Bank Erosion and Large Woody Debris Recruitment Along the Tanana River, Interior Alaska

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ABSTRACT

The management intent of the Alaska Forest Resources and Practices Act (FRPA) for riparian areas is to protect fish habitat and water quality from significant adverse effects of timber harvest. Among other things, FRPA requires maintaining short- and long-term supplies of LWD, stream bank stability, and channel morphology. In interior Alaska, concerns exist regarding the potential impact of a growing timber industry on salmon habitat. Concerns have focused on forest harvest impacts on river bank erosion and large woody debris (LWD) recruitment along the 824 km-long Tanana River.

This project was initiated to quantify baseline conditions of the amount and spatial distribution of bank erosion, and the associated LWD recruitment along the entire length of the Tanana River, which currently has been little impacted by contemporary forest harvest. River bank erosion and LWD recruitment were quantified for the 1978-80 to 1998-99 time period using change analysis within a Geographic Information System, and existing forest inventory data. Data were summarized by 10 km reaches.

For the entire river, 5,104 ha of river bank eroded, with 3,888 ha contributing LWD. The distribution of land area eroded was highly variable, and ranged from 0.3 ha to 309 ha/10 km of river. Based on erosion patterns, five distinct regions of the river were identified. The amount of land area eroded along the Tanana River was related to slope patterns and the distribution of silt-laden tributaries of glacial origin. Among vegetation size classes, eroded land area was distributed fairly evenly among stands of sapling-sized trees and dwarf forests (28.3%); stands of pole-sized trees (27.8%); and shrublands, wetlands, and other non-forested land cover (22.9%). Among vegetation types, erosion occurred most frequently in tall shrublands (21.0%), followed by stands of balsam poplar saplings (15.7%). A total of 4,266 individual erosion patches were identified along the entire Tanana River. Erosion patches varied in size from 0.01 to 58.84 ha, but the majority (78.0%) were 0.01 to 1.00 ha in size. Almost all (94.5%) of the erosion patches were ≤ 5.0 ha in size. The greatest cumulative amount of erosion (16.1%) occurred within patches that were 0.01 to 1.00 ha in size. Land area contained within erosion patches ≤ 5 ha was 47.2% of the total. Maximum erosion distance within an erosion patch varied from <2 m to 401 m, but was most commonly (26.6%) 10 to 19 m.

The volume of LWD recruited into the Tanana River totaled 448,070 m^3. The distribution of LWD was highly variable and ranged from 8.2 m^3 to 50,867 m^3/10 km of river. Spatial patterns of LWD recruitment were similar to land erosion patterns. Among vegetation size classes, the largest LWD volumes (47.6%) originated from sawlog-sized stands of trees. Among vegetation types, LWD volume was greatest (24.7%) from stands of white spruce sawlogs. Erosion patches 0.01 to 1.00 ha in size contributed the most LWD (10.6%). The majority of LWD (53.6%) was recruited from erosion patches ≤ 9 ha in size.

Information obtained from this project will allow resource managers to better understand natural processes of river bank erosion and LWD recruitment, and to highlight future research needs that can be used to assess the implications of management actions.

INTRODUCTION

The Alaska Forest Resources and Practices Act (FRPA) of 1990 established fish habitat protection standards that comply with non-point source pollution requirements under state law and section 319 of the Clean Water Act. FRPA regulations establish standards for both riparian and non-riparian areas in order to minimize adverse effects on water quality and fish habitat. The management intent of FRPA for riparian areas is to protect fish habitat and water quality from significant adverse effects of timber harvest by maintaining: (1) short- and long-term sources of large woody debris (LWD), (2) stream bank stability, (3) channel morphology, (4) water temperatures, (5) stream flows, (6) water quality, (7) adequate nutrient cycling, (8) food sources, (9) clean spawning gravels, and (10) sunlight. Current FRPA regulations were written primarily to address concerns related to potential impacts of riparian forest management activities in the forests of southeast Alaska. In interior Alaska, there is a lack of understanding about the relative importance of the 10 fish habitat and water quality variables, especially in the large rivers along which much of the productive timber is located (Neiland and Viereck 1978, Van Cleve et al. 1993).

Despite the lack of understanding of the role of the above variables in interior Alaska, concerns have been raised regarding the impact of forest management activities on fish habitat and water quality. These concerns have been focused primarily along the 824 km-long Tanana River, the largest tributary of the Yukon River (Mason and Begét 1991). The major concerns about the potential for timber harvest to affect the Tanana focus around riverbank erosion and LWD recruitment. It has been suggested that the harvest of riparian timber along the Tanana may increase riverbank erosion rates that might degrade productive spawning or rearing areas through sedimentation processes or changes in channel morphology (e.g. simpler channels with fewer scour holes and fewer eddies and meanders). Conversely, it has been suggested that timber harvest near the river will decrease the supply of LWD that is recruited into it through natural erosion processes. In large glacially-influenced rivers such as the Tanana, the role of vegetation on river bank stabilization is poorly understood, and the role of LWD in the river is virtually unknown. It is apparent, however, that bank erosion processes and the function of LWD in rivers such as the Tanana are very different from the small, clearwater streams of coastal Alaska.

Greater public concerns and interest regarding the interaction of riparian forest management and fish habitat and water quality in interior Alaska have resulted in efforts to fill the information gap, especially along large river systems. Ott (1998) investigated the impact of winter logging roads on vegetation and permafrost on the Tanana River floodplain. Ott and Putman (1999) described the data collection protocol for an ongoing study to determine the long-term dynamics of riparian buffer strips, and LWD recruitment in the absence of erosion, along glacial rivers in interior Alaska. Magoun and Dean (2000) synthesized the most recent research regarding floodplain ecosystems and their management, with an emphasis on the Tanana Valley. Welbourn Freeman (2000) compiled an annotated bibliography of research relevant to riparian management issues in interior Alaska as part of a recent review of FRPA. Topics covered in Welbourn Freeman (2000) included buffer strip function and design, factors affecting stream bank and river bank stability, large woody debris, permafrost and silty soils, winter fish use of glacial streams, fish use of upwellings, and ice thickness and ice bridges. Durst (2001) described fish habitats and use of the Tanana River near Big Delta, Alaska, and discussed fish habitat sensitivity and forest management practices in the context of a recent review of FRPA.

The primary concerns about the potential for timber harvest to affect bank erosion and LWD recruitment along large rivers such as the Tanana have not been addressed, despite the efforts to better understand issues related to riparian forests, fish habitat, and water quality in interior Alaska. To that end, this project was initiated to quantify baseline conditions (1978-80 through 1998-1999) of the amount and spatial distribution of bank erosion, and the associated LWD recruitment along the entire length of the Tanana River, which currently has been little impacted by contemporary forest harvest. Estimates of bank erosion of the Tanana River have been previously conducted by several researchers (Gatto 1984, Collins 1988, Collins 1990, Adams 1999), but those studies were limited to small lengths of the river near Fairbanks. To our knowledge, the only study of LWD recruitment in interior Alaska was conducted for 71 km (44 mi) of the Chena River (McFadden and Stallion 1976), a tributary of the Tanana River that flows through the city of Fairbanks.

Information obtained from this project will allow resource managers to better understand natural processes of bank erosion and LWD recruitment along a large, glacially-influenced river, and to prioritize research needs. To our knowledge, this project represents the first time that bank erosion and LWD recruitment has been quantified for an entire river.

STUDY AREA

Geographic and Hydrologic Features

The study area consisted of the entire 824 km-long Tanana River corridor (Figure 1), plus land within 0.80 km of the riverbanks. Elevation of the Tanana River (Figure 2) ranges from about 522 m at the source (the confluence of the Nebesna and Chisana Rivers) to 71 m at the river mouth (Anderson 1970), where it empties into the Yukon River. The width of the active floodplain varies from 300 m to greater than 2000 m (Collins 1990).

The Tanana River watershed comprises an area of about 115,500 km^2 (Collins 1988; Figure 1); it is bordered on the north by the Yukon-Tanana uplands and on the south by an extensively glaciated area of the Alaska Range. The Tanana River basin is located within the discontinuous permafrost zone, with permafrost reaching 80 m in depth (Neill et al. 1984). The Tanana River valley is a structurally-controlled basin filled by Tertiary and Quaternary sediments from 100 to 250 m in thickness (Péwé and Reger 1983). The width of the Tanana River valley varies from 16 to 97 km (Anderson 1970).

Tributaries of the Tanana River are primarily either non-glacial streams and rivers draining to the south from the Yukon-Tanana uplands or they are glacial streams and rivers draining to the north from the Alaska Range. Eighty-five percent of the Tanana River basin discharge originates from the Alaska Range, with 50% of the discharge being contributed by 4 glacially-fed tributaries—the Nabesna, Delta, Nenana, and Kantishna Rivers (Anderson 1970). From 1978-99 (the time period of this study), average annual discharge of the Tanana River was 688 m^3/sec at the U.S. Geological Survey streamflow station at the village of Nenana, located about 575 km from the river source. Over the same time period, the average peak discharge at Nenana was 2279 m^3/sec.

Climate

Climate of the Tanana River basin is continental—characterized by hot summers and cold winters. Temperatures range from –54 to +37^o C, and the mean annual temperature is –3.3^o C (Neill et al. 1984). Annual precipitation averages 254 to 559 mm water equivalents per year.

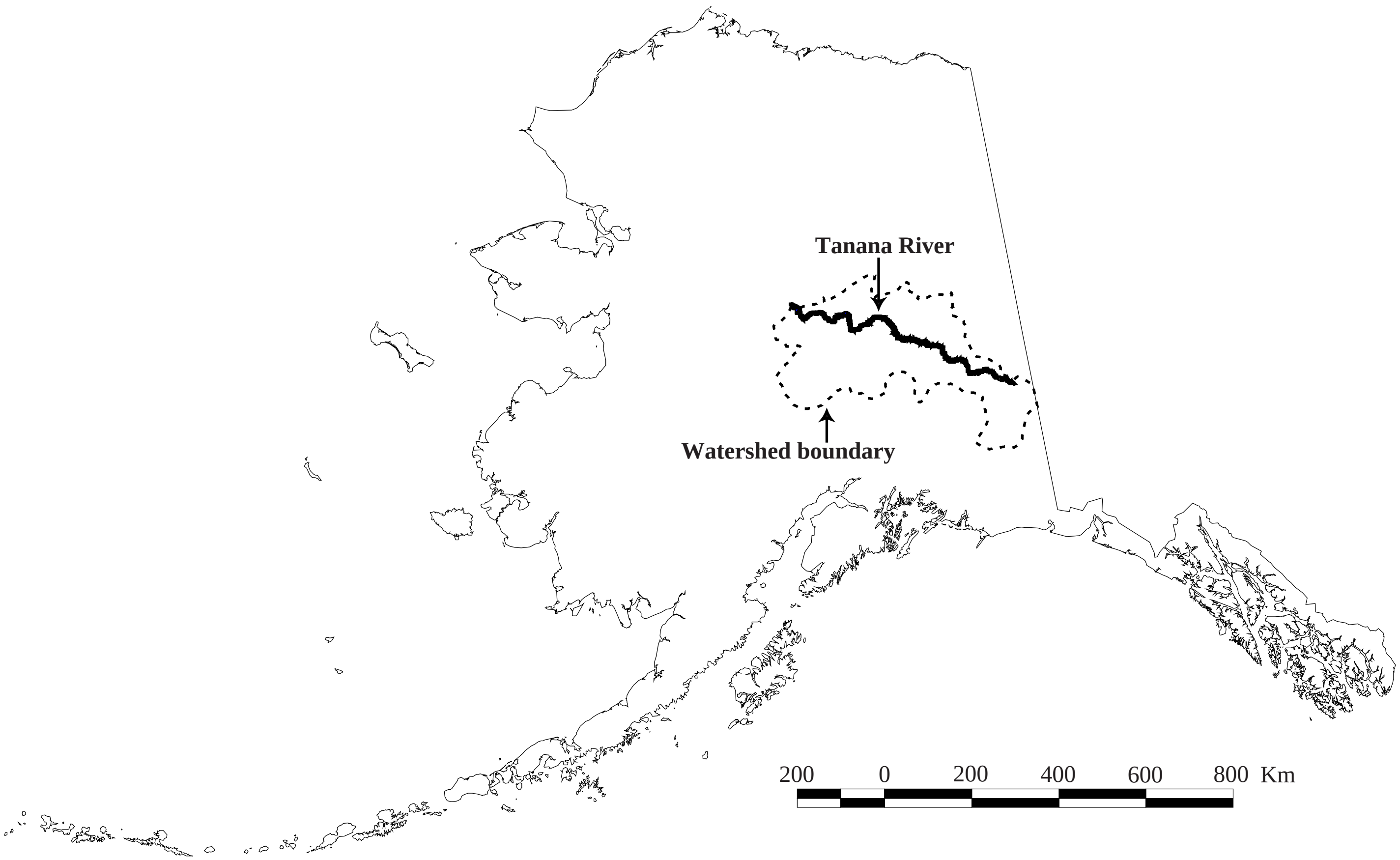

Figure 1. Location of the Tanana River and its watershed boundary within Alaska.

