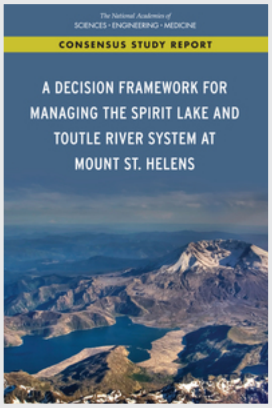

A Decision Framework for Managing the Spirit Lake and Toutle River System at Mount St. Helens (2018)

DETAILS

336 pages | 6 x 9 | PAPERBACK
ISBN 978-0-309-46444-4 | DOI 10.17226/24874

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SUGGESTED CITATION

National Academies of Sciences, Engineering, and Medicine 2018. *A Decision Framework for Managing the Spirit Lake and Toutle River System at Mount St. Helens*. Washington, DC: The National Academies Press. https://doi.org/10.17226/24874.

A DECISION FRAMEWORK FOR MANAGING THE SPIRIT LAKE AND TOUTLE RIVER SYSTEM AT MOUNT ST. HELENS

Committee on Long-Term Management of the Spirit Lake/
Toutle River System in Southwest Washington

Committee on Geological and Geotechnical Engineering
Board on Earth Sciences and Resources
Water Science and Technology Board
Division on Earth and Life Studies

Board on Environmental Change and Society
Division of Behavioral and Social Sciences and Education

A Consensus Study Report of

The National Academies of
SCIENCES · ENGINEERING · MEDICINE

THE NATIONAL ACADEMIES PRESS
Washington, DC
www.nap.edu

THE NATIONAL ACADEMIES PRESS • 500 Fifth Street, NW • Washington, DC 20001

This activity is supported by the U.S. Department of Agriculture's U.S. Forest Service under Grant No. 16-DG-11261952-008. Any opinions, findings, conclusions, or recommendations expressed in this publication do not necessarily reflect the views of any organization or agency that provided support for the project.

International Standard Book Number-13: 978-0-309-46444-4
International Standard Book Number-10: 0-309-46444-7
Digital Object Identifier: https://doi.org/10.17226/24874

Additional copies of this publication are available for sale from the National Academies Press, 500 Fifth Street, NW, Keck 360, Washington, DC 20001; (800) 624-6242 or (202) 334-3313; http://www.nap.edu.

Printed in the United States of America

Cover: Front image: Mount St. Helens, 100 miles south of Seattle, Washington, boasts the deadliest and most economically destructive volcanic explosion in U.S. history when it erupted on May 18, 1980. Its original height of 9,667 feet was reduced to 8,363 feet. Spirit Lake, seen here, was raised approximately 200 feet in the eruption. The image is courtesy of Barry Maas and his images are available at https://www.flickr.com/photos/bmaas. The rear cover is courtesy of C. Scott Cameron of GeoLogical Consulting, LLC, and a member of the Board on Earth Sciences and Resources. View is looking east to the upper Toutle River valley, Mount St. Helens, and the 1980 blast zone, Spirit Lake, and in the distance, Mount Adams. Taken October 31, 2017.

Suggested citation: National Academies of Sciences, Engineering, and Medicine. 2017. *A Decision Framework for Managing the Spirit Lake and Toutle River System at Mount St. Helens.* Washington, DC: The National Academies Press. doi: https://doi.org/10.17226/24874.

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Preface

The 1980 eruption of Mount St. Helens resulted in a massive debris avalanche and pyroclastic flow into the Toutle River valley. This event caused sweeping changes to the hydrology of the Toutle River and to the Cowlitz River into which the Toutle flows. The headwater of the Toutle River in Spirit Lake was blocked by volcanic debris hundreds of feet in depth, and the lake bottom itself was raised 200 feet. Catastrophic breaching of the blockage by high water in Spirit Lake could release more than 300,000 acre-feet of water and 2.4 billion cubic yards of sediment into the Toutle, Cowlitz, and Columbia Rivers, causing massive damage and loss of life.

The U.S. Forest Service (USFS) is responsible for a large part of the region around and including Mount St. Helens and Spirit Lake. Following the eruption, several alternatives were considered for draining the lake and maintaining a safe water level. The solution chosen was to bore a tunnel through Harry's Ridge into the Coldwater Creek drainage and thus into Coldwater Lake. Now, some 36 years later, that tunnel has undergone and is again in need of expensive repairs. While the tunnel is located on land managed by the USFS, it was constructed by the U.S. Army Corps of Engineers (USACE). Using funds provided by the USFS, the USACE has inspected and repaired the tunnel since its construction. The U.S. Geological Survey (USGS) has responsibility for monitoring geologic activity in the region.

The technical issues precipitated by the 1980 eruption include management not only of Spirit Lake and its drainage but also of the massive volume of sediments resulting from the eruption. Those sediments continue to be transported down the North Fork Toutle River where they create hazards to the environment, flood risk, and hazards to navigation. In 1989, the USACE constructed a sediment retention structure (SRS) in the North Fork Toutle River to minimize sediment transport into the

Toutle and Cowlitz Rivers by trapping that sediment upstream of the SRS. Whereas the SRS provided a temporary solution for sediment management downstream, its existence and management affects other aspects of river management, for example, restoring passage for anadromous fish in the system and protecting cultural and recreational resources.

Today, a complex system of infrastructure exists to control water and sediment flow. This infrastructure is subject to multiple natural hazards, including volcanic, seismic, and hydrologic, and is the responsibility of separate federal, state, and local agencies. The need for millions of dollars of repairs on the tunnel prompted members of Congress to request that the USFS, the USACE, and the USGS develop a long-term plan to manage water levels. An ad hoc committee of the National Academies of Sciences, Engineering, and Medicine was ultimately convened at the request of the USFS to "recommend a framework for technical decision making related to long-term management of risks related to the Spirit Lake and Toutle River system in light of the different priorities of federal, tribal, state, relevant local authorities, and other entities." The management of a system of this complexity requires a methodical framework suitable to the systems aspects of the problem and the uncertainties that attend it. Identifying such a framework has been the committee's goal.

The committee is grateful for the competence and efficiency of the National Academies staff assigned to this project. Complicated logistical arrangements were handled with ease and good humor by Nicholas D. Rogers, financial and research associate, and Courtney R. DeVane, administrative assistant. Leonard A. Shabman, resident scholar at Resources for the Future, served as an unpaid consultant to the committee. Paul Stern, a National Academies scholar, contributed to the committee's meetings and report, as did Edmond Dunne. We would also like to thank National Academies staff member David Policansky for providing comments on the draft report.

The staff director for the project has been Sammantha L. Magsino, senior program officer with the Board on Earth Sciences and Resources.

Without her, this study would not have been successful. She has an ability to convert energetic discussion into consensus, miscellaneous prose into coherent text, and rambling discourse into a rational report.

Gregory B. Baecher
Chair

Acknowledgments

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

Shane J. Cronin, The University of Auckland and GNS Science Ltd., New Zealand
Robin Gregory, Decision Research, Halfmoon Bay, British Columbia, Canada
William Hansmire, NAE, WSP USA, Los Angeles, California
James K. Mitchell, NAE/NAS, Virginia Polytechnic Institute and State University, Blacksburg
Doug Plasencia, Moffatt & Nichol, Phoenix, Arizona
Bob Royer, Gallatin Public Affairs, Seattle, Washington
Jeff Rubin, Tualatin Valley Fire and Rescue, Tigard, Oregon
Colin Thorne, University of Nottingham, Nottingham, United Kingdom
Thomas Yancey, Texas A&M University, College Station

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by John Christian, an independent consultant, and Catherine Kling of Iowa State University. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

The committee met four times over a 6-month period: three times in Kelso, Washington, and a final meeting in Washington, DC. In the course of those meetings, the committee consulted with interested and affected parties, including those from the private and public sectors. The committee would like to thank, in alphabetical order: Gene Crocker, Cowlitz Game and Anglers Club; Gregory Drew, Drew's Grocery, Toutle; Joe Gardener, Cowlitz County Board of Commissioners; Ashley Helenberg, Port of Longview; Dave Howe, Regional Habitat Program, Washington Department of Fish and Wildlife; Claudia Hunter, Toutle Valley Community Association; Steve Ogden, Pacific-Cascade Region, Washington Department of Natural Resources; Nathan Reynolds, Natural Resources Department, Cowlitz Indian Tribe; Ernie Schnabler, Cowlitz County Emergency Management; and Ray Yurkewycz, Mount St. Helens Institute. The committee also met with and heard presentations from representatives of local, state, and federal agencies. They included, alphabetically, from the USACE, Sean Askelson, Jeremy Britton, Christine Budai, Angela Duren, Tim Kuhn, Paul Sclafani, and David Scofield; from the USFS, Charlie Crisafulli, Gordon Grant, Tedd Huffman, Gina Owens, and Jim Peña; and from the USGS, Jon Major.

During its open session meetings, town hall discussions, and site visits in the region, the committee had the opportunity to interact with and learn from numerous individuals from affected communities and various interest groups. Individuals also provided written feedback to the committee. Their voluntary engagement with the committee is an indication of the importance placed on the sound and responsive management of the Spirit Lake and Toutle River system.

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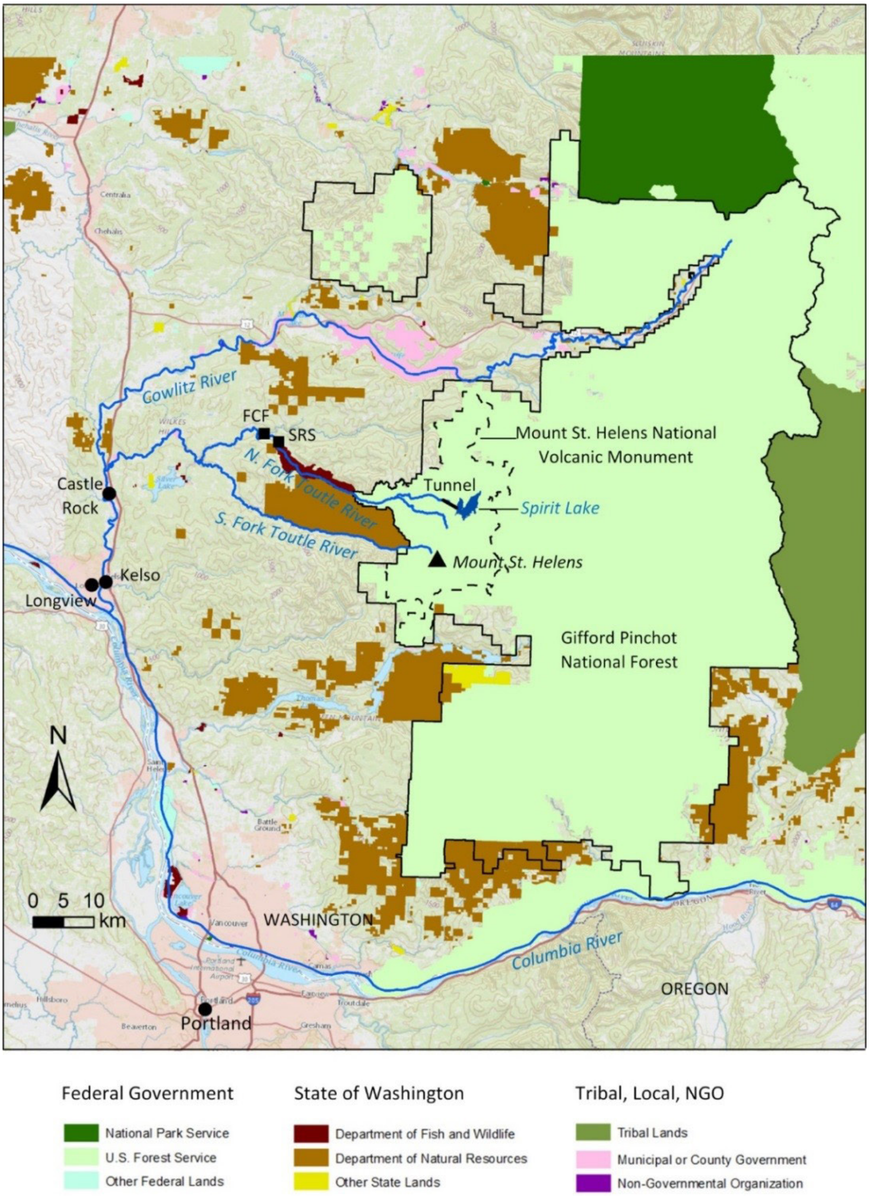
Summary

The 1980 eruption of Mount St. Helens in southwest Washington State radically changed the physical and socioeconomic landscapes of the region. The eruption destroyed the summit of the volcano, sending large amounts of debris into the North Fork Toutle River and blocking the sole means of drainage from Spirit Lake 4 miles (6.4 km) north of Mount St. Helens (see Figure S.1). Rising lake levels could cause failure of the debris blockage, putting the downstream population of approximately 50,000 at risk of catastrophic flooding and mud flows. Furthermore, continued transport of sediment to the river from volcanic debris deposits surrounding the mountain reduces the flood carrying capacity of downstream river channels and leaves the population vulnerable to chronic flooding.

Engineering measures were implemented in the 1980s to manage both catastrophic and chronic risks associated with the debris blockage and sediment loads in the rivers. These included construction of a 1.56 mile (2.6 km) tunnel at Spirit Lake to drain the lake and control lake levels, a sediment retention structure (SRS) on the North Fork Toutle River approximately 8 miles (~13 km) downstream of Spirit Lake, and implementation of flood risk management measures, including levee upgrades in the lower Cowlitz River valley. River dredging has also been necessary to maintain navigation.

Engineering measures now in place, however, do not represent long-term solutions to the region's risk management challenges. Because the Spirit Lake outflow tunnel serves as the only drainage for Spirit Lake, disruption of tunnel operations leaves the debris blockage vulnerable to breaching. The tunnel has required major repairs and is not operating optimally. Additional expensive repairs are necessary, and, as for any constructed facility, continued costly maintenance will be needed. Downstream, the SRS is close to reaching its sediment trapping capacity, and


Gowlitz River
FCF
SRS
N. Fork Toutle River
S. Fork Toutle River
Mount St. Helens National Volcanic Monument
Tunnel
Spirit Lake
Mount St. Helens
Gifford Pinchot National Forest
Castle Rock
Kelso
Longview
N
0 5 10
km
WASHINGTON
Columbia River
OREGON
Portland
Federal Government
National Park Service
U.S. Forest Service
Other Federal Lands
State of Washington
Department of Fish and Wildlife
Department of Natural Resources
Other State Lands
Tribal, Local, NGO
Tribal Lands
Municipal or County Government
Non-Governmental Organization

plans to increase that capacity by raising the SRS spillway provide only short-term solutions to the sediment transport problem.

The legacy of the 1980 eruption and the prospect of future volcanic, seismic, and flood events mean that risk management in the Spirit Lake and Toutle River system will be challenging for decades to come. Future actions need to accommodate a much broader range of objectives and priorities of all interested and affected parties in the region. Meanwhile, the responsibilities for managing risk and the natural resources in the watershed are dispersed among federal, state, and local agencies of government with different and sometimes conflicting goals and authorities.

THE STUDY CHARGE

Inspections of the Spirit Lake outflow tunnel in 2014 indicating a need for millions of dollars in repairs to avoid failure led members of Congress to request that the U.S. Forest Service (USFS), the U.S. Army Corps of Engineers (likely), and the U.S. Geological Survey (USGS)—agencies with mandated responsibilities in the region—develop a long-term plan to manage Spirit Lake water levels. At the request of the USFS, the National Academies of Sciences, Engineering, and Medicine convened a committee to develop a decision framework to support the long-term management of risks related to the Spirit Lake and Toutle River system in light of the

FIGURE S.1 Mount St. Helens (triangle) is located in the Mount St. Helens Volcanic Monument (dashed line) and Gifford Pinchot National Forest (green) in southwest Washington. Spirit Lake is approximately 4 miles to the north of Mount St. Helens. The Toutle and Cowlitz Rivers and a portion of the Columbia River are shown. The USACE sediment retention structure (SRS; square) is on the North Fork of the Toutle River. Approximately 50,000 people in the towns on the Toutle and Cowlitz Rivers are at risk of chronic and catastrophic flooding associated with material from the 1980 volcanic eruption. SOURCES: Map by authors; base map: @OpenStreetMap and contributors, including the USGS's The National Map: National Boundaries Dataset, 3DEP Elevation Program, Geographic Names Information System, National Hydrography Dataset, National Land Cover Database, National Structures Dataset, and National Transportation Dataset; U.S. Census Bureau—TIGER/Line and USFS Road Data.

different regional economic, cultural, and social priorities and the respective roles of federal, tribal, state, and local authorities, as well as other entities and groups in the region (referred to herein as interested and affected parties).

