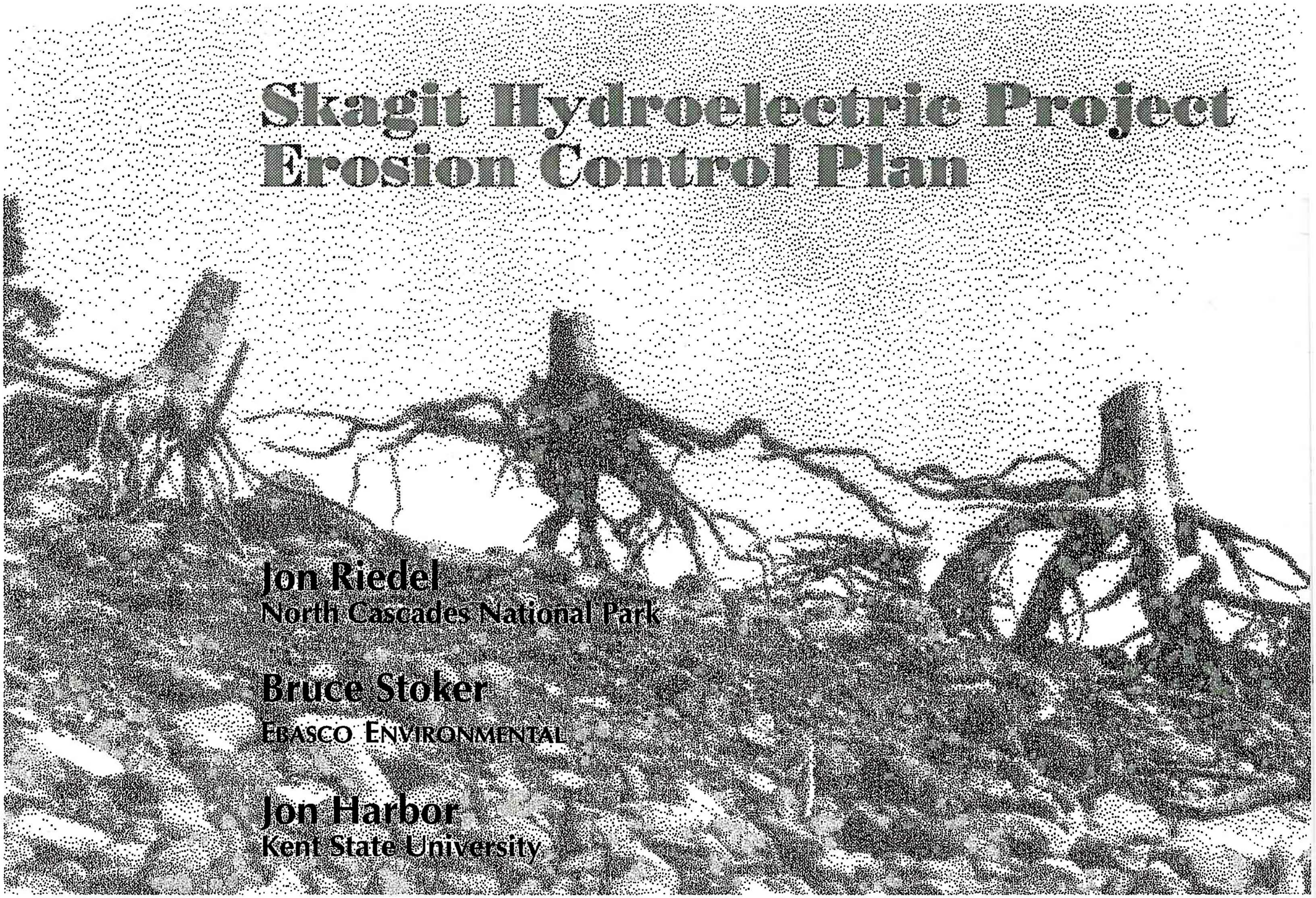
Skagit Hydroelectric Project Erosion Control Plan



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ABSTRACT

The Skagit Project consists of three hydroelectric dams built by Seattle City Light (SCL) on the Skagit River, Washington between 1927 and 1961. The Skagit Project is within the Ross Lake National Recreation Area, which is part of the North Cascades National Park Complex. To fulfill part of the Federal Energy Regulatory Commission's (FERC) relicensing requirements an existing conditions report (Riedel, 1990) and an Erosion Control Plan (SCL, 1991) were developed for SCL in a cooperative effort between North Cascades National Park (NPS) and the SCL consultant, EBASCO Environmental. These studies focused on shoreline erosion along the margins of Ross, Gorge, and Diablo reservoirs, along the road and transmission line corridors and downstream effects of the projects. This paper focuses only on shoreline erosion in the reservoirs. Effects of the project on downstream river conditions and erosion along the roads are not included in this paper.

The existing conditions report provides surficial geologic and landform maps of the project area (Riedel, 1990) and classification of 78 miles of shoreline into erosion classes. The existing conditions report identified erosion at 1,238 sites along the three project reservoirs, and 16 sites along project roads and borrow pits. Erosion is related to landform and surface material types, and to operation of the project - primarily the annual drawdown of up to 128 feet. Erosion is most severe along valley walls and terrace edges 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.

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

Wave impact is the dominant erosion process. Other active processes include freeze-thaw, surface water erosion, and groundwater piping. 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. Erosion along the remaining 90% of eroding shoreline is characterized by gradual retreat of banks and small scale debris slides and slumps. Banks on Ross Lake have receded laterally as much as 133 feet from the full pool. Bank recession rates range from 0.3 ft/yr to 5.5 ft/yr resulting in an estimated loss of 1.7 acres per year along Ross Lake. Erosion in the 128 foot Ross Lake drawdown zone has removed as much as 9 feet of sediment. The depth of erosion in the drawdown zone is controlled by development of an armor layer which is controlled by the surface materials and slope.

Recognizing that it would be impractical to attempt to prevent erosion along all 16.2 miles of eroding reservoir shoreline, criteria were developed for selecting sites at which erosion control would be of most value. The primary criterion used to select sites for erosion control assessment was potential effects on recreational resources, project facilities, known areas of sensitive or rare habitat or species, and archaeological sites. On the basis of this assessment 34 recreation and project facility sites and 15 road sites are recommended for erosion control measures. Twenty severe erosion sites, one osprey nesting tree and one archaeological site are recommended for monitoring to better evaluate future bank recession rates and processes.

