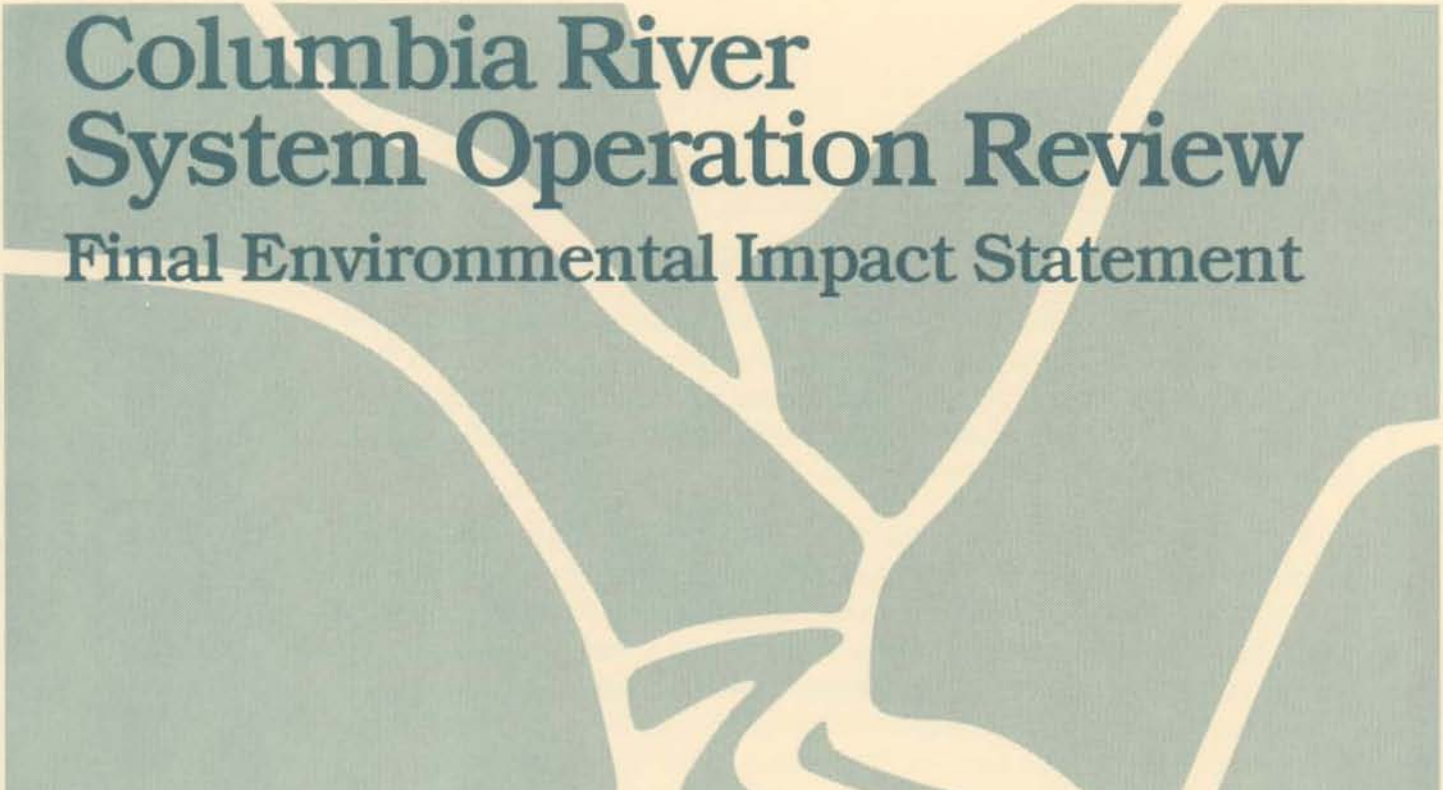
# Columbia River System Operation Review

## Final Environmental Impact Statement



# Appendix L

## Soils, Geology and Groundwater

BONNEVILLE POWER ADMINISTRATION

US Army Corps of Engineers
North Pacific Division

U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

DOE/EIS-0170

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## PUBLIC INVOLVEMENT IN THE SOR PROCESS

The Bureau of Reclamation, Corps of Engineers, and Bonneville Power Administration wish to thank those who reviewed the Columbia River System Operation Review (SOR) Draft EIS and appendices for their comments. Your comments have provided valuable public, agency, and tribal input to the SOR NEPA process. Throughout the SOR, we have made a continuing effort to keep the public informed and involved.

Fourteen public scoping meetings were held in 1990. A series of public roundtables was conducted in November 1991 to provide an update on the status of SOR studies. The lead agencies went back to most of the 14 communities in 1992 with 10 initial system operating strategies developed from the screening process. From those meetings and other consultations, seven SOS alternatives (with options) were developed and subjected to full–scale analysis. The analysis results were presented in the Draft EIS released in July 1994. The lead agencies also developed alternatives for the other proposed SOR actions, including a Columbia River Regional Forum for assisting in the determination of future SOSs, Pacific Northwest Coordination Agreement alternatives for power coordination, and Canadian Entitlement Allocation Agreements alternatives. A series of nine public meetings was held in September and October 1994 to present the Draft EIS and appendices and solicit public input on the SOR. The lead agencies received 282 formal written comments. Your comments have been used to revise and shape the alternatives presented in the Final EIS.

Regular newsletters on the progress of the SOR have been issued. Since 1990, 20 issues of *Streamline* have been sent to individuals, agencies, organizations, and tribes in the region on a mailing list of over 5,000. Several special publications explaining various aspects of the study have also been prepared and mailed to those on the mailing list. Those include:

The Columbia River: A System Under Stress
The Columbia River System: The Inside Story
Screening Analysis: A Summary
Screening Analysis: Volumes 1 and 2
Power System Coordination: A Guide to the Pacific Northwest Coordination Agreement
Modeling the System: How Computers are Used in Columbia River Planning
Daily/Hourly Hydrosystem Operation: How the Columbia River System Responds to Short–Term Needs

Copies of these documents, the Final EIS, and other appendices can be obtained from any of the lead agencies, or from libraries in your area.

Your questions and comments on these documents should be addressed to:

SOR Interagency Team
P .O. Box 2988
Portland, OR 97208–2988

# PREFACE: SETTING THE STAGE FOR THE SYSTEM OPERATION REVIEW

## WHAT IS THE SOR AND WHY IS IT BEING CONDUCTED?

The Columbia River System is a vast and complex combination of Federal and non–Federal facilities used for many purposes including power production, irrigation, navigation, flood control, recreation, fish and wildlife habitat, and municipal and industrial water supply. Each river use competes for the limited water resources in the Columbia River Basin.

To date, responsibility for managing these river uses has been shared by a number of Federal, state, and local agencies. Operation of the Federal Columbia River system is the responsibility of the Bureau of Reclamation (Reclamation), Corps of Engineers (Corps) and Bonneville Power Administration (BPA)

The System Operation Review (SOR) is a study and environmental compliance process being used by the three Federal agencies to analyze future operations of the system and river use issues. The goal of the SOR is to achieve a coordinated system operation strategy for the river that better meets the needs of all river users. The SOR began in early 1990, prior to the filing of petitions for endangered status for several salmon species under the Endangered Species Act.

The comprehensive review of Columbia River operations encompassed by the SOR was prompted by the need for Federal decisions to (1) develop a coordinated system operating strategy (SOS) for managing the multiple uses of the system into the 21st century; (2) provide interested parties with a continuing and increased longterm role in system planning (Columbia River Regional Forum); (3) renegotiate and renew the Pacific Northwest Coordination Agreement (PNCA), a contractual arrangement among the region's major hydroelectric generating utilities and affected Federal agencies to provide for coordinated power generation on the Columbia River system; and (4) renew or develop new Canadian Entitlement Allocation Agreements (contracts that divide Canada's share of Columbia River Treaty downstream power benefits and obligations among three participating public utility districts and BPA). The review provides the environmental analysis required by the National Environmental Policy Act (NEPA).

This technical appendix addresses only the effects of alternative system operating strategies for managing the Columbia River system. The environmental impact statement (EIS) itself and some of the other appendices present analyses of the alternative approaches to the other three decisions considered as part of the SOR.

## WHO IS CONDUCTING THE SOR?

The SOR is a joint project of Reclamation, the Corps, and BPA–the three agencies that share responsibility and legal authority for managing the Federal Columbia River System. The National Marine Fisheries Service (NMFS), U.S. Fish and Wildlife Service (USFWS), and National Park Service (NPS), as agencies with both jurisdiction and expertise with regard to some aspects of the SOR, are cooperating agencies. They contribute information, analysis, and recommendations where appropriate. The U.S. Forest Service (USFS) was also a cooperating agency, but asked to be removed from that role in 1994 after assessing its role and the press of other activities.

## HOW IS THE SOR BEING CONDUCTED?

The system operating strategies analyzed in the SOR could have significant environmental impacts. The study team developed a three–stage process–scoping, screening, and full–scale analysis of the strategies–to address the many issues relevant to the SOR.

At the core of the analysis are 10 work groups. The work groups include members of the lead and cooperating agencies, state and local government agencies, representatives of Indian tribes, and members of the public. Each of these work groups has a single river use (resource) to consider.

Early in the process during the screening phase, the 10 work groups were asked to develop an alternative for project and system operations that would provide the greatest benefit to their river use, and one or more alternatives that, while not ideal, would provide an acceptable environment for their river use. Some groups responded with alternatives that were evaluated in this early phase and, to some extent, influenced the alternatives evaluated in the Draft and Final EIS. Additional alternatives came from scoping for the SOR and from other institutional sources within the region. The screening analysis studied 90 system operation alternatives.

Other work groups were subsequently formed to provide projectwide analysis, such as economics, river operation simulation, and public involvement.

The three–phase analysis process is described briefly below.

- **Scoping/Pilot Study–**After holding public meetings in 14 cities around the region, and coordinating with local, state, and Federal agencies and Indian tribes, the lead agencies established the geographic and jurisdictional scope of the study and defined the issues that would drive the EIS. The geographic area for the study is the Columbia River Basin (Figure P–1). The jurisdictional scope of the SOR encompasses the 14 Federal projects on the Columbia and lower Snake Rivers that are operated by the Corps and Reclamation and coordinated for hydropower under the PNCA. BPA markets the power produced at these facilities. A pilot study examining three alternatives in four river resource areas was completed to test the decision analysis method proposed for use in the SOR.

- **Screening–**Work groups, involving regional experts and Federal agency staff, were created for 10 resource areas and several support functions. The work groups developed computer screening models and applied them to the 90 alternatives identified during screening. They compared the impacts to a baseline operating year–1992–and ranked each alternative according to its impact on their resource or river use. The lead agencies reviewed the results with the public in a series of regional meetings in September 1992.

- **Full–Scale Analysis–**Based on public comment received on the screening results, the study team sorted, categorized, and blended the alternatives into seven basic types of operating strategies. These alternative strategies, which have multiple options, were then subjected to detailed impact analysis. Twenty–one possible options were evaluated. Results and tradeoffs for each resource or river use were discussed in separate technical appendices and summarized in the Draft EIS. Public review and comment on the Draft EIS was conducted during the summer and fall of 1994. The lead agencies adjusted the alternatives based on the comments, eliminating a few options and substituting new options, and reevaluated them during the past eight months. Results are summarized in the Final EIS.

Alternatives for the Pacific Northwest Coordination Agreement (PNCA), the Columbia River Regional Forum (Forum), and the Canadian Entitlement Allocation Agreements (CEAA) did not use the three–stage process described above. The environmental impacts from the PNCA and CEAA were not significant and there were no anticipated impacts from the Regional Forum. The procedures used to analyze alternatives for these actions are described in their respective technical appendices.

For detailed information on alternatives presented in the Draft EIS, refer to that document and its appendices.

## WHAT SOS ALTERNATIVES ARE CONSIDERED IN THE FINAL EIS?

Seven alternative System Operating Strategies (SOS) were considered in the Draft EIS. Each of the seven SOSs contained several options bringing the total number of alternatives considered to 21. Based on review of the Draft EIS and corresponding adjustments, the agencies have identified seven operating strategies that are evaluated in this Final EIS. Accounting for options, a total of 13 alternatives is now under consideration. Six of the alternatives remain unchanged from the specific options considered in the Draft EIS. One is a revision to a previously considered alternative, and the rest represent replacement or new alternatives. The basic categories of SOSs and the numbering convention remains the same as was used in the Draft EIS. However, because some of the alternatives have been dropped, the numbering of the final SOSs are not consecutive. There is one new SOS category, Settlement Discussion Alternatives, which is labeled SOS 9 and replaces the SOS 7 category. This category of alternatives arose as a consequence of litigation on the 1993 Biological Opinion and ESA Consultation for 1995.

The 13 system operating strategies for the Federal Columbia River system that are analyzed for the Final EIS are:

**SOS 1a Pre Salmon Summit Operation** represents operations as they existed from around 1983 through the 1990–91 operating year, prior to the ESA listing of three species of salmon as endangered or threatened.

**SOS 1b Optimum Load–Following Operation** represents operations as they existed prior to changes resulting from the Regional Act. It attempts to optimize the load–following capability of the system within certain constraints of reservoir operation.

**SOS 2c Current Operation/No–Action Alternative** represents an operation consistent with that specified in the Corps of Engineers' 1993 Supplemental EIS. It is similar to system operation that occurred in 1992 after three species of salmon were listed under ESA.

**SOS 2d [New] 1994–98 Biological Opinion** represents the 1994–98 Biological Opinion operation that includes up to 4 MAF flow augmentation on the Columbia, flow targets at McNary and Lower Granite, specific volume releases from Dworshak, Brownlee, and the Upper Snake, meeting sturgeon flows 3 out of 10 years, and operating lower Snake projects at MOP and John Day at MIP.

**SOS 4c [Rev.] Stable Storage Operation with Modified Grand Coulee Flood Control** attempts to achieve specific monthly elevation targets year–round that improve the environmental conditions at storage projects for recreation, resident fish, and wildlife. Integrated Rules Curves (IRCs) at Libby and Hungry Horse are applied.

**SOS 5b Natural River Operation** draws down the four lower Snake River projects to near riverbed levels for four and one–half months during the spring and summer salmon migration period, by assuming new low level outlets are constructed at each project.

**SOS 5c [New] Permanent Natural River Operation** operates the four lower Snake River projects to near riverbed levels year–round.

**SOS 6b Fixed Drawdown Operation** draws down the four lower Snake River projects to near spillway crest levels for four and one–half months during the spring and summer salmon migration period.

**SOS 6d Lower Granite Drawdown Operation** draws down Lower Granite project only to near spillway crest level for four and one–half months.

**SOS 9a [New] Detailed Fishery Operating Plan** includes flow targets at The Dalles based on the previous year's end–of–year storage content, specific volumes of releases for the Snake River, the drawdown of Lower Snake River projects to near spillway crest level for four and one–half months, specified spill percentages, and no fish transportation.

**SOS 9b [New] Adaptive Management** establishes flow targets at McNary and Lower Granite based on runoff forecasts, with specific volumes of releases to meet Lower Granite flow targets and specific spill percentages at run–of–river projects.

**SOS 9c [New] Balanced Impacts Operation** draws down the four lower Snake River projects near spillway crest levels for two and one–half months during the spring salmon migration period. Refill begins after July 15. This alternative also provides 1994–98 Biological Opinion flow augmentation, integrated rule curve operation at Libby and Hungry Horse, a reduced flow target at Lower Granite due to drawdown, winter drawup at Albeni Falls, and spill to achieve no higher than 120 percent daily average for total dissolved gas.

**SOS PA Preferred Alternative** represents the operation proposed by NMFS and USFWS in their Biological Opinions for 1995 and future years; this SOS operates the storage projects to meet flood control rule curves in the fall and winter in order to meet spring and summer flow targets for Lower Granite and McNary, and includes summer draft limits for the storage projects.

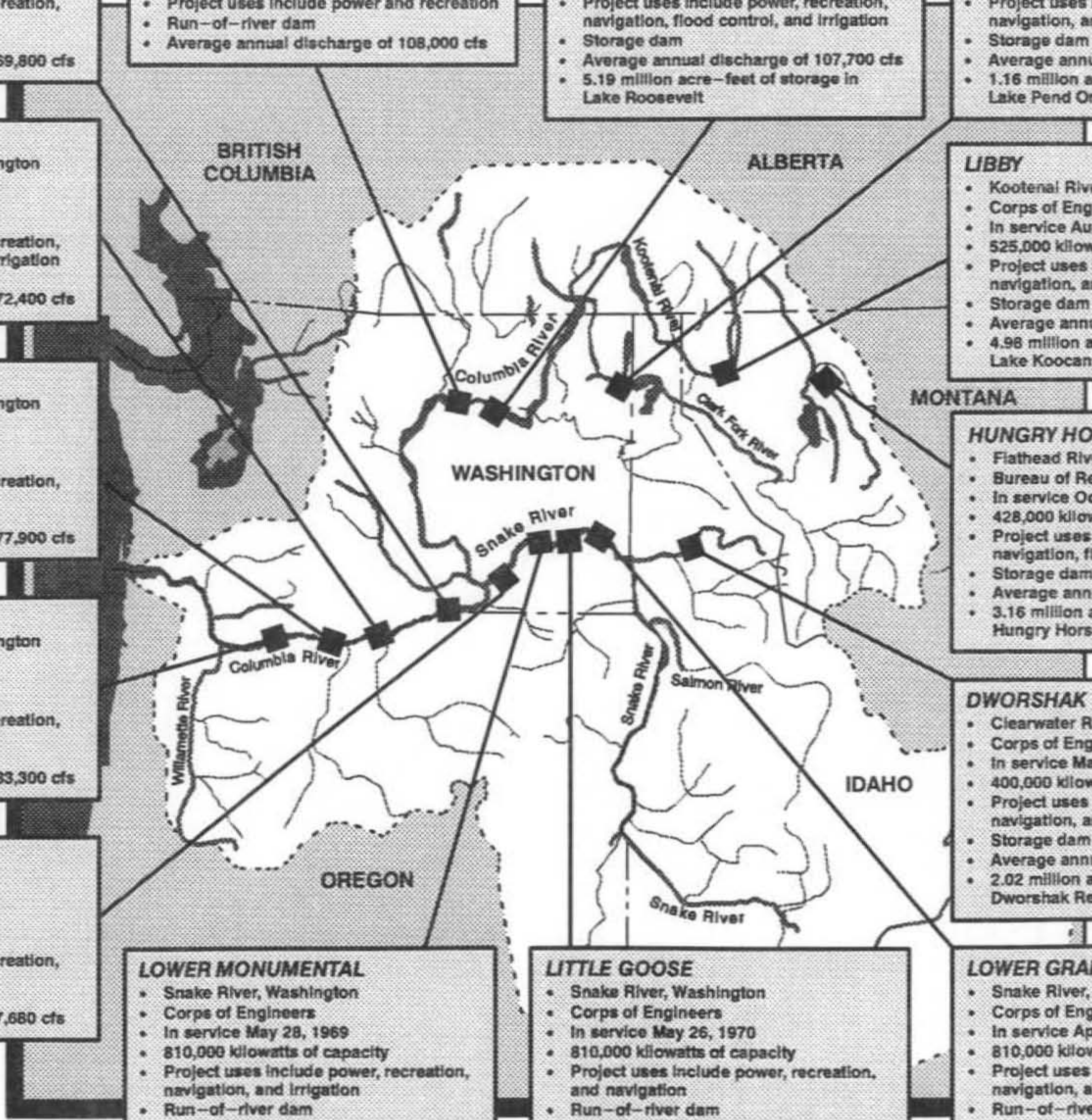
## WHAT DO THE TECHNICAL APPENDICES COVER?

This technical appendix is one of 20 prepared for the SOR. They are:

A. River Operation Simulation
B. Air Quality
C. Anadromous Fish & Juvenile Fish Transportation
D. Cultural Resources
E. Flood Control
F. Irrigation/Municipal and Industrial Water Supply
G. Land Use and Development
H. Navigation
I. Power
J. Recreation
K. Resident Fish
L. Soils, Geology, and Groundwater
M. Water Quality
N. Wildlife
O. Economic and Social Impacts
P. Canadian Entitlement Allocation Agreements
Q. Columbia River Regional Forum
R. Pacific Northwest Coordination Agreement
S. U. S. Fish and Wildlife Service Coordination Act Report
T. Comments and Responses

Each appendix presents a detailed description of the work group's analysis of alternatives, from the scoping process through full–scale analysis. Several appendices address specific SOR functions (e.g., River Operation Simulation), rather than individual resources, or the institutional alternatives (e.g., PNCA) being considered within the SOR. The technical appendices provide the basis for developing and analyzing alternative system operating strategies in the EIS. The EIS presents an integrated review of the vast wealth of information contained in the appendices, with a focus on key issues and impacts. In addition, the three agencies have prepared a brief summary of the EIS to highlight issues critical to decisionmakers and the public.

There are many interrelationships among the different resources and river uses, and some of the appendices provide supporting data for analyses presented in other appendices. This Geology appendix relies on supporting data contained in Appendix M. For complete coverage of all aspects of geology, soils, and groundwater readers may wish to review both appendices in concert.



***McNARY***
- Columbia River, Oregon/Washington
- Corps of Engineers
- In service November 6, 1953
- 980,000 kilowatts of capacity
- Project uses include power, recreation, and navigation
- Run-of-river dam
- Average annual discharge of 169,800 cfs

***CHIEF JOSEPH***
- Columbia River, Washington
- Corps of Engineers
- In service August 20, 1955
- 2,069,000 kilowatts of capacity
- Project uses include power and recreation
- Run-of-river dam
- Average annual discharge of 108,000 cfs

***GRAND COULEE***
- Columbia River, Washington
- Bureau of Reclamation
- In service September 28, 1941
- 6,494,000 kilowatts of capacity
- Project uses include power, recreation, navigation, flood control, and irrigation
- Storage dam
- Average annual discharge of 107,700 cfs
- 5.19 million acre-feet of storage in Lake Roosevelt

***ALBENI FALLS***
- Pend Oreille River, Idaho
- Corps of Engineers
- In service April 1, 1955
- 42,000 kilowatts of capacity
- Project uses include power, recreation, navigation, and flood control
- Storage dam
- Average annual discharge of 25,340 cfs
- 1.16 million acre-feet of storage in Lake Pend Oreille

***JOHN DAY***
- Columbia River, Oregon/Washington
- Corps of Engineers
- In service July 16, 1968
- 2,160,000 kilowatts of capacity
- Project uses include power, recreation, navigation, flood control, and irrigation
- Run-of-river dam
- Average annual discharge of 172,400 cfs

***LIBBY***
- Kootenai River, Montana
- Corps of Engineers
- In service August 13, 1975
- 525,000 kilowatts of capacity
- Project uses include power, recreation, navigation, and flood control
- Storage dam
- Average annual discharge of 11,350 cfs
- 4.98 million acre-feet of storage in Lake Koocanusa

***THE DALLES***
- Columbia River, Oregon/Washington
- Corps of Engineers
- In service May 13, 1957
- 1,780,000 kilowatts of capacity
- Project uses include power, recreation, and navigation
- Run-of-river dam
- Average annual discharge of 177,900 cfs

***HUNGRY HORSE***
- Flathead River (South Fork), Montana
- Bureau of Reclamation
- In service October 29, 1952
- 428,000 kilowatts of capacity
- Project uses include power, recreation, navigation, flood control, and irrigation
- Storage dam
- Average annual discharge of 3,517 cfs
- 3.16 million acre-feet of storage in Hungry Horse Reservoir

***BONNEVILLE***
- Columbia River, Oregon/Washington
- Corps of Engineers
- In service June 6, 1938
- 1,050,000 kilowatts of capacity
- Project uses include power, recreation, and navigation
- Run-of-river dam
- Average annual discharge of 183,300 cfs

***DWORSHAK***
- Clearwater River (North Fork), Idaho
- Corps of Engineers
- In service March 1, 1973
- 400,000 kilowatts of capacity
- Project uses include power, recreation, navigation, and flood control
- Storage dam
- Average annual discharge of 5,820 cfs
- 2.02 million acre-feet of storage in Dworshak Reservoir

***ICE HARBOR***
- Snake River, Washington
- Corps of Engineers
- In service December 18, 1961
- 603,000 kilowatts of capacity
- Project uses include power, recreation, and navigation
- Run-of-river dam
- Average annual discharge of 47,680 cfs

***LOWER MONUMENTAL***
- Snake River, Washington
- Corps of Engineers
- In service May 28, 1969
- 810,000 kilowatts of capacity
- Project uses include power, recreation, navigation, and irrigation
- Run-of-river dam
- Average annual discharge of 47,670 cfs

***LITTLE GOOSE***
- Snake River, Washington
- Corps of Engineers
- In service May 26, 1970
- 810,000 kilowatts of capacity
- Project uses include power, recreation, and navigation
- Run-of-river dam
- Average annual discharge of 47,230 cfs

***LOWER GRANITE***
- Snake River, Washington
- Corps of Engineers
- In service April 3, 1975
- 810,000 kilowatts of capacity
- Project uses include power, recreation, navigation, and irrigation
- Run-of-river dam
- Average annual discharge of 49,680 cfs

1 million acre feet = 1.234 billion cubic meters
1 cubic foot per second = 0.028 cubic meters per second

**Figure P–1. Projects in the System Operation Review.**

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# CHAPTER 1

# INTRODUCTION: SCOPE AND PROCESS

This appendix addresses the study of geology, soils, and groundwater concerns relative to the System Operation Review (SOR). Chapter 1 provides an overview of the study, scope, and process for this resource area. In order, the respective sections of this chapter discuss the relevant issues for the study, and the means by which the SOR team carried out the study.

## 1.1 SUMMARY OF ISSUES RAISED IN SCOPING

Public comment specifically relating to geology, soils, and groundwater that was received during the SOR scoping process was limited. The SOR Interagency Team identified only two comments expressing concern over erosion caused by reservoir fluctuations. A few comments referred to groundwater aquifer depletion and noted concern over dropping water levels in wells, but these comments appeared to relate to depletion through pumping rather than potential effects of system operations on groundwater levels. Specific references to geologic considerations are not evident in the scoping comments.

While the volume of scoping input that directly and specifically addressed geology, soils, and groundwater was limited, comments that indirectly related to this subject area were more frequent. For example, a number of comments identified water quality as a general concern without specifically mentioning the amount of sediment in the water as an issue. Similarly, many comments raised protection of cultural resources as a significant concern. Because erosion is a primary process by which cultural resources are damaged, these comments indirectly identify the influence of system operations on erosion as an issue to be addressed by the SOR.

Given the nature and the limited extent of public comment on geology, soils, and groundwater, the scope of investigation for this subject area was largely determined internally by the assigned SOR staff. The study team assigned to this resource reviewed and interpreted the public scoping comments that were directly or indirectly applicable. They also reviewed documents that address the effects of system operations on reservoir physical processes, including recent National Environmental Policy Act (NEPA) documentation on short–term river system operations and reports on the 1992 physical drawdown test of Lower Granite and Little Goose reservoirs on the lower Snake River. Based on these activities, the study team identified three specific issue areas that are summarized as follows:

**Erosion**

Reservoir operations cause or contribute to shoreline erosion through a variety of processes. The effect on the rate and extent of erosion could vary significantly among alternatives. A key requirement for the SOR is to investigate how operations relate to erosion, and the extent to which different operations would affect the rate and location of erosion. This information on erosion impacts will be key inputs to the analyses of water quality and cultural resources.

**Sedimentation**

Material that is eroded is typically transported by air or water. Transport and deposition of sediment in water is a significant SOR issue, as a result of potential effects on river and reservoir morphology and water quality, and thereby on uses influenced by these characteristics.

**Groundwater Levels**

Surface water and groundwater bodies are often hydrologically connected; a change in the level of one could result in a corresponding change in the other. Therefore, the SOR analysis needs to include investigation of connections between reservoirs and groundwater and identification of operations effects on groundwater levels, including potential influence on wells.

## 1.2 STUDY PROCESS

Geology, soils, and groundwater comprise a subject area that was not assigned to 1 of the 10 resource work groups established by the SOR. These factors overlap with or influence a variety of resource areas, including water quality, cultural resources, air quality, irrigation/municipal and industrial water supply, navigation, recreation, and possibly others. Given the degree of subject overlap, geology, soils, and groundwater became the responsibility of the SOR NEPA Group, one of the functional work groups intended to serve the entire SOR organization. The process followed by this group in conducting the study and developing the appendix is summarized below.

### 1.2.1 Work Group Coordination

As indicated previously, a separate SOR work group was not convened for geology, soils, and groundwater. The SOR NEPA Action Group coordinated study efforts for this subject area. Foster Wheeler Environmental Corporation (formerly Enserch Environmental), a private consulting firm, conducted the bulk of the staff work on the studies and the appendix under a contract with Bonneville Power Administration (BPA) (see Technical Exhibit 1 for a list of preparers for this appendix). Both entities coordinated with other SOR work groups to ensure appropriate distribution and exchange of information. Among the various SOR work groups with an interest in geology, soils, and groundwater, the linkage with the Water Quality Work Group was the strongest. Foster Wheeler Environmental developed and applied a shoreline erosion model to quantify sediment contributions to the river system from shoreline exposure, as under drawdown conditions. The results of this model analysis are reported in this appendix, and were also provided as direct inputs to the water quality modeling analysis.

### 1.2.2 Pilot Study and Screening

Geology, soils, and groundwater issues were not directly incorporated into either of the initial phases of study for the SOR. The pilot study was a demonstration assessment involving a very few selected resource considerations. The screening analysis incorporated review of the screening alternatives by the 10 resource work groups, which were established on the basis of the SOR scoping input (see the previously issues Screening Analysis Report for additional information on these study phases). As a result of the relative lack of scoping comment on geology, soils, and groundwater concerns, a separate work group for this subject area was not established. However, erosion and sedimentation concerns were indirectly reflected in the screening analyses conducted by other SOR work groups, particularly those for water quality and cultural resources.

### 1.2.3 Full-Scale Analysis

Study methods used for full-scale analysis are described in more detail in Chapter 3 of this appendix. Briefly, the study process involved the standard steps of characterizing the existing conditions; identifying the physical processes by which system operations could affect geology, soils, and groundwater; and evaluating the consequences of the system operating strategy (SOS) alternatives, based on the reservoir operating patterns indicated in the hydroregulation model results. The studies were set up to specifically address the three issues identified above in Section 1.1. Because of their direct physical linkage, erosion and sedimentation were investigated jointly in one study track, while groundwater represented a second track.

Impact assessment for these subject areas was generally conducted in a qualitative manner, as detailed; site-specific inventory and analysis would not be appropriate for a programmatic environmental impact statement (EIS) on such a complex system. As an exception to this general approach, a shoreline erosion model was a key part of the analysis for selected alternatives. This model yielded quantitative estimates of sediment contributions from exposed reservoir shorelines.

When selecting the method of analysis, the availability of data and the types and degrees of impacts of the various alternatives had to be considered. Some of the alternatives were addressed using analysis from previous NEPA documents on river system operations.

The alternatives that would involve the most significant impacts are those with major drawdowns (SOSs 5, 6, 9a, and 9c, with their respective options). These alternatives could be studied using the data from the March 1992 drawdown test of Little Goose and Lower Granite reservoirs. In addition, much data already existed on the hydrology and sedimentology of Lower Granite.

The literature was reviewed for general information on shoreline erosion and sedimentation in reservoirs, as well as specific information on Columbia River system reservoirs. While some information exists on shoreline erosion processes in general, no predictive models have been developed. The most intensively studied erosional process among those determined to be most significant is wave erosion. However, most theoretical models of wave erosion consider beach erosion with a relatively constant base level. Many of these concepts are not readily applicable to rapidly fluctuating shorelines. The processes of slumping and incision induced by reservoir drawdown are not well known. Surface erosion due to rainfall has been studied intensively in relation to agricultural applications. As is discussed in Chapter 3, a mixture of theoretical and empirical studies was used to formulate a model for shoreline erosion to evaluate the most impacting alternatives.

# CHAPTER 2

# GEOLOGY, SOILS AND GROUND WATER IN THE COLUMBIA RIVER BASIN TODAY

Rivers, and therefore reservoirs, are the geomorphic focal point of the drainage basins they occupy. To a great extent, their nature is determined not only by the physical characteristics of the basin, but by the recent geologic history as well. Understanding the nature of the valleys and the stream channels helps in understanding the impacts that reservoirs and their operation have on their immediate surroundings and downstream areas.

