Skagit River Project

FERC No. 553
Report on Existing Conditions of Reservoir and Streambank Erosion

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EXECUTIVE SUMMARY

Erosion associated with the Skagit project (F.E.R.C. no. 553) is occurring primarily along the three reservoirs. Erosion is most severe along valley walls where slopes are steep and glacial and colluvial deposits are thick. Landforms with gentle slopes, such as alluvial fans and floodplains, have few erosion problems. Environmental factors that control the severity and location of erosion along steep slopes include sediment type and stratigraphy, groundwater movement and pool level fluctuations.

Shoreline erosion is most severe along Ross Lake, where 25% of the shoreline is in some stage of retreat. In comparison, 10% of the shoreline on Diablo Lake and 2% on Gorge Lake are eroding. The shores of Diablo and Gorge lakes are more stable because the lakes are located in river canyons where bedrock is the dominant bank material.

Shoreline erosion on steep slopes with thick accumulations of sediment has created slope instability problems at 42 locations accounting for 10% of the total eroding shoreline. In loose sediments such as colluvium and glacial outwash, mass failure occurs by debris slides. In cohesive bank sediments, including lacustrine sediments and till, mass failure occurs by slumping of large blocks of sediment and vegetation. Erosion along the remaining 90% of shoreline is characterized by gradual retreat of banks and small scale debris slides and slumps.

Processes of erosion on the three reservoirs are essentially the same, although measurements of the contribution of each process to total erosion were not made. Wave impact appears to be the dominant cause of erosion. Other active processes include freeze/thaw, surface water erosion, and groundwater piping. Ultimate bank recession is a result of mass movement initiated by wave undercutting of slopes and modification of bank material by groundwater activity and freeze/thaw.

Pool level fluctuations contribute to erosion by seasonally focusing wave energy on different parts of the bank. During pool drawdown and filling material previously eroded is transported downslope, preventing the establishment of beaches or equilibrium shore profiles. As a result wave energy at full pool is dissipated directly on bluffs.

Banks on Ross Lake have receded as much as 133 ft. above full pool over the life of the reservoir. Bank recession rates estimated by two methods vary for individual stretches of shore and vary with time. Measurements of bank recession rates range from 0.2 ft./year to over 5.5 ft./year. These rates are within the range of those reported for other reservoirs. Assuming an average recession rate of 1 ft./year for all eroding shorelines on Ross Lake, approximately 1.7 acres per year are lost to erosion along the entire 60 miles of shoreline. Similar rates of recession were measured on Diablo and Gorge lakes.

Erosion of areas below full pool on Ross Lake has removed as much as 10 ft. of sediment from below stumps along steep slopes. In most areas erosion has completely removed erodible sediment leaving behind a lag deposit of coarse gravel and cobbles. The lag deposits protect the bank from further recession, but are prone to downslope movement as the reservoir level falls.

The effects of the project on the Skagit River between Newhalem and Bacon Creek were more difficult to identify than along the reservoirs. In general, the dams have reduced extremes in discharge and virtually eliminated sediment supply from the upper portion of the valley. The elimination of large floods on the river below Newhalem has stabilized the position of the river on the floodplain. Only minor modification of in-stream bars and islands is evident since 1956. The primary affect of increased stability has been to decrease the movement of sediment from the river banks into the river. Changes in channel shape and elevation of the bed of the river have been minor since project construction. Degradation of the river bed by 0.6 ft. between 1943 and 1950 at the Alma Creek gauging station is related to closure of Ross Dam. A large 1967 flood, however, caused aggradation of the bed at the same site to within 0.2 ft. of its pre-Ross level. Stable bed elevations at a gauging station farther upstream may be due to armoring of the bed with coarse clasts. Changes in bed material size and sediment movement were not addressed.

Erosion along roads and powerlines is not a significant problem. Minor problems were identified at 16 sites where the drainage of small streams around and under the road system created erosion of the roads themselves and where small amounts loose sediment failed off of the top of roadcuts.

Deposition of sediment behind the dams has increased drastically as a result of reservoir inundation. All major tributaries have deposited large deltas at their junction with the reservoirs. The largest of these deltas are associated with streams draining glaciers, including Little Beaver, Big Beaver and Thunder creeks. The delta at the mouth of Big Beaver Creek is at least 20 ft. thick. Estimating the length of time before the reservoirs fill with sediment was beyond the scope of this study.

I Introduction

Seattle City Light's hydroelectric project on the Skagit River is located in the North Cascade Range of northwestern Washington. The area examined in this study extends from the Canadian border through three reservoirs to the confluence of the free-flowing Skagit River with Bacon Creek (Figure 1). The project includes three dams (Ross, Diablo and Gorge) constructed between 1927 and 1961, with a total generation capacity of 739 megawatts and a total flood storage capacity of 1.5 million acre-feet (Table 1). Ross, Diablo and Gorge dams flood 12,400 acres of the Skagit River Basin, including additional land in British Columbia. In addition to the dams, the project includes three powerhouses, transmission lines, roads, sand and gravel pits and two communities (Figures 1 and 2). Seattle City Light's developments lie within the Ross Lake National Recreation Area (N.R.A.), which is part of the North Cascades National Park Complex. The land

TABLE 1. FEATURES OF SEATTLE CITY LIGHT'S SKAGIT HYDROELECTRIC PROJECT.

	DAM		
	ROSS	DIABLO	MODERN GORGE*
YEAR BUILT	1937-49	1927-30	1950-61
HEIGHT (FEET)	540	389	300
RESERVOIR LENGTH (MILES)	24	4.5	4.5
STORAGE CAPACITY (ACRE FEET)	1,435,000	50,000	8,500
GENERATOR CAPACITY	400MW	169MW	170MW
SHORELINE LENGTH (MILES)	54.6	14.6	8.8

* A wood dam completed in 1925 was replaced by a concrete structure completed in 1961

surrounding the project is primarily designated wilderness where recreational uses such as fishing, camping, rafting and hiking dominate. Downstream from the Ross Lake N.R.A. the Skagit River has been designated a Wild and Scenic River.

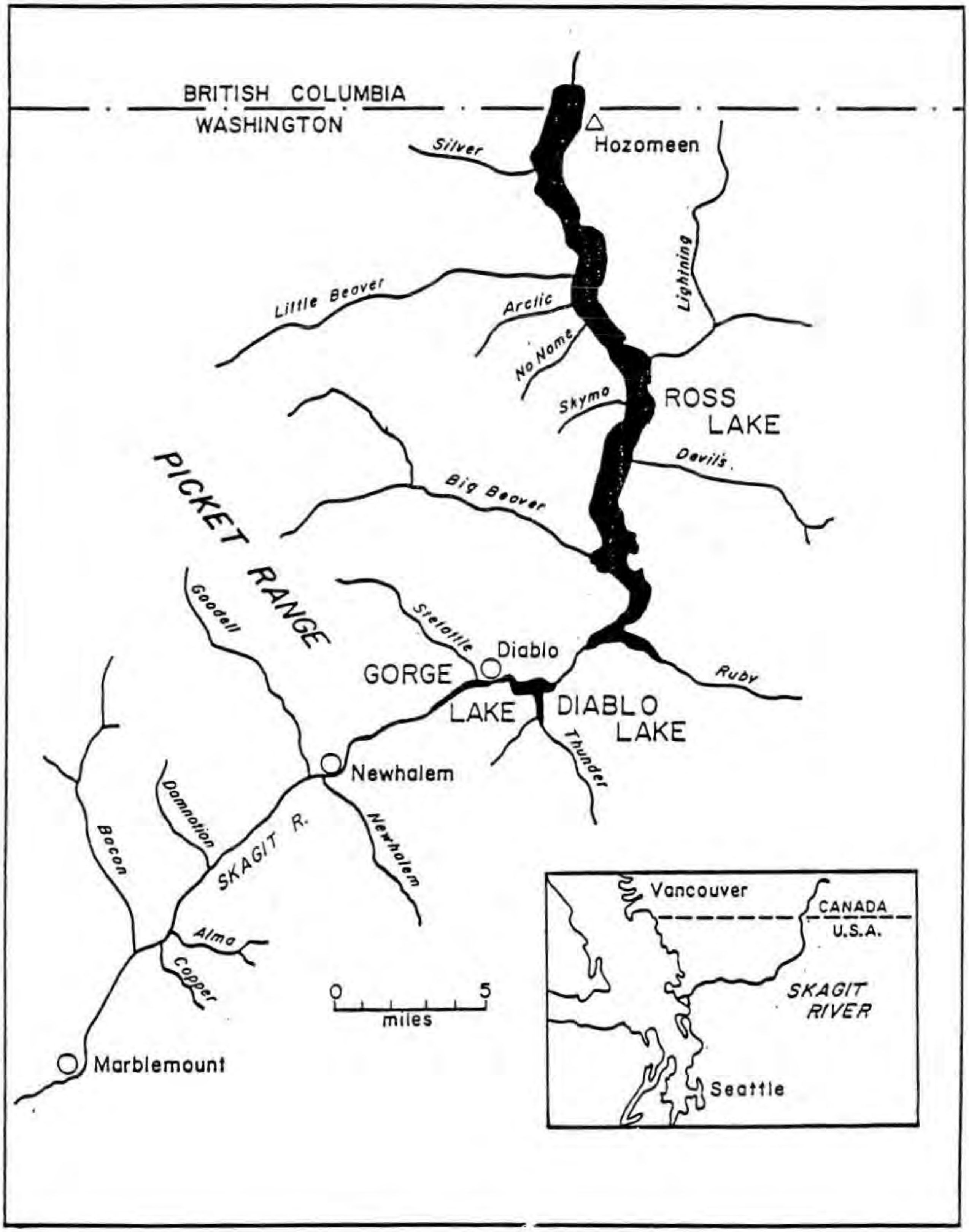

FIGURE 1. UPPER SKAGIT RIVER BASIN.

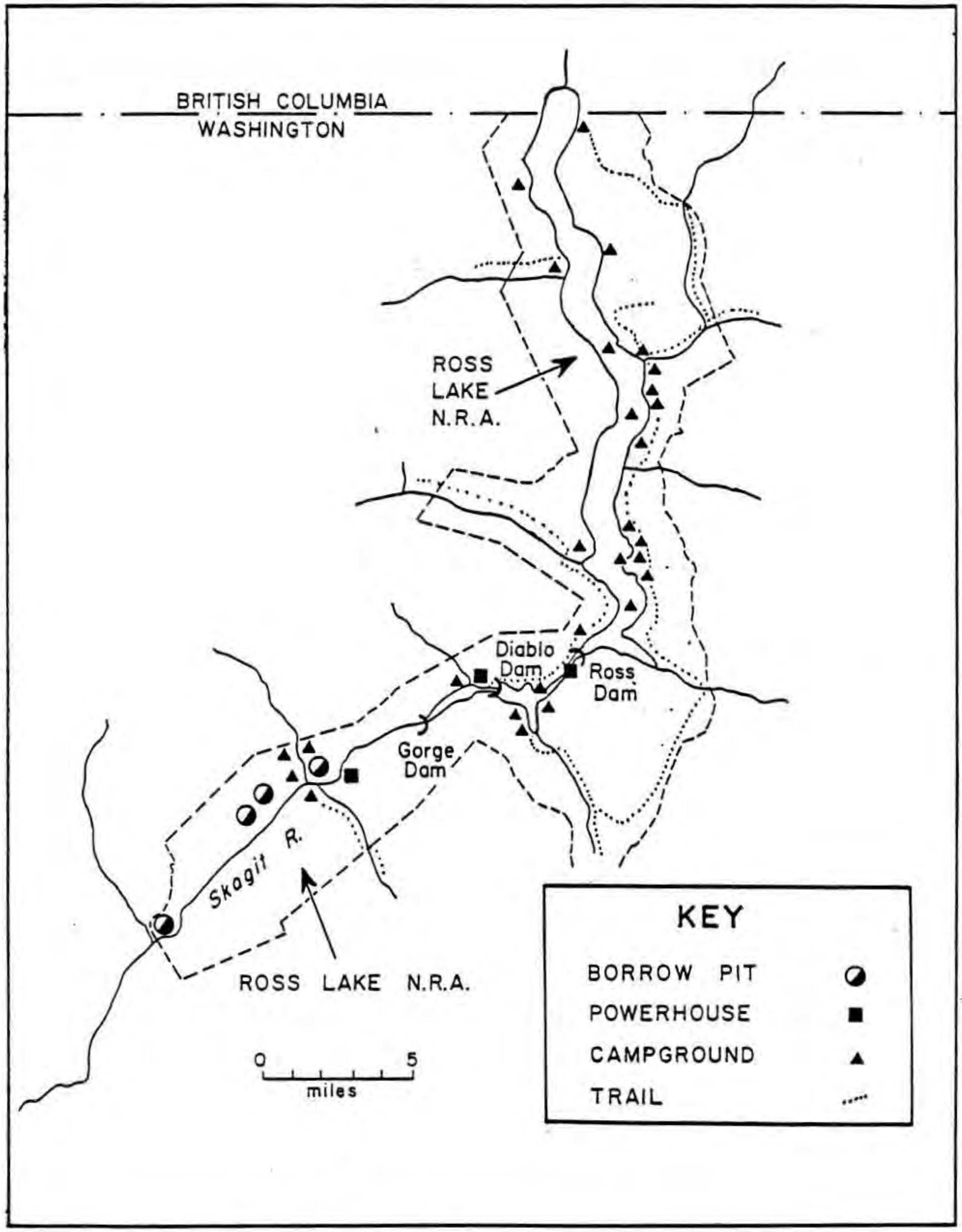

FIGURE 2. PROJECT AND STUDY AREA DEVELOPMENTS.

The objective of this study is to examine the impacts of the Skagit Hydroelectric project on sediment erosion, transport and deposition. The area of interest includes all land below a level 290 feet above the full pool elevation of the three reservoirs and below a level 98 feet above the Skagit River below Gorge Dam.

Post-construction impacts of the Skagit Hydroelectric project on sediment erosion, transport, and deposition result from the formation of the reservoirs. Reservoirs trap sediment otherwise transported along the river system, resulting in the accumulation of sediment in the reservoirs. Water released from the powerhouses, therefore, is essentially sediment-free and potentially very erosive. Below dams large flood flows that move sediment down the river are restricted by reservoir flood-water storage. As a result of changes in sediment supply and peak discharge, river channel shape and position may change. In addition to altering river processes and sedimentation, reservoir formation radically alters slope processes along the reservoirs. Slopes adjusted to subaerial conditions are flooded and vegetation removed, resulting in additional reservoir sedimentation and bank recession.

Reservoir shoreline erosion affects aesthetic, cultural, and ecological resources. It alters the aesthetic quality of an area by exposing roots, killing trees, and scarring the landscape with slope failures. Cultural resources such as trails, docks, campgrounds, and archeological sites are threatened by bank recession and sedimentation. Bank recession also causes loss of habitat. Sedimentation caused by erosion can effect water quality (turbidity, nutrient loading, and temperature) and biological activity (primary production, species composition, reproduction, and feeding). The loss of sediment delivery to the river environment below the dams may also effect biological activity - particularly by reducing the amount of suitable spawning gravel.

This study focuses on the problem of shoreline erosion along the margins of Ross, Gorge, and Diablo lakes, but considers erosion below the full pool elevation of Ross Lake, erosion associated with transmission line corridors and the deposition of sediment within the reservoirs. The effect of the project on the river environment downstream from Gorge Dam is also examined, although changes associated with the project are difficult to identify because of the dynamic nature of the river environment. The initial objective was to collect background information on landforms and surficial geology. This information was then used to describe the study area and assess the effect of the project on sediment erosion, transportation and deposition.

II GEOLOGIC SETTING

The project is located in the North Cascade Range, which has been uplifted higher and has fewer volcanic rocks than the Southern and Central Cascades (Tabor, Haugerud, and Miller, 1989). Relief within the study area is locally as much as 7900 ft. because of rapid uplift of the range and deep dissection by glaciers and major streams.

A. Bedrock Geology

The bedrock geology of the North Cascades is complex because of the range's location along the tectonically active western edge of the North American lithospheric plate. The area's geologic history has been punctuated by the accretion, metamorphism, and movement of exotic terranes and the intrusion of igneous and associated extrusive rocks. Tabor et al.(1989) summarize the geologic history of the North Cascades in terms of four major events:

(1) Accretion of terranes to the North American continent with a northwest-southeast orientation during the pre-to-late Cretaceous Period between approximately 150 and 70 million years before present (YBP);
(2) Uplift and mountain building in the late Mesozoic to Eocene deformed and metamorphosed the rocks of the terranes;
(3) Crustal extension during the Eocene Epoch (57 to 36 million YBP) created faults that broke the terranes and may have displaced parts of some terranes hundreds of kilometers; and
(4) The intrusion of magmatic bodies and the emplacement of their associated extrusive rocks. This began during the Oligocene Epoch (35 million YBP) and continued into the Holocene (present) Epoch.

Rock types and geologic structures of the study area reflect the active geologic history of the North Cascades as a whole. The metamorphosed rocks of the Hozameen, Little Jack, Methow, and Chelan Mountain terranes dominate the geology of the Ross Lake N.R.A.(Figure 3). Rocks of these terranes include: from the Chelan Mountains terrane, the Cascade River Schist, the Skymo unit, and the Napeequa unit; from the Methow terrane, sandstone, argillite, and conglomerate; from the Little Jack terrane, the Elijah Ridge Schist, Jack Mountain Phyllite, and North Ridge Volcanics; and from the Hozameen Terrane, Hozameen Chert (Figure 4). The most extensive rock type in the study area is the Skagit Gneiss of Misch (1966), which was formed during the late Mesozoic to early Cenozoic orogeny (Figure 4). Rocks altered and emplaced during Eocene faulting are rare in the study area, but include the Ruby Heterogenous Plutonic Belt (Figure 4). Also exposed in the study area are rocks associated with the more

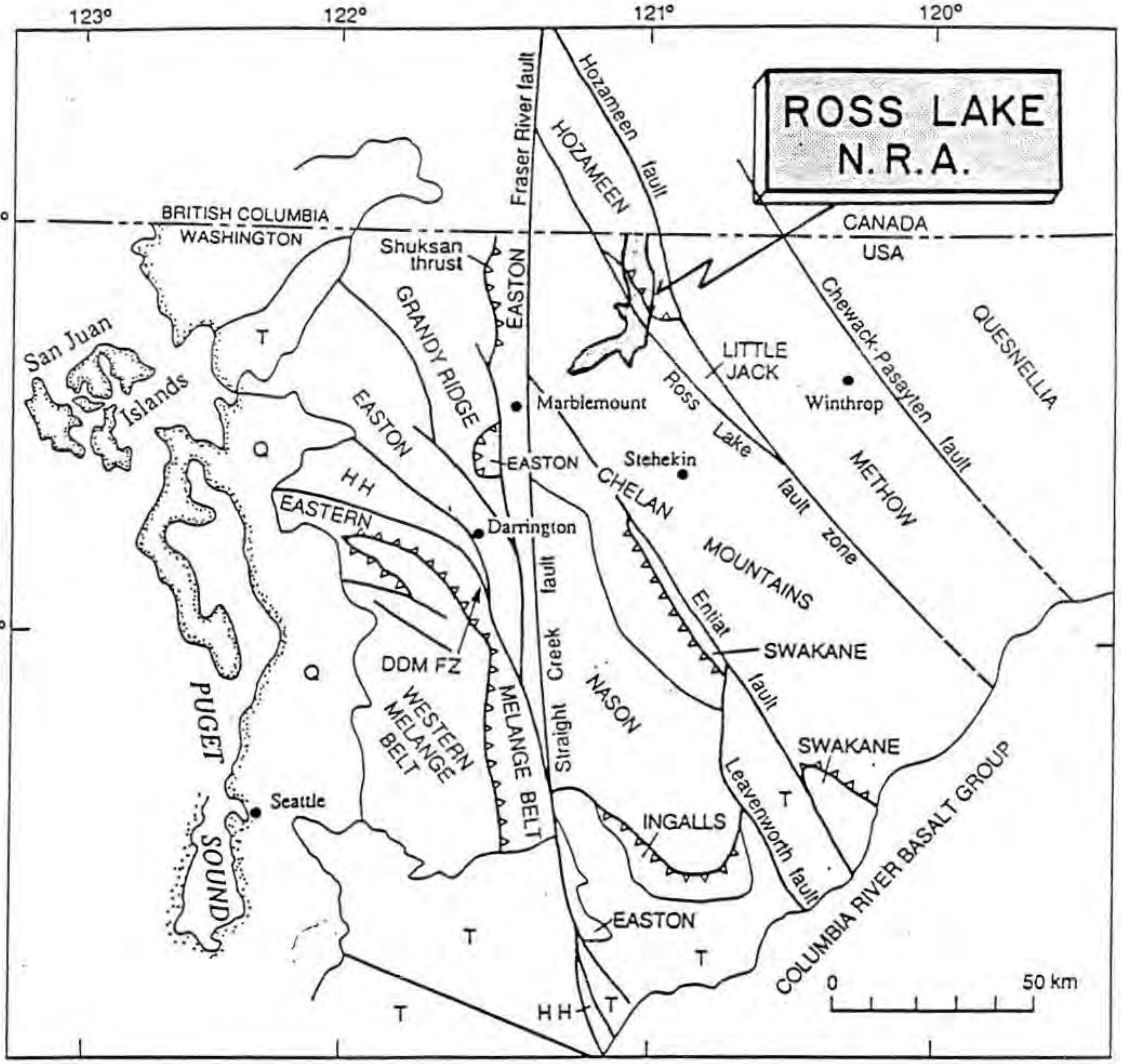

FIGURE 3. ACCRETED TERRANES OF THE NORTH CASCADES. MODIFIED FROM TABOR, HAUGERUD, MILLER, BROWN AND BABCOCK, 1989.

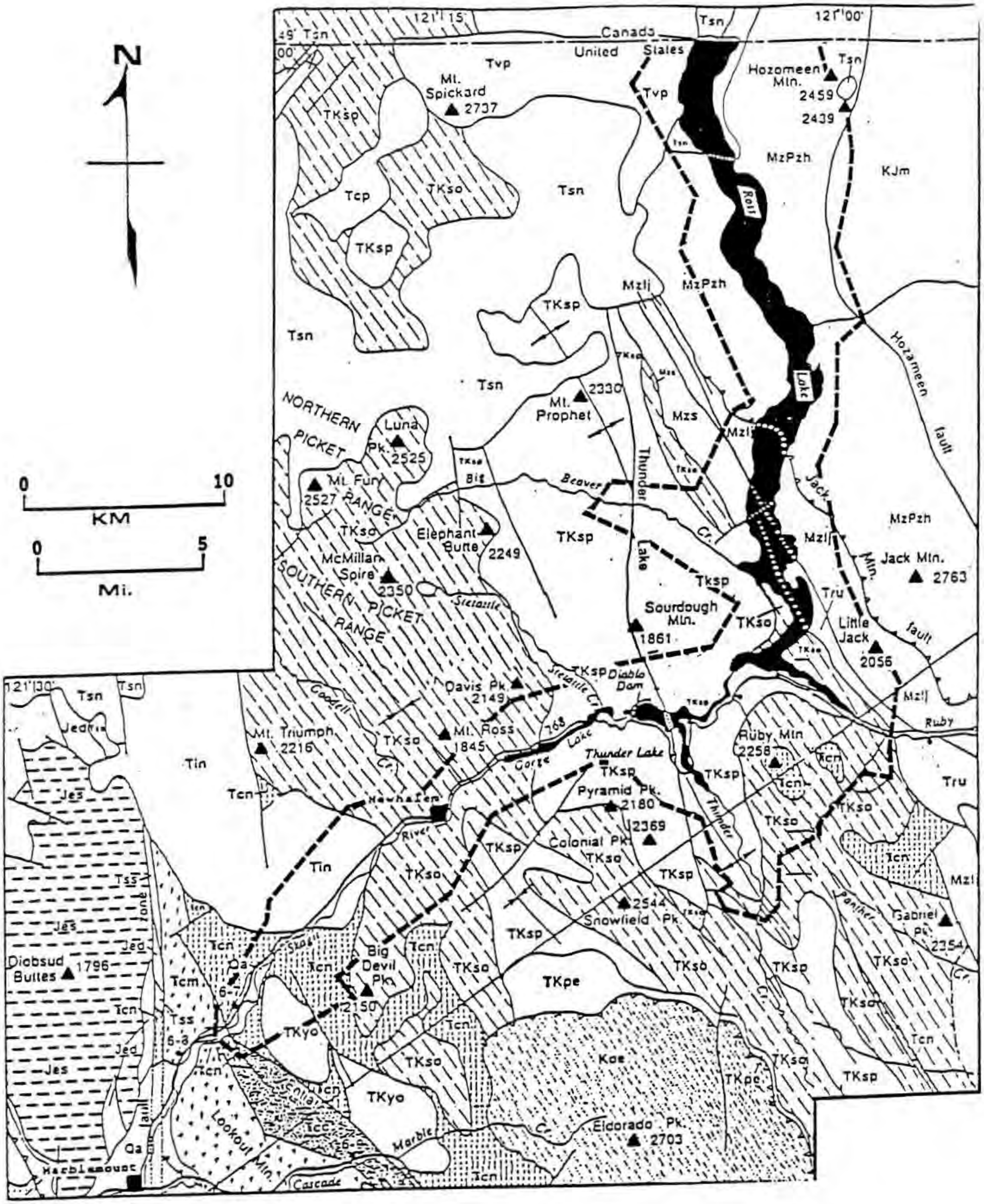

FIGURE 4. BEDROCK GEOLOGY OF ROSS LAKE NATIONAL RECREATION AREA AND VICINITY. SEE FACING PAGE FOR EXPLANATION. MODIFIED FROM TABOR, HAUGERUD, MILLER, BROWN AND BABCOCK, 1989.

recent (Oligocene) emplacement of a igneous rocks into the range. These include rocks of the Chilliwack composite batholith (Misch,1966), and the Paleogene Skagit Volcanic Formation (Staatz, Tabor, Weis, Robertson, van Noy, and Pattee, 1972) (Figure 4).