INTRODUCTION

The Skagit Project (Federal Energy Regulatory Commission Project Number 553) consists of 3 hydroelectric dams (Ross, Diablo and Gorge dams) built between 1927 and 1961 (Table 1) by Seattle City Light (SCL) on the Skagit River, in the North Cascade Range of northwestern Washington State (Figure 1). Ross, Diablo and Gorge dams flood 12,400 acres of the Skagit River Basin, not 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. The Skagit Project is within the Ross Lake National Recreation Area (N.R.A.), which is part of the North Cascades National Park Complex. The land 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.

SCL developed a comprehensive settlement agreement with all project interveners for the relicensing or the Skagit Project with FERC. As part of the settlement agreement an existing conditions report (Riedel, 1990) and an Erosion Control Plan (SCL, 1991) were developed for SCL in a cooperative effort between the North Cascades National Park and the SCL consultant, EBASCO Environmental.

Table 1. Project Features of the Skagit Hydroelectric Project (FERC Number 553).

	Ross	Diablo	Gorge
Year built	1937-49	1927-30	1950-61
Dam height (FT)	540	380	300
Storage capacity (acre-feet)	1,435,000	50,000	8,500
Reservoir length (mi.)	24	4.5	4.5
Shoreline length (mi.)	54.6	14.6	8.8
Generator capacity (MW)	400	169	170

The objectives of the existing conditions and erosion control plan were to collect background information on landforms and surficial geology, examine the impacts of the Skagit Hydroelectric project on sediment erosion, transport and deposition, and prepare erosion control guidelines to be implemented during the 30 year term of the new FERC license. The area of interest included 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. The study focuses on the problem of shoreline erosion along the margins of Ross, Gorge, and Diablo lakes, and erosion associated with transmission line and access road corridors.

Glaciers and rivers have deeply incised and shaped the North Cascades during its geologically recent uplift. Relief within the study area is locally as much as 7,900 ft. Alpine glaciation of the valleys in the Skagit River Basin resulted in the creation of two distinct valley segments; glaciated and unglaciated (Waitt, 1977). The glaciated valleys have thick accumulations of glacial till, outwash, and alluvium along valley walls and on valley bottoms, whereas sedimentary deposits in the unglaciated reaches are usually thin and coarse-grained, and are concentrated at the bottom of the valley. Unglaciated valley walls are typically bedrock with steep gullies.

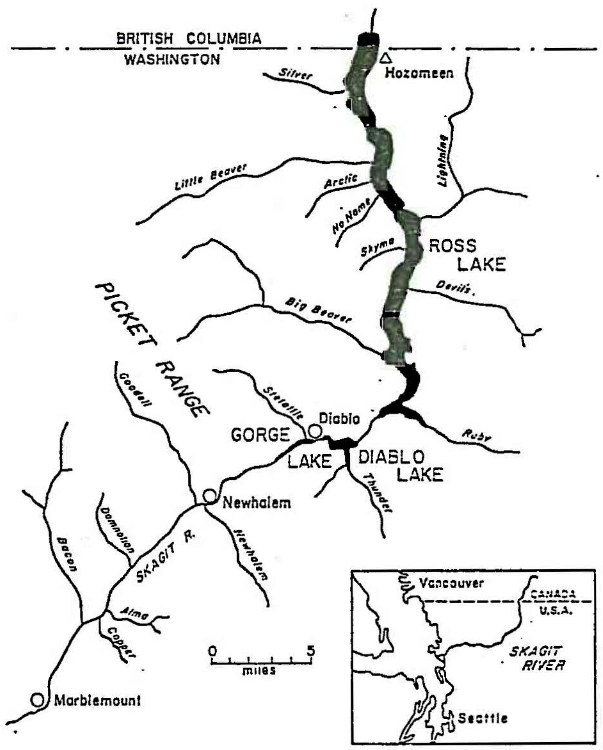

Figure 1. Upper Skagit River Basin.

LANDFORMS

A landform map of the study area was developed to aid in the analysis of shoreline erosion. Landforms mapped and their general descriptions are given in Table 2. The landform map was constructed using 1:24,000 scale topographic maps 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. The 112 ft drawdown on Ross Lake allowed field checking of some landforms below full pool elevation. The map was reduced to 1:50,000 scale to include the entire study area on one sheet (Riedel, 1990).

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

Table 2. Landform Mapping Units.

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.

SURFICIAL GEOLOGY

Surficial geology was mapped using a methodology similar to that used for the landform map. Unlike the landform map, areas below reservoir pool elevations were not mapped. Mapping units 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. Only the surficial unit was mapped where complicated stratigraphic relationships were identified. Variations between genetically and geotechnically different glacial till and outwash deposits were not mapped. The surficial geology map is reproduced in (Riedel, 1990).

Table 3. Surficial Geology Mapping 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 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

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. 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 large fluctuations in water level uncommon in natural lakes.

Aspects of a given hydroelectric project such as dam height and valley gradient also determine where reservoir water intersects the landscape. Near dams in steep mountain valleys the operational elevation of the reservoir is typically high above the valley floor, and intersects landforms such as valley walls, high terraces and bedrock benches. Moving upstream from the dam, the valley floor emerges. At the head of the reservoir water intersects landforms such as floodplain, alluvial fan and mass movement deposits that rest on the valley bottom.

POOL LEVEL FLUCTUATIONS

The modern full pool elevation of Ross Lake was reached in several stages between 1940 and 1967. Annual pool fluctuations on Ross Lake are between 80 and 120 feet. 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 determine the seasonal drawdown pattern of the three reservoirs: the critical rule curve, the refill guide curve 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 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. 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.

SHORELINE ORIENTATION

The orientation of reservoirs can be important because of the influence of predominant winds on shoreline erosion. Wind data from the Hozomeen and Marblemount stations (Figure 1) 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.

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).

SHORELINE GEOLOGY

Slopes affected by the Skagit Project reservoirs consist primarily of bedrock and bedrock-related deposits (talus and colluvium) in unglaciated reaches. Shorelines in glaciated reaches of the valley are composed primarily of glacial till, outwash and alluvial deposits.