In addition to developing a decision framework, the committee was asked to consider the history and adequacy of characterization, monitoring, and management associated with the Spirit Lake debris blockage and outflow tunnel; to consider other efforts to control transport of water and sediment from the 1980 and later eruptions; and to suggest additional information needed to support implementation of the recommended decision framework. The committee was also asked to identify alternatives that might be considered for long-term management of water and sediment transport within the Spirit Lake and Toutle River system. The statement of task does not call for the committee to quantitatively examine the viability of long-term management alternatives. Instead, regional authorities, guided by the proposed decision framework, would perform detailed analyses later. The committee concluded that such an examination could include a quantitative risk assessment, benefit-cost analyses, and analyses of other data.

THE EVOLVING DECISION LANDSCAPE

Two types of long-term and system-wide risks need to be considered in the Spirit Lake and Toutle River region. First are the relatively high-probability, moderate-consequence risks associated with chronic flooding along the Toutle and Cowlitz Rivers. These could cause social and economic disruption in populated and commercial areas and are mostly the result of channel infill from the movement of sediment out of the Toutle River and into the Cowlitz River. Second is the likelihood of life loss and community destruction caused by catastrophic flooding and mudflows into populated areas along the Toutle River and the lower Cowlitz River. These risks are of relatively low probability but high consequence, likely the result of the destabilization of sediment above the SRS or due to a breach of the Spirit Lake debris blockage.

Following the 1980 eruption, two principal considerations influenced management decisions: (1) the costs of possible management actions and (2) their impacts on the safety of downstream communities.

Decision making related to water and sediment transport in the region has tended to be linear: a responsible agency formulated a specific problem within its authority, analyzed options, and made a decision. Engagement with interested and affected parties consisted largely of public meetings held by the agency at certain points in the decision process to receive public comments. Although this process accomplishes some goals, it typically limits opportunities to explore the values and management ideas of other interested and affected parties, misses opportunities to identify joint gains, and can leave the excluded parties lacking trust in decisions made by those in authority. Decades past the initial response, values such as those related to ecological conditions and recreational benefits have gained currency in stakeholder perceptions. For example, prior to the eruption, the North Fork Toutle River valley was an important recreation area for fishers, hunters, and other users. Commonly discussed among local residents today are the impacts of management decisions on the possibility of recovering fish species, including salmon, steelhead, and the sea-run coastal cutthroat trout, all of which spawn naturally within river systems.

DATA AND ANALYTICAL NEEDS

Since 1980, natural and engineered processes have changed the Spirit Lake and Toutle River system. Engineering practice has evolved, as have concerns among interested and affected parties. Many data collection activities, however, such as groundwater monitoring within the debris blockage and most measurements of sediment sources and transport, stopped in the 1980s or 1990s, and few new data have been collected in response to changing priorities, such as those related to aquatic ecology. The information available to correctly inform long-term management of the region is outdated and incomplete. Physical characterization of components of the system needs to be updated. Monitoring capabilities and data collection programs need to be updated, and analytic capabilities need to be reevaluated. Key data that could inform decisions need to be identified collaboratively.

Decisions related to the long-term management of Spirit Lake water levels need to be informed by a current characterization of the debris blockage damming the lake; the location and behavior of groundwater in the blockage; current meteorological trends; a quantified characterization of risks posed by volcanic activity on Spirit Lake water levels; and on the response of the blockage to local and regional seismic events. Recent insights regarding the likelihood of a Cascadia Seismic Zone earthquake affecting the Mount St. Helens vicinity warrant greater examination. Systematic site-specific seismic hazard studies to develop reliable estimates of anticipated ground shaking are needed (particularly at Spirit Lake and the SRS) but have not been performed although such analyses are routine for infrastructure around the country.

Recommendation: Agencies engaged in risk management in the Spirit Lake and Toutle River region should develop a coordinated and targeted monitoring system to track changes in factors that affect risk. Data and analyses should be shared and made available to all. (Chapter 4)

OPERATIONAL RISK

Among the more credible risk scenarios for Spirit Lake is the rapid lake level rise observed during periods when the tunnel is closed for repair. This represents an operational risk. Another operational risk could be failure of such engineered structures as the SRS or levees. Occupational safety and health risks associated with operating infrastructure (e.g., wood debris removal near the Spirit Lake tunnel intake or opening and closing the tunnel gates) represent another kind of operational risk. It appears that such operational factors have not been systematically considered in appraising risks associated with the Spirit Lake and Toutle River system.

Modern approaches to risk management are increasingly based on probabilistic risk analyses, which address the capability of a system to withstand extreme loads such as the demand caused by the probable maximum flood or a maximum credible earthquake. Probabilistic risk analysis is especially useful in appraising design and rehabilitation decisions and corresponding factors of safety.

Assessing operational risk involves considering the vagaries of weather, human operators, sensors, supervisory control and data acquisition (SCADA) systems, and other operational factors. It may be that the risks posed by the system derive in part from these operational factors rather than from natural hazards and extreme events alone.

Recommendation: Operational risk should be explicitly considered when evaluating alternatives for management. (Chapter 5)

THE DECISION FRAMEWORK

Given the uncertainties associated with potential moderate intensity and catastrophic events, as well as the analytic uncertainty associated with incomplete or outdated information, an analytic decision process that establishes risk management as an organizing principle is needed. But, given the competing values of interested and affected parties in the region; the lack of agreement on planning time frames; the overlapping but sometimes competing management responsibilities and authorities in the region; and the limited budgets of those authorities, that process needs to promote communication and trust among agencies and the public so that technical decisions effectively and satisfactorily incorporate the priorities of those interested and affected parties.

Recommendation: Adopt a deliberative and participatory decision-making process that includes technical considerations; balances competing safety, environmental, ecological, economic, and other objectives of participants; appropriately treats risk and uncertainty; and is informed by and responsive to public concerns. Dialogue among interested and affected parties and technical experts should be iterative, begin with the formulation of the problem, and continue throughout the decision process. (Chapter 6)

The multiple objectives of enhanced safety of downstream communities and the protection of the local and regional ecology and economic activities, per the statement of task, need to be integral to the decision-making process. A decision framework is defined herein as a model to guide the systematic processes for making choices in the face of complexity and uncertainty. It assists interested and affected parties in the region in addressing management issues. The "PrOACT" framework (Keeney, 1988) is one such model that includes the following steps: (1) clarify the decision **Pr**oblem; (2) identify the decision **O**bjectives and ways to measure them; (3) create a diverse set of **A**lternatives; (4) identify the **C**onsequences; and (5) clarify the **T**rade-offs. These steps are similar to those in other frameworks.

Although originally intended for use by a single decision maker, the PrOACT framework has been modified for decisions made by multiple decision makers and applied successfully to other water management decisions of significant complexity. The committee recommends the PrOACT construct in this modified form because it is based on an analytical-deliberative process that relies on the results of scientific and engineering investigations and incorporates deliberation with representatives of the broader public throughout the decision process to both influence and be influenced by technical analysis. Second, the decision framework explicitly calls for use of decision analysis techniques to properly account for the multiple objectives and multiple values of interested and affected parties.

Step 1: Clarifying the Decision Problem in a Participatory Setting

A decision problem is defined as that issue or set of issues about which management decisions need to be made. Broadly stated, the decision problem in this case is to determine a long-term solution for managing water and sediment transport in the Spirit Lake and Toutle River system. An overall goal of the recommended decision framework is to search for and identify mutually supportable, effective, and defensible management alternatives. The process requires agreeing on the following elements:

- Who leads the process?
- Who is involved, and what are their roles?
- What types of solutions can be considered?
- What is the geographic scope under consideration?
- What is the time frame being considered for this decision problem?

Early in the decision process, the full range of interested and affected parties needs to be engaged at a depth sufficient for management decisions to be adequately informed by their concerns and values. Agencies may already include other interested and affected groups in community outreach, but their methods of inclusion are in need of reshaping.

Participants in the decision process may include, but are not limited to, agencies with authority or other interests in the area; those who experience the safety, economic, cultural, or life-quality impacts resulting from management decisions; and those with specialized knowledge related to potential management impacts. The number of people participating in focused discussions needs to represent the broad spectrum of interests of the region but also needs to be small enough (i.e., not more than 25 people) so that technical and socioeconomic trade-off discussions can be of sufficient depth to be meaningful and effective. In addition to this group, there must be a neutral support team that includes expertise in the technical and scientific fields of concern, decision analysis, stakeholder engagement, and group facilitation. This team is responsible for implementing the decision framework.

Recommendation: Broaden and deepen the participatory decision-making process from its early stages to include and assimilate the knowledge and interests of affected groups and parties whose safety, livelihoods, and quality of life are affected by management decisions. (Chapter 6)

Identifying a Lead

No single agency in the region (e.g., the USFS or the USACE) has unilateral authority to make choices and funding decisions about management across the system. Outcomes may be perceived as biased if a multiparty process is implemented primarily using the internal resources of any single agency. A framework implementer—a lead—needs to be identified that is responsible for understanding and applying the collaborative analytic decision-making process. This may be the agency with authority over the primary issue at hand, but agreement among interested and affected parties (including agencies with management authorities in the region) regarding the choice of the lead builds trust in the decision process. If the lead or the lead agency lacks the skills needed to provide high-quality and neutral support for decision making, those skills could be recruited externally.

Ideally, the lead would be a new system-level entity or a formal consortium of existing agencies. This would provide a central focus for congressional mandates and appropriations, ensure collaboration across agency and jurisdictional boundaries, and maintain continuous engagement by all interested and affected parties. Such an arrangement would likely require a number of congressional actions.

Recommendation: Create a system-level entity or consortium of agencies to lead a collaborative multiagency multi-jurisdictional effort that can plan, program, create incentives, and seek funding to implement management solutions focused on the entire Spirit Lake and Toutle River system. This effort should also be open and accountable to interested and affected parties involved in management decisions. (Chapter 6)

Identifying the Geographic Scope

The Spirit Lake and Toutle River system is a physically and socio-economically dynamic system that changes in response to natural and anthropogenic processes. Adequate long-term risk management of the system depends on recognition of the interconnections and interdependencies among subsystems, including engineered elements. Addressing risk in one part of the system (e.g., associated with sedimentation) can affect risk to other aspects of the system (e.g., associated with aquatic ecology). Responsibilities and concerns among interested and affected parties are also connected in ways that become clear only with system-level analysis. Responsible agencies and other affected parties, however, tend to focus on their respective responsibilities and interests, on specific locations or features, and over short time frames. This divergence of interests is contrary to sound management. While the post-1980 eruption efforts by the USACE addressed flood mitigation and related sediment control options (e.g., the SRS, levee improvements), these individual solutions to system-wide problems were considered separately and rarely in consideration of other issues affecting the region. This pattern continues today for management of almost all elements of the system by all parties.

Recommendation: Engage in system-wide thinking when making decisions about management objectives, approaches, and alternatives for the Spirit Lake and Toutle River system. Depending on the issues being considered, the system may include the Cowlitz River or extend beyond it. (Chapter 6)

Developing Common Understanding of the System and Management Options

Wise system management requires the development of shared knowledge and shared recognition of the visions, values, and objectives of key actors, but views on the nature and causes of problems in the Spirit Lake and Toutle River system diverge among interested and affected parties. Similarly, views on the feasibility and requirements of management alternatives diverge. This is exacerbated by fragmentation of information and expertise held by the various agencies given their respective agency missions. No single organization is responsible for investigating all aspects of the system. Various interested and affected parties sometimes use terminology or discuss concepts without appreciation of the ways others define those terms and concepts. For example, a surface outlet channel for Spirit Lake, which would allow passage of spawning fish (presumably with fish passage around the SRS ensured), has been described by some as representing a more "natural" management alternative for controlling lake levels than does a tunnel. The hydraulic constraints of such an outlet, however, may require a steep and heavily reinforced spillway—far from "natural"—that may be inimical to fish passage.

Recommendation: Responsible agencies and other interested and affected parties should develop a common understanding of the Spirit Lake and Toutle River system, its features, hazards, and management alternatives. (Chapter 3)

Choosing a Time Horizon

Identifying a time horizon creates the potential for institutional and social conflict because different planning time frames may require different management strategies. Long time frames may result in avoidance of short-term solutions to immediate problems. They may focus on low-probability but catastrophic seismic or volcanic events that could overwhelm hydraulic infrastructure and make prior planning seem irrelevant. On the other hand, short time horizons may favor management alternatives that resolve existing problems, but they may preclude desirable capital-intensive projects. They may also result in understating the importance of high-consequence, low-probability events. Defining a time frame for risk management decisions is critical and should be explicit. Management time frames need to be reconsidered in light of short- and long-term risk, the finite engineering design life of infrastructure, and unanticipated events or conditions as well as in terms of the financial burdens left to future generations. The time frames need to be revisited during the decision process to determine their appropriateness as new information is gathered.

Recommendation: Alternatives for managing the Spirit Lake and Toutle River system should be judged over both short and long time frames to ensure consideration of the range of the concerns of interested and affected parties. (Chapter 5)

Step 2: Identifying Decision Objectives

Once interested and affected parties are identified, the decision participant group is selected, and the team of experts that provides neutral support is in place, a set of decision-specific objectives can be clarified and structured. Decision objectives are the goals that matter to the participants of the deliberative process when comparing alternatives. They are always phrased as verbs—for example, to maximize economic well-being or to minimize adverse environmental impacts. Objectives become quantitatively defined once metrics are assigned for their measurement.

Objectives of all interested and affected parties need to be identified and the compiled list used as the basis for further deliberations among decision makers. Identifying objectives includes developing a common understanding of the underlying interests of decision participants. For example, an often-stated objective is to restore the "naturalness" of the system, but "naturalness" means different things to different people. Objectives related to such an ill-defined goal could be more specifically placed into such categories as increasing fish passage through the SRS and into Spirit Lake, increasing the "pristineness" of the area, or pursuing management solutions that require little human intervention.

Decision objectives serve as a basis for comparing alternatives. For example, the USACE developed a comprehensive plan in 1983 that compared management alternatives based on flood control (including both the risk of a catastrophic breakout of Spirit Lake and the risks of chronic floods), navigation, water quality, erosion, fish and wildlife, and maintenance of cultural resources. Decision group participants today may want to elaborate on that list to include ecosystem services (e.g., establishing an environmental landscape of the Toutle River), cost (both expected cost to implement and cost risk associated with potential nonperformance), and safety, including operational safety of workers inherent in the different alternatives.

Management alternatives could be studied in ways that allow for a better understanding of the relationships between objectives and alternatives—for example, through use of an objectives hierarchy, which helps decision participants to better understand the relationships between or among specific goals. An objectives hierarchy is created by deciding which objectives represent the highest-level goals (e.g., minimize adverse impacts to the ecology of the system) and which are intermediate objectives that must be met to obtain the highest-level objectives (e.g., minimize impacts to anadromous fish, minimize impacts to large mammals, minimize impacts to waterfowl). Each of those subgoals can be further broken down into more subgoals, eventually representing the relationships of all the objectives identified by interested and affected parties.

Performance metrics will need to be established to give decision participants a means to quantify a desired objective outcome so that expected progress toward or away from that objective can be modeled. Some metrics may directly measure the consequences of interest in their own terms (e.g., maintenance cost can be measured in dollars). Other metrics are best stated as proxies (correlates) for the consequences of an alternative (e.g., acres or hectares of accessible fish spawning habitat as a proxy for fish abundance). Other objectives may be difficult to quantify directly or indirectly because of unobservable or hard to measure impacts. In such cases, scales may be constructed for the problem at hand, with each level of the scale defined with a succinct and relevant narrative agreed to by the decision makers.