The beds and banks of alluvial rivers are composed of the same materials that the rivers transport. These rivers are "self–formed" and are able to adjust their shape in response to changes that occur within their drainage basin (Richards, 1985). In contrast, the beds and banks of bedrock–controlled rivers are constrained by rock, which resists or inhibits adjustments of river form to upstream (drainage basin) changes or downstream (base level) variations. The main stems and tributaries of the Columbia and Snake Rivers are constrained within mostly bedrock channels. The SOS alternatives being considered for the SOR involve only variations in reservoir pool levels to control water velocity within the Columbia River system; potential basin-wide land use or management changes are not within the SOR scope. Given these conditions, and the fact that the reservoirs are within bedrock–floored valleys, the SOS impacts must be restricted to the reservoir shorelines and to the unconsolidated materials within the drawdown zones and in minor alluvium–floored tributary valleys that intersect the reservoirs.

This chapter provides general background information on the various regions within the Columbia River Basin. It first looks at the physiographic regions within the basin, then at the general geology and groundwater conditions in those physiographic regions. Because system operations affect the mainstem valleys themselves, and not the distant sources of sediment and water, the main focus of this chapter is the mainstem valleys and the influences of physiography on the inputs to the rivers. The effects of geology and groundwater conditions on the mainstem valleys are discussed at the end of the chapter.

## 2.1 PHYSIOGRAPHY

The Columbia River and its tributaries drain much of the northwest interior of the United States and a significant part of southern British Columbia. Seven physiographic regions are prominent in the Columbia River Basin (see Figure 2–1). The upstream (northern and eastern) portions of the basin are generally within the Columbia Mountains/Okanogan Highlands and the Rocky Mountain provinces. The Columbia and Snake River Basalt Plains are in the center and eastern parts of the basin. The North Cascade Range, the South Cascade Range, and the Blue/Wallowa Mountains form the southern and western parts of the basin. The western edge of the basin also takes in small portions of the Coast Range and the Willamette – Puget Lowland provinces, but these regions do not include any SOR projects.

The Columbia River originates in Canada and flows south through the Columbia Mountains/Okanogan Highlands. This region is characterized in the north by high mountains, deep post–glacial valleys, and dense forest, with broad, semi–arid uplands to the south. The river then flows west, initially along the boundary between the Columbia Basalt Plain and the Columbia Mountains/Okanogan Highlands. The river subsequently becomes bounded on the northwest by the North Cascades. Several major tributaries drain the east slope of the North Cascades, including the Wenatchee, the Methow, and the Chelan. Many of these rivers have glacial headwaters and flow through deep forested valleys.

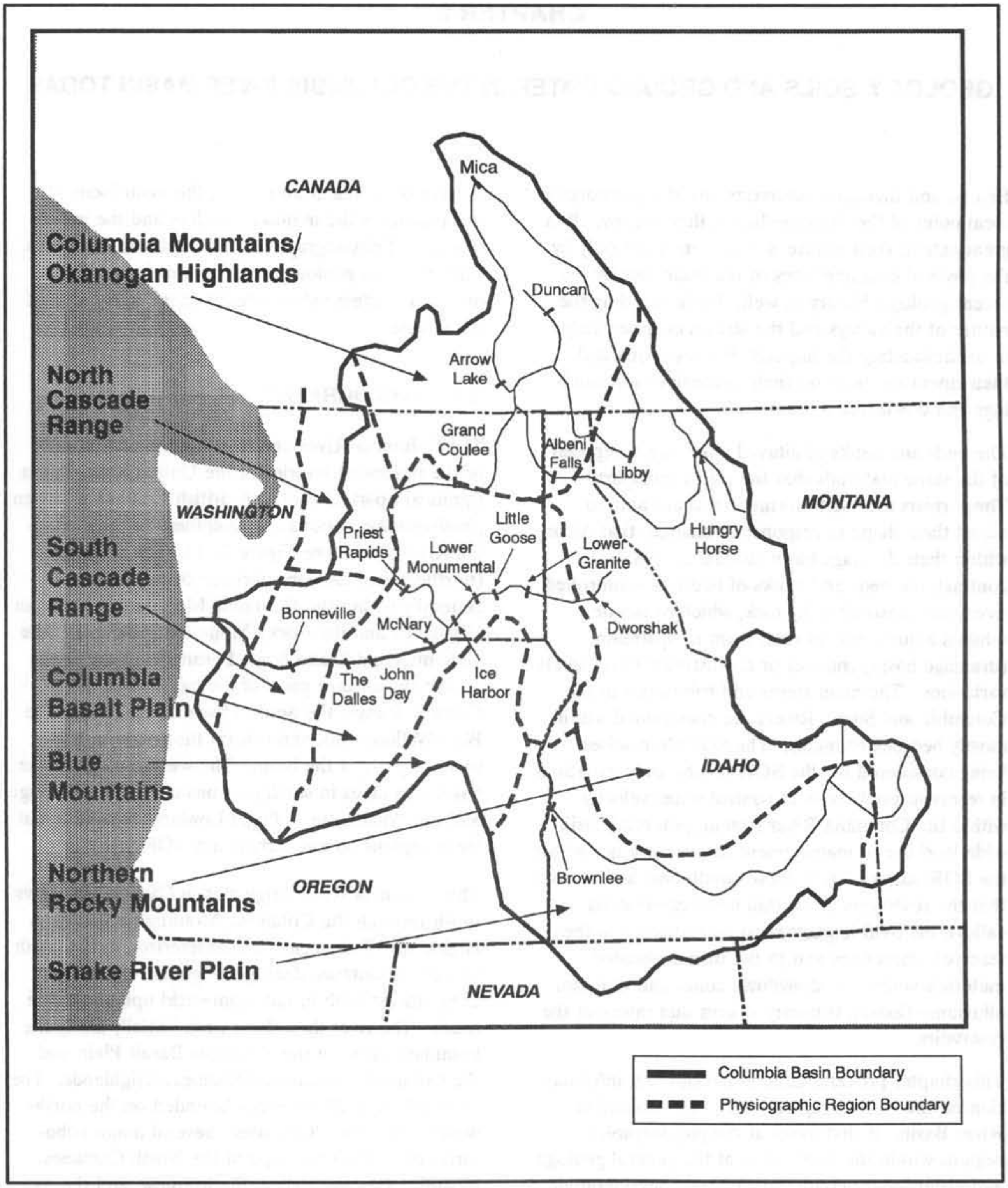


Figure 2–1. Physiographic Provinces (Only SOS–Affected Dams are Shown)

The Columbia then crosses the center of the Columbia Basalt Plain, joins with the Snake River, and flows through the Wallula Gap before turning west. The Columbia Basalt Plain is semi–arid to arid, and consists of flat to gentle rolling hills and a few higher ridges. The river flows through the South Cascades, the Willamette–Puget Lowland, and the Coast Range before heading out to the Pacific Ocean. The South Cascades are generally lower in elevation than the North Cascades. Exceptions include the notable stratovolcanos lying along the crest of the range.

The Snake River originates in Yellowstone National Park, in the Rocky Mountains Province. The Rocky Mountains consist of high, linear mountain ranges separated by deep and often broad valleys. Extensive upland forests are present in this area. In eastern Idaho, the river flows into the Snake River Basalt Plain, a generally flat, arid area. It then flows through Hell's Canyon, a 7,000–foot (2,134–m) deep gorge on the eastern edge of the Blue Mountains. The Blue Mountains are a broad, semi–arid to subhumid range. The Snake River then flows west through small canyons of the Snake River Basalt Plain to meet the Columbia.

Other key tributaries to the Columbia River are the Kootenai, Flathead, Clark Fork, Pend Oreille, and Clearwater rivers. The Kootenai also originates in British Columbia, flows south into northwestern Montana, then loops back into Canada where it joins the Columbia at Castlegar, B.C. The Flathead River lies entirely in the Rocky Mountains region of Montana. It flows south to meet the Clark Fork River, which flows into the Pend Oreille River and then the Columbia. The Clearwater River originates in the Rocky Mountains of central Idaho and empties into the Snake River at the Lewiston–Clarkston area on the Washington–Idaho border.

## 2.2 GEOLOGY

This section addresses the regional geology in the physiographic provinces and, in more detail, the shoreline geology of the reservoirs affected by SOR activities. Areas having specific geologic hazards (e.g., landslides along reservoir shorelines) or surficial deposits (loess) susceptible to impact by SOR activities are also described. Emphasis is placed on the existing and historical conditions of the geologic material. As the purpose of this section is to provide a description of the present environment, and the factors that have shaped the existing conditions, the influence that reservoir operations have had on geologic material has been included.

### 2.2.1 Geology of Physiographic Provinces

The geology (bedrock and surficial) within each physiographic province determines the character of the sediments that reach the rivers and reservoirs. This section provides the regional geologic framework necessary for understanding physical processes and their relation to reservoir operations. Organization is by physiographic province in a general upstream to downstream order.

#### Columbia Mountains/Okanogan Highlands

The Columbia Mountains/Okanogan Highlands have a complex sedimentary and tectonic history. Within this province are found the Purcell Mountains and the Selkirk Mountains. The Purcell Mountains consist of the Precambrian Purcell Group, a very thick sequence of slightly metamorphosed sandstones, shale, and limestone (see Technical Exhibit 2 for Geologic Time Scale). The Selkirk Mountains consist primarily of Mesozoic granites. The central and western parts of the Columbia Mountains are composed of the Shuswap Metamorphic Complex. East of here lies the Kootenai Arc, a band of Late Precambrian to early Jurassic sedimentary rocks intruded by numerous granite plutons, including the Kuskanax and Nelson Batholiths (McKee, 1972).

#### Rocky Mountains

The Rocky Mountains within the Columbia River Basin consist of metamorphic and igneous rocks. This area is relatively small compared to the overall Northern Rocky Mountains. The Idaho Batholith is included here as part of the Rockies. It is a huge granitoid intrusion of Mesozoic age. East of the batholith, parts of the Purcell Group (called the Belt Supergroup in the U.S.) extend into this section of the Rockies. Numerous thrust faults have placed older rocks on top of younger rocks. The ranges are separated by valleys often partially filled with younger, unconsolidated sediments.

### Columbia And Snake River Plains

The Columbia and Snake River Basalt Plains consist primarily of thick successions of gently dipping basaltic lavas. In the Columbia Plateau area, numerous basaltic formations are distinguished within these lavas, and they are collectively known as the Columbia River Basalt Group (Galster and Sager, 1989). The sequence of basalts and interbedded sedimentary deposits is shown schematically in Figure 2–2. This group includes five distinct basalt members. Interbedded with the basalt layers are thin layers of sediments deposited in former rivers and lakes between eruptions. In the Pliocene, about 4 million years ago, the terrain to the west began to uplift, the beginning of what is now the Cascade Range. These incipient mountains began to erode, and some sediment eroded from this uplift forms the sandstones of the Ellensburg Formation. Similarly, nearly 1,200 feet (366 m) of sandstone, siltstone, and conglomerate are present in the Ringhold Formation, an early Pleistocene unit located in the low parts of the plateau, near Hanford.

The Snake River Plain has a volcanic history that extends to the present, while the Columbia Plain is mostly Tertiary. The two plains are thought to have been formed by a mantle–derived "hot spot", which is stationary. The North American Plate has moved west over the hot spot, and the locus of volcanism has migrated eastward. Its present position is now in the Yellowstone area. On the Snake River Plain, thick sequences of basalt are found frequently interbedded with river gravels and other sediments. The young volcanic surface of the plain has not had time to develop strong drainage patterns, and many of the streams flowing into the plain from the Rocky Mountains to the north seep underground through the porous surface material into the Snake River Aquifer. The Snake River Canyon cuts this aquifer, and consequently thousands of high–volume springs flow into the river in the area between Milner Dam and Hell's Canyon.

The surficial geology of the basin has been heavily influenced by continental glaciation. During the Quaternary period, repeated advances of the Purcell Trench lobe of the Cordilleran ice sheet dammed the Clark Fork River and impounded glacial Lake Missoula. This lake released catastrophic floods numerous times during the Late Pleistocene, scouring much of the surface of the Columbia Basalt Plain. The floods also topped glacial Lake Columbia at the site of the present Lake Roosevelt behind Grand Coulee Dam (Hansen, 1989; Atwater, 1986). Over 700 feet (213 m) of glacial lake sediment are exposed along the banks of Lake Roosevelt.

These floods eroded the river valleys and coulees, or dry canyons, and produced large deposits of river sediments (Baker, et al., 1987). These river deposits occur as scattered terraces along the river valleys. The flood erosion also carved steep slopes that have undergone some retreat, producing steep, coarse–grained talus slopes along bedrock cliffs. Post–glacial river incision has reworked some of the older river deposits, producing the younger, lower elevation, alluvial terraces that are scattered along the rivers. Since impoundment of the rivers by dams, tributaries have deposited alluvial fan deltas where they enter the reservoirs. In steep, small drainages, these alluvial fan deltas consist of gravels and sand with minor amounts of silt and clay. Some of the larger deltas consist mostly of sand and silt.

Landslides are relatively common along the Columbia River. They generally occur within the surficial sediments, especially those that are somewhat poorly drained due to an admixture of finer grained sediment. Some landslides involve the Columbia River Basalt Group and its interbedded river and lake deposits (Sager, 1989a, 1989b, 1989c). Some of the larger landslides are currently immobile, while others are moving at slow rates (Sager, 1989a).

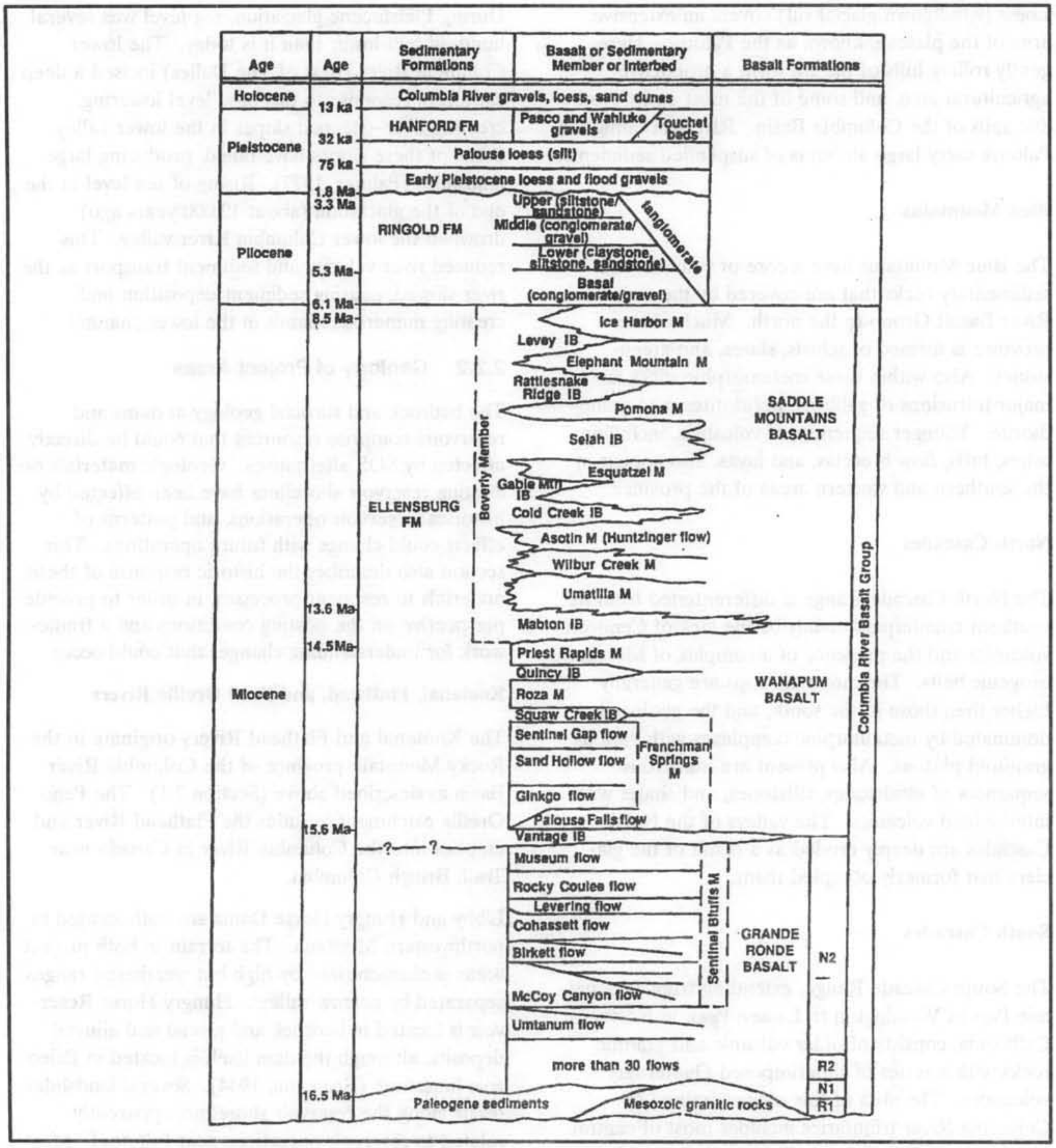


**Figure 2–2. Stratigraphic Column for the Mid–Columbia River Region.**
[Galster and Coombs, (1989), modified from Mackin (1961), Reidel and Fecht (1981), and Swanson et al. (1979).] M, member; FM, formation; IB, interbed; N, normal magnetic polarity; R, reversed magnetic polarity.

Loess (windblown glacial silt) covers an extensive area of the plateau, known as the Palouse. Here gently rolling hills of the silt form a productive agricultural area, and some of the most easily erodible soils of the Columbia Basin. Rivers draining the Palouse carry large amounts of suspended sediments.

**Blue Mountains**

The Blue Mountains have a core of volcanic and sedimentary rocks that are covered by the Columbia River Basalt Group to the north. Much of the province is formed of schists, slates, and greenstones. Also within these metamorphic rocks are major intrusions of gabbros, peridotites, and granodiorite. Younger sequences of volcanics, including ashes, tuffs, flow breccias, and lavas, also appear in the southern and western areas of the province.

**North Cascades**

The North Cascade Range is differentiated from its southern counterpart mainly by the lack of Cenozoic volcanics and the presence of a complex of Mesozoic orogenic belts. The mountain tops are generally higher than those in the south, and the geology is dominated by metamorphic complexes with various granitoid plutons. Also present are numerous sequences of sandstones, siltstones, and shales with interbedded volcanics. The valleys of the North Cascades are deeply eroded as a result of the glaciers that formerly occupied them.

**South Cascades**

The South Cascade Range, extending from Snoqualmie Pass in Washington to Lassen Peak in Northern California, consists of older volcanic and granitic rocks with a series of superimposed Quaternary volcanoes. The area of this region drained by Columbia River tributaries includes most of central and northern Oregon and all of south–central Washington. The geologic history of this province is complex, with numerous episodes of volcanism with various composition and styles. Today the landscape is dominated by relatively recent volcanic landforms. Soils are generally thin and highly erodible.

During Pleistocene glaciation, sea level was several hundred feet lower than it is today. The lower Columbia River (west of The Dalles) incised a deep canyon in response to this base level lowering, creating over–steeped slopes in the lower valley. Some of these slopes have failed, producing large landslides (Palmer, 1977). Rising of sea level at the end of the glaciation (about 12,000 years ago) drowned the lower Columbia River valley. This reduced river velocity and sediment transport as the river slowed, causing sediment deposition and creating numerous islands in the lower channel.

### 2.2.2 Geology of Project Areas

The bedrock and surficial geology at dams and reservoirs comprise resources that could be directly affected by SOS alternatives. Geologic materials on existing reservoir shorelines have been affected by historical reservoir operations, and patterns of effects could change with future operations. This section also describes the historic response of these materials to reservoir processes, in order to provide perspective on the existing conditions and a framework for understanding changes that could occur.

**Kootenai, Flathead, and Pend Oreille Rivers**

The Kootenai and Flathead Rivers originate in the Rocky Mountain province of the Columbia River Basin as described above (Section 2.1). The Pend Oreille catchment includes the Flathead River and empties into the Columbia River in Canada near Trail, British Columbia.

Libby and Hungry Horse Dams are both located in northwestern Montana. The terrain in both project areas is characterized by high but weathered ranges separated by narrow valleys. Hungry Horse Reservoir is located in bedrock and glacial and alluvial deposits, although the dam itself is located in Paleozoic limestone (Erdmann, 1944). Several landslides occur along the reservoir shoreline, apparently related to reservoir operations near full pool. Most of the colluvium formerly covering the hillslopes that now form the reservoir shoreline has been stripped away by erosion, exposing bedrock.

Libby Dam is located in Precambrian greenschist of the Belt supergroup. Wedge rock slides are present on the left abutment of the dam. Undercutting of the rocks during construction of the dam triggered one slide (Voight, 1979). Four potential rockslides are present on the left bank near the dam (Voight, 1979). The slides extend to the current drawdown zone, however, historic movement of a similar slide appears to have been triggered by an extreme precipitation event and not by water level fluctuation.

The northern end of Lake Koocanusa lies in lake sediments and consolidated glacial outwash and till. The town of Rexford lies in the Tobacco River valley. The Tobacco River itself cuts through these sediments before flowing into Lake Koocanusa. Extensive erosion has occurred in this area, and shoreline retreat has been noted as a problem.

Albeni Falls Dam is located on the Pend Oreille River in northern Idaho, in the Columbia Mountains/Okanogan Highlands province. The dam raised the level of the natural Lake Pend Oreille by 10 feet (3 meters). The Purcell Trench lobe of the Cordilleran ice sheet extended across this region in the late Pleistocene, exposing the area to the full force of the Lake Missoula flood when the lobe receded (Baker et al., 1987). Surficial flood deposits compose areas of the dam site and reservoir shoreline. Gatto and Doe (1983) documented that Lake Pend Oreille shorelines have experienced sliding since before Albeni Falls Dam construction and raising of lake level.

**Upper and Middle Columbia River**

For presentation purposes, the Columbia River is divided into upper, middle, and lower reaches. The upper Columbia River extends from the headwaters area in Canada to Grand Coulee Dam. The middle reach extends from below Grand Coulee to the head of the McNary Pool, near the confluence with the Snake River.

The Columbia River originates in the Purcell Mountains of British Columbia and flows northwest through Paleozoic sedimentary strata (McKee, 1972). The river loops to the south in the vicinity of Mica Dam, where it flows through mostly Pre–Jurassic metamorphic rocks and Late Mesozoic granitic intrusive rocks. Keenleyside Dam, which forms Arrow Lakes, is located in this section of river just above its confluence with the Kootenai River in Canada. As the Columbia flows into the United States, it passes through predominantly Paleozoic sedimentary rocks and granitic intrusives before it enters the basalts of the Columbia River Basalt Group along the shores of Lake Roosevelt behind Grand Coulee Dam.

Seven hydroelectric projects have been built on the upper and middle Columbia River in the United States, although only two of these (Grand Coulee and Chief Joseph) are directly affected by SOR activities. Grand Coulee Dam was built in the granitic rock of the Colville Batholith. During the Pleistocene, the Okanogan lobe of the Cordilleran ice sheet extended across the ancestral Columbia River and created glacial Lake Columbia. The lake persisted long enough to accumulate thick deposits of silts and clays as well as sands. Approximately 90 percent of the Lake Roosevelt shoreline lies within these deposits (Grand Coulee Project Office, 1992). The lake deposits have been prone to mass wasting since before construction of the dam (Hansen, 1989). Various methods have been used to stop mass wasting, including laying back slopes, dewatering the banks, and vegetating slopes. Two hundred and forty–five landslides occurred along the 635 miles (1,022 kilometers [km]) of shoreline during initial filling of the reservoir. After full pool was attained, 255 additional slides occurred between 1943 and 1953. Jones et al. (1961) provide detailed descriptions of selected areas of slide activity.

Stream terraces and alluvial fans are also present along the Lake Roosevelt shoreline. Groundwater conditions can make wet silts and clays weak and more susceptible to slides and slumps. Soil creep also occurs in these areas. In many sections, the reservoir shoreline is nearly vertical and wave action plays a significant role in instability (see Section 3.1). In some reaches, the banks are 500 feet (152 m) high in the lacustrine material, creating an environment conducive to prolonged periods of episodic mass wasting. Banks composed mostly of sand are highly susceptible to wave erosion, while those banks where sand underlies silts and clays are subject to undercutting and collapse.

Landslides occur downstream of Grand Coulee Dam, with peaking operations further aggravating the situation (Hansen, 1989). Daily fluctuations in Grand Coulee tailwater elevations have been in excess of 20 feet (6.1 m). Fluctuating pore water pressures, combined with the rapid changes in water volume and velocity, may be increasing the potential for deep–seated slope failure. In 1978, landslides occurred along a 6–mile (9.7–km) stretch of river immediately downstream from the dam. The largest slide was triggered by a 13–foot (4–m) drop in tailrace elevation due to failure of a turbine unit. A number of techniques were employed to ensure stability of the downstream banks in anticipation of continued peaking operations. These included extensive removal of bank material to lay back the slope, dewatering of critical areas, and installation of an extensive monitoring network consisting of uniaxial inclinometers and pore pressure transducers. Over 600 monitoring stations are now active and linked into a warning system at the powerplant dispatcher's station.

The middle section of the Columbia River forms the boundary between the northern Cascade Province to the west and the Columbia Plateau to the east. The river flows over mostly Paleozoic metamorphic and intrusive rocks until around Rock Island Dam. Below Rock Island Dam the river passes into the Columbia River Basalt Group. The hydroelectric projects of the middle Columbia form a nearly continuous section of reservoirs. The geology of the Middle Columbia is shown in Figure 2–3.

Priest Rapids Dam was built on the Priest Rapids Member of the Wanapum Basalt. Two terraces are exposed on the left bank of the reservoir, a flood terrace composed of gravels and the high Wahluke terrace, a deposit of Missoula flood gravels (Galster, 1989). The river deposits extend upstream on the right bank for about 15 miles (24.1 km).

Below Priest Rapids Dam is a nearly 50–mile (80.5–km) stretch of free flowing river cut in the Columbia River Basalt Group.

### Clearwater River

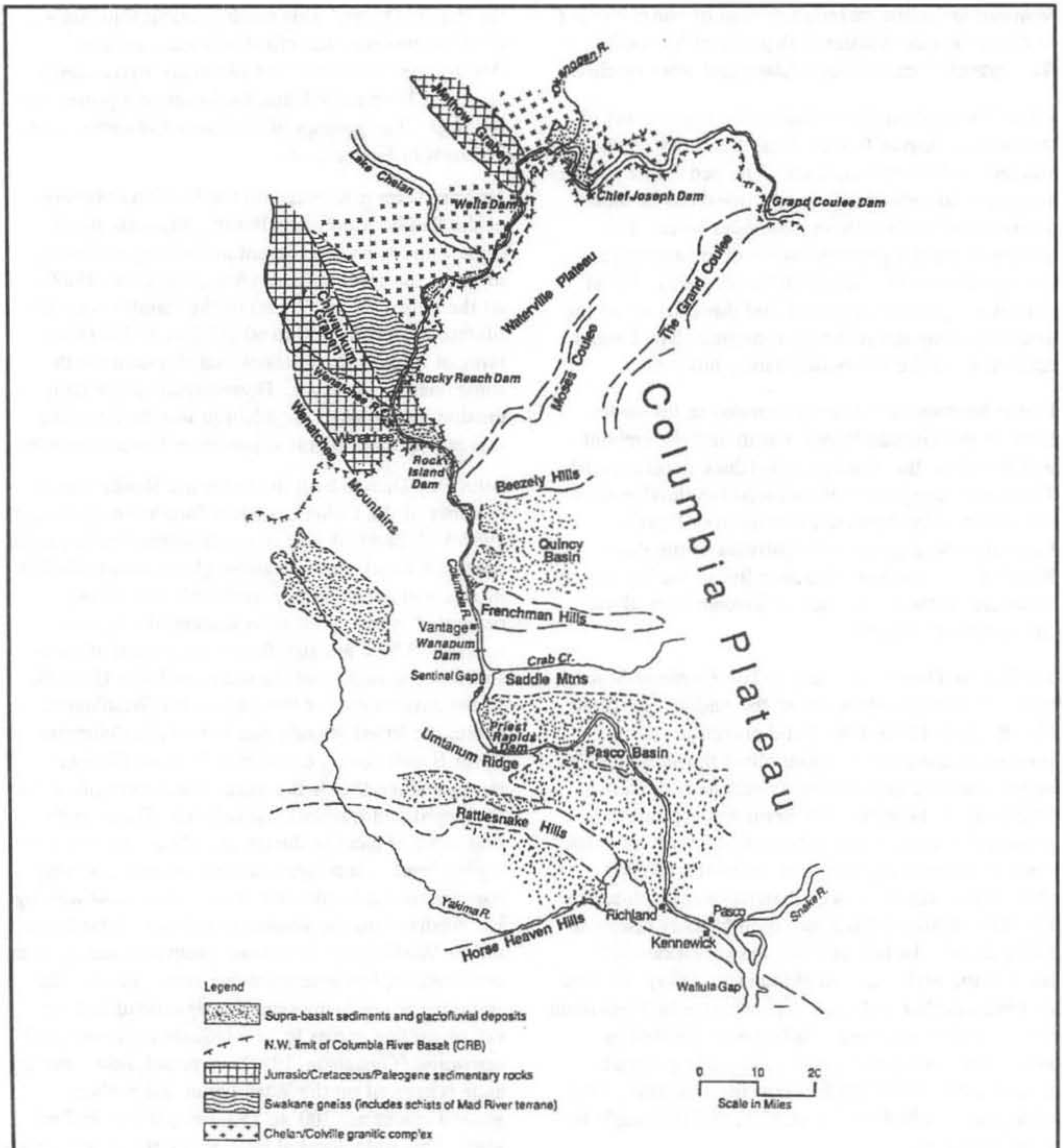
The Clearwater River flows west out of the northern Rocky Mountains in central Idaho. Dworshak Reservoir on the North Fork of the Clearwater is flanked by several unstable areas (Corps, 1975). These areas consist of semi–consolidated shales and deep clay deposits. Some of these areas are active and continue to move, albeit at slow rates (personal communication, R. Colgan, U.S. Army Corps of Engineers, Operations Manager, Dworshak Dam, Orofino, Idaho, August 17, 1992). One area currently active is located at RM 32 near Falls Creek. The slide areas are up to 2 acres (0.81 hectare) in size. In addition, much of the lake shore is in granitic soils, which are highly erodible, especially at steep angles on long slopes. Shoreline sloughing was a common occurrence during the first few years of dam operation and was expected to stabilize with time, assuming no great change in water level fluctuations (Corps, 1975). The frequency of landslides has generally decreased since then, but problem areas remain.

### Snake River

The middle and lower reaches of the Snake River are within the scope of the SOR analysis. The middle Snake River flows along the western edge of Idaho through Hells Canyon to the confluence with the Clearwater River, and includes Brownlee Reservoir. The lower Snake River extends from confluence with the Clearwater River downstream to the confluence with the Columbia. Four dams and reservoirs affected by SOS alternatives are located in this reach.

Brownlee Reservoir has significant potential for slope failure under existing operating patterns. The main impact is due to rapid drawdown decreasing the stability of existing landslide areas due to removal of the buoyant force of the water (BPA, 1985). Numerous slides are present along the perimeter of the reservoir. One large slide exists at the mouth of the Powder River and is capable of damming that drainage.

Lower Granite Dam is founded on the lower flows of the Grande Ronde Basalt and partially on Missoula flood gravels and recent alluvium. Most of the



Modified from Huntting et al. (1961) and Tabor et al. (1987)

**Figure 2–3. Geologic Setting of the Mid–Columbia River Dams. (Galster and Coombs,1989)**

reservoir shoreline materials consist of either basalt or riprap levees. Scattered deposits of Missoula flood gravels occur at Silcott Island and other reaches.

Little Goose Dam is founded in the upper flows of the Grande Ronde Basalt. Here the flows are 30 to 100 feet (9.1 to 30.5 m) thick. The beds dip 1 degree and are relatively undeformed. Interbeds include scoriaceous basalt with an ash/cinder layer. The interbeds are the primary source of groundwater leakage around the dam (Miklancic, 1989). Flood gravels are present upstream and downstream of the dam and along the reservoir shoreline. The basalts form most of the reservoir's banks, however.

Lower Monumental Dam is founded in the upper flows of the Grande Ronde Basalt and the embankments rest on the Touchet beds (thick flood gravels). These beds are part of the alluvial fan developed at the outlet of the Missoula Floods from Devil's Canyon, a deep gorge just upstream of the dam. Much of the reservoir shoreline lies in the basalt, but there are scattered patches of Touchet beds along the reservoir's length.

Ice Harbor Dam is founded in The Elephant Mountain and Pomona Members of the Saddle Mountain Basalt. Late Pleistocene flood gravels are also present in scattered locations along the shoreline. A major landslide occurred in a berm near the left abutment of the dam. The berm was created to protect the bank, which is formed primarily of eolian sand, from wave erosion. An estimated 500,000 (382,300 m) cubic yards of material was displaced in the slide of March 1962, two months after reservoir filling began. In July of 1962, the slide extended back to the bedrock bluff (Miklancic, 1989). In June of 1962, another slide about 1 mile (1.6 km) upstream from the dam occurred. Sliding was initiated by storm–induced wave action. The slide material moved 1,200 (365.8 m) feet into the reservoir. This slide, too, reached the basalt cliffs and is thought to have stabilized.