Bedrock and talus form stable shorelines since the bedrock is primarily coarse, crystalline igneous and metamorphic rock. 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 the reservoir shores are listed in Table 4.

Glacial till is the other common reservoir bank material. The percent of shoreline that is till decreases downvalley from Ross Lake to Gorge Lake 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, homogeneous, and resistant to erosion than supraglacial till.

On Ross and Diablo lakes subglacial till is overconsolidated, has few joints, and forms vertical bluffs where eroded. Alluvial fan deposits form the majority of the remaining shoreline length. They are generally stable because of their coarse nature and low slope in a depositional environment. 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 loose non-cohesive sand and gravel. Small amounts of glacial outwash are found along Ross Lake (Table 4). Landslide deposits exhibit wide variation in stability. Alluvium deposited on low-relief floodplains and terrace tops is variable in composition and resistance to erosion. Steeply sloping terrace edge alluvial deposits are very susceptible to erosion but are not widely distributed as a bank material.

In several areas, complex stratigraphic relationships between various sediments complicate the stability of a given shoreline. For example where till and outwash deposits overlie impervious lacustrine or compact subglacial till, groundwater saturation of the overlying strata may result in mass failures, particularly when reservoir bank erosion has undercut these deposits.

Table 4. Length of Shoreline (ft) of Various Materials and Percent of Total Shoreline.

Material	Ross	Diablo	Gorge
		RESERVOIR	
Bedrock	95670 (33%)	38090 (48%)	19195 (40%)
Talus	18440 (6%)	5250 (7%)	8365 (17%)
Colluvium	56675 (20%)	8990 (11%)	970 (4%)
Undifferentiated	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%)

RESERVOIR CLIMATE

The climate of the study area is 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 surface erosion and freeze-thaw processes. Temperature affects freeze-thaw and the distribution of ice cover, which inhibits reservoir waves. Ice cover can directly cause erosion when ice is run-up on a shoreline. Ross Lake occasionally freezes over and Thunder Arm on Diablo Lake occasionally freezes, but to the authors' 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.

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 et al, 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 et al, 1988). It also influences other shoreline erosion processes such as mass movements and groundwater movement.

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. In addition to causing erosion directly, waves saturate bank materials, thereby reducing their shear strength and facilitating erosion by other processes (Kachugin, 1970). 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. Observed wave heights on Ross and Diablo lakes reached 3.5 ft. Strong storm winds are also important in wave erosion and have exceeded 80 miles per hour in the study area. Boat wake 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. Lake levels on Ross Lake rose above full pool (1602.5 ft) 12 times between 1970 and 1986. In three of those years it was more than a half foot above full pool. In 1976, 1978 and 1981 the lake was above full pool for extended periods. Pool elevations can be locally high in response to wind pile-up of water and rapid stream discharge.

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 shoreline 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.

Human activity can influence shoreline erosion by killing vegetation, compacting soil, concentrating runoff and by direct displacement of soil. In the project area 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.

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 et al (1961) and Erskine (1973) noted a relationship between rapid drawdown and increased mass movements in low permeability bank sediments. Further, they suggested that this is related to movement of groundwater from the banks to the reservoir, which caused instability of bank sediments.

ADJUSTMENT OF RESERVOIR SHORELINES AT FULL POOL

The superimposition of reservoir water onto sediments and landforms created in subaerial environments represents an unstable condition (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.

EROSION BELOW FULL POOL

Erosion and sediment transport also occur below the highest reservoir shoreline. Previous studies have not focused on the processes, nature, or severity of erosion in the reservoir drawdown zone because erosion of reservoir shores is most severe and costly in terms of habitat and facility losses when the reservoir is at full pool.

Following completion of Ross Dam and the removal of vegetation, erosion of shorelines now below the modern full pool elevation probably occurred rapidly once the surface litter zone had eroded and soil-holding roots had rotted (typically within 2-5 years under subaerial conditions; Wu et al, 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 (Table 5) (Photo 1). 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).

Table 5. Drawdown Zone Erosion on Ross Lake.

Site Location	Erosion Depth (ft.)
10 Mile Island	9.2
Lightning Creek	8.2
Big Beaver	6.6
Rowland Creek	2.8
Arctic Creek	4.9

The steep slopes are now transport areas for the material eroded from shorelines and the drawdown zone. Erosion and transport of these sediments occurs by wave actions as the lake level fluctuates and it also 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.

SHORELINE EROSION ASSESSMENT METHOD

Sites along reservoir shores of the Skagit Project were surveyed on foot and by boat. Each eroding stretch of shoreline was given a number and the location mapped. 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 (slump scars, groundwater irregularities, pistol gripped trees and vegetation disturbance) were collected. Material type was classified using the same categories as the surficial geology map.

Each erosion site was classified as to the severity of erosion. Class I erosion sites were defined as areas where larger mass movements (> 1000 ft^3) 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 erosion areas were defined as areas where small slumps (< 1000 ft^3) and slides were occurring, or where the possibility existed for larger mass movements. Class II erosion 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.

Estimates of bank recession rates are important in attempts to assess the severity of erosion problems, and in determining the nature of erosion control techniques which are needed at any particular site. Bank recession was estimated by two methods; direct measurement of erosion from around dock anchors and bulkheads immediately adjacent to shorelines and from measurements of current bank topography and a knowledge of past full pool elevations. In cases where it is possible to identify past bank