Step 3: Creating a Diverse Set of Alternatives

The third step of the decision process addresses alternatives. The goal is to craft multiple and diverse sets of management alternatives that would address the collaboratively generated list of management objectives. Management alternatives need to be considered as region-wide strategies and in terms of how they affect different elements in the system (e.g., engineered infrastructure, capital works, operations of engineering works, emergency response plans, natural environment, socioeconomic elements) and in terms of all types of change. They reflect the decision objectives identified by the group of decision participants and clearly specify what actions would be needed in different parts of the system for the strategy to be implemented. A skilled facilitator and decision analyst may help decision participants navigate through the objectives to avoid a stalling of deliberations. This process may use tools such as strategy tables (see Chapter 7) to create mental models for comparing individual actions within a strategy. Interdependent elements of the system need to be identified and linked (e.g., linking alternatives to encourage fish passage to Spirit Lake with actions to enhance passage beyond the SRS) and independent elements (i.e., those that do not affect reaching stated objectives) can be considered separately to simplify analysis. Alternatives that are dependent on system response with time (e.g., alternatives to address sediment buildup behind the SRS spillway with time) need to be adequately described.

Step 4: Identifying Consequences

In the vocabulary of the decision framework, "consequences" are the estimated impacts over time—both good and bad—of the various alternatives as determined using performance metrics. There may not be a common understanding of how physical processes interact with possible management alternatives. A deliberative and participatory approach that involves both interested and affected parties and technical experts in building "if-then" hypotheses and cause-and-effect relationships can aid those participants in generating a common understanding of how management options impact the issues of concern for participants.

Analysis of possible consequences needs to include consideration of the range of uncertainties associated with the management alternative itself and those inherent in the Spirit Lake and Toutle River system. Capturing risk and uncertainty is a technical exercise that may also be value laden. Participants' attitudes toward risk may be diverse and complicated. Iterative, structured dialogue with interested and affected parties throughout the process allows attitudes toward risk to be captured in a consistent way, understood by all, and incorporated appropriately into the decision process. The resulting deeper insight related to uncertain consequences informs later trade-off discussions when choosing among alternatives.

In order to capture the risk of a breakout of Spirit Lake, for example, more work to aggregate different sources of risk into one overall measure of risk is needed. This would allow alternatives intended to address other (perhaps, non-flood-related) objectives to be adequately assessed for how they might also affect the risk of a catastrophic breakout. The results would then be translated into a useful measure of "risk of catastrophic flood" to help participants compare options and understand trade-offs.

Comparing alternatives using quantitative performance metrics defined by the decision group is important for understanding the alignment between the consequences of alternatives and the stated objectives. The development of detailed consequence tables (see Chapter 8) based on those metrics helps focus value-laden discussions on key trade-offs and minimizes deliberation over what may be inconsequential technical issues.

Step 5: Clarifying the Trade-Offs

Identifying and closely considering trade-offs (i.e., compromises) is the last step of the decision process. Getting to this step, however, may require an iterative revisiting of previous steps. The overall purpose of the decision process is not to find some objectively defined optimal solution, but rather to find a good solution that is supportable at some level by all the decision participants. In most cases, this support hinges on participants' awareness and acceptance of various trade-offs. Some anticipated trade-offs could revolve around downstream sedimentation versus a more "natural" drainage system; cost versus catastrophic flood risk; sediment retention versus anadromous fish abundance; fish populations downstream versus fish populations upstream of the SRS; and short-term versus long-term actions and consequences.

A well-implemented decision process should help participants balance competing objectives in searching for a mutually acceptable solution. Complex trade-offs that involve multiple conflicting objectives and multiple alternatives may be addressed with decision analysis techniques that focus consideration on key value trade-offs, perhaps through quantitative ranking and weighting methods.

THE FIRST APPLICATION OF THE DECISION PROCESS: MANAGING SPIRIT LAKE WATER LEVELS

It is likely that the first attempt to apply this decision framework will be related to decisions regarding management of water levels in Spirit Lake. These currently fluctuate seasonally approximately 11 feet (~3.4 m), and it is assumed by regional experts the lake will breach its blockage if water levels rise another 26 feet (~8 m). The repeated need for repairs on the outflow tunnel controlling lake levels has led to a recent, largely non-quantitative potential failure modes analysis (PFMA)—based largely on professional judgment—of management alternatives that were first considered shortly after the 1980 eruption. These include major rehabilitation of the Spirit Lake outlet, the creation of a permanent pumping facility, installation of a buried conduit through the debris blockage, and digging a riverine channel across the debris blockage. Though the committee was neither asked to evaluate the PFMA nor was it provided direct access to the PFMA, committee members nevertheless concluded that there is a substantive knowledge gap regarding practical design issues that needs to be resolved before alternatives can be usefully compared by decision group participants.

As decision participants consider long-term management of Spirit Lake, they may want to consider a broader and bolder set of alternatives. Options for consideration could include, for example, lowering lake levels, draining the lake, installing a second modern drainage tunnel on a different alignment, or constructing a dry spillway as a backup outlet. A second tunnel would allow unconstrained rehabilitation of the existing tunnel and provide redundancy in the control of Spirit Lake and may also open the possibility for more flexible long-term management. A second tunnel might also allow restoration of a more natural drainage through the debris blockage more than a reinforced engineered outflow channel would as currently envisioned. The viability of such options is best quantified through an analytical-deliberative process as outlined in the report.

CHAPTER 1

Introduction

The explosive 1980 eruption of Mount St. Helens in southwest Washington State destroyed the summit of the volcano, resulting in a massive debris avalanche. Debris avalanche material and large volumes of pyroclastic flow deposits were directed north of Mount St. Helens into the North Fork Toutle River valley (see Figures 1.1 and 1.2). Lahars (mudflows consisting primarily of volcanic materials) transported volumes of sediment large enough to cause radical changes to the long-term hydrology of the Toutle River watershed and that of the Cowlitz River into which the Toutle flows. Enough sediment was transported to the Columbia River that 4 miles (6.4 km) of shipping channels approximately 50 miles (80 km) downstream of Portland, Oregon, had to be dredged to allow normal shipping. The headwater of the Toutle River—Spirit Lake, located approximately 4 miles (6.4 km) north of Mount St. Helens—was dammed by debris avalanche deposits with thicknesses in some areas of greater than 400 feet (120 m). That debris blockage remains today as do concerns regarding its possible failure. Failure could result in the release of 314,000 acre-feet (390 million m^3) of water and 2.4 billion cubic yards (1.8 billion m^3) of sediment into the Toutle, Cowlitz, and Columbia Rivers (Swift and Kresch, 1983), directly impacting 50,000 people living in communities along the Toutle and Cowlitz Rivers.

The Spirit Lake that existed prior to 1980 was essentially eradicated by the landslide and pyroclastic debris from the eruption. The Spirit Lake that replaced it resides in the same basin, but it is larger in aerial extent, greater in volume, and higher in elevation. Whereas the earlier Spirit Lake drained by gravity flow through a natural surface channel to the North Fork Toutle River, the Spirit Lake that replaced it has no natural drainage. Left as it was

(a)

(b)

FIGURE 1.1 Views of Mount St. Helens with Spirit Lake in the foreground taken (a) before the 1980 eruption, and (b) in 1982 after the eruption (note the absence of trees). The summit of the volcano prior to the eruption was 9,677 feet (2,950 m). The elevation of the crater rim following the eruption was 8,363 feet (2,550 m). Much of the material from the eruption debris avalanche was deposited in the North Fork Toutle River valley, blocking the flow of water from Spirit Lake to the North Fork Toutle River. SOURCES: U.S. Forest Service and U.S. Geological Survey.

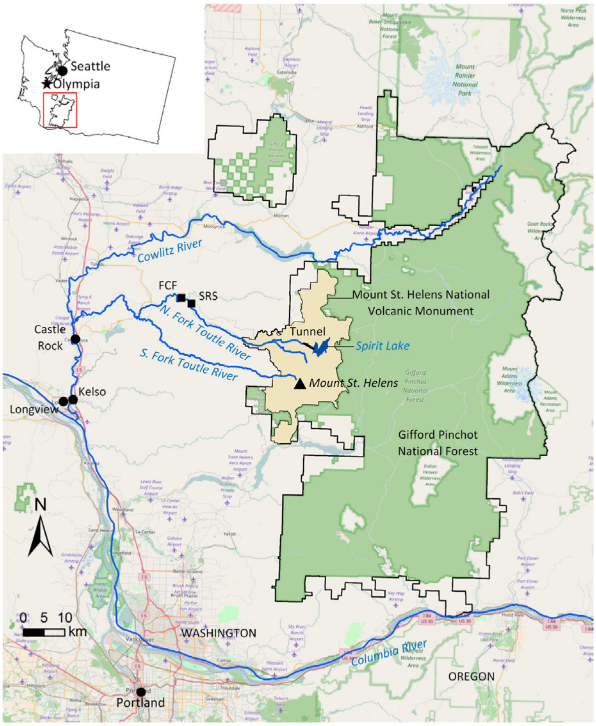


FIGURE 1.2 Regional map of the Spirit Lake and Toutle River system. Spirit Lake is located approximately 4 miles (6.4 km) northeast of Mount St. Helens and drains via the Spirit Lake outflow tunnel into South Coldwater Creek and then the North Fork Toutle River. Also shown are the locations of the USACE sediment retention structure (SRS) and State of Washington Fish Collection Facility (FCF) on the North Fork Toutle River. SOURCES: Map by authors; base map: @OpenStreetMap and contributors, including the USGS's The National Map: National Boundaries Dataset, 3DEP Elevation Program, Geographic Names Information System, National Hydrography Dataset, National Land Cover Database, National Structures Dataset, and National Transportation Dataset; U.S. Census Bureau—TIGER/Line and USFS Road Data.

following the eruption, the lake would slowly fill and eventually overtop and erode its blockage. The fear is that breaching could lead to a catastrophic flood and associated lahars when a large fraction of the lake volume escapes down the North Fork Toutle, inundating everything in its path. The size and other characteristics of this catastrophic flood were predicted using engineering models in the aftermath of the eruption (Swift and Kresch, 1983), but there is uncertainty associated with those models. Loss of life among residents of communities along the Toutle and Cowlitz Rivers is likely given a worst-case flooding scenario and the number of people residing in flood-prone regions. Impacts of a catastrophic breach, discussed in the literature and described in Chapter 4, would be felt beyond the immediate region; a major highway (Interstate 5) and rail transportation corridor that parallels the Cowlitz River and connects Portland, Oregon, and Seattle, Washington, could be buried. Such catastrophic events are not unprecedented in the area, as geologic evidence indicates breakouts of an ancestral Spirit Lake with lahars of similar magnitudes (Scott, 1988a).

Alternatives for draining the new Spirit Lake and controlling the lake's water surface elevation were considered (USACE, 1984a), and the decision was ultimately made to construct an 8,600-foot-long (2,600-m), 11-foot-diameter (3.4-m) gravity-fed tunnel to drain water west into South Coldwater Creek and eventually into the North Fork Toutle River (see Figure 1.3). The tunnel was completed in 1985 (details were summarized by Grant et al., 2016a) and is now the sole egress of water from the lake and the sole means of controlling water levels in the lake. It has worked effectively, but the tunnel has required major repairs to prevent its failure at different times during its operation. A 2014 inspection of the tunnel revealed that it was again at risk of failure (Britton et al., 2016a). Whereas failure of the tunnel does not imply immediate failure of the debris blockage, it raises the risk of such failure until the outlet is restored or some other means of controlling water levels is created. Repairs of the tunnel create additional risk because drainage through the tunnel must be stopped to allow access to the tunnel. Prolonged repairs, especially during the region's rainy season, leave the lake vulnerable to rising water levels.

FIGURE 1.3 Alignment of the Spirit Lake tunnel and location of the tunnel intake and outflow structures. The summit of Mount St. Helens is located 5 miles (8 km) southwest of the tunnel intake. Water exiting the tunnel enters the North Fork Toutle River circa 6 miles (10 km) downstream of the tunnel outflow. SOURCES: Map by authors; base map: @OpenStreetMap and contributors, including USGS's The National Map: National Boundaries Dataset, 3DEP Elevation Program, Geographic Names Information System, National Hydrography Dataset, National Land Cover Database, National Structures Dataset, and National Transportation Dataset; U.S. Census Burea—TIGER/Line and USFS Road Data.

Members of the U.S. Congress, aware of the increased hazard of a Spirit Lake breakout following the 2014 tunnel inspection, requested immediate corrective action (see Appendix D). The U.S. Forest Service (USFS), in cooperation with U.S. Army Corps of Engineers (USACE) and the U.S. Geological Survey (USGS), were requested to "review and analyze the array of options for a long-term plan that removes the threat of catastrophic failure of the tunnel and takes the unstable nature of the surface geology into account" (Beutler et al., 2015). The three agencies embarked on coordinated and simultaneous efforts to identify long-term management alternatives. This National Academies of Sciences, Engineering, and Medicine (National Academies) report is a response to a request from the USFS to develop a framework for technical decision making regarding management not just of water levels in Spirit Lake but also of coordinated management of water and sediment transport in the entire Spirit Lake and Toutle River system. Managed as a system, decisions could address the risk of catastrophic flooding associated both with failure of the debris blockage and with the management of sediment still transported through the river system today. These sediments result in a river hydrology that is drastically different from that before the 1980 eruption, making the population of the region more vulnerable to chronic flooding associated with annual rainfall events.

In addition to the tunnel, the USACE constructed and manages a sediment retention structure (SRS) on the North Fork Toutle River approximately 8 miles (13 km) downstream of Spirit Lake (see Figure 1.2 for location). Levees near towns have also been modified in response to the increased risk of chronic flooding. The SRS traps sediment before it is transported to the Toutle and Cowlitz Rivers. It therefore limits the amount of dredging necessary to decrease the hazards associated with chronic annual flooding and to keep channels open on the lower Cowlitz River. Sediments trapped above the SRS have changed the upstream landscape, affecting the ecological, cultural, and economic health of the area. As presently configured, the SRS is reaching capacity and decisions must soon be made regarding the future management of the structure and the sediments behind it. The decision framework presented in this report would allow determination of the objectives, alternatives, consequences, and trade-offs associated with the technical management of the river system as a whole. The framework also supports consideration of the regional economic, cultural, and societal priorities as they relate to the various technical decisions. Sediment and water transport for the region to date has not been a coordinated effort among those with management responsibility in the region, and management decisions have not included much consideration of socioeconomic priorities of interested and affected parties.

THE CHARGE TO THE COMMITTEE

Under the sponsorship of the USFS, the National Academies convened an ad hoc committee of experts to review existing information regarding the Spirit Lake and Toutle River system and to develop a framework for decision making related to management of water and sediment transport. The statement of task provided to the committee is found in Box 1.1. The committee was also asked to identify alternatives for future management and to describe gaps in information needed to inform those decisions. The committee explored the state of the technical knowledge, the concerns of interested and affected parties, and the roles and interests of the USFS, the USACE, the USGS, and other entities with responsibilities for managing water and related land resources in the Spirit Lake and Toutle River region. The report focuses on management in the context of the post-eruption conditions and possible future volcanic and other geologic activity. This report does not discuss issues associated with emergency management nor does it provide details of management alternatives already being considered (available in multiple reports issued by the USACE). Neither does this report recommend specific management actions. Instead, it identifies the types of information necessary to characterize the problems to be addressed, to formulate alternatives to address those problems, and to evaluate and compare those alternatives. The report also offers findings regarding organizational considerations that may factor into the use of the framework.

BOX 1.1
Statement of Task

An ad hoc committee of the National Academies of Sciences, Engineering, and Medicine will recommend a framework for technical decision making related to long-term management of risks related to the Spirit Lake/Toutle River system in light of the different priorities of federal, tribal, state, relevant local authorities, and other entities. The framework will incorporate the best available science and engineering and take into consideration regional economic, cultural, and societal priorities. The framework will also take into account the respective roles of stakeholders regarding management of the Spirit Lake/Toutle River system. The multiple objectives of enhanced safety of the downstream communities and the protection of the local and regional ecology and economic activities will be integral to the framework. The history of characterization, monitoring, and management associated with the Spirit Lake debris blockage and tunnel, other efforts to control outflow of water and deposits from the 1980 debris avalanche, and the risk of failure of the debris blockage will inform committee findings and recommendations.

The committee will:

- consider the adequacy of existing information and risk analyses for the area;
- suggest additional information needed to support implementation of the decision framework; and
- identify possible alternatives for long-term management of water levels and sediment transport in the Spirit Lake/Toutle River system.

The report will inform a quantitative examination of the viability of long-term management options by the U.S. Forest Service.