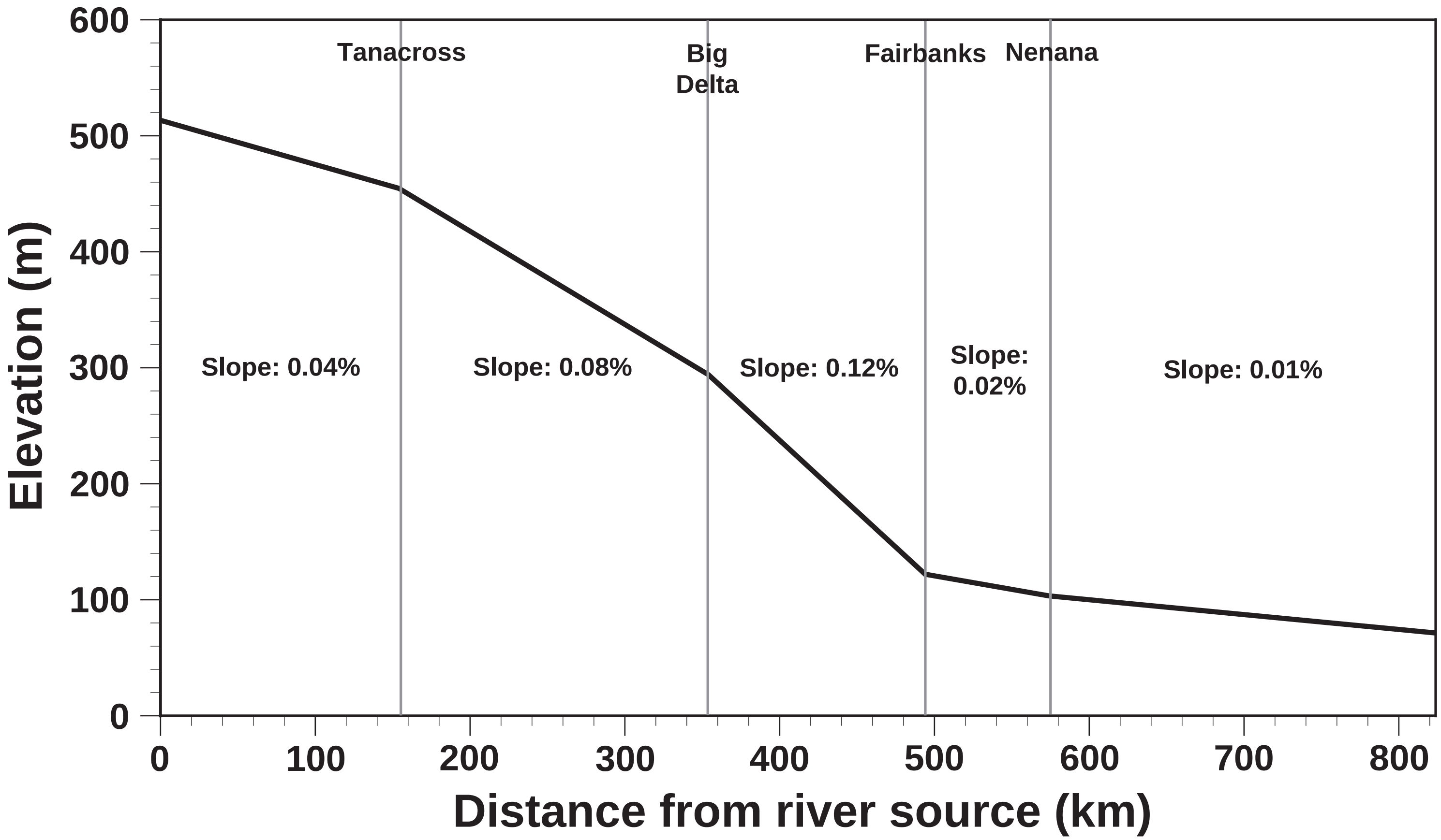

Figure 2. Longitudinal profile of the Tanana River based on published data and elevations of streamflow stations. Approximate locations of settlements with U.S. Geological Survey stream flow stations are shown. Slope values were determined based on the estimated locations of the stream flow stations along the river. (Data sources: U.S. Geological Survey, Anderson 1970)

Snowfall averages 76 to 152 cm per year (Neill et al. 1984). Precipitation tends to be greatest in the southwest corner of the river basin, and decreases in an easterly direction (Anderson 1970).

Vegetation

Vegetation of the Tanana River basin ranges from alpine tundra to boreal forest comprised of both evergreen and deciduous tree species. The Tanana River valley lies primarily within the Interior Bottomlands Ecoregion (Gallant et al. 1995). Riparian forests are comprised primarily of pure and mixed stands of white spruce (*Picea glauca*), black spruce (*Picea mariana*), and balsam poplar (*Populus balsamifera*). Floodplain forests of white spruce and balsam poplar are some of the most productive in interior Alaska. Paper birch (*Betula papyrifera*) and quaking aspen (*Populus tremuloides*) are present in riparian forests, but are more common and even dominant in upland forests.

METHODS

River Discharge

Daily streamflow (i.e. discharge) data for the Tanana River were obtained from the U.S. Geological Survey (USGS) website (http://water.usgs.gov/nwis/discharge). Discharge data were used to determine if the time period represented by this project (1978-99) was suitable as a baseline, as well as to aid in interpretation of project results. Although Tanana River discharge has been monitored in several locations over the years, most USGS streamflow stations have been discontinued. During the time period of this study, discharge data for the Tanana River existed only at Fairbanks and Nenana. Of these two sites, the discharge record was longest (1962-Present) for the Nenana streamflow station. For this reason, we analyzed the Tanana River discharge data from the USGS streamflow station at Nenana. Specifically, daily river discharge data were used to:

1.) Construct a hydrograph of the Tanana River for the period of study;
2.) Construct a graph of annual icefree (May-October) mean discharge and annual peak discharge. Icefree discharge values were analyzed instead of annual discharge, because erosion is believed to occur mostly during the icefree period when banks are not completely frozen and discharge values are greatest;
3.) Construct a graph of the departure of the annual icefree mean discharge from the mean icefree discharge; and
4.) Construct a graph of the departure of the annual peak discharge from the mean peak discharge.

River Bank Erosion

Various techniques exist for analyzing changes in fluvial systems, including, but not limited to (from Lawler 1993): sedimentological evidence, botanical evidence, historical sources (e.g. maps, aerial photographs, surveyor's notes and diaries), planimetric resurveys, repeated cross-profiling, erosion pins, and terrestrial photogrammetry. For our analysis of the Tanana River, a change analysis was conducted within a Geographic Information System (GIS). The concept behind a change analysis as a means to estimate bank erosion is to compare riverbank locations at different points in time. Change analyses of portions of rivers using time sequential aerial photographs, historical maps, and satellite images, either singly or in combinations, have been performed for diverse locations such as 21 rivers in western Canada (Hickin and Nanson 1984), the Merced River in California (Madej et al. 1994), the River Dee on the Welsh-English border

(Gurnell et al. 1994, Gurnell 1997), the Subansiri River in India (Goswami et al. 1999), and the Tanana River near Fairbanks, Alaska (Gatto 1984, Collins 1988, Collins 1990, Adams 1999).

The change analysis for this study consisted of comparing riverbank locations derived from digitized 1978-80 high-altitude color infrared (CIR) aerial photographs against bank locations derived from 5-meter resolution panchromatic Indian Remote Sensing (IRS) imagery fused with colorized 27-meter resolution Landsat 7 multi-spectral satellite images, both collected in 1998-1999. To calculate LWD recruitment, we used the results of the change analysis, in conjunction with (1) land cover data derived from a digitized land cover type map interpreted from the 1978-80 CIR photographs, and (2) existing forest inventory data.

In order to detect true changes in riverbank locations and to accurately calculate LWD recruitment, it was necessary to remove distortions from the spatial datasets. This procedure was accomplished by georeferencing the digitized CIR photos to digital orthophotoquads at a scale of 1:63,360. The georeferenced (i.e. orthorectified) CIR photos were then used as the base map to register the IRS imagery and Landsat 7 imagery. PCI™ image processing software was used to register the CIR photos to the digital orthophotoquads, and to register the IRS and Landsat 7 imagery to the georeferenced CIR photos. The georeferenced IRS and Landsat 7 satellite images were then fused to create a colorized 5-meter resolution image that depicted the location of the Tanana River in 1998-99. Bands 1-6 of the Landsat imagery were fused with the IRS images.

The digital land cover dataset was a product of vegetation mapping activities connected with forest inventory projects conducted by the Alaska Department of Natural Resources, Division of Forestry (DOF) during the 1980s. Land cover types were identified on 1978-80 CIR photos for the forest inventory. The existing land cover data were re-registered to the digital georeferenced 1978-80 CIR photos using ArcInfo™ software. Within the river corridor, partially vegetated gravel bars and river bank were often identified as single land cover polygons during the creation of the DOF forest inventory dataset. These partially vegetated areas were re-classified at a finer resolution for inclusion in this project, so that vegetated areas sometimes <0.1 ha were identified separately from surrounding unvegetated land. Outside of the river corridor, land cover polygons <1 ha in size were dissolved and merged with surrounding land cover polygons during the re-registration process. A raster dataset with 5 m resolution was created from the registered land cover data.

The actual change analysis involved overlaying the georeferenced 1978-80 land cover data and the 1998-99 classified data in ArcInfo™. The change analysis was conducted for a bankfull condition of the Tanana River because the CIR photos and satellite images were taken over a period of years and during different time periods within a given year. For the change analysis under the bankfull scenario, therefore, unvegetated land within the river corridor was pooled with the water, and not considered as part of the land area available for erosion. As a result, land areas classified as eroded were those which were classified as vegetated land on the 1978-80 CIR photographs but which were classified as water or gravel on the 1998-99 satellite images. Conducting the change analysis in this manner resulted in a conservative estimate of the land area eroded, because unvegetated land that was eroded was not enumerated. The change analysis resulted in the creation of a raster dataset of eroded land areas along the Tanana River. After performing the change analysis, the results were printed and visually inspected several times for classification errors. In order to further reduce classification errors associated with the change analysis, land areas <0.01 ha in size that were classified as eroded areas were not included in the analysis.

The maximum perpendicular distance that erosion occurred within each individual erosion area was estimated within the GIS. Lateral bank movement was calculated by running a series of spatial functions in ArcInfo ™ GRID, resulting in a raster dataset that defined proximity to the nearest riverbank for every 5m x 5m area (i.e. grid cell) in the study area. These data were overlaid with a dataset of the eroded areas, so that all cells in the eroded polygons were related to individual eroded polygons using unique ID numbers. Using relational database software, minimum and maximum distances from the riverbank, and the resulting "eroded distance" (maximum distance – minimum distance) could be defined for each eroded polygon. The longest eroded distance for each erosion area was identified and stored. Eroded polygons on islands and bodies of land between two areas of water sometimes had the point of maximum distance from the river in the interior of the polygon, because the nearest water was not on the side of the land area where the erosion occurred. Maximum eroded distance in these situations were, therefore, underestimated. A visual inspection of the results was performed to identify the areas where this problem occurred, and the measurement errors were manually corrected.

Large Woody Debris Recruitment

LWD recruitment into the Tanana River was determined using the results from the change analysis in conjunction with the land cover dataset and existing forest inventory data. Areas eroded by the river were classified by vegetation type and size (termed vegetation strata). For forested vegetation strata, LWD volume recruited into the river was calculated as the amount of area eroded, multiplied by the average wood volume per unit area for that forest cover type within the appropriate DOF management area (Table 1). Large woody debris volumes for each vegetation strata represent the volume of trees within a stand that had a diameter at breast height (DBH; measured at 1.37 m above the root collar) ≥12.7 cm (5 in). This diameter represents the minimum diameter used to define pole-sized trees by DOF in interior Alaska, and is within the range of typical minimum diameters of LWD (7.5 to 15 cm) used in western North American studies (Harmon et al. 1986).

Erosion and LWD Recruitment Data Summaries

Land area eroded and LWD recruited into the Tanana River were summarized by 10 km reaches, except for the first reach at the source of the river, which was 4 km in length. In order to define the 10 km reaches, a dataset describing the centerline of the Tanana River was created by interpreting and digitizing the main river channels from the land cover data. Starting at the river mouth at the Yukon River, 10 km segments of the centerline were identified. At the end of each 10 km segment along the centerline, line segments approximately perpendicular to the main river channel were drawn from the centerline to the edges of the study area. The result was the creation of 82 10-km reaches, and a 4 km reach at the river source. Although the actual point of origin of the Tanana River is the confluence of the Nebesna and Chisana Rivers, reaches were identified by their distance from 4 km downriver of the source—the point where the 10 km reaches begin. Land erosion and LWD values derived for the 4 km reach were not included in the figures in this report that summarize study results by reach. However, values from the 4 km reach were included in figures that did not summarize study results by reach.