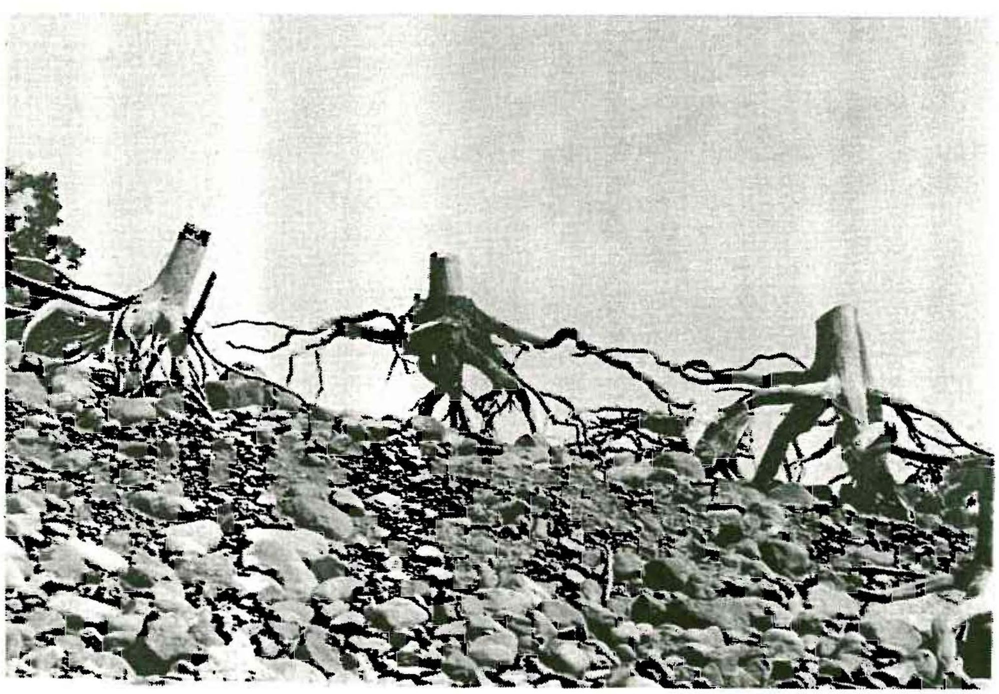

Photo 1. Drawdown Zone Erosion in Ross Lake Reservoir.

positions of known age, bank recession rates can be calculated precisely. For example, many of the reservoir boat camps have concrete bulkheads which were initially poured flush with the bank. Knowing the date of bulkhead emplacement, the distance between the bulkhead and the current bank can be used to calculate average bank recession rates (Method 1).

In many cases there is no reliable control for erosion rate calculations, and less accurate methods must be used. Making certain initial assumptions, an estimate of reservoir bank recession rates can be made from measurements of current bank topography and a knowledge of past full pool elevations (Method 2). For each site the bluff height, beach angle and the angle of the slope leading down to the shore is known from field measurements. It is also know that the full pool elevation was about 1602.5 feet from 1968 to present and 1600 feet from 1952 - 1967.

Method 2 involves extrapolating the slope leading down to the shore beyond the bluff to intersect the current full pool elevation. The method provides a first estimate of the amount of bank recession since 1968 (Figure 2). It is known that for the period 1952-1967 the full pool elevation was 2 feet below the current full pool elevation. Therefore, the method is inaccurate for situations in which the bluff height in 1967 was greater than 2 feet, and in such cases the method provides an overestimate for the amount of recession since 1968, and therefore exaggerates the recession rates. The method also assumes linear slope elements (for extrapolation), and may thus be in error if slopes were non-linear. If the true slope eroded by bluff recession was convex, the calculated recession rate will be too high, whereas if the true slope was concave, the calculated recession rate will be too low.

Both bank recession rate estimation methods only provide average recession rates (feet/year) whereas recession may be episodic, with highly variable actual recession rates for any given year. However, for shoreline protection design purposes it is preferable to have some slight overestimate of rates of recession rather than no estimates at all.

Data analyses was designed to determine what factors control shoreline erosion along the three reservoirs. Total length of shoreline eroding in each severity class (Table 6), of different material type (Table 7) and within the eight cardinal directions (Table 8) was determined from survey data. Total length of shoreline of each mapped material type (Table 7) 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 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.

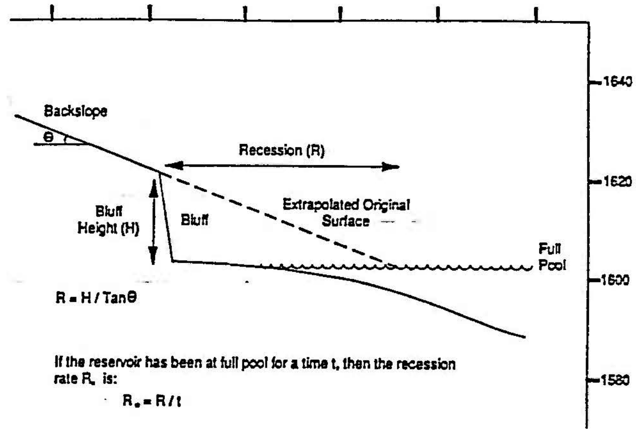

Figure 2. Recession Rate Calculation.

LOCATION AND SEVERITY OF SHORELINE EROSION AT FULL POOL

Shoreline erosion on the three project reservoirs is most severe on Ross Lake. Over 25% of the Ross Lake shoreline, approximately 14.5 miles, is in some stage of retreat. On Diablo Lake 10% of the shoreline is eroding (8,040 ft of 79,855 ft total shore length), compared to 2% on Gorge Lake 2% (925 ft of 47,900 ft).

On Ross Lake most erosion sites are located throughout the lower and midvalley sections of the reservoir where lake water intersects colluvial and glacial sediments on steep valley walls. 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.

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 (Table 7). 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 depositional shoreline. 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.

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 the state highway (Table 7). 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.

Erosion is occurring at 1,143 sites along Ross Lake, compared to 78 site at Diablo Lake and 17 sites on Gorge Lake (Table 6). 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. 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. Bank recession in these instances is sporadic. 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. 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.

Table 6. 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)

On Gorge Lake, 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 on Gorge Lake. 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.

ENVIRONMENTAL FACTORS CONTROLLING SHORELINE EROSION

The most important environmental factor controlling the distribution of erosion sites appears to be the distribution of erodible material (Table 7). Over 60% of the glacial till deposits on Ross Lake's shore are eroding, and over 55% of the total shoreline composed of colluvial deposits is eroding. The 40% of shorelines composed of glacial deposits not eroding occur primarily on low slopes or where bedrock outcrops have stopped bank recession.

Most of the eroding shoreline on Diablo Lake is composed of glacial till (Table 7). Colluvium accounts for 30% of the eroding bank material. 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. On Gorge Lake forty percent of the shoreline composed of unconsolidated sediments, including diamicton, colluvium and alluvium, are eroding (Table 7).

