicted the heat flux.

McFadden, T., and M. Stallion. 1975. 1974 ice break-up on the Chena river. Cold Regions Research & Engineering Laboratory Special Report 241. (ADA018352). U.S. Army, CRREL, Hanover, New Hampshire.

This report documents breakup of the Chena River in the spring of 1974. Ice thickness was measured at specific locations on the Chena River, from its confluence with the Tanana River upstream to the first bridge on the Chena Hot Springs Road. Average ice thicknesses were computed as well as average ice volumes per mile of river length. Water temperatures and velocities were measured at different locations on the river. Comparisons to other years’ breakups were made and it was concluded that the 1974 breakup was extremely mild. (Alaska GB 2401 U533 no. 241).

Melloh, R. A. 1990. Analysis of winter low-flow rates in New Hampshire streams. Cold Regions Research & Engineering Laboratory Special Report 90-26, U.S. Army, CRREL, Hanover, New Hampshire.

This report on winter low-flows is of marginal direct interest but does remind us that flow rates are generally declining over winter and under the ice due to reduction in liquid input to the stream-groundwater system. This recession is generally associated with the geology and climatology of the particular stream basin with some uniformity due to regional geology, elevation, and climate. (Alaska GB 2401 U533 no.90-26).

Mellor, M., and D. J. Calkins. 1988. Deployment of floating bridges in ice covered rivers. Cold Regions Research & Engineering Laboratory Report 88-20, U.S. Army, CRREL, Hanover, New Hampshire.

This report focuses mainly on clearing ice from an ice-covered river in Korea in order to deploy the U.S. Army Ribbon floating bridge. Chain saw cutting and explosives were used.

Michel, B. 1971. Winter regime of rivers and lakes. Cold Regions Science and Engineering Monograph III-B1a, CRREL, U.S. Army, Hanover, New Hampshire.

Excellent monograph summarizing the major processes and phenomenon encountered on lakes and rivers in cold regions. (Geophy Inst., GB 2401 C742 III-B1a).

Michel, B., M. Drouin, L. M. Lefebvre, P. Rosenberg, and R. Murray. 1974. Ice bridges of the James Bay project. Canadian Geotech. J. 11:599-619.

Discusses a winter road built in 1972-73 which crossed 8 rivers in the James Bay territory. Reports bearing capacity theory, design, site selection, construction and testing of the ice bridges spanning the main rivers.

Osterkamp, T. 1975. Supercooling and frazil ice formation in a small sub-arctic stream. In Williams, G. P., editor, Proceedings: Research Seminar Thermal Regime of River Ice., Technical Memorandum no.114, National Research Council Canada.

Field at Goldstream creek supplemented with lab studies suggest the possible role of ice fog crystals falling into supercooled water to initiate frazil ice formation. (Geophy.Inst., GB 1229 R48 1974).

Ott, A. 1990. Letter addressed to Dennis E. Klein, Dept. of the Army, U.S. Army engineer Dist., Alaska. RE: Arctic Warrior 91 Ice Bridges – Tanana River and Tributaries. (Obtained from CRREL files, Fort. Wainwright , AK)

Memo from ADF&G expressing concern over selected ice bridge sites requested for permitting. Concerns over ice jamming downstream, white ice formation(Tanana R., Goose Island), open water holes (Tanana R., nine mile), past bulldozer breakthrough (Tanana R., Harding Lake/Flag Hill), overflow, ice grounding, flow constriction (McDonald Creek), open water leads, bank cuts and channel fills (Salchaket Slough), equipment broken through, ice bridge grounded causing overflow (Clear Creek (Nelson Clearwater) on Tanana Flats).

Perham, R. E. 1988. Imjin river ice boom. Cold Regions Research & Engineering Laboratory Report 88-22, U.S. Army, CRREL, Hanover, New Hampshire.

This report discusses difficult yet successful efforts in obtaining materials for building an ice boom in the field from office design specifications. Provides data for reusing the boom as well as design data and background information.

Peters, D. B., J. R. Ruser, and B. J. Watt. 1982. Rational basis for design of floating ice roads and platforms. Paper OTC 4314, presented at 14th Annual Offshore Technology Conf., Houston, Texas, p.153-158 + tables.