The values of land area eroded and LWD recruitment used to construct some of the figures varied because of differences due to rounding. There were a total of 22,232 individual polygons created within the 4,266 eroded areas identified from this study. Each polygon was identified by vegetation strata, erosion area, reach number, and management area. Depending on how the data

Table 1. Forest inventory data, listed by DOF management area, used to calculate large woody debris volume [1]

Strata number	Dominant forest stand vegetation	Dominant tree size within a stand	Average wood volume (m^3/ha) Tok Area	Delta Area	Fairbanks Area	Kantishna Area
1	White spruce	Sawlog [2]	227	235	247	217
2	White spruce	Poletimber [3]	120	188	133	122
3	Black/white spruce	Saw/poletimber	62	105	51	189
4	Other	Saw/poletimber	62	105	51	189
5	Balsam poplar	Sawlog	97	97	124	91
6	Balsam poplar	Poletimber	148	88	111	73
7	Paper birch/quaking aspen	Saw/poletimber	52	124	98	90
8	White spruce/birch/aspen	Sawlog	103	304	212	180
9	White spruce/birch/aspen	Poletimber	80	138	129	103
10	Black/white spruce/birch/aspen	Saw/poletimber	60	121	83	91
11	White spruce/balsam poplar	Sawlog	283	218	278	167
12	White spruce/balsam poplar	Poletimber	170	119	193	98
20	White spruce	Dwarf/Repro/Burned [4]	NA	172	NA	16
21	Black/white spruce	Dwarf/Repro/Burned	31	18	NA	19
22	Other coniferous stands	Dwarf/Repro/Burned	NA	1	1	NA
23	Balsam poplar	Dwarf/Repro/Burned	43	39	50	37
24	Birch/aspen	Repro/burned	32	16	31	20
25	White spruce/birch/aspen	Repro/burned	59	48	35	2
26	Black/white/spruce/birch/aspen	Dwarf/Repro/Burned	30	56	19	23
27	White spruce/balsam poplar	Dwarf/Repro/Burned	38	42	33	38

[1] Large woody debris volume represents the volume of trees within a stand that had a DBH ≥12.7 cm (5 in).
[2] A coniferous sawlog had a DBH >22.9 cm (9 in), and a deciduous sawlogs had a DBH >27.9 cm (11 in).
[3] A coniferous pole-sized tree had a DBH between 12.7 and 22.9 cm (5 to 9 in DBH), and a deciduous pole-sized tree had a DBH between 12.7 and 27.9 cm (5 to 11 in DBH).
[4] Reproduction was defined as a tree with a DBH <12.7 cm (5 in). Dwarf stands were stands where the dominant trees were <6.1 m (20 ft) tall.
Burned stands were recently burned. Large woody debris within dwarf/repro/burned stands was contributed by trees with a DBH ≥12.7 cm (5 in).

were summarized, slightly different total values were derived, even though the raw data were rounded at the second decimal place for all calculations, and total values were reported to the nearest whole number. Using the totals of land area eroded and LWD recruitment for the 4,266 eroded areas as the point of reference, the discrepancy between those values and the totals derived when summarizing the variables by reach was 0.5% (28 ha) for eroded land area and 0.2% (673 m^3) for LWD recruitment.

Geomorphic and Geologic Features

An attempt was made to examine bank changes and the corresponding LWD recruitment along the Tanana River in relation to geomorphic and surficial geologic features. The distributions of the following variables were inferred from the 1978-80 CIR aerial photographs and drawn on USGS quadrangles or hardcopies of orthophotoquads:

1.) The continuity (from continuously frozen to no permafrost) and water content (from moderate to high ice content, to dry frozen) of permafrost,
2.) Types of unconsolidated deposits (e.g. active-floodplain alluvium, stream terrace alluvium) and bedrock (e.g. gneiss and schist, granitic bedrock)—this classification is termed geology (Reger 1987), and
3.) The extent and distribution of unconsolidated materials (e.g. gravel, silt, chiefly sand and silt overlying gravel) and bedrock (e.g. foliated metamorphic bedrock) inferred from geologic units (e.g. steam-terrace alluvium) described in #2 above—this classification is termed geologic materials (Reger 1987).

A geologist (Richard D. Reger), was contracted to perform this work. Consult Reger (1987) for a detailed description of the variables listed above. The distribution of these variables was then digitized into an ArcInfo ™ coverage for 7 USGS 1:63,360 quadrangles representing a gradient from relatively low to relatively high erosion areas along the river.

From the above list of geologic and geomorphic variables, we decided to consider analyses only for the relationship between bank erosion patterns and the distribution of the various classifications of permafrost. The geology maps (#2 above) and geologic materials maps (#3 above) were highly correlated because the geologic materials maps were derived from the geology maps. We felt the geologic materials maps were more directly related to bank erosion processes because they provided information about the composition of river bank materials, from which bank cohesiveness could be inferred. For this reason, we excluded the geology variables from analyses. After a visual inspection of the geologic materials maps, we also decided to exclude those variables from the analyses. The geologic materials were broadly classified as being either unconsolidated deposits or bedrock. Bedrock was excluded because, as a bank material it constitutes a very small part of the Tanana River, and it was considered a non-erodible material over the time span of this project (maximum of 21 years). Unconsolidated deposits, which are erodible, were excluded because the great majority of the active floodplain of the Tanana was classified as consisting of one type of geologic material—sand and silt overlying gravel. With so much of the floodplain consisting of one geologic material, we felt we would not be able to discriminate erosion patterns based on that information.

Several analyses were considered to determine the influence of permafrost on bank erosion along the Tanana. In the end, however, we determined that analyzing the relationship of bank erosion to the continuity of permafrost was beyond the scope of this project, because of both cost and the complexity of the analyses required.

In order to examine the spatial relationships of permafrost and bank erosion, the mapped distribution of permafrost types needed to be georeferenced to the 1978-80 digital orthophotoquads. The effort required to perform this task would have been great, even if the job was limited to the 7 USGS quadrangles where the permafrost distribution had already been digitized.

The first method we considered for investigating the relationship between permafrost continuity and bank erosion was simple. The procedure simply required overlaying the polygons of the various degrees of permafrost over the polygons of eroded areas, and then searching for significant relationships. However, several problems became apparent. First, the probability of erosion is, in part, related to distance from the river. Land not near the river was not available for erosion and should not be included in the analysis. However, we were not able to identify an objective means of defining the land area available for erosion. Second, we recognized that confounding effects could occur between the degree of permafrost development and location of permafrost along a river channel. For example, bank erosion often occurs on the outside bends of channels where the banks are high (i.e. older, elevated terraces) while deposition often occurs on the inside bends of channels (i.e. young, low terraces). Permafrost occurs primarily in old white spruce stands, mixed black and white spruce stands, and black spruce stands located on older, elevated river terraces. Conversely, shrublands and deciduous vegetation types typically occur on younger, lower river terraces with little or no permafrost (Viereck et al. 1993). Given this situation, it would be difficult to determine if erosion was related to the level of permafrost development in river terraces of varying ages, or if erosion was simply related to the location of the eroded area along the river channel (inside or outside of a river bend). Third, we recognized that confounding effects could occur between the degree of permafrost development and the relative stability of the river. For example, a preliminary analysis indicated that in a relatively stable reach of the river (i.e. low erosion), more erosion occurred in areas with little or no permafrost. However, this same reach was also bedrock constrained. Intuitively, we felt that the bedrock, not permafrost, was controlling the level of erosion. For all of these reasons, we determined that in order to adequately investigate the relationship of permafrost and erosion by overlaying polygons of the two variables, a sophisticated, multivariate analysis was required. Such an analysis was beyond the scope of this project.

We also considered comparing the maximum perpendicular distance of erosion patches (described in the River Bank Erosion section above) to permafrost continuity. However, erosion patches were often comprised of more than one permafrost type, and we were unable to construct an automated process that would allow us to determine which permafrost types influenced erosion to a greater or lesser degree.

RESULTS

River Discharge

The 1978-99 hydrograph of the Tanana River (Figure 3) was characterized as follows:

1.) Relatively low flows (mostly averaging 200-300 m^3/sec) and low variability during winter (November-April) months,
2.) Gradually increasing average discharge from May until late July, after which average discharge gradually decreased during the rest of the icefree (May-October) period,
3.) Average daily discharge peaked at 1845 m^3/sec,

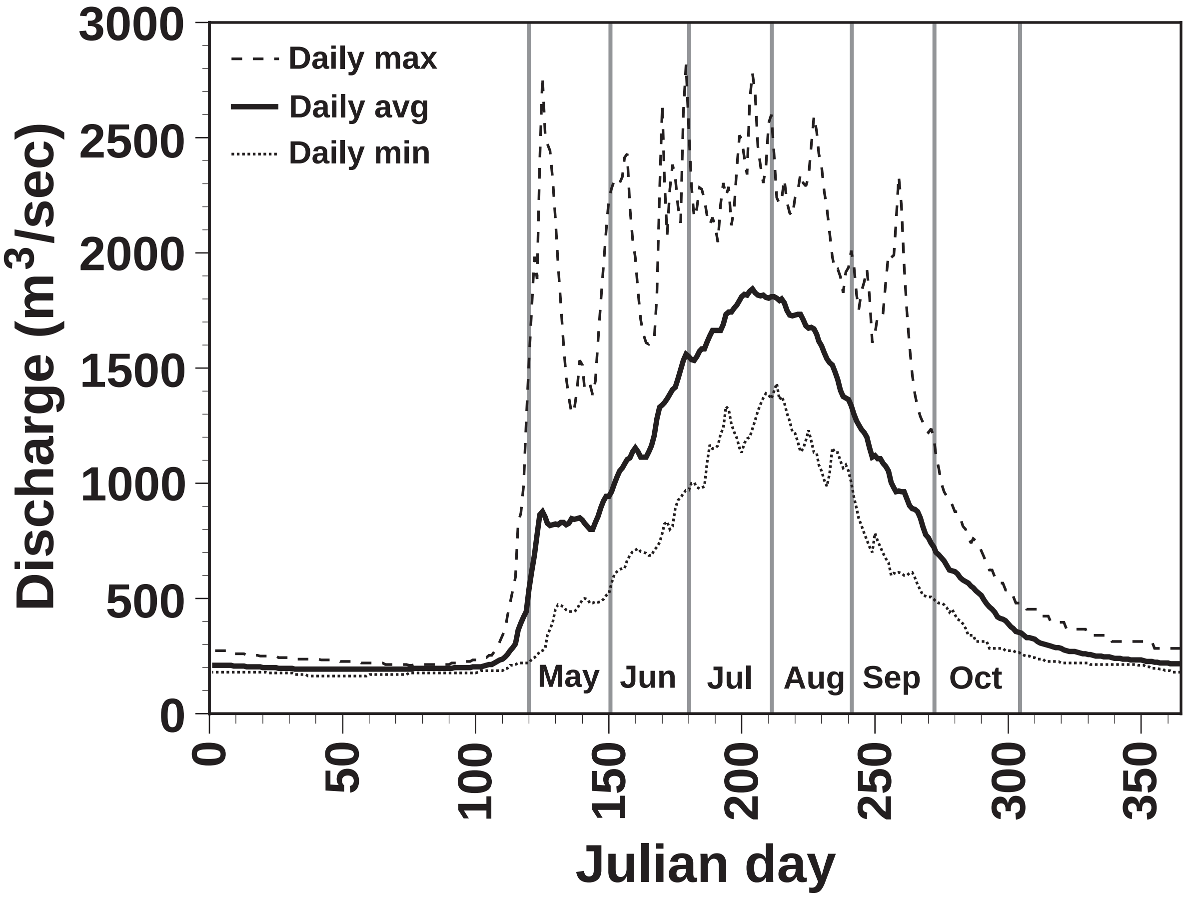

Figure 3. Hydrograph of the Tanana River, 1978-99, at Nenana, Alaska approximately 574 km from the river source. (Source: U.S. Geological Survey)

4.) Minimum daily discharge patterns closely matched average daily discharge patterns,
5.) Maximum daily discharge was highly variable during the entire icefree period,
6.) Variability of daily discharge was much greater during the icefree period compared to the winter months.

Annual icefree mean discharge of the Tanana, from 1962-99, fluctuated between 850 and 1695 m^3/sec, and averaged 1156 m^3/sec during the period of record (Figure 4). One apparent pattern was that icefree mean discharge decreased, and subsequently increased again, every 4 or 5 years from 1962-75. During the period of study, annual icefree mean discharge appeared to be relatively stable, and within the range of variability observed during the longer period of record.

More apparent patterns emerge, however, when the annual icefree mean discharge of the Tanana is expressed as a departure from mean icefree discharge (Figure 5A). The three cycles of decreasing and subsequently increasing annual icefree mean discharge from 1962-75, apparent in Figure 4, are also apparent in Figure 5. In addition, it can be seen that during the periods from 1969-81 and from 1996-99, the Tanana was more droughty (annual icefree mean discharge is less than the mean icefree discharge) than not. From 1962-68, the Tanana was generally in a flood condition (annual icefree mean discharge is greater than the mean icefree discharge). The six year period from 1988-93 was the longest sustained period of flood for the period of record. During the period of study, the Tanana River first experienced generally droughty conditions (1978-81), followed by a period of floods (1982-85, 1988-93), and most recently, a period of general drought (1996-99). The annual icefree mean discharge of the Tanana ranged from –26.5% to +46.6% of the mean icefree discharge during the period of record; it ranged from –26.5% to +14.4% of the mean icefree discharge during the period of study.

