GREEN RIVER
CHANNEL MIGRATION STUDY

King County
Department of Public Works
Surface Water Management Division
River Management Section
Seattle, Washington

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Green River Channel Migration Study

Table of Contents

	Page No.
Summary	1
1.0 Introduction	2
2.0 Methodology	3
3.0 Study Area Characteristics	5
3.1 Description of the Green River Basin	5
3.2 Human Activity and the River	6
3.3 Hydrology and Sediment Supply	8
3.4 Geology and Sediment Characteristics	10
3.4.1 Bedrock	11
3.4.2 Quaternary Deposits	11
3.4.3 Recent Deposits	13
3.4.4 Green River Alluvial Deposits	14
4.0 Channel Migration on the Green River	15
4.1 Types of Channel Migration	16
4.2 Morphology of the Green River Study Reaches	19
4.3 Historic Rates of Channel Migration	23
4.3.1 Calculation of Migration Rates	23
4.3.2 Historic Channel Migration Rates	24
4.3.3 Comparison of Measured Channel Migration Rates with Other Studies	27
4.4 Factors Affecting Channel Migration Rates	28
4.4.1 Causes of Spatial Differences in Migration Rates	28
4.4.2 Causes of Temporal Changes in Migration Rates	34
5.0 Hazards from Future Channel Migration	38
5.1 Methodology for Predicting Limits of Future Channel Migration	38
5.1.1 Determining the Validity of the Historic Meader Belt	39
5.1.2 Predicting Probable Unconstrained Limits of Channel Migration	40
5.1.3 Delineation of Mitigated Hazard Areas	41
5.1.4 Delineation of Severe and Moderate Hazard Areas	42
5.2 Channel Migration Hazard Maps	43
References	45

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LIST OF TABLES

Table Number		Follows Page
1	Maps and Aerial Photographs Used for Mapping Historical Channel Positions	4
2	Characteristics of Green River Reaches	16
3	Changes in Channel Sinuosity	17
4	Changes in Active Channel Width	19
5	Historic Channel Migration Rates by Reach	24
6	Historic Channel Migration Rates in Areas without Armored Banks	24
7	Historic Channel Migration Rates in Areas with Armored Banks	24
8	Criteria Used to Determine whether Historic Meander Belt is No Longer Valid	39
9	Meander Belt Widths and Bend Amplitudes Used to Develop Channel Migration Hazard Maps	40
10	Notes on Potential Hazards at Sites Marked on Sheet 5	43

LIST OF FIGURES

Figure Number		
1	Green River Channel Migration Study Area Map	5
2	Green River Profile	6
3	Revetment Construction History	7
4	Green River Revetments	7
5	Peak Annual Discharge	8
6	Flood Frequency Analysis -- Pre- and Post-Dam	8
7	Flow Duration Curves -- Pre- and Post-Dam	9
8	Downstream Changes in Sediment Size	15
9	Historic Channel Locations	15
10	Types of Channel Migration	16
11	Average Channel Migration Rates	25
12	Green River Channel Migration Rates -- Average Rates for Unprotected Banks	26
13	Shear Stress and Rates of Channel Shifting	30
14	Shear Stress, Gradient, and Depth	30
15	Changes in Bed Elevation, Green River near Auburn Gage	31

LIST OF MAP SHEETS

Sheet Number	
1	Geologic and Man-Made Constraints on Channel Migration
2	Pre-1960 Channels
3	1960 to 1992 Channels
4	Unconstrained Channel Migration Hazard Map
5	Mitigated Channel Migration Hazard Map

GREEN RIVER

CHANNEL MIGRATION STUDY

SUMMARY

The middle portion of the Green River is one of several rapidly migrating rivers in King County, Washington. Rates of channel migration between 1898 and 1992 were determined from aerial photographs and maps showing successive channel positions. Channel migration rates varied dramatically during the past century. Rapid channel migration and consequent channel widening and braiding were associated with large floods during the 1950s. Lower rates of channel migration occurred prior to the 1950s floods and after 1962, the onset of flood control by Howard Hanson Dam. Despite the dam, short-term migration rates of over 60 feet per year have occurred in the most active sections of the river. The White River formerly joined the Green River at Auburn. Since the White River's diversion in 1906, the Green River downstream from Auburn has narrowed and experienced very little channel migration. Large differences in channel migration rates between reaches of the Green River are attributed to patterns of shear stress and sediment deposition, as well as the extent of bank armoring. The highest channel migration rates are associated with development of avulsion channels and rapid growth of bends in the middle section of the study area. Taking flood control and other changed conditions into consideration, the probable future limits of channel migration were defined using historic meander belt widths and bend amplitudes. Land within these limits was classified according to the relative degree of hazard from channel migration, based upon historic rates of channel migration and the presence of major bank protection structures that protect arterial roads and subdivisions.

1.0 INTRODUCTION

The middle Green River between the Green River Gorge and the City of Kent is one of several rapidly migrating rivers in King County. This portion of the river has a tendency to move significant distances across its floodplain in a short period of time, sometimes during a single flood. Rapid channel migration threatens developed and undeveloped properties along the river banks. The Federal Emergency Management Agency's (FEMA) flood-insurance maps of the river 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 in some cases 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. On the Green River, King County's Department of Development and Environmental Services (DDES, formerly known as BALD) has approved residential development in accordance with the flood insurance maps in areas where a change of river course subsequently threatens the newly built residences. In many cases, landowners buy the property with no awareness of the potential hazard from bank erosion.

Downstream from Kent, channel migration has been effectively prevented for many years by channelization of the river between narrowly-spaced levees. Although the levee system requires ongoing maintenance due to bank erosion (King County, 1993), channel migration is no longer a concern on the lower part of the river. This study deals with the middle Green River, where levees and revetments (rock-armored banks) are either incomplete or nonexistent. Levees and revetments can be damaged by erosion of nearby unprotected banks, rendering them ineffective against flooding or bank erosion even if adequately maintained.

King County's historic approach to bank erosion problems has been to try to control the river through construction of extensive levees and revetments. However, since the 1970s few new projects of this type have been built, due both to a lack of funds and the adverse effects of these projects on flooding and fish habitat. Projects that have been constructed more recently tend to

protect specific small areas such as roads or houses. These projects are expensive to build and maintain, can aggravate flooding or erosion problems off-site, and are subject to failure due to bank erosion upstream or downstream from the project. In addition, levees and revetments have degraded fish habitat by eliminating side channels and reducing recruitment of gravels and woody debris into the river. Because of these problems, King County Surface Water Management (SWM) has recommended a policy of preventing future development in channel migration hazard areas through land-use regulation (King County, 1993). This policy was formally adopted by the County Council as part of the King County Flood Hazard Reduction Plan in November 1993.

In order to regulate development in hazardous zones along rapidly migrating rivers, the King County Flood Hazard Reduction Plan (King County, 1993) recommended conducting channel migration studies and hazard mapping along these rivers. This report is a result of such a study for the middle Green River. The study included determination of historic limits and rates of channel migration, estimation of probable future limits of channel migration, and development of maps that show channel migration hazard zones. Similar studies have already been completed for the Tolt and Raging Rivers (Shannon & Wilson, 1991).

In addition to producing maps showing high-risk areas as a basis for regulation of development, this study also has two secondary objectives. Firstly, the study provides an understanding of channel migration processes for analysis of possible abandonment or setback of existing dysfunctional levees. Secondly, the study compares bank erosion rates and processes before and after construction of Howard Hanson Dam in an attempt to evaluate the effect of dam operations on channel migration.

2.0 METHODOLOGY

Field work for this study was conducted primarily in October and November 1992. Observations were plotted on September 1992 color 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, eroding banks, abandoned channels and other potential avulsion sites, depositional zones, and river and floodplain morphology. Sediment on bar surfaces was sampled using the point-count method (Wolman, 1954). Access to the river was obtained primarily by raft, but in some locations by foot.

This study made extensive use of maps of historic channel positions and other data from a previous study of the Green River (Dunne and Dietrich, 1978). Other information sources used in this study include King County inventories of levee/revetment ages and repairs; a study of channel migration at the O'Grady county park (Miller, 1989); historic maps and aerial photographs; and river cross-sections, profiles, and topographic maps from previous flood studies.

Maps for this study were produced on King County SWM's GIS system using AutoCAD software and digital-line-graph (DLG) base map data from the United States Geological Survey. The historic river channel positions shown in the maps of this report were digitized from aerial photographs and maps whose sources, scales, and dates are shown in Table 1. These particular maps and photographs were selected because of their availability, scale, accuracy, and timing in relation to major flood events and dam construction. Also shown on Table 1 are other map and photo sources that were consulted, but not plotted on the maps.

To construct the channel position maps (Sheets 2 and 3), digitized images of the river channel at various dates were rectified to the scale of the base map by aligning common road intersections. To be consistent with previous maps from the Dunne and Dietrich (1978) study, the maps only show the low-flow channel(s) of the river and do not show the full active-channel width where wide gravel bars were present. The error incurred in representing river positions from map sources is quite minor, from 0 to 30 feet, although the original map sources themselves may contain considerable unknown errors (especially on the small-scale maps). The error incurred in representing river positions from aerial photographs is considerably larger due

TABLE 1

MAPS AND AERIAL PHOTOGRAPHS USED FOR MAPPING HISTORICAL CHANNEL POSITIONS

Date	Type	Scale	Source
1895	Map*	1:125000	USGS topographic map
1906	Map (RM 25-35 only)*	1:4800	US Army Corps of Engineers
1912	Map (discontinuous survey)	1:15840	King County Road Book
1936	Map (RM 35-44 only) Aerial Photographs	1:31680 1:9600	US Geological Survey Walker & Associates
1942	Aerial photographs*	1:25000	US Army Corps of Engineers
1960	Aerial photographs**	1:12000	Walker & Associates
1973	Map	1:24000	USGS topographic map
1992	Aerial photographs	1:12000	Walker & Associates

* As traced from maps in Dunne and Dietrich (1978) report.

** A gap in the 1960 photographs between RM 39 and 41 was filled using 1961 aerial 1:4800 photographs obtained from the University of Washington map library.

OTHER MAP AND PHOTO SOURCES CONSULTED FOR THIS STUDY

Date	Type	Scale	Source
1867	Maps (inaccurate survey)	1:31680	Government Land Office survey (Wa. DNR)
1959	Aerial photographs	1:7600	King County
1964	Aerial photographs (RM 25-35 only)	1:6000	US Army Corps of Engineers 1968 Survey Report Profiles
1970	Aerial photographs	1:12000	King County
1973	Aerial ortho-photographs	1:12000	US Army Corps of Engineers 1975 Water Surface Profiles
1978	Aerial photographs	1:9000	US Army Corps of Engineers
1985	Aerial photographs	1:12000	King County
1989	Aerial photographs	1:12000	Washington Dept. of Natural Resources

to distortion and variable scale of the source photographs. We estimate that this error was less than 30 feet where match points were plentiful and located on both sides of the river, but as much as 50 to 100 feet where few match points existed. These larger errors occurred primarily in the eastern half of the study area.

Historic rates of channel migration were calculated from the successive river positions shown on Sheets 2 and 3, using procedures described in Section 4.3.1 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.

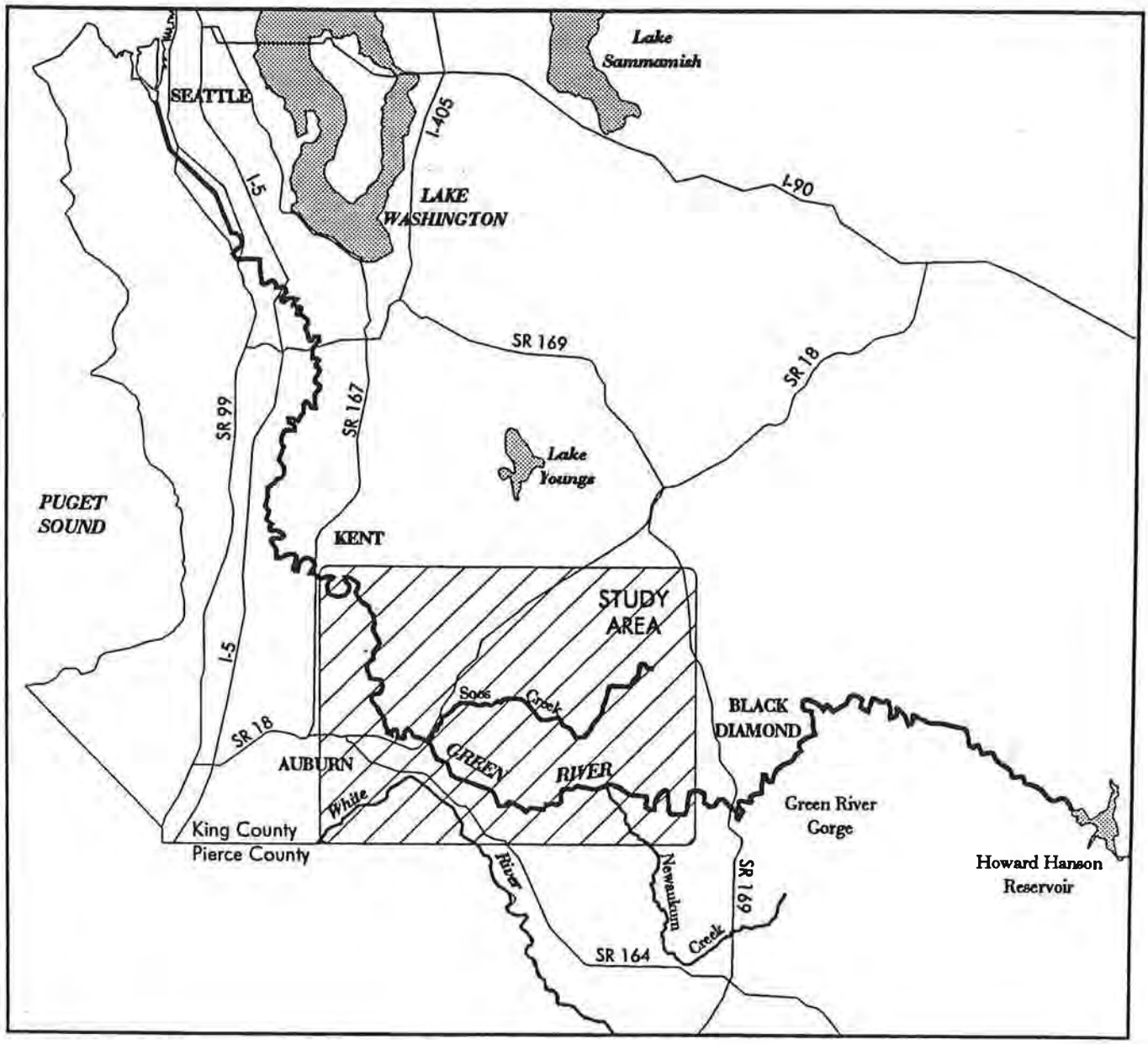
3.0 STUDY AREA CHARACTERISTICS

The Green River is located in the south part of King County, as shown in Figure 1. The river flows west from its headwaters in the Cascade range to Auburn, then north to Tukwila, from which point to Puget Sound it is named the Duwamish River. The study area comprises 20 River Miles (RM) in the middle portion of the Green River. The downstream boundary of the study area is just upstream of the completely leveed reach in Kent (RM 25). The upstream boundary is the downstream end of the bedrock Green River Gorge, at Flaming Geyser State Park (RM 45). Thus the study area includes the entire length of the middle Green River that is not constrained from migrating by either levees or cliffs. The map sheets in the back of this report show river miles and other locations referenced in the text.

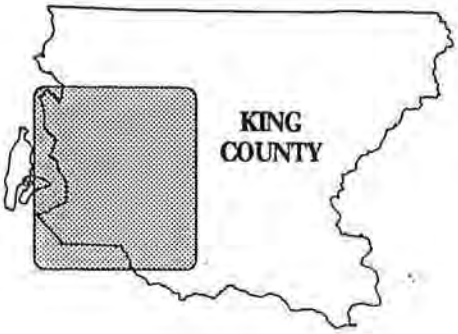
3.1 Description of the Green River Basin

The Green River originates at the western crest of the Cascade Mountains in the vicinity of Stampede Pass. Runoff from the mountainous parts of the basin drains into Howard Hanson Reservoir (Elevation 1,228 feet), which is operated for flood control. Three miles downstream of Howard Hanson Dam, the City of Tacoma operates a smaller water supply reservoir. Downstream from the reservoirs, the river flows steeply down the 13-mile long Green River Gorge (Figure 1). The river emerges from the mouth of this narrow, bedrock gorge at the edge

Figure 1
Green River Channel Migration Study Area Map



Not To Scale



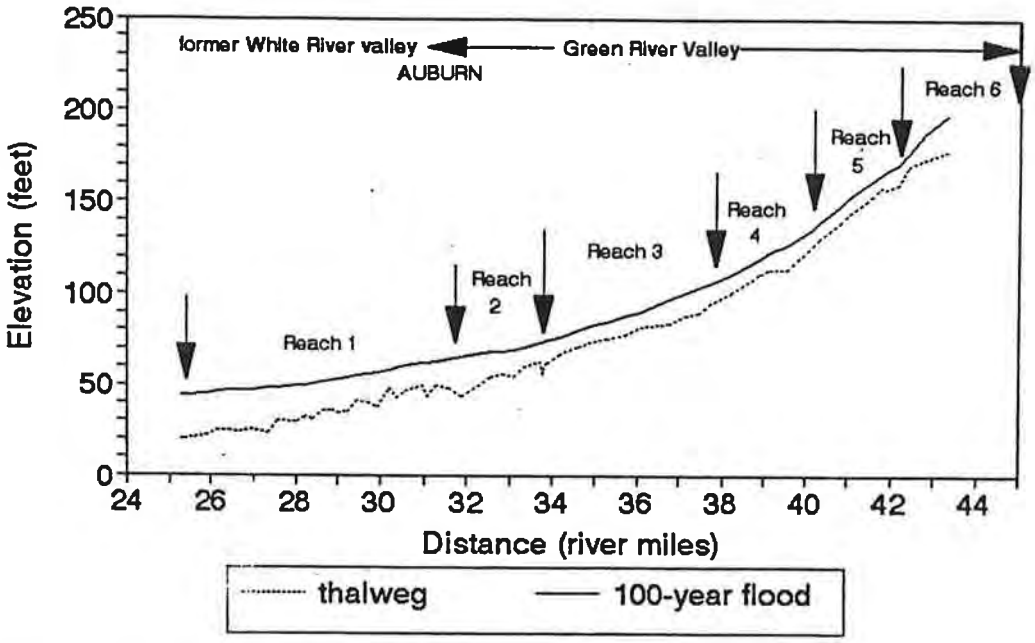
of the Cascade foothills at Flaming Geyser State Park. From here downstream to Auburn, the Green River flows through the broad Green River Valley. Upon entering the valley, the river gradient suddenly declines from steep to moderate (Figure 2), and flood waters spread over a wide floodplain instead of being tightly confined by the gorge. As a result, the river's power to transport sediment decreases abruptly, causing deposition of large quantities of gravel. This gravel deposition makes the river very unstable, causing it to erode its banks and sometimes to shift course erratically. Where channel migration is most rapid the river has a multiple-channel, "braided" pattern. In part because of the physical and hydraulic complexity brought to the river valley as the river cuts new channels periodically, this section of the Green River is among the most productive remaining mainstem areas for anadromous fish in King County (Coccoli, 1993).