This report proposes a modified limit state approach be used to design load capacities to avoid first crack development. The stress distribution is predicted using elastic theory but based on the use of finite element models which provide a more realistic simulation of the stress distribution through the sheet. The technique has been used for construction operations in the Beaufort Sea.

Power, G., R. Cunjak, J. Flannagan, and C. Katopodis. 1993. Biological effects of river ice. pp. 97-127 In Prowse, T. D., and N. C. Gridley, editors. Environmental aspects of river ice. Environment Canada, National Hydrology Research Institute Science Report No. 5.

Summarizes effects of river ice on invertebrates and fish. Includes diagrams of available habitat under icing conditions throughout the winter in arctic and temperate streams.

Purple, R. A. 1965. Crossing frozen rivers in Korea. The Military Engineer. No. 379 (Sept-Oct): 331-333.

Deals with pallet bridges, inverted balk bridges and float bridges.

Raphael, J.M. 1962. Prediction of temperatures in rivers and reservoirs. J. of the Power Division, Proceedings of the ASCE, July.

Reports an energy balance model for use in predicting water temperatures. Does not deal with ice covers. May be a useful scheme for simulating summer stream temperatures and effects of altering solar energy inputs.

Rhoads, Edwin M. 1974. Ice crossings. The Northern Engineer *5*(1):19-24.

This is an excellent, readable and informative article. Reviews some of the history of ice bridges in the north and cites examples from the late sixties of crossings on the Yukon River to facilitate getting heavy equipment north to Prudhoe Bay, as well as the Pike's Landing crossing on the Chena River near Fairbanks.

Rhoads notes the effect of removing early snow on accelerating ice thickness growth but points out that maximum thickness without snow (assuming a 3600 ^{o}F freezing degree-days) would be limited to 57 inches. After accelerating ice growth by snow removal, surface flooding is recommended for increased ice thickness (build up on the surface) and consequent load bearing capacity. For maximum strength and duration of use, he cites the practice of reinforcing the ice with brush and wood and even dusting the surface with sawdust in spring to retard surface melting.

Rundquist, L. A. and J.E. Baldrige. 1990. Fish habitat considerations. Pages 579-613 in: W. L. Ryan and R. D. Crissman, editors. Cold Regions Hydrology and Hydraulics. Am. Soc. of Civil Engineers, NY, NY.

This is a good review of general fish habitat requirements with a slant toward cold regions and Alaska. Authors note the potential significance of groundwater upwellings for winter habitat and the role of ice in winter fish habitat. This review contains little primary data.

Ryder, T. 1954. Compilation and study of ice thickness in the Northern Hemisphere. New York: Arctic Construction and Frost Effects Laboratory, Technical Rpt. 47.

Ryder has reviewed 186 references for ice thickness data and presents early information on river ice thickness and snowpack thickness for Tanana, Alaska on the Yukon River (winters 1927-41), Fairbanks, Alaska on the Chena Slough (winters 1932-35 and 1950), Noorvik, Alaska on the Kobuk River (winters 1917-24), Anchorage, Alaska on Lake Spenard (winters 1936-37), Nome, Alaska on the Snake River (winters 1932-33 and 1933-34), and Bethel, Alaska on the Kuskokwim River (winters 1918-28). (Alaska GB 2413 R95).

Scrimgeour, G. J., T. D. Prowse, J.M. Culp, and P.A. Chambers. 1992. Ecological effects of river ice break-up: a perspective. Pages 469-488 in T. D. Prowse, C.S.L. Ommanney, and K. Ulmer, editors, Proceedings of the Ninth International Northern Research Basins Symposium/Workshop , Yukon Territory to Inuvik, NWT. National Hydrology Research Institute, NHRI Symposium Series no. 10.

River ice break-up is a seasonal disturbance in northern rivers worldwide and is characterized, in part by large increases in current velocity, stage, water temperature, concentrations of suspended materials, and substrate scouring. This paper provides a hydrologic and ecological perspective on the potential effects of ice break-up on aquatic systems. Specifically, the potential importance of break-up on water temperature, river sediments and geomorphology, riverine energy sources, and their effects on river biota and food-web dynamics is evaluated. (Geophy. Inst. GB 2401 N572 vol. 2).

Shen, H. T., E. P. Foltyn and S.F. Daly. 1984. Forecasting water temperatures decline and freeze-up in rivers. CRREL Report 84-19, U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Hanover, N.H.