Annual peak discharge of the Tanana appeared to be more variable than annual icefree mean discharge (Figure 4). Annual peak discharge varied from 1470 to 5183 m^3/sec, and averaged 2329 m^3/sec during the period of record. Two different patterns of annual peak discharge were apparent. First, three periods of generally decreasing and then increasing peak flows occurred from 1962-75. Second, starting in 1978, annual peak discharge generally increased until the late 1980s to early 1990s, and then decreased until 1996.

When the annual peak discharge of the Tanana was expressed as a departure from mean peak discharge (Figure 5B), general patterns of relative flood and drought were similar to those of the annual icefree mean discharge expressed as a departure from mean icefree discharge (Figure 5A). Relative to mean peak discharge, annual peak discharge was generally less from 1972-1982, and from 1993-1999. Annual peak discharge of the Tanana was generally more then the average from 1962-67 and from 1983-92. During the period of study, peak discharge of the Tanana was less than average (1978-82), then generally greater than average (1983-92), and most recently (1993-99), less than average again. The annual peak discharge of the Tanana ranged from –36.9% to +122.5% of the mean peak discharge during the period of record; it ranged from –36.9 to +19.4% of the mean peak discharge during the period of study.

River Bank Erosion

When summarized by river reach, the amount of land area eroded along the entire Tanana River totaled 5,104 ha, with 3,888 ha (76%) contributing LWD (Figure 6). The distribution of total land area eroded along the river was highly variable, and ranged from 0.3 ha to 309 ha/10 km of river. Total land eroded averaged 62 ha/10 km of river. The amount of land area eroded that contributed LWD was also highly variable, ranging from 0.3 to 272 ha/10 km of river. The amount of land eroded that contributed LWD averaged 47 ha/10 km of river.

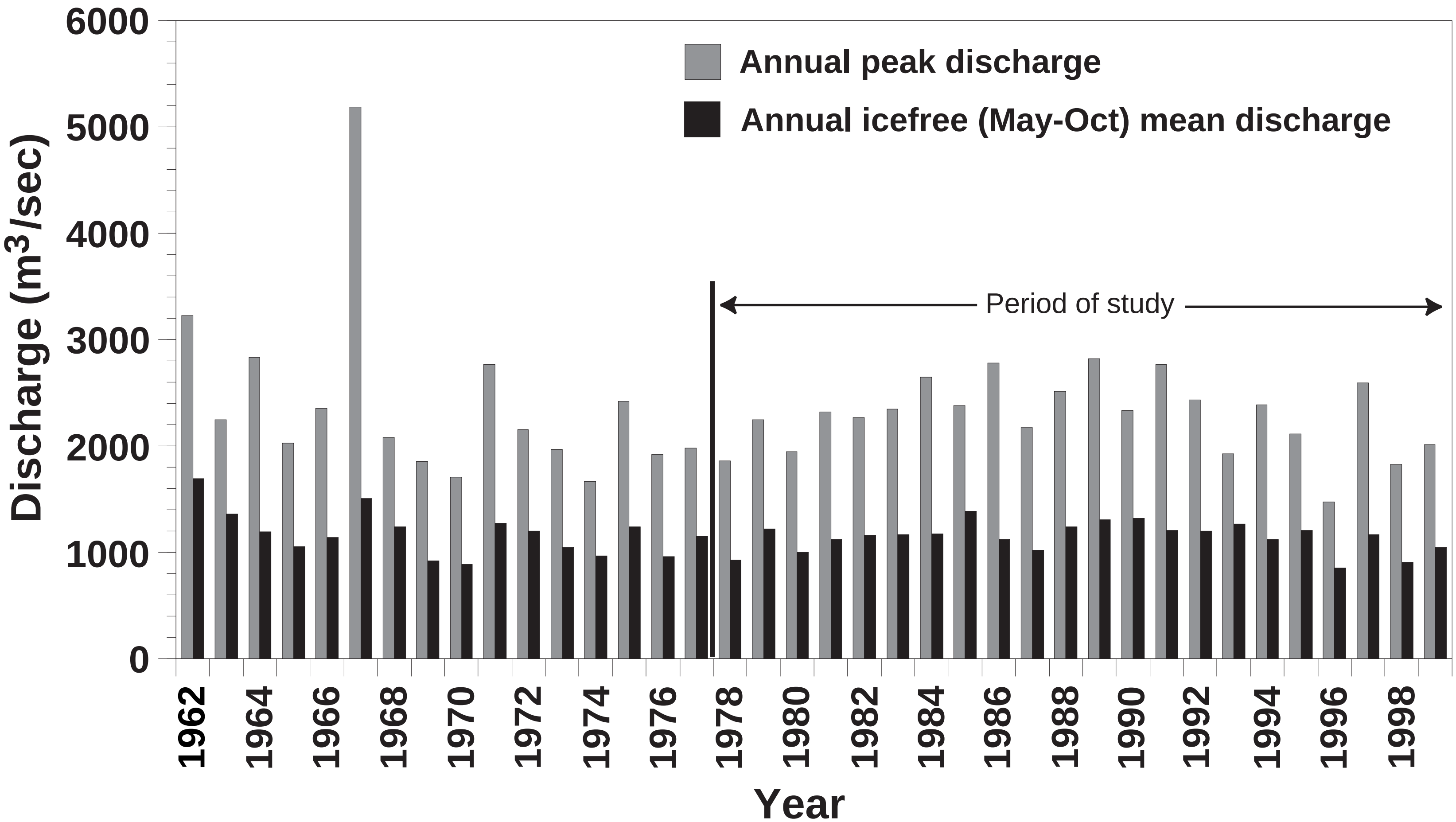

Figure 4. Annual icefree mean discharge and annual peak discharge for the Tanana River at Nenana, Alaska during the period of record. (Data source: U.S. Geological Survey)

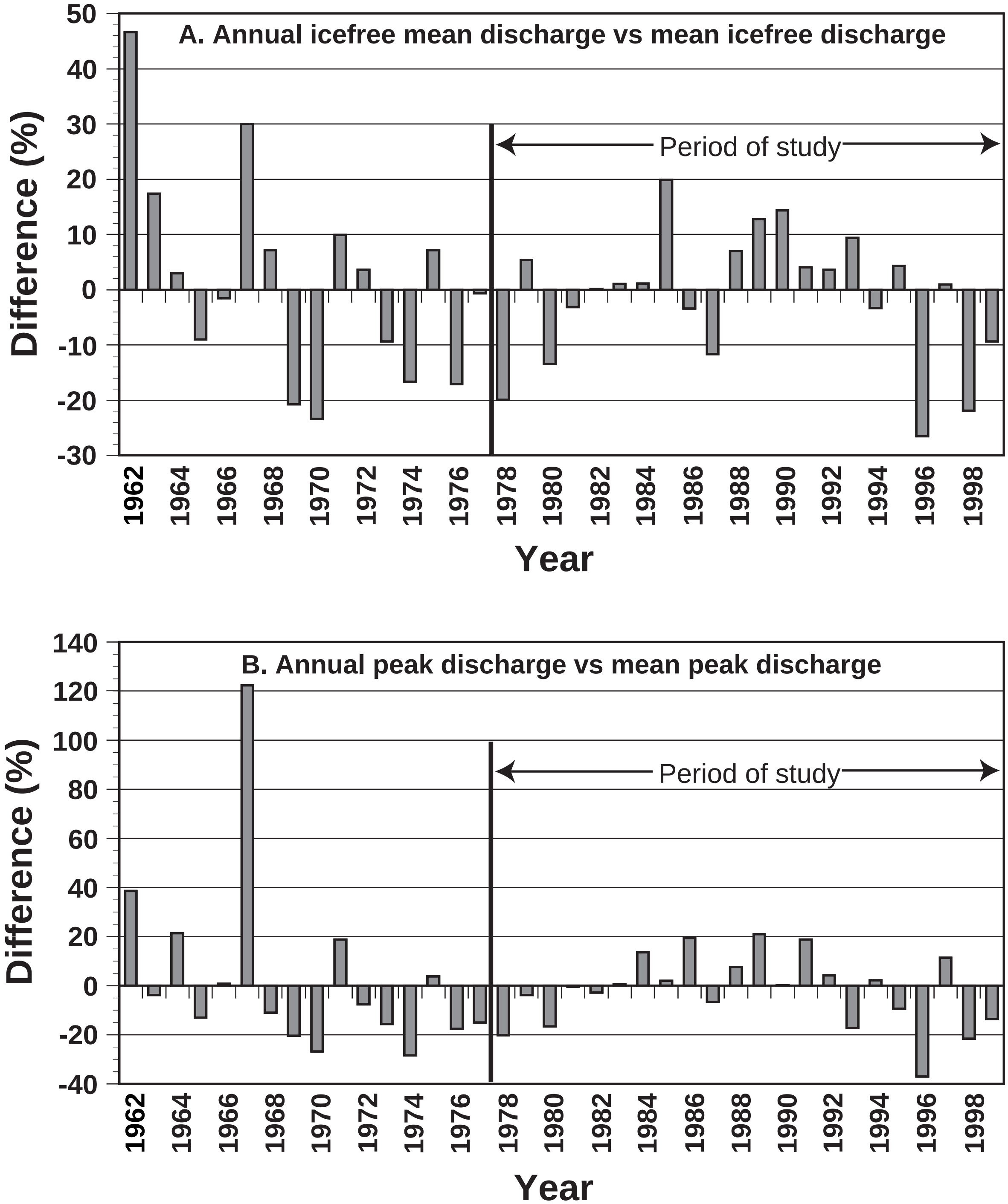

Figure 5. Comparison of the difference between annual icefree mean discharge (May-Oct) and mean icefree discharge (1156 m^3/sec), and annual peak discharge and mean peak discharge (2329 m^3/sec) of the Tanana River at Nenana, Alaska for the period of record. (Data source: U.S. Geological Survey)

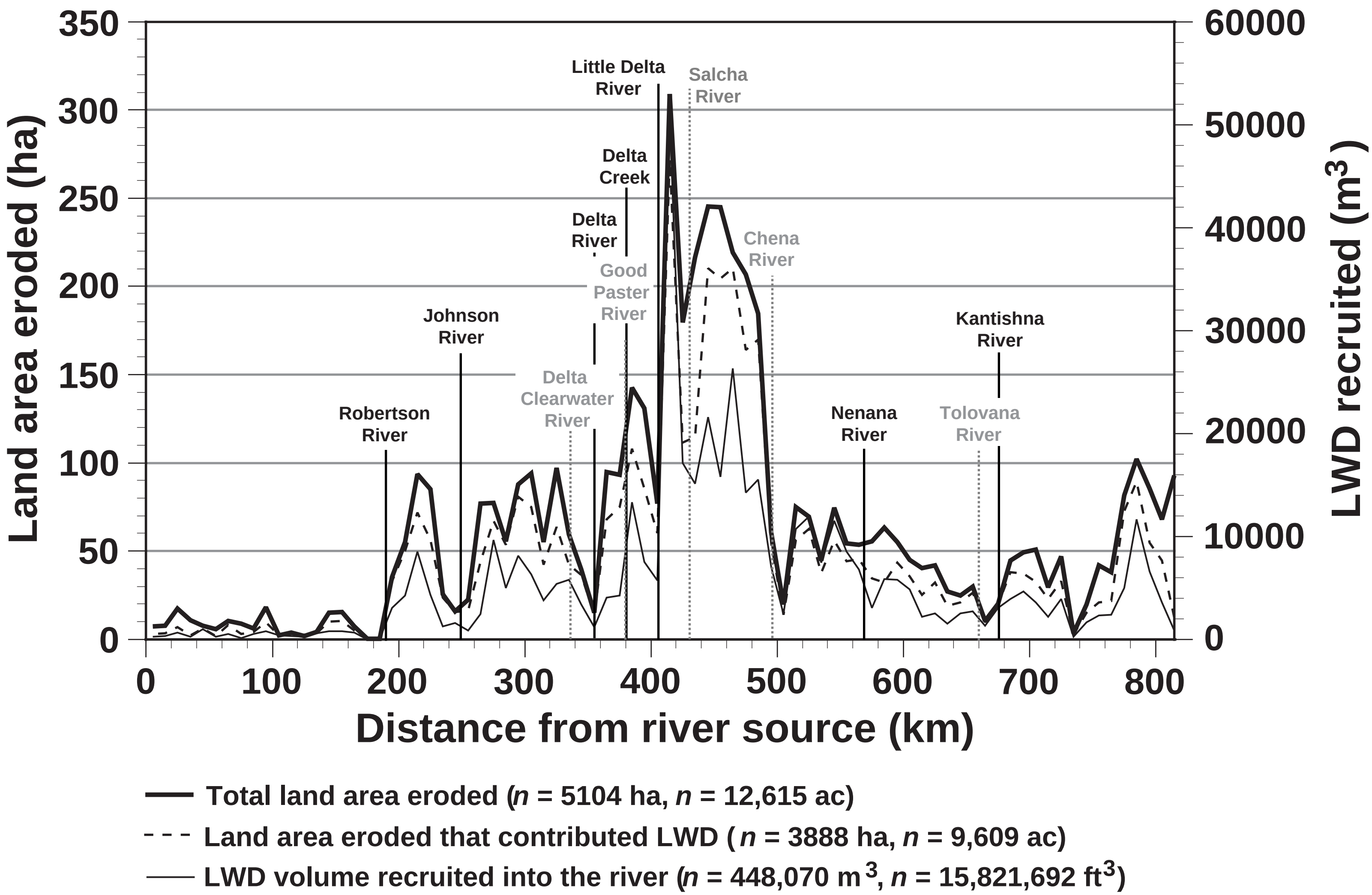

Figure 6. Distribution of land area eroded and large woody debris (LWD) recruited along the Tanana River. The source of the river actually is located 4 km beyond the zero point (i.e. -4 km) of this graph. This figure was constructed using data derived for 10 km reaches, where the values for each reach were placed at the midpoint distance for that reach. Approximate locations of major tributaries with glacial origins are shown with solid black lines, and approximate locations of major tributaries with non-glacial origins are shown with dashed gray lines.