Aspect does not appear to be a critical factor in wind-induced wave erosion in the project area. On Ross Lake, for example, 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 8). Also, no class I sites face south and only two 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 8).

Table 7. 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%)

Table 8. 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%)

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.

RATES OF SHORELINE RECESSION

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 in general higher at class I sites (Table 9). For example, total bluff crest recession was 103 ft, or 4.9 ft/yr at site E-9 and 116 ft and 5.5 ft/yr. at site E-7A (Table 9). 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 activities contribute to erosion. Average annual rates of recession range from 1.9 ft/yr. at Devil's Jct. to 0.3 ft/yr at Big Beaver (Table 9). The mean annual rate of recession at recreational sites measured from dock structures to the shoreline is 0.9 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. 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 shoreline erosion on Ross Lake. The range in rates of recession on Ross Lake from 5.5 to 0.3 ft/yr. fall within the range of those reported by Gatt and Doe (1982) for reservoirs operated by the U.S. Army Corps of Engineers. 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.

Table 9. Rates of Bank Recession on Ross Lake.

Site	Erosion Class	Total Ft. Recession	RateMethod Ft./Yr
E-9	1	103	4.92
E-7A	1	116	5.5 2
W-63	1	42.8	2.02
W-23	1	23.5	1.12
E-181	2	8.5	1.41
E-80	2	11.2	1.91
W-125	2	2.6	0.41
E-134	2	2.0	0.31
W-36	2	1.6	0.31

Method 1 From Dock Anchor or Bulkhead.
Method 2 From Shore Geometry.

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 7.9 ft, or 0.6 ft/yr.

On Gorge lake measured bank recession at two sites was 16.8 ft or 0.6 ft/yr. since 1961 when the modern Gorge Dam was closed and 1 ft/yr. or 28.4 ft since 1961 at the second site. Bank recession at most sites is probably sporadic, with higher rates during slope failure after longer periods of wave undercutting of slopes creating conditions for slope failures.

DEVELOPMENT OF EQUILIBRIUM SHORE PROFILES

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 likely due to the 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.

Considering the older age of Diablo Lake and relatively minor pool fluctuations, their shores might be expected to have adjusted to reservoir 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.

SITE SELECTION FOR EROSION CONTROL

A variety of sites were selected for the design of erosion control measures, including roads, borrow pits, areas of slope instability, archaeological sites, important biological sites, project facilities and recreational facilities. Recognizing that it would be impractical to attempt to prevent erosion along all 16.2 miles of eroding reservoir shoreline, criteria were developed for selecting sites at which erosion control would be of most value.

The primary criterion used to select sites for erosion control assessment was potential effects on recreational resources, which focused attention on campsites and trail sections adjacent to the reservoirs. In the rugged topography surrounding the project, suitable locations for recreational facilities are limited, underscoring the importance of protecting existing facilities. At these sites erosion problems are often compounded by direct human impact in terms of destruction of protective vegetation, surface soil compaction, and direct displacement (erosion) of soil.

All shoreline sites identified by NPS personnel as having particular biological or cultural value were examined for potential damage by erosion. Of three osprey nesting trees on Ross Lake, only one is threatened. Known areas of sensitive or rare habitat or species do not appear to be threatened by erosion, although additional studies may identify such areas. Surveys of archaeological sites on the shorelines of the three reservoirs have not been done. One shoreline archaeological site has been identified and was examined for erosion. Sixteen sites where erosion is occurring along project roads were evaluated (Riedel, 1990), as were all areas where erosion threatened project facilities such as transmission towers.

At each site where an assessment of erosion control needs was made, information was collected on site materials, vegetation, erosion rates, and erosion mechanisms. Site photographs, field notes, and field survey data were used to prepare maps or cross-sections to illustrate the nature and extent of existing erosion problems, and to aid in designing erosion control methods. These field data were collected when lower reservoir levels provided good exposures of the foundations of existing structures, docks, and toe-slopes of the full pool bluffs.

On the basis of the assessment of current erosion conditions at the study sites, 29 recreation and project facility sites and 16 road sites are recommended for erosion control measures. Twenty Class I sites, one osprey nesting tree and one archaeological site are recommended for monitoring to better evaluate future bank recession rates and processes. Monitoring of sites where erosion control measures are undertaken is also recommended. Of the 70 sites selected, 49 are on Ross Lake, 5 on Diablo Lake and 3 on Gorge Lake. The remaining 13 sites are located on project access roads.

Site specific descriptions of existing conditions, projected future impacts, and proposed erosion control measures were prepared for all sites selected for erosion control and monitoring (Table 10).

SITE PROTECTION PRIORITY

Due to variations in the rate of bank recession at individual sites, priority should be given to construction of mitigation measures at sites where damage to important resources (recreation facilities, habitat, archaeological sites, project facilities) is ongoing and rapid. For recreation and project facility sites, estimates of bank recession rate and consideration of environmental factors such as slope, bank material type, and dominant erosion process were used to prioritize site protection. Those sites where erosion immediately (five years or less) threatens recreation facilities such as trails and campgrounds, valuable resources such as old-growth trees and where facilities can not be relocated are given high priority. Areas where facilities are not immediately (5 to 20 years) threatened are given medium priority. Where bank recession rates are low, erosion control is given lower priority, meaning erosion protection could wait until higher priority sites are completed.

Table 10. Key to Erosion Site Descriptions.

Site Name: Based on name of recreation facility at site or nearby geographic feature.

Location #: Arbitrary letter and number code to track sites, (see Figure 5, 6A-C, and Map 3 of (Riedel, 1990).

Photo #s: Day: Hour: Minute, imprinted on photographs (all photos were taken in 1989).

Site Priority:

<u>High</u> = Erosion immediately threatens facilities(5 years or less), rare habitat, or presents threat to public safety

<u>Medium</u> = Facilities or rare habitat are not immediately threatened (five to fifty years) but will probably be sometime during the relicensing period.

<u>Low</u> = Bank recession rates are low, erosion protection could wait until higher priority sites are completed.

Site Conditions:

Description of existing site materials, vegetation, and extent of erosion processes.

Projected Impacts:

Estimate based on interpretation of site features, cross sections, and direct measurements of recession from dated shore features like dock bulkheads.

Erosion Control Measure:

Recommendations for erosion control actions to reduce rates of bank recession and prevent continued loss of land to shoreline erosion.

