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Tolt and Raging Rivers Channel Migration Study King County, Washington

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ABSTRACT

The Tolt and Raging Rivers, both tributaries to the Snoqualmie River in King County, Washington, have a history of rapid and extensive channel migration. Rates of channel migration between 1936 and 1991 were determined from aerial photographs and maps showing successive river positions. Channel migration rates varied dramatically during this 55-year period. Periods of rapid channel migration and consequent channel widening were associated with moderate to large floods (return periods of more than 5 years), although rapid growth of a new channel on the Tolt River occurred during a period with only smaller floods. The active channels of the rivers narrowed during periods between large flood events. Large differences in channel migration rates between reaches of each river are attributed to patterns of shear stress and sediment deposition, and to differences in bank materials. On the Tolt River, the highest channel migration rates were associated with development of avulsion channels. The historic rates of channel migration were used to predict probable future limits of channel migration over 10-year and 100-year time periods and to classify land in the river valleys according to relative hazard from channel migration. The results will be used to formulate regulations for development in the study areas.

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1.0 INTRODUCTION

The Tolt and Raging Rivers, both tributaries to the Snoqualmie River in King County, Washington, exhibit rapid and extensive lateral channel migration that threatens both developed and undeveloped properties along their banks. The Federal Emergency Management Agency's (FEMA) floodplain maps of these rivers show areas subject to inundation, but do not show erosion hazard areas. Because the FEMA maps assume the channel is fixed, the floodplain and floodway boundaries shown on the maps are only reliable for short periods after the maps are completed. This creates difficulties when the maps are used by regulatory agencies, landowners, and developers to determine where development can be allowed along the rivers. Along the Tolt River, for example, King County's Building and Land Development Division (BALD) has approved residential short plats that are outside the 100-year floodway shown by FEMA, only to have the river change course and threaten the newly created lots.

Bank stabilization projects to protect endangered properties are commonly expensive to build and maintain. Rock riprap must be frequently replaced to maintain the projects' effectiveness, and some stabilization projects on these two rivers have been ineffective against the forces of channel migration. On these rivers, prevention through land use planning may be a more effective, and perhaps more economical, solution.

In recognition of the problems being experienced along these rivers, the 1989 Snoqualmie Valley Community Plan called for a "study of the Tolt and Raging Rivers to accurately identify all such reaches that laterally migrate." This report presents the findings of that study, which will be used by the King County Surface Water Management Division to formulate regulations for development in areas affected by channel migration. The study included determination of historic limits of channel migration, estimation of probable future limits of channel migration, and development of maps that show channel migration hazard zones.

2.0 METHODOLOGY

Field work for this study commenced in October, 1990. Two major floods in November, 1990 caused substantial channel migration in parts of the Tolt River and Raging River study areas. We examined the changes caused by the November floods during subsequent field visits in November and December. Observations were plotted on 1989 aerial photographs and later transferred to maps. Features recorded included geologic materials, height and composition of

river banks, levees and revetments, vegetation type and age, presence of eroding banks, abandoned channels and other potential avulsion sites, depositional zones, and descriptions of river and floodplain morphology. We sampled sediment on bar surfaces using the point-count method (Wolman, 1954) and collected samples of bed and bank materials for laboratory sieve analysis. Trees in strategic locations were cored with an increment borer and the rings were counted to determine the minimum number of years since the river channel had occupied that location. During the course of field studies, we interviewed numerous local residents about the history of channel migration on the rivers.

Other data sources used in this study include cross-sections and profiles of the Tolt River and Raging River surveyed in 1975 and 1985, respectively, for flood studies; and information and records from King County concerning revetment ages and repair.

The historic river channel positions shown on Sheets 3 through 6 of this report were traced from aerial photographs and maps whose sources, scales, and dates are shown in Table 1. These particular sources were selected based on availability, scale, accuracy, and their timing in relation to major flood events or channel changes. Also shown on Table 1 are other sources of data that were consulted but were not plotted on the maps.

To construct the maps, the edges of the active channel (defined here as the low-flow channel(s) plus adjacent gravel bars that lack perennial vegetation) were traced on each set of aerial photographs. On both rivers, the channel shown on flood insurance study orthophotos or maps was used in conjunction with aerial photographs of the same date to construct a planimetrically accurate base map showing the active channel. Tracings from aerial photographs of other years were then superimposed on the base map using a projector equipped with an adjustable focal length. Common reference points such as roads and houses were used to match the photographs and base maps. The error involved in this procedure was less than 20 feet where match points were plentiful and located on both sides of the river, but as much as 40 feet where few match points existed. These larger errors occurred primarily on the upper reaches of both rivers, where trees overhanging the river banks further reduced accuracy.

Evidence for river positions that predate the 1936-1991 period of photographic record is shown on Sheets 3 and 6. For the 1873 and 1921 maps, the section corners of which do not precisely match those of later maps, we used a matching procedure similar to that used for the aerial photographs. Although the 1873 maps are not planimetrically correct, they provide a general idea of river location and bend geometry of the Tolt River and lower Raging River.

Historic rates of channel migration were calculated from the successive river positions shown on Sheets 4 through 6, using procedures described in Section 4.4 of this report. These historic rates and locations of channel migration were then used in combination with other data to determine probable future limits of channel migration, as described in Section 5.1.

3.0 STUDY AREA CHARACTERISTICS

The Tolt and Raging Rivers are located in the north and central parts of King County, as shown in Figure 1. The Tolt River flows into the Snoqualmie River at river mile (RM) 24.9, near the town of Carnation. The Raging River flows into the Snoqualmie River at Fall City, 11.3 river miles upstream from the Tolt River. The Tolt River study area comprises the downstream 5.9 river miles of the Tolt River, from the Snoqualmie River to slightly upstream of the end of the Tolt River Road. The Raging River study area consists of 8.1 miles of river, from its mouth to Highway 18. The sheets in the back of this report contain detailed maps of the study areas which show the river mile locations mentioned in the text.

3.1 The River Basins

3.1.1 Tolt River

The Tolt River drains an area of 101 square miles. Basin elevations range from 56 feet at the mouth to 5,959 feet at the northeast part of the basin. The two major branches of the river, the North Fork and South Fork, join upstream of the study area at RM 8.8. Both forks drain steep, forested terrain in the western foothills of the Cascade Range. Stossel Creek, which enters the Tolt River from the north at RM 8.3, is a lower-gradient stream which drains a somewhat flatter, forested watershed. Several smaller creeks enter the Tolt River within the study area, but these contribute relatively little runoff. Upstream from the study area, the Tolt River flows in meanders incised into a steep-sided valley with a narrow floodplain; the channel gradient averages 0.9%. Within the study area, the floodplain widens downstream from 500 feet to over 1,000 feet (locally as wide as 1,500 feet) before merging with the Snoqualmie River floodplain. The channel gradient generally decreases downstream, from approximately 0.7% at the upstream end of the study area to 0.4 % near the mouth of the river.

3.1.2 Raging River

The Raging River basin has a watershed area of 33 square miles. Basin elevations range from 79 feet at the mouth of the Raging River to 3,517 feet on Rattlesnake Mountain. Except for the valley floor of the lower 8 miles of river, the basin is generally steeply sloping and forested. Upstream from the study area, the river flows in a narrow, V-shaped valley with an average gradient of about 3%. Within the study area, channel gradients range from 0.9% to 1.6%. Major tributaries are Canyon Creek (RM 9.2), Deep Creek (RM 7.3), Lake Creek (RM 6.2), and Icy Creek (RM 3.6). From the Deep Creek confluence to Preston, the Raging River flows northwest in a gently-sloping, 1,800-foot wide valley. At Preston, the river turns abruptly to the northeast and flows through a steeper, narrower valley toward the Snoqualmie River at Fall City. In both the upper and lower valleys, the active floodplain is generally only a few hundred feet wide and lies between higher terraces. In its last mile, the river gradient flattens to 0.9% as it flows across an alluvial fan built by the Raging River across the Snoqualmie River valley floor.

3.2 Human Activity and the Rivers

Human habitation near the rivers is limited by road access in both study areas. Paved roads provide access to the right bank (viewed looking downstream) of the Tolt River for the entire length of the study area, and to the left bank from the mouth to RM 1.8. Private dirt roads provide discontinuous access to the left bank upstream to approximately RM 4. A mixture of rural residential and agricultural uses occur in the areas accessible by road. A network of logging roads provides limited access to the upper watershed, which is largely uninhabited and owned by lumber companies and the City of Seattle. A highway bridge and an abandoned railroad bridge cross the Tolt River near its mouth. A log jam formed at the railroad bridge during the 1959 flood. Removal of debris from the railroad bridge is frequently required to prevent buildup of backwater which could potentially overtop the levees.

Roads provide access to both sides of the Raging River from its mouth to RM 2, and also in the vicinity of Preston. From river miles 2 to 4, access is primarily limited to the same side of the river as the Preston-Fall City Road. Upstream from Preston, the main road is on the right (northeast) side of the river and access to houses on the left side of the river has been by three private bridges. These low, small bridges are subject to damage from log impact, and from running water if the bridges become plugged by logs. The bridges at Upper Preston Road SE (RM 7.5) and at RM 7.2 were both severely damaged in the 1986 flood, and the latter bridge is still impassable to vehicles. The bridge at the trailer park, upstream from I-90 (RM 5),

washed out in the November 24, 1990 flood. Bank erosion problems are associated with all three bridges. The river is crossed by 5 bridges between Fall City and Preston. The Preston bridge washed out in a large 1932 flood and was later rebuilt. Minor erosion problems associated with some of these bridges have been controlled by riprap. Land use is primarily residential in the portions of the Raging River study area accessible by road, with some commercial activities such as a quarry and a lumberyard.

Both rivers are confined by levees armored with riprap where they cross the Snoqualmie River floodplain (see Sheets 1 and 2 for levee and bank protection locations). The Tolt River levees were built between 1939 and 1941, and the Raging River levees date to approximately the same period. Additional levees and revetments were built later on the Tolt River and extend discontinuously along the right bank from RM 1.9 almost to RM 3; these follow the course of the river, rather than straightening it. The only bank protection on the Tolt River upstream from RM 3 is in the vicinity of RM 4.5, where two short sections of bank were riprapped prior to the 1980s. The Raging River levees were raised and reinforced in the early 1960s. Supplementary bank protection structures (primarily riprap) are widespread throughout the Raging River study area, although most are limited in length to one or two pieces of private property. Records for the County-maintained revetments on both rivers do not quantify historic expenditures but show that most of them have required repairs or maintenance at least once.

As part of the King County flood control program, gravel was removed regularly during the 1960s from the Tolt River between its mouth and the Highway 203 bridge. Gravel was also removed from the mouth of the Raging River during the 1960s (Bruce Forbes, King County Flood Control, personal communication). Sequential aerial photographs (see Table 1 for sources) show that deposition of gravel bars at the river mouths and within the levees has occurred on both rivers since the cessation of gravel removal, and many of the gravel bars have become stabilized by vegetation. Local residents on the Tolt River claim that the river bed has risen by several feet. Logs were regularly removed along the inhabited sections of both rivers and burned in the 1960s. Log removal by King County continued to a lesser extent through the 1970s, then was discontinued due to budget constraints (bond funds passed in the 1960s were exhausted by the early 1980s), concerns about fish habitat and air pollution from burning, and growing evidence that woody debris reduces flow velocities and can in some circumstances contribute to channel stability. Since 1980, sawing of large logs into smaller pieces and removal of log jams has been done on a limited basis by local residents and King County.

The history of logging in the river basins is pertinent to this study due to the increase in sediment load which typically accompanies logging in steep terrain (e.g., Larson and Sidle, 1980; Ice, 1985). On the Tolt River, most of the slopes which drain directly into the study area (downstream from RM 6) had been logged by the 1930s, and logging in these areas resumed in the 1980s. These logged areas are mostly on moderate to gentle slopes which do not drain into watercourses capable of delivering large volumes of coarse sediment to the Tolt River. An exception is Spook Creek, which enters a side channel of the Tolt River at RM 3.0. A large sediment fan deposited at the mouth of Spook Creek in 1990 is attributed by local residents to logging activities.

Most of the coarse sediment in the Tolt River study reach is ultimately derived from the upper Tolt River watershed, where landslides transport sediment from the steep valley walls directly into the river. Large parts of the upper watershed were logged in the 1960s and 1970s, but relatively little recent logging has occurred there. Sediment from 20 percent of the Tolt River watershed has been trapped by the South Fork Tolt Reservoir since 1963.

Large areas of the Raging River basin were logged from about 1900 to 1932, from the vicinity of Preston southeast to the Canyon Creek and Deep Creek drainages. The hillsides between Preston and Fall City were logged mainly by 1960. Logging of the upper basin started sometime in the 1970s, but has been most intensive in the late 1980s and has involved almost the entire watershed upstream from Highway 18 (on the order of 25 percent of the total area of the Raging River basin).

3.3 Geology and Sediment Characteristics

The Tolt and Raging Rivers are located near the eastern edge of the Puget Lowland, a north-trending basin filled with the deposits of multiple glaciations. Within the study areas, located near the mouths of both rivers, the rivers flow in floodplains of gravelly alluvium derived primarily from reworked glacial sediment. Glacial sediments form or mantle the valley walls of both rivers. Most of these sediments were deposited 15,000 to 13,500 years ago during the Vashon stage of the Fraser glaciation, the latest glaciation in which ice covered the Snoqualmie Valley area. Exposures of glacial sediments in the river banks are common throughout the Raging River study area, but limited to the upstream end of the Tolt River study area. Upstream from the study areas, both rivers flow in narrow valleys incised into glacial deposits. Tributary streams and landslides from the steep valley walls deliver sediment ranging in size from clay to boulders to the rivers. In the headwaters of the river basins, Tertiary bedrock of the Cascade Range is exposed on the hillsides and in places in the river channels.

Quaternary geology of the study areas has been mapped by Frizzell Jr. et al., 1984; Tabor et al., 1982; Booth, 1990; and Anderson; 1965. For this study, geologic materials were mapped where exposed in the river banks (Sheets 1 and 2). Because it is the material at the base of a bank that determines its resistance to erosion, our maps show the lowest material exposed in the bank. Discrepancies between our maps and the geologic maps cited above generally reflect either the scale of mapping or the common occurrence of different materials in the base of the river bank (mapped for this study) than in the overlying floodplain or terrace (shown on geologic maps). The following paragraphs describe the geologic materials observed in the river banks within the study areas, in order from oldest to youngest.

Bedrock is rare in the study reaches of the two rivers. In the Raging River valley, Eocene sedimentary rock is exposed in a steep-walled canyon about 2.3 river miles upstream from Fall City. In the Tolt River study area, Tertiary volcanic bedrock is exposed in the vicinity of RM 5.0, where it forms cliffs at the outsides of two bends.

Pre-Vashon glacial sediments occur on the Raging River upstream from Interstate 90, in the vicinity of RM 5.1, and intermittently in the banks of the Tolt River from RM 5.0 to the upstream end of the study area. The Raging River exposure is a mostly-vegetated, steep cliff of silty sand, gravel, and boulders, which is probably a till; it was assigned a pre-Vashon age on the basis of mapping by Booth (1990). Although described by Booth as primarily till, the Tolt River pre-Vashon sediments, where well-exposed, consisted of outwash sand and gravel and a cohesive clayey silt. In contrast to the younger, Vashon glacial sediments, the observed pre-Vashon sediments were oxidized and the outwash gravels were typically weakly to strongly cemented. Between RM 5.0 to RM 5.3, the pre-Vashon sediments were exposed in the base of low banks of alluvium, while further upstream these sediments form high cliffs.

Vashon glacial deposits in the study areas are comprised of glaciolacustrine sediments, outwash and till. The **glaciolacustrine sediments** are gray, laminated beds of silt and silty clay deposited in lakes impounded by the ice sheet, either during its advance or retreat. Advance glaciolacustrine sediments are generally stiff to hard due to consolidation by the overriding ice sheet, while recessional glaciolacustrine sediments are softer and therefore more erodible. Advance glaciolacustrine sediment is exposed in the Tolt River study area on the south bank at RM 2.3, where a 15-foot bank of the silt is capped by 4 feet of mixed outwash and till. Glaciolacustrine sediments are exposed intermittently in the bed and bases of banks of the Raging River from the mouth of the river valley upstream to Preston. Most of the silt exposures in the river banks vary in thickness from 1 to 15 feet and are overlain by alluvium, so their origin is

uncertain. Exposures in the valley walls may have been deposited during glacial advance, as they lie topographically below advance outwash deposits. Glaciolacustrine deposits exposed in center of the valley were typically softer, and may be recessional in origin.

Glaciolacustrine sediments are also exposed intermittently on the Raging River between Upper Preston and the upstream end of the study area, although some of these exposures are not shown in Sheet 2 because they overlie till. This lacustrine silt and clay was probably deposited in a lake which occupied the upper Raging River valley early in the recession of the Vashon ice sheet (Anderson, 1965). Unlike the glaciolacustrine sediments exposed in the lower Raging River valley, these deposits are commonly slightly oxidized and directly overlie glacial till. In most locations the till/silt banks were capped with gravelly alluvium. The beds of silt and clay exposed in the river banks varied from 1 to 11 feet thick. Over 80 feet of thinly-bedded recessional glaciolacustrine sediments capped by approximately 15 feet of recessional outwash are exposed in a streamside landslide scar 800 feet downstream from Highway 18.

Outwash deposits in the study areas consist of stratified beds of sand and gravel, with cobbles and boulders in some locations, which were deposited by meltwater streams from the Vashon ice sheet. Both the Tolt River and the Raging River served as meltwater channels during the retreat of the ice sheet. Sand-dominated recessional outwash terraces flank the Tolt River valley at its mouth and along its southwest side (Booth, 1990). However, the river presently impinges on outwash only at the outside of a large bend in the vicinity of RM 4.4. The outwash forms a 30-foot high slope which is well-vegetated and shows few signs of erosion other than a slowly-moving landslide about 150 feet in length at RM 4.6. This is an active portion of a much larger, apparently inactive landslide on the east side of the Tolt River valley. Outwash is also sparsely exposed in the Raging River banks. Sandy advance outwash forms a cliff upstream of I-90 at RM 5.0. Advance outwash, which was deposited during the advance of the glacier and later overridden by glacial ice, is typically compact and relatively resistant to erosion.

Till is an unstratified mixture of silt, sand, clay and gravel which was deposited at the sole of the ice sheet. Till has been overridden by the ice sheet and is very dense and relatively resistant to erosion. In the Tolt River study area, till forms a cliff along the east side of a recently-abandoned river channel upstream from RM 3. Till is commonly exposed in the Raging River upstream from Preston. In many locations on the Raging River the till is fine-grained, contains lenses of silt, and is less dense than the typical "hardpan" Vashon till. The grain-size distribution of a typical sample of this till is shown in Figure 2.

Terraces composed of or capped by **older alluvium** are widespread in the Raging River study area. The older alluvium is primarily sandy gravel with cobbles, similar to modern-day deposits of the Raging River. However, due to incision of the river, the terraces are no longer flooded. The gently-sloping terrace surfaces are in most cases separated from the modern floodplain by a distinct bank or steeper slope. In the upper Raging River valley, gravel caps terrace remnants which are 30 to 60 feet above the river. Although these terrace remnants could be recessional outwash, their relatively low elevation compared to Vashon recessional terraces on Issaquah Creek led Booth (1990) to consider them later alluvium deposited prior to or during incision of the river's present channel. In the lower Raging River valley, the river has incised 15 to 25 feet below the surface of a terrace capped by older alluvium and later mass-wasting deposits. This terrace probably represents the river level at the end of the last glaciation.

Younger **alluvium**, the river deposits which form the floodplains of the two rivers, is composed of two types of deposits. The alluvium is predominantly gravel, sand and cobbles which are transported as bedload and deposited in bars and on the channel bottom. As the river shifts laterally, finer sediment settles out of suspension on the former gravel bars, building them up to the level of the adjacent floodplain. These overbank deposits are typically loose, non-cohesive, fine sands and silts which vary in thickness from a few inches to 2 feet, although deposits as thick as 5 feet were observed. A typical river bank thus consists of a gravelly lower bank covered by a thinner layer of fine overbank sediment. Banks on the Tolt River typically range from 5 to 7 feet in height, but are locally as high as 10 feet where river downcutting has occurred. The Raging River banks are slightly lower, with typical heights of 4 to 6 feet. However, low terraces and alluvial banks from 8 to 10 feet high are common throughout the Raging River study area.

Grain-size data from surface sampling and limited subsurface sampling of active gravel bars are shown on Sheets 1 and 2. Median diameter of sediment on bar surfaces ranged from 50 to 115 mm (2 to 4.5 inches) on the Tolt River and from 50 to 165 mm (2 to 6.5 inches) on the Raging River. The maximum particle size on the sampled gravel bars ranged from 150 to 450 mm (6 to 18 inches) on the Tolt River and 300 to 500 mm (12 to 20 inches) on the Raging River. Neither river shows a systematic change in grain size with distance downstream; rather, finer sediment in some cases corresponds to a local decrease in river gradient. Much of the scatter in median diameter values may be due to differing degrees of armor development rather than differences in the size of sediment deposited at the site.

Samples of gravel bar sediment beneath the armor layer provide an estimate of the size distribution of bedload transported by the rivers. The results of three such samples from each river are shown in Figures 3 and 4. The volumes of samples taken by the Surface Water Management Division (designated SWM on the figures) were many times larger than the samples collected for this study, and therefore provide a more representative measurement of the proportion of large gravel and coarser particles. These SWM samples indicate that the approximate median diameter of sediment transported through the Tolt River is 38 mm (1.5 inches) and that of the Raging River is 26 mm (1 inch). In other words, more than half of the bedload transported by the rivers is coarse gravel or larger. Since the floodplain is composed primarily of former gravel bars, sediment exposed in the base of river banks would be expected to have a size distribution similar to the bedload. In our descriptions of banks made throughout the study areas, the dominant size category of the bank sediment was generally classified as coarse gravel or cobbles. Boulders (diameter larger than 256 mm, or approximately 1 foot) made up a significant portion of the bed and banks in all but the flatter portions of the Raging River study area, and in the upstream 0.6 miles of the Tolt River study area. Boulders occupied less than 5 percent of the surface areas of gravel bars sampled on the remainder of the Tolt River, and none were observed on gravel bars in the last mile of the river, indicating a downstream decline in competence.

3.4 Hydrology

The Tolt and Raging River basins experience the generally mild, wet winters and warm, drier summers typical of the Puget Sound area. Precipitation increases with elevation in both basins. Mean annual precipitation in the Tolt River basin ranges from an average of 46 inches at Carnation (USDA, 1982) to up to 180 inches in the headwaters. Mean annual precipitation in the Raging River basin ranges from about 55 inches at Fall City to about 120 inches in the headwaters. The upper reaches of both rivers (above approximately 1,100 feet in elevation) are in the transient snow zone, from which snowmelt augments rainfall during some flood events (Harr, 1983).

The largest floods in the study basins typically occur in the months of November through February, less frequently in March, and are associated with maritime frontal systems. These floods typically last from one to a few days, in contrast with the more prolonged high flows associated with snowmelt during the months of March, April, and May. Flooding near the mouths of both rivers also occurs during high flows of the Snoqualmie River. Since channel

migration in these lower reaches is controlled by rock-lined levees, the discussion of floods which follows will be limited to the non-leveed reaches of the Tolt and Raging Rivers.

3.4.1 Flooding on the Tolt River

Flows have been recorded continuously since 1938 on the Tolt River. The "Tolt River near Carnation" gaging station is located at RM 8.7, downstream from the confluence of the North Fork and South Fork and upstream from Stossel Creek, a major tributary. The drainage area above the gage is 81.4 square miles. Table 2 lists the ten largest flood events on the Tolt River during the period of record, and Figure 5 shows the highest discharge for each water year (October through September of the named year). Shorter records exist for gages on the North Fork (39.9 square miles) and South Fork (19.7 square miles) of the Tolt River. Highest annual discharges for these gages are shown in Figure 6.

The largest flood of record on the mainstem Tolt River occurred in water year (WY) 1960, on December 15, 1959. This 17,400 cfs flood had a recurrence interval of greater than 50 years. Although operated for water supply and not flood control, the 57,830 acre-feet South Fork Tolt Reservoir normally provides some storage for flood waters while sufficient head builds up to pass flows at the spillway (Dave Parkinson, Seattle City Water Department, personal communication). Flood records for gages on the North Fork and South Fork show a decrease in the sizes of South Fork flood peaks relative to North Fork Tolt River flood peaks since the dam was completed in September 1963 (Figure 6). No floods above 11,000 cfs occurred at the Tolt River gage between WY 1964 and 1990, in contrast to 5 such floods between WY 1938 and 1963 (Figure 5). The dam affects only 20 percent of the area of the 101 square mile Tolt River basin, and large-magnitude floods cannot be ruled out in the future, although they may occur less frequently than prior to dam construction. The November 24, 1990 (WY 1991) flood of 11,200 cfs is the sixth largest during the period of record, and the largest since the dam was built, although a 10,300 cfs flood in 1969 was of similar magnitude (see Table 2). The approximate recurrence intervals of these floods are only 9 and 6 years, respectively, if floods from the whole period of record (pre- and post-dam) are considered. Although no records are available for the years prior to WY 1938, floods large enough to cause channel shifting occurred in 1911 or 1912 and in the early 1930s, according to local residents.