**Lower Columbia River**

The lower Columbia reach extends from Priest Rapids Dam through the Columbia Basalt Plain and the Southern Cascade Range before emptying into the Pacific Ocean. This reach contains four run–of–river projects that effectively leave no free flowing river between the Columbia–Snake confluence and Bonneville Dam, the lowermost project on the river. The geology of the lower Columbia reach is shown in Figure 2–4.

McNary Dam is founded on the Umatilla Member of the Saddle Mountains Basalt. Missoula flood gravels and loess are present at the dam and along much of the reservoir shoreline (Miklancic, 1989). At the dam, 25 feet (7.6 m) of this basalt covers the Mabton interbed, a 40 to 60 (12.2 to 18.3 m) foot layer of tuffaceous siltstones and claystones with some coarser materials. Downstream of the dam erosion has exposed the Mabton interbed creating rapids that have migrated upstream toward the dam.

John Day Dam is built in the Grand Ronde Basalt member of the Columbia River Basalt Group (Sager, 1989c). Individual flow deposits within this sequence contain a basal zone of altered glassy basalt which is brown, soft, weak, highly fractured, and slightly cemented, making this zone susceptible to mass wasting. There are significant, deep–seated landslides in the vicinity of the dam and Lake Umatilla. In the eastern part of the lake on the Washington shore, the Priest Rapids member of the Columbia River Basalt Group contains a 25–foot (7.6–m) thick siltstone that is the main detachment plane for rotational and translational failures. Other units that serve as loci for slumps include a saprolite and tephra layer, a tuff layer, and an extensive, weakly consolidated volcaniclastic layer. Most mass wasting has occurred on the Washington shore. A landslide on the Washington shore was reactivated during dam construction, but appears stable now. Most of the shoreline is not being significantly eroded and rip rap protection seems to be adequate for lower pool operation (Gustafson, 1992). A broad, slow–moving slide is present on the Washington shore where ground cracks are 100 to 150 feet (30.5 to 45.7 m) long. This slide, located west of Alderdale, is believed to be translational rather than rotational.

At The Dalles Dam, the shoreline appears to be mostly in bedrock, which consists of the Columbia River Basalt Group, and does not appear to be affected by major landslides. However, on the

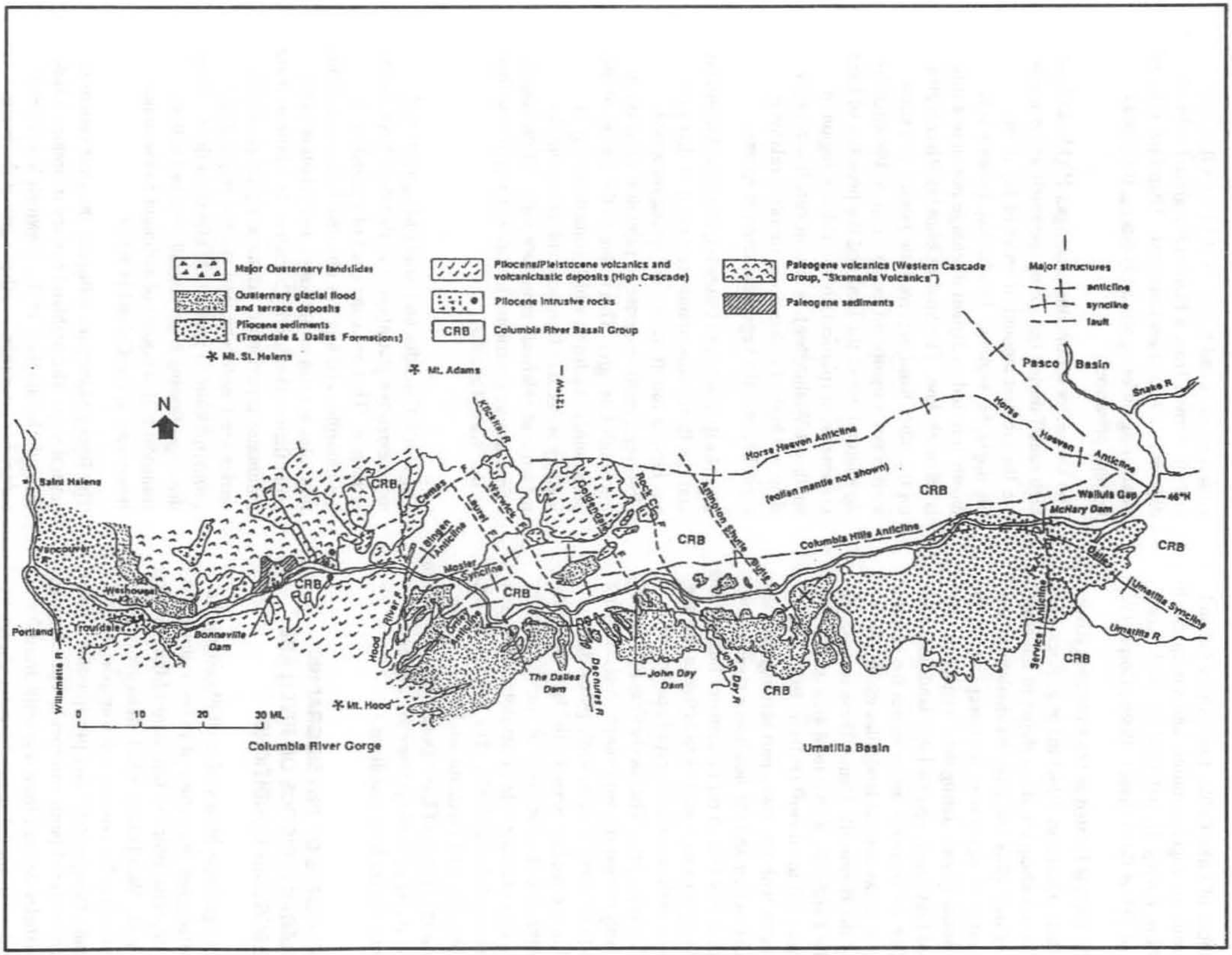


Figure 2–4. Generalized Geologic Map of the Area Along the Lower Columbia River.
[Galster and Sager, (1989), after Huntting et al.; Peck (1961); Newcomb (1970); and Walsh et al. (1987).]

Oregon shore of Lake Celilo, Quaternary fan and river deposits are highly erodible and susceptible to mass wasting, having the potential for small–scale slumps and debris flows (Sager, 1989b; Corps, 1983).

Bonneville Dam is located in the Columbia River Gorge, where 3,000 feet (914.4 m) of geologic section is exposed along the steep slopes of the gorge. A series of rock cliffs and talus accumulations are exposed, many of which were oversteepened by the Lake Missoula Floods during the Pleistocene. As mentioned previously, several large landslides have occurred or are currently active within the Gorge. Figure 2–4 shows several landslides within the vicinity of the Bonneville Dam. These include the Bonneville Landslide, with a total area of 11.6 to 14 square miles (30 to 36 $km^{2)}$ (Palmer, 1977). This slide is active, with the lower part settling, probably due to compaction and the headscarp ravelling, with blocks up to 16.4 feet (5 m) in diameter falling. The slide is thought to have first been active in the late Pleistocene, with episodes of rapid movement at around 700 years ago. The mechanism for failure was probably composite, with simple rockfall being responsible for some failure, while plastic flow occurred at the contact between the lava flows and clayey sediments. Liquefaction of landslide debris may have also played a role in developing the great lateral extent of the landslide. The Oregon Shore, Wind Mountain, and Fountain landslides also are present on the shores of Lake Bonneville. These are in various stages of activity; some are currently active while others have stabilized.

## 2.3 INFLUENCE OF PHYSIOGRAPHIC CHARACTERISTICS ON RIVER AND RESERVOIR CONDITIONS

The recent geologic history of each physiographic region determines the nature of rivers, valleys, and surficial deposits, which in turn control the reservoir environment. Weathering, which determines sediment availability for erosion and transport, varies with climate (temperature and precipitation), relief, and parent material (soils and rock). For example, coarse particles derived from a granitic intrusive in a semi–arid environment require greater energy to initiate erosion and transport than does fine sand and silt derived from a Pleistocene glacial outwash deposit in a humid environment. Therefore, rates of weathering differ significantly among the physiographic provinces.

The Columbia Mountains/Okanogan Highlands have high runoff during the spring snowmelt and contribute the greatest amount of water of any of the physiographic regions. In addition, because it is mostly forested, sediment discharge per square mile is relatively low. The Snake/Columbia River plains, on the other hand, receive little rainfall and snowmelt is not a significant factor. Due to the intensive agricultural use of the land and the presence of loess in some areas (particularly the Palouse region of southeast Washington), sediment runoff concentrations are high. Furthermore, runoff is relatively rapid because the vegetative cover is sparse.

The North and South Cascades, the Blue Mountains, and the Rocky Mountains are similar in that each has highest runoff during the spring snowmelt. However, runoff response to rainfall is different in the South Cascades. This is due to the nature of the predominant bedrock, which consists mostly of highly porous, late Cenozoic volcanics, and the presence of relatively immature soils and drainages. These factors contribute to a slower runoff rate than in the North Cascades.

The North Cascades and Rocky Mountains had more extensive glaciation, and therefore have steeper terrain. They are composed of a complex of metamorphic and igneous intrusive rocks, so infiltration rates are somewhat lower and runoff is more rapid than in the South Cascades. In addition, these mountains experienced extensive alpine glaciation during the Pleistocene, and are still responding geomorphically to present climate conditions. Steep drainages flowing from glacially–carved valleys transport high amounts of sediment to the major tributaries of the Columbia River.

The Rocky Mountains influence the river system in several ways. The highland surface maintains a flow through the summer, as the snowmelt here occurs somewhat later than in other parts of the basin.

Reservoirs within the valleys of the Rocky Mountains are subject to freeze–thaw processes acting on the shorelines, due to their relatively high elevations. Freeze–thaw action in shoreline materials is known to increase rates of shoreline erosion (Lawson, 1985).

The Blue Mountains have well developed drainages and are forested, ancient mountains. Their contribution to sediment discharge in the Columbia/ Snake system is relatively limited, due in part to a smaller contributing area, forested terrain, and less relief than the other mountainous provinces.

## 2.4 GROUNDWATER

Compared to other parts of the country, groundwater is a relatively minor water supply source in the Columbia River Basin. This is because most water supply needs are met by diversions from the main–stem or tributary rivers. Nevertheless, hydrologic connections exist between system reservoirs and groundwater aquifers in areas surrounding the reservoirs. Groundwater conditions in these areas could potentially be affected by system operations.

This report examines areas where the aquifers are known, or inferred, to be directly connected to reservoir levels and that are currently used as water sources. These are, for the most part, unconfined aquifers. They are generally near the land surface and their upper boundary, the water table, fluctuates freely. In many cases, the effect of reservoir fluctuations does not extend very far from the shoreline. How the water table responds to changes in river hydrology depends on the ability of the aquifer to transmit water, or its hydraulic conductivity. In addition, groundwater flow direction, or gradient, is affected depending on whether the river or reservoir is influent or effluent. An effluent river is one into which surrounding unconfined aquifers drain. An influent river drains into the surrounding aquifer, creating gradients that flow away from the riverbed.

Most of the reservoirs in the Columbia River Basin lie in or adjacent to the Columbia Basalt and Snake River Plains. Hydrogeology of the region is characterized by a wide range of hydraulic conductivity in the basalt aquifers. Interflow zones have high horizontal conductivities, while the basalt flows themselves have higher vertical conductivity than horizontal conductivity. This is mostly due to vertical jointing related to basalt columns, which creates vertical migration pathways. Hydraulic gradients generally parallel the dips of the individual basalt flows, which regionally dip toward the center of a structural low near Pasco, Washington. Natural groundwater recharge in the area is typically less than 2 inches (50 millimeters [mm]/year, although locally high artificial recharge due to agricultural activities is as much as 14.6 inches (370 mm/year) (Lindholm and Vaccaro, 1988; Tanaka, et. al., 1974). The Columbia and Snake Rivers are effluent streams; that is, groundwater discharges into them. The reservoirs have effectively raised the water table locally.

The Columbia Plateau occupies the large central portion of the Columbia River Basin and contains or borders six of the key dams affected by the SOR. In a recent review of groundwater pumpage in the Columbia Plateau, Cline and Collins (1992) delineate areas of groundwater usage through 1984. This study reports that groundwater accounts for only 30 percent of all acres irrigated on the Columbia Plateau, and 80 percent of all groundwater withdrawn is used for irrigation. Most of this pumpage (75 percent) comes from basalts of the Columbia River Basalt Group, with the remaining production derived from overburden (recent surficial fluvial and glaciofluvial deposits).

As surface water supplies most of the region's water needs (70 percent), the geographical distribution of groundwater use tends to be isolated from major surface water bodies such as rivers and reservoirs (Figure 2–5). This reduces the likelihood of significant groundwater use in areas where there is a hydraulic connection between the system's reservoirs and groundwater aquifers. Three key exceptions to this observation are areas near Pasco, Washington, Lewiston–Clarkston on the Washington–Idaho border, and south of Lake Umatilla in Oregon. Pasco is near the confluence of the Snake and

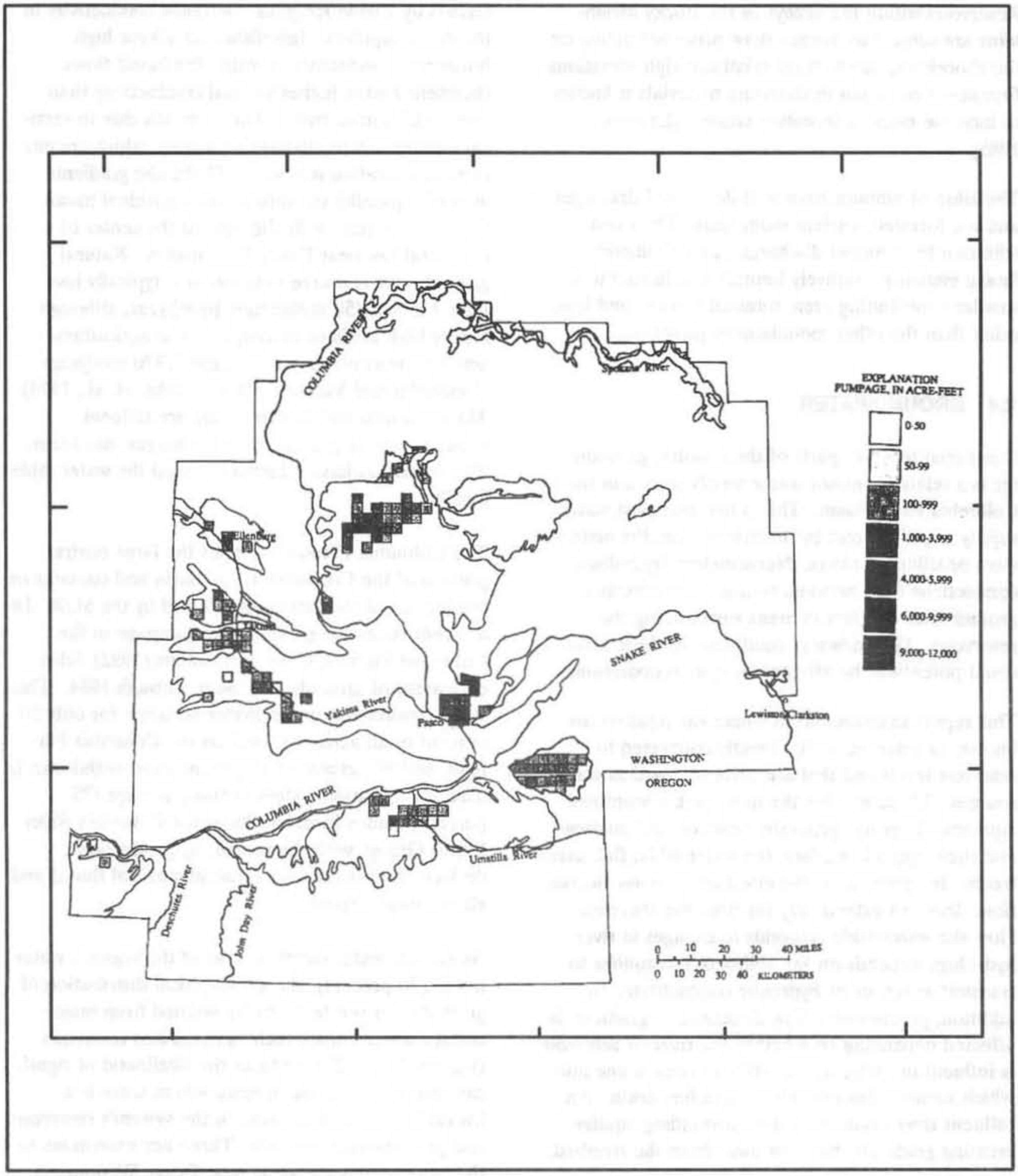


**Figure 2–5. Groundwater Pumpage from the Surface Overburden on the Columbia Plateau. (from Cline and Collins, 1992)**

Columbia Rivers, where groundwater withdrawal from nearsurface overburden accounts for 82 percent of groundwater pumpage. Groundwater pumpage from the Grande Ronde member of the Columbia River Basalt Group in the Lewiston–Clarkston area, where the Snake and Clearwater Rivers meet, supplies a significant source of domestic water in that area.

A third area of significant groundwater withdrawal from the surficial aquifer occurs south of Lake Umatilla behind John Day Dam. Aquifers in this area are located in unconsolidated Quaternary deposits and Tertiary basalts. The Pasco Gravels, a unit of Pleistocene, flood–deposited gravels, are utilized for domestic water by the city of Boardman, Oregon, and by some private wells. The water table associated with this aquifer is directly connected to the water level in Lake Umatilla (CH2M Hill, 1992). The wells in this area are thus partly dependent on the operation of John Day dam. The basalt aquifer may also be connected to the pool level, as indicated by a rise in water level associated with the filling of the John Day pool (Robison, 1971). However, the river's influence probably ends a very short distance away from the shoreline (CH2M Hill, 1992).

In the Snake River Plain, the area potentially affected by SOS alternatives is in the immediate vicinity of Brownlee Reservoir. While no comprehensive groundwater well database exists for Idaho, the U.S. Geological Survey staff report that there are only a few wells in the vicinity of Brownlee. These are mostly located near the southern end of the reservoir (personal communication, Steve Craig, U.S. Geological Survey, Boise Idaho, August 11, 1993). There are also few wells near Dworshak Reservoir.

The reservoirs behind Libby, Albeni Falls, Dworshak, and Hungry Horse dams lie in the intermontane basins of the northern Rocky Mountains. Hydrogeology of these areas is dominated by generally unconfined permeable alluvial aquifers in the valleys. In permeable, unconsolidated hydrogeologic settings, the water table tends to fluctuate directly with the reservoir level (Simms and Rorabaugh, 1971). Reservoirs here also have had the effect of locally raising the water table. These reservoirs are storage projects, and as such tend to fluctuate much more than reservoirs on the mainstem Columbia and Snake Rivers. Therefore, their influence on groundwater is probably more complex. Changes in storage reservoir elevations probably cause seasonal water table fluctuations that vary in magnitude with the composition of aquifer materials.

Groundwater use near these intermontane reservoirs is patchy and sporadic. Due to the location of reservoirs in mountainous terrain, demand for groundwater in the immediate vicinity of these reservoirs is low. Hence there are few wells near the reservoirs. The U.S. Geological Survey in Montana reports no groundwater wells in the Hungry Horse Reservoir area. There is some groundwater use near Libby Reservoir (Lake Kookanusa), though it is not extensive.

# CHAPTER 3

# STUDY METHODS

The Columbia River system comprises a complex of waterways over a vast area in which a variety of somewhat poorly understood processes act on diverse terrain and materials. The proposed SOS alternatives would superimpose varying operational controls on this river system. Given the level of complexity, the best approach to understanding the impact of SOS alternatives is to simplify the treatment of variables and processes existing in the basin to a level at which cause and effect can reasonably be established. By concentrating this investigation on the reservoir environment, as discussed in Chapter 2, coverage of both geographic area and physical processes can be limited to those likely to be affected by the proposed alternatives.

Once the geographic focus was established, a study strategy was formulated that first examined the literature for processes that dominate in the reservoir environment. Secondly, these processes were reduced (when possible) to their cause and effect in view of the proposed SOS alternatives. Third, geographic areas likely to be affected were distinguished. Where possible, quantitative impacts of the selected processes were estimated. Finally, for each of the SOS alternatives and each of the affected areas, the relative magnitude and extent of these impacts were estimated.

This section provides a review of the processes and variables that affect the reservoir environment and their causal relation to the SOS alternatives. Chapter 4 discusses each SOS alternative in relation to the processes presented here and the geographic areas discussed in Chapter 2.

## 3.1 THE RESERVOIR ENVIRONMENT

Before examining the alternatives, the behavior of reservoirs and the reservoir environment are examined in the context of historical operations.

Unlike alluvial rivers which flow through broad floodplains, the Columbia and Snake Rivers cut through bedrock canyons. Consequently, there is little to no influence of pool level variations on the upstream river valleys or the upstream tributaries. Bedrock channels are not free to adjust to pool level variations due to the relative competence of the rock. Therefore, drainage basin physiography is outside the influence of the reservoir operations being considered in the SOR. However, the physiography (shoreline geology, relief, erosional processes) of the reservoir environment itself is directly affected by SOS alternatives and determines the magnitude of resultant impacts. The characteristics of the reservoir environment are discussed in Section 3.2.

Reservoirs differ in several respects from natural lakes. First, reservoirs superimpose water on soils and landforms formerly adjusted to erosion under terrestrial conditions. Second, because reservoir shorelines are superimposed upon pre-existing river valley topography, reservoirs typically have greater shoreline development (ratio of shoreline length to water surface area) than natural lakes. Third, reservoirs usually are deepest at the dam, whereas lakes are generally deepest in the middle. Finally, reservoirs used for flood storage or hydroelectric pooling are typically subject to large and comparatively rapid fluctuations in water levels, which are uncommon in natural lakes.

### 3.1.1 Reservoir Variables

Variation of reservoir environment and operation affects the erosional processes active on and above the shoreline as well as sedimentation within the reservoir. Shoreline orientation, geology, and climate are independent variables with respect to the processes operating on the reservoir environment, while pool level fluctuation controls the magnitude of the processes and hence erosion and sedimentation for the reservoir. Differences in shoreline orientation, geology, and local climate (weather) will vary between reservoirs and affect the magnitude of erosion for that reservoir, although general processes will be similar for reservoirs in similar climates.

### Pool Level Fluctuations

Pool level fluctuation increases the area exposed to terrestrial and shoreline wave erosion. Drawdown and filling curves for reservoirs are generally smooth, but are occasionally interrupted. Variations in these curves are a result of variations in runoff and the demand for electricity. Static lake levels concentrate wave 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. Any drawdown below normal operating pool exposes non–vegetated shoreline, consisting usually of fine–grained deposits, making them subject to erosion by rainsplash and overland flow.

### Shoreline Orientation

The shoreline orientation can effect the erosion occurring in the reservoir environment due to the influence of the dominant wind directions on shoreline wave erosion. Shorelines oriented directly downwind of the average wind direction may exhibit accelerated erosion relative to other shoreline orientations. High shoreline–length to lake–surface–area ratios in reservoirs result from shorelines with many bays and promontories. These promontories and shorelines facing dominant winds are subject to greater wave erosion than bays or leeward shores (Lawson, 1985). The length of reservoir shoreline of a certain orientation is controlled primarily by the overall orientation of the reservoir and the original river valley that it fills. 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).

### Shoreline Geology

Bedrock and surficial geology determine the erosional susceptibility of materials in the reservoir environment. Erodibility, in turn, is dependent upon the grain size and cohesiveness of the materials. Drainage basin geology determines the particle size available for erosion and transport to the reservoir, while shoreline surficial deposits and bedrock control the processes occurring at the shoreline. In this section, types of shoreline materials and their effect on shoreline erosion are examined.

Igneous and metamorphic bedrock and talus form stable shorelines due to the large size of these materials and their resistance to erosion. Less–resistant sedimentary rocks such as sandstone and mudstone are more susceptible to weathering, but still resist erosion.

The various types of surficial deposits are more susceptible to erosional processes acting on reservoir shorelines. 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, reducing the possible extent of erosion. 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. Alluvial fan deposits are found where the main river's tributaries enter a reservoir. They are generally stable because of their coarse texture. However, alluvial fans are susceptible to initial incision (down–cutting) by the tributary stream, followed by bank failure and channel widening when reservoirs are operated below normal pool levels. Depth of incision is generally limited to lowest pool level. Debris cones formed by smaller, ephemeral streams with steep gradients generally have a larger particle size and are more resistant than alluvial fans to the processes of wave and overland flow erosion. Glacial outwash, typically composed of cohesionless sand and gravel, is subject to entrainment, transport, and redistribution by the processes affecting the reservoir environment.

Landslide deposits exhibit wide variation in stability. Their variable composition reacts differently to erosional processes. Overland flow and wave erosion affect the smaller particles. Accelerated sliding may be enhanced by rapid, extended drawdown that removes the supportive force of water from the slide base. Variable pool levels can cause bank failure as wave and overland flow erosion remove toe support from slides.

Alluvium deposited on low–relief floodplains and terraces is variable in composition and resistance to erosion. Fine–grained material deposited and distributed along reservoir banks over years of normal operation is relatively stable in its undisturbed state. Drafting below normal pool levels exposes these non–vegetated sediments to waves and overland flow erosion. Low–permeability deposits impede the drainage of groundwater as pool levels are lowered; increasing pore–water pressure reduces the shear strength of these materials and makes them extremely susceptible to bank blowouts, piping, sapping, and mass movement. Steeply sloping terrace risers are very susceptible to erosion but generally are not widely distributed.

The generally fine grained sediment deposited within the deeper, normally subaqueous parts of the reservoir would only be subject to erosion during extreme drawdown events. However, due to the fine–grained nature of these deposits, they are highly susceptible to wave and overland flow erosion. Once mobile, they can be transported out of the reservoir due to their low settling velocities.

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.

#### Climate

The climate of a region is an important element of the reservoir system, as it determines the weather that drives many of the shoreline erosion processes. Storms, with their accompanying winds and rainfall, directly influence waves and overland flow erosion. The intensity and distribution of precipitation events drives overland flow erosion. Prolonged strong winds from a single direction can pile up water at a windward shore, effectively raising the lake level at that location and increasing wave energy acting on the shore.

The local climate controls antecedent soil moisture, which influences erosion by reducing particle resistance to entrainment and thereby accelerating surface erosion (Stolte, et al., 1990). Soil moisture also provides the medium for freeze–thaw detachment to occur. Temperature affects freeze–thaw and the distribution of ice cover, which inhibits reservoir waves. Ice cover can directly cause erosion in some reservoirs when ice runs up on a shoreline or when the lake level falls; in such cases ice often collapses, taking soil and vegetation with it.

### 3.1.2 Reservoir Processes

Erosion processes affecting the reservoir environment include waves, reservoir currents, freeze–thaw, hillslope, groundwater, and overland flow. Total erosion is determined by reservoir operation, the magnitude of each process, characteristics of the reservoir environment, and interaction between processes. For example, wave erosion may accelerate mass movement by undercutting or steepening the shoreline. In fact the interdependence of these processes, coupled with the sheer number of processes, may make it impossible to quantify erosion attributable to a single process.

The cyclic nature of drafting and filling in storage reservoirs imparts a periodicity to reservoir shoreline erosion. This cyclic pattern accentuates climatic conditions that produce larger storms during the summer months, which transport sediment accumulated by weathering during the fall and winter. Every spring and summer, shoreline bank material and colluvium is eroded from bluffs and beaches near the full pool elevation. The eroded material is carried to lower depths by waves as the reservoir level falls in autumn and winter. The normal fall and winter drawdown exposes additional nearshore areas to mechanical freeze–thaw weathering. Continued large fluctuations in reservoir level prevent stable shoreline profiles from developing (Lawson, 1985). Shoreline erosion in run–of–river operations is generally much less than in storage reservoirs, due to the much smaller range of pool elevations.

### Wave Erosion

Of the processes acting on shorelines at normal pool levels, 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 controls where waves and their erosive force intersect the reservoir shore (see Figure 3–1) and, therefore, is the principle variable in shoreline erosion (bank recession) (Reid, 1984; Reid et al., 1988). Waves influence other shoreline erosion processes, such as mass movement and groundwater movement, by undermining slopes and saturating bank materials.

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). Reservoir pool level can influence the fetch and fetch width across which waves develop and therefore is positively related to the erosive potential of waves. 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 valleys; open broad reservoirs are more conducive to wave development than narrow, more confined reservoirs. Boat wave size is directly related to the speed and draft of the boat. Large, heavy, fast boats produce the largest waves.

### Reservoir Currents

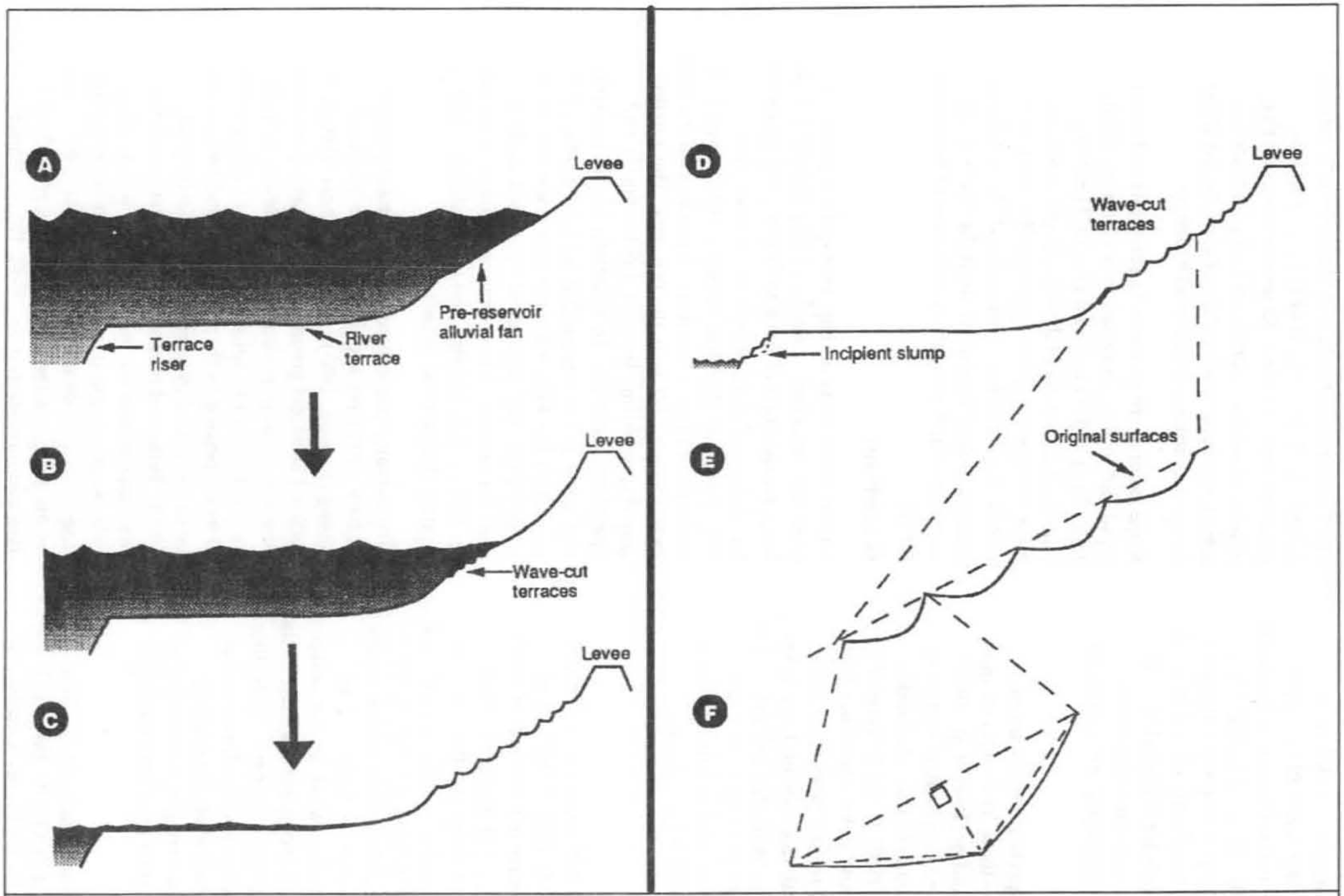
Reservoir currents originating as streamflow transport fine material (not deposited on fan deltas of tributaries) to lower portions of the reservoir or through the reservoir. Suspended sediment transport and deposition depends on the velocity of the flow through the reservoir. If current velocity exceeds the settling velocity of a particle size, then particles of that size will pass through the reservoir. Reservoir deposition occurs when the settling velocity for a particle size exceeds the transporting velocity.