General erosion patterns were observed along the Tanana even though a large amount of variability was apparent (Figure 6). The first 190 km of the Tanana were the most stable, with relatively little erosion observed. Erosion began to abruptly increase at 190 km from the river source, reaching a peak between 410 and 420 km from the river source. At 490 km from the river source, erosion quickly decreased to relatively moderate levels. This moderate level of erosion was maintained until 740 km from the river source, where erosion once again increased for the remainder of the length of the river.

This general pattern of erosion along the Tanana allowed us to distinguish five fairly distinct regions of erosion based on the amount of total land area eroded (Figure 7). Erosion Region I starts at the river source and extends 190 km downriver; it includes the length of the Tanana that experienced the least erosion. The average amount of the total land area eroded in Region I was 0.8 ha/km of river. Only 2.9% of the total land area eroded, and 2.1% of the eroded land that contributed LWD to the Tanana was located in Erosion Region I. Erosion Region II extends from 190 to 410 km from the river source. This 220 km section of river represents the second most erosive portion of the river, with erosion averaging 6.9 ha/km. About one third of the total land area eroded (29.9%) and eroded land that contributed LWD (30.4%) was located in Erosion Region II. Erosion Region III extends between 410 and 490 km from the river source. This 80 km stretch of river was the most erosive, with erosion averaging 22.6 ha/km. Erosion Region III contributed 35.4% of the total land area eroded and 37.5% of the land that contributed LWD. Erosion activity decreased substantially in Erosion Region IV, that extends from 490 to 740 km from the river source. Erosion averaged 4.4 ha/km of river within this 250 km stretch of river. Land area eroded within Erosion Region IV was 21.4% of the total and 21.5% of the land that contributed LWD. Erosion Region V extends from 740 to 820 km from the river source, ending at the Yukon River. Erosion Region V was the third most erosive section of river, with erosion averaging 6.6 ha/km for this 80 km stretch of river. Eroded land within this last region contributed 10.4% of the total land eroded, and 8.5% of the land that contributed LWD.

The distribution of eroded land was variable among vegetation sizes classes (Figure 8). The greatest amount of erosion (28.3%) occurred within stands of trees characterized as small-statured dwarf forests (e.g. black spruce stands), sapling-sized stands of tree species (i.e. reproduction), and recently burned stands[1]. The amount of erosion that occurred within pole-sized stands of trees (27.8%) was almost as much as within the smallest-statured and smallest-diameter stands. Almost one quarter (22.9%) of the erosion occurred within vegetation types classified as shrublands, wetlands, and other non-forested lands. Erosion in sawlog-sized stands of trees totaled 18.4%. Erosion in mixed sawlog and pole-sized stands of trees only totaled 2.7%.

The distribution of land area eroded by vegetation size classes within each erosion region are shown in Table 2. In Erosion Regions I, II, III, and V, the most erosion occurred (33.3 to 38.4%) within stands of trees characterized as small-statured dwarf forests, sapling-sized stands of tree species, and recently burned stands. In Erosion Region IV, the most erosion (30.6%) occurred within sawlog-sized stands of trees. In all five erosion regions, the least amount of erosion (0.9 to 7.9%) occurred within stands of mixed sawlog and pole-sized trees. In Erosion Region I, an equal amount of land area was eroded within stands of mixed sawlogs and poles and within sawlog-sized stands of trees.

[1] Small-statured dwarf forests, sapling-sized stands of trees, and recently burned stands are combined in the Dwarf/Repro/Burned vegetation size class.

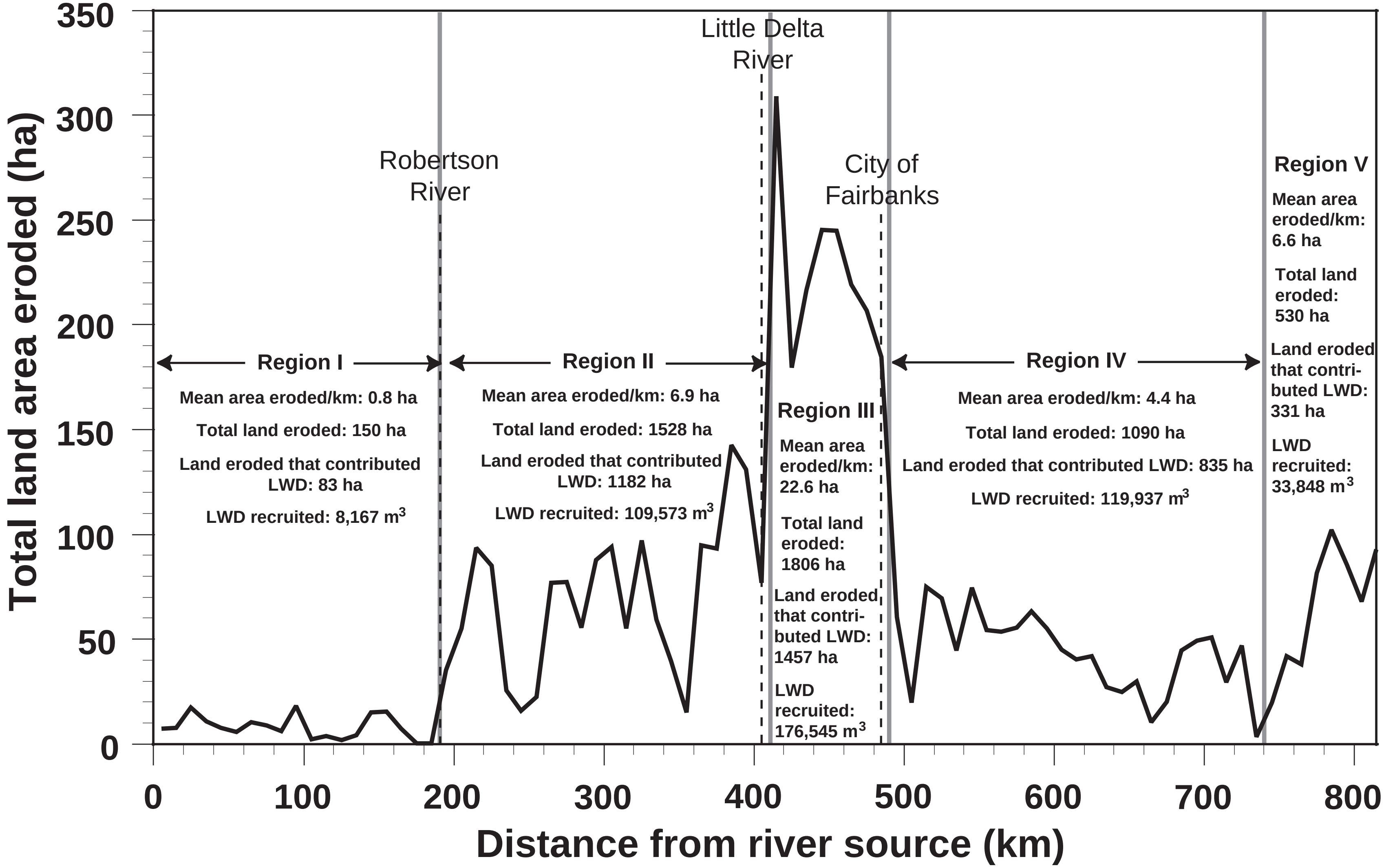

Figure 7. Erosion regions along the Tanana River based on total land area eroded. The source of the river actually is located 4 km beyond the zero point (i.e. -4 km) of this graph.

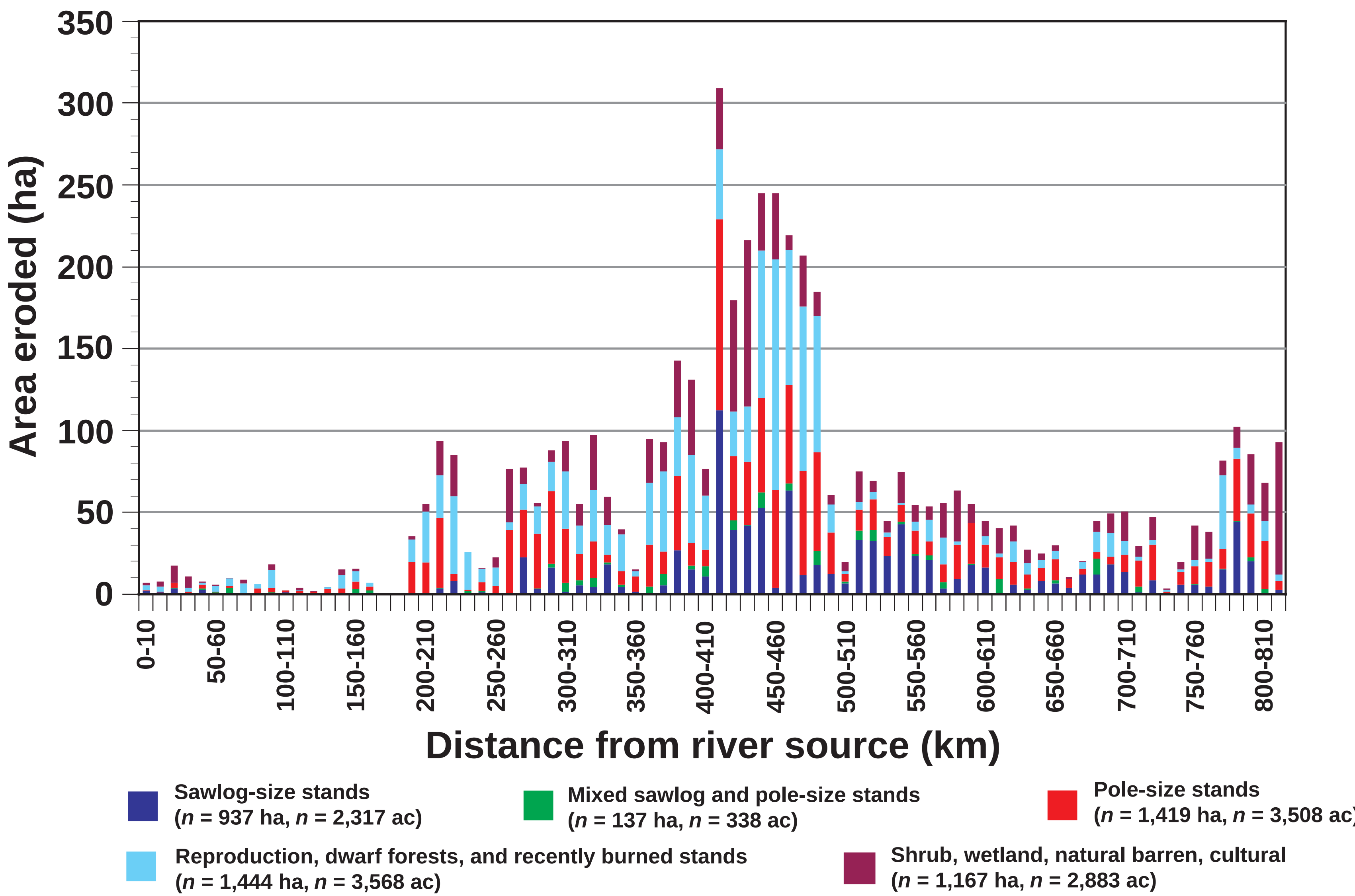

Figure 8. Distribution of land area eroded along the Tanana River by vegetation size class. The source of the river actually is located 4 km beyond the zero point (i.e. -4 km) of this graph. This figure was constructed using data derived for 10 km reaches, where the values for each reach were placed at the midpoint distance for that reach.

Table 2. Distributions (%) of land area eroded by vegetation size classes within each erosion region along the Tanana River. Land area eroded in each region is shown in parentheses.