At Auburn, the Green River turns north and enters a much larger, flatter valley where it formerly was joined by the larger White River (Figures 1 and 2). During a large flood in 1906, the White River abandoned its northern channel to the Green River and cut a new channel southward toward the Stuck River (Dunne and Dietrich, 1978). The former White River channel, shown on Sheet 2, has since been filled in and is covered by a housing tract in the City of Auburn. Downstream of the former White River Channel entrance (RM 31), channel gradient is low and the river occupies a narrow channel with few active sediment deposits.

3.2 Human Activity and the River

Human habitation is sparse upstream from the Green River study area. The land is primarily used as public and private timberland and City of Tacoma Watershed. Within the study area, the river valley is densely populated where the river flows through Auburn (RM 29 to 32). With the exception of the urban Auburn region in the middle of the study reach, the study area consists primarily of agricultural land with some park land and a growing number of single-family residences. Between RM 35 and 41, the river flows near the south valley wall and road access to the south side of the river is very limited (Sheet 1).

Figure 2
Green River Profile



Source: FEMA, 1989

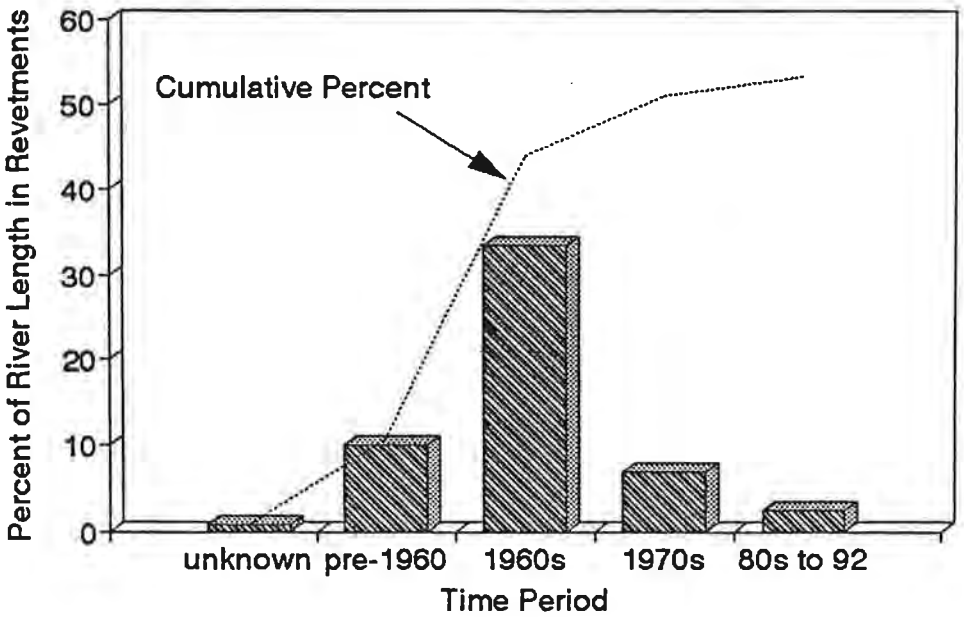
Note: The lack of complexity of the thalweg profile in Reaches 3 through 6 is due to widely-spaced survey data.

Levees and revetments impede lateral migration of the river in many locations. Levees (raised berms designed to prevent flooding, typically protected on their riverward face by rock) and revetments (rock armor placed on the bank to control erosion, not flooding) have been built in many locations along the river. The locations of existing levees and revetments and their approximate dates of construction are shown on Sheet 1. Most of these existing facilities were constructed in the 1960s with public funds raised by King County bond issues (Figure 3). Revetments and levees are present along at least one bank for just over 50 percent of the length of the study area. However, most of these facilities are concentrated in the downstream portion of the study area. As shown in Figure 4, revetments and levees line 82 percent of Reach 1 but only 10 percent of Reach 4 (see map sheets for reach boundaries). In addition to revetments, ten bridges impede channel migration within the study reach. Most of the bridges constrict the channel and have associated bank protection structures.

Few records exist of bank protection structures that were built in the first half of this century, with the exception of a 1907 Army Corps of Engineers map that shows a few bank protection structures downstream of RM 35. Similar structures were probably located upstream. These early structures included levees, wood pilings, river-rock revetments, crib walls and wing walls that have since fallen apart, have been overgrown with vegetation, or have been replaced. Early engineering efforts also included channel straightening in at least one instance, a 0.4-mile-long channel excavated in 1901 at RM 34, according to documents in the King County Archives.

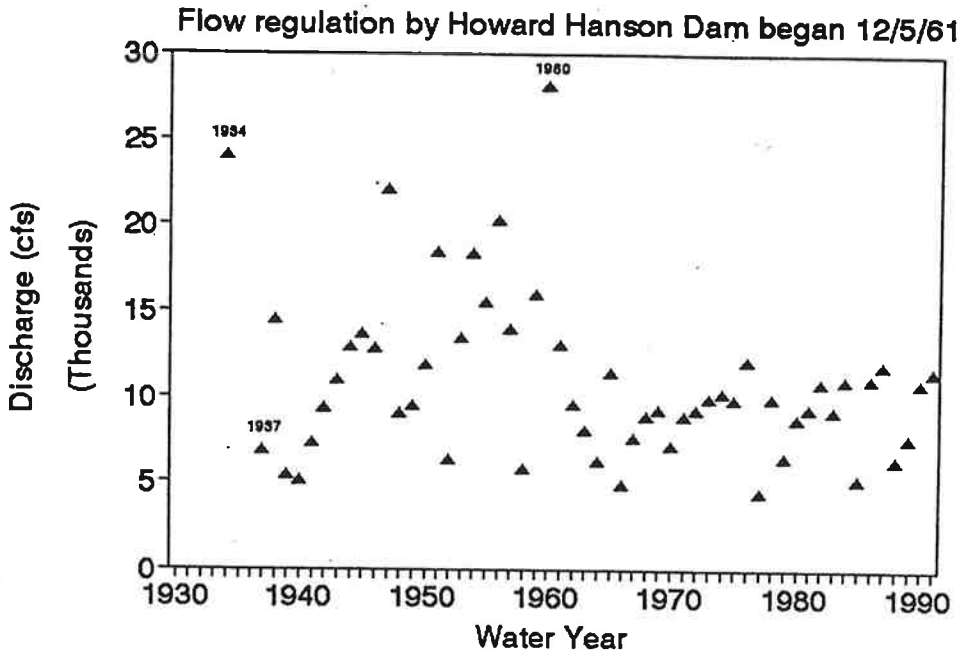
Construction of Howard Hanson Dam in 1962 greatly reduced flood flows in the study reach (see Hydrology, Section 3.3). Together with bank armoring, this has encouraged home-building and other activities in floodplain lands at risk from channel migration.

Figure 3
Revetment Construction History



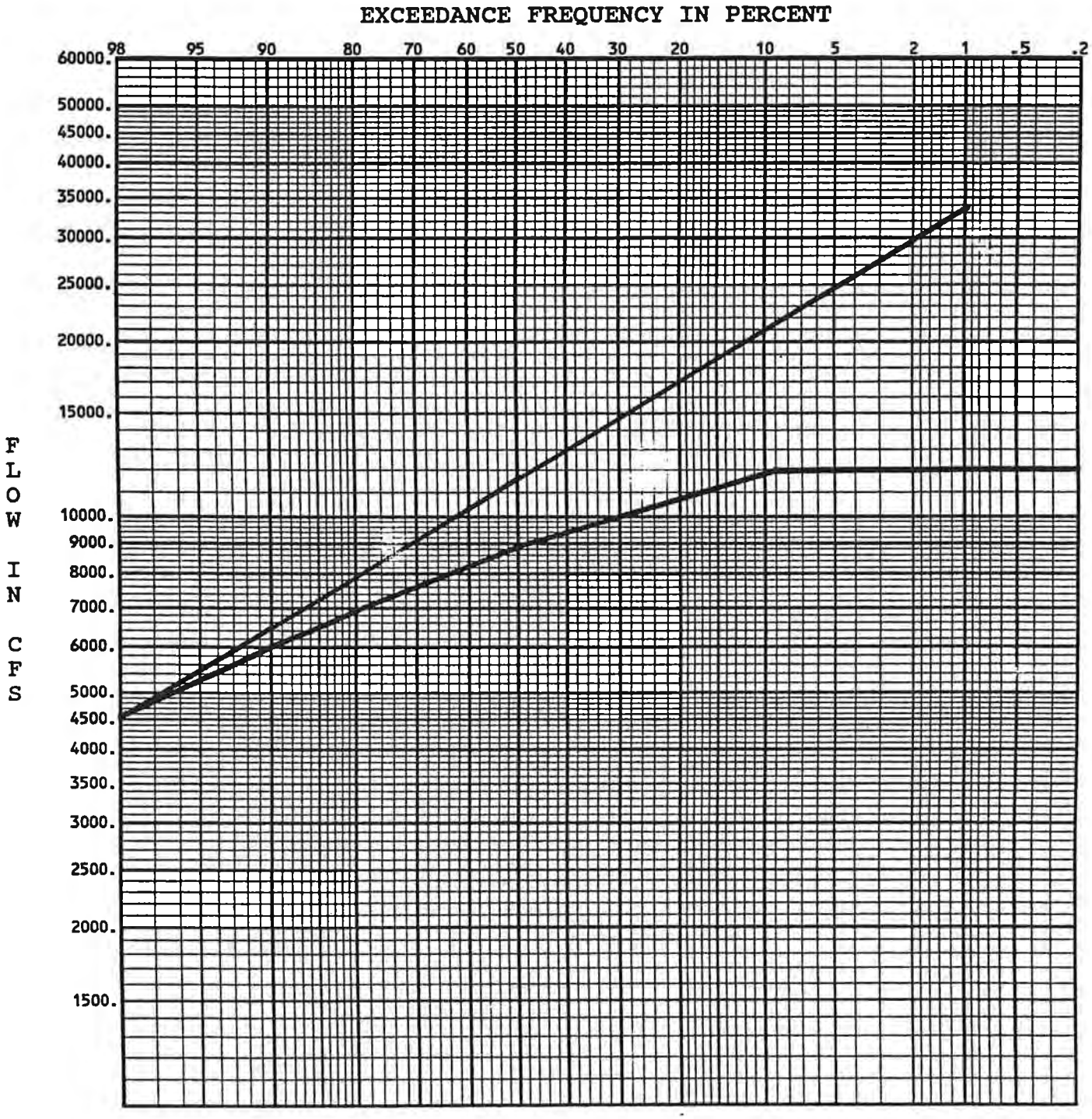
Note: The figure shows the percentage of river length with a revetment or levee along one or both banks.

Figure 5
Peak Annual Discharge
Green River near Auburn



Note: No data are available for 1935 and 1936.

Figure 6
Flood Frequency Analysis
Pre- and Post Dam



Green River near Auburn gage

Notes: Data from USGS. Log-Pearson Type III Analysis.

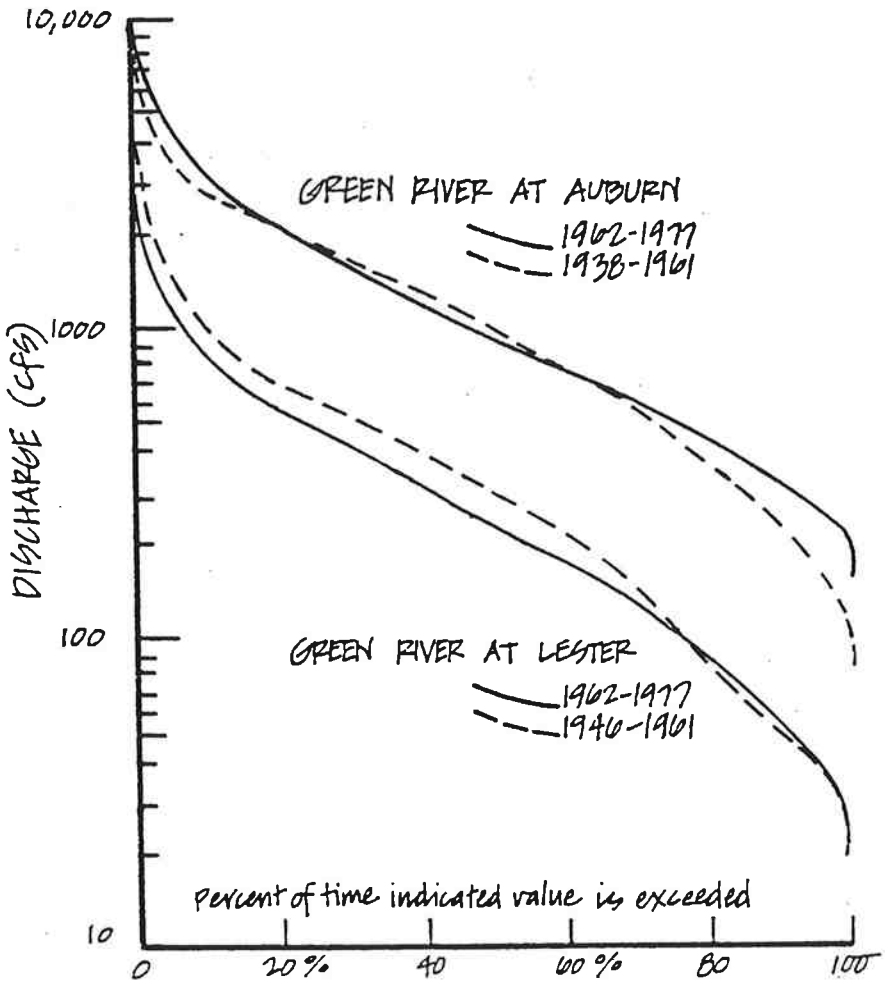
of the river's sediment load (Dunne and Dietrich, 1978). Figure 7 shows that the duration of flows between 1,500 and 10,000 cfs has increased since the dam was constructed. Since a large proportion of the sediment on the river bed begins moving above approximately 2,000 cfs (based on observations near RM 38 by Miller, 1989), significant amounts of bank erosion can occur within this range of flows.

Howard Hanson Dam traps sediment from 55 percent of the Green River's watershed above Auburn. Hence the dam has greatly reduced sediment supply to the river below the dam, although alluvial and glacial deposits between Green River Gorge and the dam continue to supply coarse sediment to the lower river. Within the study area, Newaukum Creek probably also contributes a significant amount of the post-dam coarse sediment load. Most of the coarse sediment load from Big Soos Creek, in contrast, is trapped in low-gradient stream reaches and does not reach the Green River (King County, 1989). Dunne and Dietrich (1978) speculated that the decreased sediment load and increased duration of sediment-transporting flows caused by the dam could contribute to channel instability by causing local erosion of the bed and banks. However, they noted that this effect did not appear to entirely counteract the natural tendency for sediment deposition downstream from the Green River Gorge. Since channel migration is often most severe in zones of sediment deposition, the net effect of dam operation on bank erosion is not intuitively evident and is discussed further in Section 4.4.2.1.

An even more significant hydrologic change occurred downstream from Auburn in 1906, when diversion of the White River into the Stuck River reduced flows and sediment load to the lower Green River by more than half. The Green River has adjusted its channel to the decreased flows by depositing sediment and becoming narrower.

The City of Tacoma diverts an average flow of 99 cfs from the Green River at a point three miles downstream from Howard Hanson Dam. This diversion is too small to significantly affect the duration and magnitude of bedload-sediment transport, and hence is considered to have no effect on channel migration.

Figure 7
Flow Duration Curves
Pre- and Post Dam



Notes: From Dunne & Dietrich, 1978. Data from USGS.

3.4 Geology and Sediment Characteristics

The Green River originates on the west slope of the Cascade Range. Just upstream from the study area the river flows through the Green River Gorge, a steep, narrow canyon cut into Tertiary bedrock. The river enters a wider valley lined by Pleistocene glacial deposits at Flaming Geyser State Park, the upstream end of the study reach. The modern Green River Valley was cut by the river after glacial retreat from Puget Sound approximately 13,000 years ago. In the thousands of years since then, the Green River has meandered across its valley, depositing alluvial sediment on its floodplain. The river episodically undercuts the steep valley walls as it migrates back and forth, causing landslides that line the valley walls in many places.

Within the study area, the river flows through a floodplain of gravelly and sandy alluvium derived primarily from reworked glacial sediment. Glacial sediment, landslide deposits, and (in the upstream end of the study reach) bedrock are exposed in the river banks wherever the river flows next to the valley wall. These valley-wall bank materials vary greatly in their resistance to erosion by the river, but are generally less erodible than alluvium and thus limit the lateral migration of the river. Most of the exposed valley-wall sediment within the study area is fine grained, and thus the valley walls are a relatively small source of gravel compared to that entering the study area from upstream.

Geology of the study area has been mapped and described by Mullineaux (1965a, 1965b, 1970). Because it is the material at the base of a bank that determines the bank's resistance to erosion by a river, Sheet 1 shows the geologic materials in the basal walls of the Green River valley, based primarily on Mullineaux's mapping and supplemented by our observations of riverbank exposures. The following paragraphs describe the geologic materials observed in the river banks, in order from oldest to youngest.

3.4.1 Bedrock

Tertiary bedrock is exposed only in the upstream end of the study area, above RM 42. The oldest bedrock unit is the **Puget Group (Tp)**, sedimentary rock that dates to the Upper Eocene. This rock is primarily sandstone but contains interbedded shale. It is generally well indurated and forms steep, stable cliffs which are best exposed upstream in the Green River Gorge. Locally, however, the sandstone may be severely weathered into friable sand and kaolinitic clay (Mullineaux, 1970). Such deposits are also mapped as the Beausite soil series by the USDA Soil Conservation Service (USDA, 1973). Within the study area, Puget Group rock is exposed along the river in two locations between RM 42.5 and 43.5.

The younger **Hammer Bluff Formation (Th)** formed during the Upper Miocene. It consists of clayey sand and gravel, with many of the sand and gravel clasts partly weathered to clay. Although the rock has been compacted by the weight of overlying sediments and glacial ice, it is poorly indurated, i.e., not hardened into firm rock. Due to its weakness, high clay content, and low permeability, landslides are common both within the Hammer Bluff Formation and in overlying units. The Hammer Bluff Formation crops out along the river and valley walls between RM 42 and 45. Large landslides are present within the Hammer Bluff map unit where it abuts the river on the north bank at RM 42.3 and the south bank at RM 42.8.

3.4.2 Quaternary Deposits

A variety of glacial sediments were deposited during glaciations of the last 2 million years. These sediments are exposed in the walls of the Green River Valley and include three distinct suites of glacial deposits which date to different glacial periods: the Orting Drift, Intermediate Drift, and Salmon Springs Drift (Mullineaux, 1965a,b), as well as the non-glacial Puyallup Formation which separates the Intermediate and Salmon Springs Drifts. The deposits exposed at river level become progressively younger downstream, with the Salmon Springs Drift and Puyallup Formations exposed at river level only downstream from Auburn. Although **Vashon**

glacial sediments (Qva), deposited during the most recent glaciation which ended approximately 13,000 years ago, are abundant on the plateaus on each side of the Green River Valley, they are rarely found within the valley itself, which was formed post-glacially by downcutting of the river.

The **Orting Drift (Qor)** is the oldest unit and overlies the Hammer Bluff Formation in the upstream end of the study area. It consists primarily of fluvial sand and gravel, but also includes lacustrine sediment and till. The river flows against an eroding bluff of glaciolacustrine silt of the Orting Drift at RM 40.8. A large, active landslide at RM 42.8 consists of Orting Drift overlying the Hammer Bluff Formation. The Orting Drift is a major component of the landslide sediment entering the river.