3.4.2 Flooding on the Raging River

The Raging River has more rapid runoff and a flashier flood regime than the larger Tolt River. The "Raging River near Fall City" gaging station is located at RM 2.6 and has a drainage area of 30.6 square miles. Flows have been recorded for most of the period since 1945. Table 3 lists the ten largest flood events on the Raging River during the period of record, and Figure 7 shows the highest discharge for each water year.

Five of the six largest floods of record on the Raging River have occurred since WY 1987; four of these floods occurred in WY 1990 and 1991 (Table 3). The November 24, 1990 flood of 5,540 cfs was the largest since records started in 1945; however, a flood in 1932 was of similar or greater magnitude, according to local residents. Two large streamside landslides near Upper Preston and breakage of a small dam at RM 7.3 reportedly occurred during the 1932 flood. The cause of the increased numbers of large floods in recent years has not been established, but may be the subject of a future study by King County SWM (possibly in cooperation with the University of Washington and participants in the Timber, Fish, and Wildlife agreement). The increased flooding may be linked to altered snowmelt and runoff characteristics of large areas of the Raging River basin upstream from Highway 18 which have been clearcut since the mid-1980s. It is of interest that the 1932 flood also followed clearcut logging of a large portion of the basin.

4.0 CHANNEL MIGRATION ON THE TOLT AND RAGING RIVERS

Sheets 3 through 5 show historic changes in the position of the Tolt River. The 1970 channel position is shown for reference on all three of the Tolt River maps. Sheet 6 shows historic changes in position of the Raging River. These maps show the boundaries of the active channels, defined as the low-flow channels plus adjacent gravel bars which lack perennial vegetation. Thus mid-channel bars and islands between channels are shown only if they are vegetated. River positions between 1936 and 1991 (Sheets 4, 5 and 6), traced from aerial photographs and maps, were used to calculate the channel migration rates presented in Section 4.3.2. The pre-1936 river positions, shown on Sheets 3 and 6, are not planimetrically accurate due to surveying errors and the small scales of the source maps. However, they show former river planforms and indicate, in a general manner, which parts of the valley have been occupied by the river during the past century. Also shown on Sheet 3 are numerous channels of unknown age that cross portions of the Tolt River valley which have not been occupied by the river during the period of photograph-

ic record (1936-1991). It is not possible to ascertain whether these channels are former river channels that have since filled in, or smaller channels that have only conveyed flood flows. The few floodplain channels that exist on the Raging River are shown on Sheet 6.

For the analysis of channel migration, the Tolt River study area was divided into 5 reaches which exhibit different rates and types of channel migration. These reaches, designated A through E, are shown on Sheets 3 through 5. The Raging River study area was divided into 7 reaches, designated A through G and shown on Sheet 6. In both rivers, Reach A is located at the downstream end of the study area.

4.1 Types of Channel Migration

Three distinct types of channel migration occur on the Tolt and Raging Rivers. In order of increasing size, these are lateral migration, chute cutoffs, and avulsions (Figure 8).

Lateral migration involves the erosion of one river bank concurrently with deposition of sediment near the opposite bank. Consequently, the entire river channel moves laterally, in many cases without a net increase in width. Lateral migration is typically associated with meander bends, due to the convergence of flow against the outer bank near the downstream end of a bend. Lateral migration on the Tolt and Raging Rivers resulted in downstream and, in some cases, outward migration of meander bends. New bends which formed in previously straight sections of channel typically grew outward as well as downstream.

Chute cutoffs occur when a river abandons a bend and switches to a straighter, steeper path across the back of a point bar (Figure 8). As a meander bend develops (radius of curvature decreases), the water slope decreases upstream of the bend, promoting deposition in the channel and diversion of flow over the point bar and a consequent cutoff. Well-developed back-bar channels were observed on almost all gravel bars on the Tolt River, and less commonly on the Raging River. These channels provide easy paths along which chute cutoffs can occur. Once a cutoff occurs, erosion of the outside of the bend stops, and the area between the two channels may eventually become vegetated. Cutoffs can trigger rapid lateral erosion downstream, by causing the river to impinge on the opposite bank at a sharp angle.

The third type of channel migration in the study areas is avulsion, the abrupt switching of the river course to a new location. Avulsions in many cases occur where a creek or a former channel provides a low path across the floodplain. On the Tolt River, avulsions typically involve a greater distance than the length of a single meander bend, as shown schematically on Figure

8. On the Raging River, most avulsions involve only a single meander bend. After an avulsion takes place, flow progressively diminishes in the abandoned channel as its entrance becomes plugged with sediment, although smaller amounts of flow have continued in some abandoned channels for several decades. The new channel widens rapidly and progressively carries more of the flow. Islands of forested land remain between the old and new channels.

Lateral migration is the dominant channel migration process in truly meandering rivers. However, on the Tolt and Raging Rivers, the development and growth of meander bends is severely limited by cutoffs and avulsions, which tend to destroy bends before they can become large. Consequently, the rivers remain relatively straight. Sinuosity, the ratio of channel length to valley length, is typically less than 1.25 throughout the Tolt River study area and all but Reach C of the Raging River. Low sinuosity (less than 1.3) is typical for bedload-transporting rivers with weak, non-cohesive sand or gravel banks (Schumm, 1977). In contrast, meandering rivers are commonly considered to have sinuosities of 1.5 or greater. Meandering behavior is best-developed in rivers whose banks contain sufficient silt and clay to be cohesive and to limit the rate of erosion. Such is the case in Reach C of the Raging River, where bends are well-developed in silts and silty clays and sinuosity has ranged from 1.29 to 1.45 during the study period. Most of the well-developed bends elsewhere on the Raging River also occur in cohesive till or silt, as opposed to gravelly alluvium.

The dominant type of channel migration differs between reaches of the Tolt River. Lateral migration is the dominant type of channel migration in Reach E. Avulsions and cutoffs appear to be the dominant channel migration processes in Reaches B and C, while they occur less commonly in Reach D.

On the Raging River, lateral erosion appears to be the dominant channel migration process in Reaches B, C, F, and G. Straightening of bends by cutoffs or short avulsions has occurred to some extent in Reaches C, D, E, and F. Cutoffs and avulsions leading to the formation of multiple channels has occurred recently only in Reach E. The multiple-channel appearance of Reach A and D in 1936 indicates that cutoffs and avulsions were more active in the past in those reaches.

Even on sections of river dominated by cutoffs or avulsion, lateral migration is an important catalyst for the other types of migration. Lateral migration can move the river to a position where an avulsion is more likely to occur, or cause a bend to develop to the point where the gradient is so low that water can be conveyed more efficiently directly across a point bar in a

cutoff. Rapid lateral migration can also lead to a chute cutoff by widening the channel, which spreads the flow and favors development of secondary channels.

Both cutoffs and avulsions result in the formation of multiple channels, giving parts of the Tolt River (Reaches B and C, and formerly A) and the Raging River (Reach E, and formerly A and D) a braided appearance. These reaches appear to be similar to sections of rivers on the Canterbury Plains of New Zealand, described by Carson (1984). These rivers, transitional in behavior between meandering and braided, exhibit a braided appearance following large floods, then revert to single-thread channels as former channels heal through sediment deposition and vegetative growth. These sections of New Zealand rivers are characterized by high-energy flows capable of eroding their non-cohesive gravel banks, and "neither degradation nor aggradation appears to be proceeding rapidly at present" (Carson, 1984, p. 13). Carson's proposed mechanism for braiding is dissection of the floodplain and of lateral bars within the active channel, rather than deposition of medial bars within the active channel. Although a few medial bars on the Tolt River may have formed in the latter manner, most appear to have resulted from dissection.

The next two sections set the stage for a discussion of channel migration by describing the morphology of each river. In particular, changes in river pattern and width can indicate the severity and types of channel migration which have occurred in the past. Channel gradient, floodplain width, and other morphological features can affect rates of channel migration.

4.2 Morphology of the Tolt River

The active channel width (as defined in Section 2.0) of the Tolt River generally increases in the downstream direction (from Reach E to Reach A), with the exception of Reach A, now constrained by levees. As shown in Figure 9a, differences in width of the various reaches have been more extreme in some years than others. During periods of rapid channel migration, vegetative growth cannot keep up with the rate of movement of the river, so the active channel expands. When channel migration slows or ceases, vegetation grows on abandoned gravel bars and the width of the channel decreases. All reaches of the study area were relatively wide in the 1936 and 1964 photographs, taken a few years after major floods (see Section 3.4.1). Multiple channels were also common in 1936 and 1964 (Figure 9b). The river had narrowed and assumed a single-thread form by 1970, and it remained relatively narrow through 1989. Reaches B and C widened during floods in 1990, obtaining widths comparable to 1936 or 1964. Reach D widened in some areas, but its average width remains lower than in 1936 or 1964. The width of Reach E did not change significantly during the 1990 floods.

Figure 10 shows the longitudinal profile of the river bed in 1975, the most recent date for which surveyed channel elevations are available. Channel gradient generally decreases in the downstream direction, from Reach E to Reach A.

The Tolt River follows the east valley wall throughout most of Reach E, probably due to direction by a bend in the valley wall immediately upstream. Reach E is characterized by a relatively steep, straight, narrow, single-thread channel with only a few small gravel bars. Sinuosity, the ratio of channel length to valley length, here is only 1.06. Maps and aerial photographs indicate that the position of the river channel has varied little during the past century. There is no morphologic evidence of abandoned channels on the valley floor in Reach E.

In Reach D, the river gradient decreases and the river departs from the valley wall in places, resulting in a sinuosity that has varied from 1.19 to 1.25 since 1936. The river is wider and gravel bars are larger and more widespread than in Reach E. Reach D has a primarily single-thread pattern, although limited areas with multiple channels are visible in both the 1936 and 1964 photographs (Sheet 4). Although the river has occupied the east side of the valley throughout the 1936 to 1991 period of photographic record, in 1873 and 1921 the river was considerably more sinuous and occupied the west side of the valley in the upstream portion of the reach (Sheet 3). This former river channel is still visible in places, although it is vegetated with alders and partially filled by flood deposits of silt and sand. A creek on the west side of the valley, in the southern half of Reach D, is quite large and possibly is the remnant of a river channel which predates 1873.

Reach C of the Tolt River has changed considerably during the past century. The 1873 map shows a sinuous planform, with the river abutting the east valley wall in only one location. From 1936 through the early 1980s, a 3,000-foot long section of the river flowed along the east valley wall in a straight channel, and unconfined meander bends occurred at either end of the reach where the river broke away from the valley wall. During most of this period, Reach C was a single-thread channel. However, the 1964 photographs show that it had multiple channels downstream from RM 3.0. Presently, the entire length of Reach C contains multiple channels, as a result of channel switching (avulsion) which occurred in the early- to mid-1980s. The river has progressively abandoned its channel next to the valley wall, and new channels have formed and widened in the center of the valley (see Figure 11 and Sheet 5). These recent changes have shortened the length of the main channel, reducing the sinuosity of the reach to 1.16 and presumably increasing the river gradient. Prior to the avulsions, Reach C had a sinuosity of

1.35 and an average gradient of 0.53%. Assuming that the elevations at both ends of Reach C have remained relatively constant since 1975, the avulsions have increased the average slope of the reach to about 0.6 %, approximately the same as Reach D. Reach C presently contains numerous wide gravel bars, reflecting the rapid channel migration during the last decade.

Two creeks exist on the floodplain within Reach C. The lower end of the creek on the west side of the valley, which is shown on Sheet 3 as it was mapped in 1964, was the site of one of the avulsions referred to in the previous paragraph and has since become the main river channel. The remaining portion of this creek is narrow, and shows no definitive evidence of being a former river channel. The creek on the east side of the valley, near the upstream end of Reach C, is wider and possibly represents the trace of an old river course.

Continuing downstream, the 1975 channel gradient increases slightly in the upstream part of Reach B (Figure 10), reflecting a similar increase in the slope of the river valley. Reach B is more extreme than Reach C in its frequent changes of course and tendency to form multiple channels. Sinuosity has remained fairly constant from 1964 through 1991 at about 1.25, but was higher (1.51) in 1936. The most recent avulsions occurred in November 1990, when the river reoccupied portions of two former channels (Figure 11). As with Reach C, gravel bars are large and widespread, particularly in the lower-gradient, downstream end of the reach. Local residents indicate that aggradation of the river bed has occurred in this area since the 1970s.

Reach A consists of the lower 1.7 miles of the Tolt River, which is confined between levees typically spaced 200 to 400 feet apart. Prior to construction of the levees in about 1940, the river was considerably wider, more sinuous (1.51), and contained some multiple-channel segments (Sheet 4). The 1873 channel (Sheet 3) was even more sinuous, though its general location was similar to the 1936 channel. The 1873 survey also shows an older channel which apparently passed through the outskirts of what is now the town of Carnation. The river gradient decreases in the downstream direction throughout Reach A. Alternate gravel bars have formed throughout the reach, and many of them have become stabilized by vegetation.

A terrace on the north side of the valley flanks the downstream end of Reach B and the upstream end of Reach A (see Sheet 1 for the approximate location of the edge of this terrace). This terrace is 8 to 15 feet high at its outside (river) edge, and thus lies above the mapped level of the 100-year flood (FEMA, 1989). Several small swales cross this terrace, as shown on Sheet 3. The 1873 and 1921 surveys show the river was located to the south of the terrace, in the present-day floodplain. These small channels probably carried flood overflow prior to incision

of the river below the terrace, and possibly are filled-in remnants of a former channel which pre-dates 1873.

4.3 Morphology of the Raging River

Unlike the Tolt River, the width of the Raging River does not increase consistently in the downstream direction. Average active channel widths of Reaches A through E are shown in Figure 12a. Widths for Reaches F and G are not shown in this figure, due to the short period of photographic record (1958-1991), and because tree canopy obscured much of the channel in the earlier photographs, making it difficult to accurately assess changes in width. The active channel is typically 50 to 70 feet wide in Reaches F and G, and widths do not appear to have changed since 1958, except in the downstream 0.3 miles of Reach F, where the active channel widened to between 100 and 150 feet from 1985 and 1991.

Average channel width in Reach A dropped from 175 feet to 120 feet after levees were constructed in about 1940. Reaches B through E were all relatively wide (80 to 150 feet) in 1936, four years after the 1932 flood. In general, these reaches had narrowed significantly by 1964, remained relatively stable through 1985, and widened from 1985 to 1991, a period with several large floods (Section 3.4.1). The reaches vary in their responses to flood events, however. Reaches B and D decreased in width by about 50 percent from 1936 to 1964, and have remained relatively narrow since then. Reaches C and E narrowed less after 1936, then widened more after 1985, which resulted in greater average widths in 1991 than in 1936.

As shown in Figure 12b, side channels accounted for about 12 percent of total active channel width in Reaches A and D in 1936. Later aerial photographs (1964 to 1991) show active side channels only locally in Reach E.

Figure 13 shows the longitudinal profile of the Raging River, which is considerably steeper than the larger Tolt River. Steeper and flatter sections alternate throughout the Raging River study area.

The description of river morphology begins with Reach G, at the upstream end of the study area, and proceeds downstream to Reach A at the river mouth. Refer to Sheet 6 for reach locations and historic river channel positions, and to Sheet 2 for locations of the valley wall and terraces.

In its upper valley (Reaches E, F, and G), the Raging River flows near the west valley wall. Many of the river's bends impinge on till or other valley wall materials that resist erosion and limit the westward rate of migration. Landslides have occurred where the river undercut a valley

wall composed of erodible glaciolacustrine silt or outwash, or less commonly, till (Sheet 2). The river is freer to migrate to the east, but in places it abuts terraces composed of glacial materials. These terraces also limit channel migration and, where tall enough, are subject to landslides. Sinuosity typically ranges between 1.1 and 1.2 in this section of the river.

Reach G is a narrow, steep, channel which makes several bends before entering the upper valley at the confluence of Deep Creek. Downstream from Deep Creek, the river straightens and is incised a few feet into a broad, flat alluvial terrace, so that the active floodplain is typically less than 100 feet wide (FEMA, 1989). Narrow gravel bars exist primarily at bends, and are most extensive near the downstream end of the reach where the channel gradient decreases locally. Most bends impinge on the valley wall or a terrace. The narrow floodplain, lack of abandoned channels on the valley floor, and presence of old-growth tree stumps near the river all suggest that Reach G of the Raging River has not shifted position substantially during the past several centuries.

The channel gradient decreases slightly in Reach F. Presently, this reach is relatively straight, with only a few well-developed bends. However, the 1958 and 1964 photographs show a series of bends in a section of the reach which has been straight since at least 1977, and the reach contains two relatively small channels of unknown age which may be former river courses (Sheet 6). The floodplain is typically 150 to 300 feet wide. Till is exposed in the banks at many of the bends in this reach. Two landslides exist on the right (east) bank where the river has undercut a high terrace. The upstream part of this reach is a narrow, single-thread channel with small, lateral gravel bars. Downstream from RM 6.4, the river is presently wider, with large lateral bars and a few mid-channel bars.

The Raging River follows the valley wall on its left side throughout Reach E, but its right bank is in alluvium and is presently unconfined by terraces or valley walls except near Interstate 90. Reach E has undergone substantial changes in location and channel pattern since 1936. The 1936 aerial photographs show several large-amplitude meanders, which were not present in subsequent photographs; sinuosity was correspondingly high, at 1.31. The river was relatively straight and narrow through 1985, in part due to revetments along portions of the right bank (an old right-bank revetment in the vicinity of RM 5.2 had deteriorated by the time of this study, and is not shown on Sheet 2). Since 1985, the channel has widened and developed braid bars and multiple channels in many places. Gravel bars are large and numerous, and aggradation has occurred from RM 5.1 to 5.3, according to a local resident. The right bank downstream from RM 5.1 is the only major portion of floodplain in Reach E which has not been occupied by the river

during the 1936-1991 period of photographic record. However, on the right bank at RM 4.9, a 45-foot-wide, channel-shaped feature enters the river at right angles (Sheet 6). It is likely that this is the downstream end of a former channel. If so, grading for the trailer park which now occupies the area has obscured evidence of the rest of the inferred channel.

At the upstream end of Reach D, in the community of Preston, the river turns abruptly northeast and enters the lower Raging River valley. The channel gradient is steep in the transition between the two valleys. The remainder of the reach, downstream from RM 4.5, is relatively flat (Figure 13). Aerial photographs indicate that Reach D has been straight and narrow since 1964 or earlier, in part due to a revetment on the left bank in the downstream part of the reach (Sheet 2). Downstream from Preston, the right bank of the river is confined by a 20-foot-high terrace composed of glacial deposits. The 1936 photographs of Reach D show a wider channel, with high-amplitude bends which traverse nearly the full width of the 400- to 600-foot-wide floodplain. Some abandoned segments of the 1936 main channel are still occupied by the channels of tributary creeks.

Reach C differs in character from the rest of the Raging River. It consists of a series of well-developed meanders (sinuosity of 1.45) incised into a 15- to 25-foot high terrace of glaciolacustrine deposits capped by alluvium and mass-wasting deposits. Glaciolacustrine silt and clayey silt are exposed in the banks at the outside of each bend, while in between bends the river flows through cobble-gravel floodplain alluvium and a lower terrace also composed of alluvium. A major break in slope occurs within this reach; the upstream part is a continuation of the flat gradient of Reach D, and the downstream part steepens to 1.85% as the valley floor drops even more steeply (Figure 13). The meander bends have retained their basic shape throughout the 1936-1991 period. The bends in the upstream half of the reach have widened and eroded into the terrace considerably, while the bends in the downstream half of the reach have been stable. An abandoned channel of unknown age cuts across a bend on the right bank downstream from Icy Creek. No other evidence of older channels was noted within this reach. The 1873 survey (shown on Sheet 6 for the downstream half of Reach C) is apparently in error, as it shows the channel in locations where terraces composed of glaciolacustrine silt exist.

River gradient and sinuosity decrease again in Reach B, with the exception of a steep section of bedrock canyon (Figure 13). The river flows next to the west valley wall in many places, but otherwise flows through alluvium. From 1936 to 1991, the river was narrow and stable except for the only two bends which are not confined by bedrock or the valley wall. Upstream from the bedrock canyon, the river has low banks and flows in a 200- to 300-foot-wide flood-

plain. Rating curves from the USGS gaging station in this section of the reach show that the river bed degraded between 1950 and 1975, then aggraded between 1975 and 1990, with a total fluctuation of less than 1 foot. Downstream from the bedrock canyon, the channel flows in a narrow floodplain set below a wider, 7- to 10-foot high terrace with stumps of old-growth trees. This terrace ends on the right bank by RM 1.95, and the floodplain broadens to about 400 feet. The 1873 survey is in error upstream from RM 2, since it shows the river crossing over the top of a bedrock spur. If it is correct downstream, the river was east of its present position in 1873 (Sheet 6).

Reach A consists of the lower 1.4 miles of the Raging River, the gradient of which drops to 0.94% as it crosses its alluvial fan to the Snoqualmie River. This reach of the river is confined between levees spaced 100 to 150 feet apart. Prior to construction of the levees in about 1940, the active channel was wider and multiple channels existed in many places. The 1873 survey indicates that the river flowed in approximately the same area as the 1922 and 1936 rivers. The sinuosity of the reach dropped from 1.23 in 1936 to 1.07 after channelization. Alternate gravel bars have been deposited within the levees, and are stabilized by vegetation in many cases.

4.4 Historic Rates of Channel Migration

4.4.1 Calculation of Migration Rates

Average rates of channel migration for each reach were calculated by dividing distances between the successive channel positions shown on Sheets 4 through 6 by the elapsed time between channel positions. It is often not possible to distinguish between the effects of lateral migration and cutoffs in widening a section of channel, especially when the time interval between successive aerial photographs exceeds two years. Therefore, all changes in position of a single, identifiable channel were classified as one category, "shifting and widening", for the purposes of measurement. Migration caused by avulsions was recorded as a second category.

Migration rates were calculated separately for each reach. Measurements along the length of each reach were made at 200-foot intervals on the Tolt River and 100-foot intervals on the Raging River. At each station, the distance between successive channel edges was measured if erosion had occurred (i.e., shifting or widening had converted previously vegetated ground into active channel). Where the active channel edge had shifted due to shrinkage (i.e., perennial vegetation had grown in what was formerly the active channel), a value of zero was recorded. In cases where an avulsion had occurred during the time interval, the entire width of the new channel was recorded as avulsion erosion. The distance between the former and new

channels was not measured, since the intervening land had not eroded. For the avulsions which occurred in the 1980s in Reach C of the Tolt River, subsequent rapid shifting and widening as the new avulsion channels expanded was also recorded as avulsion erosion.

As noted in Section 2.0, some errors exist in the mapping of channel positions due to uncertainty in aligning the photographs and the base map. Consequently, it was assumed that mapped changes in channel position that were smaller than the potential range of error were not valid, unless corroborated by either 1) vegetative or morphologic evidence of a former channel on the side the river migrated away from, 2) accounts of local residents, or 3) an increase in channel width.

Average rates of channel migration were calculated for each type of migration by dividing the average erosion distance for each reach by the elapsed time. Average rates of shifting and widening were calculated in two manners: for the entire reach (including non-eroding areas), and for eroding areas of the reach only. No non-eroding areas occurred in the avulsion channels.

As noted in Section 4.2.1, Reaches B, C, D, and E of the Raging River decreased in width between 1936 and 1964. The amount by which width decreased is presumably an approximate measure of the increase in width caused by the 1932 flood. We calculated the rate of shrinkage for the 1936-1964 period by measuring differences in width at each station, then dividing the average change in width by elapsed time.

Unlike the earlier sets of aerial photographs, the 1991 photographs were taken in winter, when deciduous trees did not obscure the river banks. In narrow, heavily wooded areas (Reaches D and E on the Tolt River; Reaches D, E, and B downstream from RM 2.3 on the Raging River), the 1991 channel is shown on Sheets 5 and 6 only where field observations or information from local residents confirmed that erosion had occurred since 1989. In other reaches of the river, where substantial amounts of erosion had occurred, the 1991 channel shown on Sheets 5 and 6 was mapped as traced from the photographs. In some places, the mapped increase in width between the 1989 and 1991 channels was partially an effect of the lack of tree cover. Since deciduous trees were visible on the 1991 photographs, we were able to correct for this effect by subtracting the width of tree cover extending over the river from each measurement. Corrections, typically of 10 to 30 feet, were made selectively on approximately 20 percent of the length of the Tolt River reaches, and 30 to 50 percent of the Raging River reaches.

4.4.2 Channel Migration Rates

4.4.2.1 Tolt River

The rates calculated for the different types of channel migration are given in Table 4. The combined rates for shifting, widening and avulsions (Table 4a) are displayed graphically for each reach on Sheet 5, and for all reaches in Figure 14. Table 4b shows average rates of shifting and widening (including non-eroding areas) for each reach, and Table 4c shows rates calculated for the eroding areas only. Rates for avulsion channels are shown in Table 4d. These historic rates are used in Section 5.1 to predict future rates of channel migration.