Vegetation Size class	Erosion region I (*n* = 150 ha)	Erosion region II (*n* = 1,528 ha)	Erosion region III (*n* = 1,806 ha)	Erosion region IV (*n* = 1,090 ha)	Erosion region V (*n* = 530 ha)
Sawlog-sized	7.9%	9.8%	19.0%	30.6%	18.7%
Mixed Sawlog/ Pole	7.9	2.8	1.6	4.5	0.9
Pole-sized	21.2	29.1	27.5	27.5	27.7
Dwarf/Repro/ Burned	38.4	36.2	33.3	13.9	15.1
Shrub/Wetland/ Barren/Cultural	24.5	22.2	18.7	23.4	37.5

The distributions of eroded land area within each vegetation size class across the five erosion regions are shown in Table 3. The great majority (72.2%) of erosion that occurred within sawlog-sized stands occurred within Erosion Region III (36.6%) and Erosion Region IV (35.6%). Erosion within mixed sawlog and pole-sized stands was more evenly distributed than erosion in sawlog-sized stands. Two thirds (66.9%) of erosion in this size class, however, still occurred within two erosion regions (II and IV). Two thirds (66.3%) of the erosion within pole-sized stands of trees also occurred within two erosion regions (II and III). Erosion within small-statured, small-diameter, and burned stands was concentrated in Erosion Region III (41.6%), but a large amount of erosion in this vegetation size class also occurred within Erosion Region II (38.3%). Erosion of shrublands and other non-forested land cover was fairly evenly distributed across Erosion Regions II, III, and IV (21.9 to 29.0%). Erosion of all of the vegetation size classes was least in Erosion Regions I and V.

Table 3. Distributions (%) of land area eroded within each vegetation size class across the Tanana River erosion regions.

Erosion region	Sawlog-sized (*n* = 937 ha)	Mixed sawlog and pole-sized (*n* = 137 ha)	Pole-sized (*n* = 1,419 ha)	Dwarf/Repro/ Burned (*n* = 1,444 ha)	Shrub/Wetland/ Barren/Cultural (*n* = 1,167 ha)
I	1.3%	8.8%	2.3%	4.0%	3.2%
II	15.9	30.9	31.3	38.3	29.0
III	36.6	20.6	35.0	41.6	28.9
IV	35.6	36.0	21.1	10.5	21.9
V	10.6	3.7	10.4	5.5	17.1

Erosion also varied among vegetation strata (Table 4). Erosion occurred most frequently (21.0%) in tall shrublands, followed by stands of balsam poplar saplings (15.7%), balsam poplar pole-sized stands (12.5%), and white spruce sawlog stands (9.2%). Within forested vegetation strata, erosion occurred least frequently in “other” stands of mixed sawlogs and pole-timber (<0.1%), stands of white spruce saplings (0.1%), and stands of birch and aspen saplings (0.7%). In total, erosion in non-forested strata equaled 22.9%.

A total of 4,266 individual erosion patches were identified along the entire Tanana River (Figure 9). The size of erosion patches varied from 0.01 ha to 58.84 ha, but their numbers generally decreased exponentially with increasing size. The vast majority of erosion patches (*n* = 3,328, 78.0%) were very small (0.01 to 1.00 ha) in size. Within the 0.01 to 1.00 ha size class, the number of erosion patches also decreased exponentially with increasing size. Almost one third

Table 4. Land area eroded and large woody debris recruited by land cover type (i.e.DOF vegetation strata)

Strata number	Dominant forest stand vegetation	Dominant tree size within a stand	Land area eroded		Large woody debris recruited	
			Hectares	%	m^3	%
1	White spruce	Sawlog	470	9.2	110,747	24.7
2	White spruce	Poletimber	119	2.3	16,567	3.7
3	Black/white spruce	Saw/poletimber	51	1.0	4,047	0.9
4	Other	Saw/poletimber	<1	<0.1	6	<0.1
5	Balsam poplar	Sawlog	98	1.9	11,237	2.5
6	Balsam poplar	Poletimber	640	12.5	57,872	12.9
7	Paper birch/quaking aspen	Saw/poletimber	39	0.8	3,580	0.8
8	White spruce/birch/aspen	Sawlog	69	1.4	15,323	3.4
9	White spruce/birch/aspen	Poletimber	179	3.5	21,228	4.7
10	Black/white spruce/birch/aspen	Saw/poletimber	47	0.9	4,531	1.0
11	White spruce/balsam poplar	Sawlog	301	5.9	76,028	17.0
12	White spruce/balsam poplar	Poletimber	481	9.4	75,922	16.9
20	White spruce	Dwarf/Repro/Burned	4	0.1	226	0.1
21	Black/white spruce	Dwarf/Repro/Burned	21	0.4	262	0.1
22	Other coniferous stands	Dwarf/Repro/Burned	252	4.9	182	<0.1
23	Balsam poplar	Dwarf/Repro/Burned	802	15.7	37,024	8.3
24	Birch/aspen	Repro/burned	38	0.7	988	0.2
25	White spruce/birch/aspen	Repro/burned	17	0.3	739	0.2
26	Black/white/spruce/birch/aspen	Dwarf/Repro/Burned	106	2.1	4,021	0.9
27	White spruce/balsam poplar	Dwarf/Repro/Burned	204	4.0	7,540	1.7
30	Tall shrubland		1,070	21.0		
31/32	Low shrubland		71	1.4		
33	Aquatic		13	0.3		
34	Wet sedge grass and emergent		5	0.1		
50	Barren		7	0.1		
60	Cultural		<1	<0.1		

(32.5%) of the erosion patches were 0.01 to 0.10 ha in size. Almost all (*n* = 4032, 94.5%) of the erosion patches were ≤5.0 ha in size.

The distribution of eroded land area across erosion patches of varying sizes[2] was more evenly distributed than the sizes of individual erosion patches (Figure 9). The greatest cumulative amount of erosion (*n* = 826.5 ha, 16.1%) occurred within patches that were 0.01 to 1.00 ha in size, followed by erosion patches 1.01 to 2.00 ha in size (*n* = 541.4 ha, 10.5% of land eroded). Within the 0.01 to 1.00 ha patch size, the amount of land area eroded was uniformly distributed (1.4 to 2.0 % of total land area) across the ten 0.1 ha size classes. The cumulative amount of land eroded was about equal within erosion patches 2.01 to 3.00 ha in size (*n* = 364.7 ha, 7.1%) and 3.01 to 4.00 ha in size (*n* = 372.3 ha, 7.3%). The total land area contained within erosion patches ≤ 5.00 ha was 2,420.8 ha (47.2% of the total).

The distribution of the maximum erosion distance within erosion patches was right-skewed (Figure 10). Erosion distance varied from <2 m to 401 m. Erosion distance averaged 39 m; median erosion distance was 25 m, and modal erosion distance was 10 m. Maximum erosion distance most commonly (26.6%) was in the 10 to 19 m distance category. The majority of patches (56.7%) had a maximum erosion distance of <30m, and 76.3% of the erosion patches had a maximum erosion distance <50 m.

Large Woody Debris Recruitment

When summarized by river reach, the volume of LWD recruited in to the Tanana River totaled 448,070 m^3 (Figure 6). The distribution of LWD along the river varied from 8.2 m^3 to 50,867 m^3/10 km of river. LWD recruitment averaged 5,464 m^3/10 km of river. The amount of LWD was strongly associated with the total amount of land area eroded ($r^2 = 0.78$) and more strongly associated with the amount of land area eroded that contributed LWD ($r^2 = 0.84$).

General patterns of LWD recruitment along the river generally followed those of land erosion patterns (Figures 6), although the pattern of LWD recruited by erosion region was slightly different (Figure 7). Only 2.9% of the LWD was recruited from Erosion Region I, the region that exhibited the least erosion. LWD recruitment from Erosion Region II was third highest (24.5%), although this region ranked second in total land area eroded and in land area eroded that contributed LWD. The greatest volume of LWD (39.4%) was recruited from Erosion Region III, the most erosive region of the entire Tanana. The volume of LWD recruited in Erosion Region IV was the second largest, although this region ranked third in the amount of land area eroded. Erosion Region V was ranked fourth for LWD recruitment (7.6%), just as it was ranked fourth for the amount of land area eroded.

The distribution of LWD recruitment was variable among vegetation size classes (Figure 11). The largest volume of LWD (47.6%) originated from sawlog-sized stands of trees. Pole-sized stands of trees contributed the second largest volume of LWD (38.3%), followed by forest stands characterized as small-diameter, small-statured, or recently burned (11.4%). Stands of mixed sawlog and pole-sized timber contributed the smallest volume (2.7%) of LWD.

The distributions of LWD recruitment within each vegetation size class across the five erosion regions of the Tanana are shown in Table 5. The great majority (74.0%) of LWD recruitment from sawlog-sized stands occurred within Erosion Regions III and IV. LWD from stands of mixed sawlog and pole-sized trees was recruited primarily from Erosion Regions II and IV (74.5% combined). LWD recruitment from pole-sized stands of trees occurred primarily from

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[2] Total land area eroded was 5,132 ha when summed by erosion patch size, whereas land area eroded totaled 5,104 ha when summed by vegetation strata within each 10 km reach—see the Methods section for a detailed discussion.

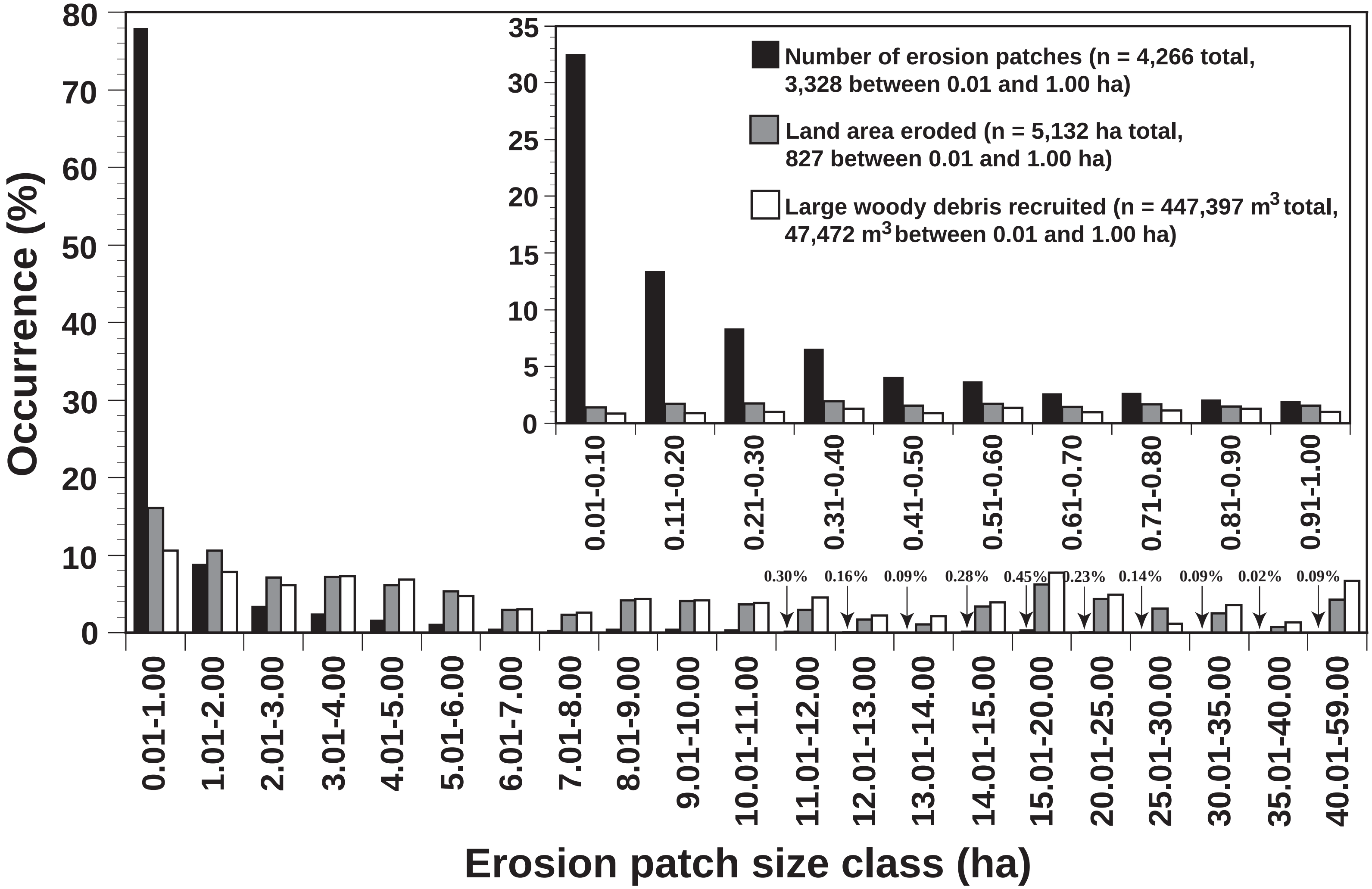

Figure 9. Distribution of the number of indivuidual erosion patches, land area eroded, and large woody debris recruited by erosion patch size class of the eroded areas along the Tanana River. The inset graph depicts the distribution of the three variables for the 0.01 to 1.00 ha size class of eroded areas.