The **Intermediate Drift (Qid)** is exposed extensively in the lower valley walls downstream from RM 41. It consists primarily of structureless silt and clay deposits with scattered gravel. These deposits were interpreted by Mullineaux as till, but may be of glaciolacustrine origin (Booth, 1993). The Intermediate Drift also contains laminated deposits of glaciolacustrine sand, silt and clay. Outcrops on the valley wall are characterized by numerous landslides, mostly small but some quite large (Mullineaux, 1970). The river currently flows against bluffs of Intermediate Drift at two locations: at RM 37 a landsliding bluff of laminated silt, and at RM 34.5 an eroding bluff of sand and silt. Two landslides in Intermediate Drift on the north valley wall in the vicinity of Auburn were probably caused by earlier river undercutting (RM 30.4 and 33.0).

The Green River flows next to densely-vegetated hillsides of **Salmon Springs Drift (Qss)** in the Horsehead Bend area (RM 26.5). The Salmon Springs Drift consists chiefly of compact outwash sand and gravel deposits, but also includes till and thin beds of silt and clay. Where undercut by the river, it tends to form steep cliffs and is generally resistant to landsliding except near its contact with the underlying fine-grained **Puyallup Formation (Qpy)**.

3.4.3 Recent Deposits

Holocene, or recent, deposits are those which formed during the approximately 13,000 years since deglaciation and are still being formed today by ongoing geologic processes as water and gravity reshape the landscape.

Landslides (Qms) are very common on the steep walls of the Green River Valley. Although most landslides occur in glacial deposits, some of the largest occur in the clayey, highly weathered "bedrock" of the Hammer Bluff Formation. **Colluvial deposits (Qmc)**, which generally form fans at the base of the valley wall, consist primarily of debris flow deposits and sediment from small streams. The texture of landslide and colluvial deposits depends on the source material and hence is highly variable, but often tends to be fine grained. The deposits are poorly consolidated and therefore weaker than the undisturbed parent material from which they originate. They are prone to renewed sliding, especially if undercut by the river. As shown on Sheet 1, the Green River flows directly against, or very close to, landslide deposits in several locations. Numerous other landslides are no doubt present, but too small to show at the scale of the original mapping. In addition, new landslides can form and old ones reactivate wherever the river shifts position and attacks the valley wall.

Sediment deposited by rivers and streams is termed **alluvium (Qa)**. The entire floor of the Green River Valley is composed of alluvium. The alluvium, which ranges in thickness from tens of feet in the upper end of the valley to probably over 120 feet in the lower end of the valley (Mullineaux, 1970), is underlain by bedrock and Quaternary glacial deposits. The alluvium is composed of two types of deposits: coarse channel deposits and finer overbank deposits. Channel deposits are predominantly gravel and sand which are transported as bedload and deposited in bars and on the channel bottom. As the river shifts laterally, fine sediment settles out of suspension on the former gravel bars, building them up to the level of the adjacent floodplain. A typical river bank thus consists of a coarse lower bank covered by a layer of finer overbank sediment. Because grain size plays an important role in determining a bank's resistance to erosion, as well as the type of bank erosion that is likely to occur, further description of bank composition and sediment size is presented here.

3.4.4 Green River Alluvial Deposits

In the upstream part of the study reach (RM 32-44) the channel deposits are primarily gravel, with lesser amounts of sand. The banks commonly contain some cobbles (diameter larger than 2.5 inches) in the upstream part of this reach. The overbank deposits are typically loose, non-cohesive, fine sands and silts ranging in thickness from a few inches to over five feet, although most commonly two to three feet of overbank deposits were observed. Since overbank deposits build up over time, they are generally thickest and most extensive in areas which have not been occupied by the river channel for many centuries. In some cases, thick overbank deposits occur on higher ground near the sides of the valley and are mixed with colluvial materials derived from hillside tributary drainages. However, some rapidly eroding river banks have very thick overbank deposits, showing that thick overbank deposits do not guarantee that the channel will not migrate to a particular area (e.g., Hamakami (RM 36.2), O'Grady Park (RM 39.7)). Banks in the upstream part of the study reach typically range from three to six feet in height. Upstream from Newaukum Creek (RM 41), many banks are ten feet high, though more recently formed banks are typically four to six feet high. The high banks may have been formed by downcutting following straightening of this section of river prior to 1900. Alternatively, the lower banks may reflect the river's adjustment to lower, but more prolonged, flows since 1962. Upstream from Newaukum Creek, river migration is generally quite slow and therefore most of the river banks were formed prior to regulation; in contrast, downstream from RM 41, the river has migrated very actively and more of the river banks are young deposits affected by flow regulation.

In the downstream part of the study reach (RM 25-32), downstream of Auburn in the former White River valley, gravel occurs only in the deeper parts of the channel. The bars and river banks are formed almost entirely of sand and silt, with gravel composing only the lower one foot of the banks. Since losing more than half of its flow when the White River was diverted south to the Stuck River at the turn of the century, the river has narrowed by forming a new, lower

floodplain within its old, wider channel. The new floodplain is at least seven feet below the former floodplain (Dunne and Dietrich, 1978). Sediment has been deposited on the insides of meander bends to form the new floodplain. Erosion typically has occurred on the higher, outer banks of the meander bends.

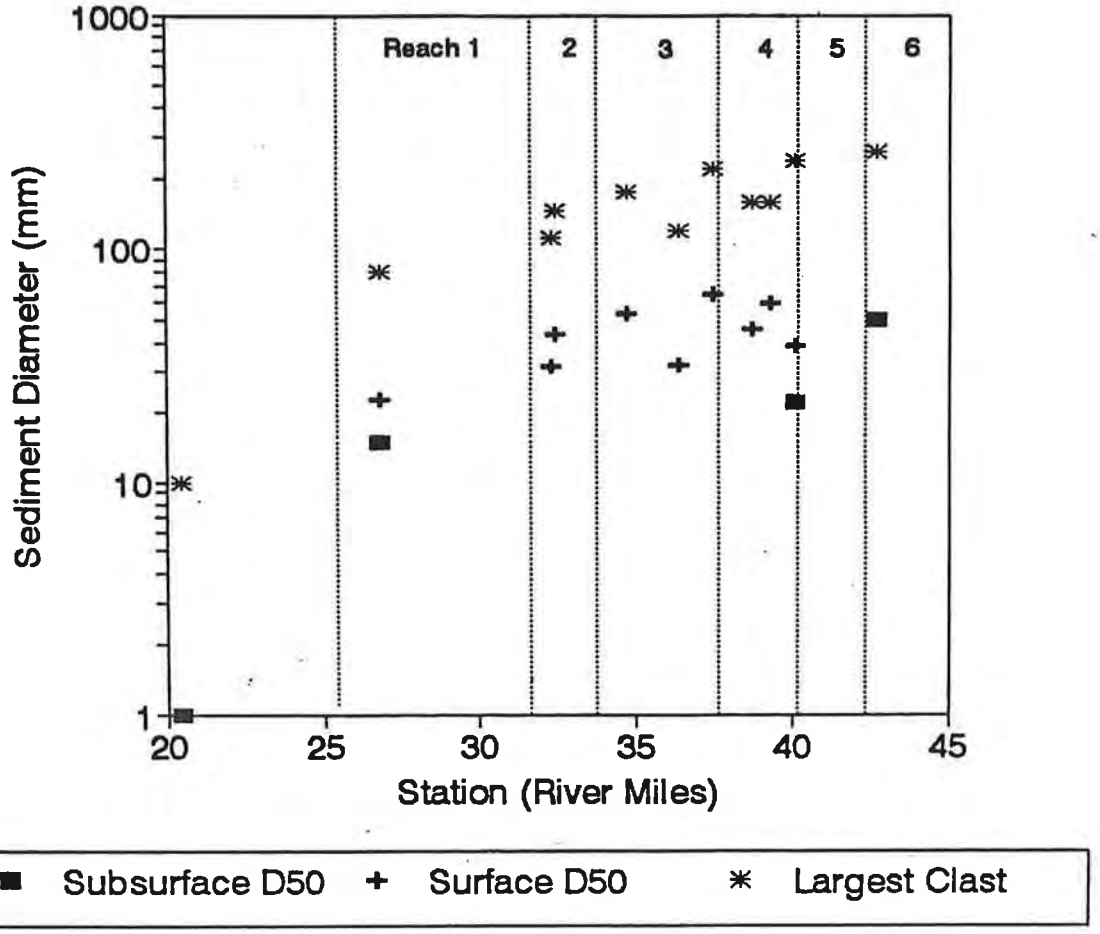
Figure 8 summarizes sediment size data for the surface of gravel bars, as well as limited data from subsurface sediment sampling by previous workers. Sampling for both data sets was performed in consistent locations on the upstream half of each point bar. This sampling convention allows comparison from bar to bar and minimizes the confounding effects of spatial variability within each gravel bar. Because sediments in the bases of river banks originated as gravel bars, these gravel bar measurements also provide information on bank material size and erodibility.

Within the study reach (RM 25 to 45), the median diameter (D_{50}) of sediment on bar surfaces decreases downstream from 65 mm to 23 mm (2.6 to 0.9 inches). Much of the scatter in the surface samples may reflect the degree of armor development rather than differences in the size distribution of the subsurface sediment deposited at the site. Both the maximum particle size and the percentage of cobbles (greater than 64 mm) decrease downstream, indicating a gradual downstream decline in the size of sediment that the river can transport. Subsurface sediment samples, which approximately represent the size of bedload being transported by the river, show a downstream decline in size from 50 mm to 15 mm within the study reach. Downstream of the study reach, the river becomes sand-bedded, indicating that virtually all gravel has dropped out upstream. This sorting of sediment by the river reflects a downstream decline in boundary shear stress caused primarily by the river's decrease in slope (Dunne and Dietrich, 1978). The effect of this decline in shear stress on sediment deposition and channel migration rates is discussed in Section 4.4.1.

4.0 CHANNEL MIGRATION ON THE GREEN RIVER

Figure 9 shows channel shifts of the Green River from the late 1800s to the present. The channels are shown at a larger scale on Sheets 2 and 3. Sheet 2 shows historic changes in

Figure 8
Downstream Changes in Sediment Size



Surface data for RM 20.5 and 42.7, and all subsurface data, are from Dunne & Dietrich, 1978.

position of the Green River from the late 1800s through 1960, the period prior to regulation by Howard Hanson Dam and construction of most levees and revetments. Sheet 3 shows historic changes in the position of the Green River between 1960 and 1992. These maps show low-flow channel(s) of the river that flow year around and are large enough to be visible on aerial photographs. Between-year differences in channel width on these maps in most cases are artifacts of differences in discharge between sets of aerial photographs, or of varying definitions of channel edge in the case of surveyed maps. The active channel, defined as the low-flow channel(s) plus adjacent gravel bars that lack perennial vegetation, was in many locations considerably larger than the low-flow channel shown on the maps.

The study area was divided into 6 reaches that exhibit different rates and types of channel migration and have corresponding differences in river morphology. These reaches are designated 1 through 6, with Reach 1 located at the downstream end of the study area. Reach boundaries are shown on the map sheets. Table 2 lists physical characteristics of the reaches such as channel gradient, pattern, and the degree of constraint by levees, revetments and cliffs. Channel gradient declines rapidly downstream within the study reach, from 0.41 percent in Reach 6 to 0.06 percent in Reach 1 (see also channel profile, Figure 2).

4.1 Types of Channel Migration

Three primary types of channel migration occur on the Green River. In order of increasing scale, these are lateral migration, chute cutoffs of bends, and large-scale avulsions (Figure 10).

Lateral migration involves erosion of one river bank concurrently with deposition of sediment near the opposite bank (Figure 10a). Consequently, the entire river channel moves laterally, generally without a net increase in width. Lateral migration is typically associated with meander bends, where it is caused by convergence of flow against the outer bank near the downstream end of a bend. Lateral migration typically results in downstream, and in some cases, outward migration of meander bends. New bends which form in previously straight sections of channel typically grow outward as well as downstream.

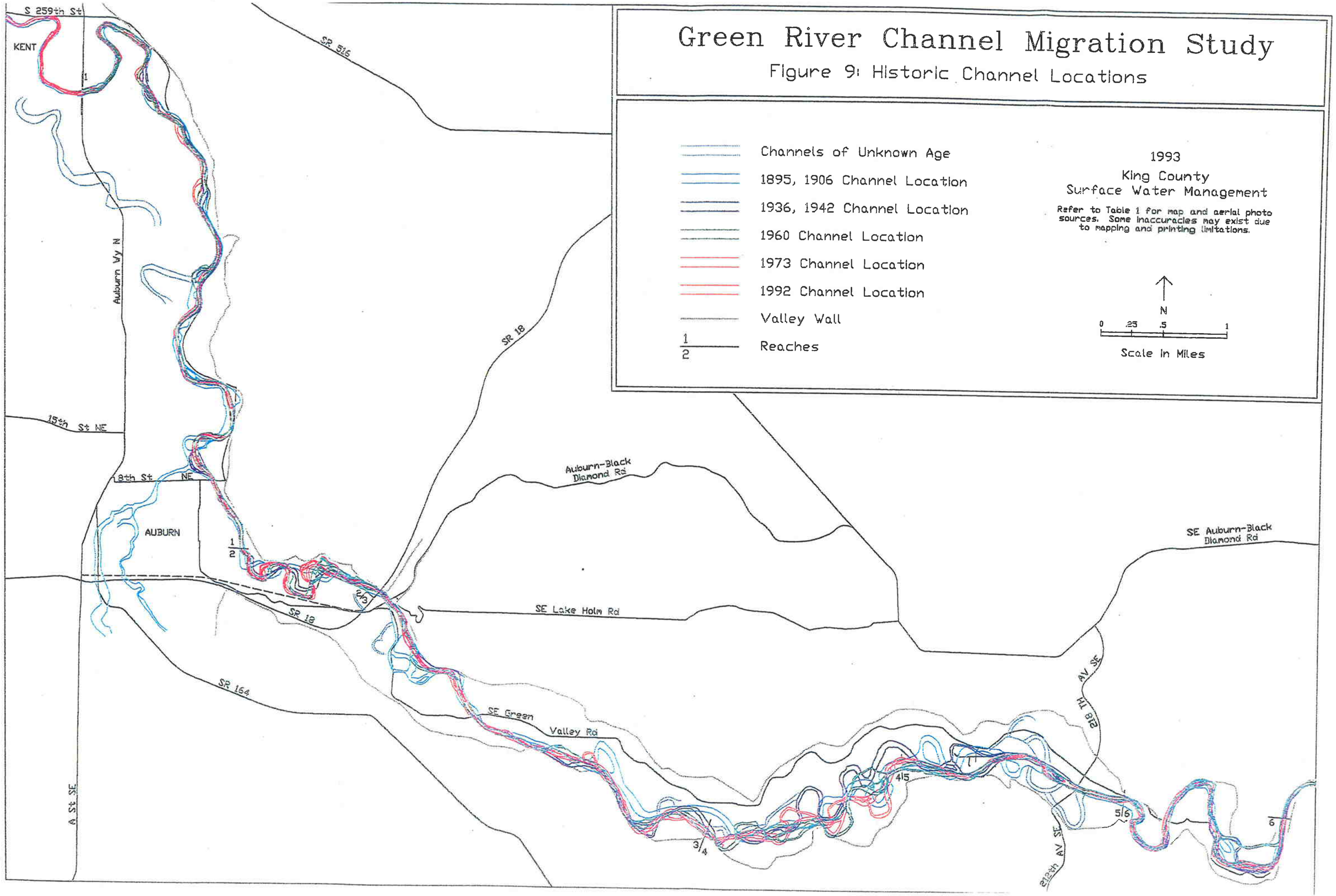

Green River Channel Migration Study
Figure 9: Historic Channel Locations
Channels of Unknown Age
1895, 1906 Channel Location
1936, 1942 Channel Location
1960 Channel Location
1973 Channel Location
1992 Channel Location
Valley Wall
Reaches
1993
King County
Surface Water Management
Refer to Table 1 for map and aerial photo sources. Some inaccuracies may exist due to mapping and printing limitations.
N
0 .25 .5 1
Scale in Miles
S 259th St
KENT
SR 516
Auburn Way N
15th St NE
8th St NE
AUBURN
SR 18
Auburn-Black Diamond Rd
SE Lake Holm Rd
SE Auburn-Black Diamond Rd
SR 164
SE Green Valley Rd
A St SE
218 TH AV SE
AV SE
AV SE
1/2
2/3
3/4
4/5
5/6
6
7
11

Figure 9

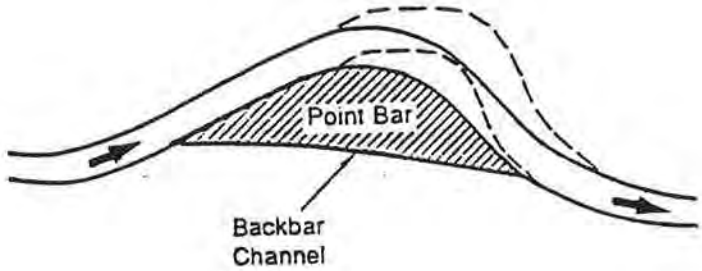
TABLE 2
Characteristics of Green River Reaches

Reach Number	From RM:	To RM:	Channel Gradient(%) In 1988	Levee and Revetment Length (%) In 1992	Cliff Length (%) In 1992	Channel Pattern
1	25.3	31.7	0.062	82	2	meandering
2	31.7	33.8	0.079	59	7	meandering or braided
3	33.8	37.8	0.164	60	7	meandering
4	37.8	40.2	0.218	10	3	braided
5	40.2	42.2	0.371	27	0	straight (formerly meandering)
6	42.2	45.2	0.413	29	43	meandering/confined

Notes:

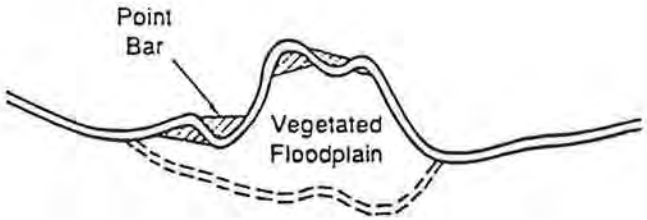
1) Channel gradient was calculated from 100-year flood water surface elevations.
2) Reach 6 gradient is for the section downstream of the old bridge site at RM 43.3.
3) Except in Reaches 5 and 6, almost all revetments were constructed after 1959. Reach 5 may contain some very old revetments that are not visible or documented.

Figure 10
Types of Channel Migration



a) Lateral Migration

b) Chute Cutoff



c) Avulsion

Note: Dashed lines denote channel position after migration takes place.

Chute cutoffs occur when a river abandons a bend and switches to a straighter, steeper path across the back of a point bar (Figure 10b). As a meander bend develops (radius of curvature decreases), the water slope in the channel 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 are common on larger gravel bars on the Green River. These channels provide 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 just downstream of the original gravel bar by causing the river to impinge on the downstream bank at a sharp angle.

The third common type of channel migration in the study area is large-scale avulsion -- the abrupt switching of the river to a new location. Although a chute cutoff is also a type of avulsion, in this report avulsion will refer to sudden changes in channel location that involve a greater distance than the length of a single point bar, as shown schematically in Figure 10c. Avulsions in many cases occur where a creek or a former channel provides a low path across the floodplain. After an avulsion takes place, flow progressively diminishes in the abandoned channel as its entrance becomes plugged with sediment, although small flows may continue in the abandoned channel for decades. The new channel typically widens rapidly and progressively carries more of the flow. Islands of forested land may remain between the old and new channels.