As shown in Figure 14, channel migration rates have varied dramatically during the past 55 years, with the highest rates generally corresponding to periods with large floods (see Section 4.5.4.1). Not surprisingly, the periods of rapid channel migration prior to 1964 and 1991 correspond to increases in active channel width, while the intervening period of slow or no migration corresponds to a decrease in channel width, as described in Section 4.1.1 (refer to Figure 9 for widths).

Ignoring Reach A, where levees have successfully prevented channel migration since 1940, the results for the 1936-1991 period of measurements show that rates of shifting and widening consistently increase in the downstream direction, from 0.5 feet/year in Reach E to 4.4 feet/year in Reach B. If avulsions are also considered, the difference between Reaches B and C and the upstream reaches is even greater. Factors contributing to the differences between reaches are discussed in Section 4.5.

In light of the extreme increases in width of Reaches B and C evident in the 1964 photographs, it is probable that migration rates during portions of the 1936-1964 period were as high as, or higher than, those for the 1977-1991 period. This is especially likely for the avulsion rates shown in Table 4d, since several of the avulsions probably occurred during the 1959 flood, the largest flood of record. Also, it is likely that avulsions complete most of their rapid growth in less than 10 years, so averaging the effects of an avulsion over a 28-year period has resulted in a rate which is probably too low. If the 1936-1964 avulsion rates for Reaches B and C are recalculated assuming a 10-year period of growth, rates of 30 to 40 feet per year are obtained, similar to the 32 feet/year rate for avulsion channels in Reach C between 1982 and 1991 (Table 4d). This rate of 32 feet/year therefore seems a reasonable value to use in Reaches B and C for predicting future rates of growth of avulsion channels, as done in Section 5.1.

4.4.2.2 Raging River

Calculated rates for the different types of channel migration are given in Table 5. The combined rates for shifting, widening and avulsions (Table 5a) are displayed graphically for each reach on Sheet 6, and for all reaches in Figure 15. Table 5e shows the proportion of each reach which had measurable amounts of bank erosion.

Average channel migration rates are consistently highest in Reach E and lowest in Reaches B and F. However, the low average erosion rates for Reaches B and F (Tables 5a, 5b) are largely due to the fact that only small parts of these reaches were eroding. Rates for Reaches B and F, calculated for only the eroding areas, are comparable to the other reaches (Table 5c).

As for the Tolt River, channel migration rates on the Raging River have varied dramatically with time. The highest measured rates are for 1985-1991, a period which included the four largest floods of record and no long periods without floods. These high channel migration rates correspond to increases in width during the same period (Figure 12). The lower erosion rates between 1936 and 1985 are the result of long periods with little channel migration interspersed with shorter periods of higher channel migration rates, associated with the moderately-large flood events which occurred within this period.

We have no Raging River data for the period prior to 1936, which included the very large 1932 flood. Local residents indicate that widespread bank erosion occurred during that flood, producing the wide channel visible in the 1936 aerial photographs (Figure 12). Assuming that the amount of widening was approximately equal to the amount by which the channel narrowed after the 1932 flood, the rate of channel shrinkage between 1936 and 1964 should give an approximate rate of channel migration prior to 1936. Calculated rates of channel shrinkage are shown on the final column of Table 5. For Reaches B and D, the rate thus obtained is greater than the 1985-1991 channel migration rate. Since channel widening probably occurred during a shorter period than the 28-year shrinkage period, these rates may underestimate the true rate of channel migration prior to 1936.

4.4.2.3 Comparison with Other Rivers

Few studies of channel migration rates have been done on low-sinuosity rivers with frequent avulsions, such as the Tolt and the Raging Rivers. However, a sizable body of literature on migration rates exists for meandering rivers. Figure 16 is a plot of bank erosion

rate and drainage area for meandering rivers, compiled by Hooke (1980). The periods of measurement vary from 2 to 250 years, and most of the rivers have a well-developed meandering pattern. Since most studies tend to focus on sections of rivers with measurable rates of migration, we have plotted the historic rates of channel migration in eroding areas of each reach (Tables 4c and 5c) for comparison. Also shown are channel shifting rates for the Green River in southern King County, which is a gravel-bedded river with both braided and meandering sections.

The channel migration rates calculated for this study generally fit within the range of rates for other rivers, including the larger Green River. However, migration rates of Reach E of the Tolt River and Reaches C, F, and G of the Raging River appear to be lower than normal for a river of their size, although rates calculated for shorter time periods fall within the general range of the other rates. It is possible that these anomalously low rates are in error, since they were calculated for a relatively small number of instances of measurable erosion. However, they may also result from the more resistant bank materials prevalent in these reaches, as discussed in Section 4.5.

4.5 Factors Affecting Channel Migration Rates

Factors which control channel migration rates in gravel-bedded rivers have been quantitatively examined by Nanson and Hickin (1986), who analyzed migration rates on 18 rivers with sand and gravel banks in western Canada. They found that bend curvature, river discharge and slope, and the grain size of sediment at the base of the eroding bank are the most important controls on bank erosion rates. Dunne and Dietrich (1978), in a study of the gravel-bedded Green River in southern King County, Washington, found a strong correlation between patterns of channel shifting and downstream changes in boundary shear stress. Since boundary shear stress is a function of flow depth and slope, it is similar to the discharge-slope variable used by Nanson and Hickin; both variables measure the ability of a river to erode and transport sediment.

Because cutoffs and avulsions cause meander bends on the Tolt and Raging Rivers to be poorly developed and short-lived, an analysis of the direction and rate of growth of individual bends based on their curvature is not useful in determining long-term rates of erosion. It is more pertinent to identify factors responsible for the differences in erosion rates between different reaches of the rivers. Some of the spatial variation in channel migration rates can be explained by patterns of shear stress and bank materials, as described below. However, some instances of channel migration on the Tolt and Raging Rivers are caused by random events whose location and timing cannot be predicted, such as deflection of flow against a bank by a log jam. In

addition, once channel migration occurs in a given location, it can trigger further channel migration downstream.

4.5.1 Bank Materials

The composition of the base of a river bank controls the resistance of the bank to erosion, since even strong upper bank materials will collapse if undermined (Thorne and Lewin, 1979). The sediments exposed in base of river banks in the study areas are shown in Sheets 1 and 2.

As described in Section 3.3, most river banks were composed of gravel and cobble alluvium. With a few exceptions, there was little downstream variation in the particle size of the alluvium exposed in the banks. Bank sediment in Reach E of the Tolt River contained numerous boulders and was noticeably coarser than in downstream reaches. Parts of Reaches B, C, and G of the Raging River were coarser than elsewhere on the rivers, with larger and more numerous boulders. The median grain size of bank sediment in these areas was typically two to three times larger than elsewhere on the rivers. Nanson and Hicken (1986) found that, for sand and gravel rivers in Canada, a 10-fold increase in the median particle size of the bank sediment resulted in only a doubling of the bank resistance to erosion. If the same relationship holds for these rivers, the effect of particle size on bank erosion is probably small except in local bouldery zones. Although historic rates of channel migration were low in the sections of river with coarse bank sediment, other factors also appear to contribute to these low rates (Section 4.5.2).

Lowest bank erosion rates were associated with bedrock, with riprap, and with exposures of till, which is typically compact and cohesive. The Tolt River flowed against a till bank in Reach C for decades, with no erosion apparent in successive aerial photographs. In the Raging River, rates of erosion are slower in till than in alluvium, although till (commonly interbedded with silt) has locally eroded at long-term rates of 1 foot per year (RM 7.3), and landslides have occurred in till (RM 6.1 and RM 6.75). The common occurrence of till in the river banks of Reach F of the Raging River probably contributes to the relatively low rates of channel migration there.

Glaciolacustrine silt and clayey silt in the study area tended to erode rapidly when undercut by a river. In Reach C of the Raging River, channel migration rates in glaciolacustrine deposits were not significantly different from rates in alluvium. Landslides in glaciolacustrine deposits have occurred in the Raging River study area in at least four locations.

River bend migration occurs when sediment is deposited in a bar on the inside of a bend, and flow concentrates against and undercuts the concave, outer bank. When bend migration causes the outer bank of a river bend to encounter resistant material of the valley wall, the river can become locked in position and a period of stability can ensue. This situation exists in parts of Reaches D and E on the Tolt River, and in Reach E of the Raging River in the vicinity of RM 5. Periods of stability can end abruptly when the river changes course and leaves the valley wall, as occurred in Reach C of the Tolt River following an avulsion in the 1980s. A similar period of instability is likely to occur at some point in the future in Reach D of the Tolt River, once an avulsion occurs at one of several potential avulsion sites in that reach.

4.5.2 Patterns of Shear Stress

A gross measure of the force available for erosion and sediment transport in a particular section of river is given by the boundary shear stress in the deepest part of the channel. Boundary shear stress can be calculated from flow depth and the slope of the water surface. If these data are not available, the product of the discharge and slope, which is proportional to 'stream power', can be used as a surrogate for boundary shear stress.

In comparing bank erosion rates of Canadian Rivers, Nanson and Hickin (1986) found that approximately half the variance in migration rates could be explained by differences in stream power; that is, higher erosion rates occurred in reaches where the rivers expended more energy at a higher rate.

Because the ability of a river to transport sediment depends on boundary shear stress, sediment tends to be deposited in locations where shear stress decreases rapidly in the downstream direction, so that sediment transport capacity in a reach becomes less than the sediment load supplied to the reach. Shear stress will decrease and sediment will be deposited where the channel becomes less steep and/or widens downstream, causing depth to decrease. Since sediment deposition causes the thalweg (the deepest part of the channel) to shift and divert flow against the banks, rapid channel migration often occurs in depositional zones (e.g., Carson, 1984).

Conversely, erosion of the bed and undercutting of banks may occur if shear stress increases downstream, thus increasing the river's capacity to transport sediment. Thus, instability should be expected in zones where shear stress either increases or decreases rapidly, unless resistant bed and bank materials are present. If shear stress remains fairly constant throughout a reach of river, no net deposition or erosion will tend to occur and the channel will

tend to be stable. However, sediment will be successively deposited in gravel bars in local zones of low shear stress (typically on the inside of bends) as it moves through the reach. On the Green River in southern King County, Washington, channel migration rates were found to be greatest in zones of high but rapidly decreasing shear stress, and lowest where shear stress was constant or increasing slightly in the downstream direction (Dunne and Dietrich, 1978).

Although sediment deposition tends to occur in zones with decreasing shear stress, deposition can only occur if sediment enters a section of river more rapidly than it can be transported downstream. The source of sediment is the sediment supply moving through the river from upstream, augmented by bank erosion or streamside landslides that supply bedload-size sediment to the channel.

High-energy rivers such as the Tolt and the Raging Rivers can transport fine sediment rapidly in suspension, so that the critical sediment sizes which affect channel migration are the cobbles, gravel, and coarse sand which move as bedload and are deposited in the channel in bars. For this reason, an increase in suspended sediment load, such as could occur from sand and silt particles carried in the runoff from logging roads, is unlikely to affect the rate of channel migration. However, an increased incidence of landslides can deliver coarse sediment to a river channel in volumes sufficient to overwhelm the bedload transport capacity of a river, causing channel shifting and bank erosion downstream. Widespread logging of steep slopes in the headwaters of the Raging River has occurred since the late 1980s (Section 3.2). Since numerous studies (e.g., Larson and Sidle, 1980; Ice, 1985) in the Pacific Northwest have shown that logging and associated road construction increases the incidence of landsliding and basin sediment yields, it is probable that the recent logging will increase the amount of coarse sediment delivered to the Raging River study area. As this sediment moves downstream through the study area over the next several decades, there is a potential for sections of channel that are presently stable to shift laterally in response to the increased sediment load. Since most areas of the Tolt River watershed that are presently being logged do not have landslide-prone slopes that abut a major watercourse, the current round of logging is unlikely to affect rates of channel migration.

4.5.2.1 Tolt River

Figure 17 shows large-scale patterns of shear stress for the Tolt River as it appeared in 1975, the latest date for which channel elevation data are available. Discharge on the Tolt River increases by only 5 percent between the upstream and downstream ends of the study area, so changes in shear stress are caused by changes in gradient and channel width. No large floods occurred and erosion rates were very low during the time when the river was in

this configuration (the river patterns in 1970 and 1977 are shown on Sheet 5). However, zones of sediment deposition are visible on the 1970 and 1977 aerial photographs as wide, unvegetated bars, and are plotted on Figure 17. With one exception, these depositional zones occur in, or immediately downstream from, zones of declining shear stress. This exception, at the upstream end of Reach B, is partly due to the presence of a point bar at a sharp bend, and may also reflect instability caused by the rapid increase in shear stress at this location. Channel widening and deposition were not evident in zones of decreasing shear stress in the 1970s in Reach E and the lower part of Reach C, probably because of the stable position of the river against the valley wall (Section 4.5.1). Also, although shear stress declines in Reach E enough to cause deposition of boulders, most of the bedload sediment delivered to the reach from upstream can still be transported. Bars in this reach can grow only slowly, since the supply of boulders to the river is likely to be small.

Except for changes in Reach C, these general patterns of sediment deposition and instability still hold in 1991; erosion rates are low in Reach E, locally high in the upstream half of Reach D, and very high in Reach B. Deposition of gravel continues to occur in Reach A, where shear stress decreases very rapidly as the river crosses the gently sloping Snoqualmie River floodplain.

As a result of the avulsion which started in approximately 1983, the channel location and shear stress pattern in Reach C have changed almost completely since 1975. The avulsion originated in a zone where sediment was apparently being deposited as a consequence of declining shear stress. The dashed line on Figure 17 shows the approximate shear stress pattern after the avulsion occurred, calculated using the 1975 channel elevations at both ends of the avulsion. Deposition at the downstream end of the avulsion and erosion of the bed upstream have occurred since 1983, reducing the extreme changes in shear stress to some extent. The avulsion shortened the river by approximately 1,500 feet, which increased its gradient. The high shear stresses that resulted from the avulsion allowed rapid widening and deepening of the new channel to occur.

Much of the sediment eroded from the new channel was initially deposited at the downstream end of the avulsion channel, where shear stress decreased rapidly. The increased sediment load moving through Reach B has probably contributed to instability in that reach. The angle at which the river enters Reach B changed as a result of the avulsion, and the 1985 and 1989 aerial photographs show progressive erosion of the left bank in the upstream end of Reach B, setting the stage for an avulsion which occurred in 1990. (Although removal of a log

jam which partially blocked the avulsion channel may have hastened its occurrence, the avulsion had a high probability of occurring anyway.) As a result of this and another avulsion just downstream, the river is now straighter and steeper in Reach B, with an increased ability to erode its bed and banks and transport sediment rapidly downstream.

4.5.2.2 Raging River

Figure 18a shows the product of discharge and channel slope (proportional to stream power) for Reaches A through D of the Raging River, calculated using elevation data from a 1958 topographic map with 20-foot contours. Shear stress was not calculated for these reaches, as sufficiently detailed topographic information was not available for determination of flood elevations. Since river width is relatively constant throughout Reaches B through D, the trends in stream power should provide an indication of large-scale trends in shear stress. Figure 18b shows patterns of shear stress on the upper Raging River (Reaches E through G), for which detailed flood elevations were available. Zones where channel migration has occurred during the study period are shown on the figures.

Flood discharge on the Raging River more than doubles within the length of the study area, and shear stress and stream power increase significantly downstream from the major tributaries of Deep Creek (RM 7.4) and Icy Creek (RM 3.5). Nevertheless, the pattern of shear stress on the Raging River is dominated by changes in channel gradient.

In the lower Raging River (Figure 18a), areas with a history of channel migration correlate well with zones of decreasing stream power, although the channel migration zone in Reach C continues downstream for approximately 2,000 feet after shear stress begins to increase. Channel migration in this area has been intermittent since 1936, and some instances may have been caused by an increased sediment load from bank erosion upstream. In 1990, bank erosion in this section of Reach C was enhanced by local disturbances in the form of a landslide at Icy Creek, and a log jam that blocked the channel at RM 3.3.

Although the upstream section of Reach B has been relatively stable during the study period, its position in a zone of declining shear stress suggests it is a likely location for channel migration to occur. Except for the bend just upstream from the bedrock canyon, where high rates of bank erosion have occurred, this part of the river is presently relatively straight. Gaging station records indicate that the stream bed in this area has filled in by about one foot since 1975, showing that a tendency for sediment deposition exists. Large amounts of sediment from eroded banks have entered the river in Reach C since 1985, and as this sediment moves

downstream into Reach B during the coming years, it is possible that deposition of sediment will promote greater rates of channel migration there.

Figure 18b shows patterns of shear stress in the upper Raging River valley in 1985. (Because of the closely spaced flood elevation data, this figure shows local variations in shear stress on the scale of one to two river bends.) Although high rates of channel migration correspond with zones of declining shear stress in some locations, patterns of shear stress fail to explain much of the observed variation in channel migration rates in this section of the Raging River, suggesting that other factors, such as bank material, are more important controls on bank erosion.

Upstream from the study area, the Raging River is much steeper, and shear stress drops substantially upon entering the study area. Reach G is fairly steep and shear stress is consequently generally high; however, the three major areas with low shear stress are zones with active gravel bars and high channel migration rates. Bank erosion rates have been low elsewhere in this reach since 1958, except for localized erosion at the outside of bends.

Shear stresses are fairly uniform throughout Reach F, but generally lower than in Reach G upstream. Although aerial photographs show little sediment deposition in this reach from 1958 to 1977, locally severe deposition and channel shifting have occurred downstream from RM 6.4 since then; the most severe instability may be attributed to a landslide at RM 6.1. Although bank erosion has occurred along much of this reach at some point during the 33 years of photographic record, it has been intermittent in most places, resulting in the low average erosion rates shown in Table 5. Reach F is presently relatively straight and stabilized by till banks in places; however, bends which develop in alluvium have the ability to migrate rapidly, as at RM 6.1 (Sheet 6), and the potential exists for rapid migration and development of bends in presently straight sections of the reach.

Sediment transported through the upstream part of Reach E would tend to drop out at RM 5.2, where shear stress drops rapidly. This low-gradient zone, in which water backs up behind a constriction in the valley floor, appears to be a bottleneck for sediment transported through the upper Raging River valley. In 1936, Reach E had a meandering, lower-gradient channel upstream from RM 5.2, so that shear stress would have been low throughout the upstream part of the reach, causing a buildup of sediment (see Sheet 6). By 1964, avulsions and cutoffs had straightened the bends, resulting in a steeper channel which could transport sediment through this zone more rapidly. These steep channel segments correspond to the zones in which shear stress increases downstream, shown in Figure 18b as they occurred in 1985.

Deposition of gravel bars has occurred and a braided channel has developed at this location since 1985. Due to its large width and steeper slope, a braided channel can transport sediment more efficiently than a single-thread, meandering channel in the same location. Because of these adjustments in channel pattern and instability in zones of sediment deposition, Reach E had the highest rates of channel migration on the Raging River (Figure 15).

4.5.3 Influence of Bank Vegetation and Woody Debris on Channel Migration

On high-sinuosity rivers that transport fine-grained sediment, bank vegetation and the percentage of silt and clay in the river banks have been found by others to significantly affect rates of bank erosion. These rivers differ from the Tolt and the Raging Rivers in having significantly lower erosive stresses on their banks.

Although bank vegetation strengthens the upper portions of river banks and reduces bank erosion rates in some instances, our observations suggest that naturally-occurring vegetation is not a significant factor in places on the Tolt and Raging Rivers where flow is concentrated against a bank. In eroded stream banks throughout both study areas, a dense root mat was visible in the upper three or four feet of bank. Very few roots (whether of shrubs, deciduous or coniferous trees) penetrated below four feet, and thus they were ineffective in preventing scour of the lower bank. Upper sections of banks, held together by roots, were commonly cantilevered as much as five feet over the river. Although tree roots in these cases delay the actual retreat of the upper bank, the structural damage has already been done. The trees and upper bank eventually topple into the river once scour has undermined the tree completely, and the long-term rate of bank retreat is thus controlled by erosion of the lower bank rather than the trees. In Reaches B and C of the Tolt River, local residents reported that in the floods of November 1990, Douglas fir trees greater than 100 feet high fell into the river like matchsticks as they were progressively undermined; one section of forested bank reportedly retreated 60 feet.

Similar observations on the lack of effectiveness of native vegetation in stabilizing gravel river banks were made by Nanson and Hickin (1986), who pointed out that vegetation affects only the subaerial portion of the bank, and that the strength of the upper bank is irrelevant once it is undermined.

Where flow depths and erosive forces are lower (e.g., banks whose toes are armored to prevent scour, banks on the opposite side of the channel from the thalweg, floodplains, and vegetated bars), roots and dense vegetation can reduce water velocity, prevent erosion, and promote deposition of sediment. In these cases, the presence of vegetation could be the

controlling factor in determining whether erosion occurs during floods. In particular, vegetation may help to prevent avulsions by preventing development or enlargement of floodplain channels.

Numerous large logs enter the rivers as a consequence of bank erosion. In places, logs were observed lodged against banks in a manner which reduced flow velocity and bank erosion. More frequently, however, logs were observed to partially block the flow of the river, diverting it into a bank and causing accelerated erosion. In some instances, partial or complete blocking of a channel entrance by logs has reduced bank erosion rates in that channel but increased erosion in another channel. Logs floating downstream on the Raging River have damaged or destroyed bridges whose openings are not large enough to pass large logs (Section 3.2).

Although cutting up or removing logs from the channel would reduce the number of potentially damaging logs in the river before a flood, it would not prevent entry of numerous logs into the river as bank erosion occurred during the flood. In severe floods, such as those which occurred in 1990, it is therefore questionable whether removal of logs would have substantially reduced bank erosion.

4.5.4 Influence of Flood Size on Channel Migration Rates

Even small floods can cause low rates of bank erosion in localized areas, and the cumulative effect of this erosion may be significant over many years. However, widespread areas of the Tolt and Raging Rivers have experienced high rates of bank erosion during certain time periods. This section examines the history of flooding to determine the size and frequency of flood events capable of causing high rates of channel migration on the rivers. Refer to Section 3.4 for information on magnitude and dates of floods in the study areas.

4.5.4.1 Tolt River

The largest flood of record (17,400 cfs) on the Tolt River occurred in 1959 and caused rapid channel migration throughout the study area. Except for the anecdotes of local residents, no information exists on the effects of several floods greater than 12,000 cfs which occurred between 1938 and 1959. The November 24, 1990 flood of 11,200 cfs (preliminary estimate), the largest since 1959, caused widespread bank erosion in Reaches B and C, localized bank erosion in Reach D, and had little effect on Reach E. Smaller amounts of erosion also occurred during two floods earlier in 1990, which had discharges greater than 7,000 cfs. A flood of similar magnitude (10,300 cfs) in 1969, 9 years after the 1959 flood, caused virtually no channel migration beyond the area of the 1959 channel. No avulsions occurred during the

1969 flood, and comparison of the 1964 and 1970 aerial photographs showed that the river was narrower after the 1969 flood than in 1964. Since the wide, multiple channels formed during the 1959 flood were probably relatively unhealed in 1969, the existing channels may have been able to accommodate the flood without significant bank erosion.

The 1990 floods occurred after a 20-year period in which the largest flood was 8,560 cfs. Except in Reach E, the 1970 river channel was significantly wider than the 1989 channel. The November 24, 1990 flood caused avulsions as well as widening of the channel. Thus the amount of channel migration caused by a flood appears to also depend upon channel width, and hence upon previous history of channel migration.

Although the exact date of the avulsion in Reach C is not known, it occurred in approximately 1983, so the flood which triggered it could have been no larger than 8,140 cfs (WY 1984) and possibly was as low as 5,690 cfs (WY 1983). The avulsion therefore occurred during a flood with a recurrence interval of 6 years or less (calculated using peak annual floods since construction of the South Fork Tolt dam in 1963). The avulsion channel widened rapidly between 1983 and 1989, a period in which peak annual floods ranged from 3,250 to 8,380 cfs.

Although storage in the reservoir on the South Fork of the Tolt River has apparently reduced the magnitude of some flood peaks since 1963 (as described in Section 3.4.1), the November 24, 1990 flood provides evidence that floods large enough to cause high rates of channel migration can still occur. The reservoir has been operating for only 28 years, so the record is too short for an accurate estimate of the probabilities of large floods. If the entire 1938 - 1991 period of record for the Tolt River is considered, the November 1990 flood of 11,200 cfs has a recurrence interval of approximately 9 years and an 11 percent probability of occurring in any given year. Because of the reservoir, a flood of this size has a somewhat lower probability. Nevertheless, floods capable of causing rapid channel migration on the Tolt River are clearly not rare events.

4.5.4.2 Raging River

The largest floods on the Raging River in this century occurred in 1932 and in the 1986 - 1991 period, and both sets of floods caused widespread channel migration. The effects of moderately large floods in the intervening years provide some information on the flood magnitude capable of causing high rates of bank erosion. Substantial channel shifting, including formation and cutting off of bends, occurred in Reaches D and E sometime between 1936 and 1960; accounts of local residents suggest that much of this activity occurred during the 1959

flood of 2,930 cfs. Parts of these reaches were stabilized by revetments during the 1960s, and a flood of 3,380 cfs in 1976 did not cause any channel migration detectable on 1977 photographs in those areas; however, the photographs do show localized areas of erosion and channel widening in Reaches B, E, and F in response to that flood. Following two floods of approximately 3,900 cfs in the early 1980s, the 1985 photographs show cutoffs had occurred in Reach F, and local zones of erosion and widening were more widespread than in 1977. Severe erosion occurred on many parts of the river in the 1987 to 1991 period, with 5 floods ranging from 3,900 to 5,540 cfs, although some areas of the river remained stable.