With all things being equal, current velocity and hence travel time through a reservoir determines the size and amount of sediment deposited in a reservoir. The strongest currents in a reservoir can generally be expected to occur in the thalweg of the pre–existing river channel. This relation will change with time as reservoir sedimentation fills in the channel, leveling the reservoir bottom. Dam conditions, such as spillway and gate outlet location and operation schedule, influence the location, magnitude, and timing of reservoir currents. Reservoir drawdown is expected to increase current velocity, thereby decreasing the travel time of water and sediment through the reservoir and promoting greater transport of suspended sediment (both pre–existing and induced by erosion during drawdown) through the reservoir. The transporting capacity of reservoir currents cannot be generically characterized because it varies with multiple factors affecting the reservoir operation, sediment and water input, and erosion processes.

The erosive capacity of reservoir currents is minimal during normal operations. Locally, other processes may interact to initiate density currents that erode and transport sediment into deeper sections of the reservoir. This redistributes sediments within the reservoir, as little or no new sediment is introduced. When pool levels are rapidly lowered, current velocities may increase and change from laminar to turbulent flow. This may increase the sediment transport and erosive capacity of a flow and entrain reservoir sediments. Reservoir currents reach a maximum velocity at natural river levels, where channel and stream bank erosion dominate. The fine–grained, unconsolidated nature of reservoir deposits make them highly susceptible to all erosive processes.

### Freeze–Thaw

Freeze–thaw is another important process of shoreline and drainage basin erosion that produces materials for transport by other mechanisms. Freeze–thaw occurs both daily and seasonally. Expansion and contraction of water in sediments during freezing and thawing disaggregates soil particles, reducing their compaction, consolidation, and shear strength (Lawson, 1985). During spring thaw, melting of one



A. Reservoir at normal pool.
B. Drawdown to halfway down alluvial fan slope.
C. Water down to level of old river terrace.
D. Reservoir at maximum drawdown; slumping occurs on steep terrace risers.
E. Closer schematic of wave-cut terraces.
F. Diagram showing geometrical approximation of material removed by wave erosion.

Figure 3–1. Schematic Diagram Showing Wave Erosion During Drawdown.

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. Within a reservoir catchment, freeze–thaw mechanical weathering of soil increases the availability of sediments for transport by overland flow, especially in semi–arid areas where biological and chemical weathering are reduced by moisture conditions.

Shores with northerly aspects generally are more likely to undergo freeze–thaw, as they retain more moisture for freeze expansion (Reid et al., 1988). Low winter sun angles and deep valleys that lie in shadows during winter enhance this relationship. Sterrett and Mickelson (1981) found 87 percent of banks on Wisconsin's Great Lakes shorelines failed because of freeze–thaw related processes. Ten to twenty percent 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.

### Mass Movements

Reid et al. (1988) noted that shoreline 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 slumps and flows in cohesive, fine–grained sediments (e.g. glacial till, lacustrine deposits). These mass movements are influenced by excessive moisture conditions, which induce failure and facilitate transport by increasing the mass of the deposit while decreasing shear strength. Deposition of the material occurs when resistive forces exceed inertial forces. This occurs when the slumped material experiences dewatering or a reduction of gradient, or when it enters a reservoir (Kachugin, 1970).

Landslides occur in all shoreline materials in response to conditions that exceed the threshold stability for that particular landform. Loading, by water or other material, and reduction of structural support, such as removal of the toe of a slope, generally trigger slides. Reservoir processes that remove structural support on a slope include wave action, excessive pore water pressure during drawdown, and erosion by channel widening.

Slope failures are common in reservoirs with both rapid and prolonged drawdowns (Lawson, 1985). Jones et al. (1961) and Erskine (1973) noted a relation 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 resulted in instability of bank sediments.

### Groundwater

Groundwater plays an important role in reservoir shoreline processes. Lawson (1985) identified water level, composition of bank sediments, and groundwater movement along shorelines as three factors contributing to shoreline erosion. Groundwater can recharge or drain a reservoir, depending on the local hydraulic gradient near the reservoir. This relation may reverse during the year due to climatic and operational controls. In situations where reservoirs lose water to the surrounding aquifer, groundwater movement has little influence on erosion except by reducing the total amount of water that could be used for erosion. More typically, though, groundwater flows into reservoirs, and can contribute to mass wasting during rapid drawdowns.

Groundwater can influence geotechnical properties of bank sediments and directly cause erosion by piping (Lawson, 1985). Sediment shear strength is reduced as excess groundwater increases pore pressure and seepage pressure. Groundwater seepage has been shown to enhance erosion of sandy material by decreasing its shear strength, and hence resistance to erosion by overland flow (Stolte et al., 1990). Failure of banks by groundwater–related mass movements are most common where permeable sediments are interbedded with impermeable 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. Blowout and bank collapse have been noted along river banks with fine grained material following rapid water level lowering. This process was noted during the March 1992 drawdown test of Lower Granite Reservoir (Corps, 1992).

**Overland Flow Erosion**

Overland flow occurs when the storm precipitation rate exceeds the infiltration rate of the surface material, resulting in runoff when ponding storage is exceeded. Flow is concentrated by microtopography, which increases flow depth, velocity, and turbulence. All of these increase the shear stress acting on the surface. Rill erosion occurs when the shear stress of the flow exceeds the resisting force of the surface material, creating small channels. Rill erosion occurs primarily by detachment from concentrated runoff (Meyer, 1986). Before rills form and between rills once they have formed, raindrop splash detaches and transports particles downslope into rills. Thin–film runoff with raindrop enhanced turbulence also occurs within this area, a process referred to as interrill erosion.

Rill erosion is accelerated by increased surface area, slope, and length of flow; rainfall intensity and duration; decreased vegetation; unconsolidated and detachable particles; high moisture; and seepage conditions. Interrill erosion is a function of rainfall intensity and duration, drop size, infiltration capacity, and the size and detachability of soil particles.

Channels and gullies are large, incised features that form as greater quantities of runoff are concentrated (by rills) and generally proceed upslope by knickpoint migration; they tend to exhibit channel widening by bank collapse (Harvey and Watson, 1986). Reservoir areas subject to these processes during precipitation events are exposed shoreline and the alluvial fans and fan deltas formed at tributary mouths. Gully incision is limited by reservoir level and intersection with bedrock.

Rill and interrill erosion operate throughout drainage basins. Interrill erosion is independent of base level control, while sediment availability controls rill erosion. Channels and gullies are influenced by changes in base level but cannot migrate past base level controls such as bedrock or very coarse alluvium. Of the factors controlling overland flow erosion, pool level variation (which affects base level, surface area, sediment availability) is reflected in the reservoir environment and in small, adjacent alluvial basins.

Human activity can influence shoreline erosion by eliminating vegetation, displacing or compacting soil, and concentrating runoff. Overland flow of water on bluff faces and bank colluvium can cause erosion, especially on non–vegetated slopes composed of sediments with low cohesion (Lawson, 1985). Rilling and gullying are more active in highly impermeable sediments, whereas rain splash and sheet flow dominate in permeable soils (Lawson, 1985).

### 3.1.3 Erosion Response to Pool Level

**Adjustment of Shorelines at Full Pool**

The imposition of reservoir water onto sediments and landforms created in terrestrial environments represents an unstable configuration (Lawson, 1985). Raising of natural lake levels by dams initiates shoreline readjustment (erosion) (Lynott, 1989). Lawson (1985) noted 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). 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.

Construction of the Columbia River dam network altered the natural flow (in fact, this was a major justification for the dams) by placing water and sediment control structures on the mainstem. The free–flowing Columbia River had high flow peaks and elevated sediment transport in response to spring snowmelt runoff and extreme precipitation events.

Since dam construction, peak flows have been reduced and sediments trapped in reservoirs. This artificial rise in local base level has caused the development of alluvial fans and deltas at the mouths of tributaries and on the mainstem rivers. Decreased sediment production in areas now flooded is offset by placing some landforms in unstable conditions; e.g., valley sideslopes formed and maintained by hillslope processes are now out of equilibrium with reservoir shoreline processes (wave erosion). The equilibrium of the Columbia River system is no longer a continuum throughout the basin. What exists now is a series of local base level controls (dams), to which the nearby tributaries and upstream mainstem river sections respond. Equilibrium, whether dynamic or static, may not be achieved again until the reservoirs fill with sediment.

### Erosion Below Full Pool

Although erosion of reservoir shores is most severe and costly in terms of habitat and facility losses when reservoirs are at 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.

Drawdown below normal operating pool level is analogous to base level reduction in fluvial systems. Many experimental and field studies have focused on the impact of lowering base level on river morphology, sediment transport and deposition, and drainage basin evolution (Schumm, 1987). Briefly, base level (or pool level) reduction increases overland flow, wave erosion and freeze–thaw by exposing additional shoreline to these processes. Lowering base level directly accelerates incision in alluvial material, with resultant knickpoint migration and channel widening by collapse. Wave erosion is complexly affected by base level reduction as waves encounter fine sediment that is normally below the zone of wave activity (Figure 3–1). However, wave energy is reduced as reservoir surface area declines when pool level is lowered. The geometry of the individual reservoir controls wave generation to a large extent. Mass movement is accelerated by removal of the buoyant force of water and increased pore water pressure. Rapid drawdown de–stabilizes banks and slopes, causing sapping, slumps, and slides. Repeated drawdowns below normal operating levels delay development of equilibrium reservoir profiles (lag beaches that protect against erosion) and contribute to accelerated reservoir erosion.

Landforms most sensitive to erosion below full pool include terrace edges and valley walls. Steep slopes on these landforms that once held thick accumulations of unconsolidated sediments have been stripped of much of their original soil cover and are now covered with loose coarse lag deposits in the drawdown zones. Below normal operating levels, these landforms do not have this coarse armoring, and thus are less resistant to shoreline processes.

The steep, former valley sideslopes are now transport areas for the material eroded from shorelines above and below full pool. Erosion and transport of these sediments occurs as the reservoir level fluctuates and influences shoreline erosion at full pool. When the normally rapid filling or drawdown is interrupted by periods of static lake elevation, wave erosion cuts strand lines into unconsolidated material and accelerates the movement of the eroded material to deeper parts of reservoir.

Another effect of lowering the base level of tributary streams is sapping. Sapping occurs when the banks of a tributary are undercut by groundwater moving through and exiting them at the base (Kachugin, 1970). In the reservoir environment, sapping occurs when the pool level is lowered, leaving saturated but permeable sediments above the mainstem river. Sapping may occur on the banks of the mainstem itself, but slumping seems to predominate there. On tributaries to the mainstem, incision of the delta sediments may initiate sapping, as groundwater begins flowing through the more permeable layers to the incised channels. Fine particles are washed out, removing support for the sediments above them. This occurred on Alpowa Creek during the 1992 drawdown test (Figure 3–2). While limited to those tributaries with broad deltas, sapping may still be a significant contributor to erosion.

### 3.1.4 Sedimentation

Reservoirs are sediment traps, capturing all but the finest particles entering the reservoir. Reservoir sedimentation is an expected process that ultimately reduces the effectiveness of the reservoir. The Columbia River system reservoirs are filling in with sediment at differing rates. For example, it is estimated that Lower Granite Reservoir has accumulated 40 million cubic yards (30.6 million $m^3$) of sediment so far during less than 20 years of operation.

Reservoir sedimentation is controlled by the erosion and delivery of sediments from the drainage basin upstream to the reservoir. Upstream and drainage basin production of sediment influences the particle size of the sediment delivered to reservoirs, while fluid properties of velocity, temperature, and sediment concentration influence transport and deposition in the reservoirs. Reservoir operations generally do not drastically alter sediment delivery to reservoirs. Operations redistribute materials already in the reservoir environment. If operations increase flow velocity through reservoirs, then some stored sediment would be flushed from the reservoir. Downstream reservoirs would receive this additional sediment, which could accelerate sedimentation if their operations are not adjusted to allow for sediment passage.

Deposition of coarser particles within a reservoir is concentrated at tributary mouths in fan deltas, where the velocity and transporting capacity of the flow are reduced as it enters the still water of the reservoir. Finer particles may be transported further into the reservoir and settle in the deeper sections near the dam. This general trend of down–reservoir fining is apparent in most reservoirs (Gottschalk, 1964). Waves are very effective at redistributing sediment delivered or eroded from shorelines to deeper sections of the reservoir.

## 3.2 STUDY PROCESS

This section describes the procedures used to link the processes described above to the existing surface and subsurface reservoir environment in light of the proposed SOS alternatives. The discussion summarizes the respective approaches taken for erosion and sedimentation issues and for groundwater.

### 3.2.1 Erosion and Sedimentation

As discussed above, reservoir pool elevation is the element of each SOS alternative that variably affects erosion, sedimentation, and groundwater. In general this influence is restricted to near–shore areas and alluvial floored tributaries. The SOS alternatives can generally be broken down into two groups based on their effects on the reservoir environment. The first group of alternatives (SOSs 1 through 4) would generally maintain pool levels within or near normal operation ranges. As such, these alternatives would not impose radically different stresses on the reservoir shorelines and would be expected to have minor impacts. The second group (SOSs 5, 6, 9a, and 9c) involves mainstem reservoir drawdown outside of normal operating levels to increase flow velocity of water through the river system. These alternatives would be expected to have major impacts on the reservoir environment.

In general, the alternatives deemed to have the potential for the most significant impacts were studied more intensively than those involving minor operational changes. Little was known about potential impacts of certain operations, and the alternatives containing those operations were treated in a qualitative way. Empirical evidence of impacts was available for other operations. The analysis of these options was more quantitative.

A useful indicator of erosion intensity is the total pool elevation range ($P_R$). While local geology and reservoir geometry greatly influence the relationship of $P_R$ to total erosion, $P_R$ does help indicate trends in erosion that can be expected at a given reservoir. As indicated in the previous discussion of reservoir

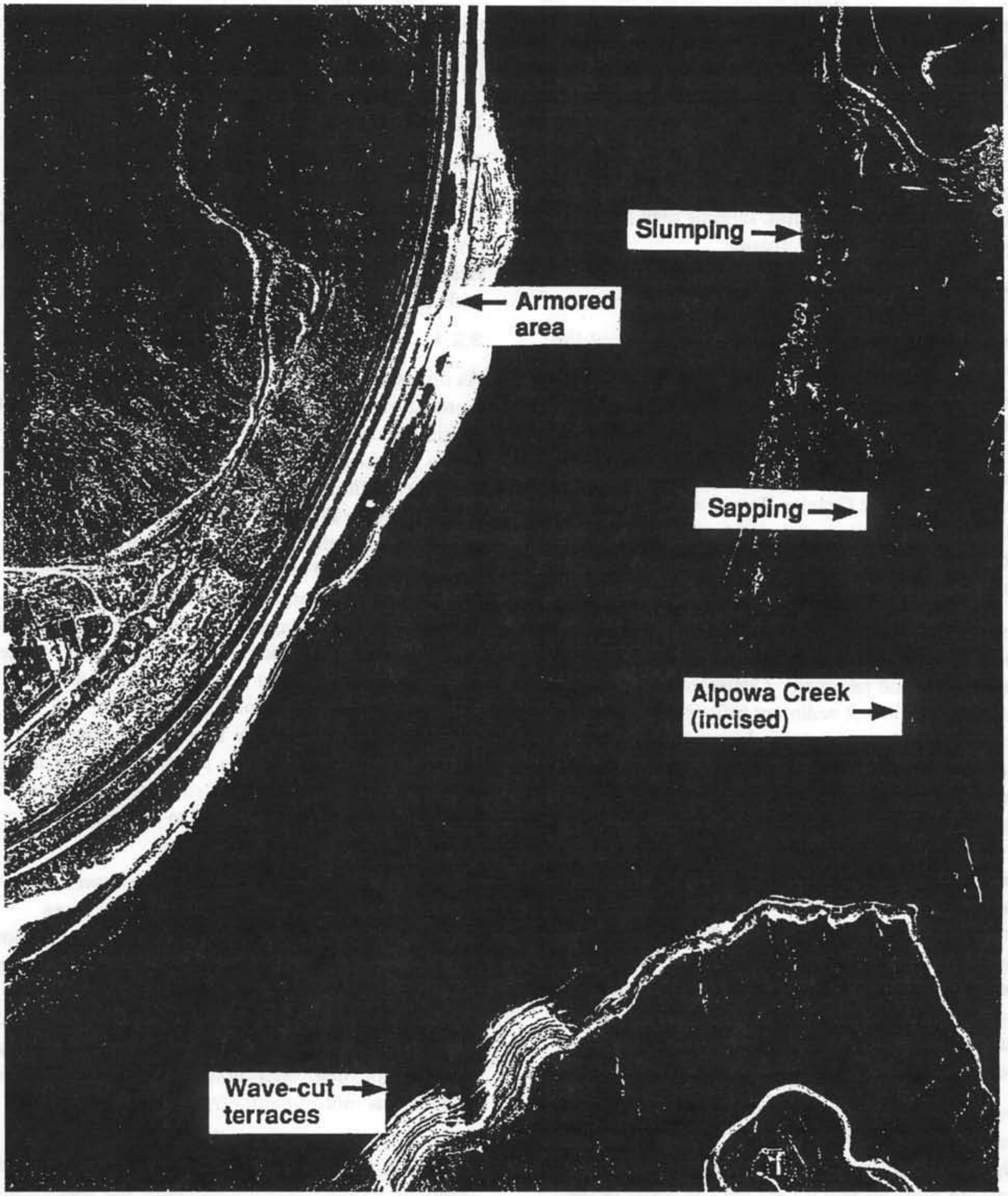


**Figure 3–2. Photo of Lower Granite During Maximum Drawdown, March 1992 at about RM 131.**

erosion and sedimentation, pool level fluctuations influence most of the processes acting on the shoreline. In addition, changes in $P_R$ tend to outlast effects of other changes related to pool levels. For instance, if the $P_R$ is reduced by 30 percent and the average annual pool elevation is decreased, the surface area above the average annual maximum level reached would increase, and would be exposed to more surface erosion (overland flow, rilling, gullying). However, the resulting erosion would be limited by prior removal of detachable particles (when waves could attack the shore at these elevations), and by re–establishment of vegetation. In addition, wave erosion tends to produce greater volumes of sediment than surface erosion. Thus, the net effect would be an overall decrease in shoreline erosion.

**Affected Environment**

Geologic and hydrogeologic studies of the basin, its provinces, and the specific project locations were reviewed to determine the nature of the existing environment. These studies primarily include U.S. Army Corps of Engineers (Corps) and Bureau of Reclamation (Reclamation) documents on their respective projects. The available studies represent somewhat dated literature, and they do not provide a complete and up to date inventory of all landslides and eroding or potentially eroding areas. The SOR is a programmatic review, however, and does not require a full, site–specific inventory and assessment of potential effects. The objective for the baseline studies relative to erosion and sedimentation was to provide a general and reasonably current overview of bedrock and surficial geologic conditions for the system.

**Impact Analysis**

Literature review was also a key part of the impact analysis. To understand the erosion and sedimentation processes involved, the literature was searched for pertinent studies on the effects of water regulation on river and reservoir banks. Because pool level is the main link between shoreline erosion/mass wasting, water table fluctuation, and dam operation, the SOR hydroregulation model results provided the basis for assessing the nature of pool level fluctuations under the proposed alternatives. The assessment of the effects of SOSs 1 through 4 is largely qualitative. Mass wasting, for instance, can only be assessed as to the likelihood it will occur, i.e., will the likelihood increase, decrease, or remain about the same as under current operations. For some areas, however, it was possible to estimate the rate of expected shoreline retreat based on existing measurements.

A more detailed analysis was appropriately pursued for SOSs 5, 6, 9a, and 9c. Based on prior assessments of river system operations, the study team recognized that the drawdown alternatives held the potential for significant changes in erosion and sedimentation. In addition, the SOR water quality analysis required specific estimates of sediment contribution with these alternatives, as inputs for model analysis of water quality parameters. Therefore, the geology and soils study process included a quantitative assessment of erosion and sedimentation under drawdown conditions.

The March 1992 drawdown test results provide an empirical study of reservoir drawdown that is well suited for analysis of the effects of larger–scale drawdowns in the same river reach. Extensive data on the nature of the reservoir sediments in Lower Granite and Little Goose exist, and the 1992 drawdown showed which processes affected the shoreline and to what extent. Although the mechanisms of all of the processes are not completely understood, the extrapolation of the impacts from the 1992 test to the proposed SOS drawdown scenarios is the best available method to predict potential shoreline impacts.

The study team developed a shoreline erosion model to assess the major processes involved in shoreline erosion and reservoir sedimentation. These included mass wasting, wave erosion, overland erosion, and incision. The universal soil loss equation was used to estimate surface erosion. The amount of mass wasting, wave erosion, and incision were calculated based on the results of the 1992 drawdown.

There are no detailed studies of shoreline behavior during drawdown, and the model relied heavily on interpretation of aerial and ground photographs of the 1992 drawdown area. The model focused on Lower Granite because more information is available for that reservoir than others. The surface area was estimated using the pre–dam river terrace topography. Armored areas, such as riprap and coarse–grained alluvial fans, were subtracted from the total estimated area exposed. Slumping/sapping was estimated using data from the 1992 drawdown test. Geometry of slumps was estimated using photos and knowledge of the behavior of slumped materials. Total slumped material was estimated for the 1992 drawdown test and adjusted for drawdown level and shoreline geometry. Tributary erosion was similarly estimated, using aerial photos and ground–based photos. Volumes of eroded materials were estimated for each major tributary using channel geometry. These estimates were adjusted for pool levels in SOS 5 and SOS 6, since both are lower than the maximum drawdown in the 1992 test. Wave erosion was estimated using the geometries of wave–cut terraces along the reservoir shoreline. Several classes of exposed areas were developed based on slope and geomorphic character. The volumes were multiplied by the number of terraces at various sites of uniform slope, and adjusted for the slope as well. The estimates were extrapolated for areas that would be exposed under SOSs 5 and 6.

Estimates for each erosion process were calculated for three different rates: low, moderate, and extreme. Because the 1992 test occurred during unusually calm conditions, the estimated wave erosion was assumed to represent a low erosion scenario. Surface erosion, mass wasting, and incision were also considered to represent the low end of the possible erosion range. For the moderate scenario, weather conditions during the test were compared to average conditions for that period and correspondingly adjusted. Adjustments were also made for the timing and duration of the proposed drawdowns.

Erosion estimates for the other three lower Snake reservoirs (Little Goose, Lower Monumental, and Ice Harbor) were made using the average erosion per mile under the moderate erosion scenario on Lower Granite and multiplying by the mileage along those reservoirs. This estimate was adjusted for amount of available sediment, noting that the dam construction sequence went progressively upstream in a relatively short period. This means that the other dams did not have very much time to accumulate thick sediments; most sediments have been trapped by Lower Granite. Some reservoirs, though, have major tributaries draining highly erosive land (the Palouse region), so further adjustments were made to account for these major sources of sediment.

More details of the model, with the assumptions and uncertainties, are presented in Appendix M, Water Quality, Technical Exhibit G. Model results are summarized in Sections 4.6 and 4.7 of Appendix L.

### 3.2.2 Groundwater

A comprehensive literature search was conducted to obtain information on groundwater wells and usage in the vicinity of reservoirs affected by the SOR. In addition, the U.S. Geological Survey in Washington, Idaho, and Montana and the Idaho Department of Water Resources were contacted to obtain well information. No comprehensive reports exist that catalogue wells in the study area. Data resources are typically non–automated and scattered among various local, state, and Federal agencies.

To gain some understanding of potential groundwater impacts, information from water resources personnel was used to assess the general location of zones of significant groundwater usage near reservoirs. Groundwater conditions under the proposed alternatives were estimated based on general aquifer characteristics and empirical studies, where possible, and on parallel material from the 1992 Options Analysis/EIS and the Supplemental EIS (SEIS). Impacts to groundwater and wells were assessed generically in most cases, although the 1992 Lower Granite drawdown test results include information for that specific project area. The assessment of impacts to groundwater should therefore be regarded as qualitative, and having a high degree of local variability.

## 3.3 RELATIONSHIP TO OTHER STUDIES

The study team responsible for soils, geology, and groundwater interacted with several other SOR groups during the course of the study. In general, this involved other SOR elements that desired information on erosion and sedimentation as inputs to impact analysis for other resource areas. Information exchange relating to water quality, air quality, and recreation is summarized below.

### 3.3.1 Water Quality

Shoreline erosion adds suspended and dissolved sediment to the reservoir. This translates into increased turbidity, a major water quality concern. In addition, chemical contaminants attached to reservoir sediments could enter the water column and affect water quality if reservoir operations resuspend the sediments.

To support the water quality studies, the geology/soils study team conducted an analysis to estimate the amount of shoreline erosion that would occur during reservoir drawdown on the lower Snake. These results were fed into the water quality model analysis and were specifically used to determine turbidity downstream. The shoreline erosion results are also reported in this appendix and used to determine some of the impacts of SOSs 5 and 6.

### 3.3.2 Air Quality

Geology and soils are usually not related to air quality issues. In the normal drawdown zone, most fines that would otherwise be exposed to eolian (wind transport) processes are winnowed out. Blowing dust may persist at some storage reservoirs, depending on the composition of the shoreline materials. In addition, events such as annual drawdowns of some run–of–river projects (as in SOS 5 and 6) would expose significant areas of unconsolidated fine materials and create potential wind–blown dust problems. Contaminants that attach to fine sediment particles might also become airborne due to exposure to wind, representing another soils–related air quality issue.

The geology/soils and air quality study teams shared information and coordinated approaches to impact analysis in response to these areas of overlapping issues. Both analyses required estimates of reservoir subsurface area exposed under different operating conditions. The air quality group developed these estimates and shared the results with other parties. The geology/soils team obtained and applied grain–size data for reservoir sediments, for use in the shoreline erosion model analysis. This information was shared with the air quality team, which required data on sediment composition to develop quantitative results for dust generation. Both teams also shared meteorological data, which were used as inputs to the shoreline erosion and air quality modeling processes.

### 3.3.3 Recreation

Geologic and soil conditions can have a direct impact on the recreation potential of the reservoir environment. They determine the nature of the shoreline, which is the most intensively used portion of the reservoir. Rocky, bedrock, or muddy shorelines may not be conducive to some recreation activities. Suitability for other recreational activities changes as shorelines develop. Furthermore, high levels of turbidity may lower the aesthetic appeal and sport fishing potential of a reservoir, thus decreasing its recreational value.

Addressing these issues will require the Recreation Work Group to obtain and apply information on existing conditions and projected impacts from the geology/soils study team. However, this element of the recreation analysis involves assessment of user responses to various physical conditions associated with system operations. The Recreation Work Group sponsored a survey of users, and for which results are just becoming available. Incorporating information on shoreline materials and erosion with user response data, therefore, represents a future activity that is not yet reported in the SOR documents.

### 3.3.4 Cultural Resources

Erosion and sedimentation patterns can greatly affect artifact exposure and context. Historic or pre–historic features that are currently submerged are generally not subject to vandalism or theft.

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Changing the operation of reservoirs may erode the sediment that has blanketed such features, hence exposing them to view. In addition, the locational context of such features may be modified through wave action, soil displacement, and stream incision.

The Cultural Resources appendix (D) examines the general effect of shoreline (wave) erosion on zones with high potential for artifact. This appendix considers the effect of slumping/sapping, incision, and overland erosion, in addition to wave erosion. It is important to note that the effect on specific zones along a reservoir may be more or less severe than the effect on the total area exposed by reservoir operation. Thus the results of the Cultural Resources model of shoreline erosion may not always appear to be in agreement with the results of the model used in this study. However, any differences are due to the site–specific nature of the cultural resources model.

# CHAPTER 4

# ALTERNATIVES AND THEIR IMPACTS

## 4.1 GENERAL DESCRIPTION OF ALTERNATIVES

Seven alternative System Operating Strategies (SOS) were considered in the Draft EIS. Each of the 7 SOSs contained several options, bringing the total number of alternatives considered to 21. This Final EIS also evaluates 7 operating strategies, with a total of 13 alternatives now under consideration when accounting for options. Section 4.1 of this chapter describes the 13 alternatives and provides the rationale for including these alternatives in the Final EIS. Operating elements for each alternative are summarized in Table 4–1. Later sections of this chapter describe the effects of these alternatives on geology.

The 13 final alternatives represent the results of the third analysis and review phase completed since SOR began. In 1992, the agencies completed an initial effort, known as "Screening" which identified 90 possible alternatives. Simulated operation for each alternative was completed for five water year conditions ranging from dry to wet years, impacts to each river use area were estimated using simplified analysis techniques, and the results were compared to develop 10 "candidate SOSs." The candidate SOSs were the subject of a series of public meetings held throughout the Pacific Northwest in September 1992. After reviewing public comment on the candidate strategies, the SOR agencies further reduced the number of SOSs to seven. These seven SOSs were evaluated in more detail by performing 50–year hydroregulation model simulations and by determining river use impacts. The impact analysis was completed by the SOR workgroups. Each SOS had several options so, in total, 21 alternatives were evaluated and compared. The results were presented in the Draft EIS, published in July, 1994. As was done after Screening, broad public review and comment was sought on the Draft EIS. A series of nine public meetings was held in September and October 1994, and a formal comment period on the Draft EIS was held open for over 4 1/2 months. Following this last process, the SOR agencies have again reviewed the list of alternatives and have selected 13 alternatives for consideration and presentation in the Final EIS.

Six options for the alternatives remain unchanged from the specific options considered in the Draft EIS. One option (SOS 4c) is a revision to a previously considered alternative, and the rest represent replacement or new alternatives. The basic categories of SOSs and the numbering convention remains the same as was used in the Draft EIS. However, because some of the alternatives have been dropped, the final SOSs are not numbered consecutively. There is one new SOS category, Settlement Discussion Alternatives, which is labeled SOS 9 (see Section 4.1.6 for discussion).

The 13 alternatives have been evaluated through the use of a computerized model known as HYDROSIM. Developed by BPA, HYDROSIM is a hydroregulation model that simulates the coordinated operation of all projects in the Columbia River system. It is a monthly model with 14 total time periods. April and August are split into two periods each, because major changes can occur in streamflows in the first and second half of each of these months. The model is based on hydrologic data for a 50–year period of record from 1928 through 1978. For a given set of operating rule inputs and other project operating requirements, HYDROSIM will simulate elevations, flows, spill, storage content and power generation for each project or river control point for the 50–year period. For more detailed information, please refer to Appendix A, River Operation Simulation.

The following section describes the final alternatives and reviews the rationale for their inclusion in the Final EIS.