Describes a prediction scheme for river ice formation. St. Lawrence river. Method requires initial water temperature at an upstream station, long-range air temperature forecast, predicted mean flow velocity in reach, and water temperature response parameters. The latter can be estimated from air and water temperature data. (Alaska GB 2401 U53 no. 84-19).

Shen, H. T., and P. D. Yap. 1985. A unified degree-day method for river ice cover thickness simulation. Canadian Journal of Civil Engineering 12(1):54-62.

Provides a degree-day method for simulating the growth, decay and breakup of river ice covers and applies the technique to the St. Lawrence River . The model variables include initial ice thickness, freezing degree-days since formation of ice cover, number of days since initial ice formation, and 3 empirical coefficients. Simulated ice thickness compared well with measured values over a range of ice thickness from 25 to 60 cm.

Sinokrot, B. A., and H. G. Stefan. 1993. Stream temperature dynamics: measurements and modeling. Water Resources Research 29(7):2299-2312.

A numerical model (MNSTREM) based on a finite difference solution of the unsteady heat advection-dispersion equation is formulated to predict water temperatures in streams at time increments of 1 hour. An energy balance accounts for the effects of air temperature, solar radiation, relative humidity, cloud cover, and wind speed on the net rate of heat exchange through the water surface, and heat conduction between water and streambed. After calibration, accuracies of hourly and daily water temperature predictions over periods of several weeks are of the order of 0.2 ^{o} to 1 ^{o}C. Ice conditions are not included.

U.S. Dept. of the Army. 1980. Training: Ice Bridging. 172d Brigade Pamphlet no. 350 Headquarters, 172d Infantry Brigade (Alaska), Fort Richardson, Alaska, 15 pp. (Obtained from CRREL files, Fort. Wainwright , AK)

Contains similar to that in U.S. Army (1985) and (1986b) below. Contains a table of how fast flooded layers of water will freeze under different air temperature conditions. Also contains some different illustrations. This pamphlet in conjunctions with the other references mentioned, might serve as an initial basis for publishing a guide for use of ice bridges in logging.

U.S. Dept. of the Army. 1982. Ice Engineering. Engineer Manual 1110-2-1612. U.S. Army Corps of Engineers, Washington, D.C. (Obtained from CRREL files, Fort. Wainwright, AK)

This is a section of the U.S. Army Engineer Manual dealing with ice formation and characteristics, ice jams, ice breaking, ice adhesion, ice control, floating ice dispersion, river and ice hydraulic computations, ice forces on structures, sediment transport, and bearing capacity of floating ice.

U.S. Dept. of the Army. 1985. CRREL Notes for the winter battlefield. Excerpts from FM 31-71, Northern Operations. U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Hanover, N.H. (Obtained from CRREL files, Fort. Wainwright , AK)

Contains an appendix on ice bridges. This appendix lists the following requirements for an ideal ice bridge site:

a. river channel fairly straight
b. only one main channel wide enough for slow river current
c. gradual approaches to the ice
d. no streams or creeks tributaries immediately upstream
e. site near an existing road network
f. the ice should be level
g. site should be free of warm springs and sand bars
h. site should be free of major snow drifting

Field procedures are given for testing the depth of ice downstream of proposed ice bridge centerline. Methods outlined for determining the "class" of ice that involves thickness, color factor, and strength factor. Guidelines for marking and using the roadway are given.

U.S. Dept. of the Army. 1986a. Field Guide: Fresh Water Ice Crossings. CRREL, U.S. Army, a pocket laminated card. (Obtained from CRREL files, Fort. Wainwright , AK)

This two-sided card has Vehicle Class ratings, the required ice thickness, and the distance between vehicles as about 100 times the required ice thickness in feet or meters. Additional annotations adjust if parking on ice, ice strength ratings, water support of ice, and cracks.

U.S. Dept. of the Army. 1986b. Training: squad leader's guide for constructing ice bridges. 6th Infantry Division (Light) Pamphlet no. 350-11, Headquarters, 6th Infantry Division

(Light) and U.S. Army Garrison, Alaska, Fort Richardson, AK. (Obtained from CRREL files, Fort. Wainwright , AK)

Contains similar information as is contained in U.S. Army (1985), cited above. Discusses snow removal to accelerate freezing and surface flooding to build ice thickness. Minimum width recommended is 150 feet. Bridge maintenance considerations are discussed including ice thickness checking, new snowfall compaction or removal, crack checking. Approaches should be less than 3% grade. Refrozen wet snow can be used to re-grade approaches that are greater than 3%.