The USFS intends to use the framework recommended by the National Academies to collaboratively examine the viability of various management alternatives and make informed decisions, first about management of water levels in Spirit Lake—which is within their jurisdiction—and then about the larger system.

COMMITTEE MEMBERSHIP

Members of the ad hoc committee that conducted the study and prepared this report were nominated by their peers and selected by the National Academies based on their professional qualifications and lack of undo bias or conflict of interest. The committee includes researchers and practitioners with expertise in civil, geotechnical, hydraulic, tunnel, and earthquake engineering; waterway infrastructure protection, hydrology, and water resource management; fluvial geomorphology, landscape ecology, and volcanology; and natural resource economics, decision analysis, and disaster resilience. Brief biographies of the committee members can be found in Appendix A.

INSTITUTIONAL SETTING

The USFS has responsibility for management of lands and water within the footprint of the Gifford Pinchot National Forest and the Mount St. Helens National Volcanic Monument (the Monument). Mount St. Helens, Spirit Lake, and the Spirit Lake tunnel are located on USFS land. The broad language that created the Monument instructs the USFS as follows:

> *The Secretary shall manage the Monument to protect the geologic, ecologic, and cultural resources, in accordance with the provisions of this Act allowing geologic forces and ecological succession to continue substantially unimpeded.* (P.L. 97-243, Sec 4. (b)(1))[1]

A memorandum of understanding between the USFS and the USACE, however, makes the USACE responsible for annual inspections and routine operation and maintenance of the Spirit Lake tunnel, to be performed at the expense of the USFS. Repairs beyond the routine require the USFS to seek additional funding from Congress and for the work to be contracted to the USACE.

The USFS has no authority over land use, flood and sediment control infrastructure investment or management, or fishery and other wildlife

[1]See http://uscode.house.gov/statutes/pl/97/243.pdf.

management decisions outside of USFS lands; nor does it have control of the federal and state funding streams that support all of those. The USFS does recognize, however, that management decisions regarding any of these can have short- and long-term impacts on the whole region. Decisions made about control of water levels at Spirit Lake, for example, can have consequences for sediment management downstream, while decisions made regarding management of the SRS can have implications on the ecology of the region up- and downstream. Any decision made in the region may impact the responsibilities and concerns of federal, state, and local agencies; Native American Tribes; private-sector organizations; and individual citizens and citizen groups. The responsibilities, missions, and interests of those groups sometimes overlap and even conflict. No single entity exists to coordinate their activities. Chapter 3 provides more information about the institutional setting of the region and how that setting affects land management.

NATURAL HAZARDS AFFECTING REGIONAL MANAGEMENT

The Toutle and Cowlitz River basins are similar to other coastal drainages in the Pacific Northwest. They contain bucolic forests and wildlife and a community that, through the years, has made its livelihood from natural resources and recreation. Further downstream the drainages enter the urbanized communities of Kelso and Longview that depend on the Toutle and Cowlitz Rivers for navigation, manufacturing, and other economic activities. These river basins are dominated by the volcanic landscape and activity of Mount St. Helens, however, and also are subject to other natural hazards (e.g., seismic, meteoric, landslide, consequences of fire).

Indigenous peoples have occupied the region around Mount St. Helens for 6,000 years and consider eruption as the mountain's natural state. Stories of the Cowlitz Indian Tribe are deeply entwined with the landscape. Tribal elders advise people to adopt a philosophy of "living with the mountain" (personal communication with the committee, N. Reynolds, August 1, 2016). Management of the region needs to be mindful of the reality that

Mount St. Helens continues to be active, and volcanic events can be expected to change the landscape. The 1980 eruption of Mount St. Helens resulted in a reshaped landscape, a new regional hydrology, and new hazards for the region's populations, the risks associated with which can never be completely eliminated. These are now the "new normal" to which the population needs to adjust. Future events may include another catastrophic eruption of the magnitude of the 1980 event, although the probability of such an event in the near future is less likely than that of lahars and smaller eruptions. No level of mitigation or repair can ever result in the elimination of all natural hazard risk. Zero risk is not an option unless residents choose to move elsewhere (and face the risks of living in that location).

The region also is commonly subject, in both human and geologic timescales, to seismic events associated with regional fault zones. Shaking from seismic activity could result in, for example, lahars and mudflows that might increase the sediment loads in the river basins or affect the stability of the debris blockage. The region is subject to annual rainfall typical of the Pacific Northwest, and meteorological events called atmospheric rivers (known colloquially as the "Pineapple Express") or rain-on-snow events may have major impacts on flooding and sediment transport on the Toutle and Cowlitz Rivers. Chapter 4 describes natural hazards of the region.

A catastrophic threat other than another large-scale eruption of Mount St. Helens hangs over the Toutle and Cowlitz River basins in the form of a major earthquake on the Cascadia Subduction Zone (i.e., of magnitude [M] greater than 9.0). A mega earthquake on the subduction zone would likely be a disaster, with local consequences of similar magnitude to or greater than the 1980 eruption of Mount St. Helens depending on where the earthquake originates. The specific consequences of a mega earthquake on the Spirit Lake and Toutle River region have not been quantified by investigators.

THE CURRENT DECISION LANDSCAPE

Immediately following the eruption, two principal considerations influenced management decisions: the costs of possible management actions and their impacts on the safety of downstream communities (USACE, 1984a). The tunnel, the SRS, community and federal flood risk management programs (e.g., land use controls, levees, flood insurance), and USACE dredging contracts are measures put in place to manage catastrophic and chronic flood hazards. Many of the original decisions around these measures, however, were made under emergency conditions and were based on limited physical characterization of the region. These measures have been generally adequate in temporarily managing routine flooding and sediment transport given the stresses experienced since the last major eruption, but the measures have also had ecological and socioeconomic consequences. Management decisions resulted in hindering sediment in a mid-reach of the river system (i.e., behind the SRS) in a nonequilibrium position, forestalling the river reaching a natural equilibrium, changing the landscape even further, and potentially creating a different set of anthropogenic risks that need to be assessed and monitored. Moreover, management of the different elements of the Spirit Lake and Toutle River system have not been adaptable or flexible to changing conditions, nor has it encouraged monitoring those conditions to deepen an understanding of how the system might be better managed in the long term.

Input from interested and affected parties other than those with direct management authority has not been incorporated into many of the management decisions made in the region. As a result, there is expressed dissatisfaction with and lack of trust in the management of the various control elements. For instance, interested and affected parties in the region have called for river restoration measures that would enhance recreational benefits and restore natural fish runs and wildlife habitat and populations. Concerns have also been raised about social and economic disruption resulting from increases in routine flooding along the Toutle and Cowlitz Rivers; the environmental and cultural effects of the sediments captured behind the SRS; flooding caused by continued channel infilling; and potential volcanic or seismic activity that may destabilize large quantities of water and sediment behind the SRS.

The USACE anticipates that further major repairs of the tunnel will be necessary (Britton et al., 2016a). The need for a long-term strategy to manage water levels at Spirit Lake prompted the USFS to request this National Academies report. The immediate decision to be made is whether to continue to repair the current tunnel to keep it operational or to abandon the current tunnel and replace it with a different engineering measure to control Spirit Lake water levels. A different measure might be one that was previously identified (see USACE, 1984a) or it might be some other as-yet unidentified measure. There is opportunity now to better constrain uncertainties associated with various management alternatives. These management alternatives could be studied in ways that allow for a better understanding of the relatonships between objectives and alternatives—for example, through use of an objectives hierarchy (Keeney, 1996; see also the section on objective hierarchies in Chapter 7). This results from more adequate characterization and modeling using improved tools and methods and informed by advances in science. The consequences of those alternatives may also be better anticipated and compared with a complete range of management objectives, including those of regional stakeholders. More informed decisions may be reached that will better serve the region.

DEFINING TERMS IN THE STATEMENT OF TASK

Several terms in the committee's statement of task (see Box 1.1) may be defined differently by interested and affected parties given their various perspectives. The terms "framework for technical decision making," "region," "system," "stakeholder," and "long-term" are defined in the next sections as they are used in this report. The exercise of defining these terms helped the committee bound its task and facilitated committee deliberations.

Framework for Technical Decision Making

In this report, a technical decision is that which requires the expertise of trained individuals to analyze available data and inform appropriate management. The expertise may be related, for example, to engineering issues; to the physical, biological, or ecological sciences; to the social sciences (e.g., economic, sociological); or to some combination of these. A decision framework is a procedural tool to guide users through a decision process. It supports a future-oriented strategy that leads decision makers through assessment of decision objectives, alternatives and their respective consequences, and, ultimately, to a management decision that is mutually supportable by all involved by the decision process. A decision framework helps decision makers define what is to be decided and the processes for getting to decisions. This includes processes for determining who is to be involved and how as well as for gathering input to identify and compare decision objectives and alternatives in light of available information, constraints, and uncertainties. A decision framework guides how input can be used to create and eliminate alternatives in the search for a set of mutually acceptable solutions. The process should help participants reach and justify decisions and clarify the bases of any disagreements to inform future decisions.

The decision framework described in Chapters 6 through 8 is participatory in nature so that stakeholder priorities will both inform and be informed by the different analytical processes and information gathering. The framework is applicable to any technical management decision made for the region under any specific agency's jurisdiction. The intent of the committee, however, is that the framework be used to coordinate management for the region as a whole.

The "System" and "Region" Under Consideration

A system is a set of interacting or interdependent processes or elements. A region is the geographic area in which the elements of the system are located. There are numerous agencies in the region with often overlapping or conflicting authorities. Their respective missions can be relatively limited in scope, resulting in the ad hoc management of infrastructural elements at Spirit Lake, the North Fork Toutle and Toutle Rivers, and downstream into the Cowlitz River. As already stated, however, few if any elements of the system are truly independent of other elements. The effects of management decisions on one element of the system need to be considered in light of the consequences of those decisions on the system as a whole. Ideally, management for all elements of the system will be simultaneous and made with the understanding that sediment transport in the Toutle River will be continuous for the foreseeable future.

For the purpose of discussion around developing a decision framework, the committee defined the system as the drainage of Spirit Lake to the Toutle River and to the Toutle River's confluence with the Cowlitz River. The committee considers the effects of these water bodies to the extent that they derive from or are otherwise related to the drainage of Spirit Lake and the management of sediment transport within the drainage. During future decision making, the system may need to be defined more broadly or narrowly depending on the impacts of concern. With respect to fish migration, for instance, the planning area could extend to the Columbia River or beyond. With respect to flood risk reduction, the planning area may need to extend to the confluence of the Cowlitz and Columbia Rivers. With respect to sediment control, the planning area might be limited mostly to the North Fork Toutle River, or it may need to include the South Fork Toutle River and other tributaries. The extent of the system and region for any set of management decisions depends on the consequences of concern and varies depending on the decisions to be made.

Stakeholders (Interested and Affected Parties)

A stakeholder is typically defined as a person with a particular interest in some decision. In this report, the committee assumes a broader view of those who have an interest in a decision. Traditionally, stakeholders of decisions made about managing water levels in Spirit Lake would include those people in harm's way, including those whose homes, businesses, or livelihoods might be destroyed or damaged by a catastrophic flood. This report also includes as stakeholders those whose culture or quality of life are affected directly or indirectly. Importantly, stakeholders are those individuals and entities responsible for management of the region; federal, state, and local agencies, then, are considered to be among the region's stakeholders.

To distinguish the committee's broader usage from the more traditional definition, the committee adopts the term "interested and affected parties" in this report. Such parties include federal, tribal, state, and local entities with responsibilities in the region, land and business owners, nongovernmental organizations (e.g., environmental or recreational organizations), residents, and any individual or group with interests about public safety and health, emergency management, wildlife recovery and ecological health, economic development (e.g., forestry, those dependent on navigable channels, ecotourism), cultural preservation, recreation opportunities, and any number of other issues.

The committee attempted to hear from a wide array of interested and affected parties to determine the range of concerns and how they might affect the choice of a decision framework. The groups with whom the committee attempted to communicate during the conduct of this study are listed in Table 1.1. The table does not represent a complete list or scientific sampling of interested and affected parties, but rather lists groups that were readily identified by the committee. Invitations were extended to representatives of all these groups to participate in the committee's meetings and provide input into the committee process.

Chapter 3 includes more discussion about interested and affected parties. Many of these groups sent representatives to the committee's open session meetings or provided written input. A number of independent citizens also participated in discussions. Chapter 6 describes how interested and affected parties are identified and how interactions with them can be organized to be most useful.

Long-Term Management

The committee was tasked with developing a framework suitable for decisions made for "long-term management." When asked, however, the USFS could not quantify "long term." Formulating, evaluating, and comparing possible alternatives to address problems requires the selection of an appropriate planning period. A common choice among engineers is 50 years, reflecting the economic life of many kinds of investments and the ability to predict with any certainty ecological and socioeconomic conditions in the planning area (if that effort is made). In the case of long-lived infra-

TABLE 1.1 Interested and Affected Organizations Contacted During the Study

Type of Organization	Organization Name
Federal Agencies	U.S. Army Corps of Engineers; U.S. Forest Service; U.S. Geological Survey
Tribal Agencies	Cowlitz Indian Tribe; Yakama Nation
State Agencies	Washington Department of Archeology and Historical Preservation; Washington Department of Ecology; Washington Department of Fish and Wildlife; Washington Department of Natural Resources; Washington Department of Transportation; Washington State Governor's Office for Regulatory Innovation and Assistance; Washington State Parks and Recreation Commission
Local Agencies	Cowlitz County (Board of Commissioners, Emergency Management, Tourism); Port of Longview
Nongovernmental Organizations	Audubon Society (Washington and Willapa Hills); Cascade Forest Conservancy (formerly the Gifford Pinchot Task Force); Conservation Alliance; Conservation Northwest; Cowlitz Game and Anglers; Mount St. Helens Institute; Sierra Club; Toutle Valley Community Association; Washington Environmental Council; Washington Trails Association
Private Sector	Axiall Corporation; BNSF Railway; Castle Rock Chamber of Commerce; Chilton Logging; Cowlitz County Tourism; Drew's Grocery; Ecopark Resort; Kapstone Paper; Kelso-Longview Chamber of Commerce; Washington Forest Product Association; Weyerhaeuser Company

structure, a longer period (e.g., 100 years or longer) might be selected, although projections of relevant variables become increasingly uncertain for longer periods. On the other hand, the likelihood of various disruptive events (earthquakes, volcanic eruptions) within the planning period suggest a shorter period (e.g., 25 years).

The committee asked individuals who attended the committee's open session meetings what they interpreted "long-term management" to mean. Representatives of the Cowlitz Indian Tribe often consider the management time frames imposed on natural systems by non–Native Americans as unrealistically short. Management time frames, according to the Cowlitz Indian Tribe ecologist Nathan Reynolds, should be informed by the amount of time human beings can assist nature to restore itself and flush sediments through the system—perhaps 175 years (personal communication to the committee, August 1, 2016). Steve Ogden, a forester for the Washington Department of Natural Resources (WADNR), thinks about planning horizons in terms of the amount of time for a forest to regenerate—approximately 50 to 100 years. He also suggests that management factor intergenerational equity into decisions, reflecting on how decisions today will affect our children and grandchildren (personal communication to the committee, August 1, 2016). Dave Howe of the Washington Department of Fish and Wildlife (WDFW) described the need for making planning horizons long enough to accommodate the reestablishment of dynamic riparian landscapes, but he also mentioned his concern about overengineering infrastructure that will subsequently be destroyed in a catastrophic event (personal communication to the committee, August 1, 2016). Planning horizons need to be chosen with both the understanding that longer time frames increase the likelihood of destructive events (and thus the loss of capital investment) occurring within the planning period and the understanding that longer time frames are necessary for ecosystem regeneration. Many of the interested and affected parties who provided input to the committee expressed concern over what they perceived to be the overly short management time frames for structures like the SRS (discussed further in Chapters 5 and 6).

Rather than provide a definition of long term, this report lays out how those participating in the decision process could choose an appropriate time horizon based on the priorities and objectives of interested and affected parties participating in the decision process. Chapter 6 includes further discussion of considerations for choosing a planning horizon.

COMMITTEE APPROACH TO ITS TASK

There are two distinct but related components of the committee's task. One is related to the technical aspects of the problems at hand. Geologic, hydrologic, ecological, and meteorological processes, in conjunction with the engineering infrastructure in place, control the flow of water and sediment in the river system. These engineering projects are expected to reduce the risk of property damage and loss of life from flooding and mudflows in the short term. The physical processes and the structures interact in ways not completely understood, and the return of vegetation and wildlife to the plains of debris avalanche deposits are being studied for the first time in modern history.