EROSION PROCESSES AND CONTROL TECHNIQUES

The most frequent erosion setting at sites identified for erosion control measures occurs when erosion at the reservoir high water level has undercut steep slopes with thick accumulations of Quaternary sediments, leading to various degrees of surface instability. Instability ranges from slump failures in thick accumulations of relatively compact materials (over consolidated glacial deposits), to surface ravelling in the less compact outwash deposits and colluvium. In either case the removal of material at the base of the slopes de-stabilizes the overlying sediments, leading to bank collapse and recession. Subsequent wave action focused on different elevations as lake levels rise and fall removes the collapsed material, causing renewed undercutting and a continuation of the erosion cycle. The primary goal of erosion control is to reduce continued toe-slope erosion and stabilize the surface deposits in a visually acceptable manner.

Erosion control measures developed in this plan include both active and passive techniques. Active techniques include placement of structures and vegetation to stop erosion. Passive measures include monitoring schemes designed to provide more information on process and rates of erosion, such as at Class I sites. Active erosion control and stabilization methods in the Recreation area are limited by park service management objectives to maintain the natural and wilderness conditions in the project area. Stabilization structures such as extensive concrete walls and chemically treated lumber are inappropriate. Preferred methods include biotechnical slope protection measures that include a combination of vegetation and structural controls (Sotir, 1989; Gray and Leiser, 1982; Schiechtl,1980). These measures are designed to minimize the visual impacts of erosion control by using naturally occurring materials (local earth, rock, timber and vegetation) that blend with the surrounding site conditions. For the types of problems encountered in the study area a number of standard erosion control measures are appropriate, which can be tailored to individual site conditions. Depending on slope angles, wave energy levels, and materials, reduction of toe-slope retreat could involve protective measures such as anchored individual or networks of logs, riprap, cribbing, and vegetation. Surface stabilization can primarily be accomplished with vegetation, using local, fast rooting plants adapted to disturbed conditions. In certain areas, successful revegetation will require planning to minimize human disturbance of sensitive slopes.

TYPICAL EROSION CONTROL MEASURES ALONG THE RESERVOIRS

Undercutting of toe-slopes along the reservoir shoreline is the primary cause of bank recession and slope instability. Therefore, slope protection measures stress stabilizing the bottom of eroding shoreline slopes. Such erosion control measures vary in scale and effectiveness, and for this discussion have been sub-divided into four broad groups of erosion control measures, anchored logs, rock shore protection, cribbing, and vegetation. This discussion includes vegetation, which, although generally ineffective in toe-slope protection alone when wave action is a major erosion process, is important in stabilizing disturbed slope surfaces in conjunction with rock armor or retaining structures. Vegetation is also important in reducing surface erosion from rain splash and rilling and in enhancing the visual aspects of rock and cribbing structures.

ANCHORED LOGS

Perhaps the simplest and cheapest means to reduce wave erosion at the base of slopes where there is relatively minor erosion is to anchor logs along the shore at the full pool level. In some areas of the project, logs naturally collect against the shore where the dominant winds blow onshore. In these areas wave energy is reduced when the waves break on the logs rather than directly against the bank material. However, in some cases the logs are repeatedly pushed against the shore by wave action, increasing erosion as the momentum of the logs is expended against localized points of contact with the shore. This latter effect only occurs where the logs are buoyant and free to move with the fluctuating water levels associated with individual waves. Anchoring logs to the shore restricts log movement, and thus ensures that the net effect is one of slope protection rather than erosion enhancement. A major disadvantage of logs is that water still washes behind them potentially allowing fine soil material to wash out.

Figure 3 shows a typical example of slope protection using anchored logs. If bedrock is located on one or both ends of a wedge of eroding soil, cables passed through holes drilled in the logs may be anchored with rock bolts in the bedrock. In many areas the underlying material is not bedrock, and in these cases it is important to ensure that the logs can be anchored securely. In very compact substrate (over-consolidated till), logs may still be effectively anchored into the substrate, but for looser substrates anchored logs should not be used as an erosion control measure unless the logs can be tied off at both ends to large immobile objects such as existing dock anchors, stumps, and concrete or large rocks placed as anchors.

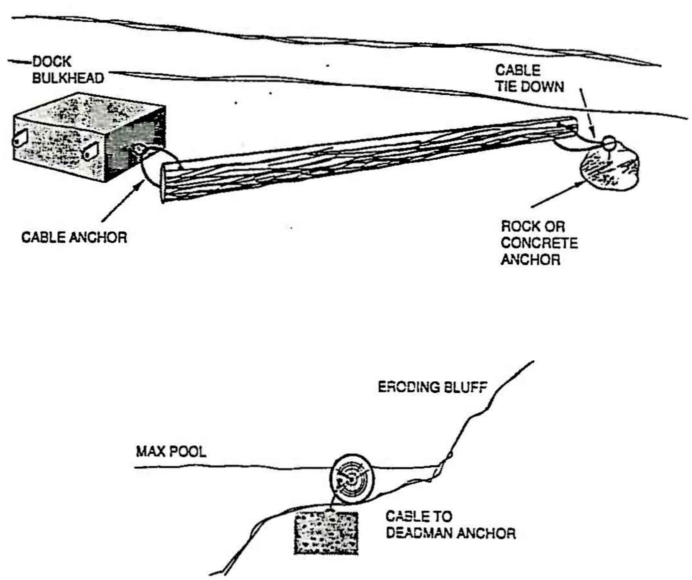

Figure 3. Typical Log Shore Protection.

One of the advantages of using anchored logs for shore protection is that the measure replicates a natural occurrence in the reservoir setting, and thus has less negative visual impacts than other means of erosion control. Anchored logs are generally only appropriate for conditions of relatively minor wave erosion. Where slopes are steep and several erosion processes are active, logs alone are inappropriate.