Wankiewicz, A. 1984. Analysis of winter heat flow in an ice-covered Arctic stream. Can. Jour. Civil Eng. 11:430-443.

Ice growth is modeled for an Arctic stream near Inuvik, Northwest Territories. Shows how water flows in narrow conduits under the ice in winter, generating friction and convected streambed heat. Includes some useful diagrams relating ice thickness variations along the channel to pool-riffle structure. Also reports daily streambed temperature measurements during winter.

Wilcox, Dorothy E. 1980. Geohydrology of the Delta-Clearwater area, Alaska. U.S. Geol. Survey, Water Resources Investigations 80-92. Prepared in cooperation with the AK Dept. of Nat. Resources, Division of Forest, Land and Water Management, Anchorage, AK, 26 pp.

Describes the groundwater hydrology associated with the Delta-Clearwater Creek network and Clearwater Lake, the mouth of the Delta River, and the Tanana River along the study area's north boundary. Average annual ground water discharge is estimated to be > 1,200 cubic feet per second. The aquifer is recharged by seepage through streambeds and by infiltration of precipitation. Some uncertainty still surrounds the contributions from the Delta River, Jarvis Creek, and the Tanana River east of the Clearwater Creek aquifer area.

Williams, G. P. 1963. Probability charts for predicting ice thickness. Engineering Journal 46(6):31-35. (reference unavailable for review).

Williams, J. R. 1951. Observations on river-ice conditions near highway bridges in Alaska, winter, 1949-1950. U.S. Geological Survey, 40 pp.

General descriptive report. Does include section on "River crossings on ice" which includes discussion of bearing capacities of ice, approaches to ice-crossing sites, and damage to highways and bridges by river ice. Observations include Copper River Valley (Tazlina River, Chistochina River) and the Tanana River valley (Tanana River – east of Tok Junction and at Big Delta; Chena Slough near bridge north of Badger Road; Chena River at Fairbanks; Salcha River near Richardson Highway bridge; Chisana river near Northway; Robertson River; Gerstle and Little Gerstle Rivers; Johnson River; Tok River), the Matanuska River at Palmer and the Yukon River at Beaver. (Alaska GB 1398.4 A4 W57 1951).

Wilson, W. J., E. H. Buck, G. F. Player, and L. D. Dreyer. 1977. Winter water availability and use conflicts as related to fish and wildlife in arctic Alaska – a synthesis of information. FWS/OBS-77/06, Biological Services Program, Fish and Wildlife Service, U.S. Dept. of Interior.

Includes a chapter on "Importance of unfrozen water during winter to arctic fish and wildlife". Discusses use patterns by fish during winter; importance of unfrozen water to fish and non-fish organisms during winter; Arctic lake ice thickness; Arctic grayling. (Alaska TC 424 A4 W4).

Woo, M., and R. Heron. 1989. Freeze-up and break-up of ice cover on small arctic lakes. Pages 56-62 in Mackay, W. C., editor, Northern Lakes and Rivers. Occasional Publ. No. 22, The Boreal Institute for Northern Studies.

Lake ice growth in Canadian Arctic is strongly affected by snow depths and ice thickness is predictable using heat conduction equations. Breakup involves both thermal and mechanical processes; at Resolute, NWT, 40% of ice ablation occurred at the upper ice surface, 10% at the bottom, and the rest involved internal melt. While a process-oriented approach produces superior results in ice prediction, the cost of acquiring the requisite data may necessitate use of empirically based, but simpler, degree-day techniques. (Alaska GB 1629 N67 1989).

Wortley, C. Allen. 1990. Ice engineering for rivers and lakes bibliography. College of Engineering, Dept. of Engineering Professional Development, University of Wisconsin-Madison.

An excellent literature review sorted by the following topics:

Ice formation, growth, deterioration, classification, characterization
Simulation, processes, thermal regimes.
Ice strength, deformation, mechanics, properties.
Bearing capacity and deflection, ice roads and bridges, construction methods.
Ice forces and pressures on structures, buckling, vibrations.
Hydraulics of river and reservoir ice, ice jams and hanging dams, frazil ice problems.
Design of structures, harbors, ports, quays, wharves, marinas.
Instrumentation, testing, measurements, mapping.
Data bases- climatological, hydrological.
General references, historical, anecdotal.
Primary Author Index.