The second component of the task includes sociopolitical considerations. A large number of interested and affected individuals and groups at local, state, regional, and national levels of society—influenced by the wide array of safety, economic, environmental, and cultural priorities held by those groups—make decisions about the physical system more complex. Conflicting goals of those charged with management of different parts of the physical and social landscapes are not often addressed. The framework for decision making recommended by the committee assumes active collaboration and engagement among interested and affected parties so that both physical and sociopolitical considerations can be addressed fairly.

During the conduct of its study, the committee found either that few new data have been collected and analyzed since initial hazard characterization efforts immediately following the 1980 eruption, or that such data and analyses could not be provided to the committee. There are multiple reasons for the latter: in some cases, a loss of institutional memory associated with turnover in agency leadership means that knowledge of the characterization efforts has been lost; in other cases, information was withheld from the committee to avoid the need for public disclosure.[2] The committee complied with its task by reviewing available information and identifying the types of information and analyses necessary to quantify the viability of the various management options. It will be up to the decision makers to obtain either existing or new information for their own analyses.

Information Gathering

The conclusions and recommendations in this report are based on the assessment of publicly available information and data. The USFS, in collaboration with the USACE and the USGS, provided a compendium of characterization and management data related to the Spirit Lake and Toutle River system. All three agencies provided information upon request during conduct of the study. An important work by USFS and USGS researchers was published late during the conduct of this National Academies study (Grant et al., 2016a). That work provides an excellent description of the physical context associated with decisions related to management of Spirit Lake water levels. The present report includes frequent references to discussions provided by Grant and others (2016a).

Any presentations or discussions with the committee by agencies or members of the public occurred during open sessions of committee meetings. Members of the public were welcomed and could participate either in person or remotely. Meetings were announced widely and in advance through communications mechanisms of both the National Academies and the USFS. Members of the public were also invited to provide input to the committee via links through websites established for that purpose. The committee held three meetings that included information gathering sessions. These were held in Kelso, Washington, a major population center

[2]The National Academies of Sciences, Engineering, and Medicine comply with the Federal Advisory Committee Act (P.L. 92-463) which requires that all information provided to the committee during the conduct of a study be made available to the public. The public can request any of this information through the National Academies' Public Access Records Office: http://www8.nationalacademies.org/cp/ManageRequest.aspx?key=49785.

in the region affected by conditions and sediments in the Toutle River. Agendas for all open session meetings are provided in Appendix B, which also include the names of individuals who were explicitly invited to make presentations or participate in panel discussions.

The first meeting, held June 21-23, 2016, focused on the state of scientific and technical knowledge about Mount St. Helens, Spirit Lake and its outflow tunnel, and the SRS. Presentations were made by scientists, engineers, and managers from the USGS, the USACE, and the USFS, with substantial time dedicated to questions from and discussions with the public. The meeting was organized to orient the committee to its task. One day of the meeting included visits to points of interest in the Toutle River valley and the Monument, including the Johnston Ridge Observatory, the Spirit Lake tunnel outlet, the SRS, and one of the levees that was improved following the eruption. Scientific and technical experts from the USFS, the USACE, the USGS, and Centralia College in Chehalis, Washington, guided the visits. Members of the public were invited to register to participate in the site visits on a limited basis.[3]

The committee's second meeting, held August 1-3, 2016, focused largely on obtaining input from nonfederal interested and affected parties. Panels were organized representing (1) local and regional interests, including the Cowlitz County Board of Commissioners, the Port of Longview, the Cowlitz County Department of Emergency Management, and local business interests; (2) nonprofit organizations, including the Cowlitz Game and Anglers Club, the Mount St. Helens Institute, and the Toutle Valley Community Association; and (3) state and tribal natural resource management agencies, including the Natural Resources Department of the Cowlitz Indian Tribe, the WDFW, and the WADNR. A study committee member moderated each of the panel discussions. Panelists were provided with sets of questions in advance of the meeting and asked to respond verbally and in turn to those questions during the meeting. The questions were intended to identify panelist perceptions and major concerns regarding management of Spirit Lake and Toutle River issues. There was ample

[3]Public participation in the site visits was limited for logistical and safety reasons.

opportunity for discussion between panelists and committee members as well as with observers of the proceedings. Additional panel discussions were organized with sets of USACE experts to discuss lessons learned from a recent interagency potential failure modes analysis of the Spirit Lake blockage and long-term sediment management in the region. To allow broader participation by the public, a town hall–style meeting was held in the evening.

The third meeting, held October 31, 2016, included a presentation and discussion with USFS and USGS experts regarding the recently published report on the geologic, geomorphologic, and hydrological concepts that underlie currently considered options for management of Spirit Lake water levels (Grant et al., 2016a). The committee organized another panel discussion with USACE technical staff to hear their response to the report by Grant and colleagues (2016a).

In addition to this input received from the agencies, experts, and other interested and affected parties, the committee relied on published literature and their own expertise and experience to inform their findings and support the conclusions and recommendations in this report.

REPORT ORGANIZATION

This report provides a technical foundation and organization process for decision making that draws on lessons from risk management decision processes established elsewhere. It is assumed that decisions made using the framework will be grounded in reliable data; that those data will be used in analytically rigorous models of the larger system and system interconnections; that the concerns of the multiple interested and affected parties will be recognized; and that preferred actions will be selected in consideration of the sources and levels of available funding. To that end, the report is organized to first provide a general overview of the physical setting, infrastructure, and implications for assessing risk and long-term management (Chapter 2); the institutional setting of the region, including the land ownership and management setting and other interested and affected parties (Chapter 3); the natural hazards in the region and the adequacy of risk analyses conducted to date (Chapter 4); and the engineering landscape, including descriptions of risks associated with engineered controls and structural alternatives for engineering management (Chapter 5). Thereafter, the report provides a detailed discussion of the recommended decision framework (Chapters 6-8) and a summary of next steps that could be taken by those with management authority in the region to implement the recommendations found within this report (Chapter 9). Whereas Chapters 6-8 satisfy the requirement in the statement of task to recommend a decision framework, the committee identifies good practices throughout the report. The syntheses of the key requirements for implementing the decision framework are labeled explicitly as “recommendations” and are found in bold typeface in Chapters 3 through 6 and have also been compiled in the report summary. These tend to be general in nature, but they do not reflect common management practices in the region.

CHAPTER 2

Regional Setting

The regional conditions that contribute to risk must be taken into account in decisions regarding long-term management of the Spirit Lake and Toutle River system. This chapter discusses various aspects of the regional setting that provide the context for decision making: the physical geography of the region; the geologic setting; the groundwater hydrology; the ecological setting; the socio-demographic and economic setting; and other important features within the region, including the debris blockage and built-environment elements such as the drainage tunnel from Spirit Lake, the sediment retention structure (SRS), and levees. This chapter provides only a general overview of the technical information available regarding the region that informed the committee's deliberation of its statement of task (see Box 1.1). More information is available in materials published by the U.S. Army Corps of Engineers (USACE), the U.S. Geological Survey (USGS), and the U.S. Forest Service (USFS). Greater detail regarding the institutional setting is provided in Chapter 3, and details about hazards and engineering controls to minimize risk is provided in Chapters 4 and 5. Alternatives for controlling water levels in Spirit Lake are also discussed in Chapter 5. A major point emphasized in the concluding section of this chapter is that regional characteristics must not be considered in isolation but instead must be analyzed as interrelated elements within a broader system.

PHYSICAL GEOGRAPHY

Mount St. Helens is located in southwestern Washington, roughly 50 miles (80 km) northeast of Portland, Oregon, and 100 miles (160 km) south of Seattle, Washington. The region that includes Mount St. Helens and the

Toutle River drainage is a volcanic and glaciated terrain that drains into a small number of high-elevation lakes, including Spirit Lake, Coldwater Lake, and Castle Lake, and then into the north and south forks of the Toutle River. Downstream sediment movement through the North Fork Toutle River drainage is affected by the SRS, which was constructed by the USACE in 1989 to limit downstream sediment deposition in areas where it had the potential to increase flood risk and affect shipping. From the SRS, water and untrapped sentiments are transported into the main channel of the Toutle (approximately 33 miles [53 km] downstream of Spirit Lake), then on to the Cowlitz River (another 15 miles [24 km]), and eventually into the Columbia River downstream of Portland (roughly an additional 20 miles [32 km]).

The lateral blast of the 1980 eruption of Mount St. Helens scorched 230 square miles (600 km^2) of forest, predominantly to the north of the mountain (see Figure 2.1), and it greatly affected forests, fish and wildlife,

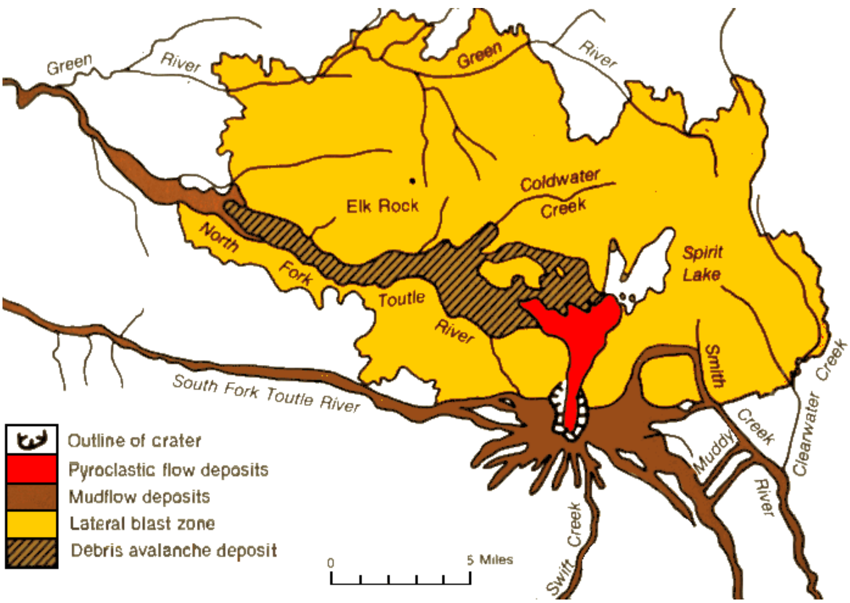


FIGURE 2.1 Areas impacted by the 1980 eruption of Mount St. Helens. SOURCE: USGS. See https://pubs.usgs.gov/gip/msh/mudflows.html.

and waters in the blast vicinity. In 1982 the U.S. government created the Mount St. Helens National Volcanic Monument (the Monument), which included much of this devastated land, for purposes of research, recreation, and education (see Figure 2.2). Within the Monument, which is a part of

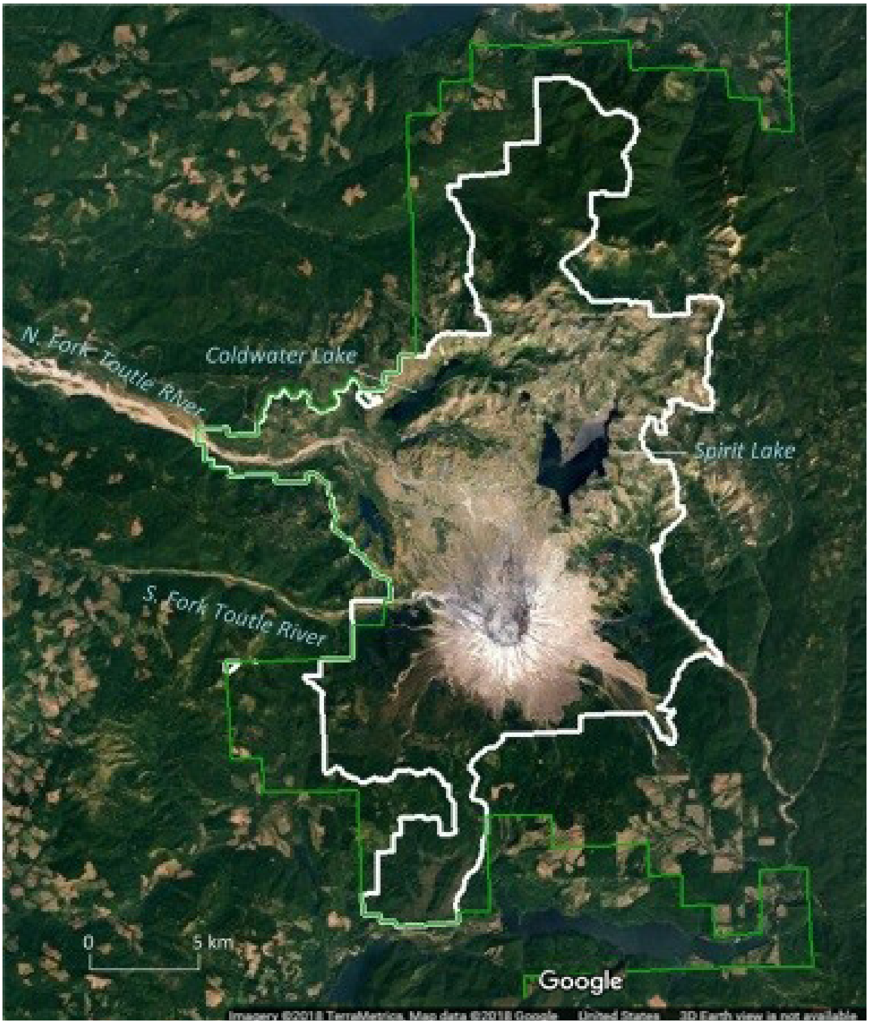


FIGURE 2.2 Boundary of the Mount St. Helens National Volcanic Monument (white) within the Gifford Pinchot National Forest (green). SOURCE: Google Earth.

Gifford Pinchot National Forest and is managed by the USFS, the natural setting of the mountain and its surrounding lands is left free to respond in its own way to the historic disturbance. More detail about management of the Monument is provided in Chapter 3.

Streams that originate on Mount St. Helens are fed by rain and snowmelt and enter three main river systems: the Toutle River to the north and northwest, the Kalama River to the west, and the Lewis River to the south and east. The Monument itself contains Spirit, Coldwater, and Castle Lakes, as well as the headwaters of the North Fork and South Fork Toutle Rivers. It does not include the lower reaches of the North Fork Toutle River, within which the SRS was constructed. Because the current outflow pathway for Spirit Lake is through the North Fork Toutle River system (which was the river most heavily impacted by the eruption), discussions in this report will emphasize that drainage system, but there are management issues related to the decision framework that may involve other river systems in the region.

Spirit Lake

Spirit Lake is an intermittent (from a geologic perspective) subalpine lake that currently contains approximately 275,000 acre-feet (339 million m^3) of water. Before the 1980 eruption, the lake had a surface area of 1.9 square miles (5 km^2) and a surface elevation of 3,140 feet (975 m) (Meyer and Carpenter, 1983). It was connected to the North Fork Toutle River through a natural outlet stabilized by gravel and boulders, which allowed outflow from the lake to rise and fall within a narrow range in response to seasonal rainfall and snowmelt runoff. The debris avalanche associated with the collapse of the volcanic edifice during the 1980 eruption partly flowed into the lake, and thick avalanche deposits buried the original lake outlet. No rivers flow into the lake, which is fed solely by rainfall and snowmelt. A fraction of water stored in the lake is now released into South Coldwater Creek via the Spirit Lake tunnel (see Figure 1.3 for location of the tunnel). The surface elevation of Spirit Lake now fluctuates seasonally between approximately 3,438 and 3,449 feet (1,048-1,051 m), with a gradual rise in the past decade. Storage as a function of lake elevation is shown in Table 2.1.

TABLE 2.1 Spirit Lake Stage-Storage Relationship

Elevation (ft., NGVD29)	Storage (ac-ft.)[a]	Storage (ac-ft.)[b]
3,437.1	205,500	Values from the 1984 Design Memorandum were used for these values.
3,438.2	208,300	
3,440.0	213,000	
3,441.1	215,900	
3,442.6	219,920	
3,443.1	221,180	
3,444.1	223,700	
3,445.0	226,000	
3,446.3	229,470	
3,448.8	235,900	
3,450.0	239,300[c]	238,840
3,451.8	244,400	243,627[c]
3,454.8	252,900	251,606[c]
3,455.1	253,481[c]	252,138
3,460.0	268,000	265,782
3,470.0	297,100	294,016

[a]These values are from the 1984 Design Memorandum.
[b]These values were updated using 2009 LIDAR (Light Detection and Ranging) data. The full elevation storage curve was not updated, just values above 3,445.
[c]These values were estimated using linear interpolation with immediate elevation-storage information.
NOTE: All information appears exactly as provided by the USACE.
SOURCE: USACE, 2016a.