The above data indicate that floods in the range of 2,900 to 4,000 cfs are capable of causing substantial channel shifting on localized parts of the river. These events have recurrence intervals of 5 to 10 years (10 to 20 percent probability in any given year), based on the 1945 to 1991 period of record. Assignment of a return period to the larger flood events is difficult, since hydrologic conditions in the watershed may have changed in the past 5 to 10 years due to widespread logging within the transient snow zone. The FEMA (1989) estimate of 4,610 cfs for the 100-year flood (made in 1985 before any hydrologic effects of logging would have been manifested) may be too low, given the occurrence of 3 larger floods in 5 years. Since a flood of similar magnitude to the 1990 flood occurred in 1932, a more accurate estimate of the return for a 5,500 cfs event is perhaps 60 years.

5.0 HAZARDS FROM FUTURE CHANNEL MIGRATION

The results presented in Section 4.0 were used to predict the probable future limits of channel migration over both short (10-year) and long (100-year) time periods. The predictions are conservative; that is, they tend to maximize the land area affected by channel migration. Based on these predictions, land in the study areas was classified according to its relative level of hazard from channel migration. The results of this classification are shown on Sheets 7 and 8.

5.1 Methodology for Predicting Limits of Future Channel Migration

The procedure used to predict probable limits of future channel migration is based upon that used in a similar study of the Yakima River, a gravel-bedded river which experiences sudden avulsions (Dunne et al., 1976). The method assumes that future rates and types of migration in each river reach will, on average, be similar to past behavior. This approach was chosen in preference to models which attempt to predict migration of individual bends based on their

curvature. Such models are inaccurate at best, and are particularly ill-suited for long prediction periods and for rivers with rapidly changing channel patterns.

The basic elements of this procedure are as follow. The total distance of lateral migration by shifting and widening of the channel was calculated by multiplying the average annual migration rate for a particular reach by the number of years in the prediction period. In addition, avulsions were assumed to occur at likely sites, then grow laterally by shifting and widening. Modifications were made to these procedures where the migrating river encountered a valley wall or high terrace.

Table 6 shows the channel migration rates which were used for predicting the limits of future channel migration. These rates were obtained from the historic rates shown in Tables 4 and 5, as described in more detail below.

5.1.1 Extreme Hazard: 10-year Limits of Channel Migration

For this relatively short prediction period, it was assumed that bank erosion would occur only in the following locations: currently-eroding areas (as mapped during field studies and from comparison of 1989 and 1991 aerial photographs), outer banks of bends, "more-probable" avulsion sites (Section 5.1.4), and sites likely to erode as a result of upstream channel shifting. With the exception of avulsion sites (described below in Section 5.1.4), these areas where erosion is probable were assumed to migrate laterally for 10 years. For simplicity, it was assumed that the channel would migrate outward at right angles to the edge of the existing active channel. While this is not strictly accurate, it produces a band of erosion of a reasonable width, and a more detailed treatment is not possible due to the rapid shifting and destruction of bends on these rivers.

The shifting-and-widening erosion rates used for the 10-year prediction (Table 6) were obtained from Tables 4c and 5c, the historic rates of migration for eroding areas (i.e., non-eroding areas were excluded). Because a conservative prediction was desired, rates were selected from periods of at least 10 years in length which included one or more severe floods. Two periods met these criteria: 1936-1964 and 1977-1991. The higher rate from the two periods was selected for each reach (Table 6).

5.1.2 High and Moderate Hazard: 100-year limits of channel migration

Based on past behavior, the river pattern in most reaches of the two rivers is likely to change completely in much less than 100 years. Therefore, instead of selecting the areas most likely to erode, average shifting-and-widening migration rates were applied throughout the length of each reach. Prediction of avulsions for the 100-year period is described below in Section 5.1.4.

Where not confined by a valley wall or a high terrace, the river can migrate in either direction from its present position. In the "less-conservative" prediction used for the **High Hazard** classification, the river migrates for 50 years in both directions from its present position. The resulting total amount of migration is consistent with the historic rates.

It is less likely, although possible, that channel migration would continue in a single direction for 100 years. Accordingly, "more-conservative" limits of channel migration were calculated by assuming the river could migrate in either direction from its present position for the full 100 years. Since channel migration is less likely to occur in these additional areas, they are classified as **Moderate Hazard.** Also included in the Moderate Hazard class are two short sections of former river channels in Reaches C and E of the Tolt River study area. These areas, which are not potential avulsion sites, fell outside the limits of channel migration predicted as described above.

Because the rivers were assumed to have an equal probability of shifting and widening at all locations, the average channel migration rates calculated for each reach (including non-eroding areas) from Tables 4b and 5b were used for the 100-year predictions. Rates for the entire period of photographic record (1936-1991 in most cases) were selected. Because the rates for the 100-year predictions include periods and locations with no channel migration, they are considerably lower than the prediction rates used for the 10-year period (Table 6).

For Reaches B through D of the Raging River, the calculated rates of channel shrinkage between 1936 and 1964, which serve as an estimate of the erosion rate in the period including the large 1932 flood, were higher than the 1936-1964 channel migration rates (see Section 4.4.2.2). Because a conservative prediction was desired, these shrinkage rates were used to obtain the weighted average 1936-1991 rates used for the 100-year prediction period.

The historic average channel migration rates used for the 100-year predictions were calculated from a 55-year period of record for the Tolt River and most of the Raging River, and only a 33-year period of record for Reaches F and G of the Raging River. It is therefore quite probable that these rates are higher or lower than the true average 100-year channel migration rates for these rivers. The actual rates of channel migration during the next 100 years will depend upon the particular sequence of rainfall and snowmelt events, as well as the extent of revetments and hydrologic or sediment-load changes in the river basins. Because the period of record for both rivers includes at least one rare, large flood which caused extensive channel migration, it is assumed that the predicted rates do not seriously underestimate long-term average rates of channel migration.

5.1.3 Valley Walls and Terraces

Modifications to the above procedures were made where the river encountered a valley wall or high terrace. If the river impinged on a terrace greater than 10 feet in height, the rate of channel migration was reduced in proportion to the increase in height, so that the volumetric rate of bank erosion remained constant. (This adjustment for bank height has been used in statistical analyses of rates of bank erosion, with reasonable results; e.g., Nanson and Hickin, 1986). Where the river impinged on a terrace higher than 25 feet or on a valley wall, no further channel migration was predicted; however, these areas represent potential landslide hazards due to future undercutting of the toe of the slope by the river.

5.1.4 Avulsions

Potential avulsion sites on both rivers were divided into two groups. "More-probable" avulsion sites are those where an avulsion could occur under present conditions. For example, an existing creek or side channel which diverges from the main channel of the river in a downstream direction would be a "more-probable" site. "Less-probable" sites are those for which one or more conditions would have to change for an avulsion to become likely. For example, an abandoned channel whose bed is higher than the river because of downcutting of the main channel is a "less-probable" site for an avulsion under present conditions.

On the Tolt River, avulsions were followed by rapid growth of new channels. The rate of growth of avulsion channels between 1982 and 1991 in Reach C was used for avulsions in Reaches B and C (Table 4d). For Reach D of the Tolt River, for which there are no data on the growth rate of avulsions, the highest shifting and widening rate for the reach was selected from Table 4c. On the Raging River, where avulsions are less prevalent and there was no

evidence of a significant increase in migration rates following avulsions, separate rates were not used for avulsions.

Basing the prediction scheme on the behavior of recent avulsions, an avulsion on the Tolt River was assumed to start as a 30-foot wide channel, erode at the higher avulsion rate for 10 years, and then drop back to the normal channel migration rate for the remainder of the prediction period. Avulsions on the Raging River were assumed to immediately attain the full width of the river channel, then erode at the normal channel migration rate for the remainder of the period.

Because avulsions are triggered by unpredictable, random events such as log jams, landslides, large floods, or upstream changes in river position, it is not possible to predict when or if an avulsion will occur at the identified potential avulsion sites. Since a conservative prediction was desired by the King County Surface Water Management Division, the "more-probable" avulsions were assumed to occur at the beginnings of the prediction periods. "Less-probable" avulsions would occur after 50 years, halfway through the 100-year prediction period. In addition, avulsions could occur at other times within a prediction period if shifting and widening caused the river to intersect a potential avulsion site. However, since the possibility remains that these avulsions would not occur, sections of river channel which would be abandoned by an avulsion were assumed to continue to shift laterally throughout the prediction period.

5.1.5 Levees and Revetments

No attempt was made to evaluate possible effects of levee failures within Reach A of both rivers, both because there are few data on migration rates prior to levee construction in about 1940, and because these structures have effectively prevented channel migration for the past 50 years. However, this record of success does not guarantee continued effectiveness in the future. Sediment has built up in leveed reaches of both rivers since the late 1960s. In the future, the channel area within the levees is likely to be further reduced as more gravel builds up, decreasing the size of flood that would be necessary to overtop or breach a levee. It is recommended that channel surveys be conducted to determine the rate of gravel accumulation, and that flood elevations be calculated for present conditions to evaluate whether buildup of gravel within the levees has resulted in a significant risk of levee overtopping.

Upstream from Reach A of both rivers, channel migration predictions include the effects of potential failure at the entrances to the levee systems, where they are most vulnerable to damage. For existing levee and revetment structures upstream from Reach A of both rivers,

Sheets 7 and 8 denote areas which would be at risk from channel migration if the structures did not exist. No attempt was made to evaluate the condition of existing revetments or levees, or to evaluate the probability of their failure. Existing revetments were assumed to be effective for the 10-year prediction. For the 100-year prediction, revetment-protected avulsion sites were given a "less-probable" status (Section 5.1.4) and channel migration was calculated in the normal manner, assuming that the revetments were not in place.

5.2 Channel Migration Hazard Maps

The Channel Migration Hazard Maps (Sheets 7 and 8) show areas at various levels of risk from channel migration, as predicted by the procedures described in Section 5.1. The areas threatened by channel migration if a revetment fails are indicated by cross-hatching on Sheets 7 and 8. The outer limits of the hazard zones represent the probable limits of channel migration during the specified time periods. In many reaches of the study areas, the 100-year limits of channel migration predicted with the "more-conservative" procedure (Moderate-Hazard zone) include the entire floodplain as well as portions of adjoining terraces. Because simultaneous erosion of all possible channels was assumed, it is likely that some areas within these zones will not be occupied by the river channel during the specified time periods.

On the other hand, there is a low, but real, possibility that the rivers could occupy portions of the valley floor beyond the limits of the Moderate-Hazard zone shown on Sheets 7 and 8. Avulsions triggered by landslides or log jams could occur in locations which were not predicted. Additionally, the historic migration rates on which these predictions are based could be too low, since the rates were obtained from a shorter period of record than the 100-year prediction period. Accordingly, all unshaded areas of the valley floors, excluding higher terraces, should be considered to have a low risk of encroachment by channel migration.

6.0 LIMITATIONS

The probable limits of future channel migration are based upon extrapolation of historic rates and trends of channel migration into the future. Future changes in conditions, for instance aggradation of the river beds, or climate fluctuations or land-use changes beyond those experienced in the past 55 years, could change migration rates and avulsion probabilities substantially. It is therefore recommended that the rivers be reevaluated in approximately 20 years, and that the hazard zones be readjusted if warranted.

Channel migration rates on the Tolt and Raging Rivers have historically varied dramatically over time, with long periods of relative stability interspersed with periods of rapid channel migration. Because the timing of future floods capable of causing rapid channel migration is unknown, ***the mapped channel migration limits should be used as an indication of relative hazard, rather than a precise prediction of the time at which the river will reach a given location.*** The consequences of possible levee failures were not evaluated for Reach A of either river.

This report was prepared as a basis for regulation of future development in areas at risk from channel migration. This study did not evaluate the risk of flooding at present or as a result of future channel migration; the adequacy of existing levees or revetments; or the stability of existing slopes which are now, or could in the future be, undercut by the rivers. Where the stability of structures or slopes is in question, site-specific studies should be performed, including subsurface explorations where bank materials are poorly exposed.

Sincerely,

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SJP:WTL:WPG/tlm

7.0 REFERENCES

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Dr. Thomas Dunne served as special consultant for this study and reviewed a draft of the report. King County provided aerial photographs, maps, and records of revetment repair. CH2M Hill provided cross-section survey data, contour maps and aerial photography for the Raging River study area. The USDA Soil Conservation Service provided cross-section survey data for the Tolt River study area. Numerous residents of the study areas contributed historical information and allowed access to their property for field studies.

TABLE 1

MAPS AND AERIAL PHOTOGRAPHS USED FOR MAPPING HISTORICAL CHANNEL POSITIONS SHOWN ON SHEETS 3 THROUGH 6

Date	Type	Scale	River	Source
1873	Map	1:31680	Tolt & Raging[1]	Government Land Office survey
1919-21	Map	1:125000	Tolt	USGS Sultan quadrangle
1922	Map	1:2400	Raging[2]	King County Public Works, Roads Division
9/16/36	Photo	1:9600	Tolt & Raging[3]	Walker & Associates
1952	Map	1:24000	Raging	USGS Fall City and Hobart quadrangles
sum. 1958	Photo	1:13200	Raging[4]	DNR
7/64	Photo	1:12000	Tolt & Raging	King County Public Works, Roads Division
1/30, 2/3/64 10/61	Map	1:2400	Tolt	King County Eng. Department, Flood Control Division (contour interval 5 feet)
6/2 & 8/10/70	Orthophoto	1:4800	Tolt	1982 SCS Flood Hazard Analysis, Tolt River
4/20/77	Photo	1:18000	Tolt	Walker & Associates
1985	Map	1:4800	Raging	CH2M/Hill Flood Insurance Study Work Map (contour interval 5 feet)
spr. 1985	Photo & orthophoto	1:4800	Raging	CH2M/Hill
7/22/89	Photo	1:14000	Tolt & Raging	DNR
1/4/91	Photo	1:9600	Tolt & Raging	Walker & Associates
The following sources were consulted but not shown on Sheets 3 through 6:				
1893	Map	1:31680	Upper Raging[5]	Government Land Office survey
1910-11; 1919-21	Map	1:125000	Raging[5]	USGS Sultan and Cedar Lake quadrangles
4/7/60	Photo	1:12000	Tolt, Raging[6]	
1970	Photo	1:13200	Raging & Tolt	King County Public Works, Road Division
4/20/77	Photo	1:18000	Raging	
3/9/85	Photo	1:18000	Tolt	
1989	Photo	1:14000	Raging	

1) Maps not planimetrically correct; not used on Raging River upstream from RM 3.2 due to gross inaccuracies. 2) RM 0-1.4 only. 3) No coverage available on Raging River upstream from RM 6.0. 4) Upstream from RM 6.0 only. 5) Too inaccurate to use. 6) Incomplete coverage.

1-31-91/W5666-1.TRL/SJP-lkd/cbt

TABLE 2

LARGEST FLOODS SINCE WATER YEAR 1929[1]
TOLT RIVER NEAR CARNATION, USGS GAGE 12148500

Water Year	Discharge (cfs)	Date
1960	17,400	12/15/59
1951	16,800	02/09/51
1956	15,000	12/11/55
1945	12,700	01/07/45
1943	12,300	10/31/42
1991	11,200[2]	11/24/90
1950	10,600	03/14/50
1938	10,600	04/18/38
1969	10,300	01/05/69
1963	10,200	11/19/62

1. Excluding water years 1933-1937
2. Preliminary estimate from USGS

W5666TBL.2/SJP-lkd/srn

TABLE 3

LARGEST FLOODS SINCE WATER YEAR 1946
RAGING RIVER NEAR FALL CITY, USGS GAGE 12145500

Water Year	Discharge (cfs)	Date
1991	5,540[1]	11/24/90
1987	5,330	11/23/86
1990	4,640	01/09/90
1990	4,140	02/10/90
1984	3,960	01/24/84
1991	3,900[1]	11/09/90
1980	3,880	12/15/79
1951	3,430	02/09/51
1976	3,380	12/03/75
1960	2,930	11/22/59

1. Preliminary estimate

TABLE 4

Tolt River Channel Migration Rates

a) Average rate for reach, including avulsion channels (feet/year)

REACH	1936-1964	1964-1977	1977-1989	1989-1991	1936-1991	1977-1991
A	0	0	0	0	0	0
B	7.54	0.28	2.66	67.40	6.38	9.85
C	5.8	1.62	7.29	54.60	6.47	12.54
D	3.43	0.96	0.72	4.25	2.27	1.11
E	0.98	0.13	0*	0*	0.53	0*

b) Average shifting and widening rate for reach (feet/year)

REACH	1936-1964	1964-1977	1977-1989	1989-1991	1936-1991	1977-1991
A	0	0	0	0	0	0
B	4.70	0.28	2.66	49.57	4.43	7.87
C	3.09	1.62	2.17	21.25	3.04	4.29
D	3.43	0.96	0.72	4.25	2.27	1.11
E	0.98	0.13	0*	0*	0.54	0*

c) Average shifting and widening rate of eroding areas only (feet/year)

REACH	1936-1964	1964-1977	1977-1989	1989-1991	1936-1991	1977-1991
A	0	0	0	0	0	0
B	5.95	2.05	4.90	54.29	6.12	10.39
C	4.41	4.04	4.64	42.50	5.42	8.85
D	4.37	2.69	2.60	17.60	3.94	4.27
E	1.99	3.08?	0*	0*	1.76?	0

d) Average shifting and widening rate for avulsion channels (feet/year)

REACH	1936-1964	1964-1977	1977-1989	1989-1991	1982-1991
A					
B	14.29 **			124.40	
C	10.64 **		11.81	87.06	32.04
D					
E					

* Channel shifting rate too low to be detected using aerial photographs.
** Rate is probably too low, since many of the avulsions presumably occurred during the 1959 flood.

TABLE 5

Raging River Channel Migration Rates

a) Average rate for reach, including avulsion channels (feet/year)

REACH	1936-1964	1964-1985	1958-1985	1985-1991	1936-1991	1958-1991	Shrinkage 1936-1964
A	0	0	***	0	0	***	***
B	0.33	0.29	***	0.83	0.37	***	1.40
C	0.26*	1.46*	***	4.39	0.81	***	1.05
D	1.11	2.21	***	2.06	1.70	***	3.74
E	2.57	1.48	***	10.00	2.90	***	0.60
F	***	***	0.92	4.10	***	1.46	***
G	***	***	0.09	1.47	***	0.32	***

b) Average shifting and widening rate for reach (feet/year)

REACH	1936-1964	1964-1985	1958-1985	1985-1991	1936-1991	1958-1991	Shrinkage 1936-1964
A	0.00	0.00	***	0.00	0.00	***	***
B	0.33	0.29	***	0.83	0.37	***	1.40
C	0.26*	1.46*	***	4.39	0.81	***	1.05
D	1.11	2.21	***	2.06	1.63	***	2.85
E	1.35	1.48	***	10.00	2.27	***	0.60
F	***	***	0.92	4.10	***	1.46	***
G	***	***	0.09	1.47	***	0.32	***

c) Average shifting and widening rate of eroding areas only (feet/year)

REACH	1936-1964	1964-1985	1958-1985	1985-1991	1936-1991	1958-1991
A	0.00	0.00	***	0.00	0.00	***
B	4.70	1.77	***	4.62	3.57	***
C	1.33*	2.42*	***	8.07	1.40	***
D	2.59	3.99	***	4.13	3.29	***
E	2.44	2.41	***	11.10	3.03	***
F	***	***	1.67	5.96	***	2.40
G	***	***	0.90	3.83	***	1.41

d) Average rates for avulsion channels (feet/year)

REACH	Erosion 1936-1964	Shrinkage 1936-1964
A		
B		
C		
D		
E	6.77	6.76
F		
G		

e) Proportion of reach eroded (%)

1936-1964	1964-1985	1958-1985	1985-1991
0	0	***	0
7	17	***	18
19	38	***	56
43	55	***	58
70	62	***	90
***	***	55	69
***	***	7	38

* These rates may be too high as a result of a plotting error, since the 1964-1985 changes in some places negate the 1936-1964 changes. Average net rate for 1936-1985 is 0.41 ft./yr. for reach, 0.68 ft./yr. for eroding areas.

TABLE 6

CHANNEL MIGRATION RATES SELECTED FOR PREDICTIONS OF FUTURE MIGRATION LIMITS

REACH	RATE (feet/year)		
	10-year	100-year	Avulsion
TOLT RIVER			
B	10.4	4.4	32.0
C	8.9	3.0	32.0
D	4.4	2.3	17.6
E	2.0	0.5	N/A
RAGING RIVER			
B	4.7	0.9	
C	4.7	1.1	
D	4.0	2.5	
E	5.9	2.3	
F	3.4	1.5	
G	2.1	0.6 *	

* The rate of 0.6 ft/yr is the possible error in mapping changes in channel position for Reach G. The lower calculated historic rate of 0.3 ft/yr (Table 5b) was used for most areas upstream from Deep Creek (RM 7.3), based on lower discharge and evidence of historic stability. All other rates shown on this table are larger than the possible mapping errors.

TABLE 7

NOTES ON POTENTIAL HAZARDS OF SITES MARKED ON SHEET 7, TOLT RIVER CHANNEL MIGRATION HAZARD MAP

Site Number on Sheet 7	Location	Description
1	RM 1.8 right bank* (downstream section of "Holberg" in SWM revetment records)	Levee damaged by scouring of toe during 11/24/90 flood. Due to an avulsion during that flood, a major portion of the river now flows in this channel, and progressively more flow is likely in the future. This portion of the levee is therefore vulnerable to more damage in future floods.
2	RM 2.0 right bank (upstream section of "Holberg" revetment)	Since the 11/90 flood, widening of the avulsion channel described above has destroyed a portion of the revetment in this area. The river now flows along the side of a terrace approximately 6'-10' in height. If this terrace were to erode to the north for approximately 100 feet, the river would intersect the head of a westward-flowing swale (Sheet 3), increasing greatly the risk of flooding of downstream areas currently protected by levees. The risk of an avulsion into the swale is low, due to its elevation above the floodplain.
3	RM 2.4 left bank	Rapid retreat of a 20'-high bank of glaciolacustrine silt has occurred in the past 10 years. Although the river has mostly abandoned the channel next to this bank due to an avulsion, there is a substantial risk that it could switch back to this channel. Further retreat of the bank would cut off the access road to 5 properties on the south side of the Tolt River.
4	RM 4.5 right bank ("Sans Souciville" in SWM revetment records)	Rapid erosion of a 6'-7' high bank occurred during the 11/24/90 flood at this site, which is the upstream end of former revetment. Continued erosion would expose lower ground, resulting in overbank flow and possibly in an avulsion. An avulsion would cut off approximately 10 residences in the San Souciville community.
5	RM 4.6 right bank (same as RM 5.1 "Rio Vista" in SWM revetment records)	Overtopping of a low revetment at this site contributes to flooding and causes floodplain erosion of the San Souciville area. A mid-channel bar which protected this revetment from the full force of the river was destroyed by the 11/24/90 flood. An avulsion at this site would also cut off the Sans Souciville community.

Site Number on Sheet 7	Location	Description
6	RM 4.95 right bank	The former 1873 channel is a potential avulsion site. The right bank risk of avulsion is lower than at Site 5 because the river has incised several feet below the level of the former channel, which experienced sediment deposition rather than erosion during the November 1990 flood.