## Table 4–1. SOS Alternative–1

### Summary of SOS

| SOS 1<br>Pre-ESA Operation | SOS 2<br>Current Operations | SOS 4<br>Stable Storage Project Operation |
|---|---|---|
| SOS 1 represents system operations before changes were made as a result of the ESA listing of three Snake River salmon stocks. SOS 1a represents operations from 1983 through the 1990–91 operating year, influenced by Northwest Power Act; SOS 1b represents how the system would operate without the Water Budget and related operations to benefit anadromous fish. Short-term operations would be conducted to meet power demands while satisfying nonpower requirements. | SOS 2 reflects operation of the system with interim flow improvement measures in response to the ESA salmon listings. It is consistent with the 1992–93 operations described in the Corps' 1993 Interim Columbia and Snake River Flow Improvement Measures Supplemental EIS. SOS 2c represents the operating decision made as a result of the 1993 Supplemental EIS and is the no action alternative for the SOS. Relative to SOS 1a, primary changes are additional flow augmentation in the Columbia and Snake Rivers and modified pool levels at lower Snake and John Day reservoirs during juvenile salmon migration. SOS 2d represents operations of the 1994-98 Biological Opinion issued by NMFS, with additional flow aumentation measures compared to SOS 2c. | SOS 4 would coordinate operation of storage reservoirs to benefit recreation, resident fish, wildlife, and anadromous fish, while minimizing impacts to power and flood control. Reservoirs would be managed to specific elevations on a monthly basis; they would be kept full longer, while still providing spring flows for fish and space for flood control. The goal is to minimize reservoir fluctuations while moving closer to natural flow conditions. SOS 4c attempts to accommodate anadromous fish needs by shaping mainstem flows to benefit migrations and would modify the flood control operations at Grand Coulee. |

### Actions by Project

| | SOS 1 | SOS 2 | SOS 4 |
|---|---|---|---|
| **LIBBY** | **SOS 1a**<br>Normal 1983–1991 storage project operations | **SOS 2c**<br>Operate on system proportional draft as in SOS 1a | **SOS 4c**<br>• Meet specific elevation targets as indicated by Integrated Rule Curves (IRCs); IRCs are based on storage content at the end of the previous year, determination of the appropriate year within the critical period, and runoff forecasts beginning in January<br>• IRCs seek to keep reservoir full (2,459 feet) June-Sept; minimum annual elevation ranges from 2,399 to 2,327 feet, depending on critical year determination<br>• Meet variable sturgeon flow targets at Bonners Ferry during May 25-August 16 period; flow targets peak as high as 35 kcfs in the wettest years |
| | **SOS 1b**<br>• Minimum project flow 3 kcfs<br>• No refill targets<br>• Summer draft limit of 5–10 feet | **SOS 2d**<br>• Provide flow augmentation for salmon and sturgeon when Jan. to July forecast is greater than 6.5 MAF<br>• Meet sturgeon flows of 15, 20, and 12.5 kcfs in May, June, and July, respectively, in at least 3 out of 10 years | |

KAF = 1.234 million cubic meters

MAF = 1.234 billion cubic meters

## Table 4–1. SOS Alternative–1

| SOS 5<br>Natural River Operation | SOS 6<br>Fixed Drawdown | SOS 9<br>Settlement Discussion Alternatives | SOS PA |
|---|---|---|---|
| SOS 5 would aid juvenile salmon by increasing river velocity. The four lower Snake River projects would have new outlets installed, allowing the reservoirs to be drawn down to near the original river elevation. The "natural river" operation would be done for 4 1/2 months in SOS 5b and year-round in SOS 5c. John Day would also be operated at MOP for 4 months, and flow augmentation measures on the Columbia River portion of the basin would continue as in SOS 2c. | SOS 6 involves drawing down lower Snake River projects to fixed elevations below MOP to aid anadromous fish. SOS 6b provides for fixed drawdowns for all four lower Snake projects for 4 1/2 months; SOS 6d draws down Lower Granite only for 4 1/2 months. John Day would also be operated at MOP for 4 months, and flow augmentation measures on the Columbia River portion of the basin would continue as in SOS 2c. | SOS 9 represents operations suggested by the USFWS, NMFS, the state fisheries agencies, Native American tribes, and the Federal operating agencies during the settlement discussions in response to the *IDFG v. NMFS* court proceedings. This alternative has three options, SOSs 9a, 9b, and 9c, that represent different scenarios to provide increased river velocities for anadromous fish by establishing flow targets during migration and to carry out other actions to benefit ESA-listed species. The three options are termed the Detailed Fishery Operating Plan (9a), Adoptive Management (9b), and the Balanced Impacts Operation (9c). | SOS PA represents the operation recommended by NMFS and the USFWS Biological Opinions issued March 1, 1995. This SOS supports recovery of ESA-listed species by storing water during the fall and winter to meet spring and summer flow targets, and protects other resources by setting summer draft limits to manage negative effects, by providing flood protection, and by providing for reasonable power generation. |

| SOS 5 | SOS 6 | SOS 9 | SOS PA |
|---|---|---|---|
| **SOS 5b**<br>Operate on system proportional draft as in SOS 1a<br>**SOS 5c**<br>Operate on system proportional draft as in SOS 1a | **SOS 6b**<br>Operate on system proportional draft as in SOS 1a<br>**SOS 6d**<br>Operate on system proportional draft as in SOS 1a | **SOS 9a**<br>• Operate on minimum flow up to flood control rule curves year-round, except during flow augmentation period<br>• Provide sturgeon flow releases April-Aug. to achieve up to 35 kcfs at Bonner's Ferry with appropriate ramp up and ramp down rates<br>**SOS 9b**<br>• Operate on minimum flow up to flood control rule curves year-round, except during flow augmentation<br>• Provide sturgeon flow releases similar to SOS 2d<br>• Can draft to elevation 2,435 by end of July to meet flow targets<br>**SOS 9c**<br>• Operate to the Integrated Rule Curves and provide sturgeon flow releases as in SOS 4c | **SOS PA**<br>• Operate on minimum flow up to flood control rule curves beginning in Jan., except during flow augmentation period<br>• Strive to achieve flood control elevations in Dec. in all years and by April 15 in 75 percent of years<br>• Provide sturgeon flows of 25 kcfs 42 days in June and July<br>• Provide sufficient flows to achieve 11 kcfs flow at Bonner's Ferry for 21 days after maximum flow period<br>• Draft to meet flow targets, to a minimum end of Aug. elevation of 2,439 feet, unless deeper drafts needed to meet sturgeon flows |

1 kcfs = 28 cms

1 ft = 0.3048 meter

## Table 4–1. SOS Alternative–2

### Actions by Project

| | SOS 1 | SOS 2 | SOS 4 |
|---|---|---|---|
| **HUNGRY HORSE** | **SOS 1a** | **SOS 2c** | **SOS 4c** |
| | Normal 1983–1991 storage project operations | Operate on system proportional draft as in SOS 1a | • Meet specific elevation targets as indicated by Integrated Rule Curves (IRCs), similar to operation for Libby<br>• IRCs seek to keep reservoir full (3,560 feet) June-Sept.; minimum annual elevation ranges from 3,520 to 3,450 feet, depending on critical year |
| | **SOS 1b** | **SOS 2d** | |
| | • No maximum flow restriction from mid-Oct. to mid-Nov.<br>• No draft limit; no refill target | Operate on system proportional draft as in SOS 1a | |

| | SOS 1 | SOS 2 | SOS 4 |
|---|---|---|---|
| **ALBENI FALLS** | **SOS 1a** | **SOS 2c** | **SOS 4c** |
| | Normal 1983–1991 storage project operations | Operate on system proportional draft as in SOS 1a | Elevation targets established for each month, generally 2,056 feet Oct.–March, 2,058 to 2,062.5 feet April–May, 2,062.5 feet (full) June, 2,060 feet July–Sept. (but higher if runoff high); Oct.–March drawdown to 2,051 feet every 6th year |
| | **SOS 1b** | **SOS 2d** | |
| | No refill target | Operate on system proportional draft as in SOS 1a | |

KAF = 1.234 million cubic meters

MAF = 1.234 billion cubic meters

## Table 4–1. SOS Alternative–2

| SOS 5 | SOS 6 | SOS 9 | SOS PA |
|---|---|---|---|
| **SOS 5b**<br>Operate on system proportional draft as in SOS 1a | **SOS 6b**<br>Operate on system proportional draft as in SOS 1a | **SOS 9a**<br>• Operate on minimum flow up to flood control rule curves year-round, except during flow augmentation period | **SOS PA**<br>• Operate on minimum flow up to flood control rule curves year-round, except during flow augmentation period<br>• Strive to achieve flood control elevations by April 15 in 75 percent of the years<br>• Draft to meet flow targets, to a minimum end-of-August elevation of 3,540 feet |
| **SOS 5c**<br>Operate on system proportional draft as in SOS 1a | **SOS 6d**<br>Operate on system proportional draft as in SOS 1a | **SOS 9b**<br>• Operate on minimum flow up to flood control rule curves year-round, except during flow augmentation<br>• Can draft to meet flow targets, to a minimum end-of-July elevation of 3,535 feet | |
| | | **SOS 9c**<br>• Operate to the Integrated Rule Curves as in SOS 4c | |

| SOS 5 | SOS 6 | SOS 9 | SOS PA |
|---|---|---|---|
| **SOS 5b**<br>Operate on system proportional draft as in SOS 1a | **SOS 6b**<br>Operate on system proportional draft as in SOS 1a | **SOS 9a**<br>Operate on minimum flow up to flood control rule curves year-round, except during flow augmentation period | **SOS PA**<br>• Operate to flood control elevations by April 15 in 90 percent of the years<br>• Operate to help meet flow targets, but do not draft below full pool through Aug. |
| **SOS 5c**<br>Operate on system proportional draft as in SOS 1a | **SOS 6d**<br>Operate on system proportional draft as in SOS 1a | **SOS 9b**<br>• Operate on minimum flow up to flood control rule curves year-round, except during flow augmentation period<br>• Can draft to meet target flows, to a minimum end-of-July elevation of 2,060 feet | |
| | | **SOS 9c**<br>• Elevation targets established for each month, generally no lower than 2,056 feet Dec.—April, no lower than 2,057 feet end of May, full (2,062.5 feet) June—Aug., 2,056 feet Sept.—Nov. | |

1 kcfs = 28 cms

1 ft = 0.3048 meter

## Table 4–1. SOS Alternative–3
### Actions by Project

| | SOS 1 | SOS 2 | SOS 4 |
|---|---|---|---|
| **GRAND COULEE** | **SOS 1a**<br>• Operate to meet Water Budget target flows of 134 kcfs at Priest Rapids in May [1/]<br>• Meet minimum elevation of 1,240 feet in May<br>**SOS 1b**<br>• No refill target of 1,240 feet in May<br>• Maintain 1,285 feet June–Sept.; minimum 1,220 feet rest of year<br>• No May–June flow target | **SOS 2c**<br>• Storage of water for flow augmentation from January through April<br>• Supplemental releases (in conjunction with upstream projects) to provide up to 3 MAF additional (above Water Budget) flow augmentation in May and June, based on sliding scale for runoff forecasts<br>• System flood control space shifted from Brownlee, Dworshak<br>**SOS 2d**<br>• Contribute, in conjunction with upstream storage projects, up to 4 MAF for additional flow augmentation<br>• Operate in summer to provide flow augmentation water and meet downstream flow targets, but draft no lower than 1,280 feet | **SOS 4c**<br>• Operate to end-of-month elevation targets, as follows:<br>1,288 Sept.-Nov<br>1,287 Dec.<br>1,270 Jan.<br>1,260 Feb.<br>1,270 Mar.<br>1,272 Apr. 15<br>1,275 Apr. 30<br>1,280 May<br>1,288 Jun.-Aug.<br>• Meet flood control rule curves only when Jan.-June runoff forecast exceeds 68 MAF |

| | SOS 1 | SOS 2 | SOS 4 |
|---|---|---|---|
| **PRIEST RAPIDS** | **SOS 1a**<br>• Meet May-June flow targets [1/]<br>• Maintain minimum flows to meet Vernita Bar Agreement [2/]<br>**SOS 1b**<br>• No May flow target<br>• Meet Vernita Bar Agreement | **SOS 2c**<br>Operate as in SOS 1a<br>**SOS 2d**<br>Operate as in SOS 1a | **SOS 4c**<br>Operate as in SOS 1a |

1/ Flow targets are weekly averages with weekend and holiday flows no less than 80 percent of flows over previous 5 days.

2/ 55 kcfs during heavy load hours October 15 to November 30; minimum instantaneous flow 70 kcfs December to April

KAF = 1.234 million cubic meters MAF = 1.234 billion cubic meters

## Table 4–1. SOS Alternative–3

| SOS 5 | SOS 6 | SOS 9 | SOS PA |
|---|---|---|---|
| **SOS 5b** | **SOS 6b** | **SOS 9a** | **SOS PA** |
| Operate on system proportional draft and provide flow augmentation as in SOS 2c | Operate on system proportional draft and provide flow augmentation as in SOS 2c | • Operate to meet flood control requirements and Vernita Bar agreement<br>• Provide flow augmentation releases to help meet targets at The Dalles of 220-300 kcfs April 16-June 15, 200 kcfs June 16-July 31, and 160 kcfs Aug. 1-Aug.31, based on appropriate critical year determination<br>• In above average runoff years, provide 40% of the additional runoff volume as flow augmentation | • Operate to achieve flood control elevations by April 15 in 85% of years<br>• Draft to meet flow targets, down to minimum end-of-Aug. elevation of 1,280 feet<br>• Provide flow augmentation releases to meet Columbia River flow targets at McNary of 220-260 kcfs April 20-June 30, based on runoff forecast, and 200 kcfs July-Aug. |
| **SOS 5c** | **SOS 6d** | **SOS 9b** | |
| Operate on system proportional draft and provide flow augmentation as in SOS 2c | Operate on system proportional draft and provide flow augmentation as in SOS 2c | • Operate on minimum flow up to flood control rule curves year-round, except during flow augmentation period<br>• Can draft to meet flow targets, bounded by SOS 9a and 9c targets, to a minimum end-of-July elevation of 1,265 feet | |
| | | **SOS 9c** | |
| | | • Operate to meet McNary flow targets of 200 kcfs April 16-June 30 and 160 kcfs in July<br>• Can draft to meet flow targets, to a minimum end-of-July elevation of 1,280 feet<br>• Contribute up to 4 MAF for additional flow augmentation, based on sliding scale for runoff forecasts, in conjunction with other upstream projects<br>• System flood control shifted to this project | |

| SOS 5 | SOS 6 | SOS 9 | SOS PA |
|---|---|---|---|
| **SOS 5b** | **SOS 6b** | **SOS 9a** | **SOS PA** |
| Operate as in SOS 1a | Operate as in SOS 1a | Operate as in SOS 1a | Operate as in SOS 1a |
| **SOS 5c** | **SOS 6d** | **SOS 9b** | |
| Operate as in SOS 1a | Operate as in SOS 1a | Operate as in SOS 1a | |
| | | **SOS 9c** | |
| | | Operate as in SOS 1a | |

1 kcfs = 28 cms

1 ft = 0.3048 meter

## Table 4–1. SOS Alternative–4

### Actions by Project

| | SOS 1 | SOS 2 | SOS 4 |
|---|---|---|---|
| **SNAKE RIVER ABOVE BROWNLEE** | **SOS 1a**<br>Normal 1990—91 operations; no Water Budget flows | **SOS 2c**<br>Release up to 427 KAF (190 KAF April 16—June 15; 137 KAF Aug.; 100 KAF Sept.) for flow augmentation | **SOS 4c**<br>Same as SOS 1a |
| | **SOS 1b**<br>Same as SOS 1a | **SOS 2d**<br>• Release up to 427 KAF, as in SOS 2c<br>• Release additional water obtained by purchase or other means and shaped per Reclamation releases and Brownlee draft requirements; simulation assumed 927 KAF available | |

| | SOS 1 | SOS 2 | SOS 4 |
|---|---|---|---|
| **BROWNLEE** | **SOS 1a**<br>• Draft as needed (up to 110 KAF in May) for Water Budget, based on target flows of 85 kcfs at Lower Granite<br>• Operate per FERC license<br>• Provide system flood control storage space | **SOS 2c**<br>Same as SOS 1a except for additional flow augmentation as follows:<br>• Draft up to 137 KAF in July, but not drafting below 2,067 feet; refill from the Snake River above Brownlee in August<br>• Draft up to 100 KAF in Sept.<br>• Shift system flood control to Grand Coulee<br>• Provide 9 kcfs or less in November; fill project by end of month<br>• Maintain November monthly average flow December through April | **SOS 4c**<br>Same as SOS 1a except slightly different flood control rule curves |
| | **SOS 1b**<br>• No maximum flow restriction from mid-Oct. to mid-Nov.<br>• No draft limit; no refill target | **SOS 2d**<br>Same as SOS 2c, plus pass additional flow augmentation releases from upstream projects | |

KAF = 1.234 million cubic meters

MAF = 1.234 billion cubic meters

## Table 4–1. SOS Alternative–4

| SOS 5 | SOS 6 | SOS 9 | SOS PA |
|---|---|---|---|
| **SOS 5b** | **SOS 6b** | **SOS 9a** | **SOS PA** |
| Same as SOS 1a | Same as SOS 1a | Provide up to 1.927 MAF through Brownlee for flow augmentation, as determined by Reclamation | Provide 427 KAF through Brownlee for flow augmentation, as determined by Reclamation |
| **SOS 5c** | **SOS 6d** | **SOS 9b** | |
| Same as SOS 1a | Same as SOS 1a | Provide up to 927 KAF through Brownlee as determined by Reclamation | |
| | | **SOS 9c** | |
| | | Provide up to 927 KAF through Brownlee as determined by Reclamation | |

| SOS 5 | SOS 6 | SOS 9 | SOS PA |
|---|---|---|---|
| **SOS 5b** | **SOS 6b** | **SOS 9a** | **SOS PA** |
| Same as SOS 4c | Same as SOS 4c | • Draft up to 110 KAF in May, 137 KAF in July, 140 KAF in Aug., 100 KAF in Sept. for flow augmentation<br>• Shift system flood control to Grand Coulee | Draft to elevation 2,069 feet in May, 2,067 feet in July, and 2,059 feet in Sept., passing inflow after May and July drafts |
| **SOS 5c** | **SOS 6d** | **SOS 9b** | |
| Same as SOS 4c | Same as SOS 4c | • Draft up to 190 KAF April-May, 137 KAF in July, 100 KAF in Sept. for flow augmentation<br>• Shift system flood control to Grand Coulee<br>• Provide an additional 110 KAF in May if elevation is above 2,068 feet and 110 KAF in Sept. if elevation is above 2,043.3 feet | |
| | | **SOS 9c** | |
| | | Same as SOS 9b | |

1 kcfs = 28 cms 1 ft = 0.3048 meter

## Table 4–1. SOS Alternative–5

**Actions by Project**

| | SOS 1 | SOS 2 | SOS 4 |
|---|---|---|---|
| **DWORSHAK** | **SOS 1a**<br>• Draft up to 600 KAF in May to meet Water Budget target flows of 85 kcfs at Lower Granite<br>• Provide system flood control storage space | **SOS 2c**<br>Same as SOS 1a, plus the following supplemental releases:<br>• 900 KAF or more from April 16 to June 15, depending on runoff forecast at Lower Granite<br>• Up to 470 KAF above 1.2 kcfs minimum release from June 16 to Aug. 31<br>• Maintain 1.2 kcfs discharge from Oct. through April, unless higher required<br>• Shift system flood control to Grand Coulee April–July if runoff forecasts at Dworshak are 3.0 MAF or less | **SOS 4c**<br>Elevation targets established for each month: 1,599 feet Sept.-Oct.; flood control rule curves Nov.-April; 1,595 feet May; 1,599 feet June-Aug.; |
| | **SOS 1b**<br>• Meet minimum project flows (2 kcfs, except for 1 kcfs in August); summer draft limits; maximum discharge requirement Oct. to Nov. (1.3 kcfs plus inflow)<br>• No Water Budget releases | **SOS 2d**<br>• Operate on 1.2 kcfs minimum discharge up to flood control rule curve, except when providing flow augmentation (April 10 to July 31)<br>• Provide flow augmentation of 1.0 MAF plus 1.2 kcfs minimum discharge, or 927 KAF and 1.2 kcfs, from April 10-June 20, based on runoff forecasts, to meet Lower Granite flow target of 85 kcfs<br>• Provide 470 KAF from June 21 to July 31 to meet Lower Granite flow target of 50 kcfs<br>• Draft to 1,520 feet after volume is expended, if Lower Granite flow target is not met; if volume is not expended, draft below 1,520 feet until volume is expended | |

KAF = 1.234 million cubic meters

MAF = 1.234 billion cubic meters

## Table 4–1. SOS Alternative–5

| SOS 5 | SOS 6 | SOS 9 | SOS PA |
|---|---|---|---|
| **SOS 5b**<br>• Operate to local flood control rule curve<br>• No proportional draft for power<br>• Shift system flood control to lower Snake projects<br>• Provide Water Budget flow augmentation as in SOS 1a<br>• Draft to refill lower Snake projects if natural inflow is inadequate | **SOS 6b**<br>Same as SOS 5b | **SOS 9a**<br>• Remove from proportional draft for power<br>• Operate to local flood control rule curves, with system flood control shifted to Grand Coulee<br>• Maintain flow at 1.2 kcfs minimum discharge, except for flood control or flow augmentation discharges<br>• Operate to meet Lower Granite flow targets (at spillway crest) of 74 kcfs April 16-June 30, 45 kcfs July, 32 kcfs August | **SOS PA**<br>• Operate on minimum flow-up to flood control rule curve year-round, except during flow augmentation period<br>• Draft to meet flow targets, down to min. end-of-Aug. elevation of 1,520 feet<br>• Sliding-scale Snake River flow targets at Lower Granite of 85 to 100 kcfs April 10-June 20 and 50 to 55 kcfs June 21-Aug. 31, based on runoff forecasts |
| **SOS 5c**<br>• Operate to flood control during spring<br>• Refill in June or July and maintain through August<br>• Draft for power production during fall | **SOS 6d**<br>Same as SOS 5b | **SOS 9b**<br>• Similar to SOS 9a, except operate to meet flow targets at Lower Granite ranging from 85 to 140 kcfs April 16-June 30 and 50-55 kcfs in July<br>• Can draft to meet flow targets to a min. end-of-July elevation of 1,490 feet | |
| | | **SOS 9c**<br>• Similar to SOS 9a, except operate to meet Lower Granite flow target (at spillway crest) of 63 kcfs April-June<br>• Can draft to meet flow targets to a min. end-of-July elevation of 1,520 feet | |

1 kcfs = 28 cms　　1 ft = 0.3048 meter

## Table 4–1. SOS Alternative–6

### Actions by Project

| | SOS 1 | SOS 2 | SOS 4 |
|---|---|---|---|
| **LOWER SNAKE** | **SOS 1a**<br>• Normal operations at 4 lower Snake River projects (within 3 to 5 feet of full pool, daily and weekly fluctuations)<br>• Provide maximum peaking capacity of 20 kcfs over daily average flow in May | **SOS 2c**<br>• Operate reservoirs within 1 foot above MOP from April 16 to July 31<br>• Same as SOS 1a for rest of year | **SOS 4c**<br>Same as SOS 2c |
| | **SOS 1b**<br>Same as 1a, except:<br>• No minimum flow limit (11,500 cfs) during fall and winter<br>• No fish-related rate of change in flows in May | **SOS 2d**<br>Same as SOS 2c | |

| | SOS 1 | SOS 2 | SOS 4 |
|---|---|---|---|
| **LOWER COLUMBIA** | **SOS 1a**<br>• Normal operations at 4 lower Columbia projects (generally within 3 to 5 feet of full pool, daily and weekly fluctuations)<br>• Restricted operation of Bonneville second powerhouse | **SOS 2c**<br>Same as SOS 1a except: lower John Day to minimum irrigation pool (approx. 262.5 feet) from April 15 to Aug. 31; operate within 1.5 feet of forebay range, unless need to raise to avoid irrigation impacts | **SOS 4c**<br>Same as SOS 2c, except operate John Day within 2 feet of elevation 263.5 feet Nov. 1 through June 30 |
| | **SOS 1b**<br>Same as 1a, except no restrictions on Bonneville second powerhouse | **SOS 2d**<br>Same as SOS 2c | |

KAF = 1.234 million cubic meters

MAF = 1.234 billion cubic meters

## Table 4–1. SOS Alternative–6

| SOS 5 | SOS 6 | SOS 9 | SOS PA |
|---|---|---|---|
| **SOS 5b**<br>• Draft 2 feet per day starting Feb. 18<br>• Operate at natural river level, approx. 95 to 115 ft below full pool, April 16-Aug. 31; drawdown levels by project as follows, in feet:<br>Lower Granite 623<br>Little Goose 524<br>L. Monumental 432<br>Ice Harbor 343<br>• Operate within 3 to 5 ft of full pool rest of year<br>• Refill from natural flows and storage releases | **SOS 6b**<br>• Draft 2 feet per day starting April 1<br>• Operate 33 feet below full pool April 16-Aug. 31; drawdown levels by project as follows, in feet:<br>Lower Granite 705<br>Little Goose 605<br>L. Monumental 507<br>Ice Harbor 407<br>• Operate over 5-foot forebay range once drawdown elevation reached<br>• Refill from natural flows and storage releases<br>• Same as SOS 1a rest of year | **SOS 9a**<br>• Operate 33 feet below full pool (see SOS 6b) April 1-Aug. 31 to meet L. Granite flow targets (see Dworshak); same as SOS 1a rest of year<br>• Spill to achieve 80/80 FPE up to total dissolved gas cap of 120% daily average; spill cap 60 kcfs at all projects | **SOS PA**<br>• Operate at MOP with 1 foot flexibility between April 10 - Aug. 31<br>• Refill three lower Snake River pools after Aug. 31, Lower Granite after Nov. 15<br>• Spill to achieve 80% FPE up to total dissolved gas cap of 115% 12-hour average; spill caps range from 7.5 kcfs at L. Monumental to 25 kcfs at Ice Harbor |
| **SOS 5c**<br>Same as SOS 5b, except drawdowns are permanent once natural river levels reached; no refill | **SOS 6d**<br>• Draft Lower Granite 2 feet per day starting April 1<br>• Operate Lower Granite near 705 ft for 4 1/2 months, April 16-Aug. 31 | **SOS 9b**<br>• Operate at MOP, with 1 foot flexibility April 1-Aug. 31; same as SOS 1a rest of year<br>• Spill to achieve 80/80 FPE up to total dissolved gas cap of 120% daily average; spill caps range from 18 kcfs at L. Monumental to 30 kcfs at L. Granite | |
| | | **SOS 9c**<br>• Operate 35 to 45 feet below full pool April 1-June 15 to meet L. Granite flow targets (see Dworshak), refill by June 30; same as SOS 1a rest of year<br>• Spill to achieve 80/80 FPE, as in SOS 9b | |

| SOS 5 | SOS 6 | SOS 9 | SOS PA |
|---|---|---|---|
| **SOS 5b**<br>Same as SOS 2, except operate John Day within 1.5 feet above elevation 257 feet (MOP) from May 1 through Aug. 31; same as SOS 2c rest of year | **SOS 6b**<br>Same as SOS 5 | **SOS 9a**<br>• Same as SOS 5, except operate John Day within 1 foot above elevation 257 feet April 15-Aug. 31<br>• McNary flow targets as described for Grand Coulee<br>• Spill to achieve 80/80 FPE, up to total dissolved gas cap of 120% daily average, as derived by agencies | **SOS PA**<br>• Pool operations same as SOS 2c, except operate John Day at 257 feet (MOP) year-round, with 3 feet of flexibility March-Oct. and 5 feet of flexibility Nov.-Feb.<br>• Spill to achieve 80% FPE up to total dissolved gas cap of 115% 12-hour average; spill caps range from 9 kcfs at John Day to 90 kcfs at The Dalles |
| **SOS 5c**<br>Same as SOS 5b | **SOS 6d**<br>Same as SOS 5 | **SOS 9b**<br>• Same as SOS 2, except operate John Day at minimum irrigation pool or 262.5 feet with 1 foot of flexibility from April 16-Aug. 31<br>• McNary flow targets as described for Grand Coulee<br>• Spill to achieve 80/80 FPE, up to total dissolved gas cap of 120% daily average, as derived by Corps | |
| | | **SOS 9c**<br>Same as SOS 9b, except operate John Day at minimum operating pool | |

1 kcfs = 28 cms

1 ft = 0.3048 meter

### 4.1.1 SOS 1-Pre–ESA Operation

This alternative represents one end of the range of the SOR strategies in terms of their similarity to historical system operations. This strategy reflects Columbia River system operations before changes were made as a result of the ESA listing of three Snake River salmon stocks. This SOS has two options:

- **SOS 1a (Pre–Salmon Summit Operation)** represents operations as they existed from 1983 through the 1990–91 operating year, including Northwest Power Act provisions to restore and protect fish populations in the basin. Specific volumes for the Water Budget would be provided from Dworshak and Brownlee reservoirs to attempt to meet a target flow of 85 kcfs (2,380 cms) at Lower Granite Dam in May. Sufficient flows would be provided on the Columbia River to meet a target flow of 134 kcfs (3,752 cms) at Priest Rapids Dam in May. Lower Snake River projects would operate within 3 to 5 feet (0.9 to 1.5 m) of full pool. Other projects would operate as they did in 1990–91, with no additional water provided from the Snake River above Brownlee Dam.

- **SOS 1b (Optimum Load–Following Operation)** represents operations as they existed prior to changes resulting from the Northwest Power Act. It is designed to demonstrate how much power could be produced if most flow–related operations to benefit anadromous fish were eliminated including: the Water Budget; fish spill requirements; restrictions on operation of Bonneville's second powerhouse; and refill targets for Libby, Hungry Horse, Grand Coulee, Dworshak, and Albeni Falls. It assumes that transportation would be used to the maximum to aid juvenile fish migration.

### 4.1.2 SOS 2-Current Operations

This alternative reflects operation of the Columbia River system with interim flow improvement measures made in response to ESA listings of Snake River salmon. It is very similar to the way the system operated in 1992 and reflects the results of ESA Section 7 consultation with NMFS then. The strategy is consistent with the 1992–93 operations described in the Corps' *1993 Interim Columbia and Snake Rivers Flow Improvement Measures Supplemental EIS* (SEIS). SOS 2 also most closely represents the recommendations issued by the NMFS Snake River Salmon Recovery Team in May 1994. Compared to SOS 1, the primary changes are additional flow augmentation in the Columbia and Snake Rivers and modified pool levels at lower Snake and John Day reservoirs during juvenile salmon migration. This strategy has two options:

- **SOS 2c (Final SEIS Operation- No Action Alternative)** matches exactly the decision made as a result of the 1993 SEIS. Flow augmentation water of up to 3.0 MAF (3.7 billion $m^3$) on the Columbia River (in addition to the existing Water Budget) would be stored during the winter and released in the spring in low–runoff years. Dworshak would provide at least an additional 300 KAF (370 million $m^3$) in the spring and 470 KAF (580 million $m^3$) in the summer for flow augmentation. System flood control shifts from Dworshak and Brownlee to Grand Coulee would occur through April as needed. It also provides up to 427 KAF (527 million $m^3$) of additional water from the Snake River above Brownlee Dam.

- **SOS 2d (1994–98 Biological Opinion)** matches the hydro operations contained in the 1994–98 Biological Opinion issued by NMFS in mid–1994. This alternative provides water for the existing Water Budget as well as additional water, up to 4 MAF, for flow augmentation to benefit the anadromous fish migration. The additional water of up to 4 MAF would be stored in Grand Coulee, Libby and Arrow, and provided on a sliding scale tied to runoff forecasts. Flow targets are established at Lower Granite and McNary.

In cases such as the SOR, where the proposed action is a new management plan, the No Action Alternative means continuing with the present course of action until that action is changed (46 FR 13027). Among all of the strategies and options, SOS 2c best meets this definition for the No Action Alternative.

### 4.1.3 SOS 4-Stable Storage Project Operation

This alternative is intended to operate the storage reservoirs to benefit recreation, resident fish, wildlife, and anadromous fish while minimizing impacts of such operation to power and flood control. Reservoirs would be kept full longer, but still provide spring flows for fish and space for flood control. The goal is to minimize reservoir fluctuations while moving closer to natural flow conditions. For the Final EIS, this alternative has one option:

- **SOS 4c (Stable Storage Operation with Modified Grand Coulee Flood Control)** applies year–round Integrated Rule Curves (IRCs) developed by the State of Montana for Libby and Hungry Horse. Other reservoirs would be managed to specific elevations on a monthly basis; they would be kept full longer, while still providing spring flows for fish and space for flood control. The goal is to minimize reservoir fluctuations while moving closer to natural flow conditions. Grand Coulee would meet elevation targets year–round to provide acceptable water retention times; however, upper rule curves would apply at Grand Coulee if the January to July runoff forecast at the project is greater than 68 MAF (84 billion $m^3$).

### 4.1.4 SOS 5-Natural River Operation

This alternative is designed to aid juvenile salmon migration by drawing down reservoirs (to increase the velocity of water) at four lower Snake River projects. SOS 5 reflects operations after the installation of new outlets in the lower Snake River dams, permitting the lowering of reservoirs approximately 100 feet (30 m) to near original riverbed levels. This operation could not be implemented for a number of years, because it requires major structural modifications to the dams. Elevations would be: Lower Granite – 623 feet (190 m); Little Goose – 524 feet (160 m); Lower Monumental – 432 feet (132 m); and Ice Harbor – 343 feet (105 m). Drafting would be at the rate of 2 feet (0.6 m) per day beginning February 18. The reservoirs would refill again with natural inflows and storage releases from upriver projects, if needed. John Day would be lowered as much as 11 feet (3.3 m) to minimum pool, elevation 257 feet (78.3 m), from May through August. All other projects would operate essentially the same as in SOS 1a, except that up to 3 MAF (3.7 billion $m^3$) of water (in addition to the Water Budget) would be provided to augment flows on the Columbia River in May and June. System flood control would shift from Brownlee and Dworshak to the lower Snake River projects. Also, Dworshak would operate for local flood control. This alternative has two options:

- **SOS 5b (Four and One–half Month Natural River Operation)** provides for a lower Snake River drawdown lasting 4.5 months, beginning April 16 and ending August 31. Dworshak would be drafted to refill the lower Snake River projects if natural inflow were inadequate for timely refill.
- **SOS 5c (Permanent Natural River Operation)** provides for a year–round drawdown, and projects would not be refilled after each migration season.