Lateral migration is the dominant channel migration process in meandering rivers such as the Green. However, on some parts of the Green River, the development and growth of meander bends has at times been limited by cutoffs and avulsions, which tend to destroy bends before they become large. Consequently, the river remains relatively straight or, in extreme cases, assumes a braided pattern with multiple channels. A measurement of the straightness of a river can thus indicate the type of migration process at work. Sinuosity, the ratio of channel length to valley length, is such an index (Table 3). A sinuosity of 1.0 indicates a perfectly straight channel; in contrast, rivers commonly considered to be truly meandering commonly have sinuosities of 1.5 or greater. Meandering behavior is best developed in low-gradient rivers whose banks contain enough silt and clay to be sufficiently cohesive to limit the rate of erosion,

TABLE 3
Changes in Channel Sinuosity
(Channel Length Divided by Valley Length)

Reach Number	Sinuosity circa 1900	Sinuosity circa 1940	Sinuosity in 1960	Sinuosity in 1992
1	1.37	1.36	1.38	1.37
2	1.10	1.19	braided	1.60
3	1.21	1.12	1.12	1.12
4	1.30	1.58	braided	1.48
5	1.19	1.07	1.04	1.03
6	1.41	1.49	1.51	1.48

NOTES:

Reach 1 and 2 sinuosity was calculated for the years 1906 and 1943.

Reach 3 through 6 sinuosity was calculated for the years 1898 and 1936.

or where the river abuts a resistant material such as a valley wall or bank armoring that can lock a bend in place. Such is the case in Reach 1 (low gradient, silt banks) and Reach 6 (valley wall and revetments). As shown in Table 3, sinuosity has been consistently fairly high in these reaches. Low sinuosity (less than 1.3) or braiding is typical for steeper, bedload-transporting rivers with weak, non-cohesive sand or gravel banks (Schumm, 1977). Sinuosity has been consistently low in Reaches 3 and 5 (Table 3). Rivers constantly adjust their planforms, dimensions and slopes to most efficiently convey their water and sediment loads. Since straightening increases a river's slope, sinuosity may change over time in response to changing conditions. Such changes may be reflected in the variable sinuosity found for Reaches 2 and 4. For example, if the sediment load from upstream decreases, the river pattern may change from a relatively straight, perhaps braided pattern to a more gently-sloping, high-sinuosity channel with large meander bends.

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

Cutoffs and avulsions result in the formation of multiple channels, giving parts of the Green River study area (Reaches 2 and 4) a braided appearance at times, similar to portions of the Tolt River and Raging River (Shannon & Wilson, 1991). These reaches, transitional in behavior between a meandering and fully braided channel (in which two or more channels of roughly equal size are present), exhibit a braided appearance following periods with large floods, then revert to single-thread channels with high-amplitude bends as former channels heal through sediment deposition and vegetative growth. Braiding on Reaches 2 and 4 was most pronounced in the 1950s and early 1960s, following a period with large floods (Figure 5). These reaches have become less braided, with a single predominant channel, since flood control by Howard Hanson Dam began in 1962.

4.2 Morphology of the Green River Study Reaches

Morphological features such as channel gradient and floodplain width strongly influence channel migration. Conversely, historic changes in river pattern and width reflect the magnitude and type of past channel migration. This section sets the stage for a discussion of channel migration rates by describing the morphology of each reach of river, based on interpretation of successive aerial photographs.

Channel gradient declines in the downstream direction throughout the study reach (Figure 2), and the valley floor generally widens downstream. However, river width does not systematically increase downstream. Active channel width (river channel plus non-vegetated gravel bars) presently is largest in Reaches 2 through 4, and relatively narrow in Reaches 1, 5 and 6. However, channel width has changed significantly during the past century (Table 4). During periods of high flows and 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 in response to lower flows or bank armoring, vegetation grows on formerly active gravel bars and channel width decreases. Reach 1 became narrower after the White River was diverted in 1906. Reaches 2 through 4 widened between 1943 and 1960, presumably in response to a series of large floods in the 1950s. All reaches narrowed significantly between 1960 and 1970 and have remained narrow since then, except in localized areas. This narrowing occurred in both revetted and non-revetted sections of river and appears to correspond to flood regulation by Howard Hanson Dam (Section 3.3).

Reach 1 consists of the lowermost 6.4 miles of the study area, between Kent and Auburn. The river is a single-thread, meandering channel that is constrained by bank armoring at the outside of most bends. The river flows near the east valley wall in places, but is unconstrained to the west except locally by levees. Scars of former meander bends on aerial photographs show that the river (then the combined White and Green Rivers) formerly flowed a mile west of its present location, probably as recently as 200 years ago (Sheet 2). Based on these old meander scars and turn-of-the-century maps, the pre-diversion river was characterized by large, high-amplitude bends with a wavelength of approximately one mile. Some of these large, relict bends have been

TABLE 4
CHANGES IN ACTIVE CHANNEL WIDTH

	Year	Typical width (ft)	Maximum width
REACH 1	1906	130 to 400	700
	1960	100 to 150	300
	1989	100	200

	Year	Typical width (ft)	Maximum width
REACH 2	1906	100 to 200	350
	1936	200 to 300	300
	1960	150 to 300	700
	1989	100 to 200	200

	Year	Typical width (ft)	Maximum width
REACH 3	1906	200 to 350	700+
	1936	150 to 200	300
	1960	200 to 300	600
	1989	130 to 200	250

	Year	Typical width (ft)	Maximum width
REACH 4	1936	300 to 400	700
	1960	600 to 1200	1200
	1989	300 to 500	500

	Year	Typical width (ft)	Maximum width
REACH 5	1936	200 to 300	500
	1960	150 to 250	500
	1989	100 to 200	200

	Year	Typical width (ft)	Maximum width
REACH 6	1936	100 to 200	400
	1960	120 to 150	250
	1989	100 to 150	150

frozen in place by levees and revetments. Where not thus constrained, new meander bends with a smaller wavelength (2,000 feet) have grown since the diversion of the White River. One such new bend threatened to cut off the neck of the tight bend at RM 26.8 until erosion was halted in 1984 by a revetment.

The 1906 map, surveyed at the time of the diversion, shows 20 large bars in Reach 1 downstream of the White/Green River confluence, at RM 31. For half a mile downstream of the confluence, bedload sediment deposition in response to a decline in gradient caused the river to braid and double in width to 700 feet. After the White River diversion removed most of the river's water and sediment supply, channel width downstream decreased by about 25 percent as a lower and narrower new floodplain formed within the margins of the old channel (Dunne and Dietrich, 1978). Even more substantial decreases in width occurred where vegetation grew up on former gravel bars (Table 4). By 1960, 13 bars remained, only six of which were still large enough to have been mapped in 1906. Extensive levee building occurred in the 1960s and 1970s. By 1992, the channel was 100 feet wide in most places and only one bar remained that was large enough to show at the scale of the 1906 map. The remaining bars are almost completely vegetated, with only a narrow, active strip at the water's edge. The almost complete absence of depositional sites in this reach reflects both the low coarse-sediment load (most gravel having already dropped out upstream) and, to a lesser extent, the river's increased ability to transport the remaining coarse sediment due to narrowing of the channel. Unlike the steeper reaches upstream, banks in this low-gradient reach are fine grained. The relatively few bars that are present are composed primarily of sand (Section 3.4.4).

Reach 2 is a short reach that has generally been characterized by rapidly-moving, large meander bends that leave broad gravel bars in their wakes (Figure 2). However, in the late 1950s Reach 2 was braided, with multiple channels that rapidly changed positions. Large amounts of gravel are deposited in this reach in response to a decline in gradient. Levees were built along nearly 60 percent of the reach in the early 1960s. The late 1960s and 1970s saw gradual healing of braid channels, tree growth on the islands between channels, and re-establishment of a single main channel with rapidly-migrating bends (Sheet 3). Because the upstream portions of meander bends continued to migrate down-valley while the downstream ends were locked in place by

levees or the valley wall, these bends have become very tight. As a result, sinuosity is now much higher (1.60) than former values of 1.1 to 1.2 (Table 3). Vegetation continued to grow in the 1980s and as a result active gravel deposits are presently quite narrow along most of reach. Nevertheless, a few small braided areas persist.

Reach 3 has been a low-sinuosity, single-thread channel throughout most of this century, although it contains localized, narrow zones with multiple channels. However, at the turn of the century the downstream part of this reach contained multiple channels with a total width of 1,400 feet (Sheet 2). According to records in the King County archives, a new channel next to the east valley wall was excavated in about 1901. This channel is shown on the 1906 map, although at that time the river had not yet abandoned its other channels. By 1936, the river had abandoned the other channels and assumed its present course in the east channel and had straightened upstream as well. Further upstream (RM 36), faint scars of former river channels that are probably several centuries old are visible on the north side of Green Valley Road across from the Hamakami farm, in low ground that reportedly floods almost every year (not shown on Sheet 2).

During most of the study period this river reach has occupied a narrower belt and migrated less actively than adjacent reaches. Currently, 60 percent of Reach 3 has a levee or revetment on or near one of its banks. In addition, three meander bends are locked into place by the valley wall. Attempts by the river to re-establish bends in the formerly braided reach have been thwarted by levee construction. Three of the levees built during the 1960s further straightened the river by cutting off bends. Although County records show that most levees were built in the 1960s, aerial photographs show that at least two levees were built earlier (Sheet 1). Other undocumented early bank-protection structures may have existed, especially in the straight, stable section near Neely Bridge (RM 35.3). Despite the bank armoring, some major channel shifts have occurred in recent years. Most notable is the development in 1990 of a meander bend at the upstream end of the Hamakami levee (RM 36.3) that by 1993 had destroyed 300 feet of levee. Half a mile upstream, a new bend began to develop in the late 1980s but was halted (at least temporarily) by construction of the Ross revetment.

Reach 4 is characterized by large gravel bars and rapidly-moving channels that have migrated across a zone nearly half a mile wide during this century. This reach has been least altered by man, with no bridges and only one levee near its downstream end. Channel migration is virtually unconstrained by the valley wall in this broad portion of the valley. Reach 4 was dominated by high-amplitude meander bends in the 1930s and again in the mid-1980s to mid-1990s, but was braided during the intervening decades. Cutoffs and avulsions with minor braiding have occurred even during periods when a single-thread channel pattern was dominant. Numerous abandoned channels still function as flood channels and in some cases as perennial creeks. Extremely rapid channel movement (short-term rates of up to 60 feet per year in the 1980s) at "Mad Braid" in the O'Grady Park area (RM 39 to 40) is documented in more detail by Miller (1989).

Reach 5 has been nearly straight and quite stable since the 1930s, with a typical meander belt width of about 500 feet. However, aerial photographs and old maps provide ample evidence that this reach previously had high-amplitude bends and, in places, multiple channels. The meander belt was formerly 2,600 feet wide. Downstream from Whitney Bridge, channel straightening was accomplished shortly before 1936 by levees built across the upstream ends of two former river channels on the north bank (Sheet 2). From Whitney Bridge upstream, the river was already straight by 1898, the earliest reliable map. It seems likely that this section of channel was straightened by human intervention sometime before 1898, both to achieve a stable bridge crossing and to protect farmland. The evidence for any such early tampering is now hidden beneath the well-vegetated banks of the river. The left abutment of Whitney Bridge apparently washed out in a 1911 flood, and plans for the new bridge specify protection on the left bank. The 1936 photographs show revetments of unknown age on the left bank both upstream and downstream from the bridge.

Because of its straightness, Reach 5 is now quite steep relative to Reach 4 downstream (Figure 5 and Table 2). Since 1960 vegetation has colonized and generally stabilized lateral and mid-channel gravel bars, although localized bank erosion has occurred where mid-channel bars direct flow sharply into the bank. The near absence of active gravel deposits suggests that sediment entering this reach moves rapidly downstream to drop out in Reach 4. However, before the

river became straight its slope would have been commensurately less, probably causing gravel to deposit in large bars similar to those in Reach 4. Channel migration rates in the 1800s presumably were correspondingly high.

Reach 6 forms a transition zone between the broad alluvial Green River valley and the narrow, bedrock-walled Green River Gorge. This reach is both steeper and narrower than downstream reaches. The river flows against the valley walls for 43 percent of its length, and against revetments for another 29 percent of its length. These resistant banks have locked the sharp, major bends of this reach in place for half a century or more, although undercutting by the river periodically triggers renewed sliding of an old slide on the south valley wall at RM 42.8. Several shifting channels were present in the vicinity of RM 44.2 in the 1930s through the 1950s, and possibly earlier. Since 1960, the river has narrowed to a single main channel and remained in essentially the same position, although the former north channel still exists as a narrow creek that conveys flood flows. Mid-channel bars that formed in the 1950s have since been colonized and stabilized by trees.

4.3 Historic Rates of Channel Migration

4.3.1 Calculation of Migration Rates

Average rates of channel migration for each reach were calculated by dividing distances between successive channel positions shown on Sheets 2 and 3 by the elapsed time between channel positions. Detailed large-scale maps provided partial coverage of the river in 1906 and 1936. These map sources were used for calculating migration rates where possible. For reaches not covered by these maps, less detailed 1898 and 1943 sources were used instead (see Table 1 for map sources). Migration rates for sections of river with bank armoring were calculated separately; erosion did occur in these areas, typically when the river moved away from the levee or revetment, and rarely when the river destroyed a levee. It is often not possible to distinguish between the effects of lateral migration, cutoffs, and avulsions on this river, especially when the time interval between successive aerial photographs or maps exceeds ten years. Accordingly, no attempt was made to differentiate types of migration except qualitatively. These calculations provide estimates of average migration rates; actual rates may have varied substantially during the intervals between photographs from which channel positions were measured. Average

migration rates were calculated separately for each reach. Measurements were made at 200-foot intervals along the length of each reach. At each station, the distance between successive channel edges was measured if erosion had occurred. Where the channel had shifted but remained within the boundaries of the previous channel (or in between previously-existing channels in the case of braided zones), a value of zero was recorded.

As noted in Section 2.0, 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 real, 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, 3) an increase in channel width, or 4) field evidence of recent bank erosion. In Reaches 1, 5 and 6, where erosion rates have been low, the calculated rates may therefore be slightly lower than the true rates.

Average rates of channel migration were calculated for revetted and non-revetted areas by dividing the average erosion distance for each reach by the elapsed time. For both revetted and non-revetted areas, average rates were calculated in two manners: for the entire reach (including non-eroding areas), and for eroding areas of the reach only.

4.3.2 Historic Channel Migration Rates

Average calculated historic channel migration rates for each reach are shown in Table 5. Rates for non-revetted areas are given in Table 6, and for revetted areas in Table 7. These historic rates are used in Section 5.1 to predict future rates of channel migration. For all tables, section **a** shows average migration rates for the reach including non-eroding areas, section **b** shows average migration rates calculated for eroding areas only, and section **c** shows the proportion of each reach that actively eroded during each time period. The left four columns of each table give data for the shorter time periods between successive maps and photographs. The right two

TABLE 5
HISTORIC CHANNEL MIGRATION RATES
BY REACH

a) Average rates for reach (feet/year)

REACH	circa 1900 to circa 1940	circa 1940 to 1960	1960 to 1973	1973 to 1992	pre-dam circa 1900 to 1960	post-dam 1960 to 1992
1	0.7*	1.1*			0.5*	0.5*
2	7.3	9.3	4.8	2.0	7.4	2.8
3	4.1	5.0	3.0	3.2	2.9	2.0
4	10.3	20.3	12.5	10.6	6.8	7.8
5	2.1	3.7	0.5*	0.8*	2.5	0.4*
6	1.9	0.8*	1.5*	0.7*	1.2	0.4*

b) Average rates for reach, eroding areas only (feet/year)

REACH	circa 1900 to circa 1940	circa 1940 to 1960	1960 to 1973	1973 to 1992	pre-dam circa 1900 to 1960	post-dam 1960 to 1992
1	2.8	2.8			1.5	1.9
2	9.3	9.9	7.5	3.1	8.3	3.3
3	6.0	6.3	8.1	5.9	3.8	4.1
4	13.7	20.8	18.9	13.4	8.0	9.8
5	5.3	10.1	7.0	2.3	6.1	1.2
6	4.7	2.9	5.2	2.6	3.3	1.7

c) Proportion of reach length with measurable net erosion during time period (%)

REACH	circa 1900 to circa 1940	circa 1940 to 1960	1960 to 1973	1973 to 1992	pre-dam circa 1900 to 1960	post-dam 1960 to 1992
1	25	41			34	15
2	79	95	56	39	90	46
3	68	80	40	56	75	54
4	75	98	66	77	85	72
5	40	37	8	34	40	36
6	40	34	27	25	36	23

NOTES:

Reach 1 and 2 rates were calculated with data from 1906 and 1943.

Reach 3 through 6 rates were calculated with data from 1898 and 1936.

Blank entries indicate rates not measured due to poor map resolution relative to the amount of erosion.

* Indicates measured migration rate is lower than potential measurement error.
True rate is probably higher than measured rate (see text, Section 4.3.1).

TABLE 6
HISTORIC CHANNEL MIGRATION RATES
IN AREAS WITHOUT ARMORED BANKS

a) Average rates for reach, non-armored areas (feet/year)

REACH	circa 1900 to circa 1940	circa 1940 to 1960	1960 to 1973	1973 to 1992	pre-dam circa 1900 to 1960	post-dam 1960 to 1992
1	0.7*	1.1*			0.5*	1.2
2	7.3	9.3	7.9	4.5	7.4	5.0
3	4.1	5.0	3.9	4.0	2.9	2.2
4	10.3	20.3	11.9	11.7	6.8	9.0
5	2.1	3.7	0.5*	0.8*	2.5	0.4*
6	1.9	0.9*	1.7*	0.8*	1.2	0.4*

b) Average rates for reach, eroding non-armored areas only (feet/year)

REACH	circa 1900 to circa 1940	circa 1940 to 1960	1960 to 1973	1973 to 1992	pre-dam circa 1900 to 1960	post-dam 1960 to 1992
1	2.8	2.8			1.5	3.8
2	9.3	9.9	9.1	5.8	8.3	6.0
3	6.0	6.3	7.2	5.4	3.8	3.3
4	13.7	20.8	18.9	14.2	8.0	11.2
5	5.3	10.1	7.0	2.4	6.1	1.2
6	4.7	3.1	5.2	2.7	3.3	1.7

c) Proportion of non-armored reach length with measurable net erosion during time period (%)

REACH	circa 1900 to circa 1940	circa 1940 to 1960	1960 to 1973	1973 to 1992	pre-dam circa 1900 to 1960	post-dam 1960 to 1992
1	25	41			34	32
2	79	95	87	78	90	83
3	68	80	54	74	75	68
4	75	98	63	83	85	80
5	40	37	8	35	40	37
6	40	37	32	29	36	25

NOTES:

Reach 1 and 2 rates were calculated with data from 1906 and 1943.

Reach 3 through 6 rates were calculated with data from 1898 and 1936.

Blank entries indicate rates not measured due to poor map resolution relative to the amount of erosion.

* Indicates measured migration rate is lower than potential measurement error.
True rate is probably higher than measured rate (see text, Section 4.3.1).