ROCK SHORE PROTECTION

Where there is no substrate suitable to anchor logs, and where erosion is severe, construction of a rock wall or slope revetment in combination with vegetation to protect the base of an eroding bluff would ensure a greater level of shore protection. Rock shore protection consists of placing material along the shore that is large enough to withstand movement by wave action. Wave energy is expended against the large boulders rather than more erodible bank materials. In some situations in the project area, natural rock armor has developed (Photo 1). This occurs where the shore material consists of both fine soil material and very large boulders that are common at eroding sites where the bank material is glacial till or outwash. Wave erosion removes the finer soil material, leaving behind the large boulders as a coarse lag deposit. Thus, placement of riprap as a bank protection measure replicates a situation developed naturally in the project area, and is less likely to be perceived as a negative visual impact. Shrubs and trees such as willows, alders, and vine maple can be placed in amongst the rocks during or after installation to help prevent movement of the rocks and provide a more natural looking shoreline.

To successfully protect shorelines from erosion, rock walls must extend above the highest water level and below the wave scour level. Further, they must extend up the shoreline far enough to accommodate wave run-up and have toe protection so that erosion will not remove the foundation of the rock when the reservoir is lowered. On Ross Lake, full pool elevation is 1602.5 feet, but lake levels occasionally rise as much as 0.9. ft above this level (Riedel, 1990). Wave heights on Ross Lake can be as high as 3.5 to 4 feet (Figure 4) (Gray and Leiser, 1982) (Riedel, 1990).

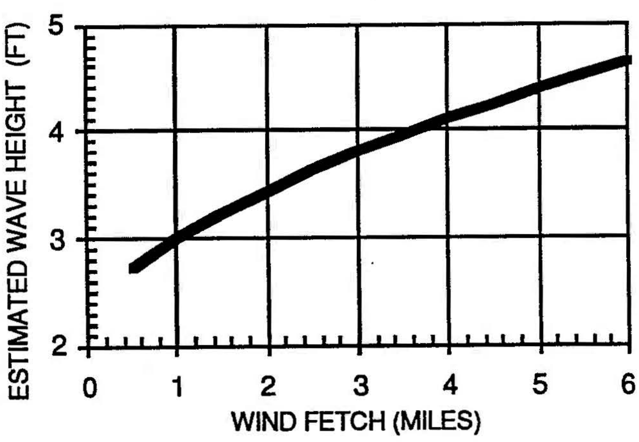

Figure 4. Wind Fetch and Estimated Wave Heights.

Wave run-up varies with slope and the texture of the rock used for a rock wall or slope revetment.

Considering wave heights and pool elevations rock shore protection should extend to a minimum of 1606.5 feet at sites open to a long fetch on Ross Lake, and 1212 feet on Diablo Lake where eroding bluff heights are greater than four feet. Where bluff heights are less than four feet, walls should extend to the top of the eroding bluff. Wave run-up must also be considered. Figure 5 shows some typical examples of rock slope protection.

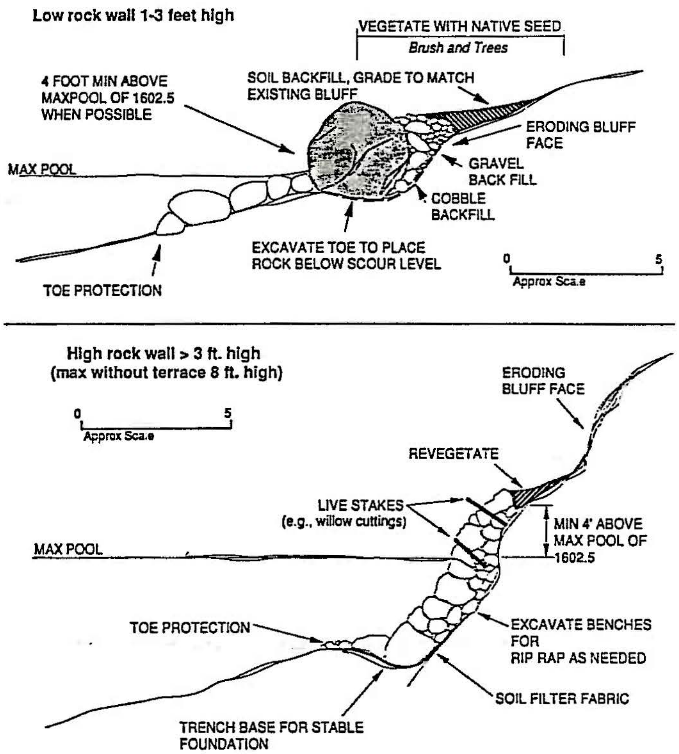

Figure 5. Typical Rock Shore Protection.

The rock must be large enough to prevent rock movement due to wave action, and must be trenched down into the slope to provide a stable foundation for the rock below scour levels. The U.S. Army Corps of Engineers recommends burial of rock one-wave height below the surface to prevent scouring at the base of a rock wall or slope revetment.

To prevent removal of loose backfill and shoreline soils from between and behind the larger rocks a fabric or soil filter is used behind the riprap. Geotextile fabric is commonly used in this case, however, it would need to be carefully installed using a dark color fabric so that portions of the fabric are not visible. Over time portions of the riprap walls will fail exposing the fabric. Therefore, use of a soil filter behind the riprap walls may be a better choice for the visually sensitive project area. Soil filter material is available along the foreshore at many of the sites.

A soil filter is a porous backfill material behind the riprap with openings small enough to prevent movement of backfill soil, but sufficiently permeable to allow little resistance to seepage (Peck et al, 1974; Craig, 1983; Sowers, 1979). A typical soil filter design for the rock structures would require a gradation from the 1 to 4 foot rock protection material to a cobble/gravel mixture in the first backfill layer and a gravel/sand mixture in the second backfill layer.

When used in combination with vegetation, this method provides reliable long term protection that can be constructed with abundant local material to fit visually with many sites. Rocks are locally available near most sites in the drawdown zone, but should not be removed from beaches within 30 feet of eroding sites or beaches immediately adjacent to a site. At a few sites, rocks will need to be transported at least a mile by barge.

To move and place the rock will require a back-hoe for sites with low gradient beach areas and a barge based boom for steeper areas and areas where the rock must be moved in from other locations. In some cases a helicopter may by the only cost effective method to move-in large rocks.

CRIBBING

Cribbing structures are recommended for sites where eroding bluffs are higher than 8 feet (Figure 6). This includes repair of some existing wood cribs that were built along the East Bank Trail in the early sixties.