### 4.1.5 SOS 6-Fixed Drawdown

This alternative is designed to aid juvenile anadromous fish by drawing down one or all four lower Snake River projects to fixed elevations approximately 30 to 35 feet (9 to 10 m) below minimum operating pool. As with SOS 5, fixed drawdowns depend on prior structural modifications and could not be instituted for a number of years. Draft would be at the rate of 2 feet (0.6 m) per day beginning April 1. John Day would be lowered to elevation 257 feet (78.3 m) from May through August. All other projects would operate essentially the same as under SOS 1a, except that up to 3 MAF (3.7 billion $m^3$) of water would be provided to augment flows on the Columbia River in May and June. System flood control would shift from Brownlee and Dworshak to the lower Snake projects. Also, Dworshak would operate for local flood control. This alternative has two options:

- **SOS 6b (Four and One–half Month Fixed Drawdown)** provides for a 4.5–month drawdown at all four lower Snake River projects beginning April 16 and ending August 31. Elevations would be: Lower Granite – 705 feet (215 m); Little Goose – 605 feet (184 m); Lower Monumental – 507 feet (155 m); and Ice Harbor – 407 feet (124 m).
- **SOS 6d (Four and One–half Month Lower Granite Fixed Drawdown)** provides for a 4.5–month drawdown to elevation 705 feet at Lower Granite beginning April 16 and ending August 31.

### 4.1.6 SOS 9-Settlement Discussion Alternatives

This SOS represents operations suggested by USFWS and NMFS (as SOR cooperating agencies), the State fisheries agencies, Native American tribes, and the Federal operating agencies during the settlement discussions in response to a court ruling in the *IDFG v. NMFS* lawsuit. The objective of SOS 9 is to provide increased velocities for anadromous fish by establishing flow targets during the migration period and by carrying out other actions that benefit ESA–listed species. The specific options were developed by a group of technical staff representing the parties in the lawsuit. The group was known as the Reasonable and Prudent Alternatives Workgroup. They developed three possible operations in addition to the 1994–98 Biological Opinion. This strategy has three options:

- **SOS 9a (Detailed Fishery Operating Plan [DFOP])** establishes flow targets at The Dalles based on the previous year's end–of–year storage content, similar to how PNCA selects operating rule curves. Grand Coulee and other storage projects are used to meet The Dalles flow targets. Specific volumes of releases are made from Dworshak, Brownlee, and upper Snake River to try to meet Lower Granite flow targets. Lower Snake River projects are drawn down to near spillway crest level for 4 1/2 months. Specific spill percentages are established at run–of–river projects to achieve no higher than 120 percent daily average total dissolved gas. Fish transportation is assumed to be eliminated.
- **SOS 9b (Adaptive Management)** establishes flow targets at McNary and Lower Granite based on runoff forecasts. Grand Coulee and other storage projects are used to meet the McNary flow targets. Specific volumes of releases are made from Dworshak, Brownlee, and the upper Snake River to try to meet Lower Granite flow targets. Lower Snake River projects are drawn down to minimum operating pool levels and John Day is at minimum irrigation pool level. Specific spill percentages are established at run–of–river projects to achieve no higher than 120 percent daily average for total dissolved gas.
- **SOS 9c (Balanced Impacts Operation)** draws down the four lower Snake River projects to near spillway crest levels for 2 1/2 months during the spring salmon migration period. Full drawdown level is achieved on April 1. Refill begins after June 15. This alternative also provides 1994–98 Biological Opinion flow augmentation (as in SOS 2d), IRC operation at Libby and Hungry Horse, a reduced flow target at Lower Granite due to drawdown, limits on winter drafting at Albeni Falls, and spill to achieve no higher than 120 percent daily average for total dissolved gas.

### 4.1.7 SOS PA-Preferred Alternative

This SOS represents the operation recommended by NMFS and USFWS in their respective Biological Opinions issued on March 1, 1995. SOS PA is intended to support recovery of ESA–listed species by storing water during the fall and winter to meet spring and summer flow targets, and to protect other resources by managing detrimental effects through maximum summer draft limits, by providing public safety through flood protection, and by providing for reasonable power generation. This SOS would operate the system during the fall and winter to achieve a high confidence of refill to flood control elevations by April 15 of each year, and use this stored water for fish flow augmentation. It establishes spring flow targets at McNary and Lower Granite based on runoff forecasts, and a similar sliding scale flow target at Lower Granite and a fixed flow target at McNary for the summer. It establishes summer draft limits at Hungry Horse, Libby, Grand Coulee, and Dworshak. Libby is also operated to provide flows for Kootenai River white sturgeon. Lower Snake River projects are drawn down to minimum operating pool levels during the spring and summer. John Day is operated at minimum operating pool level year–round. Specific spill percentages are established at run–of–river projects to achieve 80–percent FPE, with no higher than 115–percent 12–hour daily average for total dissolved gas measured at the forebay of the next downstream project.

### 4.1.8 Rationale for Selection of the Final SOSs

Table 4–2 summarizes the changes to the set alternatives from the Draft EIS to the Final EIS. SOS 1a and 1b are unchanged from the Draft EIS. SOS 1a represents a base case condition and reflects system operation during the period from passage of the Northwest Power Planning and Conservation Act until ESA listings. It provides a baseline alternative that allows for comparison of the more recent alternatives and shows the recent historical operation. SOS 1b represents a limit for system operation directed at maximizing benefits from development–oriented uses, such as power generation, flood control, irrigation and navigation and away from natural resources protection. It serves as one end of the range of alternatives and provides a basis for comparison of the impacts to power generation from all other alternatives. Public comment did not recommend elimination of this alternative because it serves as a useful milepost. However, the SOR agencies recognize it is unlikely that decisions would be made to move operations toward this alternative.

In the Draft EIS, SOS 2 represented current operation. Three options were considered. Two of these options have been eliminated for the Final EIS and one new option has been added. SOS 2c continues as the No Action Alternative. Maintaining this option as the No Action Alternative allows for consistent comparisons in the Final EIS to those made in the Draft EIS. However, within the current practice category, new operations have been developed since the original identification of SOS 2c. In 1994, the SOR agencies, in consultation with the NMFS and USFWS, agreed to an operation, which was reflected in the 1994–98 Biological Opinion. This operation (SOS 2d) has been modeled for the Final EIS and represents the most "current" practice. SOS 2d also provides a good baseline comparison for the other, more unique alternatives. SOS 2a and 2b from the Draft EIS were eliminated because they are so similar to SOS 2c. SOS 2a is identical to SOS 2c except for the lack of an assumed additional 427 KAF of water from the upper Snake River Basin. This additional water did not cause significant changes to the effects between SOS 2a and 2c. There is no reason to continue to consider an alternative that has impacts essentially equal to another alternative. SOS 2b is also similar to SOS 2c, except it modified operation at Libby for Kootenai River white sturgeon. Such modifications are included in several other alternatives, namely SOS 2d, 9a, 9c, and the Preferred Alternative.

SOS 3a and 3b, included in the Draft EIS, have been dropped from consideration in the Final EIS. Both of these alternatives involved anadromous fish flow augmentation by establishing flow targets based on runoff forecast on the Columbia and Snake Rivers. SOS 3b included additional water from the upper Snake River Basin over what was assumed for SOS 3a. This operation is now incorporated in several new alternatives, including SOS 9a and 9b. Public comment also did not support continued consideration of the SOS 3 alternatives.

## Table 4–2. Summary of Alternatives in the Draft and Final EIS

| Draft EIS Alternatives | | Final EIS Alternatives | |
|---|---|---|---|
| SOS 1 | Pre–ESA Operation | SOS 1 | Pre–ESA Operation |
| SOS 1a | Pre–Salmon Summit Operation | SOS 1a | Pre–Salmon Summit Operation |
| SOS 1b | Optimum Load Following Operation | SOS 1b | Optimum Load Following Operation |
| SOS 2 | Current Practice | SOS 2 | Current Practice |
| SOS 2a | Final Supplemental EIS Operation | SOS2c | Final Supplemental EIS Operation – No–Action Alternative |
| SOS 2b | Final Supplemental EIS with Sturgeon Operations at Libby | **SOS 2d** | **1994–98 Biological Opinion Operation** |
| SOS2c | Final Supplemental EIS Operation – No–Action Alternative | | |
| SOS 3 | Flow Augmentation | | |
| SOS 3a | Monthly Flow Targets | | |
| SOS 3b | Monthly Flow Targets with additional Snake River Water | | |
| SOS 4 | Stable Storage Project Operation | SOS 4 | Stable Storage Project Operation |
| SOS 4a1 | Enhanced Storage Level Operation | **SOS 4c** | **Enhanced Operation with modified Grand Coulee Flood Control** |
| SOS 4a3 | Enhanced Storage Level Operation | | |
| SOS 4b1 | Compromise Storage Level Operation | | |
| SOS 4b3 | Compromise Storage Level Operation | | |
| SOS 4c | Enhanced Operation with modified Grand Coulee Flood Control | | |
| SOS 5 | Natural River Operation | SOS 5 | Natural River Operation |
| SOS 5a | Two Month Natural River Operation | SOS 5b | Four and One Half Month Natural River Operation |
| SOS 5b | Four and One Half Month Natural River Operation | **SOS 5c** | **Permanent Natural River Operation** |
| SOS 6 | Fixed Drawdown | SOS 6 | Fixed Drawdown |
| SOS 6a | Two Month Fixed Drawdown Operation | SOS 6b | Four and One Half Month Fixed Drawdown Operation |
| SOS 6b | Four and One Half Month Fixed Drawdown Operation | SOS 6d | Four and One Half Month Lower Granite Drawdown Operation |
| SOS 6c | Two Month Lower Granite Drawdown Operation | | |
| SOS 6d | Four and One Half Month Lower Granite Drawdown Operation | | |
| SOS 7 | Federal Resource Agency Operations | **SOS 9** | **Settlement Discussion Alternatives** |
| SOS 7a | Coordination Act Report Operation | **SOS 9a** | **Detailed Fishery Operating Plan** |
| SOS 7b | Incidental Take Statement Flow Targets | **SOS 9b** | **Adaptive Management** |
| SOS 7c | NMFS Conservation Recommendations | **SOS 9c** | **Balance Impacts Operation** |
| | | **SOS Preferred Alternative** | |

Bold indicates a new or revised SOS alternative

SOS 4 originally included 5 options in the Draft EIS. They were similar in operation and impact. In SOS 4a and 4b, the primary feature was the use of Biological Rule Curves for Libby and Hungry Horse reservoirs. SOS 4c also included these rule curves but went further by optimizing the operation of the other storage projects, particularly Grand Coulee and Dworshak. For the Final EIS, the SOR agencies have decided to update the alternative by substituting the IRC for the Biological Rule Curves and by eliminating SOS 4a and 4b. The IRCs are a more recent, acceptable version of minimum elevations for Libby and Hungry Horse. Significant public comment in support of this alternative with IRCs was received. Similar to SOS 2 above, SOS 4a and 4b were not different enough in operation or impacts to warrant continued consideration.

The Natural River (SOS 5) and the Spillway Crest Drawdown (SOS 6) alternatives in the Draft EIS originally included options for 2 months of drawdown to the appropriate pool level and 4 1/2 months of drawdown. The practicality of 2–month drawdowns was questioned during public review, particularly for the natural river. It did not appear that the time involved in drawing down the reservoirs and later refilling them provided the needed consideration for other uses. Flows are restricted to refill the reservoirs at a time when juvenile fall chinook are migrating downstream and various adult species are returning upstream. The 2 1/2 month drawdown strategies (SOS 5a, 6a, and 6c) have been dropped from the Final EIS. However, 2 1/2 month spillway crest drawdown at all four lower Snake projects is still an element in SOS 9c, so the impacts associated with this type of operation are assessed in the Final EIS.

A new option was added to SOS 5, namely SOS 5c. This option includes natural river drawdown of the lower Snake River projects on a permanent, year–round basis. The Corps received comment on this type of alternative during the review of Phase I of the SCS, a reconnaissance assessment of potential physical modifications for the system to enhance fish passage. Many believe the cost for such modification would be less than that required for periodic, temporary drawdowns, which would require specialized facilities to enable the projects to refill and operate at two different pool elevations.

SOS 7 Federal Resource Agencies Operations, which included 3 options in the Draft EIS, has been dropped from the Final EIS and replaced with an alternative now labeled as SOS 9 that also has 3 options. SOS 7a was suggested by the USFWS and represented the State fishery agencies and tribes' recommended operation. Since the issuance of the Draft EIS, this particular operation has been revised and replaced by the DFOP (SOS 9a). The SOR agencies received comment that the DFOP was not evaluated, but should be. Therefore, we have included this alternative exactly as proposed by these agencies; it is SOS 9a. SOS 7b and 7c were suggested by NMFS through the 1993 Biological Opinion. This opinion suggested two sets of flow targets as a way of increasing flow augmentation levels for anadromous fish. The flow targets came from the Incidental Take Statement and the Conservation Recommendation sections of that Biological Opinion. The opinion was judged as arbitrary and capricious as a result of legal action, and these operational alternatives have been replaced with other alternatives that were developed through settlement discussions among the parties to this lawsuit. SOS 7b and 7c have been dropped, but SOS 9b and 9c have been added to represent operations stemming from NMFS or other fishery agencies. In particular, SOS 9b is like DFOP but has reduced flow levels and forgoes drawdowns. It is a modification to DFOP. SOS 9c incorporates elements of operation supported by the State of Idaho in its "Idaho Plan." It includes a 2 1/2–month spillway crest drawdown on the lower Snake River projects and several other elements that attempt to strike a balance among the needs of anadromous fish, resident fish, wildlife and recreation.

Shortly after the alternatives for the Draft EIS were identified, the Nez Perce Tribe suggested an operation that involved drawdown of Lower Granite, significant additional amounts of upper Snake River water, and full pool operation at Dworshak (i.e., Dworshak remains full year round). It was labeled as SOS 8a. Hydroregulation of that operation was completed and provided to the Nez Perce Tribe. No technical response has been received from the Nez

Perce Tribe regarding the features or results of this alternative. However, the elements of this operation are generally incorporated in one or more of the other alternatives, or impose requirements on the system or specific projects that are outside the range considered reasonable. Therefore, this alternative has not been carried forward into the Final EIS.

The Preferred Alternative represents operating requirements contained in the 1995 Biological Opinions issued by NMFS and USFWS on operation of the FCRPS. These opinions resulted from ESA consultation conducted during late 1994 and early 1995, which were a direct consequence of the lawsuit and subsequent judgement in *Idaho v. NMFS*. The SOR agencies are now implementing this operating strategy and have concluded that it represents an appropriate balance among the multiple uses of the river. This strategy recognizes the importance of anadromous fish and the need to adjust river flows to benefit the migration of all salmon stocks, as well as the needs of resident fish and wildlife species at storage projects.

## 4.2 SOS 1: PRE–ESA OPERATION

Many observers view SOSs 1a or 1b as a "normal" system operation that provides a frame of reference for more recent or potential future operating changes. SOS 1a represents operations that occurred from around 1983 to 1991, while SOS 1b represents the pre–1983 operation that maximizes power production within normal reservoir operations. Both options correspond to actual conditions that the reservoir environment has experienced over several years, and can be considered to reflect a "control" level of operations effects. As historical options, they have produced some level of adjustment with the reservoir shoreline. The operation of reservoirs under SOS 1a or 1b would cause continued erosion, mass wasting, sedimentation, and groundwater fluctuations that would be within normal and historical limits.

### 4.2.1 Shoreline Erosion and Mass Wasting

Bank erosion can have severe consequences on the designed reservoir purposes, including water supply, irrigation, flood control, navigation, hydropower generation, recreation, and wildlife habitat (Hagan and Roberts, 1972; Hodgins et al., 1977 (in Gatto and Doe)). Loss of land along the shoreline is the most evident impact. Structures along the shoreline can be damaged too, as has been documented on reservoirs across the country (Allen and Wade, 1991). The loss of wildlife habitat can be offset by creation of new habitat, such as bank swallow habitat (Beckett, 1978). This occurs through loss of vegetation as well as loss of land.

Erosion–caused sediment is often deposited in the immediate vicinity of the shoreline. This may have several impacts, including increased turbidity and dissolved solids, which in turn affect the amount of light reaching benthic and planktonic animals and plants (Geen, 1974; Barko, 1981). Fish may suffer due to siltation of spawning gravels, disruption of normal reproduction, gill abrasion, and decreasing feeding ability due to decreased visibility. Increased turbidity can lead to decreased aesthetic value of a reservoir, through the suspended sediment itself or by the increased nutrients in the water, which can lead to increased algae. Coarse sediments can harm or kill shallow benthic animals and plants by changing the benthic habitat (Avakyn, 1975; Cooper and Bacon, 1980).

Bank erosion can change the effective storage capacity of a reservoir. Total pool storage is decreased by sediment influx from the banks (Van Everdingen, 1967). Furthermore, the increase in surface area from bank recession increases the loss to evaporation, which can change water quality (Baxter and Glaude, 1980).

Under historical pool fluctuations and outflows, the historical patterns of erosion and mass wasting would likely continue. Some areas would experience diminished effects with time, while others would see persistent stability problems. Unexpected increases in erosion might occur in response to external events (e.g., extreme precipitation) or to exceedance of intrinsic thresholds operating in the drainage basin or reservoir environment (e.g., tributary channel shifting and incision due to elongation of its delta), but these are difficult to predict.

The lowest existing rates of shoreline erosion are probably on the run–of–river operations on the lower and middle Columbia and the lower Snake. Pool level fluctuations have been minimal and a zone of beach has been able to develop in many places. Minor landslides could be expected to continue, as on Lake Umatilla (Gustafson, 1992). Elevation patterns for these reservoirs would be identical in SOS 1a or 1b for average, wet, and dry years.

Storage projects would continue to experience significant shoreline erosion. Chief among these would be Grand Coulee. Grand Coulee would have an annual draft of about 60 feet (18.3 m) under both options, and the hydroregulation model shows almost identical monthly elevations under both options. Peaking operations would continue to undermine steep banks and expose a wide zone of the shoreline to wave erosion.

There are at least 82 active slides around Lake Roosevelt (Reclamation, 1992); "active" is defined as having moved in the past 10 years. In addition, there are numerous less–active slides. Between 1941 and 1954, approximately 500 landslides occurred along Lake Roosevelt (Jones et al., 1961). The authors demonstrated a clear relation between $P_R$ and landslides, noting that as $P_R$ increased, so did the number of landslides. Since there are large sections of shoreline showing no signs of reaching equilibrium profiles, recent levels of landslide activity could be expected to continue for decades under SOS 1.

The effects of landslides along Lake Roosevelt have generally been limited to loss of land. Reclamation has undertaken a program of acquiring or leasing lands that are subject to mass wasting. This has resulted in substantial costs for the maintenance program.

Another effect of the high landslide activity has been that the reservoir is filling with sediment more rapidly than expected. While the total volume of landslide material has not been estimated, significant infilling of the reservoir has occurred in some areas, such as Reed Terrace. The shoreline stabilization efforts instituted in the past might diminish the rate of future sedimentation.

Although few studies of the shorelines of Hungry Horse and Libby exist, these reservoirs also experience significant shoreline erosion, due to their large fluctuation in pool elevations and the composition of their shoreline materials. Much of the shoreline at Hungry Horse is in glacial till and alluvium, and significant evidence of erosion can be observed around the reservoir. Draft and refill patterns at Hungry Horse would be identical under SOS 1a and 1b, during the average water year.

Relative to Grand Coulee, however, erosion at Hungry Horse is minor. The total volume of landslides appears to be much less and, considering the large storage capacity of Hungry Horse, the effect on the lifespan of the project is negligible. Furthermore, the reservoir is located in a national forest, so acquisition of private lands has not been necessary.

Under historical operations, minor erosion and mass wasting would continue, with slight shoreline retreat in areas experiencing significant mass wasting. The only significant impact would be increased, localized turbidity during major storms and landslides, which could affect shoreline fish habitat.

Lake Koocanusa has experienced significant shoreline retreat and erosion during its lifespan. In the upstream reaches, in particular near the town of Rexford, aerial photo analysis shows erosion of as much as 10 feet (3 m) per year between 1972 and 1988. Some agricultural land has been lost. The volume of landslide material is unknown; however, its effect on siltation at the reservoir is probably negligible, given the high volume of sediment influx in the Kootenai River.

The shoreline along Lake Koocanusa is very susceptible to the freeze–thaw process due to its relatively high elevation (nearly 2,500 feet [762 m]). Erosion and mass wasting would continue at moderate rates under SOS 1a or 1b.

End–of–the–month elevations at Albeni Falls would be the same for both SOS 1a and 1b. Continued shoreline erosion and bank recession would occur under these options. The reservoir has experienced as much as 5 feet (1.5 m) of shoreline retreat during a 12–year period (Gatto and Doe, 1983). This is due to wave action and partly to freeze–thaw processes due to the relatively high elevation (about 2,000 feet [610 m]) and cool climate of the area. The resultant shoreline erosion has caused a number of lawsuits due to private land lost. Additional acquisition of land by the government may be necessary.

Future operation under SOS 1a or 1b would continue the historical pattern of erosion and mass wasting. Some shoreline retreat, attributable to wave erosion, would continue at Lake Pend Oreille. Based on the erosion rate reported in the one applicable prior study, the average rate of shoreline retreat would likely be about 0.4 feet (0.12 m) per year. Localized conditions such as bedrock ledges could limit or prevent further shoreline retreat in some areas. Comparable information on erosion rates is not available for the other storage reservoirs. Most of the erosion in these reservoirs occurs in the drawdown zone below the full–pool elevation and is not readily evident or easily studied. Mass wasting, which is more evident, would likely continue at the same or slightly decreasing rate.

Dworshak would experience identical pool level changes under both SOS 1a and 1b during average and wet years. During dry years the only difference would be in August, when the pool elevation would be about 1,560 feet (475.5 m) with SOS 1b and 1,420 feet (432.8 m) with SOS 1a. Drafting would occur more rapidly during dry years at the end of August under option 1b, indicating greater potential for slope failure along the reservoir shores. Because this would occur only during dry years, the overall increase in shoreline erosion would be relatively small.

The initial period of operations at Dworshak resulted in documented slides along about 13 miles (8 km) of shoreline (Gatto and Doe, 1983), which is about 10 percent of the total shoreline length. The authors believed that daily fluctuations in pool level of up to 5 feet (1.5 meters) during drafting and refilling periods contributed significantly to landslides. Similar patterns of mass wasting would continue under SOS 1a or SOS 1b.

The total volume of landslides around Dworshak Reservoir is small relative to Grand Coulee. The amount of decrease in reservoir lifespan is probably negligible. Thus, the only tangible effects of shoreline erosion would be localized increases in turbidity during storms and landslides.

Brownlee experiences significantly less draft than other reservoirs. The annual draft would remain the same under SOS 1a or 1b. Brownlee has experienced significant mass wasting and erosion (BPA, 1985) under historical operations. This would continue at the same rate or a somewhat decreased rate. The overall impact would generally not be significant. One exception is the potential for a landslide blocking the Powder River (BPA, 1985). This would create a lake upstream, inundating the floodplain.

Available information indicates that the run–of–river projects have generally experienced only minor amounts of shoreline erosion and mass wasting. This is primarily the result of relatively stable pool levels, and because riprap shoreline armoring has been placed in many locations that would otherwise be subject to erosion or mass wasting. Among the run–of–river projects, several low–angle slides have been documented at John Day (Gustafson, 1992), but shoreline erosion does not appear to be significant. Current erosion and mass wasting patterns, such as the minor landslides at John Day, would continue at the run–of–river projects under SOS 1a or 1b.

### 4.2.2 Sedimentation

Reservoir sedimentation, being predominantly controlled by catchment processes, would be affected slightly by this alternative. Present reservoir sedimentation rates would continue and reflect the magnitude of erosion and transport occurring in the catchment. Wave erosion would continue to be the dominant contributor to sediment redistribution in the reservoirs. However, because option 1b would increase the drafting rate at Dworshak during some years, a slight increase in turbidity would occur, adding slightly more sediment downstream at Lower Granite.

Under SOS 1a or 1b, long–term adjustment to reservoir and shoreline processes would continue and slowly decrease in magnitude as shorelines approach equilibrium profiles. This process varies greatly. At a minimum, with static shorelines, it would take 5 to 10 years (Kondratjev, 1966). With fluctuating shorelines, even if the annual fluctuation is only a few feet, adjustment would take much longer. It is difficult to quantify this length of time without detailed, site–specific surveys of shoreline materials, wind, and boat activity at each reservoir. Shorelines of storage reservoirs take longer to adjust due to their variable pool levels.

### 4.2.3 Groundwater

Under options 1a and 1b, groundwater fluctuations near system reservoirs would remain within historical limits. These fluctuations are slight variations of the water table near run–of–river projects (lower and middle Columbia, lower Snake). Greater fluctuations of the water table would likely occur near storage reservoirs (Hungry Horse, Libby, Albeni Falls, Dworshak, Grand Coulee, and Brownlee). These fluctuations vary in nature depending on the reservoir and surrounding aquifers, but have been occurring since the dams began operating. At reservoirs situated in permeable, unconsolidated material, such as Hungry Horse, the water table fluctuates directly with the reservoir level (Simms and Rorabaugh, 1971).

Under both options, spring and early summer water table levels near Libby Dam would be a maximum of 50 feet (15.2 m) higher than under SOS 2c. At Hungry Horse, the water table would be only a few feet higher during this time. Near Dworshak, February water table levels would be a maximum of 60 feet (18.3 m) lower than under SOS 2c, while spring water levels around Grand Coulee would be somewhat lower.

Water table fluctuations would be greatest near the reservoir shorelines in all cases, and would rapidly decrease in magnitude away from the reservoir. Water and pressure levels in wells that are very close to these reservoirs could be reduced somewhat on a seasonal basis.

## 4.3 SOS 2: CURRENT OPERATIONS

### 4.3.1 Shoreline Erosion and Mass Wasting

For most reservoirs, current operations instituted in response to the ESA listings are the same as or a minor departure from historical operations. Therefore, erosion and sedimentation would remain within historical ranges systemwide and for most of the projects. In other cases, long–term continuation of current operations would cause differences from historical conditions, as summarized below.

Because of their small fluctuations in pool elevation, the Bonneville, The Dalles, and McNary run–of–river projects would have minimal shoreline erosion with both SOS 2 options, and would be at about the same rate as under previous operational plans (SOS 1a). Lowering the pool at John Day to near elevation 262.5 feet (80 m) for several months each year could accelerate movement of an existing landslide west of Alderdale on the north shore (Gustafson, 1992). It would also cause a short–term increase in surface erosion from the newly – exposed areas. Isolated, sporadic mass movements would continue on other reservoirs. On the lower Snake reservoirs, up to 5 feet (1.5 m) of shoreline would be continually exposed during late spring and summer, as a result of operating near minimum operating pool (MOP). This would make the unconsolidated sediments in these areas temporarily subject to storms, and thus wave and overland flow erosion. This would result in a minor, short–term increase in overall erosion at these projects.

Storage reservoirs experience much greater amounts of shoreline erosion and mass wasting than run–of–river reservoirs. Total annual drafting would remain within the historical range on all reservoirs. However, drafting would be at a somewhat faster rate at certain times of the year particularly at Libby. The hydroregulation model results indicate the drafting rate would average 0.7 feet/day (0.2 m/day) from February to March with SOS 2c; this rate is slightly faster than at any time during the average water year under the previous operating pattern. As a result of more rapid drafting, the time it takes the shorelines of the reservoir to reach the equilibrium profile would be increased somewhat with long–term operation under SOS 2c.

Current operations (SOS 2c) continued over the long term would accelerate erosion slightly at Brownlee relative to historical conditions, due to a minor increase (less than 10 feet [3.04 m]) in $P_R$. The slight increase in the rate of drafting might also lead to a minor increase in mass wasting. Overall, however, shoreline erosion at the storage projects would remain within historical ranges. Shoreline erosion at Hungry Horse and Grand Coulee would decrease slightly, while erosion at Dworshak could decrease significantly.

With the exception of Grand Coulee and Brownlee, storage reservoir operations and resulting impacts would be essentially the same under SOS 2d as SOS 2c. At Grand Coulee, the SOS 2d would decrease $P_R$ by 5 feet (1.5 m). This would decrease shoreline erosion slightly by exposing significantly less material. At Brownlee, two small additional draft/refill cycles would occur each year, with an 8–foot (2.4–m) draft/refill in July and a 22–foot (6.7–m) draft/refill in October. This could increase shoreline erosion and mass wasting significantly. The shoreline would be subjected to much more wave action and slumping.

### 4.3.2 Sedimentation

A slight increase in reservoir sedimentation and transport of suspended material out of the reservoir environment might accompany the minor acceleration of erosion with this alternative. Reduced travel time (greater velocity) through reservoirs would reduce the amount of particulates that might settle out. Unless travel times were reduced throughout the river system, any decrease in sedimentation in a single reservoir could be negated by increased sedimentation in downstream reservoirs where operations were not altered. This situation could occur in McNary, where operations would be unchanged but velocity through the lower Snake River projects upstream could increase somewhat. This may be viewed as a reservoir–by–reservoir redistribution of sediment.

Generally, only minor increases in sedimentation (redistribution) would occur with this alternative. Localized degradation of the river channel might occur if the travel time reduction goal is met. Any additional sediment escaping reservoirs would be only in the silt and clay sizes, and would result in a slightly higher turbidity in late spring. This operation would have a negligible impact on systemwide sedimentation.

However, at Brownlee, under SOS 2d, an increase in sedimentation related to shoreline erosion would occur.

### 4.3.3 Groundwater

Local groundwater gradients near affected reservoirs would respond to reservoir pool fluctuations associated with SOS 2. Groundwater conditions would remain within historical ranges for run–of–river dams. The aquifers surrounding storage reservoirs would experience slightly greater fluctuations in levels during the spring and summer months than under previous operations, particularly at Libby and Brownlee. Although Dworshak pool elevations would fluctuate greatly (up to 155 feet [47.2 m] total yearly, as in the past), the surrounding rocks are mostly consolidated and have a low conductivity. Therefore, except in delta areas, the aquifer surrounding the reservoir would not respond quickly or completely to changes in pool level.

Both options would have the same effects on lower Snake River reservoirs, which would operate within 1 foot (0.3 m) above MOP during late spring and summer. The difference between MOP and full pool is small (3 feet [0.9 m] for Ice Harbor and Lower Monumental, 5 feet [1.5 m] for Little Goose and Lower Granite). Because this is such a small change, and because the affect on the water table would decrease rapidly away from the reservoir shoreline (Corps, 1992), the effect of SOS 2 on groundwater in the lower Snake River reach would be negligible.

Only wells very close to the reservoirs would be affected, and these would only experience a few feet of water level drop during the late spring and summer. It is unlikely that any wells would go dry under

SOS 2, as the wells most likely are screened across a depth interval large enough to accommodate existing water table fluctuations.

Similarly, only groundwater wells very close to John Day Reservoir would be affected by the maximum 5.5–foot (1.7–m) drop relative to typical maximum summer elevations. These wells might suffer a slight decrease in production. It is unlikely that they would go dry, because the resultant change in water table would be within historical conditions under which the wells have been operated.

## 4.4 SOS 4: STABLE STORAGE PROJECT OPERATION

### 4.4.1 Shoreline Erosion and Mass Wasting

In general, SOS 4 would result in a system–wide decrease in erosion and mass wasting compared to current or past operating patterns. This would be particularly true for the storage reservoirs, where the depth of annual drafts would generally be reduced and pools would be subject to less fluctuation.

SOS 4 would generally reduce shoreline erosion and mass wasting.

At Libby, the annual draft would be reduced by over 50 percent. This would result in a significant decrease in shoreline erosion and mass wasting potential. The pool elevation would not go below about 2,393 feet (729.4 m) with this option.

At Albeni Falls, the total draft in most years would decrease from about 11 feet (3.4 m) to 5 feet (1.5 m); every sixth year the pool would be drafted to previous levels. Overall, shoreline erosion and mass wasting potential would be somewhat reduced compared to historical conditions.

At Grand Coulee, winter drafting would start in January, and achieve lowest pool elevation by March instead of late April. The pool level would have a total yearly change of 28 feet (8.5 m) on average. The reservoir shorelines would continue to experience mass wasting and wave erosion, but not as much as under current operations, which involves a 50–foot (15.2–m) average annual draft. A short cycle of refilling/drafting would be added in March. However, its impact on shoreline erosion would be minimal, as this fluctuation would average only 5 feet (1.5 m). Pool levels would be similar to present conditions during summer and fall.

Brownlee Reservoir would experience erosion and mass wasting impacts within the historical range.

Dworshak pool fluctuations would generally be decreased. This would decrease erosion and mass wasting potential slightly.

Lower Snake and Columbia River reservoirs would generally be operated in SOS 4c as they are currently, and therefore the impacts would be the same as under SOS 2c. The exception is John Day, which would be operated slightly lower (about 1 foot [.3m]) than historically, causing a temporary decrease in shoreline erosion. The effect on mass wasting and erosion potential would be negligible.