TABLE 7
HISTORIC CHANNEL MIGRATION RATES
IN AREAS WITH ARMORED BANKS

a) Average rates for reach, armored areas only (feet/year)

REACH	circa 1900 to circa 1940	circa 1940 to 1960	1960 to 1973	1973 to 1992	pre-dam circa 1900 to 1960	post-dam 1960 to 1992
1	—	—			—	0.1
2	—	—	0.9	0.1	—	0.0
3	—	—	1.7	2.2	—	1.8
4	—	—	16.2	3.5	—	0.1
5	—	—	—	0.0	—	0.0
6	—	0.0	0.8	0.3	—	0.3

b) Average rates for reach, eroding armored areas only (feet/year)

REACH	circa 1900 to circa 1940	circa 1940 to 1960	1960 to 1973	1973 to 1992	pre-dam circa 1900 to 1960	post-dam 1960 to 1992
1	—	—			—	0.9
2	—	—	5.4	1.1	—	0.0
3	—	—	9.6	6.4	—	5.0
4	—	—	18.9	8.2	—	0.9
5	—	—	—	0.0	—	0.0
6	—	0.0	5.3	2.4	—	1.7

c) Proportion of non-armored reach length with measurable net erosion during time period (%)

REACH	circa 1900 to circa 1940	circa 1940 to 1960	1960 to 1973	1973 to 1992	pre-dam circa 1900 to 1960	post-dam 1960 to 1992
1	—	—			—	6
2	—	—	17	10	—	0
3	—	—	18	35	—	36
4	—	—	86	43	—	14
5	—	—	—	0	—	0
6	—	0	14	14	—	19

NOTES:

Reach 1 and 2 rates were calculated with data from 1906 and 1943.

Reach 3 through 6 rates were calculated with data from 1898 and 1936.

Blank entries indicate rates not measured due to poor map resolution relative to the amount of erosion.

Dashed entries indicate no revetments or levees were present.

Levees without rock armoring were not counted as armored banks.

columns, labeled "pre-dam" and "post-dam," give longer-term net migration rates. These long-term rates are typically lower because later migration tended to cancel out previous migration as channels shifted back and forth across the valley floor, and because they include periods of little activity.

As shown on Table 5 and Figure 11, channel migration rates have varied during the past century. The highest rates occurred during the 1940 to 1960 period in all but Reach 6, where migration rates have been lower than measurement error. Active channel width increased during the period of rapid channel migration prior to 1960, then decreased during the subsequent period of slower migration (Table 4). The post-1960 decline in migration rates resulted both from slower erosion rates in eroding areas (Table 5b) and because bank erosion was less widespread (Table 5c). Migration rates during the 19th century were probably much higher than the calculated 20th century rates in Reaches 1, 3, and 5, prior to channel straightening, levee building and (in Reach 1) flow diversion.

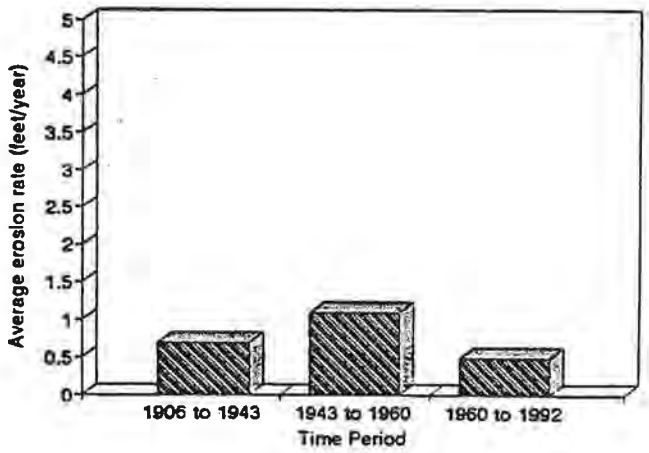
Two events in the early 1960s coincided with the post-1960 decline in migration rates shown in Figure 11: flood control and bank armoring (Section 3.2). To remove the effects of bank armoring as much as possible, migration rates in non-armored areas were computed and are shown in Table 6. Armored areas are not included in the rates shown in Table 6; nevertheless, the presence of levees and revetments could potentially have reduced average migration rates in adjacent sections of river. To the extent that levees and revetments were preferentially built in sites experiencing severe erosion, and to the extent that they stabilized the course of the river, they would have reduced the likelihood of measurable rates of channel migration occurring on adjacent unprotected banks.

Table 6 shows that even with revetted areas removed from the data set, the highest migration rates occurred in the 1940 to 1960 period. In some cases, however, post-dam migration rates are similar to earlier pre-dam rates. In all but Reach 5, 1960-1973 migration rates for unprotected banks are similar to the 1900-1940 time period. Comparing migration rates for 1973-1992 and 1960-1992 with both the 1900-1940 and 1900-1960 periods, post-dam rates in

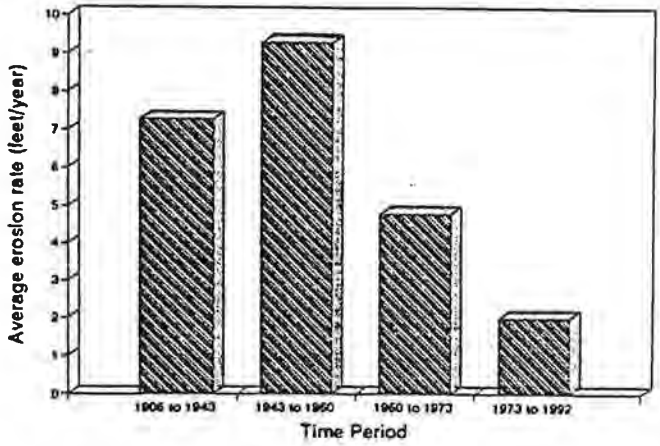
Figure 11
Average Channel Migration Rates

Source: Table 5a

Reach 1



Reach 2



Reach 3

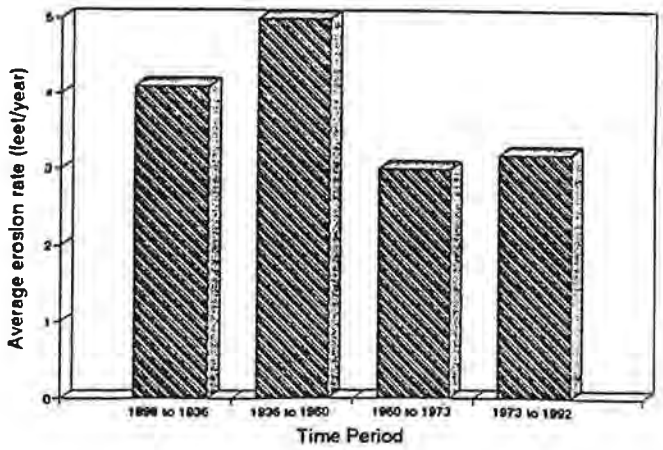
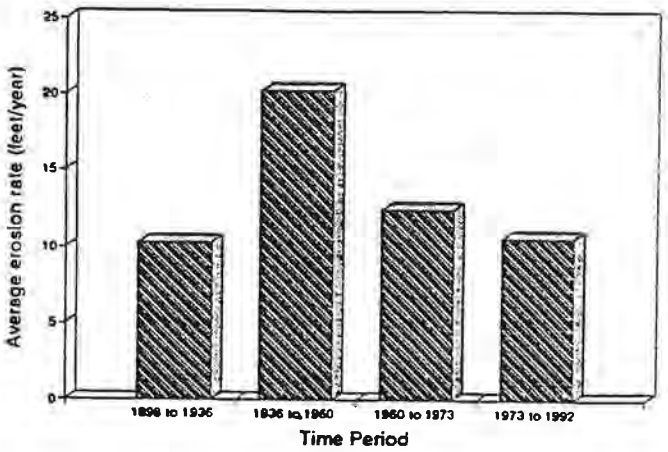
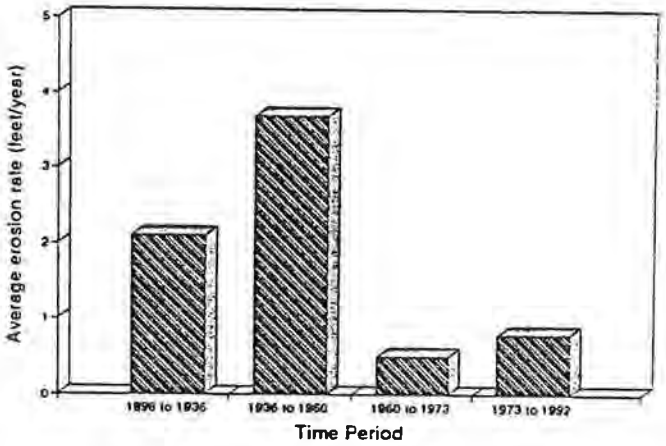


Figure 11
Continued

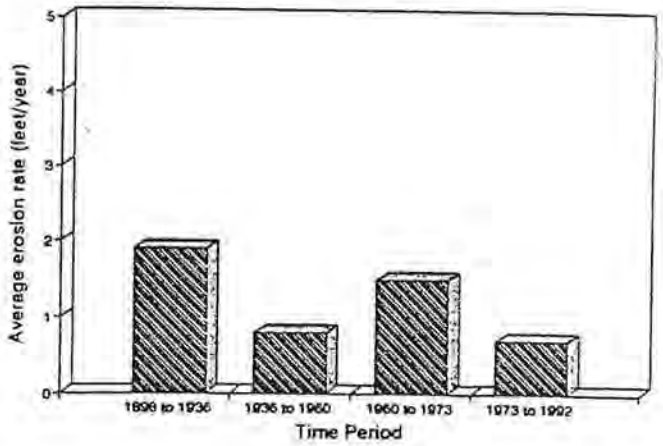
Reach 4



Reach 5



Reach 6



Reaches 1, 3 and 4 remained comparably high but post-dam rates in the Reaches 2, 5, and 6 were significantly (less than 25 percent) lower. The same relationships hold for rates computed for entire reaches (Table 6a) and rates computed just for eroding portions of each reach (Table 6b).

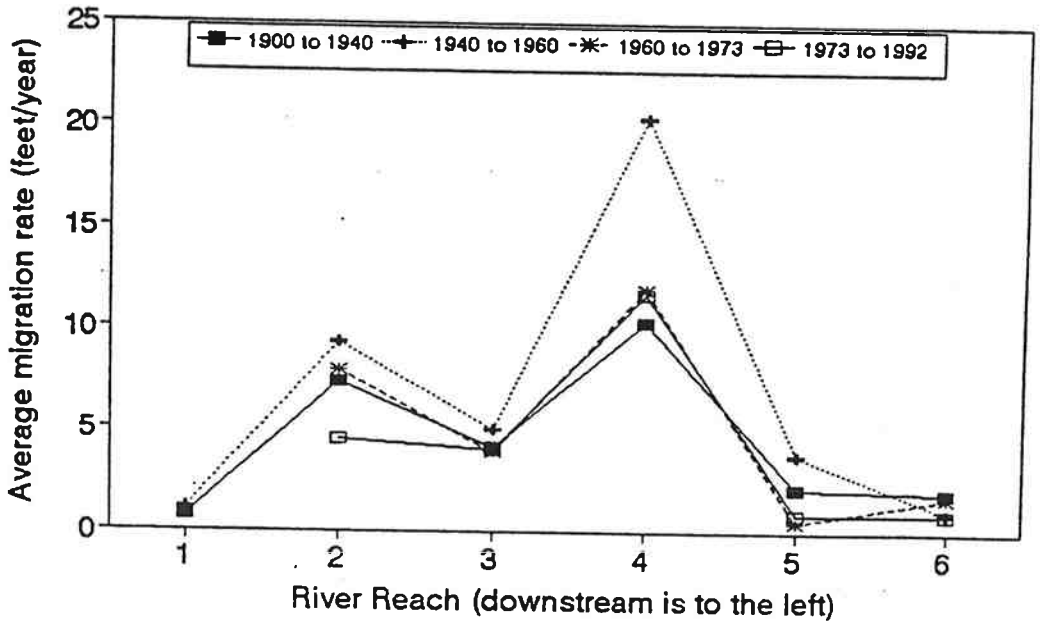
Throughout the study area, avulsions and braided areas have been relatively rare in the post-dam period compared to one or more periods prior to flood control. However, braidedness and avulsion frequency varied considerably over time even before the dam. Old maps and channel scars indicate that most reaches had at least some avulsions in the form of bend cutoffs prior to 1906, and Reaches 3 through 6 contained areas with well-developed multiple channels. Relatively little braiding was present in 1936 and 1943. The period ending in 1960 saw increased numbers of avulsions and extensive braiding in Reaches 2 and 4, localized to widespread channel widening in reaches 2 through 5, and 20 to 100 percent higher migration rates in all but Reach 6 compared to the period ending in 1936. Aerial photographs show that most of the braiding and widening, and presumably most of the bank erosion, occurred sometime after 1943 and coincided with a period of frequent large floods.

Throughout the study period, channel migration rates are consistently lowest in Reaches 1 and 6, moderate in Reach 3, and highest in Reaches 2 and 4 (Figure 12). In reaches with low average migration rates, erosion tends to occur only in localized areas while the majority of the banks remain stable (Table 6c).

Channel migration rates are generally low on armored sections of the river (Table 7a). However, because most levees and revetments on the Green River study reach are discontinuous and are located on just one side of the river, they do not necessarily stop the river from migrating. Localized rates of channel shifting in revetted reaches have been quite high (Table 7b). This is particularly the case for levees located in and just downstream from rapidly-shifting zones of the river, such as Reach 4 and the upstream part of Reach 3. Channel migration rates along these levees have been as high as in adjoining unprotected sections of river. In most cases levees and revetments have remained intact and prevented bank erosion (though not flooding)

Figure 12
Green River Channel Migration Rates
Average Rates for Unprotected Banks

Source: Table 6a



inland from them. More rarely, as in the case of the Hamakami levee in Reach 3, channel migration destroys the levee and erodes the land behind it.

4.3.3 Comparison of Measured Channel Migration Rates with Other Studies

A sizable body of literature exists on migration rates of meandering rivers. Hooke (1980) compiled data on bank erosion rates from various rivers, primarily in the United States and Europe. The periods of measurement vary from two to 250 years, and most of the rivers in the data set have a well-developed meandering pattern. Hooke's data set contains bank erosion rates of three to 30 feet per year for rivers with drainage areas the size of the Green River at Auburn, about 400 square miles (1,000 square kilometers). Average rates of bank erosion calculated by this study for eroding, non-revetted areas of the Green River range from one to 21 feet per year (Table 6b), or generally within the range found on other rivers. Since most studies tend to focus on sections of rivers with significant rates of migration, and because some of the measurement periods were quite short, it is not surprising that some of Hooke's rates are higher than those obtained for this study.

A previous study of the Green River plotted local rates of channel shifting for three time periods: 1898-1973, 1943-1973, and 1968-1978 (Figure 11 in Dunne & Dietrich, 1978). Their rates range from one to 57 feet per year, with the highest rates occurring between RM 32 and 40 (Reaches 2 through 4 of this study) and lower rates for the longest time period. It is not surprising that many of the local rates were higher than rates calculated for this study, which were averaged over each reach. Indeed, successive aerial photographs show that new meander bends on the Green River have grown at rates of over 100 feet per year for a few years in Reaches 2 and 4, and up to 22 feet per year in Reach 1.

Channel migration rates for two other rapidly migrating rivers in King County, the Tolt and Raging Rivers, were calculated by Shannon & Wilson (1991). On the Tolt River, long-term (1936-1991) average rates for various reaches ranged from 0.5 to 6.5 feet per year. On the

much smaller Raging River, rates ranged from 0.3 to 2.9 feet per year. Long-term rates on the Green River are 0.5 to 7.4 feet per year for the 1900 to 1960, an interval of similar length albeit different hydrology and other conditions.

In summary, the channel migration rates calculated for this study of the Green River are in good agreement with rates calculated in previous studies, both on local rivers and in rivers of similar size elsewhere in the world.

4.4 Factors Affecting Channel Migration Rates

Cutoffs, avulsions, and rapid lateral migration cause meander bends on the Green River to be short lived, except where bends are locked into position by the valley wall or armored banks. Accordingly, analyzing the direction and rate of growth of individual bends based on their curvature would not be useful for determining long-term rates of erosion. Instead, our approach is to identify factors responsible for differences in channel migration rates between various reaches of the river, then examine factors that have caused migration rates to change over time. We can use this understanding to predict likely future trends and the degree of channel migration hazard along the river. However, it must be kept in mind that many instances of channel migration on the Green River 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 bank erosion starts in a given location, it can trigger rapid channel migration downstream.

4.4.1 Causes of Spatial Differences in Migration Rates

4.4.1.1 Patterns of Shear Stress and Channel Stability

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 the flow depth and the slope of the water surface. Thus, shear

stress is controlled by the gradient and width of the river's floodplain, the sinuosity of the river, and in some locations by narrowing of the floodplain by levees.

Because a river's ability to transport sediment depends on boundary shear stress, sediment tends to be deposited in locations where shear stress decreases rapidly in the downstream direction. Shear stress will decrease and sediment will be deposited where the channel becomes less steep or shallower downstream. 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, a downstream increase in shear stress increases sediment transport capacity, which in turn increases the potential for erosion of the bed and undercutting of banks. Thus, instability should be expected in zones where shear stress either increases or decreases rapidly, unless resistant bed and bank materials are present. Where 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 lower shear stress (typically on the inside of bends) as it moves through the reach.

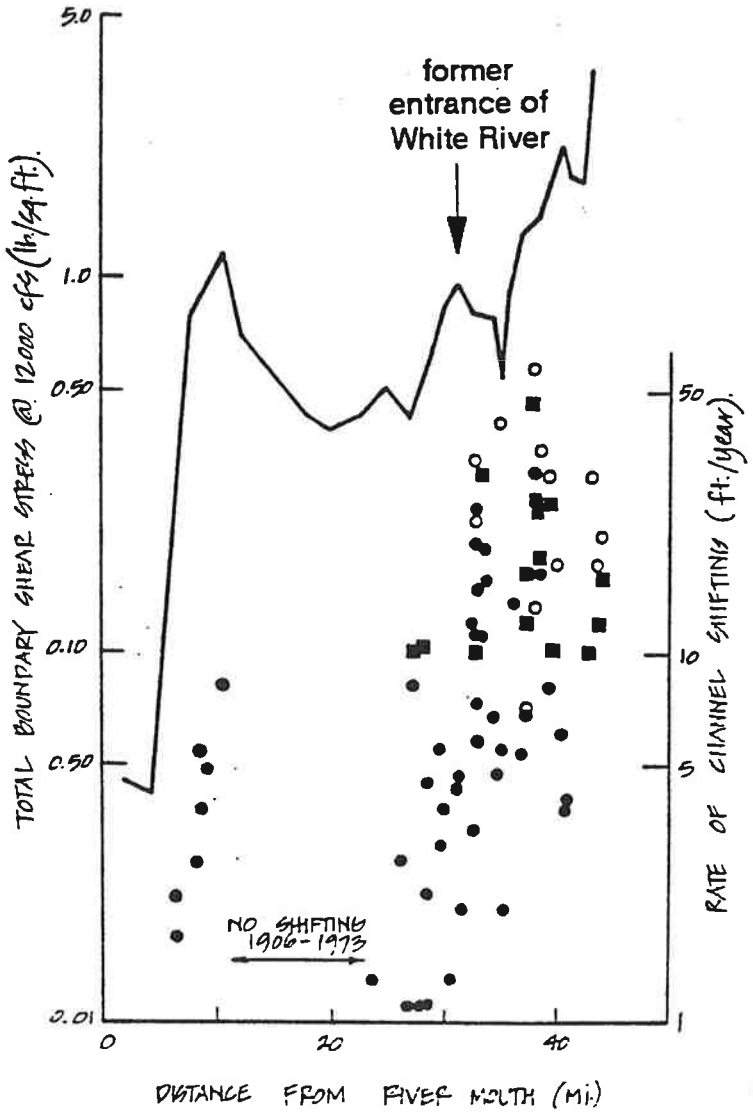
In addition to declining shear stress, for sediment deposition to occur there must also be an ample upstream supply of sediment of the relevant sizes. If shear stress declines, but still remains high enough to transport the sediment load from upstream, then no deposition will occur. Within the study reach, the Green River transports fine sediment rapidly in suspension, so 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. An increase in suspended sediment load, such as from streamside landslides of silty or sandy sediment, is unlikely to affect the rate of channel migration significantly. One exception to this may be in Reach 1, where bar deposits are largely sand.