The terranes are separated along deep, steeply dipping faults associated with Eocene crustal extension (Tabor et al., 1989). Most of the faults that were active during placement of the terranes, however, are no longer active. Movement along the Straight Creek Fault (Figure 3), for example, is inhibited by the Chilliwack Composite Batholith. In addition to the Straight Creek Fault, several other faults have been identified. These include the Entiat, Thunder Lake, Hozameen, and Ross Lake Fault Zones (Figure 3).

The area is still tectonically active, as illustrated by a magnitude 7-7.5 (Richter scale) earthquake in 1872 (WPPS, 1974) and a 4-5 magnitude event in 1915 (University of Washington Seismograph Station, personal communication, 1989). Both events appear to have been centered south of Ross Lake. Since that time, scattered events of small magnitude (2-3 on the Richter scale) have been the norm for the area (U. W. Seismograph Station, 1989).

B. Surficial Geology and Geomorphology

1. Quaternary Landscape Development

Glaciers and rivers have deeply incised and shaped the North Cascades during its geologically recent uplift. Although several phases of glacial and riverine erosion have occurred during the Pleistocene Epoch (2 million to 10,000 YBP), only events of the most recent ice age and subsequent warm period are well understood (25,000 YBP to present). It is these events of the last 25,000 years that have shaped the modern surficial geology and geomorphology of the study area.

In the Pacific Northwest the most recent period of extensive glacial cover is termed the Fraser Glaciation. The Fraser is divided into several geologic-climatic units based on varying intensities and areal extent of glacial cover. The Fraser glaciation began with the growth and advance of alpine glaciers at the heads of valleys, along divides, and within cirques in the North Cascades between 25,000 and 17,000 YBP (Figure 5). Glacial cover reached a maximum around 15,000 YBP, during inundation of the range by an ice sheet with a source area in British Columbia (Clague, 1981; Waitt and Thorson, 1983) (Figure 6). Evidence gathered in the Chilliwack Valley on the north edge of the North Cascades (Luternauer and Clague, 1983) and in the southern North Cascades (Porter, Pierce and Hamilton 1983) indicates that alpine glaciers advanced again around 12,000-11,000 YBP, following

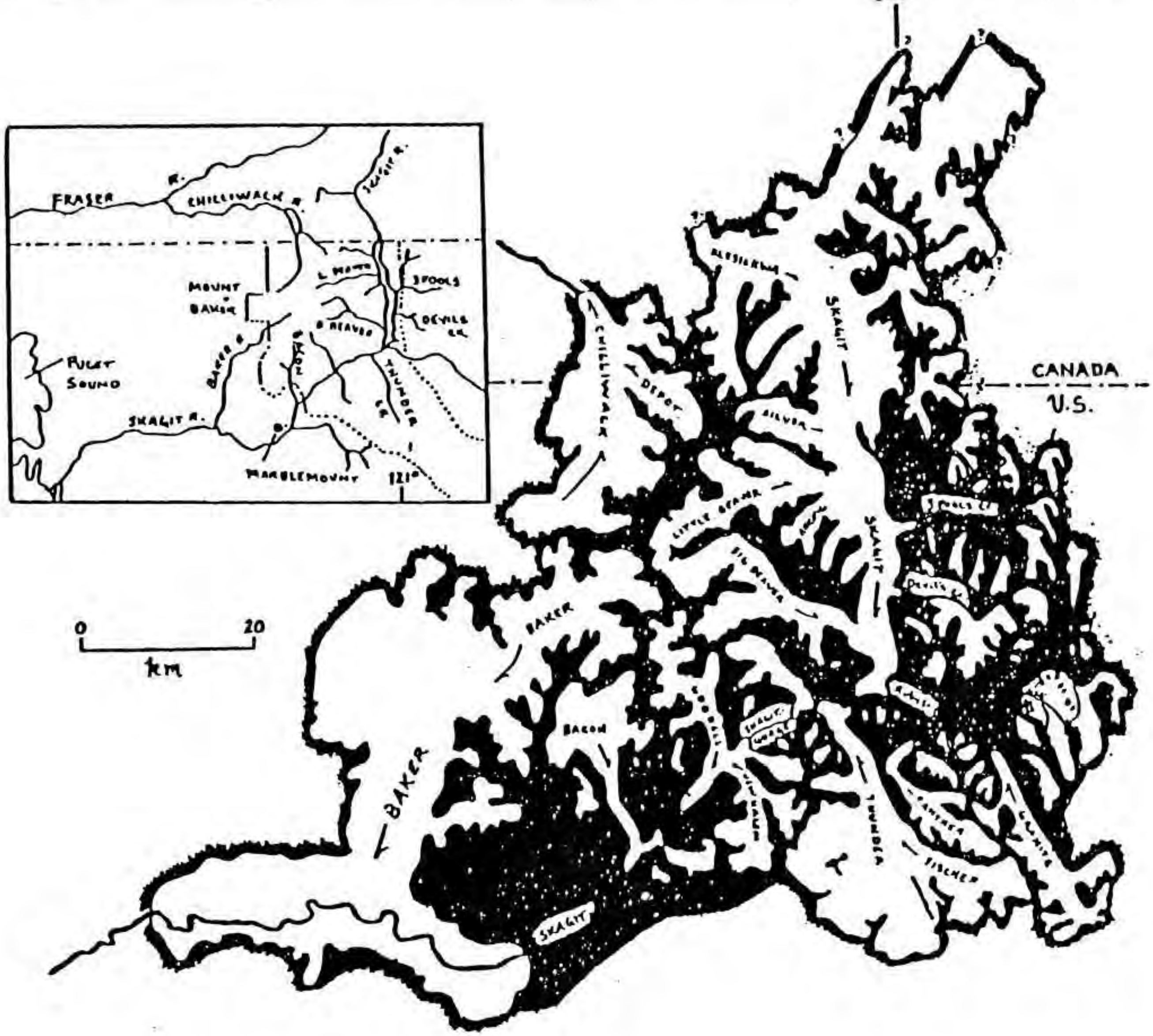

FIGURE 5. AREAL EXTENT OF ALPINE GLACIERS IN THE NORTH CASCADES.
MODIFIED FROM WAITT, 1977 AND HELLER, 1980.

deposition adjusted by mass movements (Heller, 1980; Mierendorf, Riedel, and Luxenberg, 1988). Below Newhalem it appears the Skagit River cut into glacial-age deposits some 100 ft. during the Holocene (Riedel, 1989a). Mierendorf (1986) and Riedel (1989a) discovered evidence that indicates the Skagit River rapidly cut into its valley fill following deglaciation, and built terraces (i.e. aggrading) on its floodplain over approximately the last 6,000 years.

Small glaciers remain active at the heads of valleys in the Skagit Basin. Several times over the past 10,000 years they have advanced and retreated a few miles downvalley (Miller, 1969; Burbank, 1981; and Riedel, 1987, among others). They remain an important factor in the region's hydrology and landscape evolution as they store vast quantities of water and deliver sediment to the valleys below.

2. Landforms

A landform map of the study area (Map 1) was constructed to aid in the analysis of shoreline erosion. Landforms mapped and their general descriptions are given in Table 2. The Ross Lake Basin portion of the map was completed in the early spring of 1988 (Mierendorf et al., 1988) and was extended down to Bacon Creek for this study. The map was constructed using the 1:24,000 scale topographic map as a base, and relied on initial air-photo interpretations which were then checked with extensive field investigations. Areas below reservoir pool elevations on Ross, Diablo, and Gorge lakes were interpreted primarily on the basis of contours, although the 112 ft. drawdown on Ross Lake allowed field checking of some landforms below its full pool elevation. The map was reduced to 1:50,000 scale to include the entire study area on one sheet. Field notes and the larger scale maps are on file at the National Park Service office in Marblemount, Washington.

Alpine glaciers have had the greatest influence on landforms in the Skagit Valley, which alternates between intensively glaciated (U-shaped) and primarily unglaciated (V-shaped) segments. Above Ross Dam the Skagit Valley is a glaciated valley, while between the town of Newhalem and Ross Dam it is primarily a river valley (with the exception of the town of Diablo and Colonial Creek areas) (Map 1). Below the town of Newhalem, glaciers that moved down Goodell and Newhalem Creeks eroded and opened the Skagit Valley, while downstream from Damnation Creek to Bacon Creek (Figure 1) the valley narrows again.

Landforms attributed to glaciation include glacially scoured valley spurs, ridges of streamlined glacial drift, kame terraces, kettle lakes, and small meltwater channels (Map 1). With the exception of glacially scoured bedrock, these landforms were mapped as one unit because of their relatively rare occurrence

(Map 1). Valley walls were distinguished and mapped separately from river canyons in intensely glaciated sections of the study area. Thick accumulations of glacial deposits on steep valley walls have been eroded into alternating gullies and ridges by streams and slope processes. In the narrow reaches of the Skagit

TABLE 2. LANDFORMS MAPPED.

FP	=	Floodplain, including low terraces inundated by flood water.
MM	=	Mass Movements, including debris slides and flows and other mass movements not deposited on a fan or debris cone.
VW	=	Valley Wall, including bedrock, colluvium, talus and glacial till.
AF	=	Alluvial Fan and debris cones. Smaller steep drainages form debris cones that are classified as alluvial fans.
GS	=	Glacially Scoured, flat bedrock benches.
T	=	Alluvial Terraces that sit above the floodplain. Primarily composed of outwash, but also of recent alluvium.
RC	=	River Canyon. Steep, winding, narrow, bedrock-walled river courses.

*** NOTE: LANDFORMS BELOW LOWEST 1989 RESERVOIR LEVEL ON ROSS, DIABLO AND GORGE LAKES MAPPED ON THE BASIS OF PRE-RESERVOIR PHOTOS AND TOPOGRAPHY WHERE AVAILABLE.

Valley, steep bedrock-walled canyons are broken only by occasional talus slopes and debris cones. Floodplains are generally absent or poorly developed on the floors of these canyons (Map 1).

Major tributaries entering the Skagit Valley in the Ross Lake Basin from the drier east side have long, well developed river canyons at their lower ends (eg. Lightning, Devil's, and Ruby Creeks), while those entering from the wetter west typically enter the Skagit Valley as hanging valleys (e.g. Arctic, Big Beaver, Stetattle, and Goodell creeks) (Map 1). Little Beaver, No Name, Thunder, and Newhalem creeks have short river canyons at their junctions with the Skagit Valley.

All of these tributaries have deposited large alluvial fans on the Skagit River floodplain (Map 1). Ryder (1971) related the formation of tributary fans in South-Central British Columbia to the erosion of sediment from tributary valleys following deglaciation of the trunk valley. This appears to be the case for the Lightning Creek fan, which has a large kettle hole on its northern end (Map 1) that formed when an ice mass, buried during deposition of the fan, melted. Some of the larger tributaries (e.g. Lightning Cr., Little Beaver Cr., etc.) have incised into their fans, while smaller ones (e.g. Arctic Cr., No Name Cr., etc.) are still actively migrating and building their fan surfaces. This disparity between fan abandonment (incision) and activity may be related to basin size (Ryder, 1971). The edges of these alluvial fans have all been modified by the Skagit River as it migrated across its floodplain.

Smaller tributary streams typically have much steeper gradients. Several of these creeks have periodically deposited large quantities of material on debris cones in response to heavy winter rains (e.g. Sourdough and Rhode creeks). Because of the difficulty in differentiating between debris cones and small alluvial fans on air-photos and the large number of these features, debris cones were mapped as alluvial fans (Map 1).

Alluvial terraces are found primarily along wider, more intensely glaciated parts of the valley (Map 1) where floodplains have developed. Those deposited higher on the valley wall are composed primarily of coarse outwash from glacial meltwater streams. Terraces closer to the floodplain are much younger, are composed of finer alluvium, and were mapped as floodplain because they were formed, in part, during historic floods (Riedel, 1989b) (Map 1).

The Skagit River has a well developed floodplain above Ross Dam and below the town of Newhalem (Map 1). The floodplain is a relatively flat landform, where the Skagit River meanders between valley walls and alluvial fans; it has not developed in the river canyon sections of the valley.

Several large mass movement deposits were identified during landform mapping (Mierendorf et al., 1988). The landslides emanate from escarpments along valley walls or are channeled down small stream courses. The landslide deposits are characterized by hummocky topography and may have an overall lobate form. All four of the landslides identified on Ross Lake (Map 1) appear to be ancient, inactive features, although no direct evidence dates the timing of their formation. Erosion, weathering, and stability on the surfaces of these landforms, however, attests to their old age and inactivity. They probably occurred as hillslopes adjusted to post-glacial conditions, before vegetation stabilized glacial deposits on steep valley walls.

Several large landslides have occurred along the Skagit River upstream from Bacon Creek in the last 10,000 years (Map 1). Fugro Northwest (1979) mapped five mass movements between Bacon Creek and Damnation Creek, which range in area from 0.04 mi^2 to 0.56 $mi.^2$ and are described as shallow-seated (100 to 200 ft.) debris slides. Four of these landslides occurred in the Napeequa

Unit (Cascade River Schist) on the walls of the valley (Figure 4). In this area joint and fracture planes of the schist dip steeply into the valley, which may account, in part, for the instability of this rock.

The landslides all appear inactive as scarps at the head of the landslides are rounded and no evidence of recent movement was discovered. Landslide activity in this area, however, appears to have occurred at various times in the last 10,000 years. A small landslide postdates deposition of the ash as it flowed over and incised the lacustrine deposit at the west end of the Damnation Creek alluvial fan.

One of the landslides blocked the Skagit River and created a lake. Volcanic ash was deposited to a minimum thickness of 39 ft. in the lake. The ash was analyzed and determined to be from the eruption of Mt. Mazama (Crater Lake) around 6,700 YBP. Since deposition of the ash coincides with creation of the landslide lake, it provides a minimum date for the age of the landslide. The source area for this landslide appears to be on the north side of the river, where a large scarp is visible at an elevation of approximately 1640 ft..

3. Surficial Geology

a. Methodology

There were no previous studies of the soil or surficial deposits in the study area available for reference. Surficial geology was mapped using a methodology similar to that used for the landform map. Unlike the landform map, however, areas below reservoir pool elevations were not mapped. Units mapped and their descriptions are given in Table 3. Dense vegetation cover and rugged topography made access and interpretations difficult, but over 80% of the map was field checked. Eroded lake shorelines and tree tip-ups provided an important look at the surficial geology in remote areas in the absence of road cuts, well-log data or other information. Only the surficial unit was mapped where complicated stratigraphic relationships between surficial deposits were identified. Variations between genetically and geotechnically different glacial till and outwash deposits were not mapped. Specific occurrences of stratigraphically and geologically complicated deposits are discussed with reference to individual sites of erosion.

b. Description of surficial geology

Most of the surficial geology of the study area consists of bedrock or bedrock-related deposits, including colluvium and talus (Map 2). Bedrock types are described above and in Figure 4 and will not be described further. Talus deposits are generally below steep cliffs and are distributed throughout the study area

(Map 2). Talus is composed of very angular cobble- to boulder-size blocks. Colluvium deposits are distributed between and below bedrock outcrops on steep slopes (Map 2) and are generally less than 3 ft. thick, unless filling a gully. Colluvium is composed of loose, angular rock fragments in a silty sand matrix, and forms from the weathering of bedrock. It typically moves

TABLE 3. SURFICIAL GEOLOGY UNITS

Qo	= Outwash deposited by advancing and retreating Pleistocene glaciers. Sand, gravel, cobbles and boulders. Compact where deposited by advancing glaciers, looser where deposited during recessional phases.
Qg	= Glacial till deposited by advancing and retreating glaciers. Non-sorted, non-stratified loose to very compact. Cobbles and boulders of different lithology in a matrix of clay, silt and sand.
Qaf	= Alluvial fan deposits and deposits from debris slides and flows on an alluvial fan surfaces. Loose sand, gravel, cobbles and boulders.
Qal	= Modern river deposits. Loose, subround to subangular, silt to boulders.
Qls	= Landslide and other mass movement deposits not deposited on an alluvial fan or debris cone. Loose to compact silt to boulders, poorly sorted with angular clasts of local lithologies.
Qc	= Colluvium. Also residual soils from weathering of bedrock. Silt to boulders with angular clasts of local lithology.
Qt	= Talus. Angular cobbles and boulders of local lithologies.
Qlac	= Lacustrine deposits. Clay and fine silt with horizontal stratification. Compact where overrun by advancing glaciers.
Qu	= Undifferentiated deposits, primarily mixed till and colluvium.
af	= Artificial fill for roads, towns, campgrounds and other facilities. Includes angular boulders (rip-rap) and gravel and cobbles (roads).
BR	= Bedrock. See Figure 4 for detailed description of rock type.

downslope fairly easily, due to a lack of cohesion. On the steep slopes of the Skagit Valley, thin or loose glacial deposits are often mixed with colluvium and are difficult to differentiate from them. In these instances, mixed colluvium and glacial deposits were mapped as undifferentiated (Map 2).

Glacial till is sediment deposited directly by glacial ice. Most of the glacial deposits in the Skagit Valley are assumed to have been left by the Cordilleran ice sheet. Older deposits of the alpine glaciers were most likely reworked by the Cordilleran ice sheet. Till is poorly sorted and composed of cobbles and boulders supported in a sand, silt, and clay matrix. Till deposited beneath a glacier is typically very compact because of the weight of over-riding ice. Till deposited from the surface of a glacier is typically less compact and coarser grained. Most of the mapped tills are subglacial deposits that range in thickness from 3 to 26 ft.. Till deposits are found on valley walls and on the flanks of floodplains (Map 2). In valley bottoms till exposures are rare because the deposits were either reworked by river (fluvial) activity or covered by fluvial deposits. Till is rare or not found in the river canyon sections of the valley (Map 2).

Sediments deposited by glacial meltwater (outwash) during glacial retreat once filled the Skagit Valley to considerable depth. Estimates of the amount of valley fill remaining below the bed of the Skagit River during project construction were 30 ft. at Ross Dam, 118 ft. at Gorge Dam and 299 ft. at the mouth of Copper Creek (Seattle City Light, 198; Seattle City Light well log data for the town of Newhalem) (Figure 1). Outwash is composed of sand, gravel, cobbles, and boulders with variable sorting and stratification, depending upon the distance from the glacier. From Lightning Creek south to Ten Mile Island outwash deposits are very coarse (Map 2), whereas deposits near the mouth of Ruby Creek (Figure 1) are finer (Map 2). Outwash deposited before an advancing glacier may be compact, while recessional outwash is typically loose. Erosion and redeposition of outwash valley fill by Holocene river activity has left outwash terraces more than 50 ft. above the modern Skagit River floodplain (Map 2). Outwash deposits are not found within the river canyon sections of the study area (Map 2).

Recent (Holocene) alluvial deposits dominate the lowest parts of the valley on floodplains and low terraces. Thick alluvial deposits are found along tributaries, above Ross Dam, and downvalley from the town of Newhalem along the Skagit River (Map 2). Where deposited in active river channels they are composed of rounded gravels, cobbles, and boulders, whereas the main materials deposited by floods on the flanks of the channel are silt and sand. Because of the lateral migration of the Skagit River and its larger tributaries across their floodplains, alluvial deposits can be very complex.

III CLIMATE AND VEGETATION

A. CLIMATE

Northwestern Washington's climate is classified as marine with wet, mild winters and cool dry summers (NOAA, 1979a). Primary factors influencing the climate of the North Cascades are latitude, proximity to the Pacific Ocean, height of the range, and semi-permanent high and low pressure cells located over the North Pacific Ocean (NOAA, 1979b). Prevailing westerlies continually carry wave cyclones and moisture-laden air from the Pacific into contact with the North Cascades. The orographic effect causes increased precipitation with altitude as Pacific air cools while rising over the range. The presence of semi-permanent pressure regions over the North Pacific imparts a strong seasonal component to precipitation in the Cascades: less precipitation falls during the summers because a vast region of high pressure dominates the Pacific. Circulation around the high pressure cell causes a northwesterly flow of relatively cooler, drier air onto the continent. In late fall and winter the Aleutian low pressure dominates the Pacific, bringing a predominantly southwesterly flow of warmer, moister air into the North Cascades. Cooling and condensation as a result of the orographic effect is enhanced by the relatively cool land mass.

The Skagit Valley drains the wet west slope of the North Cascades, although precipitation in the valley varies with respect to local topography and geographic position. The Ross Lake Basin lies in the rainshadow of the crystalline core of the range (the Picket Range and Mt. Prophet) and receives less rainfall than the lower valley, which has a westerly orientation.

Weather stations in the study area are located at the north end of Ross Lake at Hozomeen campground and at the Ross, Diablo, and Gorge powerhouses. A third weather station at the Marblemount Ranger Station (National Park Service) is located 4 miles downvalley from Bacon Creek (Figure 2). The Marblemount and Hozomeen stations collect fire weather data during the fire weather season (late spring to early fall). Annual precipitation decreases upvalley from 78 inches at Newhalem, to 71 inches at Diablo, 56 inches at Ross powerhouse and 31 inches at the international boundary (International Joint Commission, 1971). Mean annual temperature is 49°F at Newhalem, and 48°F at Diablo and Ross powerhouses (Phillips, 1966). Temperature extremes increase upvalley in response to increasingly continental conditions.

Wind data from the Hozomeen and Marblemount stations (Table 4) reflect strong up-valley flow from the south and southwest. The strongest winds in the valley are sea breezes that develop during summer afternoons when high inland temperatures draw air from the relatively cooler Pacific ocean. Wind speed increases in the narrow river canyon sections of the valley between Newhalem and Ross Dam. A strong northeast component to summer winds at the Hozomeen station probably reflects storm wind patterns.

B. VEGETATION

Four broadly defined vegetation zones are found in the North Cascades. They are defined on the basis of altitude and the strong west to east precipitation gradient. From west to east across the Cascade crest they are the lowland forest, the montane forest, the subalpine forest, and the alpine tundra (Heusser, 1983). The study area is dominated by the lowland forest, which grows from sea level to 2950 ft. and is dominated by western hemlock (<u>Tsuga heterophylla</u>), western red cedar (<u>Thuja plicata</u>), and Douglas-fir (<u>Pseudotsuga menziesii</u>). Dominant trees adjacent to the Skagit River and in wetland areas include big leaf maple (<u>Acer macrophyllum</u>) and cottonwood (<u>Populus trichocarpa</u>).

Within the Ross Lake basin drier plant communities are found than usually exist on the western slope of the Cascades, reflecting the drier conditions in the rainshadow of the Picket Range. These communities are particularly prevalent in rocky outcrops on the eastern shore of the lake. Dominant species within the drier communities include ponderosa pine (<u>Pinus ponderosa</u>), lodgepole pine (<u>Pinus contorta</u>), and aspen (<u>Populus tremuloides</u>). On the western shore, wetter communities (including Douglas-fir and western hemlock) more typical of the western slope are found interspersed with lodgepole pine communities.

Species that inhabit disturbed sites in the study area include red alder (<u>Alnus rubra</u>), willow (<u>Salix</u>), and fireweed (<u>Epilobium angustifolium</u>).

TABLE 4. SUMMER WIND DATA FROM THE (A)HOZOMEEN AND (B)MARBLEMOUNT WEATHER STATIONS. TABLE LISTS NUMBER OF OBSERVATIONS AT DIFFERENT SPEEDS AND DIRECTIONS SINCE 1960 (DATA FROM THE U.S.F.S., BOISE, IDAHO).

A. HOZOMEEN STATION (TOTAL OBSERVATIONS 1595)

	DIRECTION								
	NE	E	SE	S	SW	W	NW	N	CALM
WIND SPEED(MPH) 0-5	76	81	29	166	293	161	81	122	327
6-10	4	5	10	33	40	11	4	12	
11-20	0	2	4	10	7	1	4	5	
21-30	0	0	0	2	1	1	1	1	
96-100	0	0	0	0	0	1	0	0	
TOTALS	80	88	43	211	341	175	90	140	327

B. MARBLEMOUNT STATION (TOTAL OBSERVATIONS 2056)

	DIRECTION								
	NE	E	SE	S	SW	W	NW	N	CALM
WIND SPEED(MPH) 0-5	75	13	38	222	308	47	13	13	133
6-10	17	2	47	309	567	39	1	4	
11-20	3	1	5	65	122	3	4	2	
21-30	0	0	1	1	0	0	0	0	
81-85	0	0	1	0	0	0	0	0	
TOTALS	95	16	92	597	997	89	18	19	133

IV THE RESERVOIR ENVIRONMENT

The reservoirs created by Ross, Gorge, and Diablo Dams flood 12,400 acres of the Skagit Valley in the United States. Reservoirs differ in several respects from natural lakes. These differences serve as a means to outline the effects reservoirs have on a natural landscape. First, reservoirs superimpose water on soils and landforms adjusted to erosion under subaerial conditions. Second, because reservoir shorelines have not adjusted to new conditions, reservoirs typically have greater shoreline development (ratio of shoreline length to water surface area) than lakes. Third, reservoirs are deepest at the dam, whereas lakes are generally deepest in the middle. Finally, reservoirs that store flood and snow-melt water are typically subject to fluctuations in water level uncommon in natural lakes.