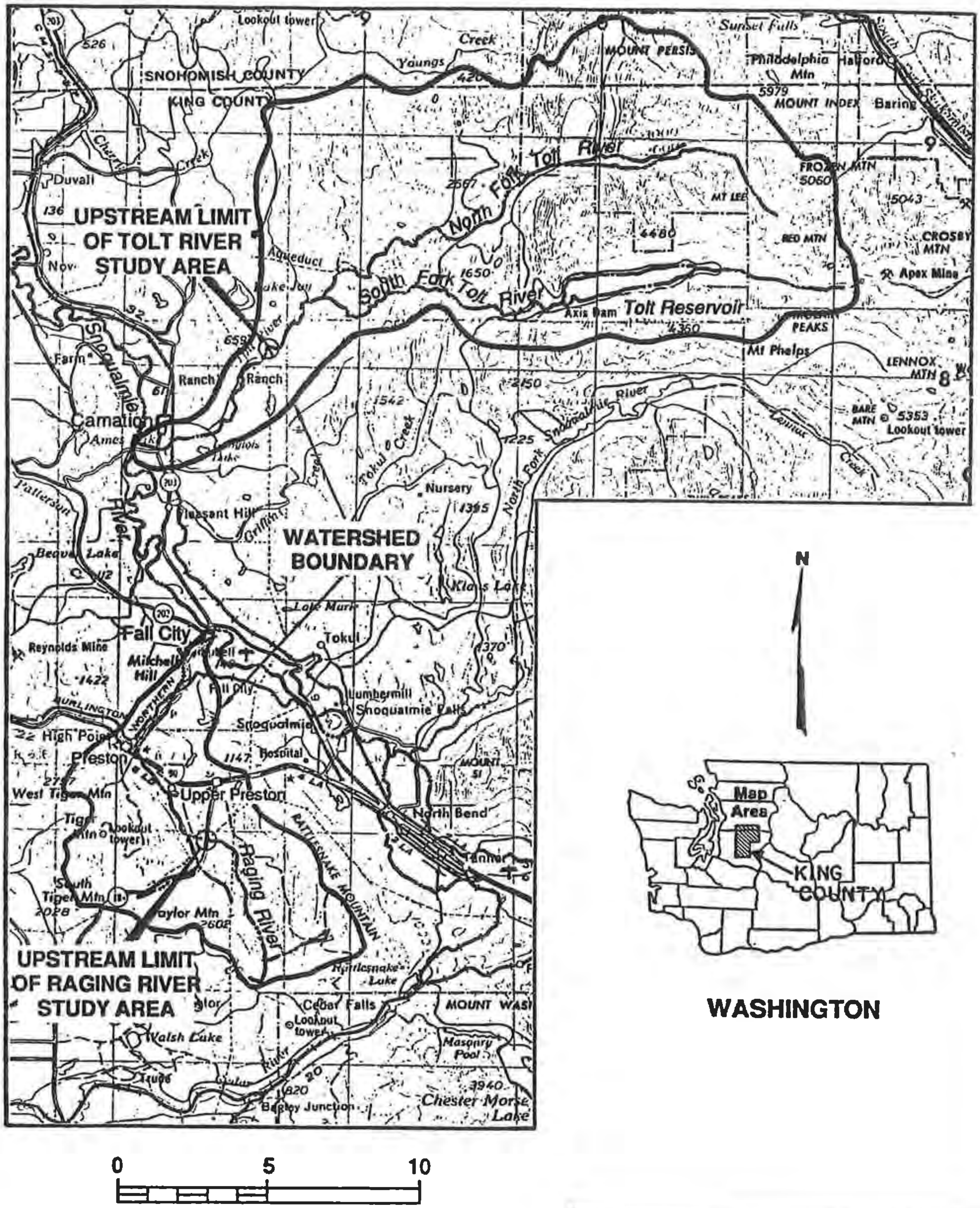
* As viewed looking downstream.

TABLE 8

NOTES ON POTENTIAL HAZARDS OF SITES MARKED ON SHEET 8, RAGING RIVER MIGRATION HAZARD MAP

Site Number on Sheet 8	Location	Description
1	RM 4.95 (trailer park bridge)	During the 11/24/90 flood, the bridge which provided access to left bank* residences was plugged by logs, then washed away. In addition to causing bank erosion near the bridge, floodwaters backed-up by the bridge cut a narrow channel across a portion of the floodplain upstream. Had the bridge not washed away when it did, an avulsion could have occurred. A permanent access road from I-90 to the left bank should be considered as an alternative to replacing the bridge, because 1) the right bank access road to the bridge could be destroyed by an avulsion, and 2) a bridge could cause similar damage in the future.
2	RM 5.1 right bank	An avulsion at this location would threaten the trailer park and houses downstream.
3	RM 6.1 right bank	Upstream from the existing concrete-block bank protection, undercutting of the bank by the river may cause the existing landslide to extend upstream.
4	RM 7.54 left bank (bridge on Upper Preston Road SE)	Repeated flooding to the left of this under-sized bridge may eventually cause a new channel to form here.
5	RM 7.9 left bank	Growth of an existing landslide, in highly erodible recessional glaciolacustrine deposits, is likely to continue as long as the river maintains its course at the toe of the landslide.

* As viewed looking downstream.



NOTE

Base map taken from U.S. Geological Survey topographic map of Wenatchee, WA Quadrangle, dated 1957, revised 1971.

King County SWM
Tolt and Raging River Channel Migration Study

STUDY AREA LOCATION MAP

January 1991 W-5666-01

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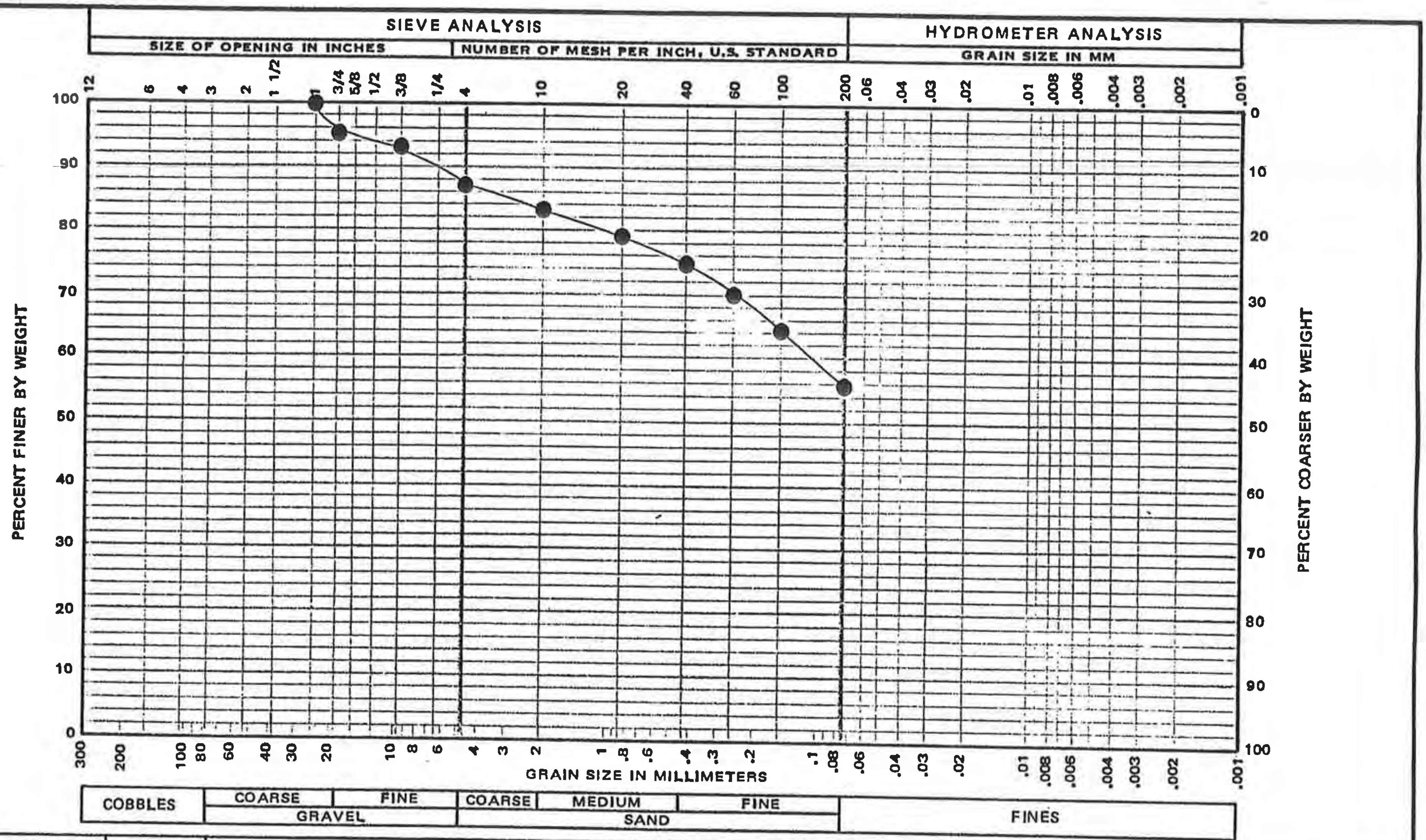
FIG. 1



SAMPLE NO.	DEPTH-FT.	U.S.C.	CLASSIFICATION	NAT. W.C. %	LL	PL	PI
"D"		ML	Gray, gravelly, sandy SILT; (TILL)	4.7			

Tolt and Raging Rivers
Channel Migration Study

GRAIN SIZE DISTRIBUTION
Raging River Sample

February 1991 W-5666-02

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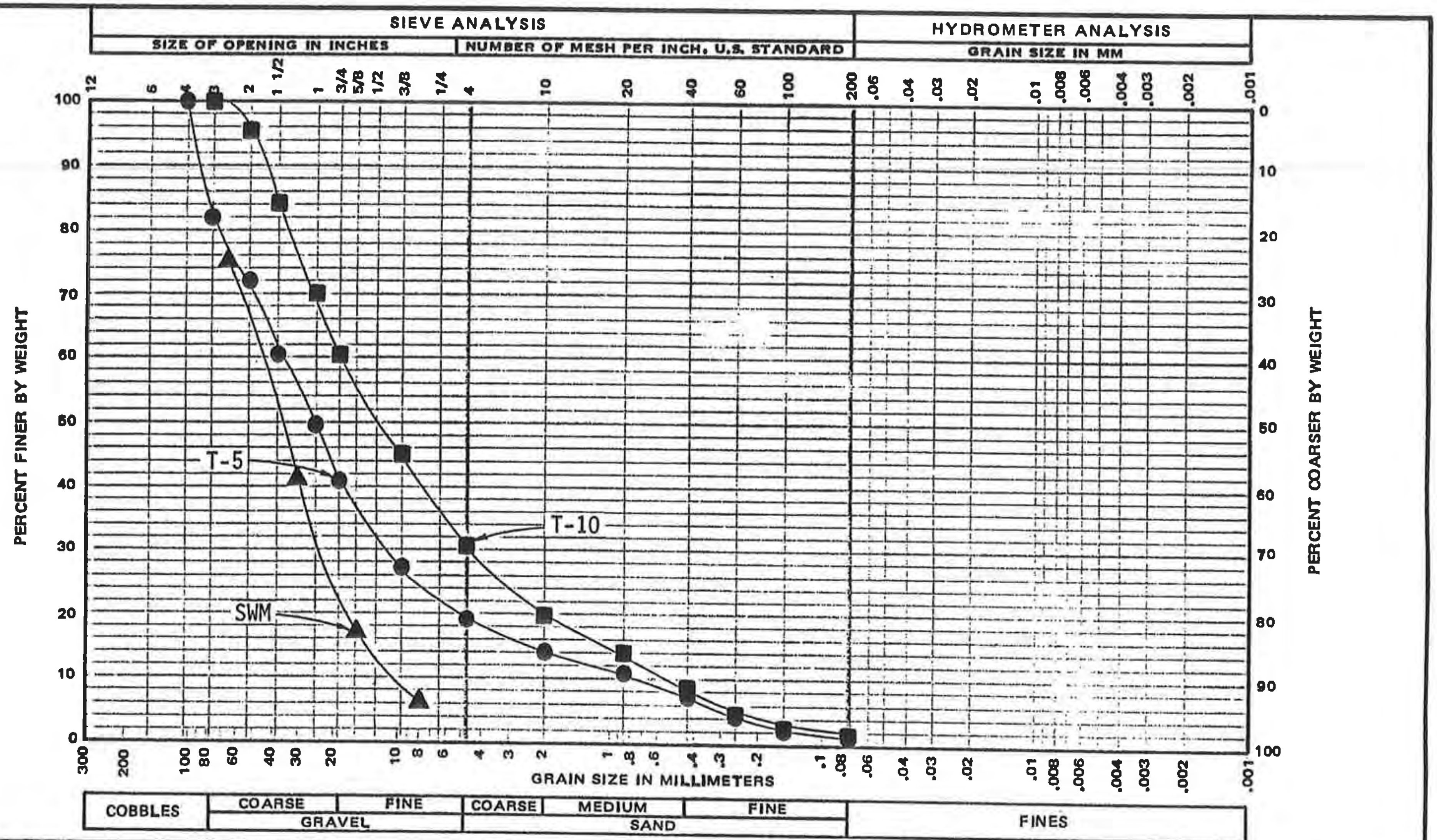
FIG. 2

FIG. 2



SAMPLE NO.	DEPTH-FT.	U.S.C.	CLASSIFICATION	NAT. W.C. %	LL	PL	PI
T-5		GP	Gray-brown, sandy GRAVEL.	0.7			
T-10		GW	Gray, sandy GRAVEL.	2.5			

Tolt and Raging Rivers
Channel Migration Study

GRAIN SIZE DISTRIBUTION
Tolt River Samples

February 1991 W-5666-02

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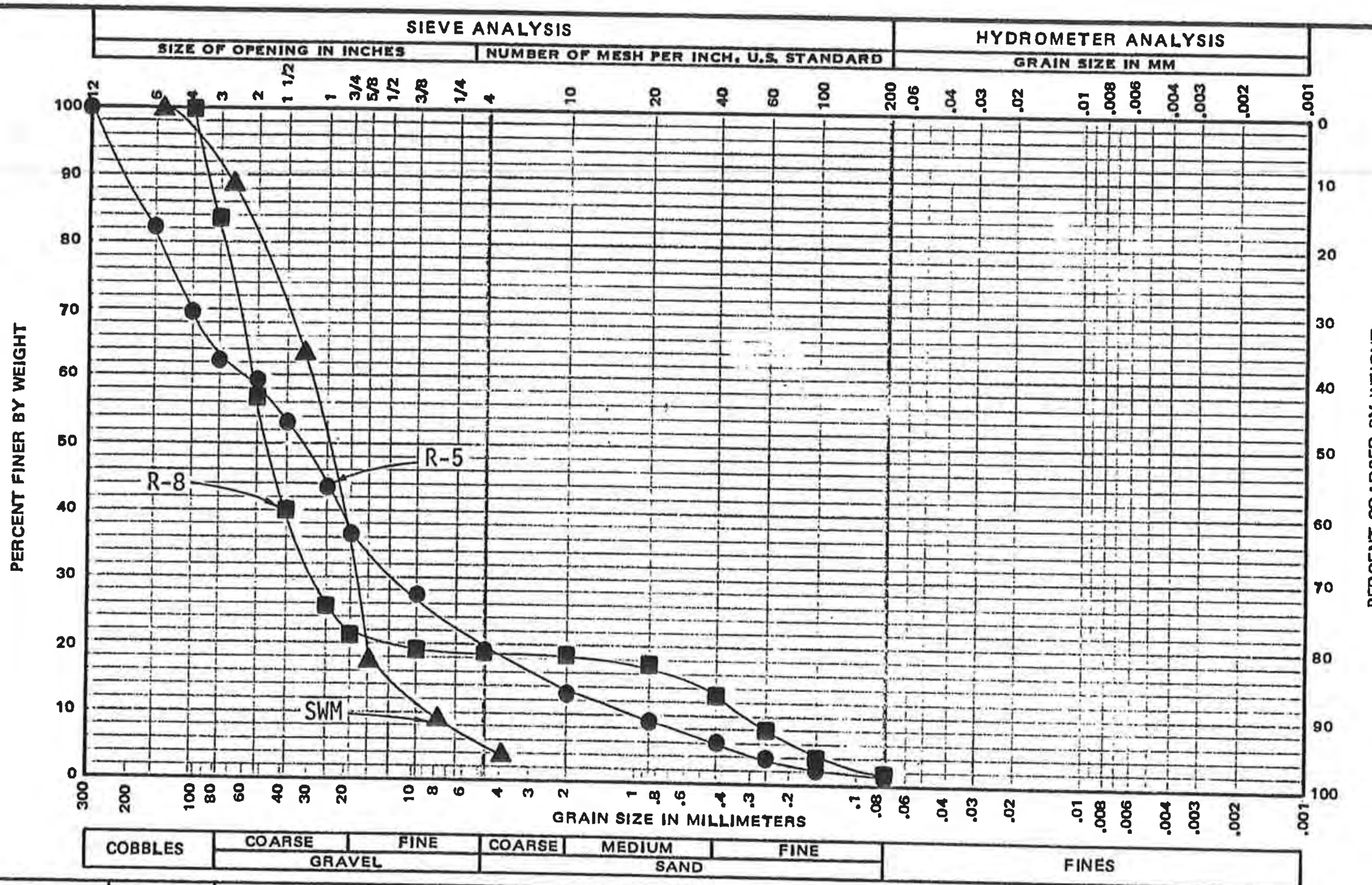
FIG. 3

FIG. 3



SAMPLE NO.	DEPTH-FT.	U.S.C.	CLASSIFICATION	NAT. W.C. %	LL	PL	PI
R-5		GW	Gray, sandy GRAVEL.	5.5			
R-8		GP	Gray, sandy GRAVEL.	10.5			

Tolt and Raging Rivers
Channel Migration Study

GRAIN SIZE DISTRIBUTION

Raging River Samples

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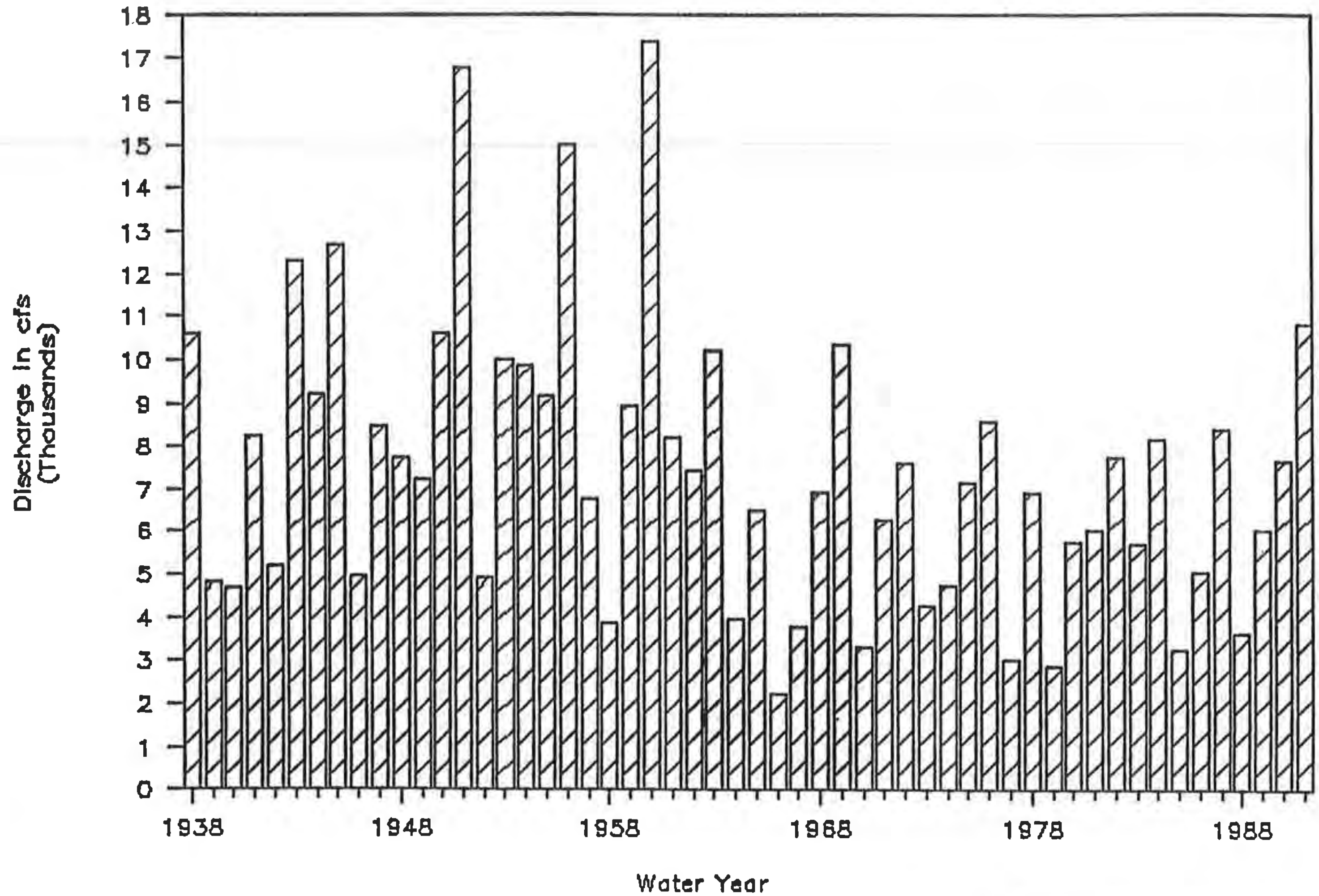
FIG. 4



King County SWM
Tolt & Raging River Channel Migration Study

PEAK ANNUAL DISCHARGE
TOLT RIVER NEAR CARNATION

March 1991 W-5666-01

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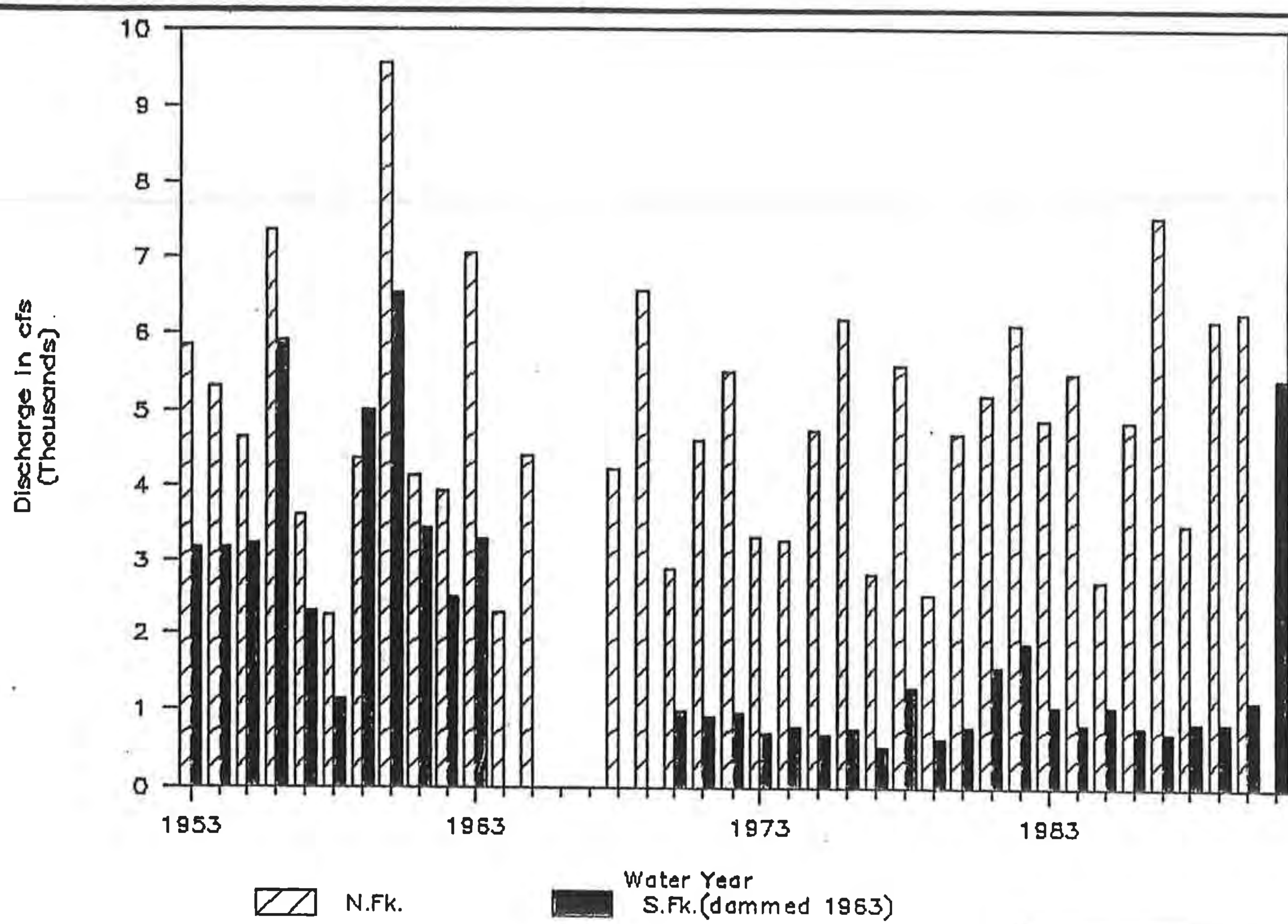
FIG. 5