### 4.4.2 Sedimentation

Based on the shoreline erosion and mass wasting conclusions presented in Section 4.5.1, identifiable changes in sedimentation patterns would likely be limited to minor decreases in sedimentation at Libby and Hungry Horse. The total sediment input would not decrease, but the yearly redistribution of delta sediments lower in the reservoirs would be reduced, due to the decrease in total yearly drafting. Over the long term, this effect could increase the life spans of the reservoirs somewhat.

Downstream of Hungry Horse, the minor increase in spring outflows could cause minor degradation in some reaches of the Flathead River. Outflows from Libby would be altered somewhat, but would remain within the magnitude of flows experienced under historical operations.

Spring outflows at Dworshak would be twice as great as under historical conditions for a typical year. This would result in incision and/or lateral erosion of material deposited in the reach between Dworshak Dam and Lower Granite Reservoir since Dworshak was completed. The erosion would likely be short–lived, and would result in increased sedimentation of

Lower Granite for the first few years of the new operation. Sedimentation would then gradually decrease, approaching historical conditions.

### 4.4.3 Groundwater

Operating the system according to SOS 4c would have little effect on groundwater in most locations and would reduce groundwater fluctuations near some projects. Fluctuation in the water table near Hungry Horse would be reduced by up to half. The water table near Libby (Lake Koocanusa) would experience significantly less fluctuation. Effects on aquifers in glaciofluvial deposits around Lake Roosevelt would be limited to a slight shift in the timing of seasonal fluctuations. A slight decrease in the amount of drafting at Albeni Falls and Dworshak would lead to smaller fluctuations in aquifers hydraulically connected to these reservoirs. Groundwater conditions near the run–of–river projects would be essentially the same as at present.

## 4.5 SOS 5: NATURAL RIVER OPERATION

As discussed in Chapter 3, reservoir shoreline erosion and mass wasting were studied in coordination with the water quality analysis. SOS 5 differs significantly from the previous alternatives in the magnitude and location of change in reservoir operation. Natural river operation would expose almost 20 years of accumulating sediments to erosion and would cause a large pulse of water to flow down the lower Snake and Columbia Rivers in the spring.

### 4.5.1 Shoreline Erosion and Mass Wasting

Erosion in the lower Snake reservoirs would be extensive with SOS 5. Overland flow erosion, wave erosion, mass wasting, and tributary incision would increase as pool levels decreased, due to the increase in surface area exposed. Most reservoir sediment previously deposited on the shorelines would eventually erode. The amount of sediment that would be eroded from Lower Granite alone during the first year is estimated at about 900,000 cubic yards (688,140 m$^3$) with SOS 5b. In comparison, the current average annual influx of sediment to Lower Granite is 3 million cubic yards (2.3 million m$^3$) (personal communication, Les Cunningham, Hydrologist, Corps of Engineers, Walla Walla District, 1993).

The shoreline erosion model analysis predicted that the most significant source of erosion would be waves, followed in order by slumping, incision, and surface erosion. This is consistent with results from the March 1992 drawdown test, during which there were no significant storm events yet waves still managed to cut small terraces in the unconsolidated sediments.

Incision of tributary deltas would accelerate as pool levels were lowered with SOS 5. On tributary fans, incision, headwall advance, and channel widening by bank collapse would add substantial eroded material to the natural river channel. Tributaries, either through baseflow or storm runoff, would incise through the unconsolidated reservoir sediments. Incision might cut through pre–reservoir coarse sediments, as it did during the 1992 drawdown test. This might be a result of the saturation of these materials, which makes them less cohesive and more subject to erosion.

Channel erosion in the reservoir sediment would work its way upstream. Knickpoint channel incision could cause significant impacts to structures along the reservoirs by migrating to the foundations of bridge abutments or embankments. The areas subject to the greatest amounts of incision would be the tributary areas, such as Alpowa Creek on Lower Granite, Deadman Creek on Little Goose, and the Palouse and Tucannon Rivers on Lower Monumental.

Drawdown would reduce the pool level faster than groundwater could drain from surrounding areas. This would create pore water pressures that could exceed the shear strength of bank material and result in the liquefaction of sandy materials and slumping and sliding in finer materials. This process would vary with the character of the deposit and the rate of drawdown. The 1992 drawdown test of Lower Granite showed that this process damaged structures, such as road and railroad embankments, levees, and docks and other port facilities along the reservoir. Slumping would occur in surficial deposits (both pre– and post–reservoir) and in fill. Slumping could damage some reservoir facilities, and might be accelerated by storm events.

Under typical climatic conditions, shoreline erosion with SOS 5b would decrease rapidly after the third year. Predicted total erosion would be 520,000 cubic yards (245,000 $m^3$) after the third year and 240,000 cubic yards (183,500 $m^3$) after the sixth year. Sediment input from the shoreline would continue at a low rate for several decades after that. The amount of sediment passing the dam each year would eventually be approximately equal to the sediment input from upstream.

SOS 5c would result in a similar pulse of sediment for the first year, followed by a rapid decline in erosion. Since the pool level would not rise again after the drawdown, no further wave erosion would take place, so the first year's erosion would be somewhat less than under SOS 5b. Additionally, most slumping and sapping would occur during the first two years, and the shorelines would gradually stabilize. Surface erosion could be significant during the first and second wet seasons following drawdown. However, revegetation efforts could ameliorate most of the surface erosion after the first wet season. Overall, the total shoreline erosion under SOS 5c is estimated to be significantly less over the long term than under SOS 5b, although the short term effects include major erosion and sedimentation compared to current operations.

Although the specific quantitative analysis was carried out for Lower Granite Reservoir, these results can be broadly extrapolated to the other lower Snake dams. The main difference between Lower Granite and the other dams is that the Clearwater and Snake River deltas in Lower Granite are much larger than the deltas at the lower three dams. Lower Granite has been trapping sediment above the other reservoirs during much of their operation, and the Clearwater is much larger than the tributaries entering the other Lower Snake River projects. Thus, more sediment would be mobilized from Lower Granite than the other dams. The Palouse River embayment on the Little Goose reservoir would also be a major producer of sediment. Based on the amount of sediment eroded per mile, the other three reservoirs would contribute about 2.5 million cubic yards (1.9 million $m^3$) of sediment during the first year under option 5b. This number should be viewed as a conservative maximum, as the sediment volume available is actually much less due to the trapping of sediments by Lower Granite Dam. Erosion would be significantly less under option 5c. Annual erosion from the three other reservoirs would decrease more rapidly than at Lower Granite. Within 5 to 15 years, the amount eroded would decrease to the yearly influx of sediment to the reservoirs.

The 1992 drawdown test showed that levee embankments were generally not susceptible to damage from lowered pool levels (Corps, 1993). Their construction prevents differential stress from building up across their width. Road and railroad embankments are more susceptible to movement, however. During the 1992 test, extensive movement occurred, as evidenced by cracks in pavement up to 15 inches (380 mm) wide, raised areas, and guardrail displacement. More widespread damage would occur with a natural river drawdown, although the severity of damage would probably not be much greater than in 1992. Railroad embankments also would suffer. Some track misalignment occurred in 1992, slowing train traffic for a period. Damage would most likely be widespread under SOS 5, as the entire length of train tracks along the lower Snake would be subject to differential settlement. Embankment damage would be similar under both 5b and 5c, as the damage would most likely occur during initial drawdown.

During 1992, extensive mass wasting occurred at the Port of Clarkston, Red Wolf Marina, Nisqually John Landing, Offield Landing, Port of Wilma, and other places, mostly on the south shore of Lower Granite and Little Goose Reservoirs. More activity could be expected at these and additional locations under SOS 5b or 5c. Damage could be more extensive under SOS 5b due to the longer period of exposure, and the increased chances of a large storm occurring during a drawdown. Repairs to roads, embankments, marinas, and port facilities would likely be expensive. Damage to embankments and port facilities would also occur on the other lower Snake reservoirs.

Under SOS 5b, on an annual basis, erosion would peak each year at the beginning of drawdown, taper off toward the middle, and then rise slightly as the reservoirs refilled. Sediment redistribution would occur as coarser particles moved lower in the reservoirs. After repeated drawdowns, a coarse lag deposit would develop on some of the Snake River shoreline as transportable particles were removed. Lag deposits would be most developed in the alluvial fan areas of small tributaries, which are numerous along the lower Snake River. Such annual effects would not occur under SOS 5c, after the first few years.

Compared to current operations, the only other reservoir affected under SOS 5 would be John Day. The expected impact to the John Day project would be minor. A study conducted by Gustafson (1992) indicates that there is "a very low probability of serious [stability] problems occurring during prolonged drawdown to 257 feet (78.3 m)." The rate of movement of the "slide #1" on the Washington side would increase slightly; this could damage Washington State Route 14, which passes near the top of the slide. Gustafson also indicates that drawdown to 257 feet (78.3 m) would not cause significant shoreline erosion.

Conditions at the storage reservoirs under SOS 5 would generally be similar to those reported for SOS 1. Compared to historical conditions, differences among the storage projects would generally be in the range of 5 to 10 feet (1.5 to 3 m). $P_R$ at Dworshak would be 20 feet (6.1 m) lower, and would decrease erosion and mass wasting potential.

### 4.5.2 Sedimentation

SOS 5b or 5c would likely cause significant changes in sedimentation in the lower reaches of the Columbia River system. The U.S. Geological Survey collected data on sediment transport and deposition resulting from the drawdown test of Lower Granite Reservoir in March of 1992. Appendix M of the drawdown report (Corps, 1992) details the methods used to collect these data. The results of this test were used to qualitatively determine the impacts of SOS 5 on the quantity and nature of sedimentation in the reservoir system. It is expected that most sedimentation would result from incision of the mainstem delta and subsequent downstream deposition of the material. The 1992 drawdown test revealed that most sediment from the Snake–Clearwater delta area moved only a short distance downstream before being redeposited. Under the natural river operation, most of the sediment currently in storage in the Snake River reservoirs would be flushed out of the Snake River. Much of the material would be deposited in the Columbia River (McNary Pool) just downstream of the confluence with the Snake. A large delta of coarser material would likely form here, while the finer particles would be routed downstream. These would include particles in the fine sand, silt and clay size ranges. Much of this would settle out within the McNary Pool. The effect of this sediment would be to increase the rate of deposition in the McNary Dam reservoir. In addition, it could constrict navigation channels in the Columbia River near the Snake River confluence, and necessitate additional dredging to maintain the channel.

A maximum of 3.7 million tons of sediment during the first year, and 9.6 million tons or 5.4 million cubic yards (4.1 million $m^3$) total during the first 6 years, would be deposited in McNary. This represents only about 14 percent of the total estimated sediment available in the lower Snake River reservoirs, there would still be 36 million cubic yards (27.5 million $m^3$) available after the first 6 years, as the erosion rate would rapidly taper off after the first year.

In addition to moving sediment that has accumulated over the years, SOS 5b would affect the transport of sediment in the lower Snake River on an annual basis. Most of the annual sediment influx to the lower Snake River reservoirs normally enters in the spring and early summer. With SOS 5b, most of this sediment would not be deposited in the lower Snake reservoirs. Because the drawdown would take place during a typically high period of sediment influx, the yearly influx of sediment to the reservoir would be reduced to almost nothing during the first few years. The sediment that did get deposited would likely be flushed by the drawdown occurring the following year. With continued annual drawdowns, there would likely be no net sedimentation within these reservoirs. Thus the lower Snake River reservoirs would no longer prevent the bulk of the annual sediment load from reaching the lower Columbia River reservoirs. Fine suspended sediment would be flushed downstream as flow velocities increased, increasing turbidity throughout the lower Columbia River (see Appendix M, Water Quality, for information on turbidity impacts). Over the long term, this would greatly extend the life spans of the four lower Snake River dams and decrease the life span of McNary (or increase the need for dredging).

Sedimentation patterns would also be dramatically altered under SOS 5c. Lower Granite would no longer be a sediment sink. Sediment redistribution patterns would be similar to SOS 5b during the first year. Following the first year, sediment would be flushed down the Snake River to McNary dam. McNary would trap most of the sediment coming from the Snake. Sedimentation would drop within a few years to near background levels, however (excluding sediment from the Upper Snake projects).

### 4.5.3 Groundwater

Groundwater well data collected in the 1992 drawdown test were used to evaluate the impact of the drawdowns on local water tables. The results of the 1992 test show that some wells in the immediate vicinity of Lower Granite Reservoir experienced the same amount of drawdown as the point of the reservoir closest to them, while wells located more than about 0.5 mile (.08 km) from the reservoir did not experience any effects from the drawdown. The wells affected by the 1992 drawdown are listed in Table 4–3. These wells are hydraulically connected to the reservoir, some more directly than others. There are few if any functioning wells near the other three lower Snake River reservoirs.

**Table 4–3. Groundwater Wells Near Lower Granite Reservoir.**

| | |
|---|---|
| Wells not affected by drawdown | 11N/45E – 24L01 |
| | 11N/45E – 24L02 |
| | 11N/46E – 29Q01 |
| | 11N/44E – 15E01 |
| Wells that fluctuated directly with the reservoir, 5– to 12–foot drops | 35N/06W 14DAA1 |
| | 35N/06W 12CCA1 |
| | 36N/06W 35ADB2 |
| | 11N/45E – 17E01 |
| | 11N/45E – 21B01 |
| Wells that fluctuated directly with the reservoir, 15– to 30–foot drops | 36N/06W 25CDA1 |
| | 11N/45E – 20J01D2 |
| | 11N/45E – 13R01 |
| | 11N/45E – 18R01 |
| | 11N/45E – 19B01 |
| | 11N/45E – 19J01 |
| | 11N/45E – 02M01 |

Based on proximity to reservoirs and depth of the aquifer, groundwater wells along the other three reservoirs were categorized into two groups—those that would be strongly affected by drawdown and those that would experience only minor effects. It is possible that some wells in the former group (19 wells total) would go dry, and some in the latter group (7 wells) would experience decreased yield. Under SOS 5b, this would occur during a season when water is in high demand, so that alternative water sources may need to be provided. Under SOS 5c, wells designed after Lower Granite was filled and connected to the alluvial aquifer would be permanently altered. Alternative sources of water would have to be found.

Based on the 1992 test results, SOS 5 would cause groundwater levels to drop significantly in wells within at least 0.5 mile (0.8 km) from the lower Snake River reservoirs. Because the natural river drawdown would be much deeper than the 1992 drawdown, it is likely that more distant wells would be affected, possibly as far away as 1 mile (1.6 km). Under SOS 5b, the water levels would most likely rise as the reservoirs refilled, with no net long–term decrease of the water table. However, for SOS 5c, the water table near the reservoir would be permanently lowered, fluctuating slightly with seasonal changes in river levels.

Groundwater effects elsewhere in the system from SOS 5 would be essentially the same as those described previously for SOS 1, with the exception of John Day. Under both options, the John Day drawdown of 8 feet (2.4 m) below normal pool level could be expected to decrease the production of some wells in the Boardman, Oregon, area. However, the designed pumping rate is less than the available water discharge for this pool elevation (CH2M Hill, 1992). Using the yield–drawdown graph provided by Ranney Method Western Corporation (CH2M Hill, 1992), the curve for river stage 258 feet (78.7 m) intercepts the design yield of 6,030 gallons/minute (27,413 liters/minute) at pumping elevation 236 feet (72 m), well above the minimum pumping elevation of 230 feet (70.1 m). Thus, the Ranney well would not be affected because of the limitation of its pump. However, other wells in the area that have high design yields relative to their pumping elevation may be affected. There are some 2,000 wells in the Lake Umatilla area (Corps, 1994). These include numerous wells in the Irrigon, Oregon area, and in the vicinity of Boardman. Some wells in the Umatilla area could be affected, although it is less certain how much, due the proximity of Umatilla to the McNary impoundment.

## 4.6 SOS 6: FIXED DRAWDOWN

This alternative is similar to SOS 5 except that the effects would not be as drastic because the depth of drawdown would be much less. While SOS 5 applies to all four lower Snake River reservoirs, SOS 6 has one option involving all four reservoirs and one option involving just one reservoir, Lower Granite. Impacts in the former case would predictably be much greater than the effect of drawing down only one reservoir.

Compared to historical conditions, the direct effects of SOS 6 would be limited to the lower Snake River projects and John Day. Operations and impacts at John Day would be the same as described in Section 4.5 for SOS 5.

### 4.6.1 Shoreline Erosion and Mass Wasting

Erosion with SOS 6b would be extensive and would be much greater than during the 1992 Lower Granite drawdown test. This is because the drawdown would be for a longer time and would involve all four lower Snake River reservoirs. Wave erosion below normal operating pool levels would initially be extensive, with the amount of erosion dependent upon weather conditions during the 15–day drafting period. Storms would accentuate wave effects. As the reservoir area decreased, wave energy would decline.

Nevertheless, wave attack on bank sediments would be severe once the reservoirs reached their fixed drawdown levels. Wave erosion would not cease at full drawdown, but would continue as waves eroded into the new shoreline and moved toward an equilibrium profile. The amount of erosion would be about half of the erosion estimated for SOS 5b.

The degree of impact under SOS 6b would not be as great because the depth of drawdown would be approximately 33 feet (10 meters) per dam, as opposed to about 100 feet (30.5 meters) with the natural river operation. Nonetheless, SOS 6 would still cause major increases in erosion and mass wasting. SOS 6b would mobilize about 1.5 million cubic yards (1.14 million $m^3$) of sediment during the first year at Lower Granite alone, which is half as much sediment as produced under SOS 5b. Similarly, the yearly rate of erosion after 6 years would be less than half of that under SOS 5b, being approximately 500,000 cubic yards (382,000 $m^3$). The rate is significantly less because most sediment would be retained within each reservoir. Based on the amount eroded per mile of reservoir, the other projects would contribute approximately 4.2 million cubic yards during the first year.

Overland flow erosion would be significantly less than with the natural river options, as only about half as much surface area would be exposed with SOS 6b and 6d. Erosion from incision would also be significantly less, as the base level would be at least 60 feet (18.3 m) higher than the natural river options. Because the amount of erosion would be much less than the annual sediment influx, SOS 6 would cause continued erosion of the shoreline, primarily in the form of wave and surface erosion, for decades.

Slumping would generally be limited to surficial deposits, due to their lack of consolidation. Slumping would be expected to cause some damage to road and railroad embankments and port facilities, and could be accelerated by storm events. Slumping would be most prominent in the upstream portions of the reservoirs. However, it would not be as severe as under the natural river alternative, because the depth of drawdown would be much less.

The impacts of SOS 6d on erosion would essentially mirror those of SOS 6b, but would be limited to Lower Granite and its vicinity. The estimated volumes of sediment mobilized in Lower Granite would be 390,000 cubic yards (298,194 cubic meters) for SOS 6d. Little Goose would trap most of the sediment passed through Lower Granite.

### 4.6.2 Sedimentation

Sedimentation would have a pattern similar to SOS 5, but would be distributed differently in time and space. Less sediment and finer sediment would be flushed out of the Snake River. Coarser sediment (i.e., gravel) would not reach the Columbia, as it would merely be moved from the shorelines and the deltas to lower elevations in each of the lower Snake River reservoirs. McNary Dam would trap most of the sediment flushed from the Snake River.

Option 6d would result in increased sedimentation in Little Goose Reservoir only, decreasing its life span significantly. Navigation could be affected by the increased sedimentation under both options.

### 4.6.3 Groundwater

Groundwater levels would drop in wells within about 1 mile (1.6 km) of the shoreline of the affected lower Snake River reservoirs under SOS 6. The decline in water level would be temporary; the water table in these wells would probably return to the typical levels as the reservoir(s) refilled. Under the 4.5–month options, a wider radius of wells would be affected, perhaps as far away as 1 mile (1.6 km). Some wells might go dry, depending on their depth. Alternative sources of water might have to be found, given that the drawdowns would take place during the high water use season. Wells in the Lewiston/Clarkston area would be affected with SOS 6d. Wells screened in the Pasco Gravels along Lake Umatilla would be affected as under SOS 5.

## 4.7 SOS 9: SETTLEMENT DISCUSSION ALTERNATIVES

This strategy has three significantly different options. SOS 9a uses drawdown to near the spillway crest on the Lower Snake River projects and establishes flow targets at the Dalles. SOS 9b establishes flow targets at McNary and Lower Granite based on runoff forecasts, and uses releases from Dworshak, Brownlee, and the Upper Snake projects to meet these flow targets. SOS 9c, like 9a, lowers the Lower Snake River projects to near the spillway crest during the spring and early summer, and uses flow augmentation based on the 1994–1998 Biological Opinion, with integrated rule curve operation at Libby and Hungry Horse. Within each subsection, option 9a will be discussed first, followed by options 9b and 9c.

### 4.7.1 Shoreline Erosion and Mass Wasting

Under SOS 9a, pool fluctuation would be reduced at Libby by 40 feet (12.2 m) and at Hungry Horse by 22 feet (6.7 m), or 33 and 28 percent, respectively. This would cause a significant decrease in the amount of shoreline erosion and mass wasting. Over time, some areas currently seasonally inundated would become vegetated and would not be subject to wave action.

At Brownlee, annual pool fluctuation would increase by 3 feet (0.9 m), though this would not result in a detectable increase in shoreline erosion. However, an extra filling/release cycle would cause a significant increase in shoreline erosion and mass wasting, and could nearly double the amount of erosion and mass wasting each year.

$P_R$ at Dworshak would increase somewhat, from 71 feet (21.6 m) to 86 feet (26.2 m). This would result in a moderate increase in shoreline erosion and mass wasting, due to the additional shoreline exposed to wave action. Increased potential for slumping could occur in some areas where the colluvial soil layer is relatively thick. In addition, since the lowest pool elevation reached would be over 10 feet (3.0 m) lower on average than under current operations, the sediments deposited at this level would be subject to wave erosion, resulting in a short–term increase in shoreline erosion during April.

On the lower Snake River projects, the effects would be similar to those under SOS 6b, with significant erosion and mass wasting. At Lower Granite alone, approximately 1.5 million cubic yards (1.15 million cubic meters) of sediment would be mobilized during the first year. After six years, the sediment eroded would be approximately 500,000 cubic yards (382,000 cubic meters). Based on the total erosion per mile, with adjustment for sediment–filled embayments, the other lower Snake River projects would contribute approximately 4.2 million cubic yards (3.2 million cubic meters) of eroded sediment during the first year. Overland flow erosion would not be as severe as under SOS 5, and incision would be significantly less. Slumping would also be significantly less.

Erosion and mass wasting at Grand Coulee would be similar to current operations, except that $P_R$ would be slightly higher. The increase in shoreline erosion and mass wasting would be negligible.

Albeni Falls would experience a slight decrease in erosion due to a small decrease in $P_R$. This would decrease the total area of shoreline subjected to erosion and mass wasting.

At John Day, effects would be essentially the same as under SOS 5, with a slight increase in $P_R$. Movement of "slide #1" (Gustafson, 1992) could occur, but shoreline erosion would remain generally within historical ranges.

Under SOS 9b, $P_R$ at Libby would decrease by 20 percent, resulting in a small reduction in shoreline erosion and mass wasting. However, because the elevation of the pool would be significantly higher during most of the year than currently, more shoreline erosion and mass wasting would occur higher on the shoreline of the reservoir. It is difficult to estimate what the net change in erosion and mass wasting would be during the first few years of operation. Over the long term, shoreline erosion and mass wasting would decrease slightly.

At Hungry Horse, the effects on $P_R$ would be the same as under SOS 9a, and would lead to a generally lower rate of shoreline erosion. The average pool elevation would be significantly higher (about 30 feet [9.1 m]) during the spring than under current operations. This could cause more mass wasting along the shoreline, when the groundwater elevations surrounding the reservoir are generally high.

On the Lower Snake River projects, the effects would be the same as under current operations, with generally minimal erosion and mass wasting.

At Grand Coulee, the $P_R$ would be slightly reduced under SOS 9b, and the effects would be similar to those under SOS 2d, with a slight decrease in shoreline erosion and mass wasting.

Brownlee would experience a lower $P_R$, but would have an extra refilling/release cycle, which would lead to a net increase in shoreline erosion and mass wasting. At Dworshak, a similar situation would occur, with a major refilling/release cycle added. This would result in a significant increase in shoreline erosion and mass wasting, since the shoreline would on average be exposed to twice as much wave action and mass wasting.

John Day would have the same operations and thus the same effects as under current operations.

Under 9c, Libby would experience a significant decrease in shoreline erosion and mass wasting. The $P_R$ would decrease by 36 percent. The higher elevation of the pool during the early spring could lead to an increase in mass wasting during the higher groundwater table in that time of year. However, the decreased fluctuation in the pool level is significant enough that a net decrease in erosion and mass wasting would probably result. Hungry Horse would have a similar situation. The $P_R$ would be reduced by 20 percent, but the higher pool levels during the spring could offset the associated decrease in mass wasting. The net effect would be a decrease in shoreline erosion but little or no change in mass wasting.

As under SOS 9a, Albeni Falls would experience a slight decrease in shoreline erosion and mass wasting, due to the small decrease in $P_R$.

On the four lower Snake River projects, the 40 foot (12.2 m) drawdown that would be required would result in significant increases in shoreline erosion and mass wasting. Based on the erosion estimated for the 100– and 30–foot (30.5– and 9.1–meter), 2.5 month drawdowns under SOS 5 and 6, the total erosion for the first year at Lower Granite under SOS 9c is estimated at 1.3 million cubic yards (994,000 cubic meters) under typical conditions, for all four reservoirs. The patterns of erosion and mass wasting would be similar to those under SOS 6, with a peak each year at the beginning of drawdown, a tapering off during the middle of drawdown, and a slight rise during refilling of the reservoirs. Slumping would be generally limited to surficial deposits, and would cause some damage to road and railroad embankments and port facilities. Slumping would be most prominent in the upper portions of the reservoir, where the unconsolidated sediments susceptible to slumping are thickest. Based on the total erosion per mile of reservoir, the other lower Snake River projects would contribute approximately 3.6 million cubic yards (2.75 million cubic meters) of eroded sediment during the first year. Erosion and mass wasting would decrease rapidly within a few years after the initial drawdown, but would reach a constant level due to the wintertime accumulation of additional sediment.

At John Day, effects would be essentially the same as under SOS 5, with a slight increase in $P_R$. Movement of "slide #1" (Gustafson, 1992) could occur, but shoreline erosion would remain generally within historical ranges.

### 4.7.2 Sedimentation

Under SOS 9a, sedimentation from shoreline erosion and mass wasting would decrease significantly at Libby and Hungry Horse. This sediment source may be relatively minor, however, compared to erosion of the deltas formed by the mainstem rivers on these projects. Sedimentation from shoreline erosion and mass wasting would decrease slightly at Albeni Falls but would increase significantly at Brownlee and Dworshak. Grand Coulee would experience sedimentation similar to that under current operations.

On the four lower Snake River projects, sedimentation would be similar to that under SOS 6b, with major redistribution of sediments within the reservoirs, particularly with the coarser fraction in Lower Granite. Some fine sediment would remain suspended and enter the Columbia River. The Water Quality Appendix estimates how much would reach Lake Walulla. Sedimentation could be of sufficient magnitude to affect shipping lanes, especially in Lower Granite and Little Goose. Sedimentation of embayments and tributary deltas would be effectively slowed, as the channel would erode each year down through the accumulated sediments.

Sedimentation on the remaining run–of–river projects would remain within historical ranges.

Under SOS 9b, sedimentation from shoreline erosion and mass wasting would decrease slightly at Libby, Hungry Horse, Albeni Falls, and Grand Coulee. At Brownlee and Dworshak, it would increase significantly due to the extra release/refilling cycle. More sediment from the eroding shoreline would settle out on the reservoir bottom.

On the four lower Snake River projects, sedimentation would remain within historical ranges and would be dominated by the sedimentation at the delta in Lower Granite.

Under SOS 9c, sedimentation from shoreline erosion and mass wasting would decrease significantly at Libby, and slightly at Hungry Horse and Albeni Falls. At Grand Coulee, sedimentation would remain within historical ranges.

Sedimentation from shoreline erosion and mass wasting would increase significantly at Brownlee due to the extra release/refilling cycle, since more sediment would be generated from the shoreline. Dworshak would not experience a detectable change in sedimentation from shoreline erosion and mass wasting.

At the lower Snake River projects, as under SOS 9a, significant sedimentation effects would occur, although sedimentation would be somewhat higher. Shipping lanes could be affected in Lower Granite and Little Goose, although erosion of the delta would account for more sediment than erosion of the shorelines.

Since John Day would be lowered by 9 feet (2.7 m), some sediment would be generated from erosion of the near–shore sediment. This sediment would settle out mostly near the shoreline at the lowest pool level, 257 feet (78.3 m).

### 4.7.3 Groundwater

Groundwater fluctuations, related to pool level fluctuations, would be affected in areas close to the reservoirs. At Libby and Hungry Horse, groundwater fluctuations would decrease near the reservoir, and the water table would rise, as the average elevation of the reservoirs would be significantly higher than under current operations.

Under all three options, groundwater fluctuations at Grand Coulee would decrease very slightly, and water table elevations would be slightly lower near the reservoir during the summer.

At Dworshak, groundwater fluctuations would increase under SOS 9a, although there are few wells in the immediate vicinity to be affected. Under SOS 9b and 9c, groundwater fluctuations would decrease near the reservoir.

At Brownlee, the range of groundwater fluctuation would be similar to that under current operations for all SOS 9 options. However, more fluctuation would occur with an extra cycle of release/refilling. In addition, the summer pool elevations would be 8 to 30 feet (2.4 to 9.1 m) lower than under current conditions, and thus near–shore wells could be significantly affected. This effect would occur only in late August and September under SOS 9a.

At the lower Snake River projects, options 9a and 9c would affect groundwater levels significantly. The effects would be similar to those under SOS 6b, although under SOS 9c, the water table would be lowered more and more wells would potentially would be affected. Wells in the Lewiston/Clarkston area within 0.5 mile (0.8 km) of the reservoir shoreline would be most affected, and the water table near the shoreline could drop. Some wells might go dry, depending on their location and depth. Table 4–3 shows which wells would be slightly or strongly affected. The effect of the drawdown would diminish rapidly away from the reservoir shorelines. Given the results of the 1992 drawdown test, most wells would recover quickly after refilling in June. During the drawdown, alternate sources of water might have to be found.

The water table near Lake Umatilla would be affected slightly by the 9 foot (2.7 m) drop in pool level under options 9a and 9c. The effects would be similar to those under options 6b and 6d, except that the water table would be low during April and May through August. Although the Ranney well at Boardman would not be affected, other wells in the area could experience diminished capacity, and alternate sources of water might have to be found.

## 4.8 SOS PA: PREFERRED ALTERNATIVE

This alternative would use flow targets at McNary and Lower Granite and would lower the John Day and lower Snake River projects to MOP during the spring and early summer. No major drawdowns would be involved.

### 4.8.1 Shoreline Erosion and Mass Wasting

Under this option, shoreline erosion and mass wasting would decrease at Libby and Hungry Horse. On average the $P_R$ would be reduced by 25 percent at Libby and by 29 percent at Hungry Horse. At Hungry Horse, the average end-of-the-month pool elevation would be 7 to 40 feet (2.1 to 12.2 m) higher than under current operations. During late spring and early summer, when groundwater levels are higher due to snowmelt, the shoreline would be subject to more wave attack. This could increase the potential for slumping along the shoreline, since the higher groundwater at that time of year would tend to make unconsolidated material less cohesive. However, the reduction in $P_R$ is large enough that the net effect would be a decrease in overall shoreline erosion.

Conditions at Albeni Falls would be similar to those under current operations.

Grand Coulee and Brownlee would experience a slight reduction in $P_R$, but a reduction in shoreline erosion and mass wasting would not be noticeable.

At Dworshak, a 17 percent increase in $P_R$ would occur, increasing shoreline erosion and mass wasting slightly.

At John Day, a temporary increase in erosion and mass wasting would occur as the pool level is lowered to 257 feet (78.3 m). Movement of "slide #1" (Gustafson, 1992) could occur, affecting nearby Washington State Route 14. Since the pool would be kept at this level year-round, eventually erosion and mass wasting would return to within historical ranges or slightly lower, as there would be fewer total miles of shoreline exposed to wave action. The shoreline above 257 feet (78.3 m) would be subject to surface erosion and incision by tributaries, but would gradually become revegetated. Mitigation could include stabilization or reseeding of unstable or highly erodible areas.

### 4.8.2 Sedimentation

Under the preferred alternative, sedimentation from shoreline erosion and mass wasting would increase slightly at Dworshak, but would decrease slightly at Libby, Hungry Horse, Grand Coulee, and Brownlee. At John Day, a pulse of sedimentation would occur during the first few years following lowering of the pool level. Gradually, sedimentation from shoreline erosion and mass wasting would return to within historical ranges.