A. POOL LEVEL FLUCTUATIONS

The modern full pool elevation of Ross Lake was reached in several stages between 1940 and 1967 (Figure 7). Pool elevations on Ross Lake are subject to large fluctuations (Figure 8). Drawdown from a full pool elevation of 1602.5 ft. usually begins in early September and reaches its lowest elevation during February or March. Full pool conditions persist for an average (1954-1972) of 8.5 weeks beginning in late June to early July. Maximum possible drawdown with continued electrical generation is 127.5 ft., although the reservoir is rarely drawn this low. The mean drawdown for the period 1954-1986 was 82.99 ft., with a minimum of 32.80 ft.in 1963 and a maximum of 128 ft. in 1975 (Seattle City Light, 1954-1972; U.S.G.S., 1972-1986).

Drawdown and filling curves are generally smooth, but are occasionally interrupted. Variations in these curves are a result of variations in runoff and the demand for electricity. For example, the 10 inches of rain that fell on the Skagit Valley on November 9th and 10th, 1989, caused Ross Lake to rise some 12 ft. in a matter of days, interrupting normal drawdown of the reservoir. Static lake levels concentrate erosion at a given elevation on slopes along the reservoir, whereas rapid drawdown may increase erosion as a result of groundwater and mass movement processes.

Three rule curves govern the seasonal drawdown pattern of the three reservoirs: the critical rule curve, the refill guide curve and the and the flood control rule curve. The critical rule curve and the refill guide curve are determined for Ross Lake by a contract between utilities in Washington, Idaho, Oregon and Western Montana (International Joint Commission, 1971). The flood control curve is determined by the U.S. Army Corps of Engineers and is determined annually by snow survey estimations of spring runoff. The critical

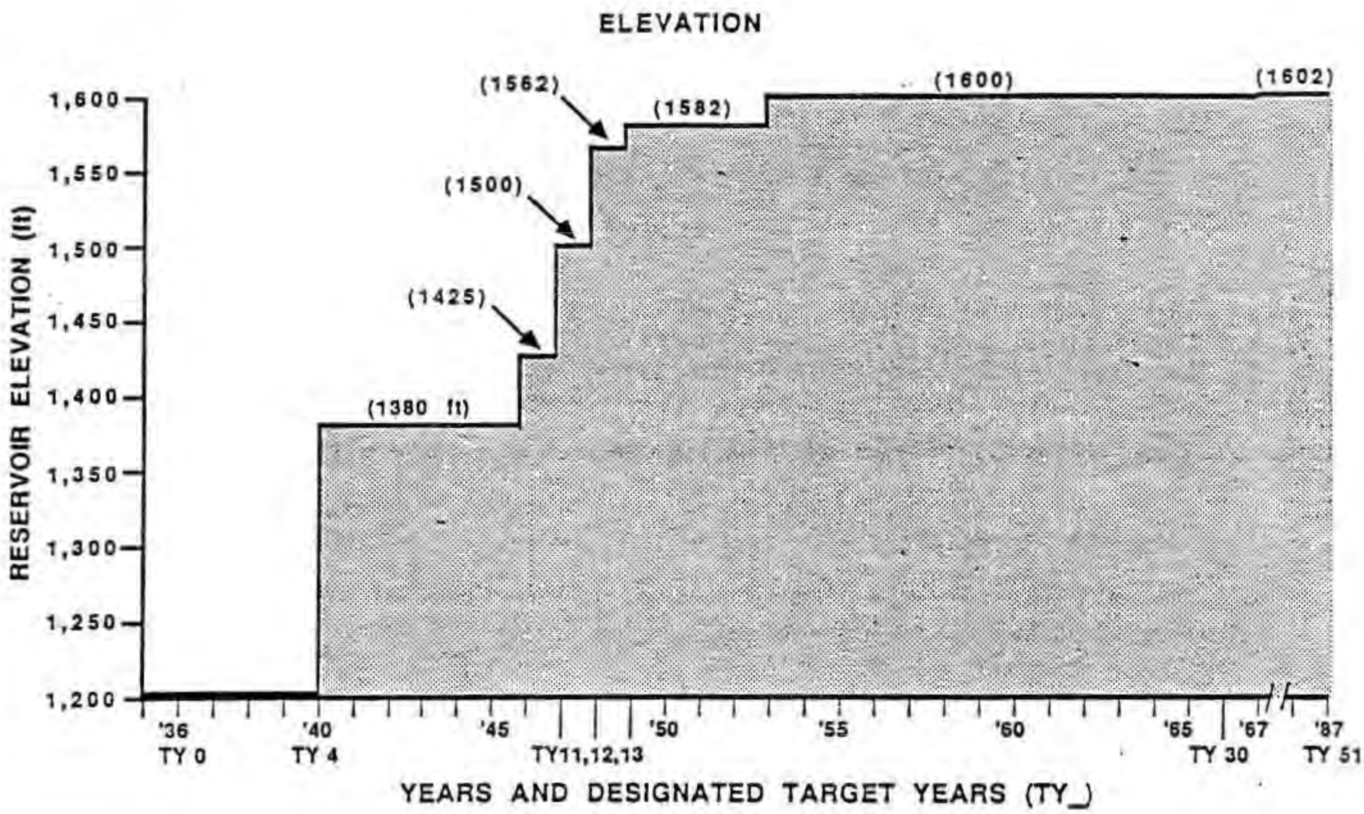

FIGURE 7. CHANGES IN ROSS LAKE ELEVATION WITH ADDITIONS TO ROSS DAM HEIGHT. FROM H.E.P. STUDY, ENVIROSPHERE, 1988.

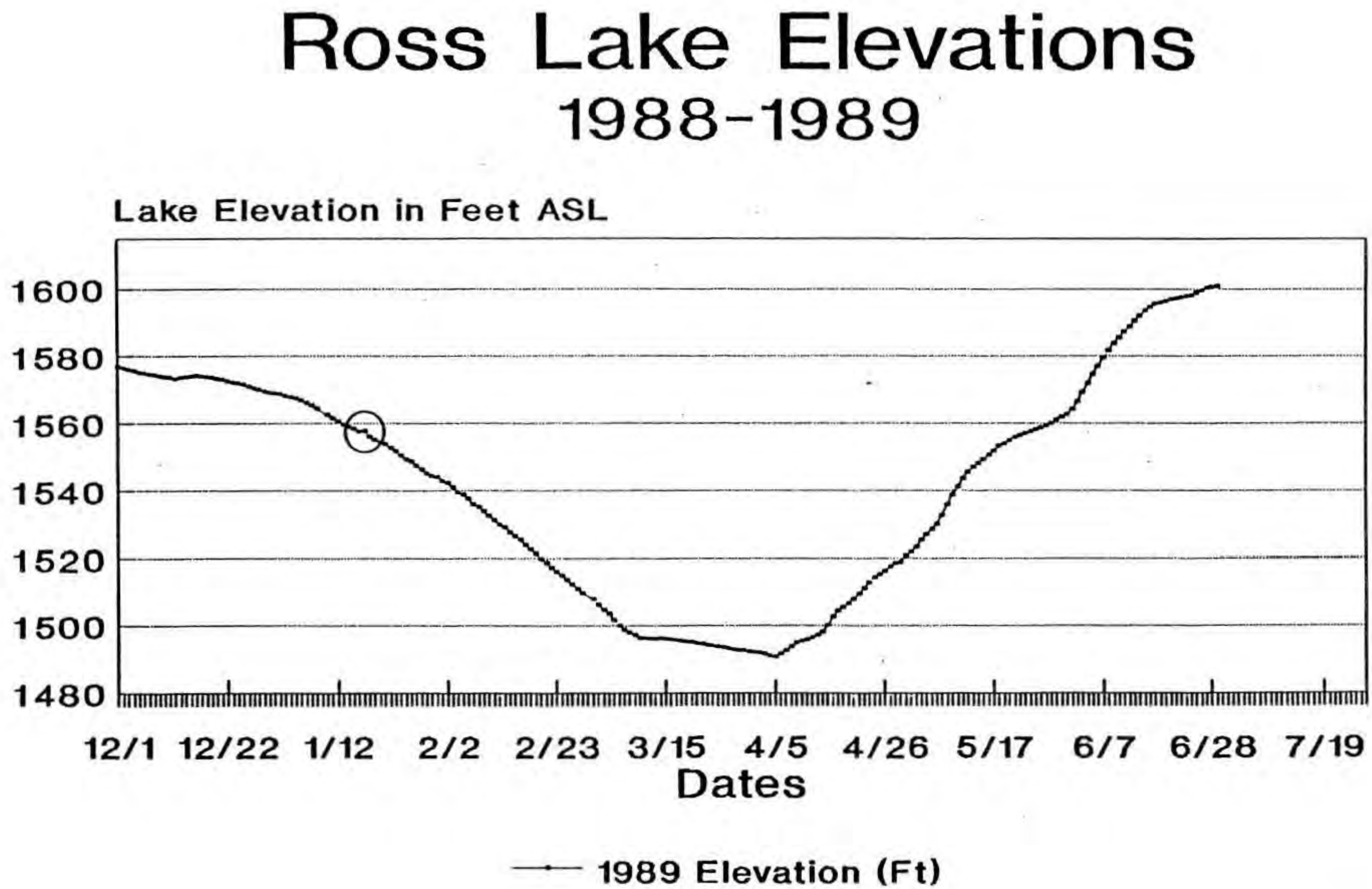

FIGURE 8. ROSS LAKE ELEVATIONS FROM DECEMBER, 1988 TO JUNE, 1989.

rule curve is followed in the event of recurrence of historical low flow conditions.

The full pool elevations of Gorge and Diablo dams were attained in 1961 and 1930, respectively. The pool levels of Diablo and Gorge lakes are not drawn as low as Ross Lake. Maximum drawdown in pool elevation for Gorge Lake between 1972 and 1986 was 20.43 ft. in 1982. Minimum drawdown was 8.07 ft. in 1973, while the average for this period was 13.76 ft.. Diablo Lake had an average drawdown of 10.10 ft., with a maximum of 24.51 ft. in 1976 and a minimum of 8.34 ft. in 1986 (U.S.G.S., 1972-1986). The smaller storage capacity of Gorge and Diablo lakes (Table 1) results in daily fluctuations in pool elevation impossible on Ross Lake. This also results in their being raised and lowered more quickly.

B. RESERVOIR BED MORPHOLOGY

Landforms flooded by the three reservoirs are diverse (Map 1), which results in a complicated reservoir bed morphology. Further, because the water surface in a reservoir is level and the Skagit River Valley has a gradient of 17 ft. per mile, the waters of the three reservoirs intersect geomorphologically different parts of the valley. This effect is most pronounced on 23.5 mile-long Ross Lake.

Mierendorf, Riedel, and Luxenberg (1988) recognized three geomorphologically different valley segments flooded by Ross Lake water, including the upper floodplain, the midvalley, and the lower gorge. The morphology of the lake bed in the upper segment (between the U.S.-Canada boundary and Little Beaver Creek, Figure 1) is dominated by the Skagit River floodplain and tributary alluvial fans (Map 1). Only a very small area of valley wall is inundated by lake water. Relief on the floodplain is generally less than 10 ft. in this zone. In the midvalley (between Little Beaver Creek and Cougar Island, Figures 1 and 2) the lake bed is dominated by high outwash terraces and valley walls (Map 1). Relief in this area is highly variable, although generally greater than the upvalley area. Terrace edges have slopes of 25 degrees or more, but relatively flat tops. Valley walls, reflecting the effects of intense glaciation, have a wide range of slope angles, with most over 25 degrees. Where glacial till deposits are thick, the topography is more variable. Glacial scouring of till deposited at the base of the glacier has formed elongate ridges with intervening depressions. In the lower gorge segment (between Cougar Island and Ross Dam, Figure 2) the observed bed topography is steep as Ross Lake water intersects the Skagit River canyon high on its walls. Low relief areas include glacially scoured bedrock benches (Map 1). Alluvial fans and the Skagit River floodplain have not been observed in the lower valley area because they are below the maximum drawdown of 128 ft..

Very little of Diablo and Gorge Lake's bed topography can be observed because of their small drawdowns. Both reservoirs, however, have bed topography similar to Ross Lake, although steep valley walls and river canyon topography is more dominant. The floodplain of Thunder Creek near Colonial Creek Campground is partially exposed during drawdown, as are parts of Colonial, Rhode, and Sourdough Creek alluvial fans (Map 2). On Gorge Lake the Skagit River floodplain adjacent to the town of Diablo is exposed during drawdown (Map 2, Figure 2). Smaller, low relief alluvial fans are also exposed along Gorge Lake (Map 2).

C. SHORELINE ORIENTATION

The orientation of the reservoirs is important because of the influence of predominant winds on shoreline erosion. High shoreline-length to lake-surface-area ratios in reservoirs result from shorelines with many bays and promontories. Promontories and shorelines facing dominant winds are subject to greater wave erosion than bays or leeward shores (Lawson, 1985). North and east facing shores are also subject to greater freezing and thawing, which can be an important process of shoreline erosion (Reid et al., 1988). The length of shoreline on a reservoir of a certain orientation is controlled primarily by the overall orientation of the reservoir. Therefore, most of Ross Lake's shoreline faces east-west because of the north-south orientation of the lake. On Gorge Lake the east-west orientation of the reservoir results in most shorelines facing north and south. Diablo Lake is aligned both north-south (Thunder Arm) and east-west (along the Skagit Valley) (Figure 1).

D. SHORELINE GEOLOGY

The slopes affected by Skagit hydroelectric development waters consist primarily of bedrock and bedrock-related deposits (talus and colluvium). Bedrock and talus form stable shorelines since the bedrock is primarily coarse, crystalline igneous and metamorphic rock. Less-resistant sedimentary rocks such as sandstone and mudstone are not found in the study area (Figure 3). The geotechnical properties of colluvium, combined with its location on steep valley walls, make it potentially unstable. When disturbed, however, colluvial deposits are generally thin and of limited areal extent, limiting the possible extent of erosion. Data summarizing the distribution of bedrock, talus and colluvium along study area reservoir shores are listed in Table 5. On Gorge Lake a considerable length of shoreline is stable fill for SR20 (Table 5, Map 2). Lesser amounts of fill are found on Ross and Diablo lakes (Table 5, Map 2).

Glacial till is the other common reservoir bank material (Table 5). The percent of shoreline that is till decreases downvalley from Ross Lake to Gorge Lake (Table 5) as a result of the pattern of glaciation of the valley. Till exhibits considerable variation in sedimentologic and geotechnical properties. In general, subglacial (lodgement) till is more consolidated, homogenous, and resistant to erosion than supraglacial till. On Ross and Diablo

TABLE 5. LENGTH (ft) OF SHORELINE OF VARIOUS MATERIALS AND PERCENT OF TOTAL SHORELINE.

	ROSS	DIABLO	GORGE
Bedrock	95670 (33%)	38090 (48%)	19195 (40%)
Talus	18440 (6%)	5250 (7%)	8365 (17%)
Colluvium	56675 (20%)	8990 (11%)	1970 (4%)
Undifferen.	0	985 (1%)	655 (1%)
Glacial Till	67750 (23%)	8840 (12%)	0
Outwash	8675 (3%)	0	0
Alluvial Fan	28740 (10%)	8775 (11%)	7710 (16%)
Alluvium	2295 (<1%)	1805 (2%)	1970 (4%)
Landslide	2625 (<1%)	0	0
Fill	5415 (2%)	6235 (8%)	8040 (17%)

lakes subglacial till is overconsolidated, has few joints, and forms vertical bluffs where eroded. Supraglacial till along all three reservoirs (mapped as Qu on Gorge Lake) is typically coarse-grained, has low cohesion, and is mixed with colluvial and melt-water deposits. Specific geotechnical properties of the tills were not measured.

Relatively small amounts of shoreline on the three reservoirs are composed of material other than glacial till, bedrock, talus, colluvium, and fill (Table 5). Alluvial fan deposits form the majority of the remaining shoreline length (Table 5). They are generally stable because of their coarse nature and low slope. Debris cones formed by smaller streams with steep gradients are less stable than alluvial fans. Glacial outwash is a highly unstable deposit on the steep slopes of the study area. It is typically composed of non-cohesive sand and gravel. Small amounts of glacial outwash are found along Ross Lake (Table 5, Map 2). Landslide deposits also exhibit wide variation in stability.

Alluvium deposited on low-relief floodplains and terrace tops is alos variable in composition and reseistance to erosion. Steeply sloping terrace edge alluvial deposits are very susceptible to erosion. They are not widely distributed as a bank material (Table 5, Map 2).

In several areas, complex stratigraphic relationships between various sediments complicate the stability of a given shoreline. On Ross Lake several sites have glacial till, outwash, and lacustrine sediments in stratigraphically different positions relative to each other. Where till and outwash deposits overlie impervious lacustrine and compact subglacial till, groundwater saturation of the overlying strata may result in mass failures, particularly when reservoir bank erosion has undercut these deposits. Specific occurrences of complicated stratigraphic relationships are discussed in the mitigation plan.

E. RESERVOIR CLIMATE

The climate of the study area is also an important element of the reservoir environment, as it affects shoreline erosion processes. Storms, with their accompanying winds and rainfall, directly influence wave and overland flow erosion. Prolonged strong winds from a single direction can pile water up at the leeward shore, effectively raising lake level at that location. Antecedent soil moisture influences erosion by surface erosion and freeze-thaw processes. Temperature affects freeze-thaw and the distribution of ice cover, which inhibits reservoir waves. Ice cover can, however, directly cause erosion when ice is run-up on a shoreline. Ross Lake occasionally freezes over (it did during the winter of 1988-1989), and Thunder Arm on Diablo Lake occasionally freezes, but to the author's knowledge Gorge Lake has never frozen. At the Diablo weather station the first freeze occurs in late October and the last in mid-March (Phillips, 1966). The freeze/thaw season extends for a longer period on Ross Lake because of its higher elevation and because it is farther inland than the other reservoirs.

V RESERVOIR EROSION

A. PROCESSES OF RESERVOIR SHORELINE EROSION

Processes of shoreline erosion include waves, currents, freeze-thaw, mass movements, groundwater and overland flow (sheet wash, rilling and gullying). Of these, waves are the predominant force eroding reservoir bank sediments (Kondratjev, 1966; Savkin, 1975; Adams, 1978; Shur, Peretrukhin, and Slavin-Borovskii, 1978; Reid, 1984; and Reid et al., 1988, among others). The elevation of the pool level controls where waves and their erosive impact intersect the reservoir shore and, therefore, is the foremost factor in shoreline erosion (bank recession) (Reid, 1984; Reid, Sandberg, and Millsop, 1988). It also influences other shoreline erosion processes such as mass movements and groundwater movement.

Lake levels on Ross Lake are monitored by the U.S.G.S. at Ross Dam and by Environment Canada at the international boundary. Between 1970 and 1986 the lake level rose above full pool (1602.5 ft.) 12 times (Table 6). In three of those years it more than a half foot above full pool. In 1976, 1978 and 1981 the lake was above full pool for extended periods (Table 6). Pool elevations can be locally high in response to wind pile-up of water and rapid stream discharge. At every occurrence of above full pool level except one, the Canadian gauge recorded a lower pool elevation than the U.S.G.S. gauge at Ross Dam. Normally, reservoir elevation is higher at the upstream end, an effect that becomes more pronounced the longer the reservoir. Lower elevations at the Canandian gauge are probably a result of the use of different datums between the U.S.G.S. gauge and the Environment Canada gauge. Therefore, the actual reservoir elevation at the north end of the lake would be relatively higher than reported in the Canadian data.

The cyclic nature of reservoir drawdowns imparts a cyclic nature to reservoir shoreline erosion. Every year banks and bank colluvium is eroded from bluffs and beaches near the full pool elevation and is carried to lower depths as the reservoir level falls in autumn and winter. Continued large fluctuations in reservoir level prevent stable shoreline profiles from developing (Lawson, 1985).

Waves are produced by wind and boats. The energy of wind waves is related to wind direction, speed, duration and the length and width of the unobstructed space the wind blows across (i.e. fetch and fetch width, respectively). Waves typically develop and subside rapidly in response to wind (Savkin, 1975). Topography influences wind strength and direction as winds accelerate and are directed through river canyons (Map 2). Observed wave heights on Ross and

TABLE 6. YEARS WHEN ROSS LAKE LEVEL ROSE ABOVE 1602.5 FEET. DATA FROM ENVIRONMENT CANADA AND THE U.S.G.S. IS BASED ON S.C.L. ROSS DAM DATUM. (N/A = DATA NOT AVAILABLE)

YEAR	USGS MAX. ELEVATION	# DAYS ABOVE 1602.5 FT.	ENV. CANADA ELEVATION	# DAYS ABOVE 1602.5 FT.
1970	N/A	-	1602.52	6
1971	N/A	-	1602.52	8
1972	1602.80	27	1602.54	5
1973	-------	-	-------	-
1974	1602.79	6	1602.68	4
1975	1602.72	4	1602.61	6
1976	1603.40	8	1602.85	6
1977	-------	-	-------	-
1978	1603.10	23	1603.08	23
1979	1602.58	1	-------	-
1980	1602.60	7	-------	-
1981	1603.23	47	1602.99	45
1982	-------	-	-------	-
1983	1602.53	1	1602.54	1
1984	-------	-	-------	-
1985	-------	-	-------	-
1986	-------	-	-------	-

Diablo lakes reached 3.5 ft.. In addition to causing erosion directly, waves saturate bank materials, thereby reducing their shear strength and facilitating erosion by other processes (Kachugin, 1980). On Ross, Diablo and Gorge lakes, the strongest winds of longest duration blow upvalley in afternoons from a west to southwest orientation, making west-facing shores on Gorge and Diablo lakes and south and southwest-facing shores on Ross most susceptible to wave erosion. Strong storm winds are also important in wave erosion and have exceeded 80 miles per hour in the study area (Table 4). Boat wave size is directly related to the speed and draft of a boat. Large, heavy, fast boats produce the largest waves.

The severity of wave erosion is directly related to wave energy and the period of time a reservoir is at or above full pool. On Orwell Lake, Minnesota, higher than normal pool elevations for two successive years resulted in a bank recession rate three times that of previous years (Reid, 1984). On Lake Michigan, Hands (1979) measured bank recession of 13 ft. with a 2.5 inch rise in water level above previous lake elevation. Gatto and Doe (1983) also noted faster rates of bank recession with high pool levels on Lake

Pend Oreille in northeastern Washington.

Freeze-thaw is another important process of shoreline erosion and can occur both daily and seasonally. Expansion and contraction of sediments during freezing and thawing disaggregates soil particles, reducing their compaction, consolidation, and shear strength (Lawson, 1985). During spring thaw, melting of one zone in a sediment column above a still-frozen layer may result in mass movement of the upper thawed unit. Fine, clay-rich soils such as lacustrine deposits and subglacial till are most susceptible to freeze-thaw failure. Northerly aspects generally are more likely to undergo freeze-thaw as they retain moisture for freeze expansion (Reid et al., 1988). Low winter sun angles and deep valleys that lie in shadows during winter complicate this relationship. Sterrett and Mickelson (1981) found 87% of banks on Wisconsin's Great Lake shorelines failed because of freeze-thaw related processes; 10-20% of all bank recession on Lake Sakakawea, North Dakota was attributed to freeze-thaw (Reid et al., 1988). Gatto and Doe (1983) saw a strong correlation between rates of bank recession and the length of the freeze/thaw season at several U.S. Army Corps of Engineers reservoirs.

Groundwater also plays an important role in reservoir shoreline erosion. Lawson (1985) identified water level, composition of bank sediments, and groundwater movement along shorelines as three factors contributing to this process of erosion. Groundwater can influence geotechnical properties of bank sediments and directly cause erosion by piping (Lawson, 1985). Sediment strength is reduced when high amounts of groundwater increase pore-pressure and seepage pressures. Failure of banks by groundwater-related mass movements are most common where pervious sediments are interbedded with impervious ones and groundwater flow is complex; glacial sediments are characterized by complex groundwater flow systems (Sterrett and Edil, 1982). Rapidly lowered pool levels result in high seepage pressures in groundwater perched above the falling lake. High seepage pressure can lead to reduced strength of bank materials.

Humans can also influence shoreline erosion by killing vegetation, compacting soil, concentrating runoff, by direct displacement of soil. There are several miles of trail and 26 campgrounds along reservoir shores in the study area, including car-access campgrounds at Colonial Creek and Gorge lakes (Figure 2).

Surface flow of water (overland flow) on bluff faces and bank colluvium can cause erosion, especially on unvegetated slopes composed of sediments with low cohesion (Lawson, 1985). Specific processes of surface erosion include rainsplash, sheet flow, rilling, and gullying. In highly impermeable sediments, rilling and gullying are more active, whereas rain splash and sheet flow are dominant in low permeability soils (Lawson, 1985).

Reid et al. (1988) note that bank recession is ultimately caused by mass movement of sediment, which occurs after modification of beach profiles and materials by other processes. Mass movements include debris slides and flows in cohesionless sediments (e.g. outwash, alluvium, and most colluvium) and by slumps and flows in cohesive, fine-grained sediments (e.g. glacial till, lacustrine).

Slope failures are common in reservoirs with both rapid and prolonged drawdowns (Lawson, 1985). Jones, Embody and Peterson (1961) and Erskine (1973) noted a relationship between rapid drawdown and increased mass movements in low permeability bank sediments. Further, they suggested that this related to movement of groundwater from the banks to the reservoir, which caused instability of bank sediments.