FIG. 5



King County SWM
Tolt and Raging River Channel Migration Study

PEAK ANNUAL DISCHARGE NORTH FORK AND SOUTH FORK TOLT RIVER

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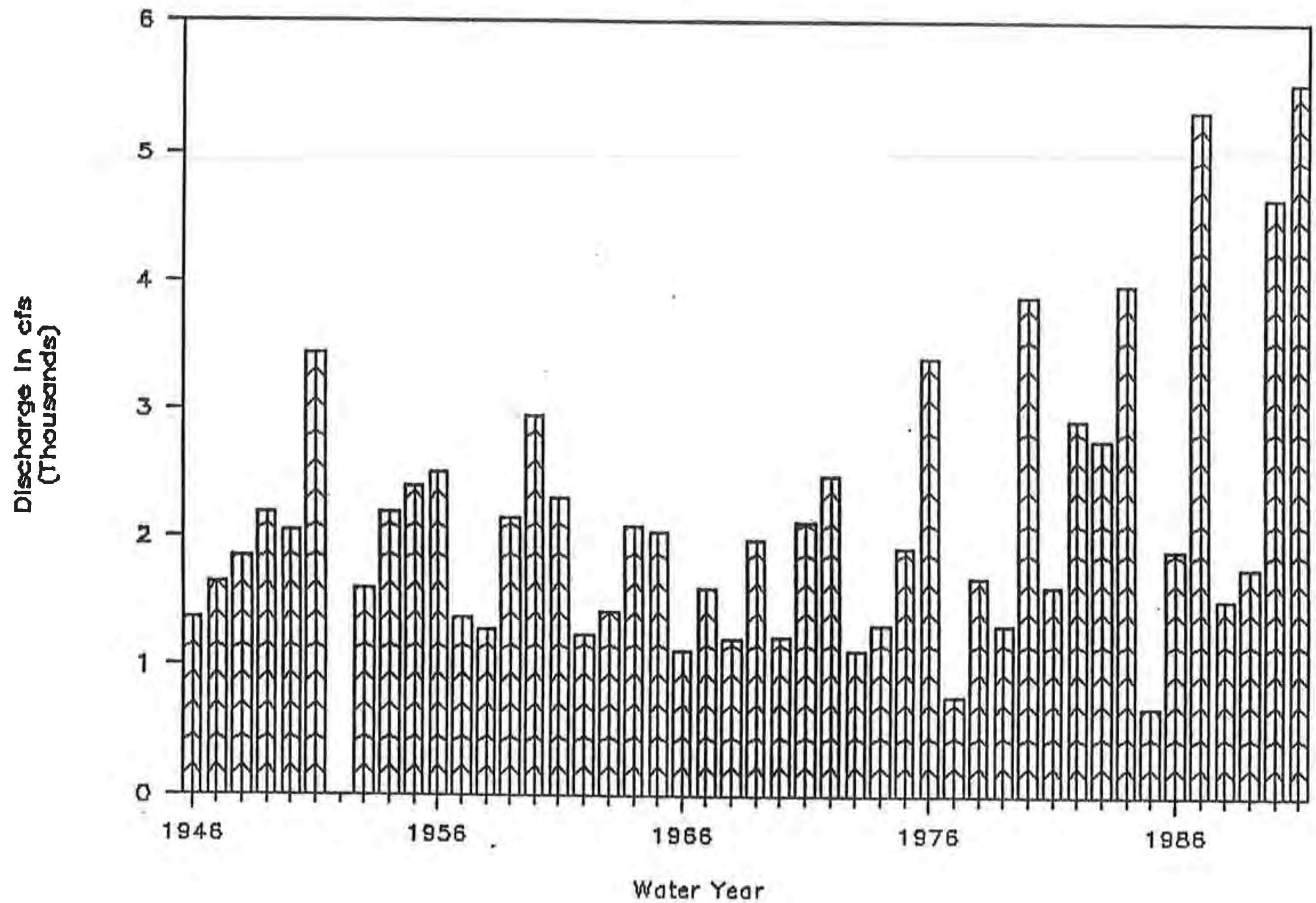
FIG. 6

FIG. 6



King County SWM
Tolt & Raging River Channel Migration Study

PEAK ANNUAL DISCHARGE RAGING RIVER NEAR FALL CITY

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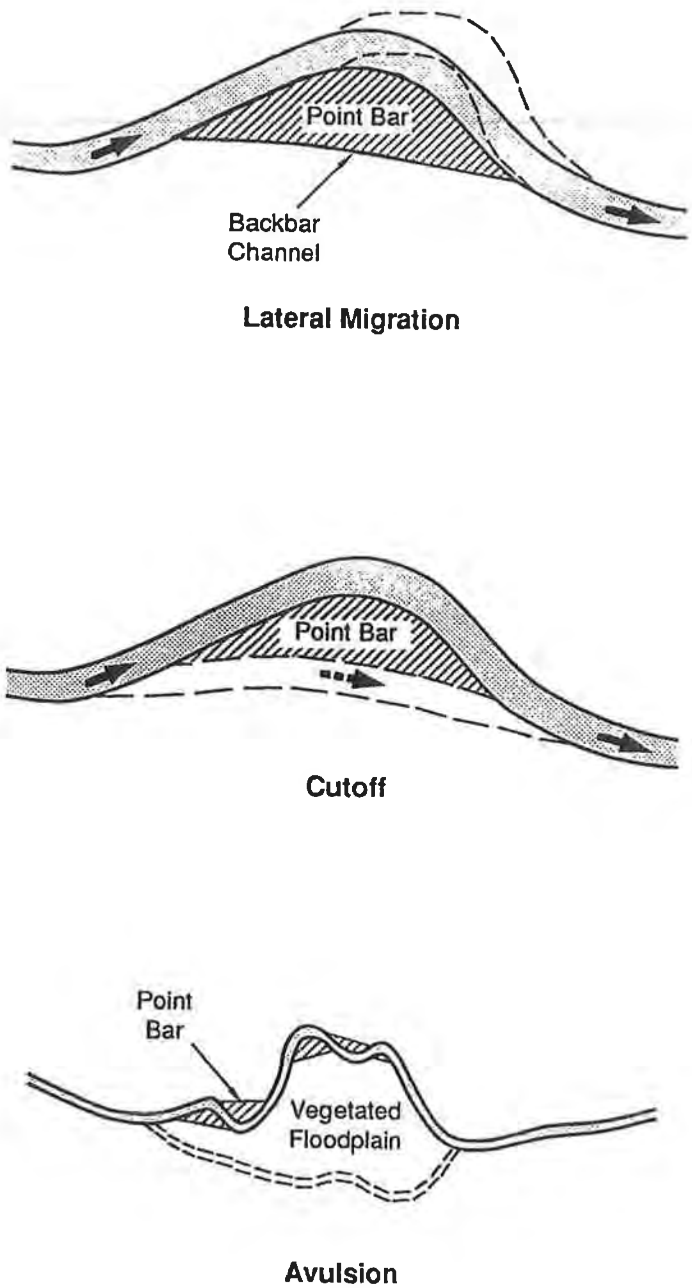
FIG. 7

FIG. 7



NOTE

Dashed lines denote channel position after migration takes place.

King County SWM
Tolt & Raging River Channel Migration Study

TYPES OF CHANNEL MIGRATION

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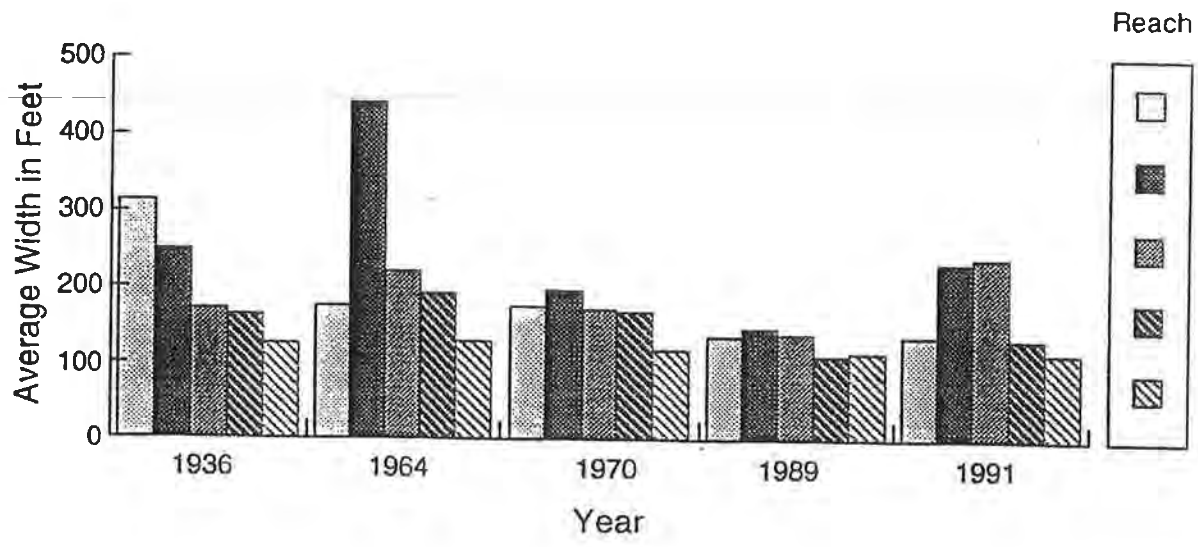
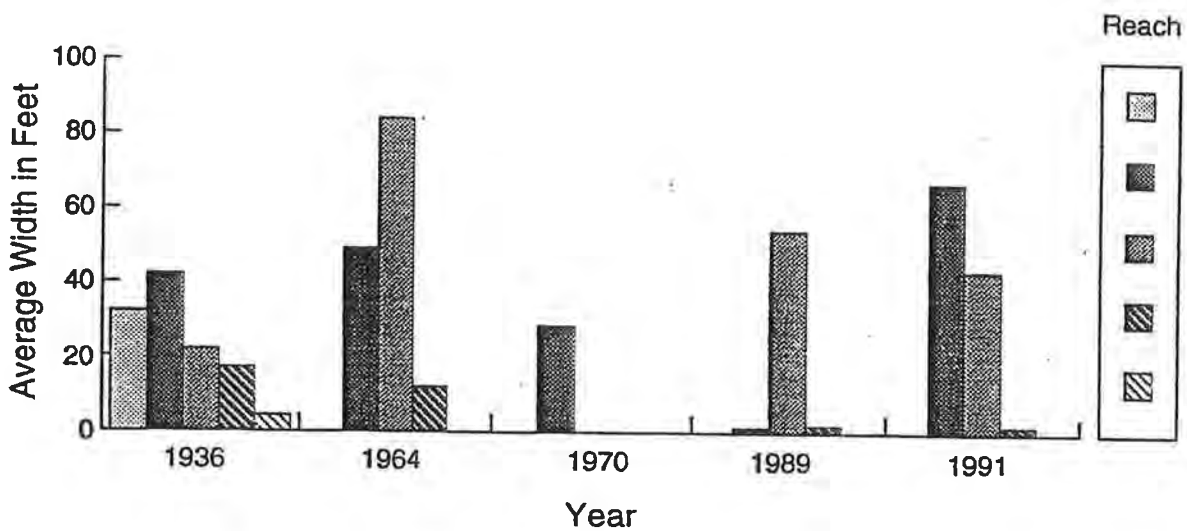
FIG. 8

a) Main Channel



b) Side Channels



NOTES

1. 1977 main channel widths (not shown) were similar to 1970. Virtually no side channels were present in 1977.

2. Where more than one side channel was present, Figure 9b shows the average combined widths of all side channels.

King County SWM
Tolt & Raging River Channel Migration Study

ACTIVE CHANNEL WIDTHS TOLT RIVER

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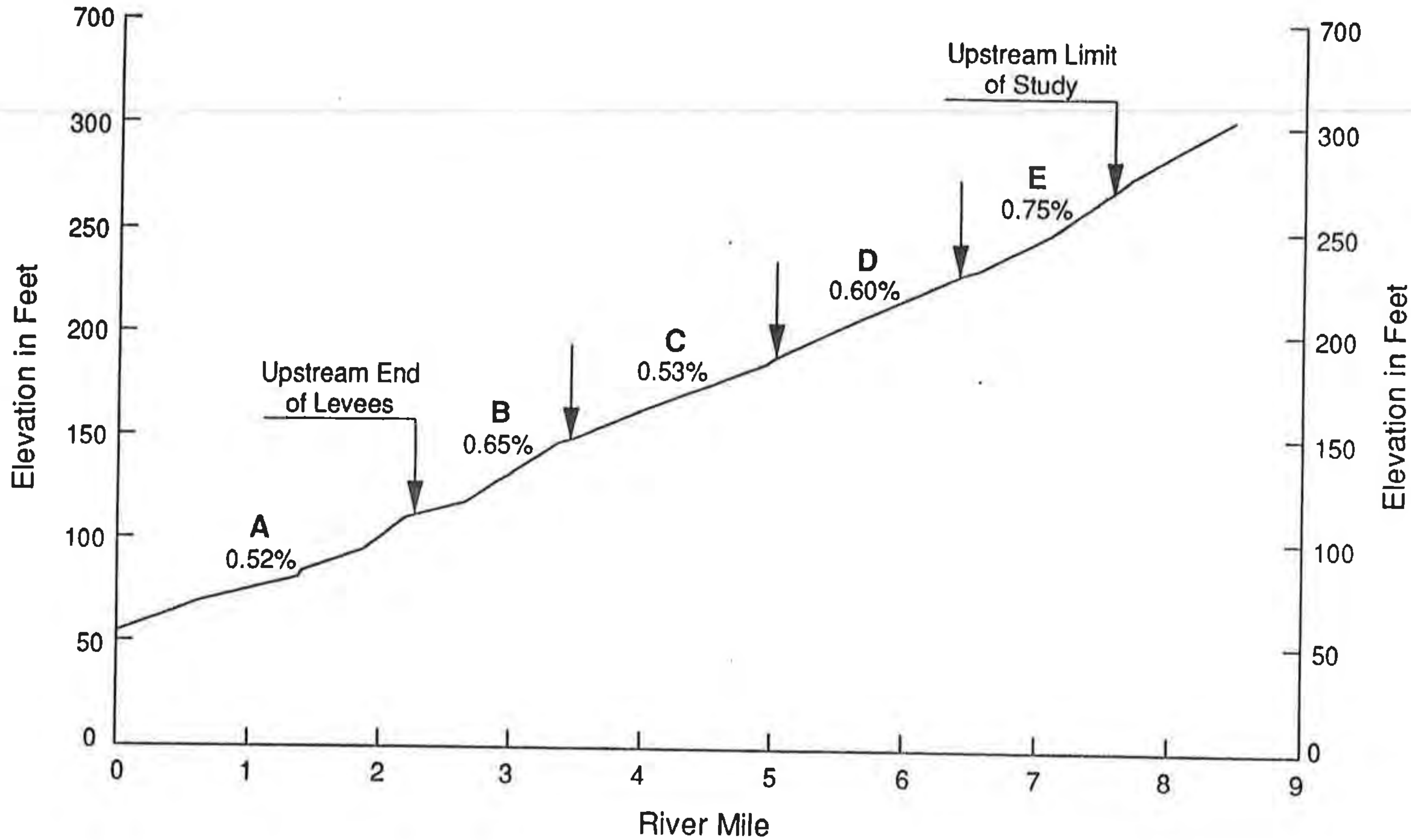
FIG. 9

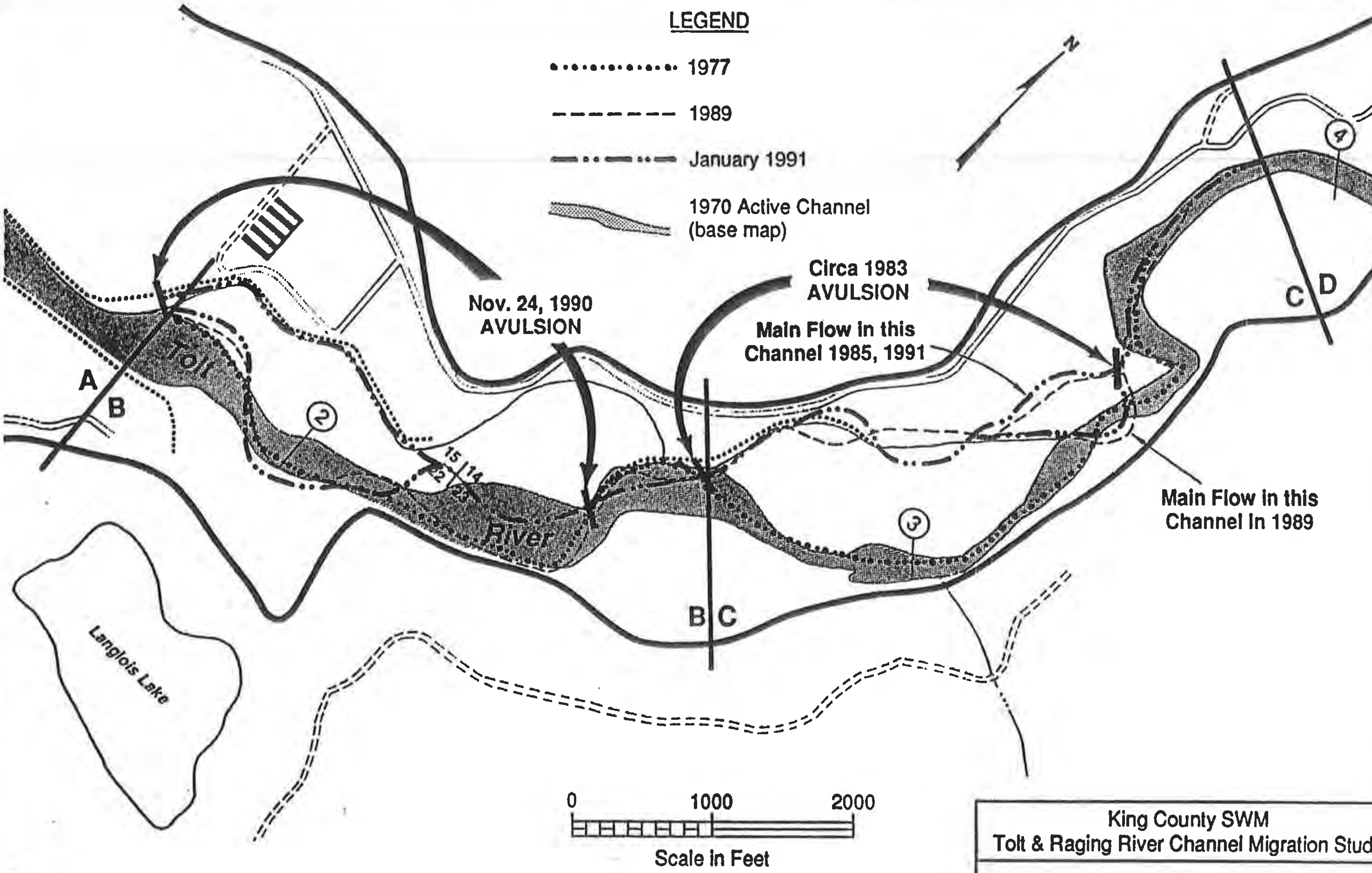


NOTES

1. Slope of river bed for each reach is given in percent.
2. See Sheet 5 for location of reaches and 1970 channel.
3. Profile taken from USDA Soil Conservation Service, 1982.

FIG. 10

King County SWM Tolt & Raging River Channel Migration Study	
TOLT RIVER 1975 PROFILE	
March 1991	W-5666-01
SHANNON & WILSON, INC. Geotechnical Consultants	**FIG. 10**



NOTE

1977,1989 and 1991 traces show the location of the thalweg, the deepest part of the channel.

King County SWM
Tolt & Raging River Channel Migration Study

RECENT TOLT RIVER AVULSIONS

March 1991 | W-5666-01

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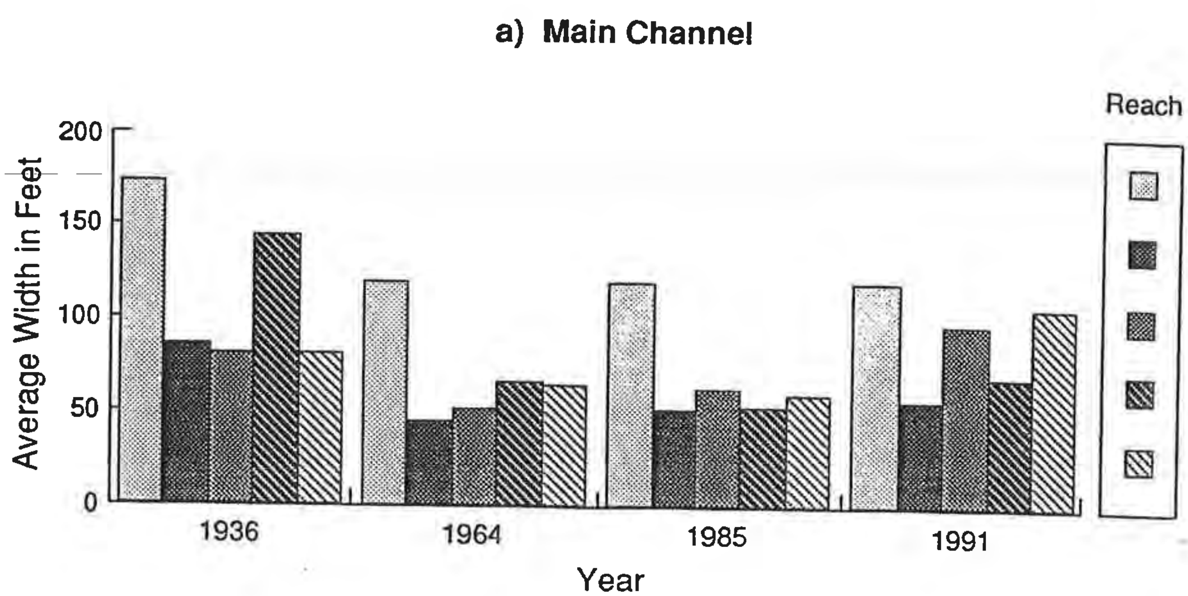
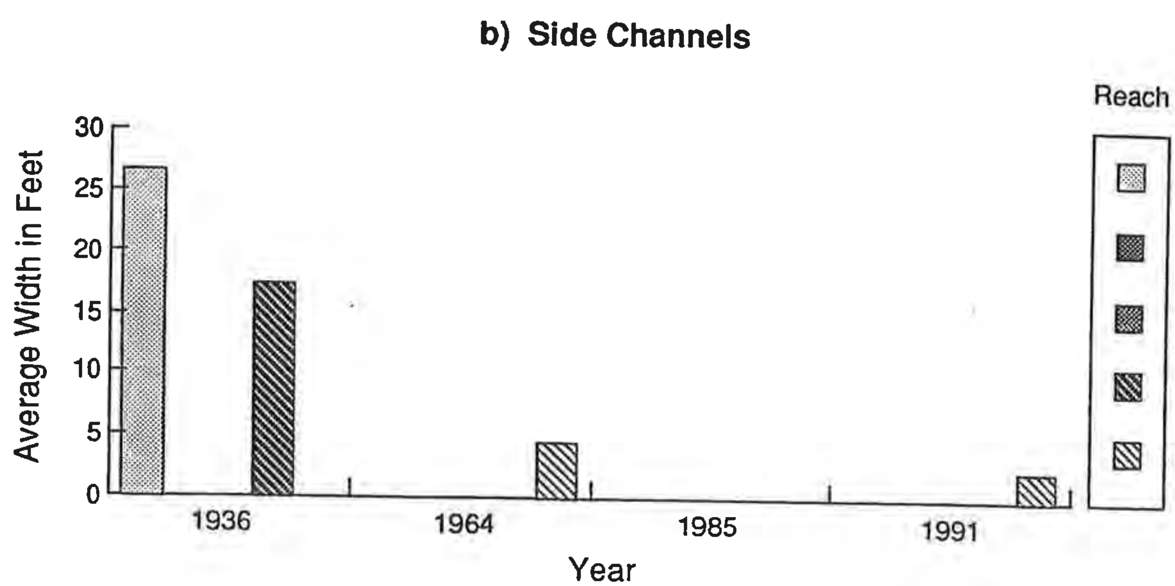
FIG. 11

FIG. 11





NOTES

1. Where more than one side channel was present, Figure 12b shows the average combined widths of all side channels.

2. Reaches F and G are not shown because tree canopy obstruction of the narrow river channel prevented an accurate measurement of the small changes in width which occurred.

3. Widths shown are not corrected for tree canopy obstruction; actual average channel widths are approximately 5 to 10 feet wider than shown.