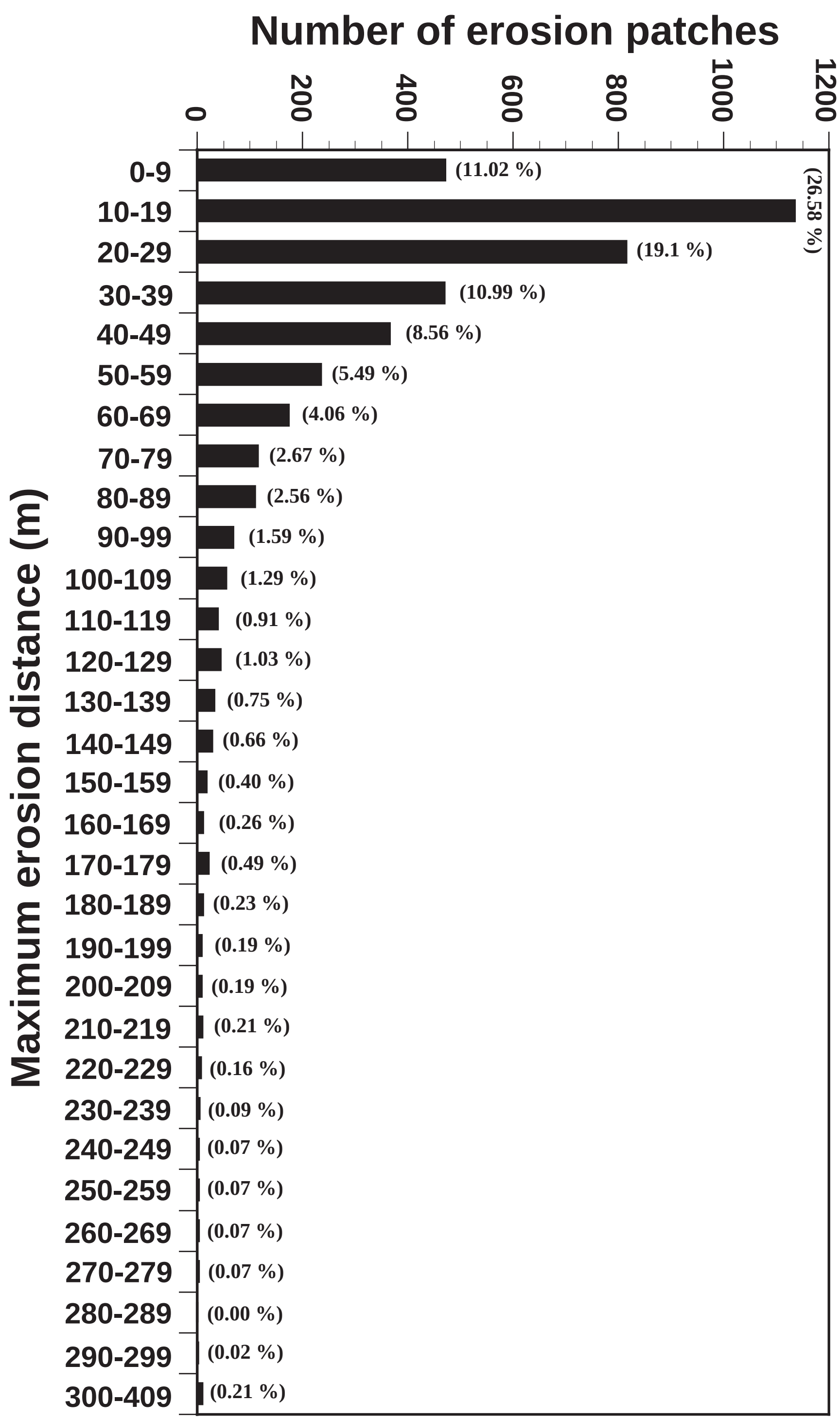

Figure 10. Distribution of the maximum distance eroded (perpendicular to the river bank) within individual erosion patches along the Tanana River. The total number of erosion patches was 4,266. The 0-9 m distance category contains 9 erosion patches whose erosion distances were <2 m but were not measurable.

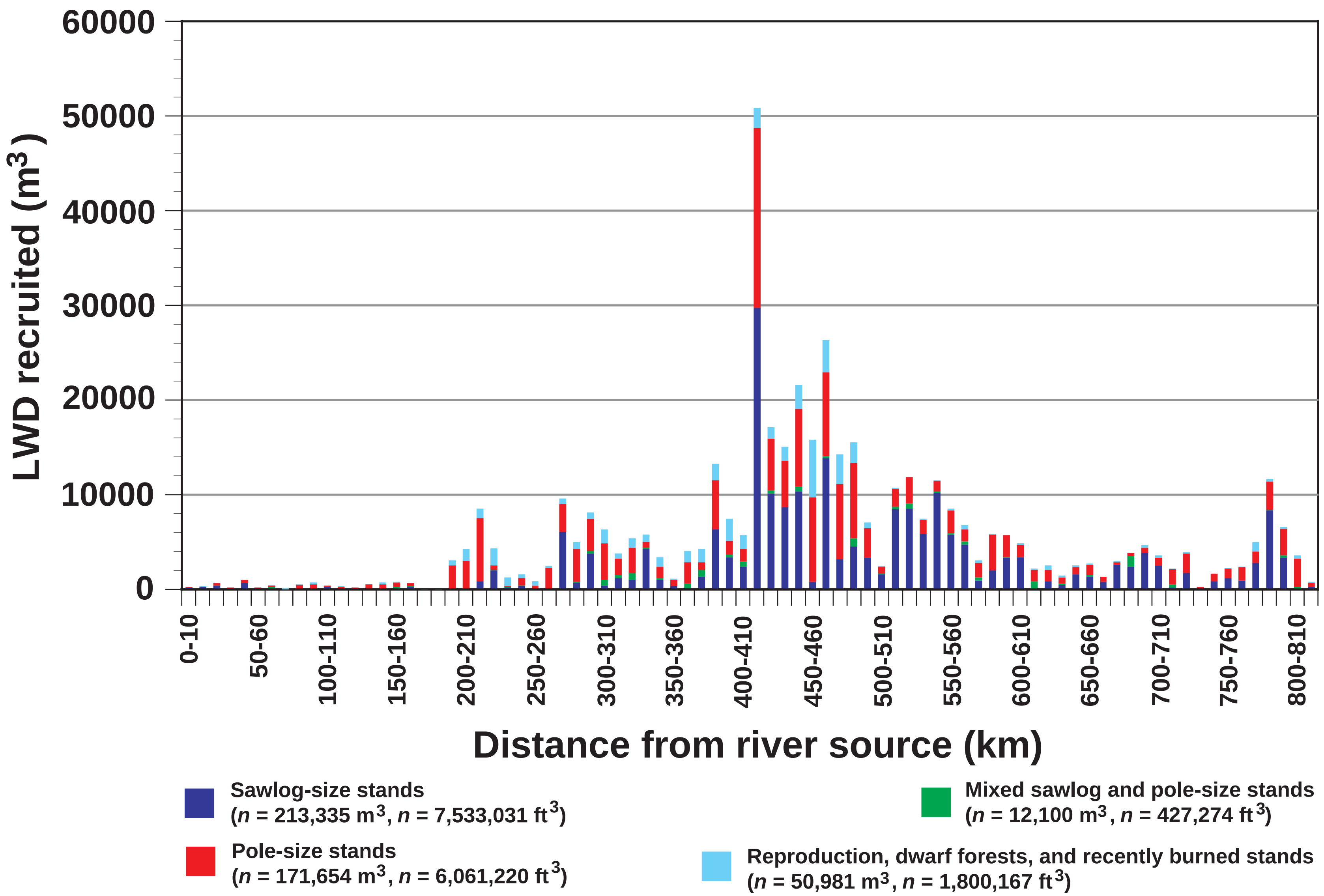

Figure 11. Distribution of large woody debris recruited along the Tanana River by stand size-class. The source of the river actually is located 4 km beyond the zero point (i.e. -4 km) of this graph. This figure was constructed using data derived for 10 km reaches, where the values for each reach were placed at the midpoint distance for that reach.

Erosion Region III (41.5%), although Erosion Regions II and IV each contributed >20% of LWD from this size class. Recruitment of LWD from small-diameter, small-statured, and recently burned stands occurred overwhelmingly within Erosion Regions II and III (86.2%). LWD recruitment from all size classes of trees was the least in Erosion Regions I and V.

Table 5. Distributions (%) of large woody debris by each vegetation size class across the Tanana River erosion regions.

Erosion region	Sawlog-sized (n = 213,335 m^3)	Mixed sawlog and pole-sized (n = 12,100 m^3)	Pole-sized (n = 171,654 m^3)	Dwarf/Repro/ Burned (n = 50,981 m^3)
I	1.0%	5.8%	2.5%	1.9%
II	16.6	37.7	27.8	42.7
III	38.1	15.3	41.5	43.5
IV	35.9	36.8	20.3	7.9
V	8.3	4.4	7.8	4.0

LWD recruitment also varied among vegetation strata (Table 4). LWD volume was greatest from stands of white spruce sawlogs (24.7%), followed by stands of white spruce/balsam poplar sawlogs (17.0%), white spruce/balsam poplar poletimber (16.9%), and balsam poplar poletimber (12.9%). Generally, the smallest volumes (often <1.0%) of LWD were contributed by small-diameter, small-statured, and recently burned stands.

The distribution of LWD recruitment across erosion patches of varying sizes[3] ranged from 1.1 to 10.6% (Figure 9). Erosion patches 0.01 to 1.00 ha in size contributed the most LWD (n = 47,472 m^3, 10.6%), followed by patches 1.01 to 2.00 ha in size (n = 35,056 m^3, 7.8%) and 15.01 to 20.00 ha in size (n = 34,729m^3, 7.8%). Within the 0.01 to 1.00 ha patch size, LWD recruitment was uniformly distributed (0.8 to 1.4% of total LWD recruitment) across the ten 0.1 ha size classes. The total amount of LWD recruited from erosion patches ≤5.0 ha was 173,595 m^3 (38.8% of total LWD recruitment). The majority of LWD (53.6%) was recruited form erosion patches ≤ 9.00 ha in size.

DISCUSSION

Appropriateness of This Project as a Baseline Study

During the time period represented by this study, discharge characteristics of the Tanana River were similar to those representing the longer period of recorded history for the river. The hydrograph of the Tanana at Nenana, Alaska from 1978-99 (Figure 3) was similar to the hydrograph of the Tanana at the same location from 1962-96 (Yarie et al. 1998). For both time periods, Tanana average discharge rose from a winter low about mid-April, peaked during mid- to late-July, and decreased again to a winter low during early November. Maximum average discharge was similar (about 1800 m^3/sec) for both time periods. For both time periods, the distribution of daily minimum discharge values was similar to average daily discharge values, peaking during late July to early August. Maximum daily discharge values were highly variable from May to September for both time periods. During the period of study, annual icefree mean discharge and annual peak discharge were within the range of variability observed during the

[3] Total LWD recruitment was 447,397 m^3 when summed by erosion patch size, whereas LWD recruitment totaled 448,070 m^3 when summed by vegetation strata within each 10 km reach—see the Methods section for a detailed discussion.

longer period of record (Figure 4). The Tanana River experienced periods of relative drought and flood during the period of study and also during the longer period of record (Figure 5). One discernable difference between the two time periods was that both annual icefree discharge and annual peak discharge of the Tanana were less variable from 1978-99 than from 1962-78 (Figure 5).

The bank erosion and LWD recruitment data derived from this study were deemed suitable as baseline datasets, to which similar studies in the future can be compared, based upon discharge characteristics of the Tanana River as discussed above. This finding is especially important because a warming trend in interior Alaska during the period of study (Juday et al. 1998) was hypothesized to result in a systematic increase of river discharge during that time.

River Bank Erosion

Differences in the amount of bank erosion along the Tanana River can be explained primarily by differences in longitudinal slope, sediment load, and resistance of the banks and bed to movement of flowing water.

Differences in erosion along the Tanana River were, in part, associated with slope differences (Figure 2). Erosion Region III, the most erosive region of the river, is located along the portion of the Tanana with the greatest slope gradient. Erosion Region II, the second most erosive region, is primarily located along the portion of the Tanana where the second steepest slope gradient exists; Erosion Region II also includes a portion of the river where the steepest slope exists. For a given volume of water, an increased slope of the riverbed results in an increased velocity of the river, thereby increasing the erosive potential of the river.

Differences in erosion along the Tanana River also were, in part, associated with the distribution of tributaries of glacial origin (Figure 6). Some of the largest spikes of erosion occurred just downriver from the mouths of such tributaries as the Robertson River, Johnson River, Delta River, Delta Creek, and Little Delta River (Figure 6). In contrast, increases in erosion along the Tanana just downriver from the Nenana River and the Kantishna River were relatively small (Figure 6), even though these are two of the four largest glacially-fed tributaries in terms of volume (Anderson 1970). Differences in sediment loads of the tributaries partly account for the differences in bank erosion along the Tanana in conjunction with the tributaries. Rivers of glacial origin have very large sediment loads as a result of the large amount of rock flour and other rock debris present in glacial meltwater. Where they meet the Tanana River, the Robertson River, Johnson River, Delta River, Delta Creek, and Little Delta River are still close to their source glaciers. As a result, these rivers deliver very large sediment loads to the Tanana, as indicated by their braided channel pattern at their mouths. The Nenana and Kantishna Rivers are sediment-laden and braided at their headwaters as well. Unlike the sediment-laden tributaries of the upper Tanana, however, these two rivers flow across the broad Tanana Flats before they join with the Tanana River. They drop much of their sediment load in the process. In fact, the Nenana River at its mouth is clearer than the Tanana River.