B. RESERVOIR EROSION OF AREAS BELOW FULL POOL

Although erosion of reservoir shores is most severe and costly in terms of habitat and recreational facility losses when the reservoir is at full pool, erosion and sediment transport occur below the highest reservoir shoreline. Previous studies have not focused on the processes, nature, or severity of erosion in this location. Of Seattle City Light's three reservoirs in the Skagit Valley, only Ross Lake was drawn down low enough in 1989 so that the condition of landscapes below full pool could be assessed. The following observations were made in Ross Lake's drawdown in the spring of 1989.

Following completion of Ross Dam and the removal of vegetation, erosion of shorelines now below the modern full pool (1602.5 ft.) elevation probably occurred rapidly once soil-holding roots had rotted (typically within 2-5 years under subaerial conditions; Wu, McKinnell and Swanston, 1979). Landforms most sensitive to erosion included terrace edges and valley walls. Steep slopes on these landforms in the drawdown that once held thick accumulations of unconsolidated sediments have been stripped of much of their original soil cover and are now covered with loose gravel lag deposits. Stumps standing well above the modern ground surface in the drawdown attest to the degree of erosion in the drawdown, which has locally removed as much as 9.2 ft. of the pre-reservoir sediments (Photo 1)(Table 7). Finer grained material from these areas has been eroded and transported to the deepest parts of the lake bed, leaving behind cobble and boulder lag deposits (Photo 1).

The steep slopes are now transport areas for the material eroded from shorelines above and below full pool. Erosion and transport of these sediments occurs as the lake level fluctuates and influences reservoir shoreline erosion at full pool. When the normally rapid filling or drawdown of Ross Lake is interrupted by periods of static lake elevation, wave erosion cuts strand lines (terracettes) into previously deposited material and accelerates the movement of the eroded material to deeper parts of the Lake (Figure 9). This is well illustrated by events of the 1989

PHOTO 1. BELOW FULL POOL EROSION OF TERRACE EDGE NEAR TENMILE ISLAND. SEDIMENT THICKNESS ERODED BELOW STUMPS 10 FT.

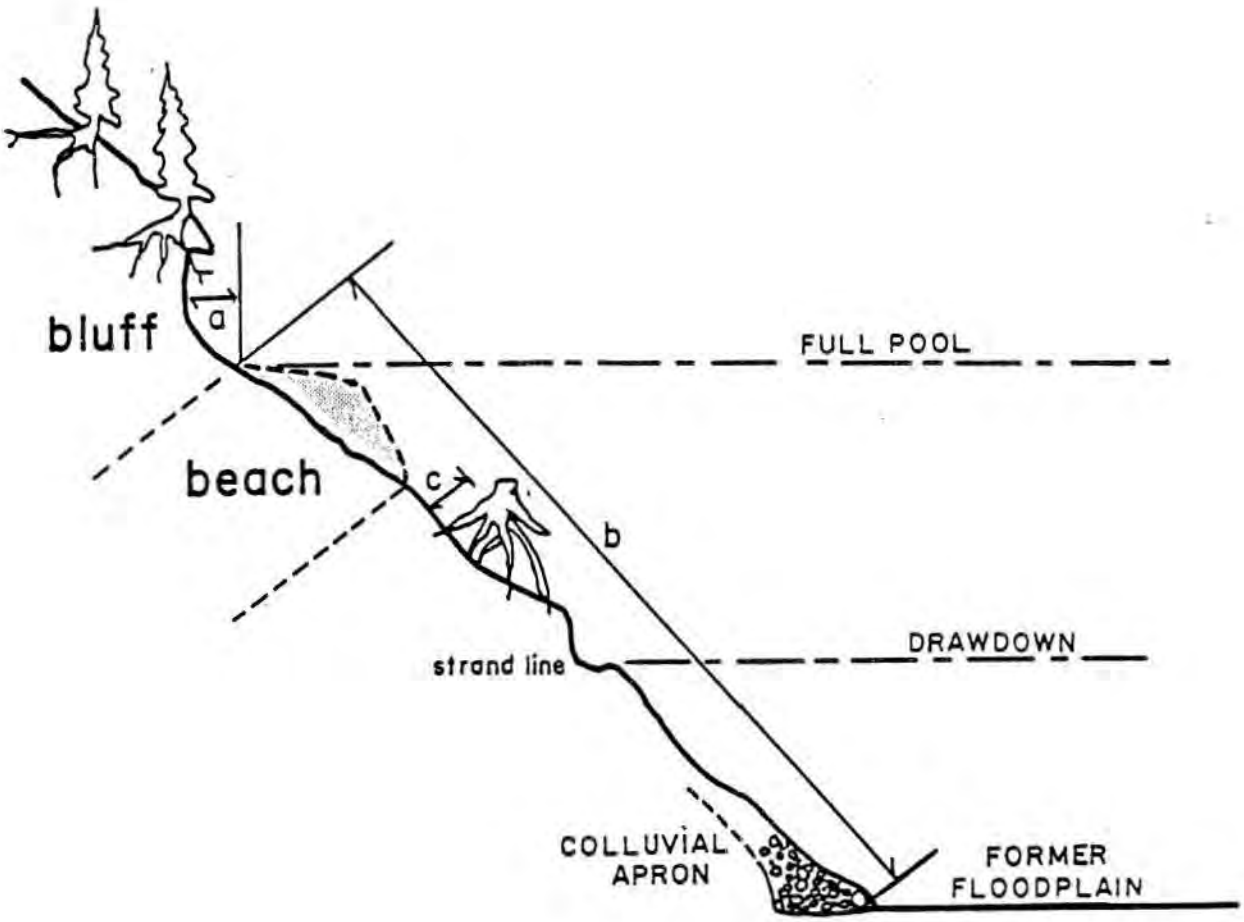

FIGURE 9. IDEALIZED SHORE ZONE PARTS ALONG A VALLEY WALL WITH QUATERNARY DEPOSITS. TERMS DISCUSSED IN TEXT INCLUDE: (a) BANK RECESSION ABOVE FULL POOL, (b) LENGTH OF SLOPE EFFECTED, AND (c) DEPTH OF SOIL ERODED.

TABLE 7. DEPTH OF EROSION IN THE ROSS LAKE DRAWDOWN.

SITE LOCATION	THICKNESS (FT.)
10 Mile Island	9.2
Lightning Creek	8.2
Big Beaver	6.6
Rowland Creek	2.8
Arctic Creek	4.9

drawdown, when lake elevation was static for several days and a prominent terrace was cut into the bank at a 1550 ft. elevation (Figures 8 and 9).

C. THEORETICAL ADJUSTMENT OF RESERVOIR SHORELINES AT FULL POOL

The superimposition of reservoir water onto sediments and landforms created in subaerial environments represents an unstable configuration (Lawson, 1985). Raising of natural lake levels by dams has initiated shoreline readjustment (erosion) (Lynott, 1989). Lawson (1985) notes differences between reservoir, lake, and ocean shore zones, and suggested that reservoir profiles reflect the immaturity of their shores. Bruun (1954) suggested ocean beaches represent part of a shore zone in dynamic equilibrium with environmental conditions. Beach zones developed along reservoir shores may also reflect a dynamic equilibrium between shorelines and environmental conditions (Kondratjev, 1966). Reservoir shores not in equilibrium with environmental conditions typically have steep bluffs and poorly developed beach zones, while severely eroding shores may have no beach zone (Lawson, 1985).

The time necessary to reach an equilibrium profile varies within a given reservoir, and within a given reach of shore (Lawson, 1985). Further, Lawson (1985) notes that a lack of studies of reservoir shoreline erosion and the complex interaction of environmental factors and processes make it difficult to predict if and when equilibrium profiles will be attained. Nonetheless, Kondratjev (1966) suggested that this process takes from 5-10 years, although a static reservoir level is necessary for beach zones to develop.

D. LOCATION AND SEVERITY OF RESERVOIR SHORELINE EROSION AT FULL POOL

a. Methodology

Erosion of shores at full pool elevation is a more severe problem than for areas below full pool for several reasons. First, erosion at full pool results in the loss of terrestrial habitat and recreational facilities. Second, it introduces new sediment into the reservoir environment. Finally, erosion at full pool alters the visual quality of a reservoir.

Sites along reservoir shores were surveyed on foot and by boat. Each eroding stretch of shoreline was given a number and mapped (Map 3). Areas of erosion on the east shore of Ross Lake, including Cat and Tenmile Islands, were numbered consecutively from 1, as were those on the west shore. Sites along the two shores were differentiated by giving them either an E or W prefix. Sites along Diablo and Gorge lakes were also numbered consecutively from 1 on each reservoir. Data concerning the length of shoreline, bank material, bank slope, bluff height and sediment thickness, site aspect (orientation), and evidence for slope instability above the bank (pistol gripped trees, slump scars, groundwater irregularities and vegetation disturbance) were collected. Material type was classified using the same categories as the surficial geology map with one exception. Diamicton was used to describe loose, poorly sorted sediment classified as glacial till on the surficial geology map. The term includes both till and mixtures of colluvium and till. Diamicton was described as a separate material type because of its lower resistance to erosion than subglacial till. Further, each site was classified as to the severity of erosion. Class I sites were defined as areas where larger (>1000 $ft.^3$) mass movements had occurred, or where conditions existed such that they might occur in the future (complicated stratigraphic relationships, groundwater seepage, thick accumulations of sediment, etc.). Additional data collected on class I areas included failure dimensions (length, height, depth), stratigraphy, groundwater movement, bank profile and surrounding geology. Class II areas were defined as areas where small slumps (<1000 $ft.^3$) and slides were occurring, or where the possibility existed for larger mass movements. Cllass II sites differed from class III ones primarily in the height of the eroding bluff face; class III bluffs were 3-5 ft. or less above the full pool elevation, whereas class II bluffs were greater than 3-5 ft. tall.

Bank recession was estimated by two methods. First, where the National Park Service had placed dock anchors and bulkheads immediately adjacent to shorelines near camps, it was possible to estimate the amount and rate of recession based on the isolation of the anchors and bulkheads by the receding shore. This method provides a bank recession distance and rate of retreat since placement of the structures. A second method used to estimate bank recession rate measured recession since 1968, when Ross Lake's elevation was raised to 1602.5 ft. (see the erosion control plan for a complete description of this method). This method slightly overestimates the rate of bank recession if the pre 1968 eroding bluff face was higher than the amount the lake level was raised in 1968 (i.e. 2 ft.)(distance a, Figure 9).

Analysis of data collected was designed to determine what factors control shoreline erosion along the three reservoirs and to identify processes of shoreline erosion. Total length of shoreline eroding in each severity class, of different material type and within the eight cardinal directions (N, NE, E, SE, S, SW, W, NW) was determined from data collected by surveys. Total length of shoreline of each material type mapped (Table 5) was determined by measuring 82 ft. (minimum) straight-line segments off of the 7.5 minute topographic maps. Total shoreline length for each reservoir was also measured using this method. These figures probably underestimate actual values because the straight line measuring technique did not take into account small bays and promontories less than 82 ft. in length. Comparison of the relative importance of environmental factors such as slope, material and aspect was made by comparing ratios of length of eroding shore associated with each of these variables with total length eroding along the shores of a given lake.

b. Results and discussion

1. Ross Lake

Shoreline erosion on Ross Lake is widespread. Over 25% of the shoreline, approximately 14.5 miles, is in some stage of retreat. Most sites are located throughout the lower and midvalley sections of the reservoir where lake water intersects colluvial and glacial sediments on steep valley walls (Maps 1, 2 and 3). Other landforms where erosion is severe include terrace slopes and river canyons where unconsolidated sediments are found. Most other landforms, including glacially scoured bedrock benches, alluvial fans, and floodplain, have low slopes and relatively little erosion (Maps 1 and 3).

Erosion is occurring at 1,143 sites along the reservoir (Table 8). Over half of the total length of eroding shore was class II erosion, with bluff heights of greater than 3 ft.. Sites with high potential for mass movement and those with active mass movements (class I) initiated by reservoir erosion at 34 sites along the lake account for over 8% of the total eroding shore (Table 8). Bluff heights at class I sites range from 5 to over 50 ft.. There are 390 class III sites along Ross Lake (Table 8), covering over 39% of the total eroding shore.

The majority of class III sites occur in colluvial deposits and till deposited along shores with gentle slopes. Waves undercut and remove lateral support of colluvial deposits resulting in shallow, planar debris slides (Photo 2). The dimensions of these sites are usually limited in area by the dimensions of the colluvial deposit. Where long stretches of shore are composed of colluvium, individual debris slides may coalesce to form a long stretch of eroding shore (Photo 3). This pattern of coalescence

TABLE 8. LOCATION AND NUMBER OF EROSION SITES AND LENGTH OF AFFECTED SHORELINE BY CLASS OF SEVERITY.

	ROSS	DIABLO	GORGE
CLASS I	34 (6529 ft.)	5 (1801 ft.)	3 (312 ft.)
CLASS II	719 (40072 ft.)	17 (2310 ft.)	3 (341 ft.)
CLASS III	390 (29878 ft.)	56 (3927 ft.)	11 (272 ft.)
TOTALS	1143 (76,479 ft)	78 (8038 ft.)	17 (925 ft.)

of small lengths of eroding shore into long stretches was also observed at class I and II sites.

Class II sites are found mainly in thick glacial till deposits on steep valley wall slopes. Wave undercutting of till slopes results in small slumps. The failures are typically associated with the fall of large individual trees or clumps of smaller trees and their root masses (Photo 4). Bank recession in these instances is sporadic.

Class I sites occur where slopes are steep, where glacial till is exceptionally thick, in areas with complicated stratigraphic relationships, or where shorelines are composed of glacial outwash. These conditions are found scattered along Ross Lake's shoreline. Three extensive stretches of shoreline exhibiting these characteristics exist north of Thursday Creek on the west shore, south of Rainbow Point Campground on the east shore and on the south shore of Ruby Arm (Map 3).

At site W-63 (Map 3) thick glacial till deposits that overlie lacustrine sediments with a minimum thickness of 10 ft. are eroding (Photo 5). The basal part of the till unit and the upper part of the lacustrine unit are both charged with groundwater, which contributes to the site instability. During the spring of 1989 over 2000 cu. yards of the bluff slumped, most likely in response to thawing of bluff sediments.

Site E-9 is an example of class I erosion initiated by the erosive effects of Ross Lake water on the steep slopes above Ruby Creek (Photos 6 and 7). The site is located in a ridge of thick recessional outwash deposits (Photo 8)(Map 3). Wave erosion at different elevations during pool level fluctuations keeps this slope unstable and has resulted in a large debris slide visible from the Ross Lake Resort (Photo 8).

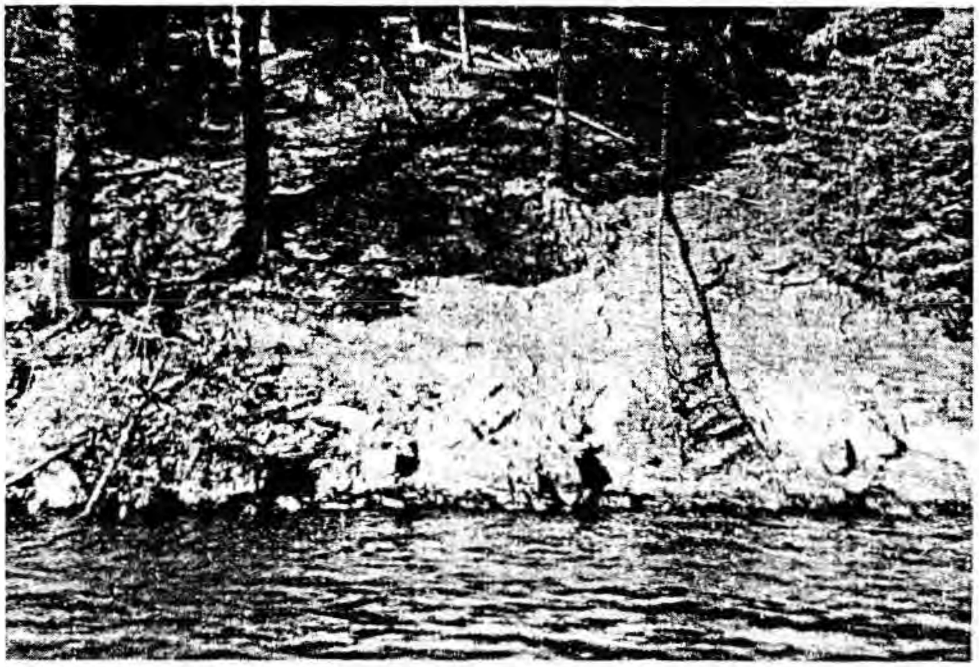

PHOTO 2. PLANAR, SHALLOW DEBRIS SLIDE IN THIN COLLUVIUM OVER BEDROCK.

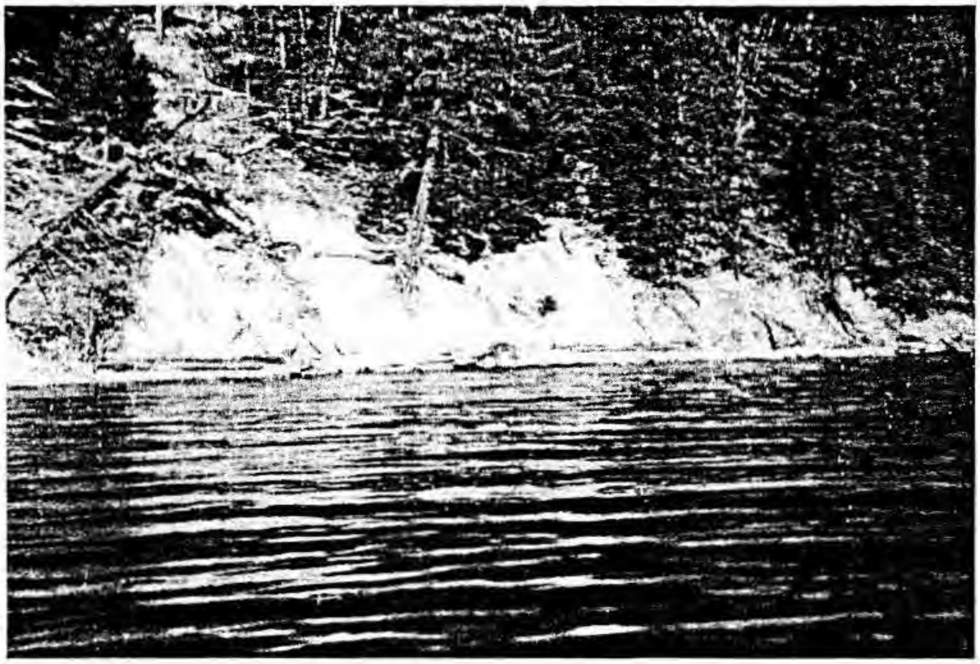

PHOTO 3. COALESCING DEBRIS SLIDES IN COLLUVIUM.

PHOTO 4. SLUMP MASS HELD TOGETHER BY ROOTS AT SITE W-23
(CLASS I, MAP 3, SHEET 2).

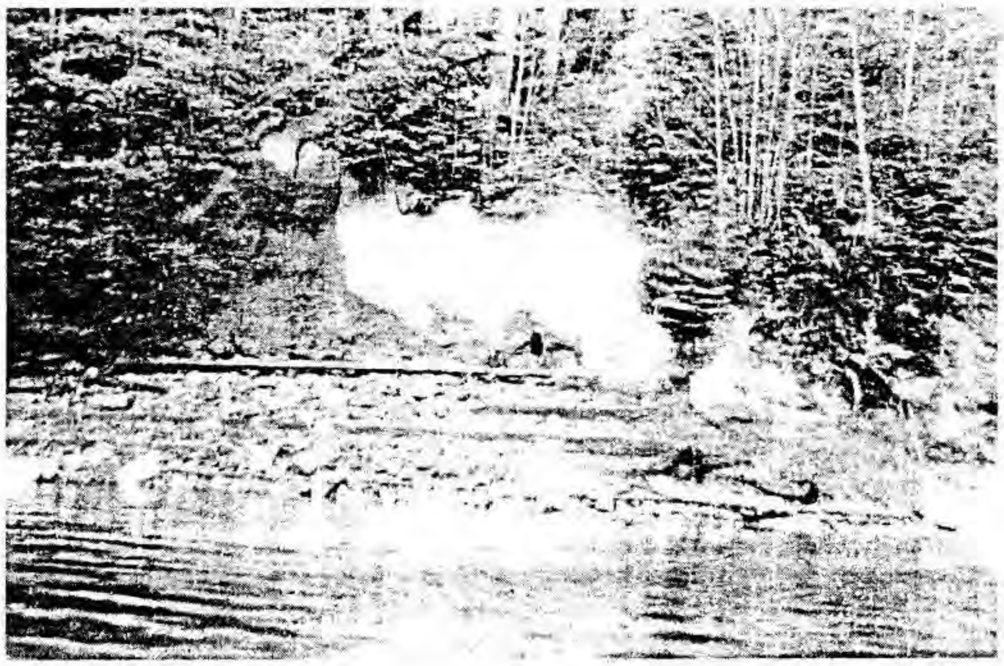

PHOTO 5. ERODING BLUFF IN TILL AND LACUSTRINE DEPOSITS AT SITE W-63 (CLASS I, MAP 3, SHEET 2).

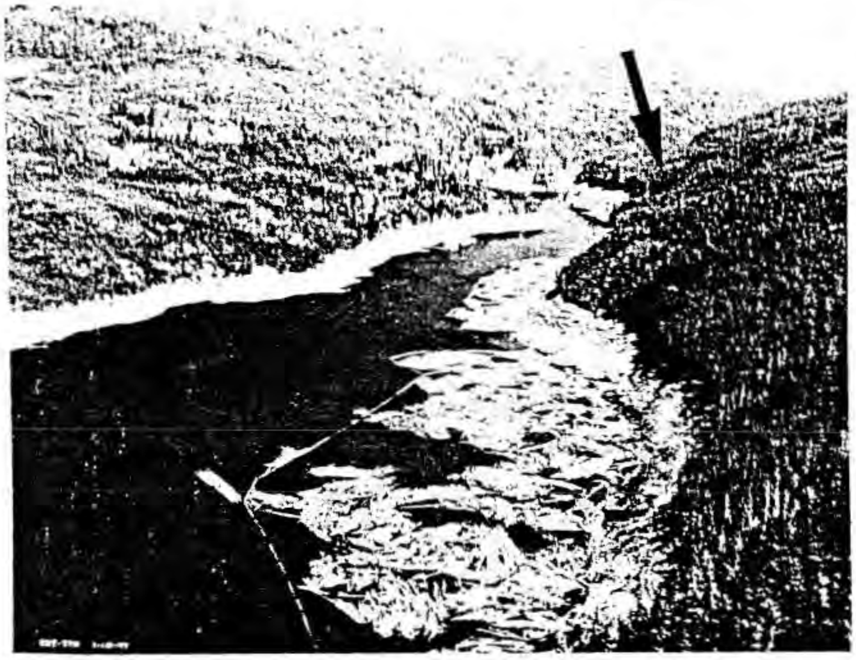

PHOTO 6. LOOKING EAST UP RUBY ARM IN 1947. ARROW INDICATES SITE OF FUTURE DEBRIS SLIDE (SITE E9). LAKE ELEVATION 1580 FT.

PHOTO 7. LOOKING EAST UP RUBY ARM AT DEBRIS SLIDE (SITE E9, CLASS I, MAP 3, SHEET 3). RESERVOIR 5 FT. BELOW FULL POOL.

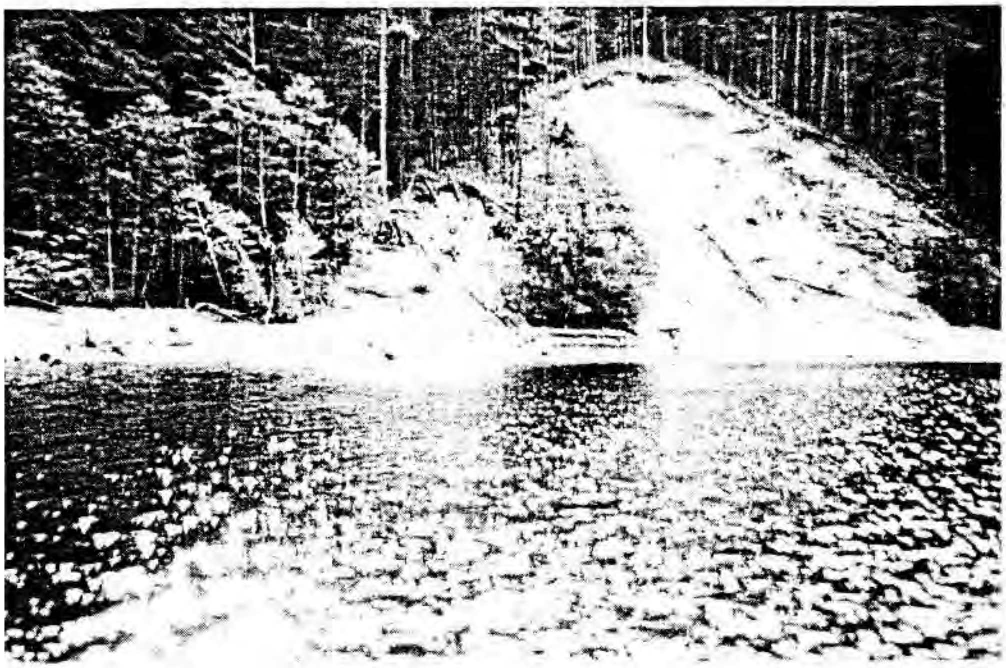

PHOTO 8. CLOSE-UP OF DEBRIS SLIDE AT SITE E9 (CLASS I, MAP 3, SHEET 3).