The northward-directed blast and debris avalanche from the 1980 eruption temporarily displaced all the preexisting Spirit Lake from its bed (see Figure 2.3). The debris avalanche deposited roughly 350,000 acre-feet (432 million m^3) of debris into Spirit Lake, raising the surface elevation of the lake by about 200 feet (61 m). As a result, the bottom of the lake was filled with avalanche deposits and therefore elevated approximately 400 feet (122 m) above that of the lake prior to the eruption. The bottom elevation of the new Spirit Lake is well above the contact of the debris deposit and

FIGURE 2.3 Aerial photo, taken the day after the 1980 eruption, showing the slopes around Spirit Lake, previously densely forested, blanketed by sediments. SOURCE: NASA. See http://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=10934.

competent bedrock. The lake is assumed to be capable of breaching that blockage at elevation 3,475 feet (1,059 m), which is the interface between the pyroclastic flow and the finer, more erodible ash above (described later in this chapter).

The North Fork Toutle River to the Sediment Retention Structure

Prior to the 1980 eruption of Mount St. Helens, the North Fork Toutle River originated at Spirit Lake, where the debris blockage currently exists. Discharge from Spirit Lake now reaches the North Fork Toutle River via the Spirit Lake tunnel and South Coldwater Creek (see Figures 1.2 and 1.3 for locations). Eventually those waters reach the SRS and the Toutle River (see Figure 1.2). USGS National Water Information System data[1] indicate that lake outflow supplies 300-400 cubic feet per second to the North Fork

[1]These data are available at https://maps.waterdata.usgs.gov/mapper/index.html.

Toutle River (depending on the condition of the outlet tunnel), which is approximately one-third of the average river flow at the SRS but only 3-4% of the mean annual flood at that location. Because it emanates from Spirit Lake and traverses Coldwater Lake on its way to the Toutle River, the lake outflow contributes no sediment until it flows across the sediment plain behind the SRS, picking up small amounts of sediment, approximately in proportion to its flow contribution. The rest of the upper Toutle River valley, outside of the Spirit Lake basin, is the source of approximately half of the mean annual flood discharge and of all the sediment arriving at the SRS and being transported to the lower Cowlitz River.

The Toutle and Cowlitz Rivers Downstream of the SRS

The north and south forks of the Toutle River converge approximately 13 miles (21 km) downstream of the SRS to become the upper Toutle River. Much of the coarser, sand-sized particles in the deposits are captured at the SRS, but when sediments reached high enough levels at the SRS and converted to run-of-river functioning in 1999 (before the spillway was raised by the USACE), more of this coarse fraction passed downstream into the Toutle River (USACE, 2011). The Toutle continues to flow westerly approximately 17 miles (27 km) until its confluence with the Cowlitz River, near the town of Castle Rock. From there, water flows to the Columbia River at Longview and Kelso. Flood levees have been constructed along these reaches to reduce flood risk to the communities of Kid Valley, Castle Rock, Lexington, Kelso, and Longview and the unincorporated communities between them. Sediments transported downriver and deposited along these lower reaches decrease the discharge capacity of the lower reaches, making the flood levee system less effective and requiring levee strengthening and river dredging. Sediment deposition also interferes with navigation on the lower Cowlitz River, similarly requiring channel dredging.

The Columbia River

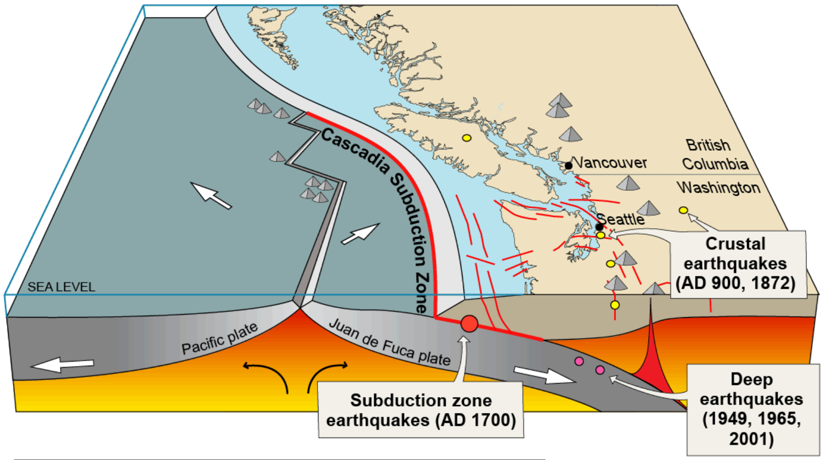
The Cowlitz River flows into the Columbia River at near Kelso and Longview, approximately 65 miles (105 km) upstream of the Pacific Ocean. The Columbia River is navigable by means of a deepwater channel to Portland. Following the 1980 eruption of Mount St. Helens, a sufficient volume of sediment was deposited in the Columbia at Longview to prohibit oceangoing vessels from transiting. This impediment was remediated by dredging the Columbia River channel; but, in principle, a similar blockage could occur again following another major eruption given the infilling of the Mount St. Helens crater with successive dome building events (see Chapter 4). Without such an eruption, the existence of the SRS upstream makes another major blockage of the Columbia channel unlikely.

GEOLOGIC SETTING

The Spirit Lake and Toutle River region is in an active geologic setting. Understanding its geology and associated hazards is important to understanding the risks associated with management decisions for the region. Mount St. Helens is part of the Cascades volcanic chain that also includes Mount Rainier and Mount Adams in Washington and Mount Hood in Oregon. This chain formed as a result of subduction of oceanic crust (the Juan de Fuca Plate) beneath the northwestern coast of North America (see Figure 2.4). The bedrock of the Spirit Lake area chiefly comprises geologically young but competent volcanic rocks, consisting mostly of andesite, basalt, flow breccias, and tuffs. Overlying these are gravelly well-drained river bottom soils in the main drainage channels and thin soil cover on the hillsides (USACE, 1984a). Subduction processes result in not only volcanic hazards but also those associated with earthquakes.

Regional Volcanism and Hazards

As the subducted oceanic crust, or slab, descends into the mantle beneath the North American Plate, it is heated and subjected to increasing pres-



Source	Max. Size	Recurrence
Subduction zone	M 9+	200–600 years
Deep Juan de Fuca plate	M 7+	30–50 years
Crustal faults	M 7+	Hundreds of years?

Volcano
Active crustal fault
Active plate boundary fault

*figure modified from USGS Cascadia earthquake graphics at http://geomaps.wr.usgs.gov/pacnw/pacnweq/index.html

FIGURE 2.4 Block diagram showing sources of seismicity in the region. The Juan de Fuca Plate is shown being subducted under the North American Plate. SOURCE: Washington Geological Survey. See http://www.dnr.wa.gov/programs-and-services/geology/geologic-hazards/earthquakes-and-faults#active-faults-and-future-earthquakes.

sure and eventually releases fluids (mainly water). These fluids interact with the overlying mantle, the melting temperature of the slab is reduced, and the slab melts and generates magmas. The magmas ascend toward the surface, with temporary ponding at different depths such as near the base of the continental crust (about 25 miles [40 km]) and at mid-crustal levels. Types of magma are produced (i.e., calc-alkaline mainly of andesitic to dacitic compositions) with two characteristics that influence the type of their eruptions: they are resistant to flow (i.e., have high viscosities) and contain a large percentage of dissolved water.

The high-viscosity magmas can well up and out of the ground in a relatively quiet manner—referred to as “effusive”—and form dome-like structures above the volcanic vent (rather than the “rivers” of lava that occur in lower-viscosity basaltic volcanoes). One of the domes now visible in the crater of Mount St. Helens is the result of an effusive episode in 2004-2008. The large fraction (several percent by weight) of dissolved water in these magmas at depth, however, can also drive highly explosive eruptions. As magma rises and decompresses, water comes out of solution and forms bubbles that are prevented, as a result of the high viscosity, from expanding and coalescing. If the vapor cannot escape the magma (such as by leaking out the sides of the volcanic vent), a large number of small pressurized bubbles are contained within the magma as it nears the surface. Eventually this mixture blows apart, the gas expands and accelerates rapidly, and the fragments of magma that originally enclosed the bubbles are carried upward with that expanding gas, which jets into the atmosphere and feeds high-standing plumes and ground-hugging pyroclastic flows. This is the type of explosive eruption that occurred on May 18, 1980.

The combination of effusive and explosive activity contributes to the construction of composite volcanoes (also called stratovolcanoes) that typify the Cascade chain, specifically Mount St. Helens. These volcanoes are essentially piles of steep-sided lava domes and flows and loose debris deposited during explosive pyroclastic activity. The combination of contrasting materials, abundant loose debris, and steep slopes contributes to additional hazardous processes. The volcanoes themselves are very unstable; large sectors may collapse and spread over surrounding valleys as debris avalanches—mixtures of loose clastic debris and intact blocks of volcanic rock. This is often facilitated by intrusion of new magma into the volcano at the beginning of an eruptive episode. The magma inflates the volcano, steepening its slopes so that they are more prone to failure. In such cases, the ensuing debris avalanche might be accompanied by a lateral blast as the pressurized magma body explosively decompresses; the opening phase of the May 18, 1980, activity at Mount St. Helens is a classic example of this process (Lipman and Mullineaux, 1981). Debris avalanches can occur without any accompanying eruption, however.

Another hazard is a type of mudflow, referred to as lahar, in which slurries of rocks, ash, and water descend from the volcano into surrounding drainages. There are several causes of lahars: lava may melt snow during an eruption or flow from open vents and mix with wet soil and mud on the slope of the volcano; a flood may be caused by a lake breakout; heavy rainfall may occur on unconsolidated pyroclastic deposits; or there may be volcanic landslides. The lahars can grow as they flow and pick up more debris, extending tens of kilometers or more downstream and inundating rivers and valleys.

Ancient Lahars

Geologic evidence interpreted from the extent, height, and sedimentological characteristics of deposits along the Toutle River and its confluence with the Cowlitz River indicates that catastrophic breakouts of a lake in the general vicinity of Spirit Lake have occurred repeatedly during past eruptions (Scott, 1988a,b). The importance of this information for today is that the magnitude of catastrophic flooding predicted by post-1980 analyses (Swift and Kresch, 1983; Kresch, 1992) is consistent with events that happened in the geologic past and thus are plausible.

There is evidence of four lahars having been deposited during the eruptive period circa 2,500 and 3,200 years before present. In each of these events, a large flood of sediment-laden water surged down the North Fork Toutle River, entraining sediment and increasing in volume for up to 12 miles (20 km) before evolving into a lahar several times more voluminous than the original lake volume. The largest of these lahars deposited 35.3 billion cubic feet (1 billion m^3) of sediment—10 times the volume of the largest lahar generated in the 1980 eruption—from the North Fork Toutle Valley. Peak discharge was estimated to be between 7.0 and 10.5 million $feet^3$ (200,000-300,000 m^3) per second, similar to that of the modern Amazon River. It inundated the site of the town of Castle Rock tens of meters deep and spread at least 6 miles (10 km) upstream and downstream of the Cowlitz River confluence. The evidence for the nature, magnitude, frequency, and age of these lahars was developed and interpreted mainly by Scott (1988a,b) and is summarized by Grant et al. (2016a). The only imaginable source of the large water volumes needed to trigger these prehistoric lahars is the sudden release of a lake in the general vicinity of the modern Spirit Lake. Hausback and Swanson (1990) identified two large debris avalanche deposits on the northern flank of the volcano that occurred within the same 2,500-3,200 years before present period, and it is likely that these deposits dammed the predecessors of Spirit Lake and provided easily erodible material that could be entrained into water during subsequent catastrophic breaching of the debris blockages.

Region Seismicity

Earthquakes in the region originate from three sources. First, the subduction zone itself is a major fault zone, referred to as the Cascadia Subduction Zone (see Figure 2.4). Subduction is not smooth; rather, the fault system is "locked" when ongoing stresses cause strain to be stored in the system. Eventually a fault (or set of faults) fails catastrophically, releasing the stored strain and causing major earthquakes exceeding magnitude (M) 9.0. Examples of such earthquakes include the March 11, 2011, M 9.0 Tōhoku, Japan, and the December 26, 2004, M 9.0 Northern Sumatra earthquakes.

The second source of seismicity is smaller but nonetheless significant earthquakes occur along faults in the continental crust (i.e., crustal faults) above the subduction zone (see Figure 2.4). These earthquakes are often closer to the site of interest and can produce stronger shaking intensity than do more distant larger-magnitude subduction zone earthquakes. At the regional scale, the crust experiences compressive forces in the direction of subduction while local settings might also experience faulting due to extensional forces. Mount St. Helens sits atop a north-northwest trending belt of shallow crustal faults known as the Mount St. Helens Seismic Zone. These earthquakes tend to have magnitude 6.0 or less, but larger-magnitude earthquakes might be possible. Both Cascadia Seismic Zone and crustal faults are considered to be of tectonic origin.

The third source of seismicity is volcanic earthquakes caused by intrusion of magma into the solid crust. This results in reactivation of existing fractures, opening of new fractures, and shifting of rock domains as the intrusions alter the state of stress in their surroundings. These volcanic earthquakes are key components of volcano monitoring because they allow scientists to track the motion of magma that might lead to an eruption. Volcanic earthquakes tend to be of relatively low magnitude, however, with a few reaching magnitudes of 5.0 to 6.0.

Engineering Geology of the Spirit Lake Debris Blockage

The 1980 eruption of Mount St. Helens created three debris dams that reshaped the Toutle River watershed: the Spirit Lake blockage, the Castle Lake blockage, and the Coldwater Lake blockage. The Castle Lake and Coldwater Lake debris blockages have received less attention to date. This report focuses on issues related to the Spirit Lake debris blockage, but management decisions in the region may also need to focus on the other two.

The Spirit Lake debris blockage consists of a poorly characterized (from a geotechnical point of view) chaotic, permeable mixture of sand, gravel, boulders, and organic materials. The boundaries of the blockage do not easily lend themselves to clear definition, or even to identification of exactly where the blockage begins and ends. Unlike an earthen dam, the slope of the blockage is relatively shallow. The northern boundary of the blockage abuts Johnston Ridge, while the southern boundary grades into the surrounding landscape. The materials composing the blockage are described by Grant et al. (2016a). The texture of the materials is highly variable. Little of the original competent rock from the mountain slope remains; instead, it is shattered and interlaced with sands and gravels (Glicken et al., 1989). At its crest the blockage ranges from 200 feet (60 m) to more than 500 feet (150 m) in thickness. Both the avalanche sediment and the overlying pyroclastic sediment are highly erodible.

Over geologic time, Spirit Lake has been dammed repeatedly by volcanic material, filled, and at least partially drained by overtopping failures of the blockage. Those failures caused major floods and mudflows down the North Fork Toutle River in the geological past (Scott, 1989). The surface boundary of the current Spirit Lake debris blockage is highly irregular.

It is approximately 6,400 feet (1,950 m) in length from east to west by 4,800 feet (1,465 m) in width from north to south (Glicken et al., 1989) and varies in depth up to 490 feet (150 m) (Grant et al., 2016a). Figure 2.5 depicts thicknesses of the debris blockage. The blockage is composed of highly heterogeneous materials and includes bedrock of well-lithified Tertiary tuff, andesite-and-basalt, older-dacite, ash cloud, pyroclastic flow, and phreatic deposits (i.e., derived from explosions related to subsurface steam) (Meyer et al., 1985; Glicken et al., 1989; USACE, 2016a). Figure 2.6 is an idealized geotechnical engineering cross-section of the debris blockage based on the original subsurface investigation conducted shortly after the 1980 eruption of Mount St. Helens. This simplified diagram shows three stratigraphic units divided between two basic units: debris avalanche and ash deposits. The stratigraphic units are described by the USACE (2016a) as

- Volcanic ash, which consists of primarily fine-grained deposits, highly erodible, of low unit weight. Generally 0 to 10 feet (0-3 m) in thickness, but may be as thick as 35 feet (11 m). Average standard penetration test values,[2] which provide an indication of the density of the sediments, are 11 blows per foot. This value is consistent with what geotechnical engineers call loose to medium dense soils.
- Pyroclastic flow material, which consists of primarily fine-grained with up to 20% gravel. The coarse fraction is of low-density, easily erodible, widely distributed, with thicknesses ranging between 0 and 37 feet (0-11 m) in thickness, except in the pumice plain area where thicknesses are up to 160 feet (49 m) (see Figures 2.5 and 2.7). Pyroclastic flow materials can also be found in outwash areas located away from the crater of Mount St. Helens. Deposits can be 76 feet (23 m) thick. The average standard penetration test value for the material is 23 blows per foot.