Patterns of boundary shear stress explain much of the spatial variation in channel migration rates along the Green River. In their study of the lower 45 miles of the Green River, Dunne and Dietrich (1978) found channel migration rates were greatest in zones of high but rapidly decreasing shear stress, and lowest where shear stress was constant or increasing slightly in the downstream direction (Figure 13).

Figure 14 shows boundary shear stress, gradient, and flow depth in more detail for the present study reach, computed from updated water surface and thalweg elevations from the 1989 flood study (FEMA, 1989). The data on which both Figures 13 and 14 are based contain errors, especially upstream from Highway 18, because water surface gradients were computed by FEMA using erroneous distances between cross sections. This occurred because stationing of river mile locations shown on the maps was not updated as the river shifted position and changed its length. Despite these errors, major trends in computed shear stress should still be valid.

As shown on Figure 14, flow depth gradually increases downstream to compensate for diminishing gradient and to accommodate discharge increases from tributaries. An increase in flow depth produces a corresponding increase in boundary shear stress. However, a decrease in shear stress caused by the rapid downstream decline in water-surface gradient overwhelms the effect of increasing flow depth. There is a seven-fold downstream decrease in shear stress within the study area, most of which occurs between Reach 6 and Reach 2. Shear stress declines in all reaches except Reach 5. Consequently, sediment-transport capacity also decreases rapidly downstream, which can cause gravels to drop out and instigate channel shifting. Patterns of shear stress thus appear to explain the abundant gravel deposits and rapid channel migration rates in Reaches 2 through 4, as well as the relative stability of Reach 5 and the far downstream end of Reach 2. The downstream decrease in shear stress also accounts for the general downstream decline in sediment size throughout the study reach (Figure 8, Section 3.4.4).

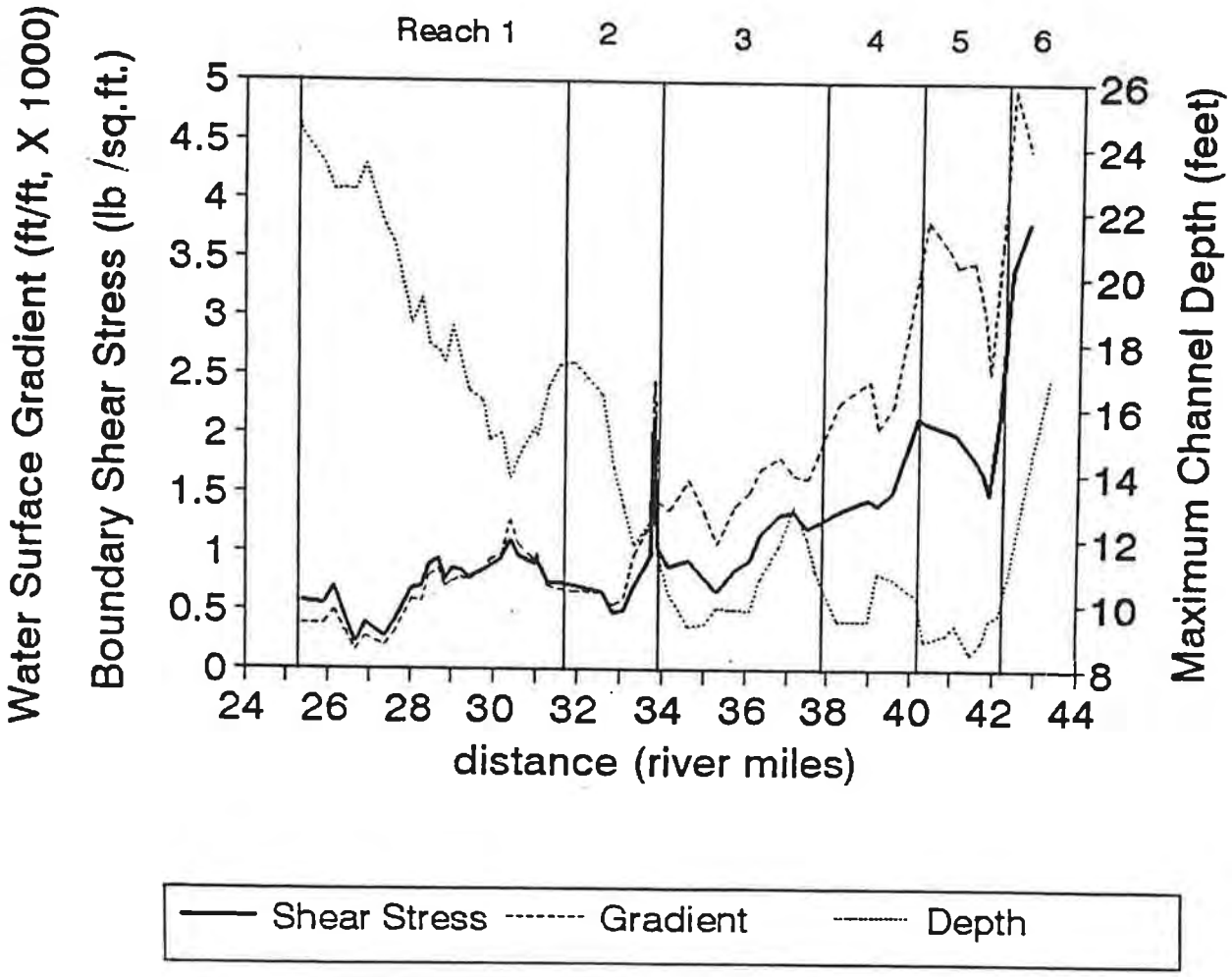
Figure 13
Shear Stress and Rates of Channel Shifting



Notes: Solid line shows shear stress in the deepest part of the channel during a flood of 12,000 cfs at Auburn. Symbols show rates of channel shifting 1898-1973 (solid circles), 1943-1973 (open circles), and 1968-1978 (squares).

From: Dunne & Dietrich, 1978, Figure 11

Figure 14
Shear Stress, Gradient, and Depth



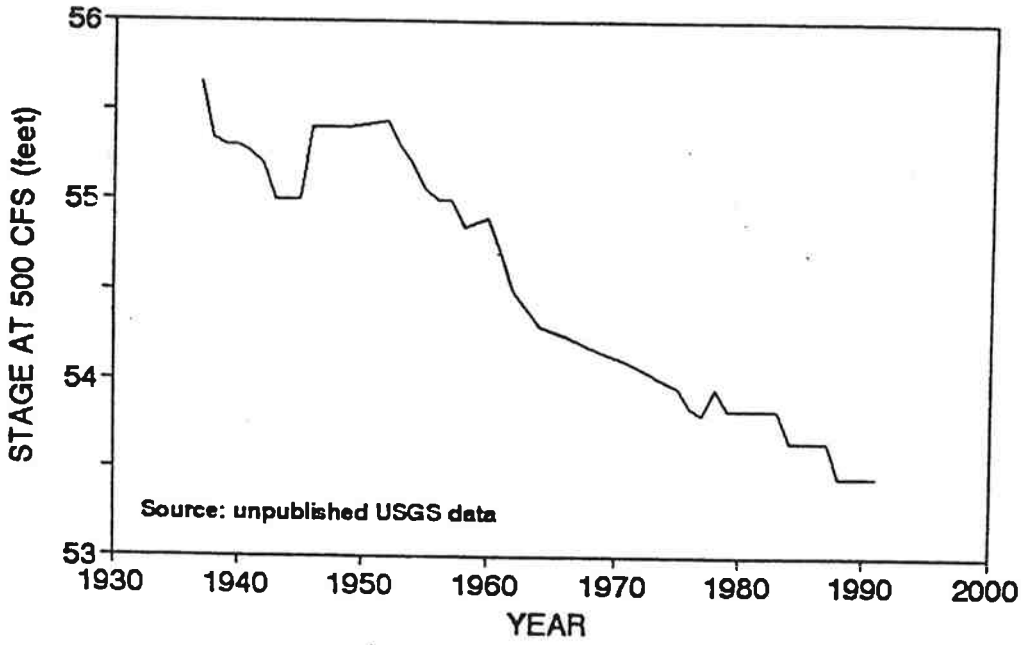
Note: Shear stress, gradient, and depth were computed for the 100-year flood of 12,000 cfs,using water-surface elevations from FEMA (1989).

Shear stress patterns alone do not account for the relative stability of Reaches 1 and 6, which also contain zones of rapidly declining shear stress. In these reaches, although shear stress is declining, it apparently remains high enough that most sediment that enters the reach can be transported through the reach. In addition, large parts of both reaches are locked into position by armored banks or the valley wall, limiting the opportunities for shifting. Rapid channel shifting and sediment deposition has occurred only in an unconstrained, gently-sloping part of Reach 6 in the vicinity of RM 44.2, upstream from the limits of the data used in Figure 14.

Sediment supply to Reach 1 was dramatically reduced by diversion of the White River in 1906. As described in Section 4.2, the reach now has almost no unvegetated gravel bars. Reach 1 was a depositional zone prior to the diversion, as shown by the numerous gravel bars and braided channel downstream from the confluence (see 1906 river channel, Sheet 2). Over thousands of years the White River deposited so much sediment at the confluence with the Green that it built a large fan at Auburn between RM 29 and 32 (Dunne and Dietrich, 1978). The sediment fan increased the slope of the river downstream from the confluence, helping to move the large sediment load downstream (Figure 13). Dunne and Dietrich speculated that erosion of the fan might be occurring because the steep slope remained even though the fan was no longer receiving much sediment. Their hypothesis is supported by two lines of evidence that the river bed has incised where it crosses the fan. Records of river stage at the USGS gage at RM 31.3 show that the river bed has lowered 2.2 feet since 1937 (Figure 15). Additionally, oxidized, compacted sandy gravel that appears to be glacial outwash is exposed in the lower one foot of the right bank of the river at RM 30.1, indicating that downcutting has occurred.

Most post-diversion bank erosion in Reach 1 has occurred downstream of the fan, where gradient and shear stress drop sharply (Figure 14). Very little bank erosion has occurred within the fan, where shear stress and gradient increase or remain steady. The limited instances of bank erosion in the fan are probably caused by downcutting of the channel rather than lateral migration in response to sediment deposition.

Figure 15
Changes in Bed Elevation
Green River near Auburn gage, RM 31



4.4.1.2 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). Sediments exposed in the base of river banks in the study area are similar to those in adjacent bars in the river channel, whose size distributions were measured for this study (Figure 8). As described in Section 3.4.4, most river banks upstream of Reach 1 were composed of sandy gravel. The median sediment diameter of the coarsest gravel bar in Reach 4 was approximately double that of the finest bar in Reach 2. Nanson and Hickin (1986) found that, for sand and gravel rivers in Canada, a ten-fold increase in the median particle size of bank sediment resulted in only a doubling of bank resistance to erosion. If the same relationship holds for the Green River, the effect on bank erosion would be about a 40 percent increase in erodibility of the finer sediments in Reach 2 compared to the coarser sediments in Reach 4, with a general downstream increase in erosion rates. Although this suggests that sediment size may contribute to rapid erosion rates in Reach 2, it clearly does not account for the erosion rates in Reach 4, which are far greater than in Reaches 2 and 3.

Previous studies on rivers that transport fine-grained sediment have shown that bank erosion decreases significantly as the percentage of silt and clay in the river banks increases. Although the toes of some banks in Reach 1contain gravel or cohesive laminated silt, most exposed banks are composed of sand or silt and do not contain enough clay to render them cohesive. Based on the reasoning above, erodibility of the uncohesive, fine-grained banks should be even greater than in Reach 2 upstream, a prediction not in accordance with observed migration rates (Table 6). As discussed above, the low erosion rates in Reach 1 are highly influenced by sediment load and transport capacity, so that bank erodibility is likely to be a factor of secondary importance.

Lowest channel migration rates occur where the river abuts riprap, bedrock or compact glacial deposits. 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 Reach 3 and Reach 6, and may account for a large part of the historic stability of these reaches. However, periods of stability can end abruptly when the river changes course and leaves the valley wall, as occurred on the Tolt River following an avulsion in the 1980s (Shannon & Wilson, 1991). Similar periods of instability could occur in the future on the Green River.

4.4.1.3 Influence of Bank Vegetation on Channel Migration

On low-gradient, high-sinuosity rivers that transport fine-grained sediment, as well as on small stream channels, bank vegetation has been found to significantly affect rates of bank erosion. These rivers differ from gravel-bed rivers such as the Green in having significantly lower erosive stresses on their banks. In my previous study of the Tolt and Raging Rivers (Shannon & Wilson, 1991), I found that naturally-occurring vegetation did not prevent bank erosion in places where flow was concentrated against a bank. Very few roots penetrated deep enough to prevent scour of the lower bank. Upper sections of banks, held together by roots, were commonly cantilevered over the river. The trees and upper bank toppled into the river once scour undermined the bank completely, so that long-term rates of bank erosion were controlled by erosion of the lower bank.

To quote from the Shannon & Wilson report:

> 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.

4.4.2 Causes of Temporal Changes in Migration Rates

Major events that have affected channel migration on the Green River are diversion of the White River, flood control by Howard Hanson Dam, and straightening and armoring of the channel. The effects of the White River diversion on Reach 1 have already been described in Sections 4.2 and 4.4.1.2. Although no data exist on migration rates prior to 1906, early maps and old channel scars show that the river actively migrated across a much wider meander belt than the smaller river of today.

4.4.2.1 Effects of Flood Control

The effects of Howard Hanson Dam on channel migration are less straightforward. The dam reduced flood size dramatically but increased the duration of bedload-transporting flows (Section 3.3, Hydrology). Current operating procedures for the dam result in rapid drawdown of the river following floods, which contributes to geotechnical failures of sandy and silty banks on the lower river (Levesque, 1993). In addition, by trapping sediment, the dam could potentially reduce downstream sediment deposition and consequent bank erosion.

Since 1962, Howard Hanson Dam has trapped sediment from 55 percent of the river's basin above Auburn. Because sediment moves swiftly through the steep Green River Gorge, Reach 6 at the upstream end of the study area may have experienced a reduction in sediment supply within a few years after the river was dammed. Downstream movement of bedload sediment

slows upon reaching the low river gradient of the study area. Direct and indirect measurements of downstream bedload movement range from 600 to 800 feet per year for small basins in the Pacific Northwest (Perkins, 1989) to 3,000 to 4,600 feet per year for the steeper Van Duzen River in California (Kelsey, 1982). Meade et al. (1981) demonstrated that the 1,640 to 2,000 foot distance between sediment storage sites on the East Fork River, Wyoming, corresponded to the mean annual distance of bedload transport . Sediment storage sites (bars) in the Green River study reach are typically 700 to 900 feet apart, suggesting that the downstream rate of bedload movement is probably less than 1,000 feet per year. Therefore, one would expect any effects of reduced sediment supply to be manifest in Reach 6 as early as the 1970s, and in Reach 5 starting in the 1980s or 1990s. If this rough approximation of sediment velocity is correct, reduced sediment supply should not yet have affected the river downstream from Reach 5.

The river's behavior since 1962 is consistent with these postulated changes in sediment supply. In Reach 5 and Reach 6, mid-channel bars have been stabilized by vegetation, braided areas have diminished, the channel has narrowed, active sediment storage sites have decreased in size and number, and bank erosion rates in the 1970s and 1980s are significantly lower than for the pre-dam period. Because most bank protection in these reaches pre-date the dam, these changes should be attributable to the combined effects of reductions in flood size and sediment supply. Reaches 2 through 4, on the other hand, have been affected by flood reduction and bank armoring but presumably not by sediment reduction. The presence of widespread, large active gravel bars indicates that the sediment load delivered to Reach 4 continues to exceed transport capacity. Although active channel width, braidedness, and non-revetted-area migration rates in these reaches all have decreased dramatically compared to the 1950s, a period with numerous large floods, they are not significantly different from earlier in the century (the lone exception is the narrower width of Reach 2, perhaps due to its extensive levees). The average long-term rate of net migration in Reach 4 actually increased after the dam, corresponding to an increase in meander belt width since 1960.

Records from the Green River gage near Auburn show that no floods above 15,000 cfs occurred during the late 1930s and early 1940s, a period with relatively little braiding and few avulsions. Between 1947 and 1960 there were seven floods larger than 15,000 cfs, including the largest flood of record in water year 1960 (Figure 5). These large floods coincided with widespread channel widening, increased numbers of avulsions, a change in pattern from meandering to braided in two reaches, and extremely high rates of channel migration. Although continuous records for the Auburn gage do not go back beyond 1937, intermittent records for the Green River gage near Palmer show that large floods also occurred in 1918 and 1934. Relatively little braiding and a narrow channel in 1936 (compared to 1960) may perhaps reflect a smaller number of large floods prior to 1936 than prior to 1960. Although this must remain speculation in the absence of flood records, periods with few large floods have been shown to result in narrowing of the channel and reduced braiding on other actively-migrating rivers (Shannon & Wilson, 1991; Carson, 1984).

Because Howard Hanson Dam is operated to release a maximum flow of 12,000 cfs, another sequence of large floods capable of producing the high channel migration rates of the 1950s is extremely unlikely. By cutting the size of flood peaks during periods of what otherwise would have been numerous large floods, Howard Hanson Dam has reduced the number of avulsions and the tendency of the river to braid, behaviors associated with the highest channel migration rates during the study period. Records for the unregulated Snoqualmie River basin and other Puget Sound basins suggest that floods between 1985 and 1990 probably would have produced such behavior on the Green River had it not been regulated. During periods with large storms, then, the dam probably reduces channel migration rates significantly. However, study results suggest that in more active reaches of the river, flood control has not reduced channel migration below the historic rates of more quiescent, and probably more representative, periods. In addition, avulsions still occur in reaches with the most propensity for them. These results are consistent with an increased duration of sediment-transporting flows caused by the dam's prolonged releases of floodwater.

4.4.2.2 Effects of Bank Armoring, Levees, and Channel Straightening

In Reaches 1 through 3, extensive construction of levees and revetments in the early 1960s coincided with flood control by the dam, whereas most facilities in Reaches 5 and 6 were built previously. In almost all cases these facilities have prevented bank erosion at the site, as reflected by reduced revetted-area migration rates (Table 7) as opposed to non-revetted area rates (Table 6). The results do not demonstrate any large-scale effect of the 1960s-generation levees on stability of adjacent, unarmored sections of river. For example, Reach 3 (extensive levees) and Reach 4 (almost no bank protection) both experienced a 56 percent decrease in post-dam unarmored-area 1960-to-1992 migration rates compared to 1940-to-1960 rates. However, these results do not rule out localized bank erosion caused by levees or revetments, either immediately downstream on the same bank or further downstream where current is deflected to the opposite bank. Localized bank erosion on a scale of a few tens of feet is difficult to detect using aerial photographs, and even if detected, would not significantly alter the average migration rate calculated for an entire reach.