Since the $P_R$ at the lower Snake River projects would be the same as under current operations, no change in sedimentation from shoreline erosion would occur.

### 4.8.3 Groundwater

Significant changes in groundwater levels or fluctuations would occur only at Libby, Hungry Horse, Dworshak, and John Day.

Groundwater fluctuations at Libby and Hungry Horse would decrease near the reservoirs. At Hungry Horse, the higher annual average pool elevation would lead to higher groundwater levels in the alluvium and colluvium adjacent to the reservoir shoreline. Since there are no wells near Hungry Horse, there would be no immediate effect on groundwater supply.

At John Day, numerous wells would be affected by the permanent lowering of the pool elevation to 257 feet (78.3 m). Wells using the Pasco Gravel aquifer would be directly affected, resulting in either a loss of capacity and increased pumping costs, or loss of water supply altogether. Some wells using aquifers in the Columbia River basalts could also be affected. Since there are approximately 2,000 wells near Lake Umatilla, the cumulative effect on water supply could be significant. Alternative sources of water would have to be found for some well users. As under SOS 5 and 6, the Ranney well at Boardman would not be affected since the design capacity would be less than the potential yield at this pool elevation (CH2M Hill, 1992).

Groundwater effects on other projects would remain within historical ranges.

# CHAPTER 5

# COMPARISON OF ALTERNATIVES

## 5.1 SUMMARY OF IMPACTS

All of the SOS alternatives would have significant absolute impacts on geology, soils, and groundwater. Table 5–1 is a listing of the alternatives and a brief summary of their impacts. With or without changes in operation, the impacts of the dam and reservoir system on the dynamic equilibrium of the river would continue for hundreds, possibly thousands of years. Flow regimes have been significantly altered and sediment transport has been greatly restricted.

To provide context for the assessment, operational impacts of the respective alternatives were compared to baseline conditions. In terms of geologic processes, baseline conditions are those that evolved under historical operations for the system, as best represented by SOS 1b. The rate of change in these conditions has been modified slightly at some projects (primarily Dworshak and Grand Coulee) since 1983, through operating patterns represented by SOS 1a, and subsequently by SOS 2c. While the actions included in SOS 2c have generally been in effect since the 1992 operating year, these operations are not drastically different from SOS 1a, and as yet have not likely caused any identifiable change in baseline conditions.

SOS alternatives 1, 4c, 9b, and the preferred alternative would have little impact on the shorelines of the lower Snake River reservoirs, because they would be operated much as they are today. SOS 1 represents typical or normal reservoir operations over approximately the past 20 years. Because the river system has had some time to adjust to this regime of operation, SOS 1 would involve relatively stable conditions and minor incremental impact in the short term. The river system would adjust to the modified regime of SOS 3 or 4 over time, and eventually their impacts would decrease.

Continuing current operations on a long–term basis would result in a minor increase in landslide activity and/or shoreline erosion at Brownlee, but would decrease these processes at Hungry Horse, Dworshak, and Grand Coulee.

SOS 4c would involve little or no change in impact levels at the run–of–river projects and would generally have net positive impacts at the storage projects. Shoreline erosion would decrease at Hungry Horse and Albeni Falls. SOS 4b1 and 4b3 would also decrease erosion and mass wasting at Libby and Dworshak.

SOS alternatives 5, 6, 9a, and 9c would have much greater impacts on both the Columbia and Snake Rivers than other alternatives, contributing additional sediment on the order of millions of tons per year over current levels. The most significant impacts on shorelines and groundwater would be on the lower Snake River. Of the many options involving drawdown, SOS 5b and 5c would have the greatest short–term impact on shoreline erosion, mass wasting, sedimentation, and groundwater. SOS 6b and 6d would also lead to sustained high levels of erosion and sedimentation, albeit lower than with SOS 5. A key difference between SOS 5 and SOS 6 is that with the natural river operation (SOS 5), sediment would be flushed out of the Snake River faster.

SOS 5 would increase the life span of the four lower Snake River reservoirs almost indefinitely, by flushing accumulated sediments from these reservoirs. This would eliminate the need for most dredging to maintain navigation when reservoirs were filled under SOS 5b. SOS 6 would increase the life span of the reservoirs as well, although they would still eventually silt up. Long–term dredging requirements would decrease significantly.

## Table 5–1. Summary of Impacts of SOS Alternatives

| | |
|---|---|
| **SOS 1: Pre–ESA Operation** | |
| 1a Pre–Salmon Summit | Erosion, mass wasting, and sedimentation would be within historical operating ranges. Absolute effects would continue to be significant, but diminishing with time. |
| 1b Optimum load–following | Similar to 1a, except slightly more erosion and mass wasting. Absolute effects would continue to be significant, but diminishing with time. |
| **SOS 2: Current Operations** | |
| 2c SEIS operation—no action alternative | Similar to SOS 1, but with increased shoreline erosion of Brownlee Reservoir due to additional drafting. Impact would still be minor. Short–term increase in erosion along lower Snake and John Day Reservoirs. |
| 2d 1994–98 Biological Opinion | Effects similar to 2c, except at Brownlee, where a significant increase in shoreline erosion and mass wasting, and associated sedimentation, would occur. |
| **SOS 4: Stable Storage Project Operation** | |
| 4c Enhanced storage level with modified Grand Coulee flood control | Minor decrease in erosion and mass wasting at Hungry Horse, Libby, and Grand Coulee; same as 2c for other reservoirs |
| **SOS 5: Natural River Operation** | |
| 5b 4.5–month natural river operation | Major increase in erosion and sedimentation by all shoreline processes on the lower Snake, declining with time as sediment availability decreases and sediment is redistributed. Eroded fine–grained materials would move out of lower Snake reservoirs, increasing reservoir life. Structural damage to shoreline facilities expected due to repeated nature of drawdowns. No upstream effect expected. Downstream operations affected by increased sediment transport and deposition in McNary project. Water table significantly lowered in the immediate vicinity of the Snake River; some wells might go dry seasonally. Slight increase in erosion at John Day. Storage projects affected generally as in SOS 1, except minor decrease in erosion and mass wasting at Dworshak. |
| 5c Permanent natural river operation | Impacts similar to SOS 5b for the first few years. Less overall shoreline erosion and mass wasting would occur than under SOS 5b, since the reservoir would not be refilled yearly. Significant surface erosion of reservoir sediments would occur unless mitigated. Permanent lowering of the water table would occur in the Lewiston–Clarkston area. |

## Table 5–1. Summary of Impacts of SOS Alternatives. – CONT

| | |
|---|---|
| **SOS 6: Fixed Drawdown** | |
| 6b 4.5–month fixed drawdown | Large increase in erosion, mass wasting, and sedimentation on the lower Snake. Maintenance of near–constant pool level would increase wave erosion impacts relative to SOS 5. Suspended sediment transported out of reservoir would settle in downstream reservoirs, while some sediment flushing would occur in operating reservoirs. Channel incision into deltas would redistribute coarse sediment lower in the reservoirs, enhancing navigability of delta segments. Water table lowered significantly, although not as much as under SOS 5. Fewer wells likely to be significantly affected. Slight increase in erosion and seasonal lowering of the water table near John Day. Storage projects affected as in SOS 5b. |
| 6d 4.5–month Lower Granite drawdown | Same as 6b, but with most impacts limited to Lower Granite and its vicinity. Groundwater effects same as 6b, but limited to Lower Granite area. |
| **SOS 9: Settlement Discussion Alternatives** | |
| 9a Detailed Fishery Operating Plan | Significant decrease in erosion and mass wasting at Libby and Hungry Horse. Major increase in erosion, mass wasting, and sedimentation, and a lowering of groundwater on the lower Snake River projects. Effects at John Day similar to SOS 5. |
| 9b Adoptive Management | Shoreline erosion and mass wasting would decrease slightly at Libby, Hungry Horse, and Grand Coulee. These processes would moderately increase at Brownlee and Dworshak. Lower Snake River projects would be affected as under SOS 2c. |
| 9c Balanced Impacts Operation | Significant decrease in shoreline erosion, mass wasting, sedimentation, and groundwater fluctuation at Libby and Hungry Horse. Major increase in erosion, mass wasting, sedimentation, and groundwater fluctuation on the lower Snake River projects. Slight increase in erosion and increase in groundwater fluctuation at John Day. |
| **SOS PA: Preferred Alternative** | Decrease in shoreline erosion, mass wasting, sedimentation, and groundwater fluctuation at Libby and Hungry Horse. Slight increase in these processes at Dworshak. Effects at John Day similar to SOS 5. |

SOSs 5, 6, 9a, and 9c would be the only alternatives to significantly affect water tables near reservoirs. SOS 5b and 5c would have greatest effect, due to the length and magnitude of drawdown with these options.

The preferred alternative would decrease shoreline erosion and mass wasting at Libby and Hungry Horse, increase these effects at Dworshak slightly, but would not significantly affect the lower Snake Projects.

## 5.2 CUMULATIVE IMPACTS

Assessing cumulative impacts is a key requirement of NEPA compliance. Impacts of system operations on the physical resources affected could be cumulative in several ways. They could accumulate over time; erosion and sedimentation impacts might be insignificant in any one year, but they might be additive over multiple years and represent significant long-term impacts. There can also be interaction effects among individual types of operations impacts, or between operations impacts and independent factors affecting the river system. The impacts of the SOS alternatives must therefore be assessed within the context of other reasonably foreseeable events that could increase or decrease the significance of expected impacts on geology, soils, and groundwater. The temporal and interactive (synergistic) aspects of the projected impacts are summarized in the following discussions.

### 5.2.1 Temporal Cumulative Impacts

The effects of the SOS alternatives would decrease significantly over the course of 20 years. The impacts of SOSs 1, 2, 4, 9, and PA would be fairly minor in the first year. In the following years, there would be an incremental decrease in impacts, as shorelines developed lag deposits as new drawdown zones were cleared of fine sediments.

The drawdown alternatives (SOSs 5, 6, 9a, and 9c) would also exhibit a rapid decrease in the amount of erosion over the first 6 years (Figure 5–1). After 6 years, erosion would approach a constant level. Continued operation of the natural river alternatives would result in no net sedimentation in the lower Snake River, as mentioned in Section 5.1. For the SOS 6 options, sediment input would also decrease rapidly, but not enough to flush out all of the annual sediment influx coming down the Snake. SOS 5d would have most of its impact the first year, with erosion and mass wasting rapidly decreasing to background levels.

### 5.2.2 Synergistic Impacts

The effects of the alternatives need to be considered in terms of the overall geologic/geomorphic picture, particularly if any thresholds might be crossed by increased sedimentation or erosion. Other activities that could affect the reservoir environment include additional landslide inputs, additional groundwater effects, and increased sedimentation.

If wet, stormy conditions prevailed during the first years of drawdown operations, erosion and sedimentation could be much more severe. Figure 5–1 shows three scenarios for shoreline erosion, based on deviations in weather patterns (see Appendix M, Water Quality, for detailed discussion). Estimated sediment quantities for the high–erosion scenario (wet, stormy conditions) are generally more than three times the quantities for the low–erosion scenario, and are nearly double the estimates for the moderate conditions (which were reported in Chapter 4).

A number of landslides along the Columbia River are known or thought to be the result of increased infiltration of water due to irrigation (National Park Service, 1992). It is conceivable that lower pool elevations at times of the year where irrigation is heavy could exacerbate the landslides. The degree of effect is difficult to estimate. The study by Jones et al. (1961) indicates that higher water tables could increase the affected area at some existing landslide areas by as much as 200 percent. They also suggest that the area around Libby Dam could be affected in this way, while the National Park Service report indicates Lake Roosevelt could be a potential impact area. The impacts of increased landslide activity could include loss of farmland structures, and road and railroad damage.

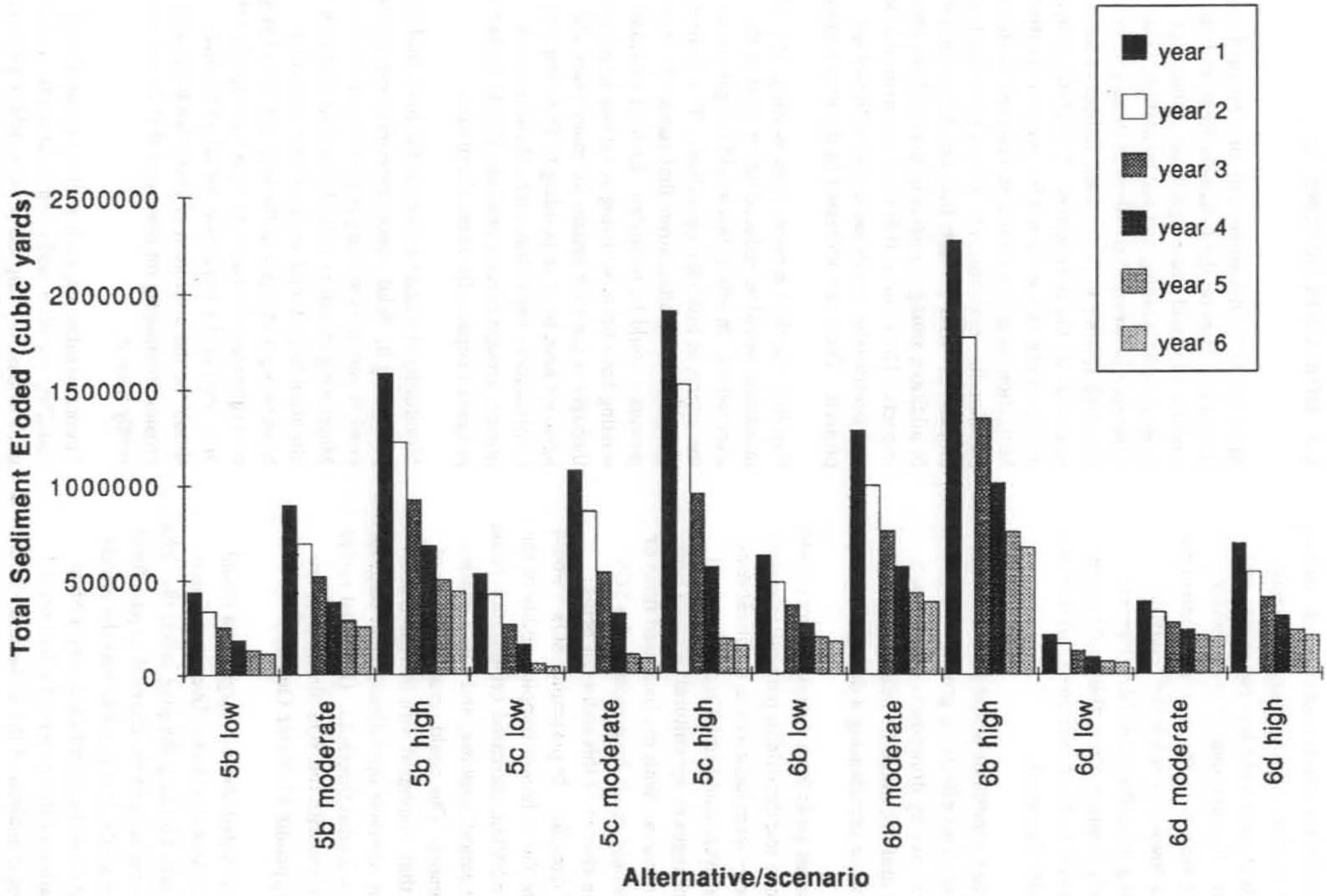

**Figure 5–1. Total Sediment Eroded, by Alternative, for First Six Years – Lower Granite.**

Additional groundwater effects could include shifting of groundwater divides. System operations could cause such shifts if pools were lowered during an already dry year. If contaminated groundwater exists within the vicinity of the river, the contamination could move toward or reach the reservoirs. Based on existing urban/industrial development patterns, the only location where this could potentially happen would be the Lewiston–Clarkston area on Lower Granite Reservoir.

Prevailing weather conditions would also interact with system operations effects on groundwater levels. Wells affected by drawdowns or increased storage project drafting would be more likely to go dry if the area were experiencing a drought.

Increased sediment yield from outside sources could affect the erosion and deposition patterns in mainstem rivers. Long–term increases in sediment contribution to the rivers could result from increased agriculture or changes in agricultural or other land management practices. With the increased flows or velocities that would result from most of the SOS alternatives, the chance of this sediment being trapped would diminish. In particular, SOS 5 would nearly eliminate the sediment trapping ability of the reservoirs. In addition, increased urbanization could locally increase runoff response, and cause incision of tributary streams. This could result in pulses of sedimentation that, combined with increased sedimentation from reservoir operations, could conceivably exceed a biological threshold. (Potential turbidity levels associated with the SOS alternatives are addressed in Appendix M, Water Quality.)

Under SOS 5, as noted above, a large delta would form at the mouth of the Snake River near Pasco. Besides potentially blocking shipping lanes, the delta would alter the capacity of the channel to pass flood waters. Consequently, it is possible that the effects of a large flood could be distributed over a wider area. Investigation of this potential effect would require hydrologic analysis of the Columbia–Snake River confluence area.

## 5.3 MITIGATION OPTIONS

All of the SOS alternatives call for continued operation of the dams on the Columbia River system. As a result, all would cause significant amounts of erosion, mass wasting, and sedimentation. The difference between alternatives in these processes are small relative to the baseline impact of what reservoirs do the river system. Therefore, mitigation measures can be considered for every alternative. Mitigation measures should be designed to stabilize the shoreline environment. This is more easily done on run–of–river projects than on storage projects. In addition, storage projects inherently have more impacts. The result is that there are unavoidable and irretrievable losses associated with storage projects. These are addressed in the next section.

Baseline shoreline erosion, mass wasting, and sedimentation would be reduced under most of the alternatives. In effect, this would mitigate some of the effects of historical operations. To a degree, the effects of those alternatives that accelerate these processes could be mitigated. Erosion and mass wasting have been occurring at various locations throughout the river system for many years and agencies have been responding to these impacts. Continuation, expansion, and enhancement of present erosion control practices should decrease the projected impacts for these alternatives.

Monitoring shoreline erosion is the basic tool for preventing it. While some reservoirs have regular erosion and mass wasting inspections, many do not. Monitoring identifies critical locations and may draw attention to potential areas of severe erosion. Monitoring is cheaper in the long run than fixing the consequences of erosion or mass wasting after the fact. Part of the mitigation for all alternatives should be the institution of yearly landslide and erosion monitoring on reservoirs that do not currently have it.

Physical treatments, such as slope removal and installing retention walls and revetments, could be used to diminish impacts in areas where property is threatened. Critical areas such as active landslides could also be protected by adding rock walls. These walls would not only protect the toes of slides from waves, but also serve to buttress them against future movement. This practice is common in shoreline protection (Davidson, 1992; City of Seattle, 1990). This could apply to all alternatives.

Additional treatments include a variety of wave dissipation structures, many of which are described in Davidson (1992). These include log booms, pontoons, log mats, and A–frame booms. Other offshore, non–floating breakwaters are made of stacked sand– or concrete–filled bags, stone structures, and gabions (rock–filled mesh boxes). All of these have been used in shoreline erosion control, although much of the use has been along marine shorelines. Floating breakwaters are more suited to shorelines that fluctuate, because the booms stay with the water level. However, most floating breakwaters are not designed for shorelines that fluctuate more than 20 feet (6 m). Most storage projects involved in the SOR have much greater fluctuation than that, even under SOS 4. In these situations, floating breakwaters would be used for protection at or near full pool. Hence, while critically eroding areas above the full pool can be mitigated, it is not feasible to protect areas significantly below this level from wave or surface erosion.

Fixed breakwaters are only suitable for reservoirs with small pool level fluctuations, such as run–of–river projects. Due to their expensive nature, erosion control structures such as these would be used only in areas of the most critical importance, such as vital or rare habitat, or in situations where historical or otherwise important structures are threatened.

Biotechnical stabilization methods are also available. These methods can be used in severely eroding areas or areas with shallow landslides. The techniques include willow wattling, using cigar–shaped bundles of freshly cut willow sprigs (Comes and McCreary, 1986). Another technique involves regrading the bank and installing alternating sequences of live branches and fill material (see Leiser, 1992). A diverse array of combinations of biotechnical and mechanical stabilization exists (Goldsmith and Bestman, 1992; Allen and Klimas, 1986). In severely eroding areas, both types of stabilization may be necessary. Given the large areas involved and the cost of the stabilization, these techniques would have to be selectively placed in only the most critical areas. Each site would have to be evaluated to determine which method is appropriate. Properly installed and maintained shoreline revegetation/stabilization programs have been very effective. These techniques would apply to all alternatives.

For the alternatives that involve drawdown (SOSs 5, 6, and 9), riprap protection would be needed on the upstream side of each embankment of the dams involved (Corps, 1991). The quantity of riprap could be quite large depending on the alternative. For SOS 5, riprap would have to be extended from the current wave protection zone to the lowest parts of the dam on all four lower Snake reservoirs. This represents a huge quantity of riprap. An alternative to using riprap would be to install grouted geotextile blankets. Mitigation for either option under SOS 5 would be the most expensive of any of the alternatives. SOS 6 would also require dam embankment protection, but only to the level of the drawdown, and not to the base of the dam. Option 6d would require embankment protection on Lower Granite only.

The drawdown alternatives represent such a severe alteration of the reservoir system that much of their impact cannot be prevented. Some potential options include armoring sensitive areas with riprap,although this would damage aquatic habitat. Railroad and highway embankments deemed sensitive should be monitored during drawdowns. These could be reinforced, if necessary. Much of the damage to these facilities may not be preventable, and may be only correctable after initial drawdown.

Interruption of water supply due to lowering of the groundwater table during drawdown could be mitigated by supplying groundwater users with alternative sources of water. In some areas, it could be difficult to find replacement sources of water. Water could be diverted from nearby surface water sources, or trucked in from other wells or surface sources.

## 5.4 IRREVERSIBLE AND IRRETRIEVABLE IMPACTS

While some mitigation techniques can be applied to the projects, only a minor amount of the effects can be prevented. For instance, at Lake Roosevelt, it is not feasible to stabilize every landslide, since there are so many. Reclamation has developed a program of property acquisition to avoid the most financially tangible impact, the loss of private property. More subtle losses, such as loss of fish and wildlife habitat, receive lower priority because they are less easily prevented.

The long–term effects of reduction in sediment transport, aggradation of tributaries, and soil loss cannot be mitigated because the dams themselves are the cause. However, SOS 5c would return the lower Snake River to natural conditions year round. Thus, it is the only alternative that would eliminate the impact of some of the dams themselves. Areas already inundated by the reservoirs, particularly the storage reservoirs, are unavoidably affected and the losses associated with them are irretrievable. The only additional unavoidable impacts, over and above the baseline conditions, are those impacts associated with drawdown.

The lower Snake River system would be dramatically altered under SOSs 5, 6, 9a, and 9c. Most of the erosion and mass wasting that would occur under these alternatives would be unavoidable. Large areas of aquatic habitat and some terrestrial habitat would be irretrievably lost. Additionally, high turbidity is unavoidable. Sedimentation downstream of the drawdown reservoirs would be unavoidable. Benthic organisms in Lake Wallula would be buried by sediment under SOS 5, although this might be a temporary effect. Under SOS 6, 9a, and 9c, sediment would primarily be redistributed within each reservoir, which would destroy aquatic habitat in the upstream reaches of each reservoir.

# CHAPTER 6

# LIST OF PREPARERS

The Geology Technical Appendix was prepared by Foster Wheeler Environmental Corporation (formerly Enserch Environmental), a consulting firm under contract to BPA. Individuals who contributed to the report are listed in Table 6–1. Contributors are listed by name, education, years of experience, experience and expertise, and role in technical appendix preparation.

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| Name | Education/Years of Experience | Experience and Expertise | Role In Preparation |
|---|---|---|---|
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| Bruce Stoker<br>Geomorphologist | M.S.E., Civil Engineering<br>M.S., Remote Sensing/Geology<br>B.S., Geology<br>16 Years | Hydrology<br>Sediment transport<br>Slope stability<br>Geology | Technical review and supervision |
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## Table 6–2. Enserch Environmental List of Preparers – CONT

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# CHAPTER 7

# GLOSSARY

**Alluvial Fan:** A low, outspread, gently sloping fan shaped stream deposit where the gradient of the stream suddenly decreases

**Alluvial River:** A river that occupies a broad flood plain over which the depth of alluvium deposited by the river equals or exceeds the depth to which scour takes place in time of flood.

**Alluvial Terrace:** A stream terrace composed of unconsolidated alluvium.

**Alluvium:** A general term for unconsolidated, sorted to semi–sorted material deposited by a stream or other body of running water during comparatively recent geologic time

**Aquifer:** Body of rock sufficiently permeable to conduct ground water in economic quantities to wells and springs

**Avulsion:** Sudden cutting off of land by a flood or by an abrupt change in the course of a stream.

**Basalt:** General term for a dark–colored, mafic volcanic rock.

**Base Flow:** Sustained or fair–weather flow of a stream

**Base Level:** The lowest level toward which erosion progresses; esp. the level below which a stream cannot erode its bed

**Batholith:** A large discordant plutonic (igneous intrusive) mass that has greater than 40 sq. mi. of surface exposure and no known floor.

**Catchment:** The area contributing flow to a given stream.

**Cenozoic:** Era of geologic time, from the beginning of the Tertiary period to present; about 65 million years ago to present

**Colluvium:** A general term applied to loose, heterogeneous, and incoherent mass of soil and rock material deposited by rainwash, sheetwash, or creep, usually at the base or sides of hills.

**Conglomerate:** A coarse–grained, clastic sedimentary rock composed of fragments greater than 2 mm in a fine–grained matrix.

**Debris Flow:** A moving mass of rock fragments, soil and mud, with more than half the particles being larger than sand size.

**Degradation:** The wearing down or away of the earth's surface by the natural processes of weathering or erosion, e.g., the deepening by a stream of its channel.

**Disaggregation:** Separation or reduction of an aggregate into its component parts.

**Drainage Pattern:** The configuration in plan view of the natural stream courses in an area

**Dynamic Equilibrium:** Condition of a system in which there is a balanced inflow and outflow of materials.

**Entrainment:** The process of picking up or carrying along.

**Eolian:** Pertaining to wind; esp. of loess and sand dune deposits and their wind–formed sedimentary structures.

**Ephemeral Stream:** A stream that flows briefly in response to precipitation in the immediate area.

**Flow Breccia:** A breccia (angular conglomerate) formed at the same time with the movement of a lava flow.

**Gabbro:** A group of dark colored, basic intrusive igneous rocks.

**Glacial Outwash:** Stratified detritus removed from a glacier by meltwater streams.

**Granite:** Broadly applied, any crystalline, quartz-bearing plutonic rock; specifically refers to plutonic rocks with quartz constituting 10 to 50 percent of the felsic components and the alkali feldspar/total feldspar ratio restricted to the range of 65 to 90 percent.

**Granitoid:** A term for plutonic rocks with quartz composition between 20 and 60 percent that includes granite, tonolite, and granodiorite

**Granodiorite:** A plutonic rock containing between 20 and 60 percent quartz and with the alkali feldspar/total feldspar ratio restricted to the range of 45 to 10 percent.

**Greenstone:** A field term for any dark green, altered or metamorphosed basic igneous rock.

**Head Scarp:** The steep surface on the undisturbed uphill side of a landslide.

**Infiltration Capacity:** The maximum or limiting rate at which soil can absorb precipitation.

**Interill:** The area between rills acted on by rain splash and thin film runoff erosion.

**Intrusion:** The process of emplacement of magma in pre-existing rock.

**Jurassic:** Second period of the Mesozoic era (after the Triassic and before the Cretaceous) between 190 and 135 million years ago.

**Lacustrine:** Pertaining to a lake or lakes

**Laminar Flow:** Water flow in which the stream lines remain distinct and flow direction remains unchanged with time.

**Limestone:** A sedimentary rock composed predominately of the mineral calcite. Many are the result of marine organic activity and contain fossils.

**Liquefaction:** In a cohesionless soil, the transformation from a soil to a liquid as a result of increased pore pressure and reduced effective stress.

**Lodgement Till:** Glacial deposit produced at the base of, and/or overidden by glaciers; very dense.

**Loess:** A widespread, homogeneous, porous, fine-grained blanket deposit consisting of silt, generally believed to be windblown dust of Pleistocene age.

**Main Stem:** The principle coarse of a stream.

**Mantle:** The zone of the earth below the crust and above the core.

**Mass Wasting:** General term for downslope transport of rock and soil material due to gravitational stress and not transported in another medium such as water or ice.

**Mesozoic:** An era of geologic time from the end of the Paleozoic to the beginning of the Cenozioc, 225 to 65 million years ago.

**Metamorphism:** The mineralogic, chemical and structural adjustment of rock to temperature, pressure, and chemically active fluids below the surface zone of weathering and under different conditions from which the rocks originated.

**Microtopography :** Topography on a small scale.

**Knickpoint:** Any interruption or break in slope, esp. a point of abrupt change or inflection in the longitudinal profile of a stream. Channel incision often migrates upstream, forming a knickpoint at the present upstream extent of incision.

**Paleozoic:** Era of geologic time from the end of the Precambrian to the beginning of the Mesozoic, 570 to 225 million years ago.

**Peridotite:** General term for a coarse-grained plutonic rock composed predominately of olivine and possibly other mafic minerals

**Physiography:** A description of the surface features of the earth, as bodies of air, water and land.

**Piping:** Erosion by percolating water in a layer of subsoil, resulting in the formation of narrow conduits (pipes) through which soil material is removed.

**Plastic Flow:** A permanent change in the shape of a solid that is not initiated by rupture.

**Pleistocene:** An epoch of the Quaternary period following the Pliocene epoch of the Tertiary and proceeding the Holocene epoch of the Quaternary period, beginning 2 to 3 million years ago and continuing until about 10,000 years ago.

**Pliocene:** An epoch of the Tertiary period following the Miocene and before the Pleistocene.

**Pluton:** An igneous intrusion

**Pore–pressure:** Pressure exerted by water in the interstitial spaces of soil.

**$P_R$:** Total pool elevation range.

**Precambrian:** All geologic time before the beginning of the Paleozoic about 570 million years ago.

**Quaternary:** Second period of the Cenozoic era following the Tertiary period, beginning 2 to 3 million years ago and continuing to present.

**Rill:** Small channel eroded in soil by water detachment

**Sandstones:** A medium–grained, clastic sedimentary rock composed of an aggregate of sand–sized particle visible to the unaided eye.

**Sapping:** Process of erosion of a cliff base by the wearing away of softer layers, generally by groundwater movement resurfacing and causing slope collapse.

**Saprolite:** A soft, earthy, typically clay–rich, thoroughly decomposed rock.

**Schist:** A strongly foliated metamorphic rock that can be split into thin flakes or slabs.

**Scoriaceous:** Volcanic texture, typically in basalt, in which the rock is composed predominately of vesicles (holes).

**Sedimentary:** Pertaining to sediment or formed by the deposition of sediment.

**Shale:** A laminated, fine–grained sedimentary rock, formed from the compression of mud, clay or silt, whose gains are not normally visible to the unaided eye.

**Shear Strength:** The internal resistance of a body to shear stress.

**Slate:** A compressed, fine–gained metamorphic rock, probably formed from shale, that can be split into slabs and thin plates.

**Slump:** Landslide characterized by shearing and rotation of a land mass about a curved slip surface.

**Soil Creep:** The gradual, steady downhill movement of soil on a slope.

**Stratovolcano:** A volcano constructed of alternating layers of lava and pyroclastic deposits.

**Subaqueous:** Conditions, processes, or deposits that occur under the surface of a body of water.

**Subglacial Till:** Till formed or accumulated on the bottom of a glacier.

**Supraglacial Till:** Till carried upon or deposited from the top surface of a glacier.

**Surficial:** Pertaining to processes and deposits on the surface of the earth.

**Tailrace:** Outlet structure at a dam.

**Talus:** Coarse rock fragments lying at the base of a cliff or steep rocky slopes.

**Tephra:** General term for all pyroclastic (hot material ejected from a volcano) material.

**Thalweg:** The line connecting the lowest or deepest points along a stream bed or valley.

**Till:** Unsorted, unstratified drift, generally unconsolidated, deposited by a glacier.

**Tuff:** General term for all consolidated pyroclastic (hot material ejected from a volcano) rocks.

**Turbidity:** The state of reduced clarity of a fluid due to the presence of suspended matter.

**Turbidity Current:** A bottom–flowing current laden with suspended sediment, moving swiftly down a subaqueous slope, which is set up and/or maintained in motion by stirred–up sediment that gives the current a greater density than that of the surrounding water.

**Turbulent Flow:** Water flow in which the flow lines are confused and heterogeneously mixed.

**Varve:** A sedimentary bed deposited in a still body of water over a year's time, often paired when associated with glacial lake deposits reflecting a seasonal variation.

**Weathering:** Destructive processes occurring at the surface of the earth involving physical and chemical deterioration without significant transport of materials.