Site E-7A on the south shore of Ruby Arm (Map 3) is also the site of a large slope failure (Photo 9). Unlike site E-9, however, the slope failed by the slumping of a large mass of cohesive sediments. The stratigraphy of the deposits is well sorted compact sand interbedded with gravel and cobble layers. Adjacent to the outwash sequence is loose, bouldery till, with boulders as large as 8 ft. in diameter. Slope instability at the site is complicated by the movement of groundwater through the well-sorted sand, which has created a large cave 3 ft. in diameter that continues for a minimum of 10 ft. back into the bluff face (Photo 9).

Other areas where complicated stratigraphic relationships have caused class I erosion include sites W-135, W-23, E-55, E-76, and E-8 (Map 3). Detailed descriptions of all class I sites are presented in the mitigation plan.

The dominant process of shoreline erosion on Ross Lake appears to be wave erosion, although not necessarily waves directed by prevailing upvalley winds. Shorelines in several areas are undercut up to 10 ft. by wave erosion. The process of wave erosion was observed during the field season when wave heights were over three ft.. Sediment eroded by waves was carried over 100 ft. out from shore, and gave the lake water a cloudy green color, similar to the summer color of Diablo Lake when it is full of glacial sediment.

Other sources of waves include boats and storm winds. The heaviest boat use on Ross Lake coincides with high pool elevations when fishing season is open from mid June through October. Rental boats at the Ross Lake resort are limited to under 10 horsepower on 12 ft. aluminum and wood boats. Larger boats with more powerfull engines include National Park Service patrol boats, resort water taxi boats and boats launched at the north end of the lake at Hozomeen. Storm winds can blow from a variety of directions, with varying intensities and durations.

Mass movements of material seem to follow wave undercutting of sediments and oversteepening of slopes. Small slides of class II and III severity were observed at 32 sites. All but one are shallow planar debris slides of colluvium. Further, 19 small slumps were observed at class II sites, all of which occurred in cohesive bank sediments (e.g. glacial till). Larger active slope failures occur in areas of thick accumulation of non-cohesive sediments or where impermeable sediments are interbedded with outwash. Failures in both slumps and slides coincide with spring thaw and the failure of trees and their root masses.

The four pre-project mass movements identified are much larger than those initiated by reservoir water. All appear to be stable, however, in contrast to those along the modern reservoir shoreline.

Groundwater plays an important role in erosion at several sites.

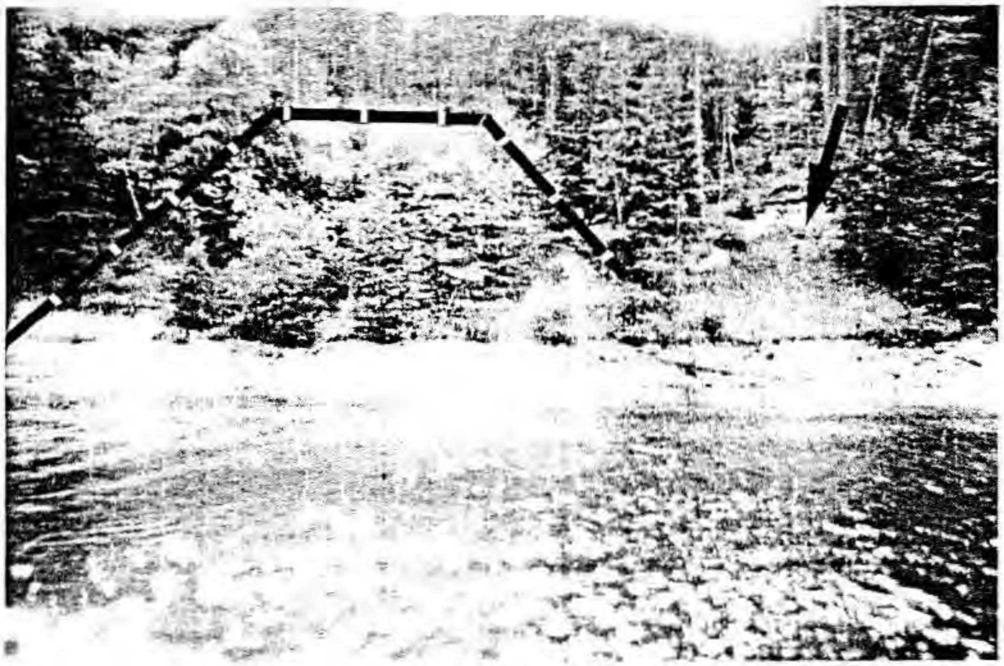

PHOTO 9. CLOSE-UP OF ERODING BLUFF AT SITE E-7A (CLASS I, MAP 3, SHEET 3). ARROW POINTS TO GROUNDWATER-ERODED HOLE. DOTTED LINE TRACES UPPER EDGE OF SLUMP MASS.

Seeps were identified at 15 sites, including site W-63 and site E-7A on Ruby Arm (Photo 9). At site E-7A groundwater erosion (piping) has created a 3 ft. diameter cavity in glacial outwash and lacustrine deposits. Conditions of subsurface (groundwater) erosion such as this often lead to slope failure. On the east end of site E-7A a large rotational failure has already occurred.

Surface water erosion (overland flow) also appears to be a process of shoreline erosion. Gullies have formed in reservoir bank materials void of vegetation at 17 sites. Most sediment removed by overland flow, however, is material previously eroded by waves, freeze/thaw and mass movements, and is deposited as colluvium at the base of bluffs. Therefore, the primary affect of this process is the secondary erosion of sediment and its transport to deeper parts of the reservoir.

Freeze/thaw processes also contribute to erosion on Ross Lake. Frozen bank sediments were observed at a number of locations along the lake in early March, 1989, while Ross Lake was frozen over. Clay-rich and groundwater charged sediments and shaded banks are most susceptible to freeze/thaw erosion.

Recreational use also influences bank erosion. Heavy foot traffic at site W-34, for example, has killed vegetation, compacted soil and caused the displacement of sediment. Other localities where human traffic has accelerated bank erosion include along the East Bank trail and near docks and camps throughout the lake (Figure 2).

The most important environmental factor controlling the distribution of sites appears to be the distribution of erodible material (Table 5). Over 60% of the glacial till deposits on the lake shore are eroding, while over 55% of the total shoreline composed of colluvial deposits is eroding (Tables 5 and 9). The 40% of shorelines composed of glacial deposits not eroding occur primarily either on low slopes or where bedrock outcrops have stopped bank recession.

Slope is also an important environmental factor. Slopes along valley walls and river canyons typically range from 30 to over 50 degrees. These two landform types account for the majority of shoreline in the study area (Map 1).

Aspect does not appear to be a critical factor in wind-induced wave erosion. South-facing shores that face into the strongest and most persistent (upvalley) winds account for only 4% of total eroding shoreline. Further, southeast and southwest facing shores account for only 25% of the total eroding shore (Table 10). Also, no class I sites face south and only two (E-76a and E76-b) face southeast or southwest. The lack of influence of shore aspect on the amount or severity of wind-related erosion is primarily a result of the north-south orientation of Ross Lake. West- and east-oriented shores account for 31% of the total eroding shoreline (Table 10).

TABLE 9. LENGTH (ft) OF ERODING SHORELINE OF VARIOUS MATERIALS AND PERCENT OF TOTAL ERODING SHORELINE.

	ROSS	DIABLO	GORGE
TILL	17635 (24%)	5585 (69%)	0
DIAMICTON	23115 (31%)	0	310(31%)
COLLUVIUM	31565 (43%)	2490 (30%)	144(14%)
OUTWASH	1370 (2%)	13 (<1%)	0
OTHER	275 (<1%)	49 (<1%)	550(55%)

Bank recession rate on Ross Lake varies with type of material, material thickness, slope, stratigraphy, and process of erosion. Bank recession rates and total bank recession are higher at class I sites in general (Table 11). For example, total bluff crest recession was 157 ft., or 7.5 ft./yr at site E-9 and 78 ft and 3.7 ft./yr. at site E-7A (Table 11). Recession rate at the four class I sites measured averages 3.4 ft./yr. Rates of bank recession are lower at class II sites, even though recreational

TABLE 10. LENGTH (ft) OF ERODING SHORELINE OF VARIOUS ASPECTS AND PERCENT OF TOTAL ERODING SHORELINE.

	ROSS	DIABLO	GORGE
N	2287 (3%)	781 (10%)	449 (49%)
NE	11119 (15%)	177 (2%)	0
E	10085 (14%)	2884 (38%)	0
SE	7523 (10%)	1755 (23%)	59 (6%)
S	2612 (4%)	764 (10%)	30 (3%)
SW	10669 (15%)	784 (10%)	26 (3%)
W	19439 (27%)	472 (6%)	0
NW	9134 (13%)	30 (<1%)	361 (39%)

activities contribute to erosion. Average annual rates of recession range from 1.86 ft./yr. at Devil's Jct. to 0.27 ft./yr at Big Beaver (Table 11). The mean annual rate of recession at recreational sites measured from dock structures to the shoreline is 0.86 ft./yr.. Average rate of recession for the lake shoreline as a whole is probably closer to that measured at recreation sites, since the class I sites represent the extreme condition. The range in rates of recession on Ross Lake from 5.5 to 0.27 ft./yr. fall within the range of those reported by Gatt and Doe (1982) for U.S. Army Corps of Engineers reservoirs. Rates reported by Gatt and Doe range from 0 to 39 ft./yr., although rates on 7 of 9 reservoirs studied were less than 10 ft./yr..

Rates of bank recession vary through time. Following clearing and flooding of the reservoir, rates were probably much higher than today as roots decayed and waves began to work on water-saturated, steep, bare slopes. Modern bluff faces, which mark the front of the retreating shore, are more resistant to erosion because they are held by vegetation. On a shorter time scale, bank recession occurs rapidly with the failure of large cohesive

TABLE 11. RATES OF BANK RECESSION AT SITES ON ROSS LAKE. METHOD 1 MEASUREMENT FROM A DOCK ANCHOR OR BULKHEAD. METHOD 2 FROM 1602 FT. ELEVATION AS DESCRIBED IN TEXT A CLASS I SITES (DISTANCE a, FIGURE 9).

SITE	LOCATION	YR. RECESSION EST. FROM	TOTAL FT. RECESSION	RATE FT./YR.	METHOD
E-9	RUBY ARM	1968	103.80	4.94	2
E-7A	RUBY ARM	1968	116.00	5.52	2
W-63	THURSDAY CR.	1968	42.80	2.04	2
W-23	COUGAR ISLAND	1968	23.50	1.11	2
E-181	BDY. BAY	1983	8.46	1.41	1
E-80	DEVIL'S JCT.	1983	11.15	1.86	1
W-125	LITTLE BEAVER	1983	2.62	0.44	1
E-134	CAT ISLAND	1976	1.97	0.33	1
W-36	BIG BEAVER	1976	1.64	0.27	1

blocks of sediment and large trees. Assuming an average bank recession rate of 1 ft./yr. for all eroding shores along the reservoir, 1.7 acres per year of land is lost to reservoir erosion.

Shorelines on Ross Lake are not in equilibrium with the reservoir environment. Active retreat is evidenced by high sediment concentrations in nearshore waters on windy days and by the amount of living vegetation falling into the lake. Detailed shore zone profiles measured at class I sites indicate that most of these areas do not have well developed shelves (or beaches) immediately offshore of bluff faces. Coarser grained colluvium eroded from the bluff faces does accumulate at the base of most sites, but is kept in transport down steep slopes by fluctuating lake levels.

The lack of stabilization of shorelines is most likely due to large pool level fluctuations. As lake level moves up and down a steep slope it continues to transport eroded material to greater depths. Sediment eroded from the modern retreating bluff, therefore, is not left near the bluff to act as a beach and absorb wave energy. This is evident as sediment aprons have formed at the base of most steep slopes. The continued movement of this material also results in continued bank recession at the edge of the reservoir.

2. Diablo Lake

On Diablo Lake 10% of the shoreline is eroding (8,040 ft. of 79,855 ft. total shore length). Diablo Lake shorelines are more stable than those on Ross Lake because much of Diablo Lake sits in a river canyon where bedrock is the most common bank material (Maps 1 and 2). Stable shores are also found at the south end of Thunder Arm, where the Colonial and Rhode Creek alluvial fans constitute a stable, low-angle shoreline (Map 1). Similarly, the north edge of the lake from the dam to Diablo Lake resort is stable because it is composed of road fill and sediments from the Sourdough Creek alluvial fan (Maps 1 and 2).

As on Ross Lake, most erosion sites and the greatest length of eroding shoreline are class II and III (Table 8). Class III sites outnumber class II sites 3 to 1 and account for 49% of the total eroding shore (Table 8). Small, planar debris slides in shallow colluvial deposits are the most frequent type of erosion at class III sites. Five class I sites covering 22% of the total length of eroding shoreline were identified (Map 3). Erosion at site 10 accounted for 76% of the total length of class I eroding shore. Erosion at these sites is dominated by slumps in thick till deposits on steep slopes. Bluff heights along the reservoir range from 1 to 13 ft..

Two boat-in camp sites on Diablo Lake are threatened by shoreline erosion. The dock bulkhead and camping areas at Thunder Point campground are threatened by recession of adjacent banks (Map 3-Sheet 3) (Photo 10). A similar pattern of erosion threatens part of the camp area at Buster Brown Camp and several other boat-in camps on Ross Lake. Colonial Creek Campground, the largest recreational development, is not threatened because it is located on the gentle slope of an alluvial fan (Figure 2, Map 3-Sheet 3).

Processes of shoreline erosion are similar to those on Ross Lake, with one exception: pool level fluctuations on Diablo Lake are not nearly as large. Waves created by boats and winds and mass movements are most likely the dominant processes, although

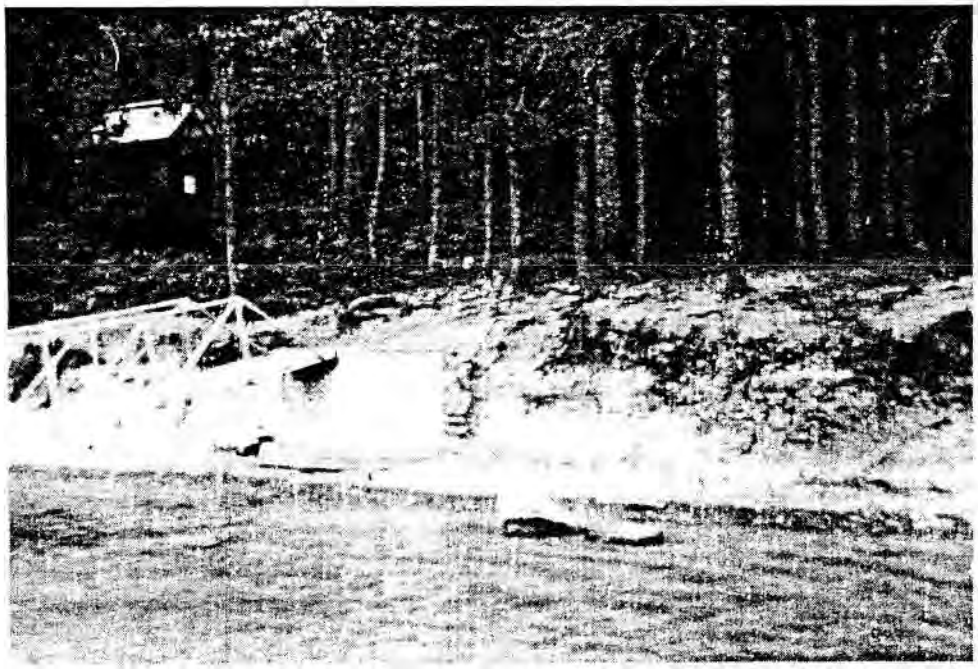

PHOTO 10. ISOLATION OF DOCK BULKHEAD AT THUNDER POINT CAMP (SITE 11, MAP 3-SHEET 3) ON DIABLO LAKE. BLUFF FORMED IN GLACIAL TILL.

freeze/thaw, ground water and overland flow probably contribute to net erosion.

Most of the eroding shoreline on Diablo Lake is composed of glacial till (Table 9). Colluvium accounts for 30% of the eroding bank material (Table 9). Erosion of colluvial banks is limited by bedrock outcrops. Over 63% of the glacial till on the lake is eroding, compared to approximately 28% of the colluvium. Therefore, the distribution of erodible sediment is one of the most important factors in the location of shoreline erosion.

Slopes above Diablo Lake shores are very steep. Landforms in the Skagit River and Thunder Creek valleys are dominated by valley walls and river canyons (Map 1). These steep slopes are a critical factor in the recession of Diablo Lake shores.

Aspect does not appear to be an important environmental factor in wave erosion, as total length of eroding shoreline is not aligned to the west into the prevailing upvalley winds (Table 4, Table 10). The large amount of eroding shoreline facing east is due to thick till accumulations on the west shore of Thunder Arm (Table 5).

Estimation of bank recession rate was limited to one site on Diablo Lake. Placement of dock anchors immediately adjacent to the shore at Thunder Point campground made it possible to measure total recession since 1976. In the 13 years since placement of the anchors the shore has receded 7.87 ft., or 0.60 ft./yr..

Considering the older age of Diablo Lake and relatively minor pool fluctuations, their shores might be expected to have adjusted to reserovir conditions. Continued bank recession on Diablo Lake, however, suggests that other environmental factors may be important, in addition to pool fluctuations. These may include the presence of steep slopes or higher than normal pool elevations.

3. Gorge Lake

On Gorge Lake 2% (925 ft. of 47,900 ft. total shoreline length) of the shoreline is in some stage of recession at 17 sites (Map 3). The small percentage of eroding shoreline on Gorge Lake compared to Diablo and Ross lakes is a result of the geographic position of the lake. Its location in a river canyon controls the landform and sediment types found there. Approximately 74% of the shoreline is stable bedrock, talus, and fill for SR20 (Table 5) (Map 2). Another 16% is relatively stable alluvial fan and debris cone deposits, although one class III erosion site is at the edge of an alluvial fan/debris cone (Map 3).

Where unconsolidated deposits are thick, erosion is severe because of the steep slopes and high winds in the river canyon. Three class I sites were identified in diamicton deposits (sites 8, 9, and 10; Map 3). All three sites have experienced relatively large (combined volume approximately 3,930 cu. yards), shallow (6 ft.), planar debris slides. The slides are all of different age, as indicated by the different age of disturbance vegetation on their surfaces. Site 10 is the most recent and has a mostly bare colluvial surface (Photo 11).

Four class II sites were also identified. A small debris slide in thin colluvial deposits was described at site 17 (Map 3), but was classified as a class II site because the slide was seated in thin colluvium surrounded by bedrock. Site one (Map 3) was also classified as a class II area. It is an eroding terrace composed of coarse, loose alluvium (Photo 12). Site five (Map 3) is in debris fan deposits, where a 50° slope is failing.

Seven of the remaining 11 sites were in isolated thin colluvial deposits and were classified as class III sites. Sites two and three are in alluvial fan/debris cone deposits 6 ft. thick, but were not classified as class II because bank slopes were gentle and there appeared to be little threat of slope failure.

The only recreational site on Gorge Lake is not threatened by bank recession. The sediment underlying Gorge Lake Campground is fill and rip-rap lines the reservoir edge of the facility (Map 2).

As on Ross and Diablo lakes the dominant processes of shoreline erosion are waves and mass movements. Freeze/thaw processes are probably not as important as on Ross Lake because of the lack of fine grained bank sediments and the lake's lower elevation.

Aspect is not an important factor in controlling shoreline erosion. The most severely eroding areas face perpendicular to predominant winds. Further, the largest length of eroding shore faces north, followed by northwest (Table 10).

As on the upvalley reservoirs, the location of erodible material and steep slopes are the most important environmental factors. Forty percent of erodible sediments, including diamicton, colluvium and alluvium, are eroding (Tables 5 and 9). Bedrock, road fill and talus are stable deposits.

Bank recession at site 10 was 16.78 ft. or 0.60 ft./yr. since 1961 when the modern Gorge Dam was closed. At site 5, average annual recession was 1 ft./yr. or 28.4 ft. since 1961. Bank recession at most sites is probably sporadic, with higher rates during slope failure after longer peroids of wave undercutting of slopes creating conditions for slope failures.

Gorge Lake shoreline slopes have not adjusted to reservoir conditions. The continuing instability of Gorge Lake's shores is probably a result of steep slopes, the age of the reservoir, pool level fluctuations and intense winds.

PHOTO 11. RECENT DEBRIS SLIDE AT SITE 10 ON GORGE LAKE
(CLASS I, MAP 3, SHEET 4).

PHOTO 12. BANK RECESSION AT SITE 1 ON GORGE LAKE (CLASS II, MAP 3, SHEET 4).

VI PROJECT EFFECTS ON THE SKAGIT RIVER AND ITS TRIBUTARIES

A. INTRODUCTION

Dams alter river systems by inundating valleys with water, modifying discharge patterns and truncating sediment supply to downstream river segments. River adjustments to variations in discharge and sediment supply below dams include changes in: (1) channel bed elevation (typically degradation); (2) channel width; (3) bed material size; (4) vegetation cover; (5) water discharge; and (6) sediment load (Williams and Wolman, 1984). Changes in sediment load and bed material size are difficult to determine for several reasons. First, pre-project data on sediment load and bed material have not been collected on the Skagit River. Second, collection of this data is difficult and costly. For these two reasons, analysis of the project on these features of the Skagit River are left to future studies. The analysis and discussion below focus on changes in discharge, channel shape, channel elevation and channel position as they relate to river erosion.

Schumm and Brackenridge (1987) identify discharge and sediment supply as the primary independent factors that determine river channel stability and morphology. Channel stability refers to the shifting of a river in the landscape, whereas channel morphology refers to the shape of the channel. Changes in channel position (stability) and shape are natural processes that occur as rivers adjust to changes in environmental conditions. Further, changes in position and shape result in erosion at both the bed and banks of a stream.

Erosion at the stream bed can result in a lowering of the bed elevation (scouring and incision), increases in the size of sediments found on the bed of a stream (armoring) and alteration of channel shape. Erosion along the banks influences channel position in the landscape, which in turn controls channel morphology and the introduction of sediment into the river.

Becuase of the natural variability of rivers, assessing the effect of the project on the Skagit River is difficult. Natural variation in the Skagit River system and its hydrology are discussed below in order to put the effect of the project into context.

B. AREAS OF CONCERN

Within the study area there are four sections of the Skagit River that flow freely (Figure 2). These reaches, however, differ in several respects based on their location in relation to project. The first, between Newhalem and Bacon Creek, is below the lowest (Gorge) dam. Discharge in this segment is regulated and water released from Gorge Dam and powerhouse is sediment free. Between Newhalem and Damnation Creek the river meanders across its floodplain between tributary alluvial fans, valley walls and terraces. Below Damnation Creek, where the river has incised into landslide deposits, the river banks are steep, and channel bars and low terraces are absent. Downstream of the landslide area the river again meanders on its floodplain. The second section of the Skagit River, between Gorge Dam and Newhalem, is normally dry but has a small discharge from tributary streams. Discharge is occasionally supplemented by water spilled from Gorge Dam. The third is a short segment between Diablo Dam and the head of Gorge Lake. Flow in this part of the river is regulated daily by discharge from the powerhouse and the level of Gorge Lake. The fourth, at the head of Ross Lake, is inundated by Ross Lake during the summer, but the rest of the year flows unregulated across the lake bed. Major tributaries in the project area include, from north to south, Silver, Little Beaver, Lightning, Devil's, Big Beaver, Ruby, Thunder, Stetattle, Gorge, Newhalem, Goodell, Damnation, Alma and Copper creeks (Figure 1).

C. NATURAL VARIATION IN RIVER PROCESS AND MORPHOLOGY.

Natural changes in river processes and morphology are generally a function of climatic change, although other events such as landslides are also important. Climatic change results in variations in runoff (discharge) and sediment supply. Since the original Gorge Dam was completed in 1925, upstream sediment supply to the river below Newhalem from the upper Skagit basin has ceased and discharge has been regulated. Not until closure of Ross Dam, however, was discharge regulated to a great degree. Few data are available to reconstruct natural variations in the river system over the last 10,000 years. Analysis of the information that has been collected on the Skagit River and comparison with better understood river systems is used here to reconstruct past events and conditions.

At the end of the last ice age, the Skagit River was a braided stream that deposited glacial outwash sediment to thicknesses of several hundred feet. As the glaciers disappeared, decreased sediment supply caused the river to cut 100 ft. into its valley fill, which left several high elevation terraces in the valley. Incision of the glacial valley fill probably was complete early in the Holocene (around 8,000 YBP).

The activity of the river since the last ice age was punctuated by two events. The first event was the damming of the Skagit River around 6,700 YBP by landslide activity between Bacon and Damnation Creeks. Before the river could breach and incise through the landslide, a large lake was created in which large quantities of fine grained sediment (including volcanic ash) were deposited. As the lake drained, the river rapidly cut the lake deposits into terraces that stand 70 ft. above the modern river. The river now has a steep gradient through the landslide deposits, and a straight, relatively stable channel.

The second major event influencing the Skagit River system since the last ice age was a change to a cooler, moister climate since approximately 6,000 YBP (Denton and Porter, 1970; Barnosky, 1981). During this period glaciers in the North Cascades have advanced and retreated several times in response ot cooler moister climates (Riedel, 1987). In response to increased runoff and sediment yield within the last 6,000 years, the river has deposited as much as 6 ft. of alluvium on low terraces and on its floodplain. In response to the assumed increase in flooding and sediment input, channel position probably shifted frequently on the floodplain, but remained more stable within the landslide zone and canyons.