In response to the inputs from the sediment-laden glacial tributaries, the Tanana River went from having a single channel or anastomosing pattern (several main channels with stable vegetated islands) just upriver of these tributaries, to a braided pattern just downriver (Worum et al. 2001a, 2001b). Braided reaches have multiple channels with unvegetated, unstable gravel bars. Banks of braided channels are more prone to erosion because channels are constantly changing course as the riverbed locally aggrades. In contrast to the response of the Tanana to inputs from sediment-laden tributaries, the Tanana did not become braided downriver from the mouths of the Nenana and Kantishna Rivers (Worum et al. 2001c).

The most erosive regions of the Tanana were characterized as having a combination of steep slopes and sediment inputs from tributaries of glacial origin. Erosion Region II, the second most erosive region (29.9% of eroded land from 26.7% of river length), has the second steepest slope and receives sediment from four tributaries of glacial origin. One of those tributaries is the Delta River. The Delta River is one of the four largest tributaries of the Tanana in terms of volume (Anderson 1970), so presumably it also contributes a significant sediment load. Erosion Region III, the most erosive region of the Tanana (35.4% of eroded land from 9.7% river length), begins just downriver from Erosion Region II. Erosion Region III has the steepest slope but it only receives sediment input from one sediment-laden tributary of glacial origin. The disproportionate amount of erosion in Erosion Region III may be a result of the combination of: (1) higher energy water resulting from the steep slope, and (2) unusually large sediment loads as a consequence of all of the erosion occurring in Erosion Region II as well as additional sediment from the Little Delta River. The abrupt decrease in slope at Fairbanks and the absence of additional large sources of sediment from tributaries of glacial origin probably accounts for the reduced erosion levels that characterize Erosion Region IV.

Relative resistance of the riverbanks to moving water also helps explain erosion patterns along the Tanana. Where the banks of the Tanana consist of bedrock, little or no erosion occurred. Examples include Cathedral Rapids located about 175 km from the river source, and Bean Ridge located about 735 km from the river source. These two areas show up as areas of very low erosion on Figure 6. The increased erosion in Erosion Region V (relative to Erosion Region IV) may be due to less cohesive river banks. Several major areas of stabilized sand dunes are located near the lower Tanana River (Péwé 1975) but no major tributaries enter the river in Erosion Region V. In fact, dune features of the Aeolian Hills near the mouth of the Tanana are apparent on the 1978-80 CIR aerial photos (Worum et al. 2001c). Banks with a higher sand component may be less cohesive, and therefore, less resistant to erosion, than banks with a higher silt component.

The distribution of land area eroded was not uniform among vegetation strata (Table 4). Almost one quarter (22.4%) of the erosion occurred in shrublands. An additional one-third of the erosion came from three forested vegetation strata. These numbers suggest that certain vegetation strata are more prone to erosion than other vegetation strata. However, we can not comment on these trends because we were unable to objectively quantify the amount of land available for erosion within each vegetation strata. Without being able to compare the actual amount of land area eroded to the total amount of land available for erosion for a particular vegetation strata, we could not determine if particular strata were prone to erosion.

The distributions of erosion patch sizes and maximum distances eroded did not provide any insights regarding the actual erosional processes that occurred. The majority of erosion, however, is likely to have occurred during the icefree period. During this time, high discharge rates give the Tanana the greatest erosive energy at a time when river banks are least resistant to erosion because they are thawed, or in the case of permafrost soils, have a seasonal thaw layer. Where erosion occurs along high river banks, it is apparent that the vegetative mat is well above normal high water and, therefore, plays a limited role in reducing or inhibiting natural erosion. The apparent, limited role of vegetation in controlling bank erosion on large rivers has also been observed by Gatto (1984) and Nanson and Hickin (1986). We are unable to attribute erosion to chronic erosional processes or to more infrequent, larger flood events.

Large Woody Debris Recruitment

Erosion is the dominant process by which LWD is recruited into the Tanana River. As a result, the same processes that dictate land erosion patterns (see the Discussion on river bank erosion) also dictate LWD recruitment patterns. For this reason, and because the entire Tanana River is located in a forested watershed, the strong positive correlation between land area eroded and LWD recruited is not surprising. Occasionally, fire does extend to the river, with subsequent recruitment of LWD as trees decay and fall into the river. It is unknown what effect active fire suppression over the last 50 years has had on the vegetation composition along the river. In the absence of erosion, individual tree mortality along the river does occur, but the amount of LWD added to the river from these trees is very small (R. Ott, unpublished data).

The contribution of LWD volumes by different vegetation size classes was not uniformly distributed. Relative to the land area eroded, sawlog-sized stands contributed a disproportionately large amount of LWD (47.6% of LWD volume from 18.4% of eroded land). Conversely, small-diameter and small-statured stands contributed a disproportionately small amount of LWD relative to the amount of land eroded in that size class (11.4% of LWD volume from 28.3% of eroded land). These relationships are strictly a function of tree density and diameter. Sawlog-sized stands of trees were dominated by large-diameter trees (DBH >22.9 cm for conifers, DBH >27.9 cm for deciduous species) that contained a large volume of wood. However, in small-diameter and small-statured stands, the minimum DBH of trees large enough to contribute LWD was smaller (DBH ≥12.7 cm), and the stands were dominated by trees too small to meet our definition of LWD. On average, sawlog-sized stands of white spruce and white spruce/balsam poplar (the two dominant tree species on eroded lands) contributed more than double the amount of LWD volume per hectare compared to pole-sized stands of trees of the same species, and almost five times the amount of LWD per hectare compared to sapling-sized stands of balsam poplar (Table 1). As a consequence, 507 fewer hectares of sawlog-sized stands of trees contributed 162,354 m^3 more LWD to the river.

The distribution of LWD recruitment by vegetation size class within each erosion region (Table 5) is probably due the character of the river in each erosion region in conjunction with differences in species composition. For example, the great majority of LWD from sawlog-sized stands (74.0%) came from Erosion Regions III and IV. In Erosion Region III, the Tanana River is highly braided, but it also contains large islands with mature trees. In the process of cutting new channels, the river eroded several of the large well-forested, large-volume islands (Worum et al. 2001b). In Erosion Region IV, the Tanana has an anastomosed pattern, with several large channels and large, stable, well-forested islands. Erosion in this region occurred primarily along the edges of these well-forested islands (Worum et al. 2001b, 2001c). At the other end of the spectrum of vegetation size classes, LWD recruitment from dwarf forests and stands of small-diameter trees occurred primarily within Erosion Regions II and III. These two regions are the most unstable and are highly-braided. As a result, these regions have a large number of islands with young forest stands that were eroded (Worum et al. 2001a, 2001b).

LWD recruitment was not evenly distributed across vegetation strata (Table 4). Almost 80% of the LWD volume came from five of the 20 vegetation strata that could contribute LWD. Four of the five stands that contributed the majority of LWD were either sawlog or poletimber stands. This finding is not surprising. Sawlog stands are dominated by large diameter, high-volume trees that contribute much LWD. Compared to sawlog stands, poletimber stands are dominated by trees that individually may not have as much volume, but stand densities are greater so that wood volumes are quite large on a stand basis (Table 1).

The distribution of LWD by tree size and species (i.e. vegetation strata, Table 4) could influence its persistence in the Tanana. Larger trees would take longer to be depleted through wood abrasion processes. Relatively decay-resistance tree species (e.g. white spruce) would persist longer than tree species that are prone to decay (e.g. balsam poplar). Hyatt and Naiman (2001) determined that LWD from hardwoods was depleted from river channels faster than LWD from conifers in western Washington. Differences in LWD depletion were thought to result from increased transport rates, increased burial in the floodplain, or increased breakdown. Hyatt and Naiman (2001) also noted that hardwood depletion was affected as much by decay as by tree size.

The distribution of LWD to erosion patch size indicates that the small numbers of larger erosion patches contributed a disproportionate amount of LWD (Figure 9). Although 94.5% of erosion patches were ≤5.00 ha in size, 61.2% of the LWD volume was contributed from erosion patches >5.00 ha in size. These small slivers of land that contribute a large amount of the LWD to the river probably eroded from larger , stable islands with well-developed forest.

MANAGEMENT APPLICATIONS

The management intent of FRPA for riparian areas is to protect fish habitat and water quality from significant adverse effects of timber harvest. Understanding the natural variability of the 10 variables identified in FRPA (see the Introduction) is the first step to understanding the potential impacts of management activities on those variables. Without knowledge of natural variation of the variables of concern, human impacts on those variables can not be assessed accurately.

FRPA was written primarily to address fish habitat concerns in southeast Alaska. Limited guidelines were established for riparian forest management for the Tanana, and other interior Alaska rivers because: (1) these river were observed to function in a completely different manner compared to streams of coastal Alaska, and (2) very little research existed that allowed specific management standards and guidelines to be developed. Results of this project will increased the understanding of three of the variables of concern identified in FRPA: (1) LWD supplies, (2) bank stability, and (3) channel morphology. Increased understanding the largely natural bank erosion and LWD recruitment patterns of the Tanana River should prove invaluable to the management intent of FRPA for interior Alaska for two reasons: (1) riparian management standards and guidelines for large, glacially-influenced rivers can be refined, and (2) understanding natural processes controlling bank erosion and LWD recruitment will allow natural resource managers to better determine the extent to which future riparian forest management activities are in compliance with FRPA requirements in interior Alaska.

Understanding the dynamics of the Tanana River also will allow resource managers to investigate the impacts of various management activities and to make management decisions. For example, reforestation in harvest areas can focus on areas that are not in danger of immediate erosion. Cultural resource managers can use knowledge of river dynamics and erosion patterns to prioritize mitigation activities of known sites of archaeological and historical significance along the river (Ott et al. 2001). Knowledge of river bank erosion patterns will also prove useful for land use permitting and planning activities in the riparian zone of the Tanana River. The images depicting the Tanana River bank erosion patterns found in Worum et al. (2001a, 2001b, 2001c) should prove especially useful for these resource management activities.

FUTURE RESEARCH

The project described in this report was designed primarily to quantify bank erosion patterns and the associated LWD recruitment into the Tanana River, as well as gain a better understanding of the landscape-level processes that control erosion. There are several related questions, however, that this project did not address, that are very relevant to riparian forest and fisheries management.

The first and most important questions is: What role(s) does LWD play in river dynamics (e.g. channel formation) and fish habitat creation in large, glacially-influenced river systems of interior Alaska? FRPA mandates the maintenance of 10 fish habitat and water quality variables (see the Introduction), including maintenance of short- and long-term sources of LWD. However, the relative value of LWD in large glacial systems is unknown. FRPA regulations establish best management practices (BMPs) designed to meet the management intent of FRPA. FRPA regulations, however, were written primarily to address concerns related to the potential impacts of riparian forest management activities along small, relatively stable clearwater streams of coastal Alaska. Conflicts between fish and forest management are greater along, and in, coastal streams, and as a result, understanding of the role of LWD in aquatic systems in coastal forests is also greater. In interior Alaska, there is a lack of understanding about the relative importance of the 10 fish habitat and water quality variables, especially in the large rivers along which much of the productive timber is located (Neiland and Viereck 1978, Van Cleve et al. 1993). As a result, BMPs designed to protect fish habitat and water quality in interior Alaska, especially along the large rivers, are not nearly as refined. Understanding the role of LWD, as well as the other nine habitat and water quality variables, in aquatic habitats in interior Alaska is needed before the impacts of land management activities can be assessed.

The second question is: What is the residence time of LWD in large rivers such as the Tanana? FRPA mandates the maintenance of short- and long-term sources of LWD. In order to adequately protect LWD supplies in an aquatic system, information is required not only on the amount of LWD entering the system, but also the length of time LWD persists. Another way to frame the question is: What is the rate of removal of LWD from the aquatic system? Results from this project only provide information regarding LWD inputs into the Tanana river.

The third question is: To what degree do geomorphic and geologic features control bank erosion? Results of other studies indicate that bank stabilization by vegetation tends to be most effective along relatively small water courses, while fluvial processes tend to control bank stability on larger water courses (Ott 2000). We attempted to address this issue, but quickly found that answering it was beyond the scope of the study described in this report. The constraint was primarily a financial one. As described in the Methods section, the extent and distribution of the geology, geologic materials, and continuity of permafrost were interpreted and mapped for the entire study area. In order to conduct a spatial analysis, however, these data first need to be georeferenced before a multivariate analysis is performed. This step is time consuming and, therefore, expensive.

The fourth question is: How much new land has accreted along the Tanana River during the time period of study? Understanding erosion is to understand only half of a process, because as existing land erodes, new land is formed through deposition. The extent and distribution of new land in and along the Tanana will affect the spatial distribution of new forests, which in turn will affect LWD recruitment patterns in the future. Additionally, island formation will affect fluvial dynamics, and thereby influence the quality and quantity of fish habitat features.

The fifth question is: Will the same general patterns of erosion and LWD recruitment identified in this study persist in the future? More reliable and refined guidelines for riparian forest management can be developed for the Tanana River if this is the case. Building on the project reported here, another change analysis should be conducted sometime in the future to determine the variability of erosion and LWD recruitment patterns along the Tanana River.

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