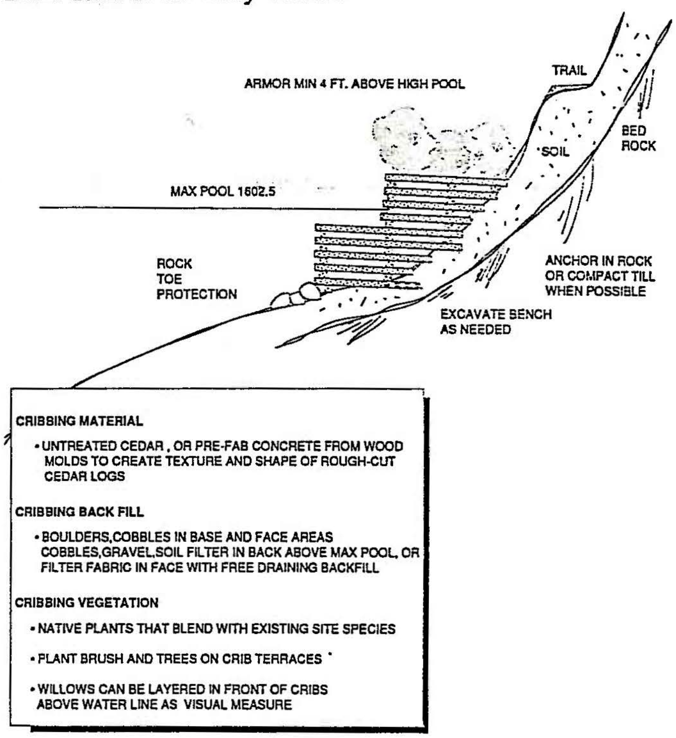

Figure 6. Typical Cribbing Shore Protection.

The most common mode of failure to these cribbing structures was caused by damage to the crib foundation. Most of the split cedar wood is still in good condition. Excavation of a bench to place the first level of cribbing, use of cable tiedowns, and 1 to 4 foot rock armor at the base of cribs is recommended for many of the new and restored cribs. Soil filter backfill for the portions of the cribs in the water zone is required to prevent soil from washing out of the cribs. Trees and brush planted among the cribbing members and on crib terraces is recommended to reduce the visual affect and help stabilize backfill soils.

Visual aspects of the project area require the use of logs, roughcut timber or split timber. Use of untreated cedar wood which is naturally resistant to rotting and can be purchased locally is recommended. The condition of the existing cedar cribbing indicates untreated cedar will last at least 25 to 30 years. Custom precast cribbing members could be made from molds of logs that simulate the appearance of wood but provide the durability of concrete.

VEGETATION

Vegetation slows water flow velocities, helps hold together soils and broken rocks, reduces surface erosion, and helps blend erosion control structures with the surrounding terrain. Vegetation can be used alone or in conjunction with other methods to stabilize slopes, depending on soil type and thickness, slope, wave energy and other environmental factors.

NPS vegetation plans require the use of local species to protect the genetic integrity of species and the plant community as a whole. Therefore, seeds or transplants must be collected within the Skagit River Basin as close as possible to the site. Use of local varieties also provides plants that are better adapted to site conditions.

Revegetation generally involves transplanting or direct seeding of an area. At North Cascades National Park, transplanting has been the traditional method of the revegetation program. Recent experiments in the park suggest that direct seeding may be a viable alternative, although additional experimentation is needed. Transplants can come from mature plants in undisturbed areas or by growing them from seeds.

Eight general vegetation methods are proposed at the various erosion sites. Most sites will use a combination of vegetation methods. Revegetation protection alone will be tried at several sites where the intensity of erosional processes is low and shore sediments not too compact. Typical brush layering methods to protect slopes will be effective at many of the project sites as shown in Gray and Leiser (1982).

The main species used for revegetation of disturbed areas will include shrubs trees such as sitka alder, willow, vine maple, Oregon grape, salal and other local berries, grasses and sedges.

Shrubs are preferred because their light weight does not add overburden to the slope, they grow quickly and are often robust enough to survive transplanting.

Vegetation collection must be arranged seasonally. Cuttings and transplants must be taken during periods of plant dormancy (i.e., late fall to early spring), and seeds collected during the fall. Seed sources within the study area include the power line, roads and trail corridors, shoreline areas, and valleys adjacent to the reservoirs such as Big Beaver, Thunder and Lightning Creeks. Live stakes and transplants within the study area may also be obtained from the same areas used to obtain seed sources with the exception of shoreline areas.

ESTIMATED PROGRAM COSTS

Cost estimates for implementation of the Skagit Project Erosion Control Plan were prepared based on unit costs per site calculated from engineering tables (Lynott, 1989; Sotir, 1989; Kortenhof, 1988; Sotir, 1989; Water Resources Administration, 1983; Madej et al, 1980; White and Franks, 1978). Costs to perform proposed erosion control measures in the project area are strongly dependent on the unique and remote location, management constraints and site specific aspects at each site. The negotiated settlement agreement doubled the estimated cost of $420,000 dollars and added a contingency fund of $500,000 for unexpected conditions and new sites, thereby providing 1.34 million dollars over a 10 year period for final design, construction, monitoring, development of a nursery program to provide native plant materials and contingency erosion control actions. An interim program of $33,000 per year for 3 years was provided to start erosion control at critical sites prior to issuance of the FERC license.

CONCLUSIONS

1) Reservoir shoreline erosion can be a severe problem in mountainous landscapes where pool levels are subject to annual fluctuations. Shorelines in these environments take greater than 6 decades to develop stable profiles and may never develop equilibrium shorelines in many locations.

2) In the Skagit Project area the location and severity of erosion is related to dam height, valley gradient and landform type. High dams superimpose water on different landscapes within a given valley. At the dam and mid-reservoir areas the operational levels of the reservoir focus waves on valley walls, and erosion problems can be severe. Where the valley emerges at the head of the reservoir, waves work against lower gradient floodplain and alluvial fans landforms and erosion is less severe. Glaciated valleys are subject to more severe erosion problems because of the existence of glacial till and outwash deposits on steep valley walls. Unglaciated valleys have fewer erosion problems because erosion-resistant bedrock and talus are the dominant bank materials.

3) Erosion control can be designed to accommodate strict aesthetic values. Rock, earth and native vegetation are the materials to accomplish this goal.

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