Shorter term climatic fluctuations within the last few hundred years have also influenced the Skagit River and the geomorphology of its floodplain. Although little data is available, floodplain building was still active at the time of project construction, as indicated by the presence of abandoned channels and island formation and attachment to banks.

The modern Skagit River's coarse-grained sediment load is transported predominantly along its bed (i.e. as bed load). Sediment is moved through the river system sporadically and is stored within the system as gravel bars, which create riffles (high spots on the bed of a river). Finer sediment is stored in deeper, quieter sections (pools) between riffles.

Heavy vegetation cover along its banks reduces the rate of bank erosion along the Skagit River. River banks are subject to erosion on the outside of meander bends and when channel position shifts in response to blockage of the main channel or the opening of new channels during high (flood) discharges. Bank materials in the Skagit Valley are composed of a variety of material, including landslide deposits, volcanic ash, alluvium, bedrock, talus, colluvium, artificial fill, till and glacial outwash. Alluvium composes most of the bank material, but varies from fine sand and silt, to coarse gravel and cobbles.

D. HYDROLOGY AND DISCHARGE

The Skagit River above Marblemount drains over 1,380 square miles of the North Cascades, 381 of which are in Canada (Figure 1). The maximum recorded discharge before dam construction was 60,000 cubic feet per second (cfs) during a winter flood in 1922 (Figure 10). Stewart and Bodhaine (1961) estimated discharge at 105,000 cfs for an 1815 flood. Mean discharge of the Skagit River at the Newhalem gauging station over the past 27 years was 5,800 cfs. The lowest recorded discharge at this station was 54 cfs in 1943.

There are two general types of floods on the Skagit River (Stewart

Annual Peak Discharge
Skagit River at Newhalem

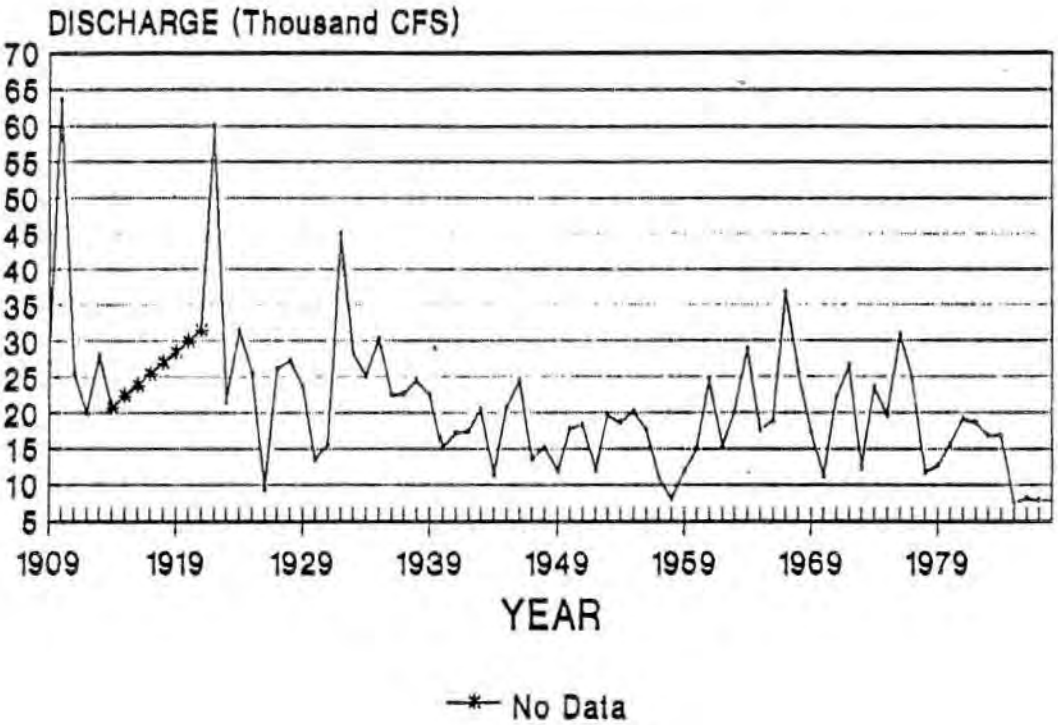

FIGURE 10. ANNUAL PEAK DISCHARGE OF THE SKAGIT RIVER AT THE NEWHALEM GAUGING STATION SINCE 1909. DATA FROM THE U.S.G.S..

and Bodhaine, 1961). Winter floods occur as a result of heavy precipitation, whereas spring floods occur primarily because of the melting of mountain snowpack. Winter floods have higher flood discharge peaks, but are of shorter duration and smaller volume than spring floods (Stewart and Bodhaine, 1961). Floods also occur during spring and fall in response to rapid rises in snow level, which result from warm rains on preexisting snowpack. Snowpack depth and water content are measured several times during the winter by helicopter surveys and automatically at snotel stations located throughout the area.

E. METHODS

Several methods were used to assess changes in channel shape, elevation and position. Airphotos taken in 1956 and 1978 and a videotape made in 1989 were used to assess changes in channel position and channel shape. Gauging station records from two locations below Newhalem were used to identify changes in channel shape and bed elevation (Figure 11). The gauging stations are located in areas with stable banks where there are consistent relationships between river height and discharge. Therefore, data collected at these locations may not reflect changes in less stable areas. The gauging stations, however, are the only areas where detailed measurements of channel shape are available. Where possible, comparisons were made between pre-project records and those collected since project construction to assess natural variation. Such information was not available for any part of the Skagit River above Newhalem. Records from the Newhalem gauging station date to 1908, although some data from 1908-1963 are currently missing. The Alma Creek gauge has been in operation since 1943 and all records were available. Rating tables, which are measured periodically, were used to assess changes in mean bed elevation. A rating table compares measured discharge to a given fixed gauge height (elevation). Changes in this relationship were used to approximate a mean change in elevation (Williams and Wolman, 1984). Discharge measurement notes were used to plot channel cross sections through time. The limited availability of pre-project data and natural variation of the Skagit River limited the depth of analysis and scope of the conclusions.

F. RESULTS AND DISCUSSION

1. Tributaries

Tributaries in the study area are affected by the project in two ways: either they are flooded or they are channelized through developed areas. Channelization adjacent to bridges and towns results in channel incision into the river bed. The drainage and channel position of all tributaries below Diablo Dam on the north side of the valley are affected by project roads and developments.

In the reservoirs, erosion at tributaries occurs at the mouth of

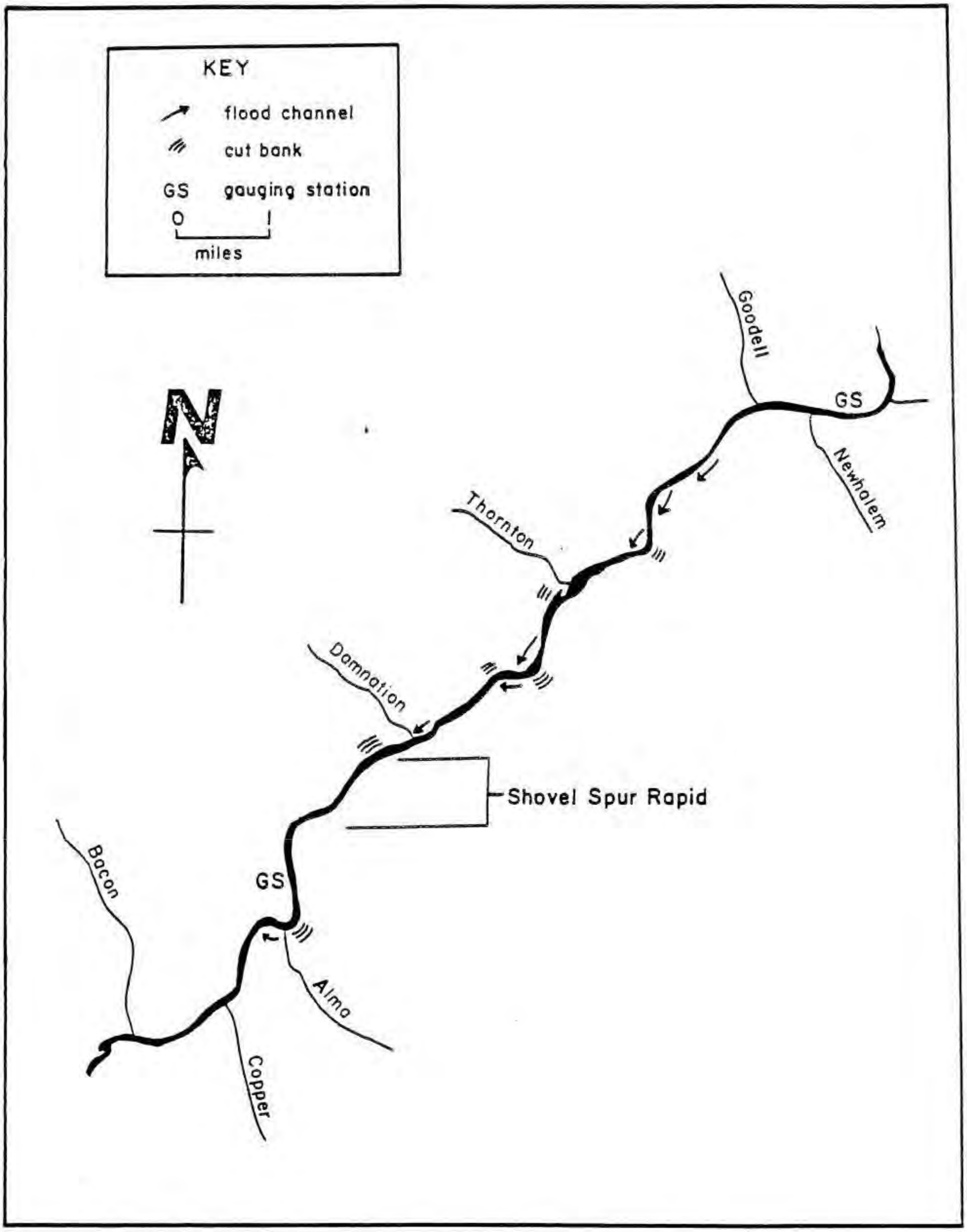

FIGURE 11. THE SKAGIT RIVER BETWEEN NEWHALEM AND BACON CREEK.

every tributary exposed in a drawdown. Erosion of sediment deposited in a deltaic environment by streams that flow into the reservoir is cyclic. These streams deposit sediment when the lake is full and subsequently erode and transport the sediment to lower elevations as lake level drops. This phenomenon is most pronounced in larger tributary streams that carry sediment eroded by glaciers, such as Thunder, Big Beaver and Little Beaver Creeks, but was observed in streams of all sizes.

2. Upper Ross Lake

The Skagit River at the head of Ross Lake is subject to seasonal cycles of erosion and deposition. During high lake levels the river deposits its sediment load into the low-energy environment of the reservoir. During low lake levels this sediment is eroded by the river as it meanders across its floodplain.

The banks of the river in the drawdown are composed of alluvium deposited before the project, and fine silt and clay deposited by the river into the reservoir. Erosion of the river banks is accelerated because there is no vegetation to stabilize them.

Old channel scars and oxbow lakes are scattered across the floodplain in the midvalley and upvalley portions of the Ross Lake basin. These features underscore the instability of the Skagit River's position before project construction. The loss of vegetation, therefore, should result in increased channel instability on the Ross Lake drawdown. Near Hozomeen the river has changed its course since Seattle City Light mapped the area in 1933. The river now flows in a new channel to the west of its 1933 location. Farther upstream the Skagit changed position three times between 1949 and 1971, eliminating sharp bends (I.J.C., 1971).

3. Diablo

Between Diablo Dam and the head of Gorge Lake the Skagit River flows through a steep canyon before the valley widens at the mouth of Stetattle Creek. The upper portion of the river flows only when water is spilled from Diablo Dam, an infrequent event. Below Diablo Powerhouse the river has a more consistent discharge.

A survey of this section of the river identified only one area of former streambank erosion upstream of the Diablo Powerhouse. The area is now rarely affected by river erosion and is becoming stabilized by vegetation. The remaining stream bank areas in this stretch of the river are stable because they are composed of bedrock and rip-rap placed by Seattle City Light to protect the town of Diablo.

4. Gorge Bypass

Diversion of water from Gorge Dam through a five mile bedrock tunnel leaves a three mile stretch of the Skagit River dry (Figure 16B). The river in this section flows through a steep river canyon. No areas of streambank erosion were noted in a reconnaissance survey.

Skagit River discharge in the bypass and below Diablo Dam is regulated by release of water from Diablo Dam and Powerhouse, and from Gorge Dam, respectively. Discharge of the Skagit River at the head of Ross Lake between 1916-1922 and 1935-1955 varied from a peak of 10,200 cfs to a low of 81 cfs, with a mean flow of 1,000 cfs (I.J.C., 1971).

5. Below Newhalem

a. discharge

The storage capacity of the three project reservoirs (Table 1) has moderated flooding in the Skagit Valley below Newhalem. Ross Lake provides the majority of the storage capacity for the system, with 120,000 acre-feet of winter storage capacity (maximum drawdown with continued generation capability). Reservoir storage has eliminated floods over 40,000 cfs (Figure 10).

Floods over 20,000 cfs play an important role in determining channel morphology and position on the floodplain. According to the Copper Creek Dam EIS, the bed of the Skagit River is generally stable below 20,000 cfs (Seattle City Light, 1981). The river's coarse bedload protects the river bed from scouring at lower discharges. High discharges also flood out and modify riffle and pool sequences and can create new channels and abandon others. The net effect of large floods is to remove fine material from the channel and armor the bed of the stream with material that can not be moved during low flows.

The effect of the project on the river environment is also identified by changes in bankfull discharge. Bankfull discharge occurs when a river channel is filled to a level equal to the top of its point bars. It typically represents the most frequent flood discharge for a given river, with a recurrence interval of 1.5 to 5 years (Wolman and Leopold, 1957; Brown, 1971; Richards, 1982). On the Skagit River below Newhalem, Conner (1989) estimated that bankfull discharge before the project was 21,000 cfs. His estimation of post-project bankfull discharge is 11,000 cfs, although he does not examine long term trends in discharge associated with climatic change. If Conner's estimates are correct, however, the river has become narrower in response to decreased discharge.

Below Newhalem, discharge is also affected by the demand for electricity, which causes small variations in the amount of water released. The amount of water released from Gorge Powerhouse (Figure 2) is typically 2,000-3,000 cfs greater during peak demand for electricity (e.g. 6 AM to 10 PM) than during periods of low demand (10 PM to 6 AM). This variation in discharge results in water-level fluctuations of one to two ft. at Marblemount. Further, the rate of change in discharge is 2,000 cfs/hour (ramp rate) as limited by flow agreements.

Agreements and flow restrictions in 1981 and 1984 set guidelines for stabilizing river flow during fall and early winter salmon spawning periods. In general, the 1981 agreement limited maximum discharge on the Skagit River below Gorge Powerhouse to 5,000 cfs or less between mid-August through December. The 1984 agreement further reduced flow fluctuations around 3,000 cfs between mid-November and January 6.

b. channel position

Changes in the location of the Skagit River channel below Newhalem since 1956 have been minor. Several cutbanks on the outside of meander loops are still active, but no major channel shifts have occurred between 1956 and 1989 (Figure 11). Flood channels are still occupied during high discharge events, which have not been completely eliminated by the project. One island below Goodell Creek has completely disappeared. Six other islands in the channel have had minor modification in their morphology. In general, they appear to have become more stable, as indicated by the growth of shrubs and trees on their surfaces. These islands are covered during discharges of 20,000 cfs or greater.

Potential locations for future changes in channel position include the borrow pits on the north side of the river (Figure 1), along flood channels and near large meander loops (Figure 11). Minor changes in channel position will occur where cutbanks erode into terraces at the outside of meander loops. The borrow pits are on low terraces that will be inundated by the largest floods (>30,000 cfs). It is possible that the long, narrow ponds will become favored positions for future channels should the narrow dikes erode.

The overall effect of the project appears to have been to increase stability of the Skagit River channel. Armoring, a 50% decrease in bankfull flood discharge and elimination of flood events in excess of 40,000 cfs are responsible for increased stability. As a result of increased stability of the river and protection by riprap, developed areas within the study area are not threatened by river erosion. The introduction of sediment into the river by bank erosion associated with changes in channel position, however, has probably decreased.

c. channel shape

Change in the shape of the channel of the Skagit River since project dam closure was examined at the Newhalem and Alma Creek gauging stations. At the Newhalem gauge, pre-project data were unavailable. Slight changes in the profile since 1969 indicate the channel has changed little in the last 20 years (Figure 12). The deepest part of the channel remained on the south side of the river and the only noticeable change was apparent deposition (aggradation) at the cross section between 1969 and 1989. This was an unexpected change because the sediment supply to this portion of the river is limited to sediment moved through the bypass by releases of water from Gorge Dam and by Ladder Creek.

There are several possible explanations for the stability of the channel, including vegetation holding banks, armoring and measurement error. Livesey (1965) reported that as little as 50% cover of coarse material on the bed of a stream is enough to successfully armor a bank and prevent incision. Since the Skagit is a bed-load stream, coarse material is available to armor the bed. Thick vegetation cover and rip-rap also limit changes in channel shape at the gauging station site. Finally, the change may be within the range of measurement error.

At the Alma Creek gauge longer records were available. Since 1951 the only notable change was a shift of position of the main channel to the south side of the river between 1951 and 1953 (Figure 13). No large floods that may have caused a change in the channel occurred between measurement of the 1951 and 1953 cross sections. The cause of this minor change cannot be attributed to closure of Ross Dam because records are not long enough to permit assessment of natural variability at the site. The change in channel position, however, did occur shortly after completion of the final stage of Ross Dam. This change may have been caused by changes in discharge associated with the project. No major changes in channel shape have occurred since 1953 (Figure 13).

d. bed elevation

The mean elevation of the bed at the Newhalem gauging station has not changed more than .25 ft. since 1920 (Figure 14). Further, there has been no apparent major trend in the bed elevation. The changes that have occurred fluctuated within 0.25 ft. above the 1920 elevation (Figure 14). Minor degradation of the bed (<0.1 ft.) occurred following initial closure of Ross Dam in 1943, but since 1960 the bed has aggraded some 0.25 ft. (Figure 14). Considering the small amount of overall change in the bed elevation, these changes could be attributed to natural variation or measurement error.

At the Alma Creek gauge the river degraded almost 0.6 ft. between 1943 and 1950 (Figure 15). The timing of the degradation coincides with the closure of Ross Dam in stages between 1943 and 1959. Since this degradation closely followed the closure of Ross Dam, and because no change of this magnitude has occurred since 1950, despite several large floods (Figure 10), the

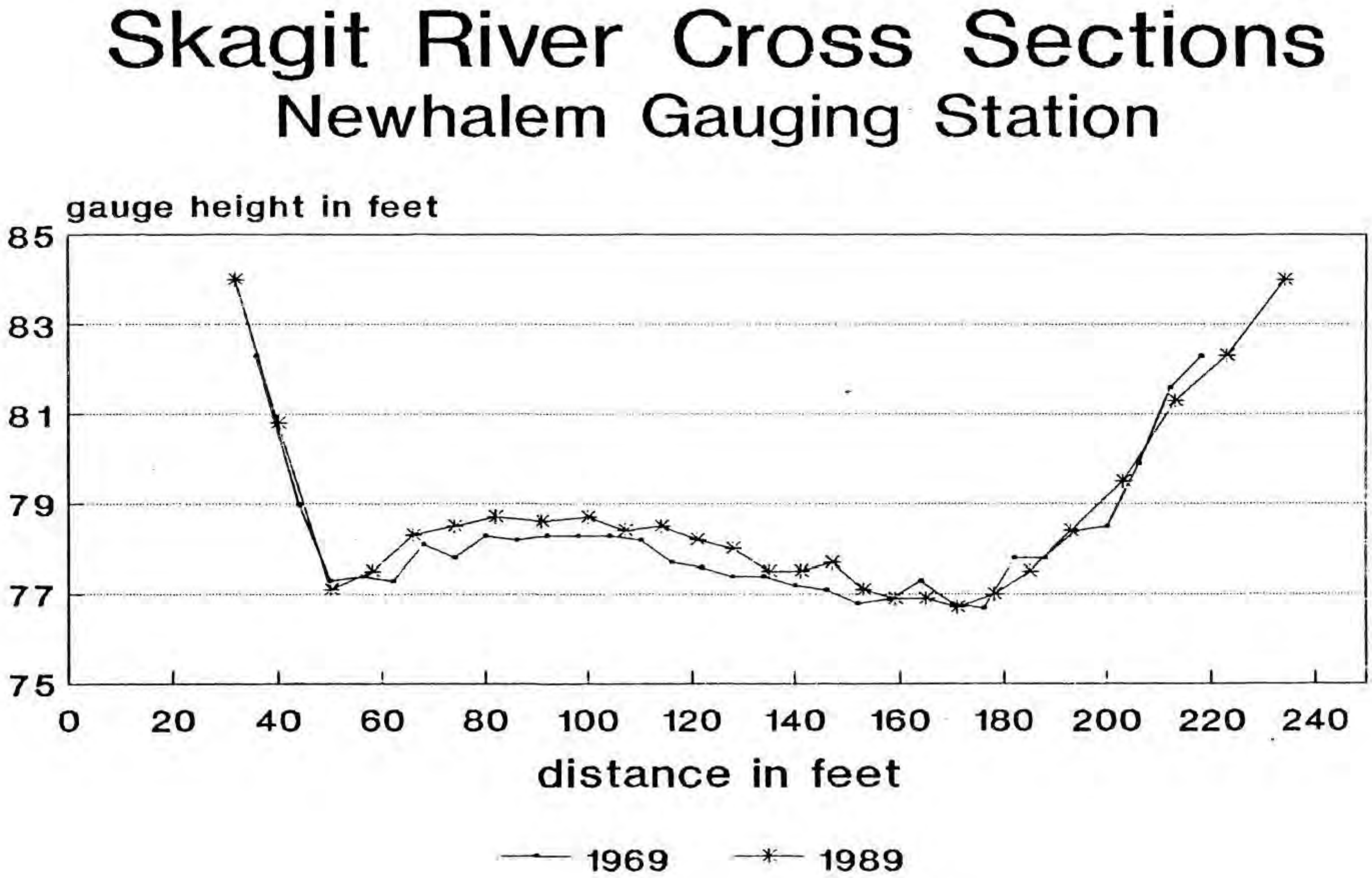

FIGURE 12. CHANGES IN A SKAGIT RIVER CROSS SECTION AT THE NEWHALEM GAUGING STATION. SEE FIGURE 11 FOR LOCATION. DATA FROM THE U.S.G.S..

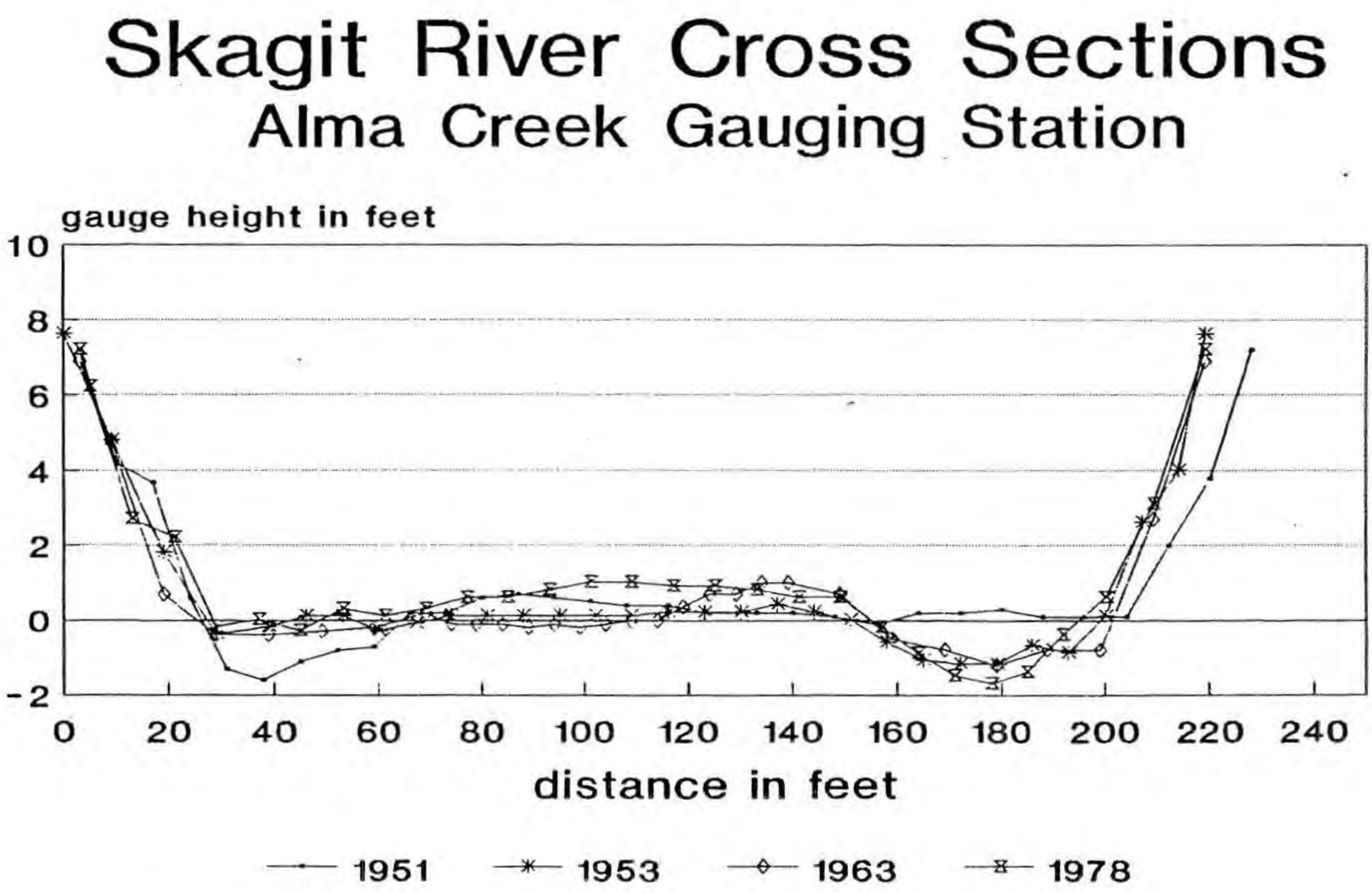

FIGURE 13. CHANGES IN A SKAGIT RIVER CROSS SECTION AT THE ALMA CREEK GAUGING STATION. SEE FIGURE 11 FOR LOCATION. DATA FROM THE U.S.G.S..