King County SWM
Tolt & Raging River Channel Migration Study

ACTIVE CHANNEL WIDTHS RAGING RIVER

March 1991 W-5666-01

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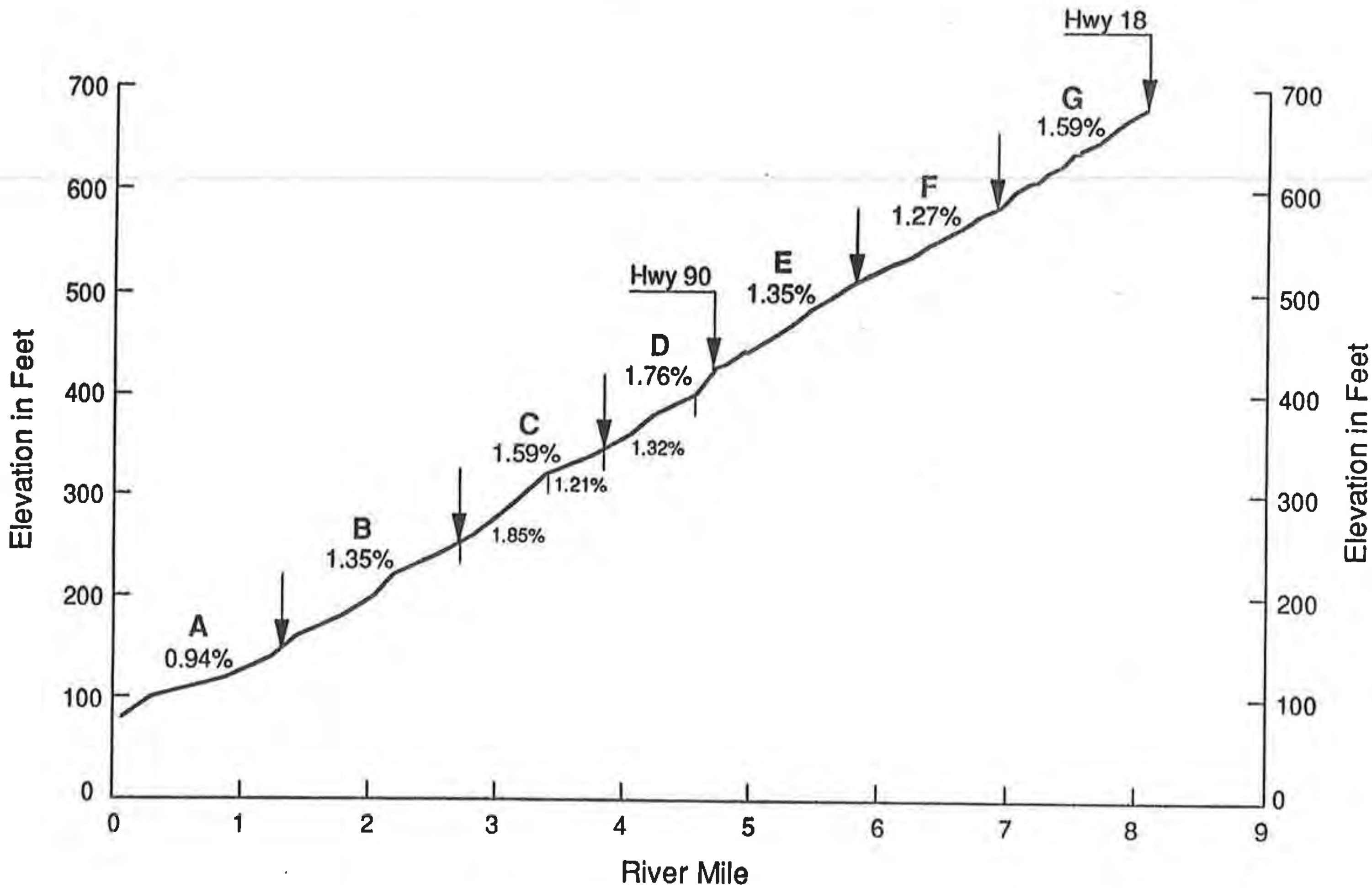
FIG. 12

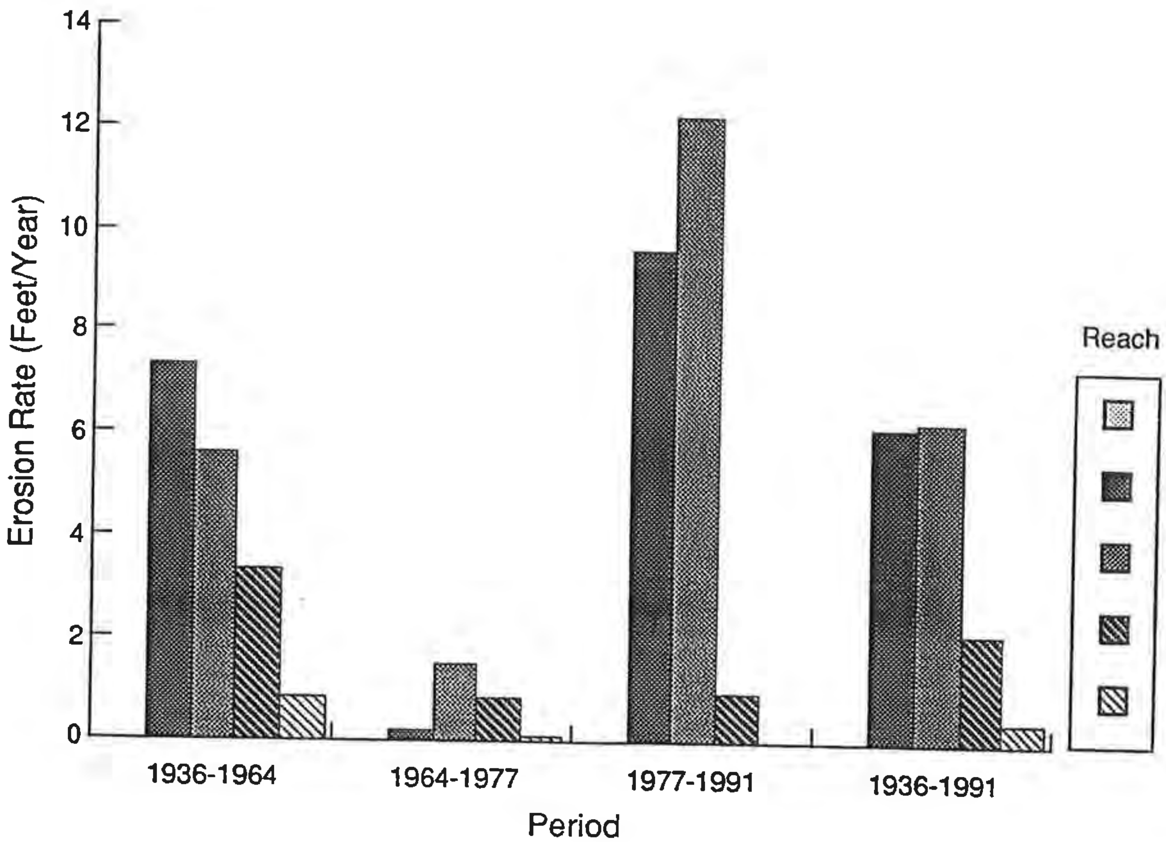


NOTES

1. Profile downstream from Hwy 90 was constructed from 1958 USGS topographic map; profile upstream from Hwy 90 is from more precise 1985 Survey (FEMA, 1989).
2. Slope of river bed for each reach is given in percent; slopes of selected sub-reaches are shown below the solid line.
3. See Sheet 6 for location of reaches.

King County SWM Tolt & Raging River Channel Migration Study	
RAGING RIVER PROFILE March 1991	W-5666-01
SHANNON & WILSON, INC. Geotechnical Consultants	FIG. 13

FIG. 13



NOTE

This figure shows average rates for each reach, including avulsions (Table 4a).

King County SWM
Tolt & Raging River Channel Migration Study

CHANNEL MIGRATION RATES
TOLT RIVER

March 1991 W-5666-01

SHANNON & WILSON, INC.
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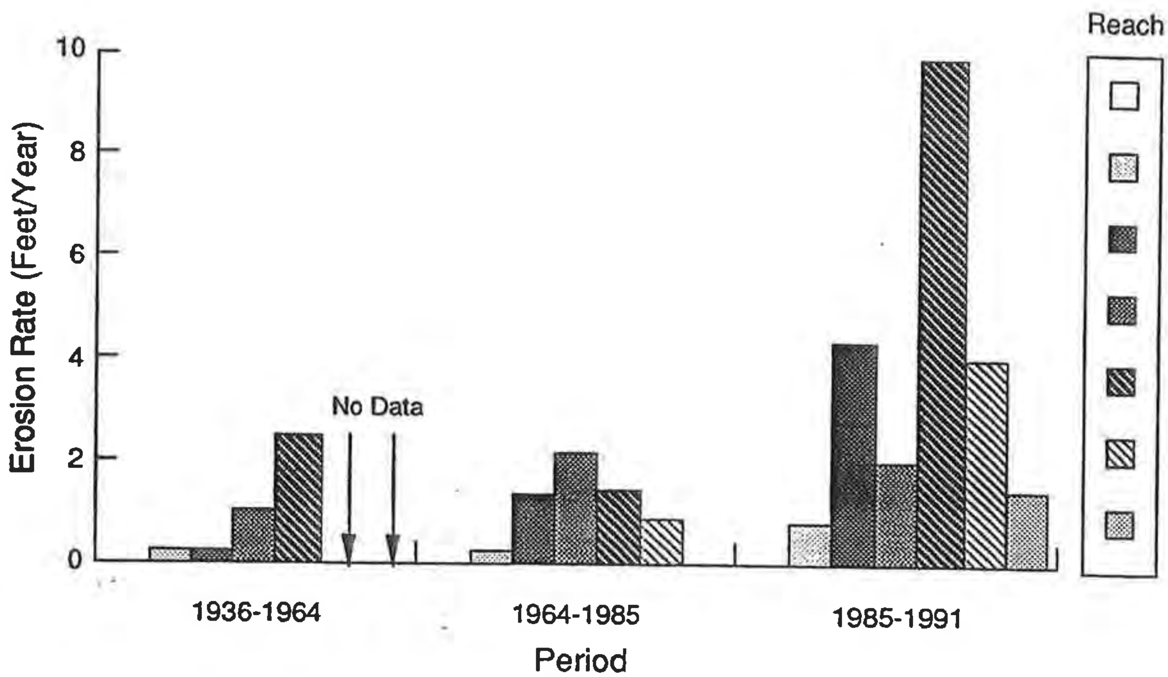
FIG. 14



NOTE

This figure shows average rates for each reach, including avulsions (Table 5a).

King County SWM
Tolt & Raging River Channel Migration Study

CHANNEL MIGRATION RATES
RAGING RIVER

March 1991 W-5666-01

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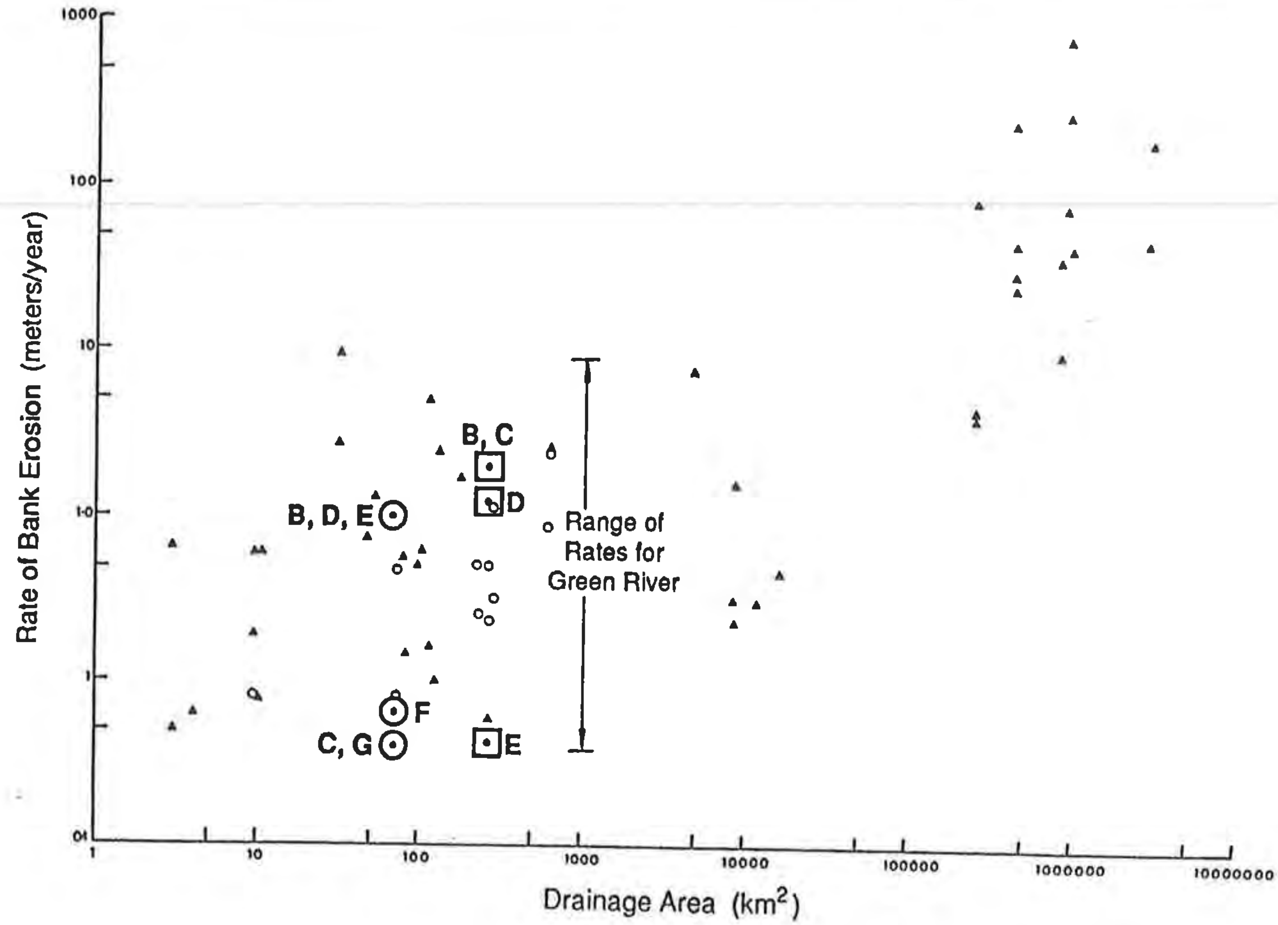
FIG. 15



NOTES

1. Rates shown for the Tolt and Raging River rates are average shifting and widening rates for eroding sections of each reach, for the 1936-1991 period (1958-1991 for Reaches F and G of the Raging River).

2. Rates of 1898-1973 channel shifting of the Green River, WA., are from Dunne & Dietrich (1978).

3. The other data shown on this figure are for meandering rivers, primarily in the United States and Europe, as compiled by Hooke (1980).

LEGEND

F ⊙ Raging River

D ⊡ Tolt River (letters denote reaches)

∘ Devon Streams

▲ Published Rates

King County SWM
Tolt and Raging River Channel Migration Study

RELATIONSHIP BETWEEN BANK EROSION RATES AND DRAINAGE AREA

March 1991 W-5666-01

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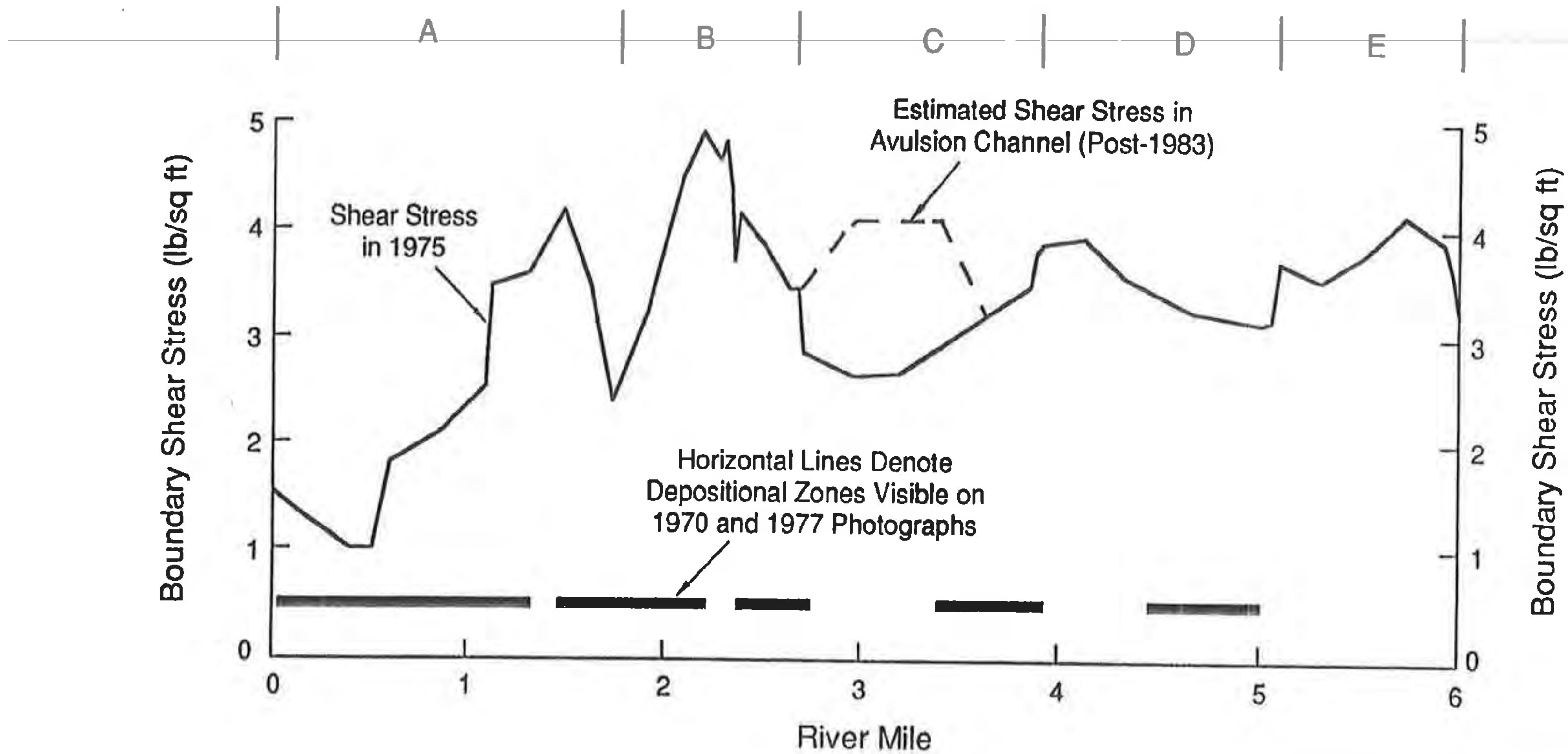
FIG. 16

FIG. 16



NOTES

1. Figure shows boundary shear stress in the thalweg for the 10-year flood.
2. Shear stresses were computed from water depth and slopes for 1975 river conditions, as shown on profiles of the SCS flood study (USDA, 1982).

King County SWM
Tolt & Raging River Channel Migration Study

SHEAR STRESS AND DEPOSITIONAL ZONES TOLT RIVER, 1975

March 1991 W-5666-01

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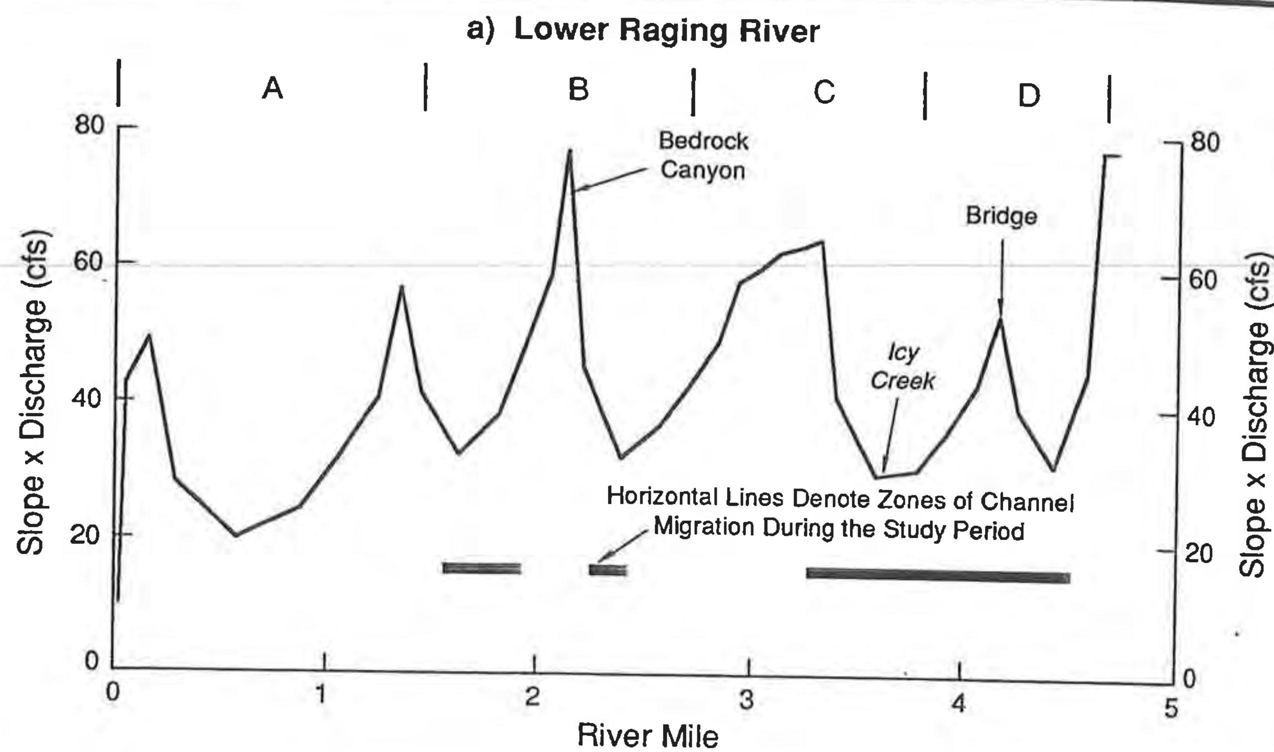
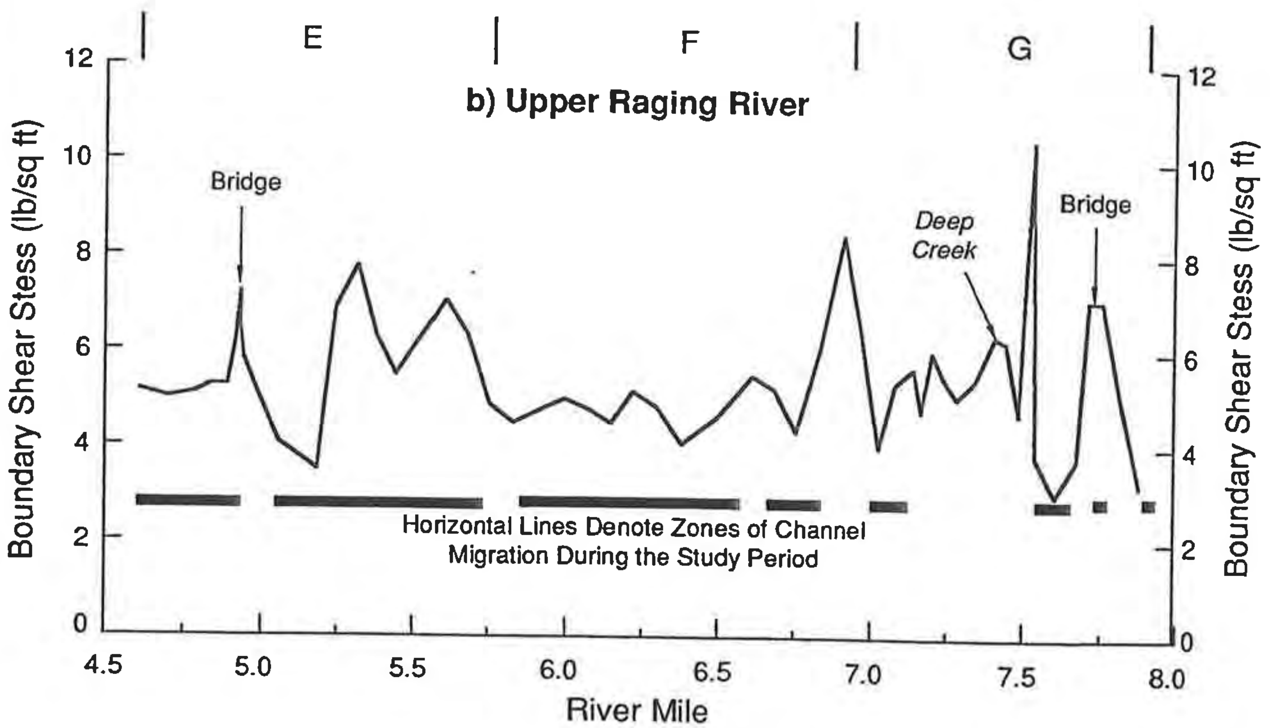
FIG. 17

FIG. 17





NOTES

1. Figure a shows slope-discharge product (proportional to shown power), computed for the 10-year flood (FEMA, 1989) using slopes calculated from 1958 topographic map.
2. Figure b shows boundary shear stress in the thalweg for the 10-year flood, computed from water depths and slopes for the 1985 river, as shown in flood study profiles (FEMA, 1989).