Although the results show no demonstrable effect on the **amount** of erosion of unprotected banks, levees and revetments influence to some extent the **location** of erosion. For example, after some levees built in the 1960s locally straightened the channel by cutting off bends, other bends developed or enlarged so that overall sinuosity remained the same (Reach 3) or even increased (Reach 2). In the upstream end of Reach 3, the river shifted its meander pattern downstream by a quarter of a wavelength resulting in the same sinuosity and approximately the same area of sediment storage sites as before the levees were built. Levees and revetments tend to freeze bends in place instead of permitting them to migrate downstream. This in turn may prolong and localize erosion of the opposite bank just downstream from the levee. In some locations, levees direct flow against the opposite valley wall, which tends to stabilize the position of the channel but also causes chronic erosion or landsliding of glacial sediments exposed in the valley wall.

In contrast to the 1960s-era levees, earlier river work in Reaches 3 and 5 dramatically reduced the meander belt width of long sections of river, with a stabilizing effect even on unarmored banks. By excavating new channels and blocking off side channels with levees, these projects fundamentally changed the river pattern from braided or meandering to straight. Reach 5 has remained straight and quite stable with relatively little subsequent bank protection, with the exception of the downstream half mile where it makes a transition into Reach 4. In downstream Reach 3, armored levees were built in the 1960s to thwart the river's attempts to resume meandering.

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 within the Green River study area. Based on these predictions, land in the valley floor was classified according to its relative level of hazard from channel migration. The resulting hazard maps are shown on Sheets 4 and 5.

5.1 Methodology for Predicting Limits of Future Channel Migration

The approach used to predict probable limits of future migration is based on a simple premise: that future rates and types of channel migration in each river reach will, on average, be similar to past behavior under the same water and sediment discharge regime. This approach was chosen in preference to models that attempt to predict migration of individual river 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 the prediction methodology are as follows. First, the appropriate historical period to use for prediction was determined, based upon whether hydrologic changes had significantly influenced channel migration. Next, the probable outer limits of future channel migration were determined based on historic meander belt width and measured bend amplitudes for each reach, ignoring existing or potential revetments and levees (Unconstrained Channel

Migration Hazard Map, Sheet 4). Recognizing that features such as major roads and subdivisions will very likely continue to be protected from bank erosion, the natural limits of channel migration were scaled back to produce a Mitigated Channel Migration Hazard Map (Sheet 5). The mitigated hazard area was then subdivided into areas of severe and moderate hazard, using calculated historic channel migration rates. The following sections explain these procedures in more detail.

5.1.1 Determining the Validity of the Historic Meander Belt

The Green River has undergone significant changes in hydrology and sediment supply as well as local changes in channel pattern. Accordingly, before extrapolating past migration behavior to the future we evaluated whether each reach now behaves significantly differently compared to the period prior to these changes. This was done by evaluating each reach for the criteria shown on Table 8. For all reaches, the post-dam period was compared to the pre-dam period (pre-1960). For Reach 1, the periods before and after the 1906 diversion of the White River were also compared. For evaluating channel migration rates, post-dam non-revetted average (Table 6a) and eroding-area (Table 6b) migration rates were compared to 1900-to-1960 and 1900-to-1940 pre-dam rates. The extremely high 1940-to-1960 rates were not used for the comparison, since this period had many unusually large floods with correspondingly higher-than-average channel migration rates. The last two items on Table 8, channel straightening and sediment supply, address the causes of channel migration. Where the amount of sediment deposited in a reach decreases, either due to an increased ability to transport sediment or a reduced sediment supply, a river is less likely to shift across its floodplain.

Where a preponderance of evidence indicated that a reach has not changed significantly in response to historic changes (a "no" answer on Table 8), migration behavior for the entire period of record was used to make predictions. This was the case for Reaches 2 through 4 and the downstream half mile of Reach 5 (Reach 5a). Where a preponderance of evidence suggested that a reach has changed significantly, only more recent migration behavior was used to predict future river migration. This was the case for Reaches 5b and 6 after flood control (1962), and

TABLE 8

CRITERIA USED TO DETERMINE WHETHER HISTORIC MEANDER BELT IS NO LONGER VALID

Reach Number	Has channel stopped shifting course significantly? 1960 to 1973	Has channel stopped shifting course significantly? 1973 to 1992	Is bend amplitude or wavelength lower than pre-1960? (lower than pre-1906?)	Are Channel Migration Rates < 75% of pre-dam Rates? 1960 to 1973	Are Channel Migration Rates < 75% of pre-dam Rates? 1973 to 1992	Are Channel Migration Rates < 75% of pre-dam Rates? 1960 to 1992	Are former channels rarely or never deeply flooded? (avulsions unlikely)	Has straightening of channel increased shear stress and hence reduced sediment deposition?	Has sediment supply been reduced?	Future meander belt expected to be narrower than the historic meander belt.
1a	YES	NO	NO pre-1960 YES pre-1906	YES	NO	NO	NO pre-1960 YES pre-1906	NO	NO 1960 YES 1906	NO 1960 YES 1906
1b	YES	YES	N/A (no new bends)	YES	YES	YES	NO pre-1960 YES pre-1906	NO	NO 1960 YES 1906	YES 1960 YES 1906
2	NO	NO	NO	NO	YES	YES	NO	NO	NO	NO
3	NO	NO	YES	NO	NO	NO	NO	NO except near d/s end	NO	NO
4	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
5a	NO	NO	YES	NO	YES	YES	NO	NO	NO	NO
5b	YES	YES	N/A (no new bends)	YES	YES	YES	YES	YES	possibly since 1980s	YES
6	YES	YES	N/A (no new bends)	YES	YES	YES	NO	NO	probably since 1970s	YES

DEFINITIONS OF SUBREACHES:

Reach 1a is the part of Reach 1 downstream of the White River fan (RM 29).

Reach 1b flows through the White River fan, upstream of RM 29.

Reach 5a is the downstream half mile of Reach 5, a transitional zone into Reach 4.

Reach 5b is all of Reach 5 except the downtream half mile.

for Reach 1 after diversion of the White River (1906). Migration on the part of Reach 1 that flows through the White River fan (Reach 1b) appears to have been further reduced by flood control.

Although channel migration in Reaches 5a, 4, and farther downstream should eventually be affected by reduced sediment supply due to Howard Hanson Dam, estimates of bedload velocity are too imprecise to determine when this will occur (see Section 4.4.2.1). In these reaches, the river is still capable of rapidly shifting large distances and migration hazards were mapped assuming the same behavior will continue in the future. A re-evaluation of migration rates on all reaches of the river should be performed in approximately 20 years, by which time the dam's effects on channel migration rates will be more evident.

5.1.2 Predicting Probable Unconstrained Limits of Channel Migration (Sheet 4)

The historic meander belt widths and bend amplitudes shown in Table 9 were used to predict probable limits of future channel migration **in the absence of revetments and levees.** The resulting channel migration hazard area is shown on Sheet 4. For meander-belt width, we used the maximum valley width occupied by all the mapped channels for the relevant time period (Section 5.1.1). For bend amplitude, we used the median amplitude of bends that grew in each reach during the relevant time period. We assumed that the river could, at any point along its course, grow a new bend of the amplitude specified in Table 9. The migration hazard zone was extended from both edges of the 1992 active channel a distance specified as the greater of either the meander belt width or the bend amplitude. Where this caused the river to reach the valley wall or a high terrace, the hazard zone was extended further in the opposite direction if necessary to achieve the specified meander-belt width. For simplicity, it was assumed that the channel would migrate outward at right angles to the edge of the existing active channel. Although this is not strictly accurate, it produces a hazard band of a reasonable width, and a more detailed treatment would be unrealistic due to the changing geometry of river bends.

TABLE 9

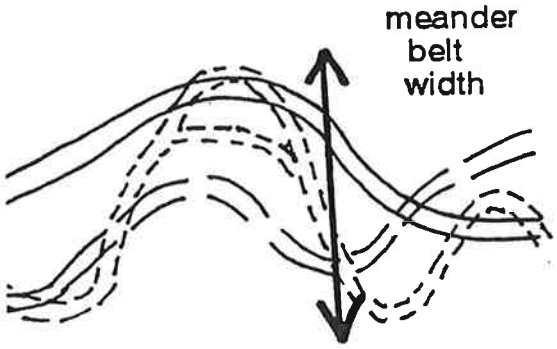
MEANDER BELT WIDTHS AND BEND AMPLITUDES USED TO DEVELOP CHANNEL MIGRATION HAZARD MAPS

	UNCONSTRAINED HAZARD MAP		MITIGATED HAZARD MAP
Reach Number	**Meander Belt Width (ft)***	**Bend Amplitude (ft)****	**Severe Hazard Erosion Width (ft)****
1a	650	300	160
1b	300	100	30
2	1600	800	300
3	1600	700	250
4	2500 (1800 downstream)	1000	560
5a	increases downstream (typically >1000)	400 feet downstream 200 ft upstream	110
5b	400	200 single channel 200 outside of bend 100 double channel	30
6	300	150 single channel 150 outside of bend 100 double channel	85

NOTES

* Minimum total width of meander belt.

** Width is applied in each direction from the edge of the 1992 active channel and avulsion channels.



The river was also assumed to shift into all potential avulsion channels (identified on aerial photographs or maps and confirmed in the field), then migrate laterally the specified distance from these channels as well. Consequently, in the vicinity of avulsion sites the resulting hazard area can be significantly wider than the specified minimum width for the meander belt. In all cases, the resulting hazard area covers the traces of all former river channels from the relevant time period. For Reaches 1a and 6, the hazard area covers older channels as well.

5.1.3 Delineation of Mitigated Hazard Area (Sheet 5)

The unconstrained, natural limits of channel migration shown on Sheet 4 were scaled back to the boundaries of major roads, subdivisions, and levees that are likely be protected from future bank erosion. The resulting migration hazard area is shown on the Mitigated Channel Migration Hazard Map (Sheet 5). The following features were assumed to be fixed boundaries beyond which channel migration will be prevented, listed from upstream to downstream: Southeast Flaming Geyser Road, Southeast Green Valley Road, Neely levee (Reach 3), the Burlington Northern Railroad track (Reach 2), the Highway 18/Auburn-Black Diamond Road bridge complex, left-bank (looking downstream) subdivisions in the City of Auburn, all levees and revetments on the left bank of Reach 1, Green River Road and other major right-bank roads in Reach 1, right-bank levees in the City of Kent, and all bridges. (Refer to Sheet 1 for locations of existing revetments and levees.) Armored banks protect many of these features already, and we assumed that politics will dictate construction of additional revetments to protect these features as necessary. We assumed that existing bank-protection facilities in Reach 1 will remain functional for many years, both due to the relative stability of this reach and its inclusion within the Green River Flood Control Zone District, which funds an active maintenance program.

With the exception of the Neely levee which protects a bridge, we did not consider the numerous levees and revetments upstream from Reach 1 to be permanent barriers to channel migration. The King County Flood Hazard Reduction Plan calls for setting back most levees in Reaches 2, 3 and 4 (Fenster, Pautski, Mueller, Porter, Horath, Kaech, Hamakami, Turley, and Loans

levees). These levees are located within the floodway and constrict flow (King County, 1993, Appendix B). In addition, most of these discontinuous levees are subject to breaching or damage from avulsions or upstream bank erosion (Fenster, Pautski, Porter, Hamakami, Turley, and Loans). Such processes are already occurring to the Hamakami and Loans levees.

5.1.4 Delineation of Severe and Moderate Hazard Areas (Sheet 5)

Obviously the risk of channel migration is not equal within the entire mapped hazard area. The probability of the river moving to a particular site within the hazard zone is greatest for sites near the river or near a former channel that the river is likely to reoccupy. Accordingly, we subdivided the mitigated hazard area into areas of severe and moderate channel migration hazard. To do so, we used historic channel migration rates in a manner similar to that used for migration-hazard mapping on the Tolt and Raging Rivers (Shannon & Wilson, 1991) and the Yakima River (Dunne et al., 1976).

Based on past behavior, the channel pattern of most river reaches will change completely in much less than 100 years. Where not confined by a valley wall or a high terrace, the river can migrate in either direction from its present position. Therefore, instead of selecting areas most likely to erode based on the current river pattern, we applied average historic 1960-1992 eroding-area rates (Table 6b) uniformly throughout the length of each reach. To define a severe-hazard zone, we assumed that during a 100-year period the river would migrate at those rates for 50 years in each direction from its present position. (An identical procedure was used by Shannon & Wilson (1991) to map "high-hazard" zones on the Tolt and Raging Rivers, with the exception that average reach rates that included non-eroding areas were used.) The distance of lateral migration in each direction was calculated by multiplying the average annual migration rate for each reach by 50 years, giving the widths shown in the right-hand column of Table 9. The resulting setbacks from the 1992 active channel and from avulsion channels range from 30 to 560 feet.

For defining the severe-hazard zone, avulsions were assumed to occur only at high-probability sites: creeks and well-defined former channels that are flooded deeply and frequently, are directly connected to the river, and diverge from the main channel in a downstream direction. Due to the scale of the map, Sheet 5 does not show the severe-hazard zone where it is narrower than 100 feet, the standard Sensitive Areas Ordinance buffer from Class 1 streams. This occurs in parts of Reaches 1b, 5b, and 6, where the small computed migration rates are questionable in any case because channel shifts were of the same magnitude as map error.

The moderate hazard area shown on Sheet 5 was defined by default as all land between the outer boundary of the severe hazard area and the outer boundary of the mitigated channel migration hazard area (section 5.1.3).

5.2 Channel Migration Hazard Maps

The Channel Migration Hazard Maps show areas at various levels of risk from channel migration, as predicted by the methodology described in Section 5.1. Sheet 4 shows the probable extent of channel migration if the river were unconstrained by revetments and levees. Sheet 5 shows a mitigated-hazard area, assuming that major roads, bridges, and subdivisions will continue to be protected from bank erosion. The mitigated-hazard area is subdivided into zones of moderate and severe hazard. Table 10 describes potential migration hazards at specific sites marked on Sheet 5.

In Reaches 2 through 4, historically the most active areas, the mapped hazard area comprises most or all of the valley floor including some areas outside the mapped FEMA floodway (FEMA, 1989) or outside the historic meander belt documented in this study. This is consistent with morphological evidence that the river has previously moved across the whole valley floor, such as embayments in the valley walls, the presence of a flat floodplain underlain by alluvial gravels, and recent movement in Reach 4 to a part of the valley floor not occupied by the river for at least a century. In other reaches, the mapped migration-hazard area consists of a relatively narrow belt adjacent to the river, reflecting changes in flood size and other conditions.

TABLE 10

NOTES ON POTENTIAL HAZARDS AT SITES MARKED ON SHEET 5, MITIGATED CHANNEL MIGRATION HAZARD AREA MAP

Site Number on Sheet 5	Location	Description
1	RM 26.8 Horsehead Bend	A cutoff at the neck of this bend is unlikely because 1) Jeff Estates revetment protects the bank from erosion, and 2) land between bends is above 100-year flood elevation.
2	RM 32.0 and 33.0	Neck cutoffs of these 2 bends could cause accelerated bank erosion downstream into Reach 1.
3	RM 36.3 Hamakami Levee	A new bend has destroyed the upstream 300 feet of this levee since 1989 and continues to grow.
4	RM 38.5 Loans Levee right bank	Upstream erosion threatens a residence upstream of the Loans levee. River could avulse into a frequently-flooded channel behind Loans levee.
5	RM 40.6 right bank	If right bank erosion continues, the river could eventually intercept and avulse into the downstream end of Crisp Creek.
6	RM 41.2 Imhoff Revetment and Meyer Dike	Although overbank flooding occurs through a 500-foot long gap between two levees, flow depths are low and an avulsion into former river channels north of the river is judged unlikely.
7	RM 42.8 left bank	A large landslide downstream of Flaming Geyser State Park adds large quantities of fine sediment to the river. The landslide is a very old, natural feature that is reactivated periodically by river undercutting.

Notes:

1. Left bank and right bank references are as seen looking downstream.
2. Refer to Sheet 5 for locations described in this table.
3. Refer to Sheet 1 for revetment names.
4. Refer to the King County Flood Hazard Reduction Plan (King County, 1993) for a discussion of problems and possible solutions at Sites 3 and 4.

The Moderate-Hazard area represents the probable limits of channel migration over a period of approximately a century. Although the outer boundaries were determined based on dimensions of meander features, rather than migration rates extrapolated into the future for 100 years, the former channels that produced those meander features were all occupied by the river within approximately the past 90 years (1898 or 1906 to 1992).

Avulsions are triggered by random, unpredictable events such as log jams, landslides, large floods, and upstream changes in river position, so it is not possible to predict when or if an avulsion will occur at each potential avulsion site. Because we conservatively assumed avulsions would occur at all identified sites, it is probable that some areas within both the Moderate-Hazard and Severe-Hazard areas will not be occupied by the river during the next century. The mapped channel migration limits should therefore 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.

On the other hand, there is a low, but real, possibility that the river could occupy portions of the valley floor beyond the limits of the Moderate-Hazard area shown on Sheet 5. Avulsions could occur in locations that were not anticipated. Additionally, erosion predictions in Reaches 1b, 5b and 6 are based on the 30-year-long post-dam period, which may prove to be too short for accurate extrapolation of long-term river behavior. Accordingly, all unshaded areas of the valley floor, excluding high terraces, should be considered to have a low risk of encroachment by channel migration.

The hazard maps do not show landslide hazards caused by steepening and undercutting of slopes by the river. The valley wall and terraces higher than 20 feet were considered barriers to channel migration. However, where not underlain by competent bedrock (Puget Group; labelled Tp on the geologic map, Sheet 1), these areas could potentially become landslide hazards if and when the river reaches them.