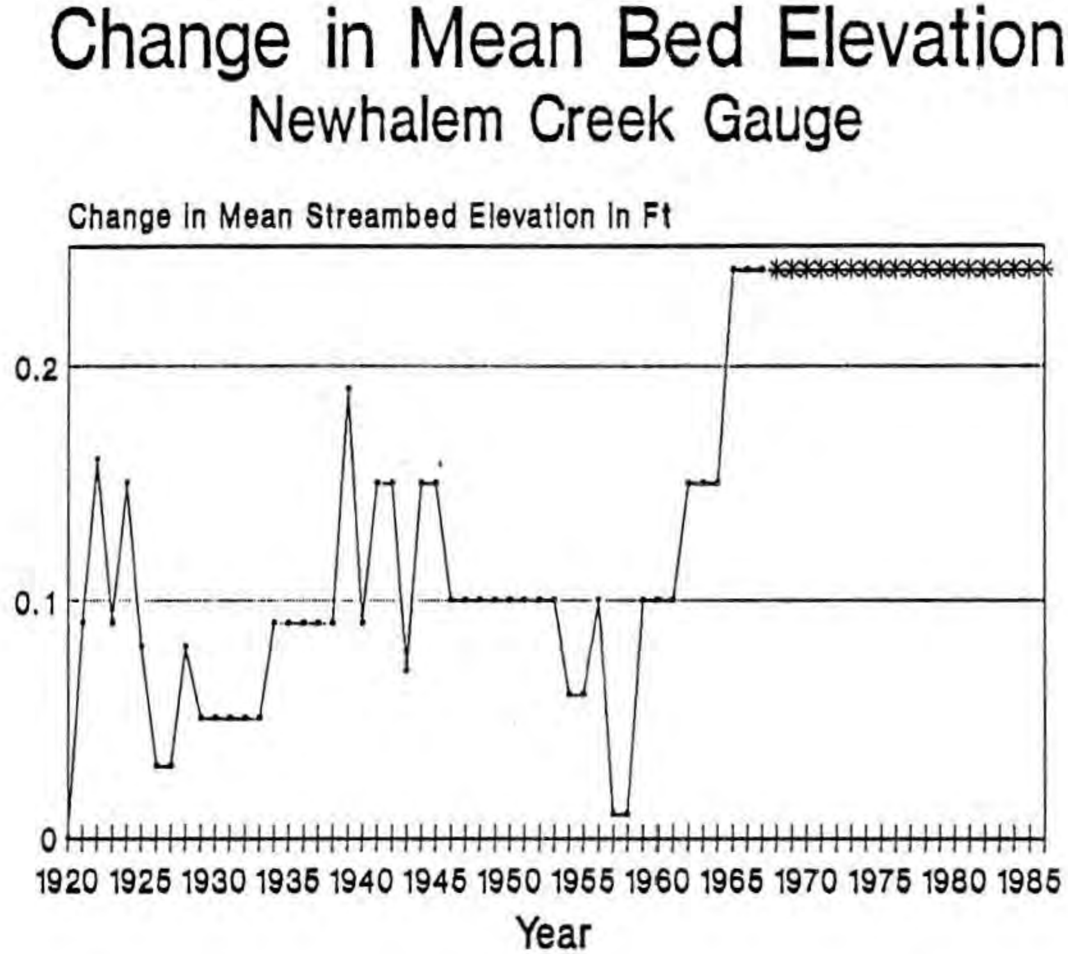

FIGURE 14. CHANGE IN MEAN BED ELEVATION AT THE NEWHALEM GAUGING STATION BETWEEN 1920 AND 1988. SEE FIGURE 11 FOR LOCATION. DATA FROM THE U.S.G.S..

Change in Mean Bed Elevation
Alma Creek Gauge

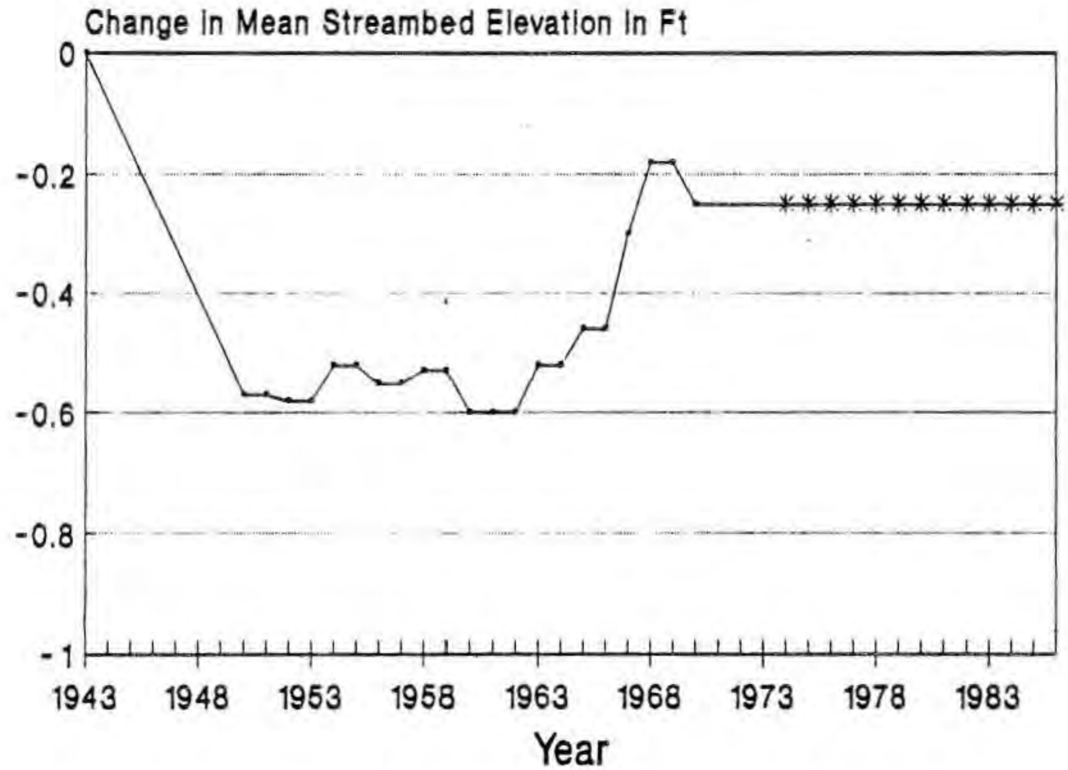

FIGURE 15. CHANGE IN MEAN BED ELEVATION AT THE ALMA CREEK GAUGING STATION BETWEEN 1943 AND 1983. SEE FIGURE 11 FOR LOCATION. DATA FROM THE U.S.G.S..

degradation may be related to the project. A possible mechanism is incision with decreased discharge as Ross Lake filled.

From 1950 to 1966 at the Newhalem gauging station the bed elevation fluctuated within a range of 0.1 ft.. Since 1968 the bed elevation has risen approximately 0.4 ft.. This rise in bed elevation occurred after two large floods in 1967. The largest, at 36,700 cfs on June 21, was the largest since closure of Ross Dam. Although speculative, it is tempting to relate the occurrence of the flood with aggradation at the Alma Creek station.

The response of bed elevation to dam closures on the Skagit River contrasts sharply with the effect of dams on Great Plains rivers. Williams and Wolman (1984) found that bed degradation occurred on all of the 21 rivers they studied. The reason for the different response of the Skagit River compared to the other rivers may relate to the fact that the Skagit is a bed-load stream. Initial incision following dam closure was probably limited at the Newhalem gauge by bed armoring. In the case of the Alma Creek Station, sediment supplied by Goodell and Newhalem Creeks may have been enough to effect the bed elevation.

VII. EROSION NEAR ROADS AND POWERLINES

There are approximately 14.8 miles of gravel roads in the project area. Most of the roads are accessed from state highway 20 (SR20). They are not used during winter (with one exception) and function mainly as access routes to remove vegetation from beneath transmission lines. In addition, there are several more miles of paved roads in the communities of Diablo and Newhalem and near Diablo Dam. A survey of the paved road system did not identify any erosion problems.

The transmission line access roads are located on a variety of landforms. Landforms where erosion problems occur are steep slopes along valley walls and landslides. Roads on floodplains, terraces, alluvial fans and other low slope areas do not have erosion problems.

Along steep valley walls and in the landslide area near Damnation Creek, minor erosion problems related to the gravel roads are associated with small slope failures at the top of road-cuts on steep slopes. In many of these areas soils are generally thin, limiting the possible future extent of erosion. The steep slopes along much of the transmission line corridor are prone to mass movements without the effects of the roads on surface water drainage. Several miles of the corridor are located on massive landslide deposits between Bacon and Damnation creeks. Survey of the towers from a helicopter detected no erosion problems.

Erosion of road fill material can occur where roads interrupt the drainage of small streams and where the material fails on steep slopes. Small streams generally flow beneath the roads through culverts and along them in ditches. Problems occur where culverts are too small to handle peak discharge, when culverts become plugged, forcing water onto the roads and where there are no culverts or ditches to direct water flow away from the roads.
Twelve road segments were surveyed on foot (Figures 16 A,B,C,D). No major problems were discovered on the transmission tower access road system. Several sites were identified, however, where culverts were subject to filling and small intermittent streams and seeps eroded roads. Small mass movements are occurring that may in part be caused by and effect certain roads. Detailed location and description of these sites is presented in the erosion control plan.

A. Ross Dam Road (Location A, Figure 16A)

A road leading from the east end of Diablo Lake up to Ross Dam an down to Ross Lake is located in a steep river canyon. The road is blasted through bedrock in a 200 ft. tunnel and cut through

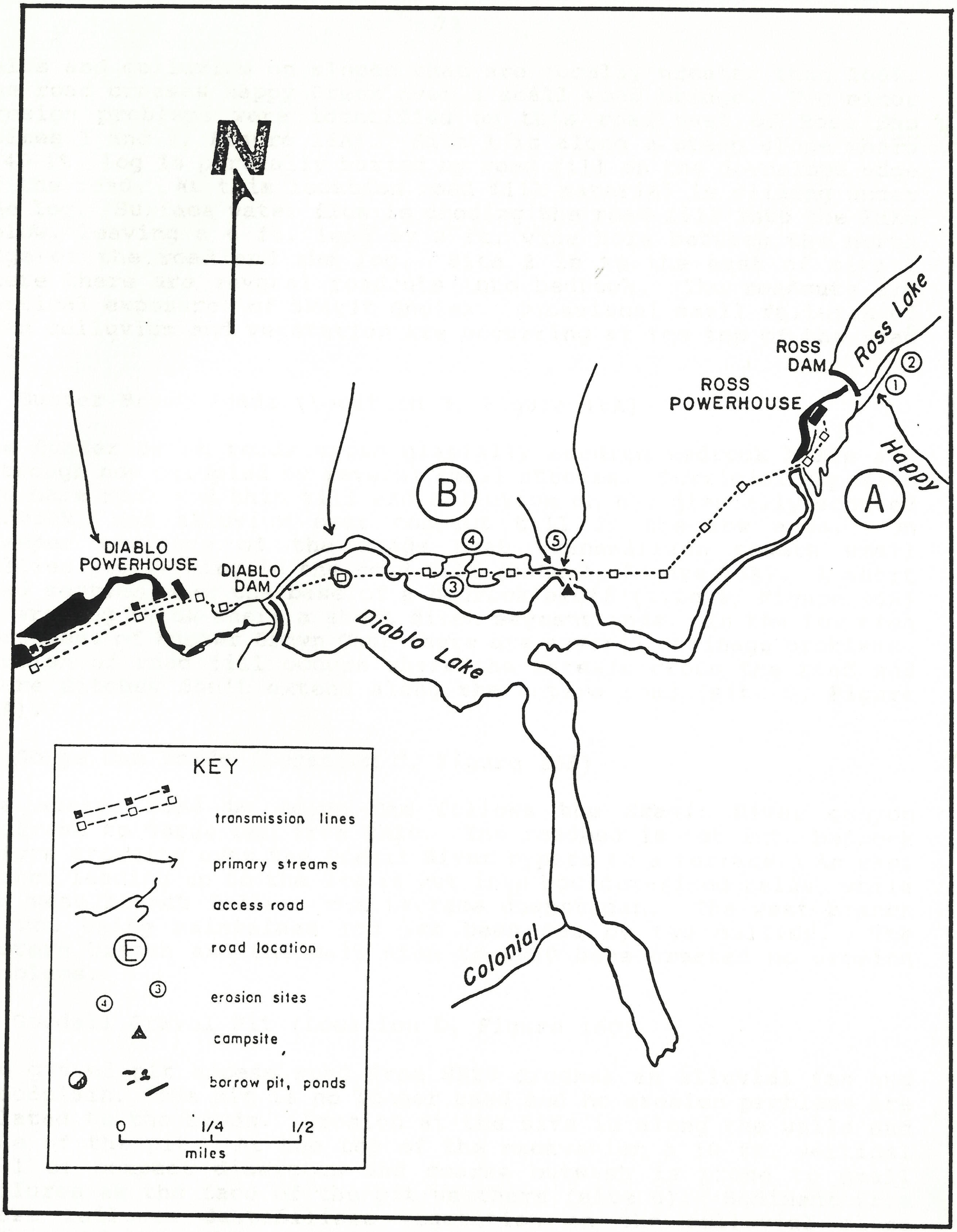

FIGURE 16A. ROAD AND EROSION SITE LOCATIONS.

talus and colluvium on slopes that are locally greater than 100%. The road crosses Happy Creek over a small wood bridge. Two minor erosion problems were identified on this road east of Ross Dam (sites 1 and 2, Figure 16A). Site 1 is along a steep slope where a 40 ft. log is partially buried by road fill on the downslope edge of the road. At this location road fill material is sliding under the log. Surface water flow is eroding the road fill into the lake below, leaving a 6 ft. long by 2 ft. wide hole between the north edge of the road and the log. Site 2 is to the east of site 1 where there are several roadcuts into bedrock. The roadcuts are vertical exposures of Skagit Gneiss. Occasional small failures of thin colluvium and vegetation are occurring at the top of the road cut.

B. Buster Brown Roads (Location B, Figure 16A)

The Buster Brown roads cross glacially scoured bedrock hills and a trough now occupied by several small streams. Surficial deposits are bare rock and thin till and colluvium on the glacially scoured bedrock, and alluvium over compact till in the low area. On steeper sections of the roads near transmission towers small gullies are forming in the road fill (site 3, Figure 16A). A short road section near the base of a bedrock bluff (site 4, Figure 16A) is eroding below where a short ditch segment ends. In the low area northwest of Buster Brown Camp there are several drainage problems. Erosion of road fill occurs where the streams cross the road and where ditches don't extend along the entire road (site 5, Figure 16A).

C. Gorge Dam Roads (Location C, Figure 16B)

The access road to Gorge Dam follows the Skagit River canyon upstream to Gorge Dam from SR20. The roadbed is cut into bedrock before crossing over the Skagit River bypass to a terrace. An east branch leading up to the dam is cut into boulder-sized talus, while the west branch follows the terrace downstream. The west branch is not being maintained and has been cut by two gullies. The eastern branch and the main stem to SR20 have created no erosion problems.

D. Goodell Gravel Pit (Location D, Figure 16C).

The gravel pit access road from SR20 crosses an alluvial fan and floodplain. The pit is no longer used and no erosion problems are related to the roads. Erosion at the site is along the walls and face of the pit. At the top of the excavation a 10 ft. vertical wall of compact diamicton and coarse outwash is prone to small failures as the face of the pit weathers (site 6). Sediment from these failures destabilizes vegetation on the colluvial slope below, which is also eroded by surface ravelling. None of the pit material is moving into Goodell creek. A campground access road

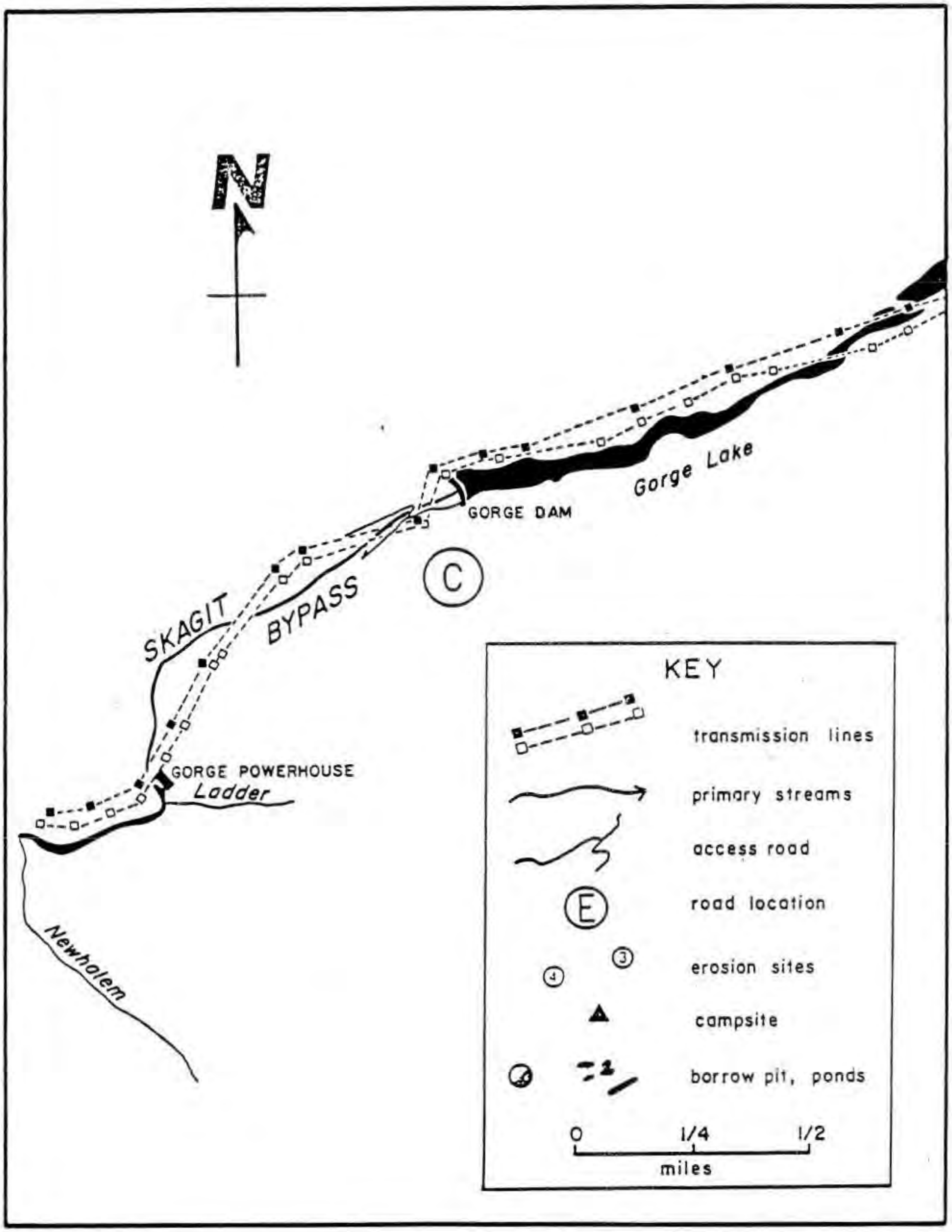

FIGURE 16B. ROAD AND EROSION SITE LOCATIONS.

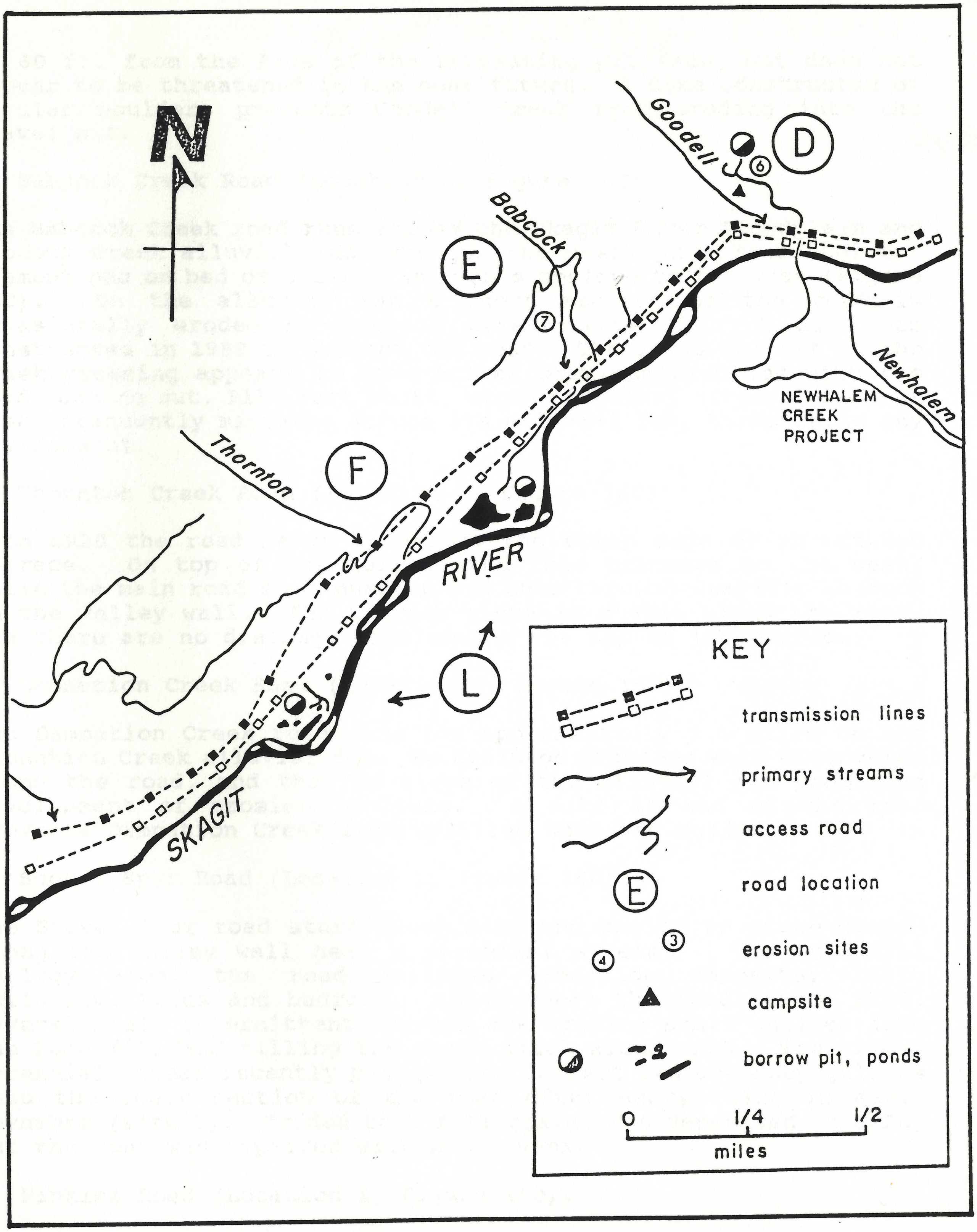

FIGURE 16C. ROAD AND EROSION SITE LOCATIONS.

is 60 ft. from the face of the retreating pit face, but does not appear to be threatened in the near future. A dike constructed of angular boulders prevents Goodell Creek from eroding into the gravel pit.

E. Babcock Creek Road (Location E, Figure 16C).

The Babcock Creek road runs across the Skagit River floodplain and Babcock Creek alluvial fan, crosses the creek on a Texas Culvert (cement pad on bed of creek), and heads upslope to the west (Figure 16C). On the alluvial fan a short segment of the road is occasionally eroded by Babcock Creek (site 7). A dike was constructed in 1988 to protect the road. The Texas Culvert at the creek crossing appears to have solved previous problems with the road washing out. Like most short, steep tributary streams, Babcock Creek frequently migrates across its alluvial fan, threatening any development.

F. Thornton Creek Road (Location F, Figure 16C).

From SR20 the road heads up across the steep edge of an outwash terrace. On top of the terrace the road branches to the west, while the main road continues up and cuts through granitic bedrock on the valley wall. The terrace slope is stable along the road, and there are no drainage problems on the top of the terrace.

G. Damnation Creek Road (Location G, Figure 16C).

The Damnation Creek road runs for approximately 0.5 miles on the Damnation Creek alluvial fan. No drainage problems were discovered along the road, and the low slope of the alluvial fan precludes development of erosion problems. A dike at end of the road prevents Damnation Creek from spilling onto the roadway.