(Alaska GB 1398.2 W67 1990)

ALPHABETICAL LIST OF REFERENCES

The references cited in the individual sections of this report are compiled here. Bracketed letters indicate the sections in which the citation appears as follows.

[BFD]	Buffer function and design
[RBS]	Factors affecting stream and river bank stability
[LWD]	Large woody debris
[PSS]	Permafrost and silty soils
[WFU]	Winter fish use of glacial streams
[FUU]	Fish use of upwellings
[ITB]	Ice thickness and ice bridges.

Abbe, T. B., and D. R. Montgomery. 1996. Large woody debris jams, channel hydraulics and habitat formation in large rivers. Proceedings of International Symposium on Habitat Hydraulics, Trondheim (Norway), 18-20 Aug 1994. Regulated Rivers: Research & Management 12:201-221. [LWD]

Abele, G. 1990. Snow roads and runways. US Army Corps of Engineers, Cold Regions Research & Engineering Laboratory, Monograph 90-3. [PSS, ITB]

Abernethy, B., and I. D. Rutherfurd. 1998. Where along a river's length will vegetation most effectively stabilise stream banks?. Geomorphology 23: 55-75. [RBS]

Adam, K. M. 1978. Building and operating winter roads in Canada and Alaska. Published under contract for Environment Division, Northern Environmental Protection and Renewable Resources Branch, Department of Indian and Northern Affairs, Ottawa, Canada. [ITB]

Alaska Dept. of Fish & Game. (undated). Tips on the weight-bearing capacity of ice. One page hand-out obtained from CRREL files, Fort. Wainwright , AK. [ITB]

Aldrich, J. W. 1981. A stochastic analysis of some existing ice thickness data. The Northern Engineer 13(1):4-10. [ITB]

Allen, W. T. R. 1977. Freeze-up, break-up and ice thickness in Canada. Fisheries and Environment Canada. Report CLI-1-77. [ITB]

Anonymous.1986. Squad leaders guide for constructing ice bridges. Dept. of the Army, 6th Infantry Division (Light) Pamphlet No. 350-11. [ITB]

Anonymous. (undated). Construction of an ice bridge across the Imjin river in Korea. (obtained from CRREL files, Fort. Wainwright , AK). [ITB]

Anonymous. (undated). Ice bridge construction : 1978-1979. (obtained from CRREL files, Fort. Wainwright , AK). [ITB]

Anonymous. (date unknown). Ice bridge construction briefing outline. (obtained from CRREL files, Fort. Wainwright , AK). [ITB]

Anonymous. (undated). Workshop on ice-bridging. Notes. (obtained from CRREL files, Fort. Wainwright , AK). [ITB]

Arctic Environmental Information and Data Center. 1984a. Assessment of the effects of the proposed Susitna Hydroelectric Project on instream temperature and fishery resources in the Watana to Talkeetna reach. Final Report for Harza-Ebasco for the Alaska Power Authority. Volume 1. [ITB]

Arctic Environmental Information and Data Center. 1984b. Assessment of the effects of the proposed Susitna Hydroelectric Project on instream temperature and fishery resources in the Watana to Talkeetna reach. Final Report for Harza-Ebasco for the Alaska Power Authority. Volume 2. APPENDICES A-H. [ITB]

Assani, A. A., and F. Petit. 1995. Log-jam effects on bed-load mobility from experiments conducted in a small gravel-bed forest ditch. Pages 117-126 *in* Poesen, J., G. Govers, and D. Goossens, editors. Experimental Geomorphology and Landscape Ecosystem Changes. Proceedings of a Memorial Symposium for Prof. Jan de Ploey, 22-26 Mar 1993. Catena 25. [LWD]

Ashton, G. D. 1980. Freshwater ice growth, motion, and decay. Pages 261-304 in S.C. Colbeck , editor. Dynamics of Snow and Ice masses. Academic Press, NY. [ITB]

Ashton, G. D. 1990. Ice Effects on Hydraulics and Fish Habitat. Cold Regions Research & Engineering Laboratory Special Report 90-8, U.S. Army, CRREL, Hanover, New Hampshire. [ITB]

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