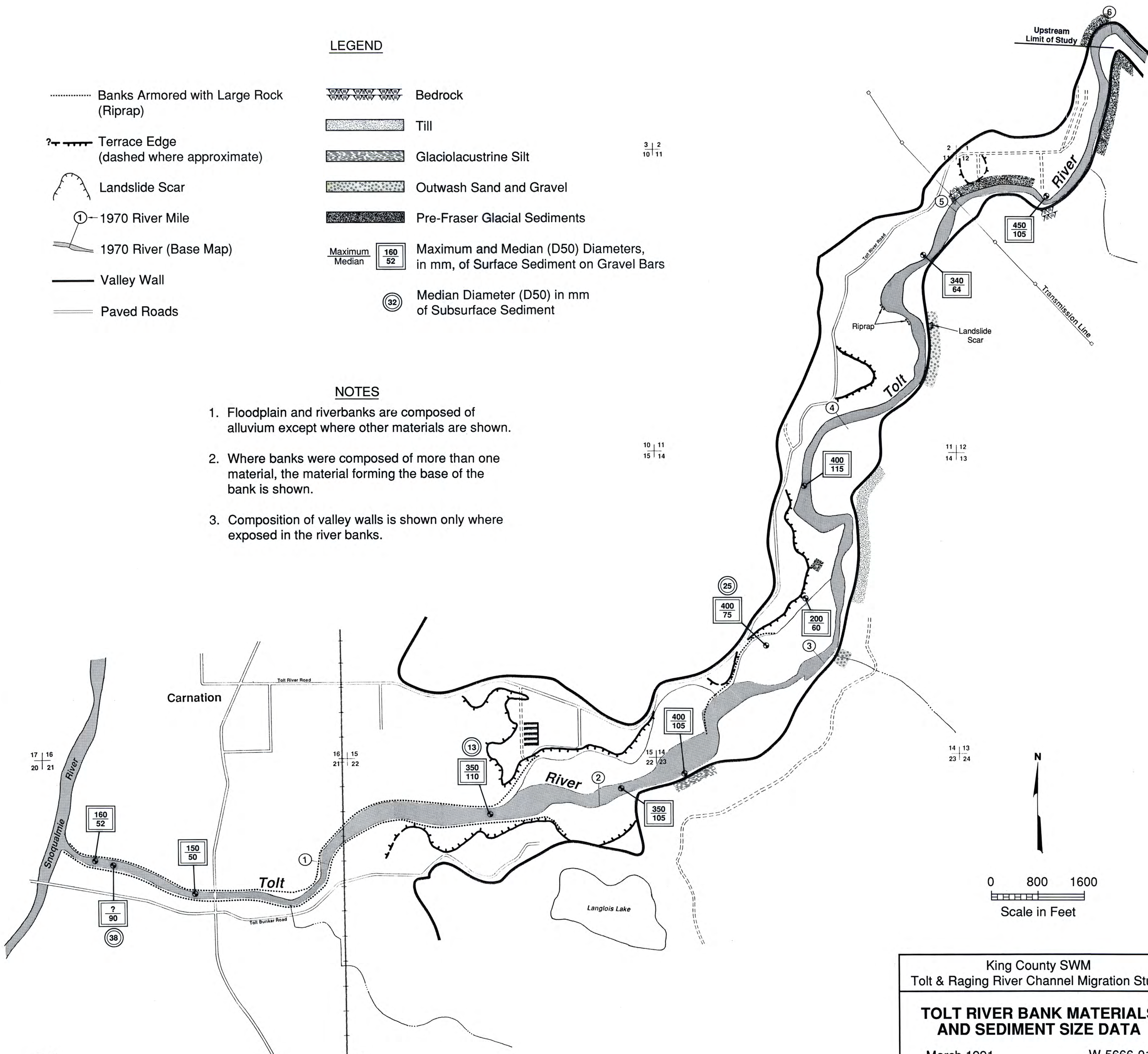
King County SWM Tolt & Raging River Channel Migration Study	
SHEAR STRESS, STREAM POWER AND CHANNEL MIGRATION RAGING RIVER	
March 1991	W-5666-01
SHANNON & WILSON, INC. Geotechnical Consultants	**FIG. 18**

LEGEND

- Banks Armored with Large Rock (Riprap)
- Terrace Edge (dashed where approximate)
- Landslide Scar
- 1970 River Mile
- 1970 River (Base Map)
- Valley Wall
- Paved Roads
- Bedrock
- Till
- Glaciolacustrine Silt
- Outwash Sand and Gravel
- Pre-Fraser Glacial Sediments
- Maximum / Median: Maximum and Median (D50) Diameters, in mm, of Surface Sediment on Gravel Bars
- Median Diameter (D50) in mm of Subsurface Sediment

NOTES

1. Floodplain and riverbanks are composed of alluvium except where other materials are shown.
2. Where banks were composed of more than one material, the material forming the base of the bank is shown.
3. Composition of valley walls is shown only where exposed in the river banks.



King County SWM
Tolt & Raging River Channel Migration Study

TOLT RIVER BANK MATERIALS AND SEDIMENT SIZE DATA

March 1991 W-5666-01

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SHEET 1

LEGEND

- Banks Armored with Large Rock (Riprap)
- Terrace Edge; denotes contact between younger alluvium and terrace composed of glacial deposits and older alluvium (dashed where approximate)
- Landslide Scar
- 1985 River Mile
- 1985 River (Base Map)
- Valley Wall
- Paved Roads
- Bedrock
- Pre-Vashon Glacial Sediments
- Till
- Glaciolacustrine Silt
  - A Advance
  - R Recessional
- Outwash Sand and Gravel
- Maximum / Median — Maximum and Median (D50) Diameters, in mm, of Surface Sediment on Gravel Bars
- Median Diameter (D50) in mm of Subsurface Sediment

NOTES

1. Floodplain and riverbanks are composed of alluvium except where other materials are shown.
2. Where banks were composed of more than one material, the material forming the base of the bank is shown.
3. Composition of valley walls is shown only where exposed in the river banks.

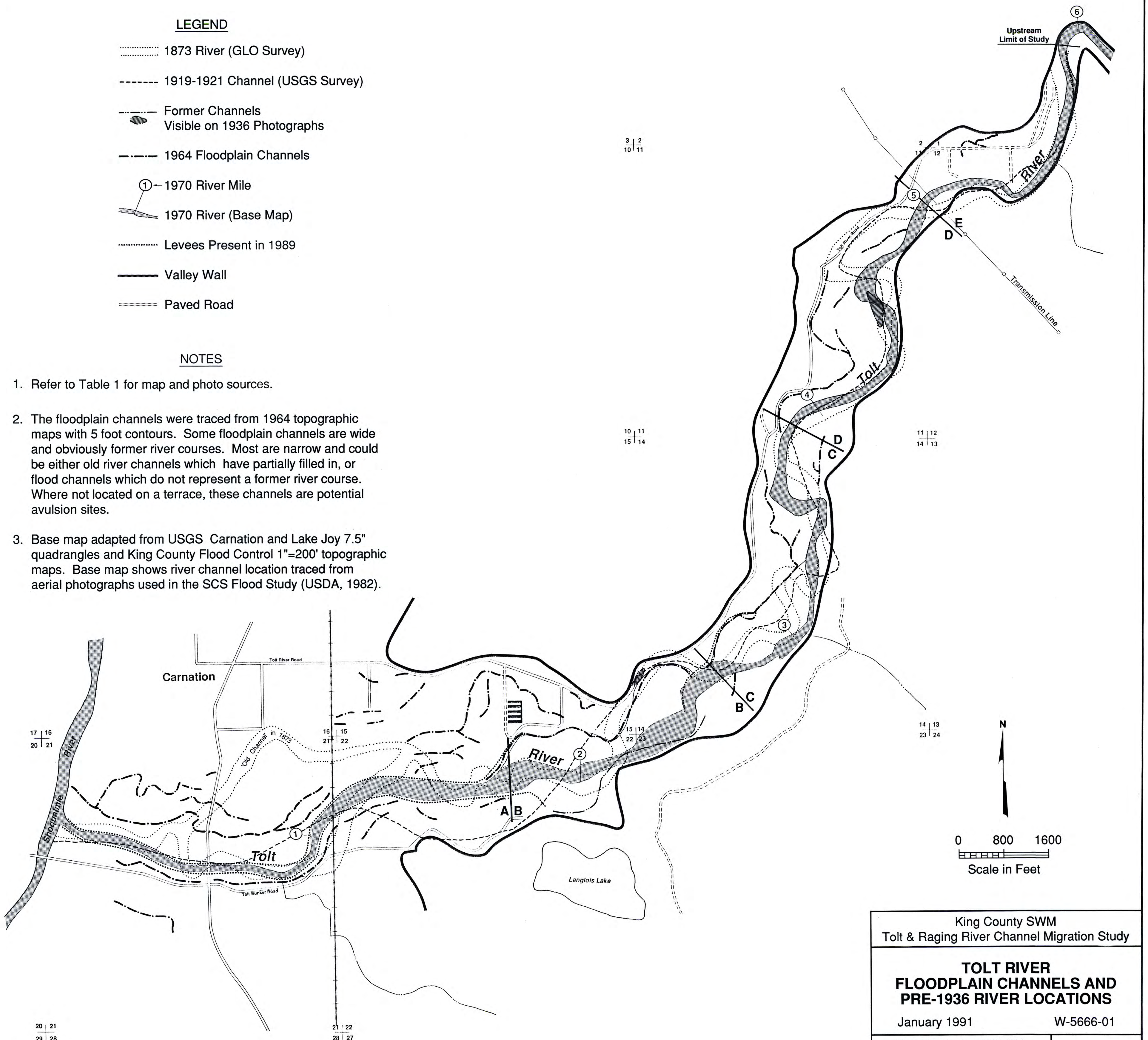
King County SWM
Tolt & Raging River Channel Migration Study

RAGING RIVER BANK MATERIALS AND SEDIMENT SIZE DATA

March 1991 W-5666-01

SHANNON & WILSON, INC.
Geotechnical Consultants

SHEET 2



LEGEND

- 1873 River (GLO Survey)
- 1919-1921 Channel (USGS Survey)
- Former Channels Visible on 1936 Photographs
- 1964 Floodplain Channels
- 1970 River Mile
- 1970 River (Base Map)
- Levees Present in 1989
- Valley Wall
- Paved Road

NOTES

1. Refer to Table 1 for map and photo sources.
2. The floodplain channels were traced from 1964 topographic maps with 5 foot contours. Some floodplain channels are wide and obviously former river courses. Most are narrow and could be either old river channels which have partially filled in, or flood channels which do not represent a former river course. Where not located on a terrace, these channels are potential avulsion sites.
3. Base map adapted from USGS Carnation and Lake Joy 7.5" quadrangles and King County Flood Control 1"=200' topographic maps. Base map shows river channel location traced from aerial photographs used in the SCS Flood Study (USDA, 1982).

King County SWM
Tolt & Raging River Channel Migration Study

TOLT RIVER
FLOODPLAIN CHANNELS AND PRE-1936 RIVER LOCATIONS

January 1991 W-5666-01

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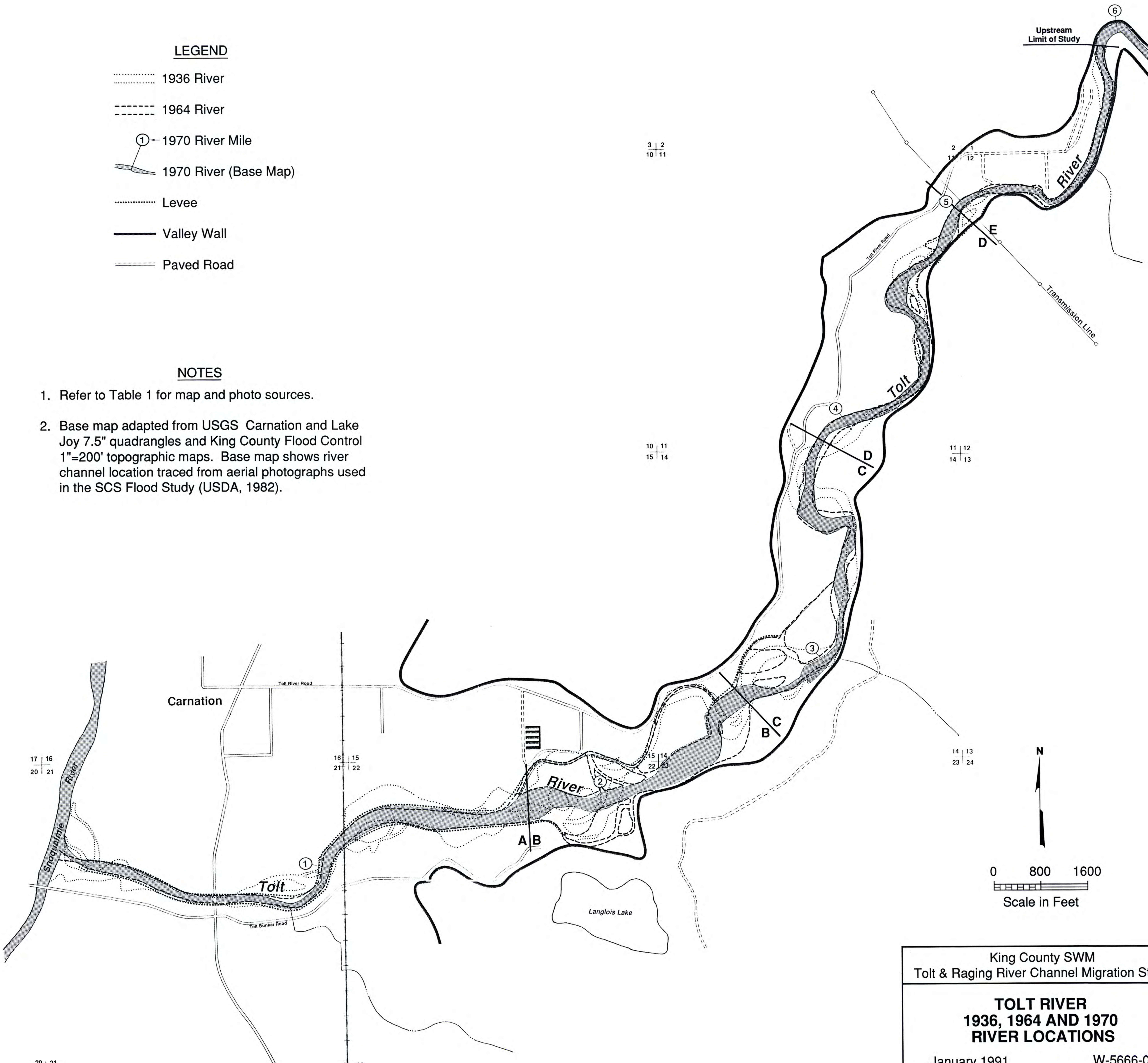
SHEET 3

LEGEND

- 1936 River
- 1964 River
- 1970 River Mile
- 1970 River (Base Map)
- Levee
- Valley Wall
- Paved Road

NOTES

1. Refer to Table 1 for map and photo sources.
2. Base map adapted from USGS Carnation and Lake Joy 7.5" quadrangles and King County Flood Control 1"=200' topographic maps. Base map shows river channel location traced from aerial photographs used in the SCS Flood Study (USDA, 1982).



King County SWM
Tolt & Raging River Channel Migration Study

TOLT RIVER
1936, 1964 AND 1970
RIVER LOCATIONS

January 1991 W-5666-01

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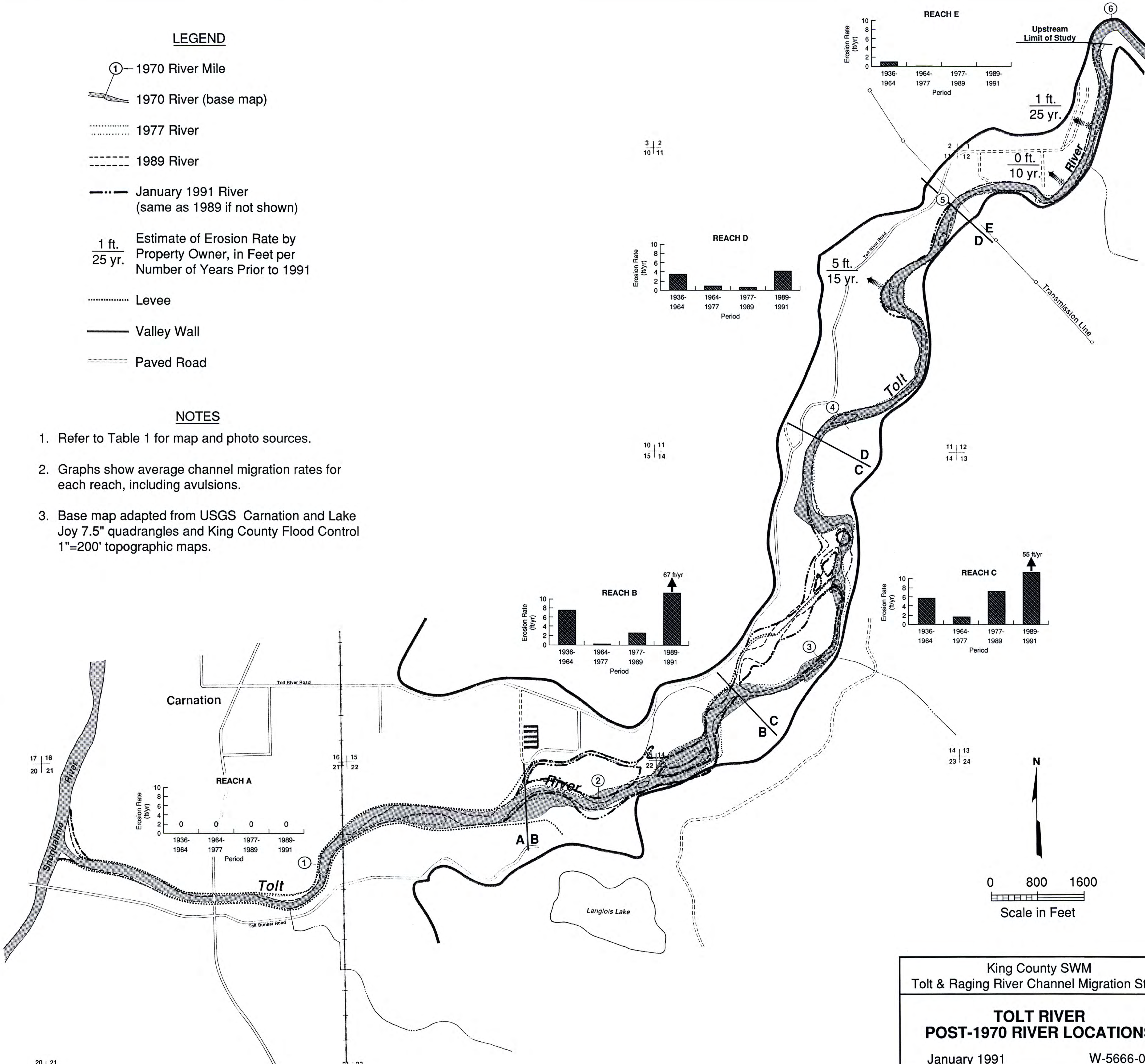
SHEET 4

LEGEND

- ① 1970 River Mile
- 1970 River (base map)
- 1977 River
- 1989 River
- January 1991 River (same as 1989 if not shown)
- 1 ft. / 25 yr. — Estimate of Erosion Rate by Property Owner, in Feet per Number of Years Prior to 1991
- Levee
- Valley Wall
- Paved Road

NOTES

1. Refer to Table 1 for map and photo sources.
2. Graphs show average channel migration rates for each reach, including avulsions.
3. Base map adapted from USGS Carnation and Lake Joy 7.5" quadrangles and King County Flood Control 1"=200' topographic maps.



King County SWM
Tolt & Raging River Channel Migration Study

TOLT RIVER
POST-1970 RIVER LOCATIONS

January 1991 | W-5666-01

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SHEET 5

NOTES

1. Refer to Table 1 for map and photo sources.
2. Graphs show average channel migration rates for each reach, including avulsions.
3. Base map adapted from Flood Insurance Maps (FEMA, 1989). Downstream from I-90, the 1985 active river channel was traced from orthophotographs used for the flood insurance study. Upstream from I-90, the river channel was partially obscured by trees in most locations and was traced directly from Flood Insurance Work Maps (CH2M Hill, 1985), which are based on surveyed cross-sections and aerial photography and show the main channel as opposed to full active channel width.
4. With the exception of the 1991 flight, the aerial photographs were taken during the summer months when deciduous trees were in leaf. Where obscured by tree cover on the aerial photographs, river position is approximate and the plotted width is probably less than the active channel width. This occurs primarily upstream from I-90.

King County SWM
Tolt & Raging River Channel Migration Study

RAGING RIVER HISTORIC CHANNEL LOCATIONS

February 1991 W-5666-01

SHANNON & WILSON, INC.
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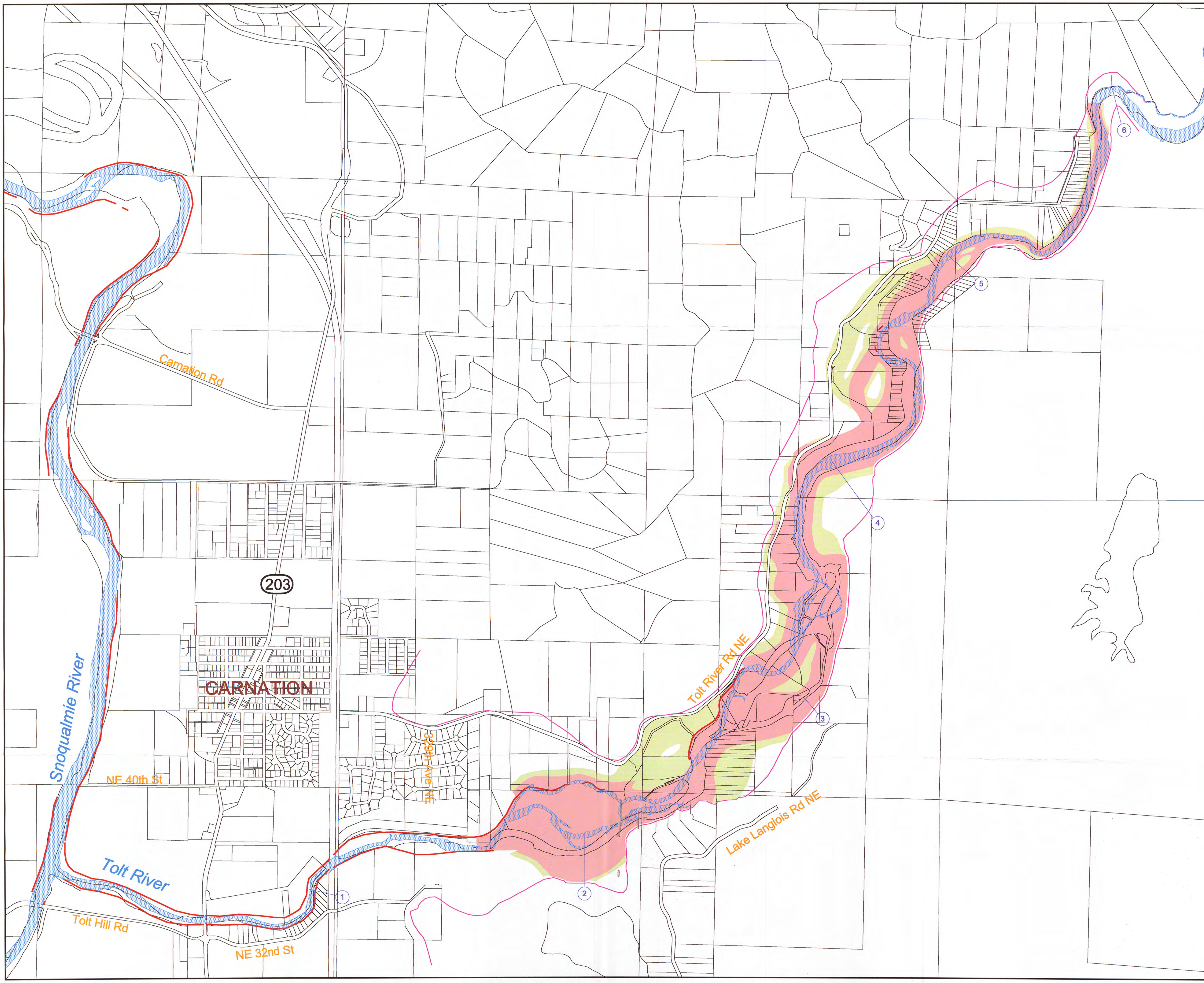
SHEET 6

TOLT AND RAGING RIVERS CHANNEL MIGRATION STUDY

In June 1999, the final maps (labeled Sheet 7: Tolt River Channel Migration Hazard Map and Sheet 8: Raging River Channel Migration Hazard Map) of this 1991 channel migration study were adopted via the King County Channel Migration Public Rule for use by King County in regulating land use in the mapped channel migration hazard areas along the Tolt and Raging Rivers. Sheet 7 and Sheet 8 of the original study have been replaced in this digital file by the adopted Tolt River Channel Migration Area Map and the Raging River Channel Migration Area Map.



Tolt River Channel Migration Area Map

Legend

Severe Hazard Area | Moderate Hazard Area | Potential Hazard Area | Channel Location | ② River Mile | Valley Wall | Levees & Revetments

Notes:

1. This hazard map was adapted from the Tolt and Raging Rivers Channel Migration Study, dated April 1991. The map was updated in April 1999 to include revisions made during preparation of the Channel Migration Public Rule. King County may make future revisions to this map based on new information or changing channel conditions.

2. King County makes no assurances regarding ongoing or continuing maintenance or repair of public levees and revetments, nor for replacement of public levees or revetments should flood events or other natural disasters significantly damage them.

3. Some inaccuracies may exist due to mapping and printing limitations.

N W E S

800 0 800 1600 Feet

King County
Department of
Natural Resources and Parks
Water & Land Resources Division

June 2001

Raging River Channel Migration Area Map

N
W E
S

400 0 400 800 1200 Feet

King County
Department of
Natural Resources and Parks
Water & Land Resources Division

June 2001

Notes:

1. This hazard map was adapted from the Tolt and Raging Rivers Channel Migration Study, dated April 1991. The map was updated in April 1999 to include revisions made during preparation of the Channel Migration Public Rule. King County may make revisions to this map based on new information or changing channel conditions.

2. King County makes no assurances regarding ongoing or continuing maintenance or repair of public levees and revetments, nor for replacement of public levees or revetments should flood events or other natural disasters significantly damage them.

3. Some inaccuracies may exist do to mapping and printing limitations.

Legend

- Moderate Hazard Area
- Severe Hazard Area
- River Location
- Parcels Boundary
- (2) River Mile
- Valley wall