[2]The standard penetration test methodology is described in the ASTM International's ASTM D1586. See https://www.astm.org/Standards/D1586.htm.

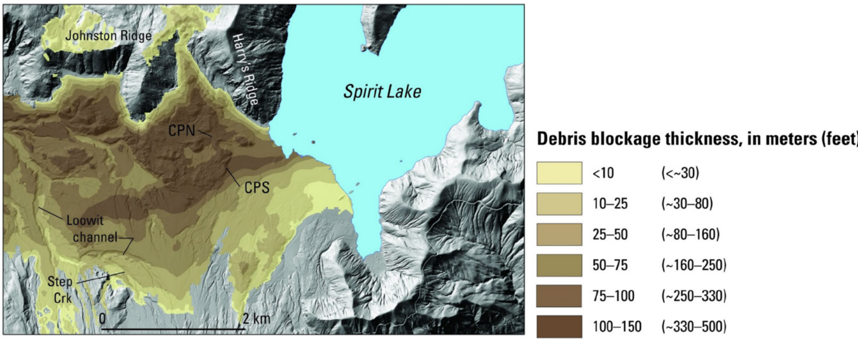


FIGURE 2.5 Debris blockage thickness shown on topographic model derived from 2009 LIDAR survey. The debris thickness contours run along the old North Fork Toutle River in the northeast-southwest direction. SOURCES: Map derived by Adam Mosbrucker, USGS. Original data from Glicken et al., 1989.

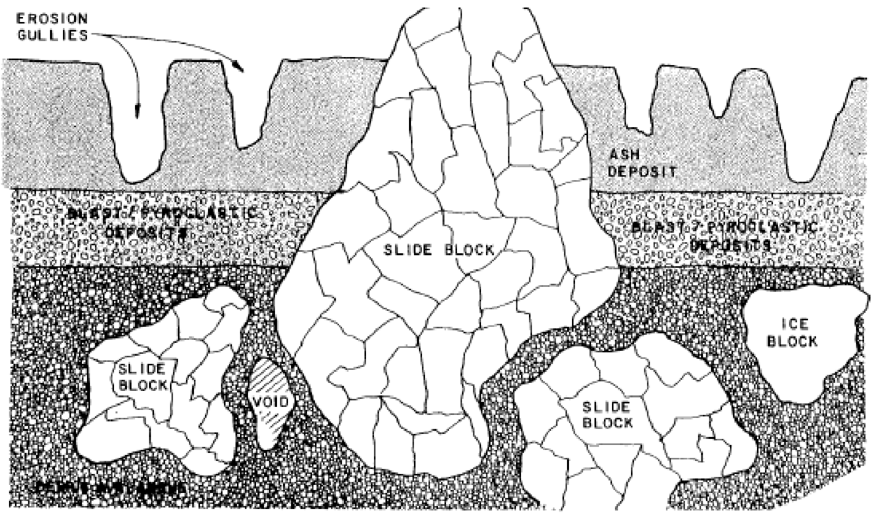


FIGURE 2.6 Idealized cross-section of the Spirit Lake blockage. The debris blockage also includes pits resulting from the melting of blocks of ice from glaciers located on Mount St. Helens and entrained in the debris slide. SOURCE: USACE, 2016a.

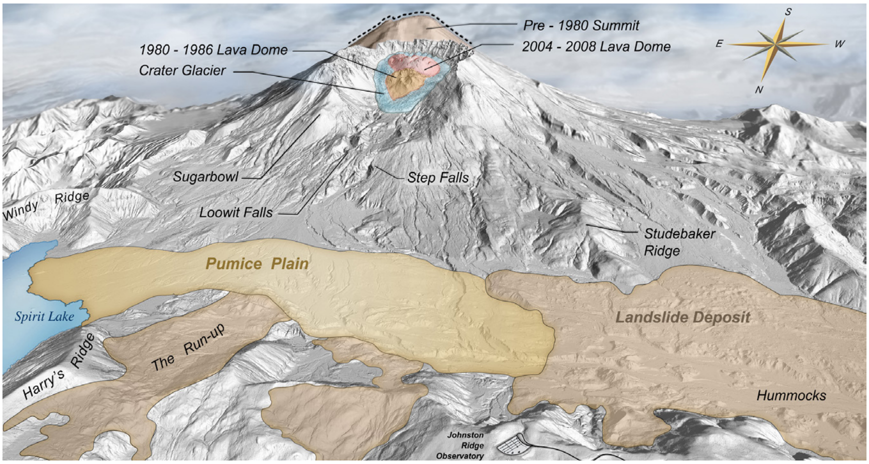


FIGURE 2.7 Raised relief image of the north side of Mount St. Helens and region based on LIDAR data showing major topographic features and deposits from the 1980 eruption of the volcano. Harry's Ridge is located immediately to the right (west) of Spirit Lake. SOURCE: USGS. See https://volcanoes.usgs.gov/volcanoes/st_helens/st_helens_geo_hist_101.html.

- Blast deposits, which include a wide range of particle sizes—from coarse sand to cobbles—and a variety of rock types. These are less erodible than the ash or pyroclastic flow materials. The aerial extent of blast deposits varies and thicknesses range from 0 to 131 inches (333 cm).

Clays and silts to gravelly sand and clasts up to meters in size can be found within the deposits (Glicken et al., 1989). The surface topography is uneven and mostly covered by the pyroclastic flow and ash cloud deposits. These highly erodible deposits vary in thickness from a few inches (cm) to 43 feet (13 m) (Glicken et al., 1989). Within a few years of the eruption, surface erosion channels and multi-meter scale seepage erosion pipes within the ash cloud deposit were observed (see Figure 2.8).

The limited test results of the geotechnical properties from the sampled materials are shown in Table 2.2 (from USACE, 2016a). In general, these materials are highly permeable, are loose, and have little cohesive

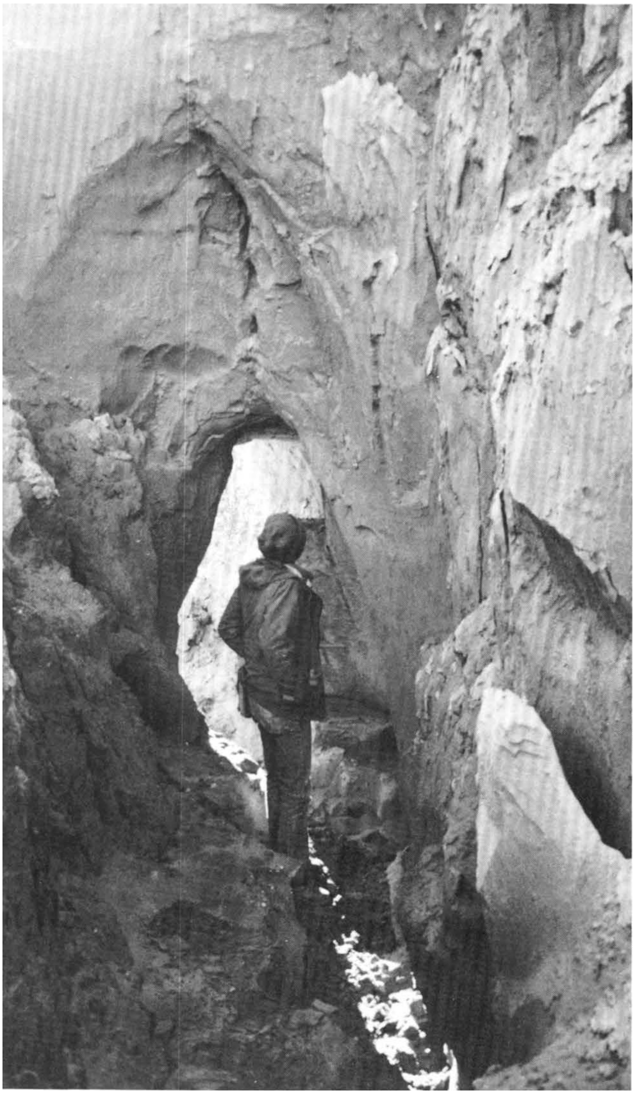


FIGURE 2.8 Photograph of erosion of the Spirit Lake debris blockage, erosion pipe within the ash deposit. SOURCE: Glicken et al., 1989.

TABLE 2.2 Summary of the Geotechnical Properties of the Spirit Lake Blockage Materials

Material	Moist Density (pcf)	Saturated Density (pcf)	Internal Friction Angle	% Fine	% Sand	% Coarse	Saturated Hydraulic Conductivity (cm/s)
Ash	84	88	30-35	50-70	30-50	0-5	8×10^{-4}
Blast Deposit	120	125	32-45	5-20	30-50	30-55	1×10^{-1}
Pyroclastic Flow	92	96	33-37	10-20	60-80	10-20	1×10^{-3}
Debris Avalanche	125	130	30-45	5-25	20-60	30-75	N/A

SOURCE: USACE, 2016a.

strength. The high heterogeneity affects the distribution of shear strength and fluid flow properties of the debris blockage.

GROUNDWATER HYDROLOGY

Because the debris blockage consists of unconsolidated sediments from different parts of the original volcanic edifice with differing grain sizes, its hydraulic properties are complex. They also receive infiltrated water from a number of sources, including streams draining the volcano and Johnston Ridge. Given that the materials of the debris blockage are heterogeneous and some have low density, preferential flow paths could well develop within the debris blockage, creating a risk for the development of piping failure if the water level in Spirit Lake rises sufficiently. The groundwater flow that emerges from the avalanche deposit also drives headward erosion of the channels that feed sediment downstream to the SRS and the Toutle and Cowlitz valleys.

Assessments were made of the hydrology and stability of these deposits with respect to piping, liquefaction, failure during seismic loading, and erosion soon after the 1980 eruption (Youd et al., 1981; Glicken et al., 1989), but no follow-up analysis has been conducted to determine how the hydrologic and hydraulic settings have changed, or how such possible changes affect the long-term geotechnical stability of the debris blockage. The USGS has occasionally resurveyed the eroding channels on the debris avalanche deposit to estimate its role as the prime sediment supply to the Toutle River valley (Major et al., in press), and the agency has carried out a low-resolution groundwater survey (Wynn et al., 2016), which documents the presence of a shallow groundwater body in the debris avalanche deposit.

Groundwater Flow in the Spirit Lake Debris Blockage

Basin-scale surface and subsurface hydrologic processes, surface erosion rates, and subsurface stability of the debris blockage are governed by precipitation patterns (rain and snow) and geologic and geomorphologic conditions. The sources of groundwater recharge in the debris blockage are the volcano itself, seepage of surface runoff from Johnston Ridge in the north, and seepage from springs near the volcano's crater in the south (Glicken et al., 1989; Bergfeld et al., 2008; Wynn et al., 2016). Limited studies, conducted prior to 1992, indicate that responses of the groundwater system to geomorphic changes were significant after the eruption (Meyer et al., 1985; Glicken et al., 1989). In the mid-1980s the groundwater in the blockage exhibited a mound producing an easterly flow into the lake and a westerly flow into the north fork of the Toutle. The current state of the groundwater was last probed using a geophysical survey by Wynn et al. (2016) and modeled to interpolate its elevation (see Figure 2.9). Since then, few data on groundwater in the region have been collected. Groundwater recharge processes in the region are complex; approximately 43 inches (110 cm) of rainfall and 79 inches (200 cm) of snow and glacial meltwater seep through young and heterogeneous geologic media and over large varying topographic reliefs and gradients (Lee, 1996). Recharge areas have not been studied in detail, but the principal recharge in the debris blockage may come from direct rainfall.

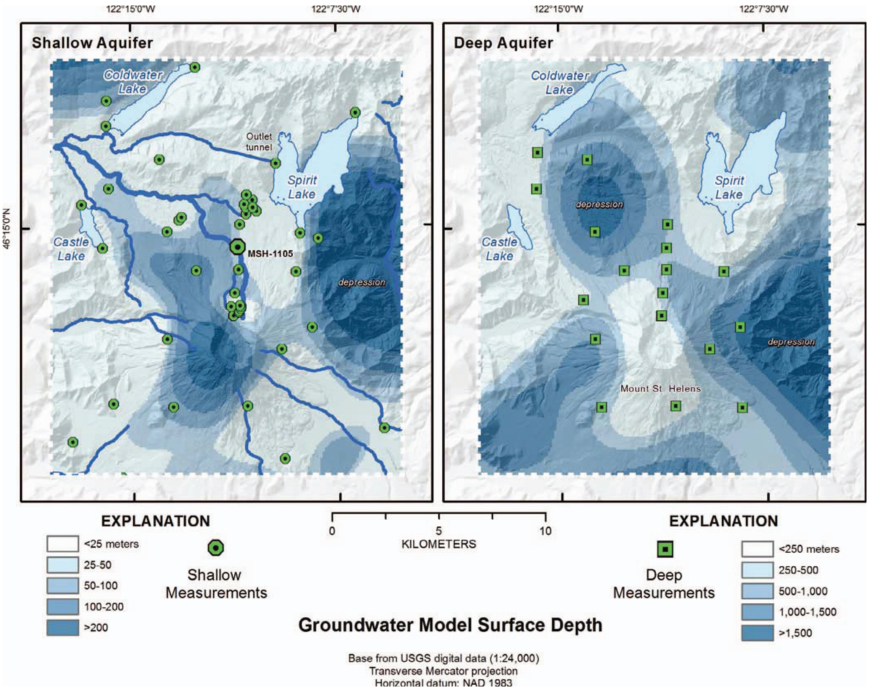


FIGURE 2.9 Groundwater surface depth from modeling and geophysical data. SOURCE: Wynn et al., 2016. The following material from the *Journal of Environmental and Engineering Geophysics*, 2016, is published with the permission of the Environmental and Engineering Geophysical Society. All copyright privileges remain with the EEGS. This material cannot be copied or used without the express written permission of the EEGS.

Piezometers were installed in the debris blockage shortly after the 1980 eruption, but groundwater monitoring was discontinued after only a few years (C. Budai, personal communication, June 22, 2016). Data collected prior to 1992 indicate the water table within the debris blockage "tends to lower between the edge of Spirit Lake and areas downstream" (USACE, 2016a). According to the USACE, and based on those early piezometer readings, groundwater levels seemed to have been influenced by the flow of subsurface waters off Mount St. Helens and the area between Johnston and Harry's Ridges. Concentrated flow seems to have developed between Spirit

Lake and downstream areas. The USACE presumed this channel "will continue to drain subsurface flows in a safe manner" (USACE, 2016a). The permeabilities of debris blockage materials, determined during post-1980 characterization efforts, indicate that groundwater can pass through debris avalanche materials more quickly than surface water can reach the phreatic surface and create a mounding effect. Permeabilities of material in the blockage typically range from moderate to high (10^0 to 10^{-4} cm/sec) and are variable (Grant et al., 2016a).

Groundwater flow within the blockage may have been a dynamic process after the eruption. Analysis (Glicken et al., 1989) indicates that groundwater in the debris blockage initially flowed from Spirit Lake through the blockage toward downstream, but then it reversed direction toward the lake. Limited water level data from within the blockage led to the conclusion that a groundwater mound or divide beneath the topographic crest of the blockage was established within a few years (Glicken et al., 1989). Groundwater flows into Spirit Lake on the east of the divide and discharges at the North Fork Toutle River on the west of the divide. This is not unexpected since this was a period of transition toward a new equilibrium.