H. Shovel Spur Road (Location H, Figure 16D).

The Shovel Spur road starts from SR20 and angles up steep slopes along the valley wall near a perennial stream. The surficial geology along the road includes landslide deposits, till, colluvium, talus and bedrock. Above where the road leaves SR20, several small intermittent streams are eroding small gullies into the road fill and filling the small ditch along SR20. The larger perennial stream recently plugged its culvert and cut deep gullies into the lower section of the road after heavy rains in early November (site 8). Eroded road fill gravel was deposited on SR20, but the road was repaired within the week.

I. Pinkies Road (Location I, Figure 16D).

Pinkies road consists of several interconnecting roads with two access routes from SR20 (Figure 16D). The roads all lie on hummocky landslide deposits where slopes are locally very steep.

In general, the roads avoid all major drainages. A problem area, however, is at the southeast end of the road system, where several small streams are interrupted by the road (site 9). One stream flows along the road for several hundred feet before disappearing beneath the road and emerging on the slope below the road. The northeastern most branch traverses a 100% slope, creating a 20 ft. tall road cut (site 10). Landslide deposits and colluvium are failing on the upper edge of the road cut.

J. Benches Roads (Location J, Figure 16D).

Benches road begins from SR20 and angles up the edge of an outwash terrace. The road then branches to the northeast and southwest onto hummocky landslide deposits (Figure 16D). The northeastern most road ends less than 200 ft. from the location of a small slump (site 11). The head of the slump continues along a 120% slope as a crack toward the road, and could possibly threaten it. Site 12 is located just west of where the road splits after leaving the terrace (Location J, Figure 16D). A small debris slide beneath the road is spreading to the southwest because water from a culvert under the road is being directed onto the unstable slope. Farther up the southwest branch of the road, three small intermittent streams flow across the road and are eroding the road fill (site 13). At the end of this branch of Benches road, landslide and colluvial sediments are sliding off of the top of a large roadcut (site 14). Retreat of the banks will be minimal because the soil is thin.

K. Hardin Road (Location K, Figure 16D).

Beginning from SR20, Hardin road traverses the steep edge of an outwash terrace before crossing onto a steep valley wall. Near the top of the road an 80 ft. crack has developed in the middle of the road (site 15). Continued growth of the crack will lead to failure of at least the road fill down a 130% slope. A second site is at the end of the road where colluvium is sliding off of the top of a 15 ft. high road cut (site 16). It is unlikely that any larger slide will occur here.

L. Aggregate Pond Roads (Location L, Figure 16C).

The roads all lie on flat terraces less than 10 ft. above the Skagit River. Erosion problems were not identified on any of the roads. No large streams drain into the aggregate ponds.

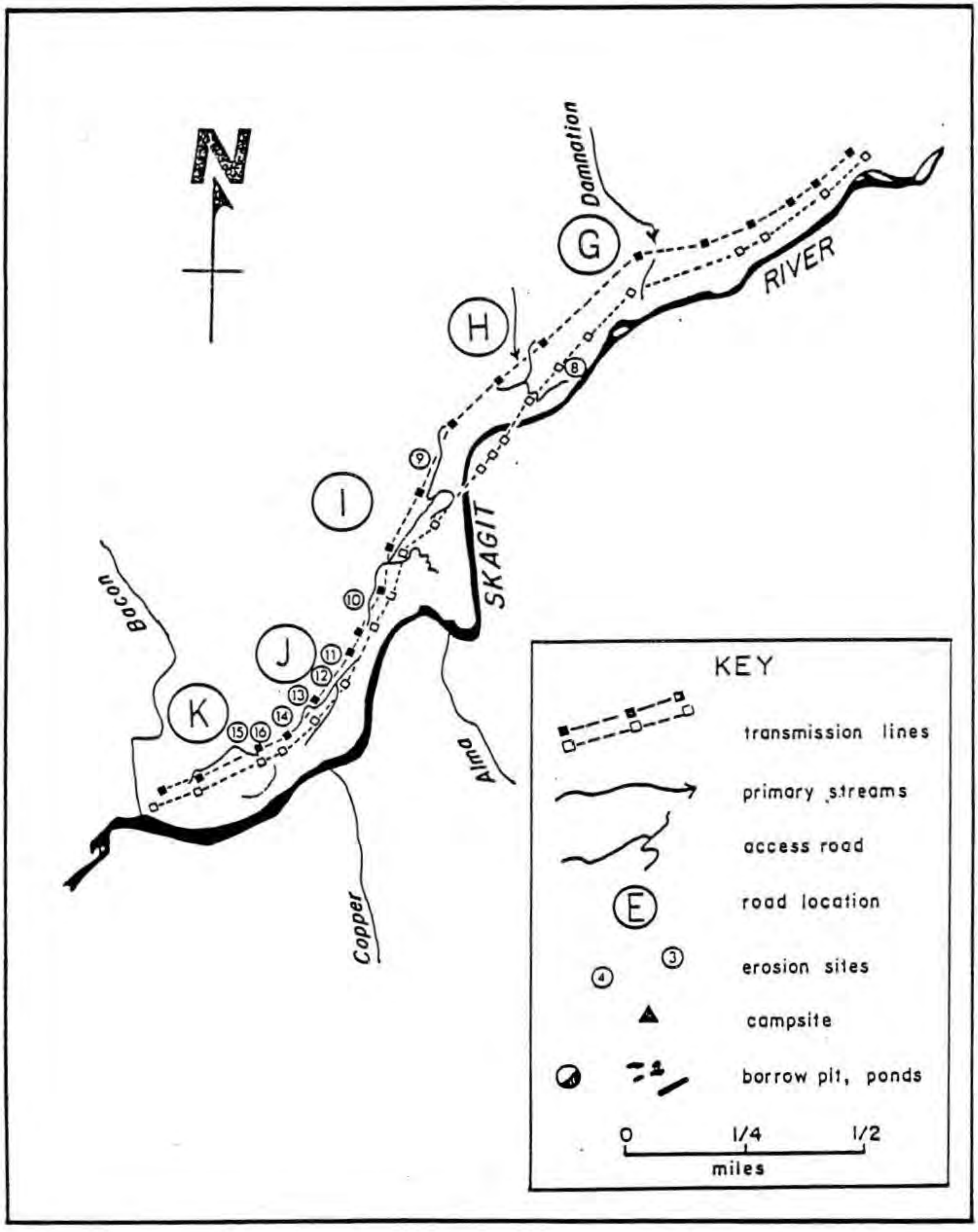

FIGURE 16D. ROAD AND EROSION SITE LOCATIONS.

VIII SEDIMENT DEPOSITION IN THE PROJECT AREA

Exclusive of the areas just above the dams the greatest thickness of sediment accumulating in the reservoirs is at the mouths of tributary valleys - particularly those that drain glaciers. Areas where thick deposits of sediment occur are at the mouths of Lightning, Devil's, Ruby, Big Beaver and Little Beaver Creeks. Measurements of sediment thickness were made at several locations by digging down to pre-reservoir ground levels. At the mouth of Big Beaver Creek, sediments deposited in a deltaic environment are over 26 ft. thick. On the Little Beaver alluvial fan sediment thickness decreases from 13 ft. at the mouth of the valley to less than 3 ft. at the edge of the alluvial fan. At the head of Ross Lake post reservoir sediments deposited by the Skagit River increase in thickness south of the Canadian boundary, but nowhere approach thicknesses measured at the mouths of Big and Little Beaver Creeks. On Diablo Lake, Thunder Creek drains a large, glaciated basin. As a result Thunder Arm is rapidly filling with sediment. The area near the boat launch at Colonial Creek Campground was dredged in 1987, reflecting the rapid filling of this portion of the lake.

IX CONCLUSIONS

Erosion caused by the project was examined in three areas: reservoir shorelines, along rivers and on roads. Over six months of field analysis and literature review led to the following conclusions:

1) Reservoir shoreline erosion is a severe problem resulting in the loss of approximately 1.7 acres of land per year along the shorelines of Ross Lake.

2) Over 16.8 miles of shoreline are eroding along the three reservoirs. This includes 25% of Ross Lake's shoreline, 10% of Diablo Lake's shoreline and 2% of Gorge Lake's shoreline.

3) Forty-two of the 1,238 sites are areas where mass movements of sediments are occurring or are likely to occur. These sites account for 10% of the total eroding shoreline. Erosion at the remaining 1,196 sites is characterized by gradual bank recession that may be punctuated by the removal of large amounts of sediment as large trees fall into the lakes.

4) Landforms and surficial geology control the location and severity of reservoir shoreline erosion by influencing the steepness of slopes and material erodibility. For this reason erosion is most severe on Ross Lake, which has thick accumulations of glacial sediments on steep valley walls.

5) Erosion is most severe and costly in terms of habitat and recreational facility loss when the reservoirs are at full pool. Measured bank recession rates on the three reservoirs vary between 0.2 ft./yr. to over 5 ft./yr.. Recession rates were probably faster during the early life of the reservoirs after clearing of vegetation. Further, rates fluctuate at any given site depending upon a number of environmental factors.

6) Operational procedures that accelerate reservoir shoreline erosion are the removal of woody debris from shoreline areas, persistence of lake levels above full pool (1602.5 ft.), and rapid drawdown from full pool.

7) Shorelines along the three reservoirs have not adjusted to inundation as indicated by the presence of suspended sediment along eroding shorelines and living vegetation falling into the lakes. The primary reasons for a lack of adjustment of shorelines to the reservoirs are fluctuating lake levels and steep slopes.

8) Erosion along the bed of the Skagit River below Newhalem at the Alma gauging station occurred after closure of Ross Dam, but was

followed by aggradation (deposition) in later years. Erosion along the bed at two areas studied was probably limited by armoring.

9) Streambank erosion is a natural process occurring along the Skagit River below Newhalem. Since closure of the three dams, however, the stability of the river between Newhalem and Bacon Creek, with respect to changes in its position in the landscape, has increased.

10) Erosion associated with project roads and borrow pits is minor. Where erosion is occurring, it involves both the interruption of small streams and slope instability along road cuts into steep slopes. Only 16 erosion sites were identified along 14.8 miles of gravel roads.

11) Observations prove that erosion caused by project developments has impacts on recreation, visual quality, cultural resources and biological systems. Analysis of these impacts, however, was beyond the scope of this study.

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APPENDIX A
SEATTLE CITY LIGHT RESPONSES TO LETTER 1
NORTH CASCADES CONSERVATION COUNCIL

NCCC Comments on

Draft Report on Existing Conditions of Reservoir and Streambank Erosion Related to FERC Project NO. 553 on the Skagit River, Washington

NCCC finds this study to be well done and quite informative about the conditions of the shorelines and streambanks in
1 the Project area. However, it is seriously deficient in the view of NCCC because it does not deal with the area most heavily affected by the Project - namely the ca. 2.5 km. of
2 reservoir extending into Canada. This deficiency must be remedied by further study. Why? Because the greatest sediment load deposited by the Skagit river is in this area and nearly all of it is exposed during low lake levels. It contains important fish and wildlife habitat under certain conditions affected by sedimentation and erosion.
3 Furthermore, it is probably the most concentrated zone of shoreline/shorebased recreation in the Project Area.

NCCC notes also that there is no companion study to this that documents shorelines/erosion/sedimentation along the
4 transmission corridor extending beyond the coverage in this study. Erosion along the Sauk river is reputed to threaten placement of one transmission tower (per discussion in intervenor forum early Sept.). NCCC does not have specific information on other aspects in this issue area but would suggest that it is essential to cover as part of the relicensing.

Aside from this major omission, there are other important issues worthy of comment in this study. The NCCC responses are organized in the form of <u>general comments</u> and then specific <u>editorial suggestions</u>.

General Comments

1. There is no justification for the limited focus of this
5 study as described (p.2) relative to the must more extensive list of reservoir and shoreline erosion. Things like turbidity, nutrient loading and temperature changes are not discussed nor is biological activity. Are these factors important in the study area? The erosion of rock, sand and gravel in spawning beds is inadequately addressed yet this figures significantly into the analysis of the effects of the water regulation regime and impact on fisheries. If so, and NCCC would expect them to be important, then why are they deleted. If they are not important, some authoritative reference should be included to justify the more limited approach taken here.

6 2. If a magnitude 7 (Richter?) earthquake is surmised in 1872, where is there discussion of seismic activity relative

to the project structures and to the behavior of the
reservoirs, i.e., with respect to seiche waves? Where is
there analysis of the potential slumping behavior of the
terraces? There is mention of what appear to be inactive
slump areas p 15. What is geological opinion about the
potential for other mass movements under current conditions?
Why would these not be expected to produce a major movement
potentially affecting project safety?

7 3. Obviously, the maps are key elements of this study. It
would have been useful to be able to review these although
the text and tables do a reasonable job of describing the
types and general location of erosion features both at the
shoreline and in the reservoir. The constant reference to
sediments being transported to lower levels in the reservoir
8 raises the question as to the final deposition of these
materials. Is there any bottom transport or longshore
transport? The study, NCCC realizes, did not ask that this
be considered but it seems quite relevant to understanding
what is happening in the reservoir.

9 4. There is relatively little discussion of the interplay
between erosion and biological processes. For example, the
shifting of sediments as the lake is raised and lowered
could be important relative to sensitive live periods of
trout - spawning in reservoir streams. Similarly, loss of
shoreside vegetation could be a result of erosion and
alteration of the water table. Downstream effects on
distribution of gravels suitable for salmon spawning is not
discussed. With the emphasis on habitat and recreation that
this study gives as major affected resources - the analysis
is scant. Will this come in the mitigation plan?
Presumably this would draw on results of other studies.
There is a considerable need to integrate the studies.

10 5. The discussion of severity of erosion at various places
in this draft consistently points to areas around recreation
sites. It also mentions habitat in vague terms. However,
there is vitually no mention of visual impacts except to
assure that control measures for boat launching/docking
facilities would utilize natural materials and would be
vegetated. The brief discussion of an erosion control plan
11 p. 53 continues this vein of reasoning. NCCC suggests that
it is premature in this erosion descriptive study to be
proposing control measures and target areas. It would seem
from NCCC reading of this account that erosion problems are
pervasive and that a systematic approach needs to be
developed to the prioritization of possible mitigation,
including but not limited to visual, habitat, recreation
impacts coupled with measures of severity, technical
feasibility, and cost. Attempts should be made to isolate
project impacts from, for example, recreational use impacts.
Proper siting of recreational facilities should be examined
carefully.

Editorial Suggestions

12 p. 1 1921 differs from date given in table I 1927

13 Why do we use acre feet for volume measures and kilometers for distance measures? Why are shorelines (Table 1) shown in metric units and reservoir lengths/dam heights shown (this time) in English units? Shouldn't all be metric?

14 We need the maps

15 p. 4 Map does not mark Rainbow Point as referenced in text

16 p. 5 Barrow pits are not discussed in text but should be. Should show roads.

17 p. 7 Suggest that fig. 3 explanation be placed on back of preceding page if it is to be on the back of any page so that the reader does not have to flip back and forth.

18 p. 10 Fig. 5 needs improvement. Could these be superimposed on a USGS Map of the area? Seems like fig. 6 should precede figure 5.

19 p. 12 Note that the Cordilleran ice sheet did not cross an international boundary around 11,000 YBP - use geologic descriptors.

20 p.13 no comment on Map I missing.

21 Note that there is no discussion of the Skagit river alluvial fan at the head of the lake -- only those of the other direct tributary streams.

22 p. 15 Discussion of stratigraphy and variation in glacial deposits in the mitigation plan (to be added later) is not very helpful to intervenors who may wish to develop an understanding of these issues through this study for use in developing mitigation measures or commenting on those to be proposed by the mitigation plan.

23 p. 16 Delete reference to "proposed Copper Creek dam site". Use a proper geographic descriptor. This type of reference, in NCCC view, is inappropriate as it lends credibility to a dead project.

24 p. 17 Rainbow Point is not marked on Figure 1.

25 Artificial fill discussion seems incomplete. No mention in text of where these materials came from.

26 p. 18 How are area measures developed? Is the Canadian Skagit really such a small proportion?

27 p. 19 It is my understanding that there are several precipitation monitoring (snow guages) operated by SCL in RLNRA/NCNP? Shouldn't these be mentioned and reference made to data on snow pack? This would seem important for hydrographic regime.

28 Are there no data on wave height under various wind conditions?

29 p. 20 If the Hozomeen data are summer only why are there so many relative to Marblemount? Please provide better information on observations at both sites.

30 p. 21 Are any of the reservoirs operated at greater than full pool? If not, what is the purpose of the general discussion of these effects. The threat of what would happen if full pool levels are exceded perhaps justifies keeping these sections in -- particularly if the mitigation plan includes proposals to avoid any excursions above full pool.

31 p. 22 This is probably semantic but is it correct to refer to a drop in lake level due to the hydrographic regime, as opposed to deliberate operation of the reservoir, as drawdown? There is difficulty for NCCC in understanding the relationship of the successive raising of Ross Lake to current full pool and the discussion of shoreline recession. Is the shoreline recession data (later) related to the 1967 level? or is the recession measure started earlier?

32 Max. drawdown is stated here as 32 m in 1956 but on page 13 it is stated that the study was started with a 36m drawdown in 1988-89. What gives?

33 Why is the mean drawdown for the period 1954-1972 used rather than the mean over a longer period of time -- or 1972 to present? Are there significant differences?

34 Ross Lake would be 38.4 km by my conversion of mile data in Table 1 - not 40 km. Is the distance of 2.5 km in Canada included?

35 p. 23 Fig. 7 is odd. Why does the 1988 line end in the middle of May? I think this would be very interesting to plot as it would show lake level in an extremely dry year (late fill and early drop).

36 Why does this figure not present mean data and extreme data on an annual basis? Could this be done? This would help portray conditions for the reservoir relative to erosion and sedimentation.

37 p. 26 There is mention of the wave dampening potential of ice but there is no discussion of ice as an agent of erosion. Does ice in a fluctuating reservoir act as an erosion agent? It would seem to be capable of considerable impacts.

38 p. 28 What happens to the 10 feet of sediment eroded? Seems like this study ought to address this question too.

39 p. 30 I do not find in Figs. 7 and 8 more explanation of the prominent terrace produced by a static lake level elevation. How frequent is such a static level? Is it something to avoid through mitigation. There should be more discussion of this issue as it appears to be quite significant. What caused the static lake level?

40 p. 41 Discussion of boat waves is weak? Do boat waves contribute significantly to erosion relative to other factors? Perhaps data are scarce on this however it would be useful to know more about the boat activity as that can be controlled by speed. route and size limits whereas wind is a tad harder to deal with. Looking at wind data, it would seem that summer winds are significant.

41 What is the cause/origin of gully erosion on land?

42 p. 42 See discussion above on what bank recession means.

43 p. 50 See discussion above concerning lack of treatment of distribution of gravels suitable for spawning in downstream sections.

44 p. 51 It is disconcerting to find such a cavalier discussion of riprap and stabilization of the Skagit river through such means in a NRA that has Wild and Scenic Designation. NCCC hopes that the final version of the report will be a vast improvement.

45 The powerline corridor along the Sauk is said by SCL personnel to have at least one transmission tower threatened by erosion -- this is probably not the result of the placement of the tower but it ought to be noted. Similarly, NCCC argues that stopping this study at the NRA boundary is not appropriate. There should be survey of the total corridor subject to licensing in this project.

46 Did the NPS really dredge the boat launch at Colonial Creek?

47 The author of this study is to be congratulated for making a rather complex subject comprehensible to non-specialists.

SEATTLE CITY LIGHT RESPONSES

1. Comment noted. Thank you.

2+3. This erosion study does not deal with the Canadian portion of Ross Lake because City Light is addressing the area over which the FERC has jurisdiction, which includes only U.S. territory (see also the responses to comments in the Envirosphere report and the Early-Season studies report).

4. The area examined in this study extends from the Canadian border through the U.S. portion of Ross Lake, Diablo Lake, and Gorge Lake to the west boundary of the Ross Lake National Recreation Area. Transmission line rights-of-way outside this area were not studied. The concern about the base of a transmission tower arises from the shifting over time of a stream by natural hydrologic forces, not from erosion due to project facilities or operation.

5. City Light recognizes that reservoir shoreline erosion can have effects on other aspects and resources of Gorge, Diablo, and Ross Lakes. The Ross Lake Early-Season studies and others have evaluated the resident fisheries, their habitat, and the condition of spawning areas in the drawdown zone. As has been reported previously, the resident fisheries are already an enhanced resource.

6. On a Geologic timescale, earthquakes are very likely to occur in a region as tectonically active as the North Cascades. The last major earthquake in the region was in 1872 (magnitude 7 to 7.2 on the Richter Scale), and since then there have been a number of small (magnitude 2 to 3) quakes approximately 50 kilometers west of Mt. Baker (personal communication, University of Washington seismograph station personnel). However, the large landslides identified in this study have all been inactive for centuries (with the exception of those initiated or reactivated by reservoir erosion), and the most unstable area in the valley is well below the three project dams and reservoirs. This does not mean that earthquake-triggered landslides could not occur in the future, but the response of reservoirs and project structures to possible mass-movement events goes beyond the scope of this erosion study. These issues are addressed in engineering and safety documents filed as part of City Light's license application, and as part of periodic safety and operations inspections conducted by the FERC.

7. City Light apologizes for NCCC's not receiving the draft maps with the draft report; these draft maps have been sent to NCCC. The final maps will accompany the final report.

8. Sediments eroded from the reservoir shore and from areas exposed during drawdown are eventually deposited below the minimum

lake level. In addition, it is likely that bottom currents and gravity flows move sediments towards the lowest levels of the lake, but there have been no attempts to monitor this redistribution of sediment within the reservoirs because the primary focus of this study is reservoir and stream bank erosion. Determining the "life expectancy" of the reservoirs was not one of the purposes of this study.

9. See response to comment #4 above. Extensive studies of downstream fisheries habitat have found no problem regarding availability and replenishment of spawning gravels. Some additional information on the project's effect on spawning gravel is included in the final report. City Light is considering funding of a study on the projects affect on spawning gravel.

10. The erosion control plan will address recreation and erosion concerns, and will consider the utilization of materials or approaches to reduce recreational/visual conflicts. These measures are beyond the scope of this document, which is an existing conditions report.

11. This erosion study does not propose erosion control measures. It does identify areas where erosion is most severe; a separate erosion control plan will be proposed for these target areas. City Light will take into consideration visual, habitat, and recreation concerns when developing erosion control measures. National Park Service staff have been consulted concerning protection of recreational, visual, habitat, and cultural resources. At this time it appears that no critical habitat would be lost through development of erosion control measures.

12. Text changed to 1927.

13. All measurements changed to english units.

14. See response to comment #6 above.

15. Reference made to the map that does show the location of Rainbow Point.

16. Additional information provided on roads and borrow pits.

17. Explanation for figure 3 changed to face figure.

18. Figure 5 improved.

19. Text changed.

20. See response to comment #6 above.

21. There is no alluvial fan at the head of Ross Lake. There is, however, a delta that forms seasonally at the head of the lake.

The delta is discussed indirectly in section VIII - Deposition of Sediment in the Project area.

22. Expanded discussion in text.

23. Reference deleted.

24. Text changed so that reference is made to the proper figure showing the location of Rainbow Point camp.

25. Sources of fill material listed in text.

26. Measurements of drainage area are traditionally made by polar planimeter, but computers are now used to make these measurements.

27. Discussion of hydrology expanded.

28. Wave height can be estimated with wind and fetch data. However, detailed measurements of wind duration are needed. This data is not available.

29. The Hozomeen and Marblemount weather stations are fire-weather observation stations. Therefore, they are not operated during the winter.

30. See Table 6.

31. Three rule curves control lake levels. Discussion of the curves, which are determined by both demand for power and hydrologic conditions, has been added. Additional information on pool level is provided in Figure 7 and Table 6.

32. Maximum possible drawdown (with continued electrical generation) is 37m, not 39m as originally stated. Text has been changed.

33. Lake level data from 1969-1987 was added to the report.

34. In the U.S. Ross Lake is 38.4 km long, not 40km as originally stated.

35. Figure 7 was changed for the final report (See figure 8).

36. Figure 7 is not meant to be a general drawdown curve. Figure 3.1 in the "Final Early-Season Lake Levels" report gives the averages and extremes for the last 10 years (data for 1977 were omitted because of the extreme drought conditions that year).

37. Ice can act as an erosive agent, but also can reduce erosion by suppressing surface waves. Other studies of reservoir erosion do not identify ice erosion as a significant problem.

38. Sediment eroded along reservoir shores and introduced by tributary streams ultimately is carried to the deepest parts of the reservoir (i.e. at the dam).

39. The references to figure 7 and 8 was made simply to show when and (schematically) where a strandline (terracette) forms in lag deposits. Such pauses in the lake drawdown are very common and are related to weekly and daily changes in demand for electricity and fluctuations in tributary in-flow. It would be extremely difficult for City Light to prevent these pauses in drawdown through operations.

40. Some additional data on boat waves provided, but boat use statistics not included in the final report. Time constraints precluded detailed analysis of the exact contribution of various processes to shoreline erosion. Analyses of these types take a number of years and time for advance planning.

41. Gully (overland flow) erosion on land is cause by surface flow of water on loose unvegetated sediments.

42. Discussion of bank recession clarified.

43. Discussion of project effect on the Skagit River is included in the final report. Also see response to comment #4 above.

44. The Skagit River in the Ross Lake NRA is not a designated Wild and Scenic River. Maintenance of SR20 and protection (including rip-rapping) are the responsibility of the State Transportation Department.

45. See response to comment #3 above.

46. Yes.

47. City Light greatly appreciates the work of Jon Riedel, National Park Service geomorphologist, who carried out this study and wrote this report, and the consultation and review assistance provided by Bruce Stoker and Jon Harbor of Envirosphere Company.