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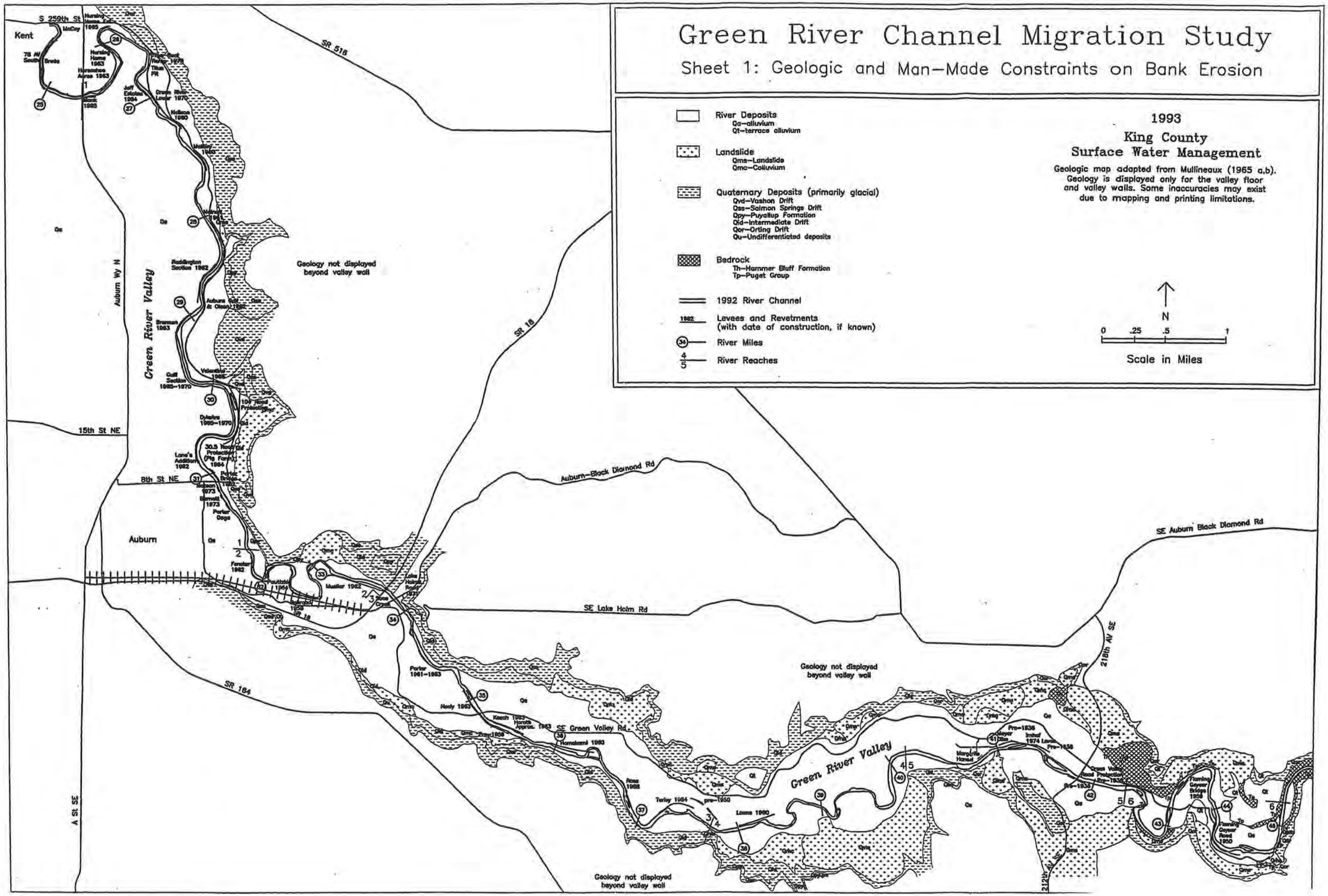
Green River Channel Migration Study

Sheet 1: Geologic and Man-Made Constraints on Bank Erosion



Green River Channel Migration Study

Sheet 2: Pre-1960 River Locations

1898 Channel Location (Upstream from RM 35.3) &
1906 Channel Location (Downstream of RM 35.3)

1936 Channel Location (Upstream of RM 35.3) &
1942 Channel Location (Downstream of RM 35.3)

1960 Channel Location

Channels of Unknown Age

River Miles

River Reaches

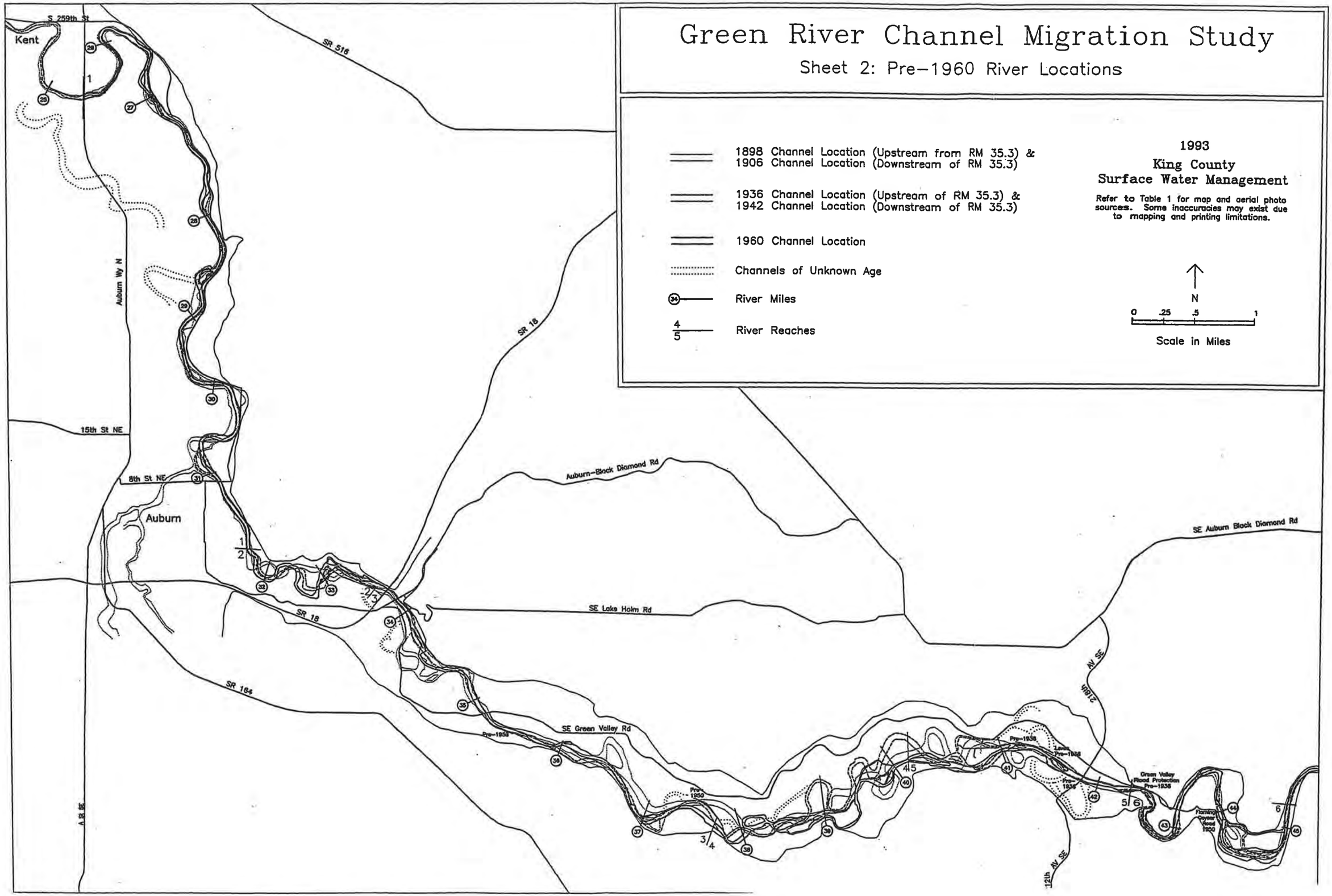
1993
King County
Surface Water Management

Refer to Table 1 for map and aerial photo sources. Some inaccuracies may exist due to mapping and printing limitations.

N

0 .25 .5 1

Scale in Miles



Green River Channel Migration Study

Sheet 3: Post–1960 River Locations

1960 Channel Location

1973 Channel Location

1992 Channel Location

River Miles

River Reaches

Valley Wall

Levees and Revetments

1993

King County

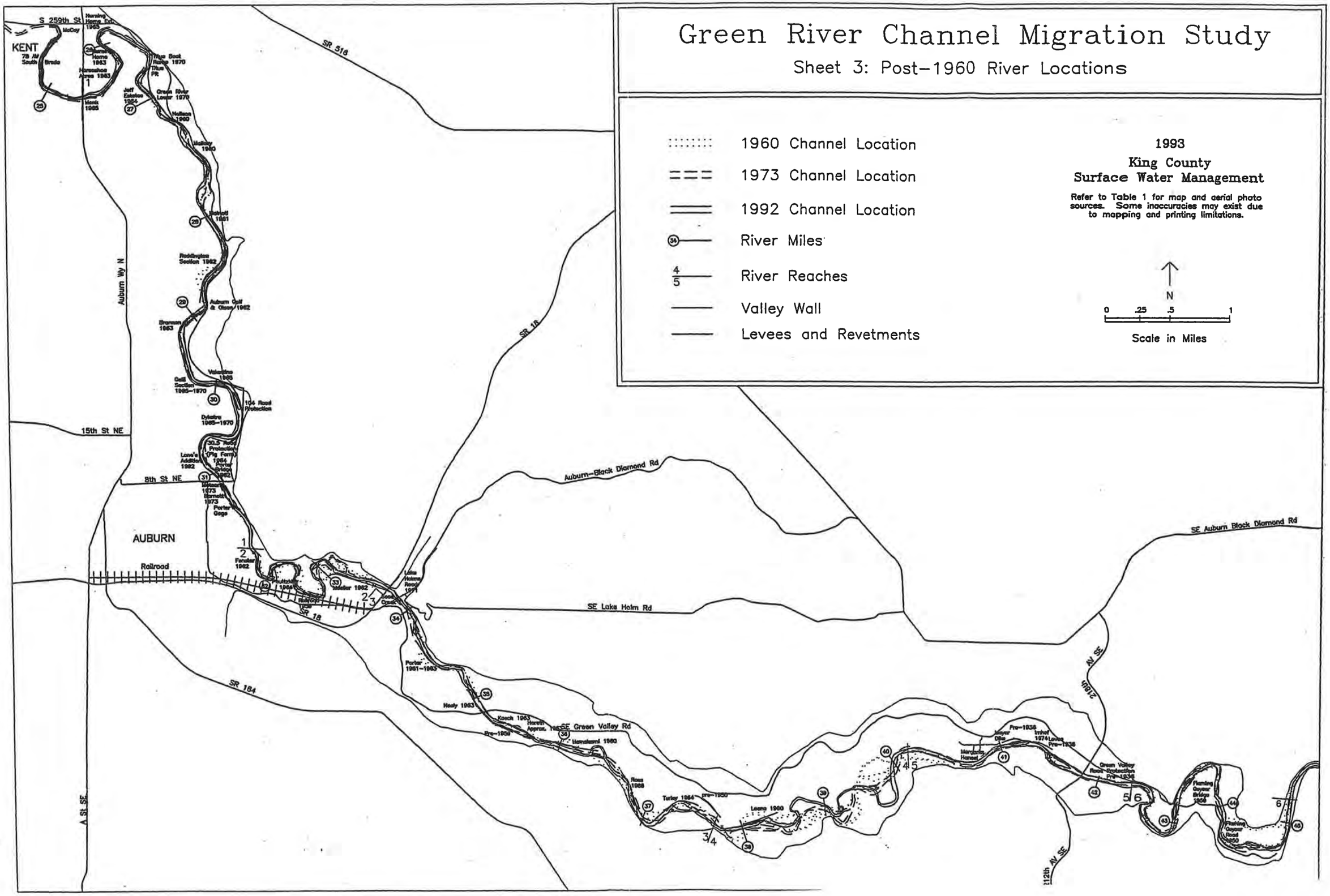
Surface Water Management

Refer to Table 1 for map and aerial photo sources. Some inaccuracies may exist due to mapping and printing limitations.

N

0 .25 .5 1

Scale in Miles



Green River Channel Migration Study

Sheet 4: Unconstrained Channel Migration Hazard Map

Migration Hazard Zone
(if contrained by levees and revetments)

1992 Channel Location

River Miles

River Reaches

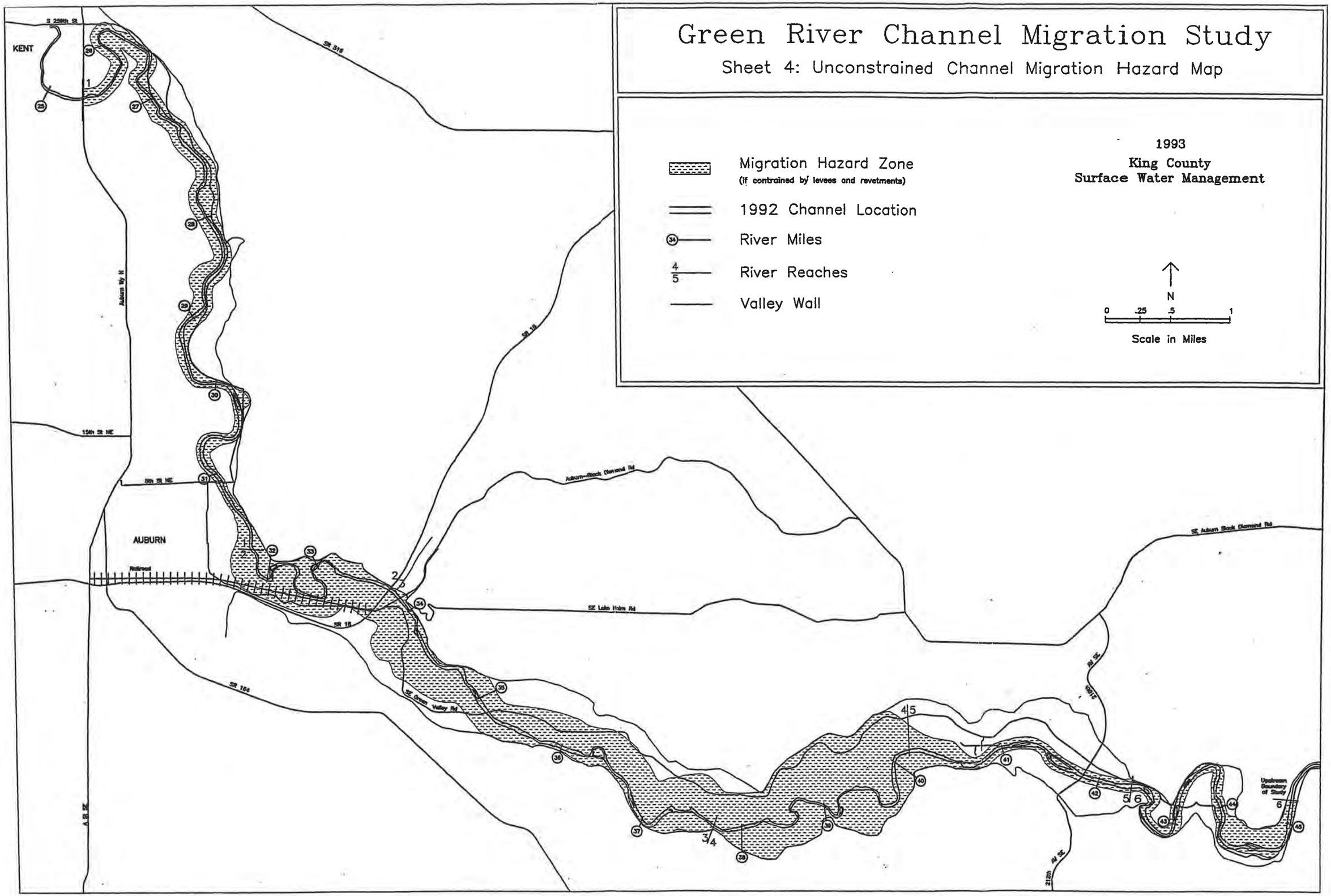
Valley Wall

1993
King County
Surface Water Management

N

0 .25 .5 1

Scale in Miles



GREEN RIVER CHANNEL MIGRATION STUDY

In June 1999, the final map (labeled Sheet 5: Mitigated Channel Migration Hazard Map) of this 1993 channel migration study was 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 Green River. Sheet 5 of the original study has been replaced in this digital file by the adopted Green River Channel Migration Area map, on the following page.

Green River Channel Migration Area Map

Notes:

1. This hazard map was adapted from the Green River Channel Migration Study, dated December 1993. 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 or printing limitations.

Legend

- Potential Hazard Area
- Moderate Hazard Area
- Severe Hazard Area
- Channel Location
- Parcel Boundary
- Levees & Revetments
- River Mile
- Valley Wall
- River Reaches

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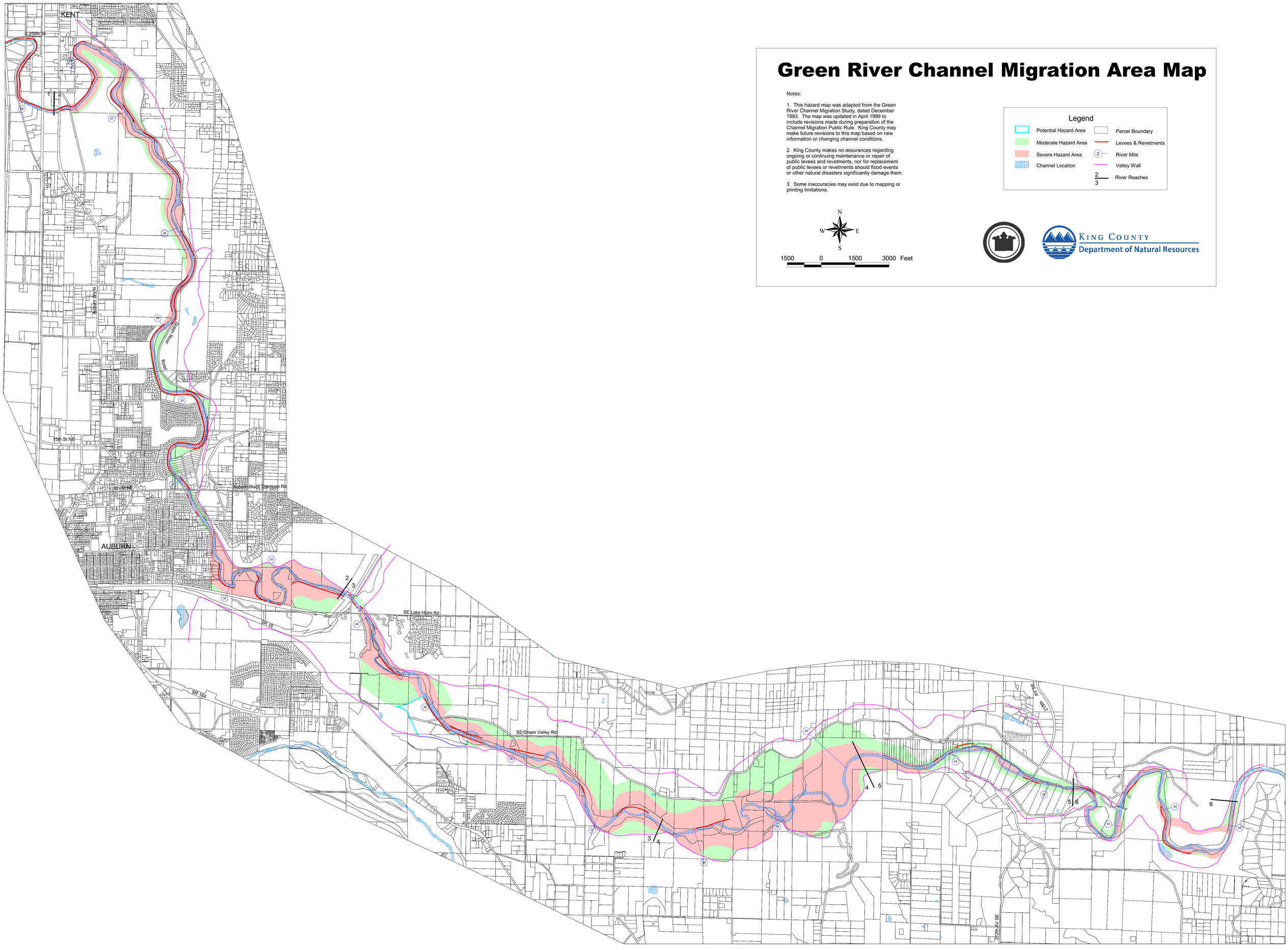
KING COUNTY
Department of Natural Resources