Recent controlled-source audio-frequency magnetotelluric (CSAMT) soundings (Wynn et al., 2016) indicate that two distinct aquifer systems separated by a thick unsaturated zone in the debris blockage area may exist: models indicate that one could be 30-165 feet (10-50 m) in depth and less than 3-5 miles (6-8 km) in lateral scale, while the other is approximately 1,640-3,280 feet (500-1,000 m) in depth and more than 6 miles (10 km) in scale. The groundwater discharge rate into Spirit Lake was estimated to be likely less than 1% of the mean annual recharge of Spirit Lake (Glicken et al., 1989). Considering the length of the blockage and the elevation differences between the groundwater divide and discharge locations (Spirit Lake and the North Fork Toutle River), the average groundwater gradient within the blockage should be less than 2%, which implies modest-to-low seepage velocities.

Because groundwater has the potential to differentially erode sediments within the blockage, it is important to understand groundwater flow within. The debris blockage consists of heterogeneous unconsolidated sediments of varying grain size from different parts of the original volcanic edifice; therefore, its hydraulic properties are complex. Lower-density materials could allow preferential flow paths to develop within the blockage (such as the piping shown in Figure 2.8), elevating a risk of failure associated with piping if water levels in Spirit Lake rise sufficiently. The groundwater flow that emerges from the avalanche deposit also drives headward erosion of the channels that feed sediment downstream to the SRS and the Toutle and Cowlitz River valleys.

Assessments of hydrology and stability of the deposits with respect to piping, liquefaction, failure during seismic loading, and erosion were assessed soon after the 1980 eruption (Youd et al., 1981; Glicken et al., 1989), but no follow-up analysis has been conducted to determine how the hydrologic and hydraulic settings have changed, or how such possible changes affect the long-term geotechnical stability of the debris blockage. The USGS has occasionally resurveyed the eroding channels on the debris blockage deposit to estimate the role of the blockage as the prime sediment supply to the Toutle River valley (Major et al., in press). Groundwater pressures and internal erosion are important factors for the long-term stability of the debris blockage.

ECOLOGICAL SETTING

The characteristics and patterns of terrestrial ecosystems of the Mount St. Helens landscape prior to the 1980 eruption were broadly representative of the Cascade Range in many respects, reflecting the interplay of gradients in soils, topography, climate, and disturbance history. Streams and lakes surrounding the volcano were numerous and diverse, with streams ranging from small, steep, cascade-dominated mountain channels to large floodplain rivers, and with lakes ranging from cool high-elevation subalpine lakes to relatively warm low-elevation lakes (Bisson et al., 2005). Swanson and others (2005: 20-26) provide an overview of the pre-eruption ecological setting, in particular, noting several specific ecological patterns regarding the ecosystems surrounding Mount St. Helens. These include

1. A diverse flora predominantly consisting of a small number of coniferous tree species and many non-forest vegetation types that comprised a small, but important proportion of the landscape. Characteristic plant species and communities varied with elevation. The volcanic cone was dominated by alpine and subalpine plant communities, with the lower flanks of the mountain containing species such as western red cedar at the lowest elevations, noble fir and western white pine in mid-elevations between, and mountain hemlock, Pacific silver fir, and Alaska yellow cedar higher. Douglas-fir and western hemlock were common throughout the lower forest zones. The riparian zone was comprised of deciduous trees and shrubs, particularly red alder, black cottonwood, and willow. Patterns of dominant species also varied with time since disturbance, including past volcanic events and infrequent wildfires and, more recently, silvicultural activities, particularly clear cut logging.
2. A diverse fauna characteristic of montane, alpine, and riparian habitats characteristic of Western Washington. The presence and distribution of specific habitat types across the Mount St. Helens landscape strongly influenced patterns of terrestrial vertebrates through associated controls on food availability, cover, parasites, predators, microclimate, and weather. The pre-eruption fauna, with the exception of introduced fish species, was comprised of native species, with several regional endemic species. While the invertebrate fauna of the Mount St. Helens landscape was poorly documented at the time of the eruption, it is thought to have comprised thousands of species. The Upper Toutle River watershed contains suitable habitat for several species that are listed as threatened or endangered or as USFS sensitive species. These include the northern spotted owl, peregrine falcon, gray wolf, grizzly bear, wolverine, and mountain goat (USFS, 1997). The area surrounding Mount St. Helens is also home to several regional endemics, including the Larch Mountain salamander, Van Dyke's salamander, Cascades frog, Cope's giant salamander, American shrew mole,

Cascades golden-mantled ground squirrel, and creeping vole (personal communication, C. Crisafulli to J. Kupfer, August 29, 2017).

3. Stream and lake ecosystems that provided habitat for numerous species contributing to landscape biodiversity. Headwater streams were small and shallow, their channels having high gradients and being composed of steep cascades and small pools with boulder, cobble, and bedrock substrates. These streams fed into mid-sized, meandering streams and rivers with localized floodplains and more open plant canopies, which eventually drained into larger rivers with more extensive floodplains, gravel bars, and riffles. The primary river systems draining Mount St. Helens all feed into the Columbia River and, thus, the Pacific Ocean. Most lakes were formed in cirques created by Pleistocene glacial activity, although several (such as Spirit Lake) were formed in lower elevation settings where volcanic debris or lava flows blocked streams. While many lakes contained no fish until active management and fish stocking began, Spirit Lake was connected to the Toutle River system without barriers, allowing the presence of coastal cutthroat trout, winter steelhead, and coho salmon. However, stocking was common to maintain levels of these species sufficient to support a thriving sports fishery industry in the Toutle River system (Swanson et al., 2005: 20-26).

The 1980 eruption had catastrophic effects on ecosystems surrounding Mount St. Helens. The lateral blast destroyed vegetation up to 15 miles (24 km) away, and the high temperatures, debris avalanche, mudflows, and pyroclastic flows killed plants and animals near the blast area. The Washington State Department of Fish and Wildlife estimated that nearly 7,000 big game animals (deer, elk, and bear), all birds, and most small mammals died in the area most affected by the eruption (Tilling et al., 1990). The debris avalanche displaced the water in Spirit Lake, killing all the fish, and buried the upper 15 miles (25 km) of the North Fork Toutle River. Mudflows originating from the deposit extended 75 miles (120 km) down the North Fork Toutle River and main stem Toutle River valleys all the way to the Columbia River (Swanson and Major, 2005). Catastrophic changes caused by the debris avalanche, mudflow, and pyroclastic flows decimated fish populations and destroyed 135 miles (218 km), or 77%, of the 174 miles (280 km) of the anadromous fish habitat formerly utilized by salmonids (Jones and Salo, 1986). These effects were especially devastating to fish populations in the North Fork Toutle River as they immediately killed many fish outright and modified riparian habitats, especially in the area impacted by the debris avalanche. High concentrations of suspended sediment in the Toutle River resulted in many adult spawners avoiding the river in 1980 and 1981 (Martin et al., 1984).

Management decisions made regarding the Spirit Lake tunnel and the SRS may affect a range of ecological components, a number of which were identified as important by interested and affected parties during the committee's open session meetings in Kelso, Washington. A commonly discussed ecological concern among those participating was the state of anadromous and resident fish species. Prior to the eruption, the North Fork Toutle River valley was an important recreation area for fishers, hunters, and other users. According to Ellifrit and others (1984), the Toutle River system usually ranked among the top five streams in Washington in total numbers of sport-caught steelhead and was a popular salmon angling stream. They noted that salmon, steelhead, and sea-run coastal cutthroat all spawned naturally within the river system. The system also supported many nongame fish species, which along with the game species were important ecological components of Mount St. Helens aquatic ecosystems (Bisson et al., 2005).

Jones and Salo (1986) echoed that the Toutle River watershed sustained a thriving sport fishery that was consistently viewed as being one of the premier salmon and steelhead areas in the region. They underscored, however, that the success of that fishery had long been dependent on hatchery-raised fish. Specifically, they noted:

> *The Wildstock Toutle River salmon and steelhead populations, unable to sustain the exploitation rates exerted by commercial and recreational fisheries, have been augmented by artificial propagation for the past*

> *30 years.[3] The Toutle River hatchery operated by the Washington Department of Fisheries produced an annual average of 1.4 million coho salmon and 3.2 million fall chinook salmon. Prior to 1969, many Columbia River hatcheries reared and released a strain of coho salmon originating from the Toutle River. Hatchery production of coho salmon, chinook salmon, and steelhead trout produced an annual estimated catch of 251,000 fish valued at more than 12 million dollars. The Washington Department of Game annually released approximately 240,000 winter and summer run steelhead smolts into the Toutle River system.* (Jones and Salo, 1986: 1-2)

It was estimated that natural spawning (hatchery and natural-origin) fall Chinook salmon from 1964 to 1979 averaged only 42% (4,517 fish) of the Toutle subbasin spawners, a number that had slipped even further by 2009.[4]

With respect to recovery of the fisheries since the eruption, Bisson and others (2005: 167) noted: "(M)any fishery managers predicted that recovery of salmon and steelhead populations would take decades because riverine habitats had been so extensively damaged." In the immediate wake of the eruption, high concentrations of suspended sediment caused large numbers of adult steelhead that had been migrating toward affected tributaries, particularly those in the Toutle River system, to swim into tributaries flowing into the Columbia River upstream of their natal streams for 1 to 3 years after the eruption (Whitman et al., 1982; Leider, 1989). Small numbers of adult salmon and steelhead did navigate the sediment-laden waters of the Toutle River system and returned in 1980 and 1981, but recreational fisheries for salmon and wild steelhead were closed immediately after the eruption and not reopened until 1987 (Bisson et al., 2005). Within 5 years

[3]For example, the North Toutle salmon hatchery was authorized under the Mitchell Act. It began operation in 1951 as part of the Columbia River Fisheries Development Program and was destroyed by the 1980 eruption. Operations resumed in 1985. The hatchery is operated to produce adult fall Chinook and coho salmon for commercial and sport fisheries in the northeast Pacific and Columbia River basin (see http://docs.streamnetlibrary.org/IHOT/NorthToutle-Cohos1997.pdf).

[4]See http://www.hatcheryreform.us/hrp_downloads/reports/columbia_river/system-wide/4_appendix_e_population_reports/lower_col-cowlitz-toutle_fall_chinook_01-31-09.pdf.

of the eruption, juvenile salmonids were found in tributaries throughout the South Fork Toutle River watershed and tributaries of the North Fork Toutle River, except those draining the landslide debris flow areas. Nevertheless, an assessment of population viability concluded that health or viability for anadromous species ranged from very low for spring Chinook to low for fall Chinook salmon, coho salmon, and winter steelhead, leading to risks of elimination for local populations of these species (USACE, 2007).

In response to concerns about the viability of anadromous fish populations, the north and south forks of the Toutle River system were both targeted as subbasins for management of fall Chinook salmon, winter steelhead, and coho salmon in the Lower Columbia River Salmon and Steelhead Endangered Species Act (ESA) Recovery Plan (National Marine Fisheries Service, 2013). Returning and reintroduced anadromous salmon populations in the Toutle River system below the SRS have grown in recent years (Liedtke et al., 2013), although populations in the South Fork Toutle River have grown much more quickly. Natural and hatchery-produced fall Chinook and coho salmon as well as winter steelhead have returned in lower reaches of the system, but the North Fork Toutle River above the SRS remains closed to fishing. More detail about the management of fish populations is provided in Chapter 3.

Prior to the eruption, Spirit Lake itself was a popular recreational fishing destination, with steelhead and coho salmon migrating to the lake to spawn and an average of 25,000 rainbow trout stocked in the lake annually (USDA Forest Service, 1997: III-29). The first recorded fish in Spirit Lake after the eruption was a rainbow trout captured in 1993, but populations rose in the late 1990s as ecological conditions within the lake improved in the two decades after the eruption (Bisson et al., 2005). It is unknown how the first fish entered the lake, but there remains a very limited amount of stream habitat available for spawning near Spirit Lake (Bisson et al., 2005), and access to Spirit Lake from the Toutle River system remains blocked by the debris avalanche.

The issue of restoring anadromous fish to the upper North Fork Toutle River is one with not only biophysical challenges related to erosion and sediment movement into the North Fork Toutle River drainage but also issues of access and fish passage associated with the SRS. A number of individuals at open session meetings held by the committee in Kelso and representing a diverse variety of interested and affected parties expressed interest in improving upstream fish passage and undertaking ecosystem restoration measures in the Toutle River for recreational, economic, and aesthetic reasons (e.g., reintroducing species that were once a part of the North Fork Toutle River ecosystem and economy); cultural reasons (e.g., concerns voiced by the Cowlitz Indian Tribe about the status of salmon and other species in the Toutle River system); and legal reasons (under the auspices of the ESA). Protection of endangered fish species (including issues associated with fish passage both upstream and downstream through the SRS) was a central issue in evaluating USACE plans to raise the SRS spillway up to 23 feet as part of its approach for managing sediment over the next 20 years[5] (see also Chapter 3). Even when fish are able to pass the SRS (e.g., through the current trap-and-haul system), they face issues of finding suitable habitat and have no access to Spirit Lake itself because of the debris blockage and the design of the Spirit Lake tunnel.

Beyond anadromous fish species, there may be other management and legal considerations associated with the ESA. Fourteen federally or state-listed threatened or endangered species, federal species of concern, and Washington state sensitive species or state candidate species occur in the area associated with the SRS, and numerous bird species that may occur in the study area are protected under the Migratory Bird Treaty Act (USACE, 2017). The impacts of management options on other species such as elk, which are an important management component in the Mount St. Helens Wildlife Area that is administered by the Washington Department of Fish and Wildlife, may be considered.

Finally, as will be discussed at greater length in the next chapter, the Mount St. Helens National Volcanic Monument was established in 1982 from lands within and adjacent to the Gifford Pinchot National Forest in part to serve as a venue for scientific research on ecological succession as

[5]See http://tdn.com/news/local/to-raise-spillway-army-corps-will-have-to-spend-millions/article_4972f60a-9dce-5089-aae7-bd7a584db181.html.

well as volcanic and seismic risks associated with Mount St. Helens. A key aspect of the Monument's authorizing legislation (P.L. 97-243) is that the 110,000-acre (445 km^2) area would be administered "to allow . . . geologic forces and ecological succession to continue substantially unimpeded," with specific provisions and limitations regarding scientific study and research, recreational and interpretive facilities, timber harvesting, and hunting and fishing being laid out. The 1980 Mount St. Helens eruption provides the most detailed case study of volcanic impacts on ecological systems ever, with research providing exceptional insights into the survival and reestablishment of both plant and animal communities (see, for example, papers in Dale et al., 2005a), and much of that work has resulted from research conducted within the Monument. Such goals and restrictions may have potential relevance to the decision framework outlined in this report and should thus be considered.

HYDRAULIC INFRASTRUCTURE

Various engineered infrastructure elements have been constructed in the Spirit Lake and Toutle River system to control the transport of water and sediment through the system. The committee considers that these infrastructure elements are now part of the system and regional setting, serving as agents of change for the system. Moreover, the committee considers that the infrastructure elements themselves have hazards associated with them or that they may lessen or exacerbate natural hazards associated with the system. The infrastructure elements are described here and in Chapter 5 from the point of view of engineering a landscape.

Tunnel

As described in Chapter 1, a 1.56-mile (2.6-km) tunnel was constructed in 1984-1985 through Harry's Ridge, west of Spirit Lake, to regulate lake levels and prevent breaching of the debris blockage (see Figure 1.3). Britton et al. (2016a) review the history of the tunnel, its construction, and the problems experienced with the tunnel in 1996 and again in 2014-

2015. The tunnel alignment crosses five mapped faults or shear zones. In 1992, shotcrete spalling and invert heave were detected along the Julie and Kathy L. shear zone. These required major repair of a 100-foot (30-m) segment in 1996 (see Figure 2.10). Significant distress and heave were again detected in this zone during an annual inspection in 2014 (see Figure 2.11), decreasing the hydraulic capacity of the tunnel below acceptable levels. Uplift of the tunnel floor reduced the tunnel diameter by about 30 inches (80 cm) and constricted water flow. An inspection 6 months later indicated an additional 6 inches (15 cm) of uplift. In early 2016, the tunnel was closed for 10 weeks to allow engineers to rebore a section of tunnel and install more than a dozen steel ribs to stabilize the area where the floor had been rising (Service, 2016). The repeated instances of deformation in this tunnel and subsequent congressional allocations for repair triggered the call by members of Congress for a long-term management solution (Beutler et al., 2015), as described in Chapter 1. During the repairs, completed in March 2016, the lake level rose 20 feet (6 m), only a few meters below where the more erodible deposits could be eroded by lake

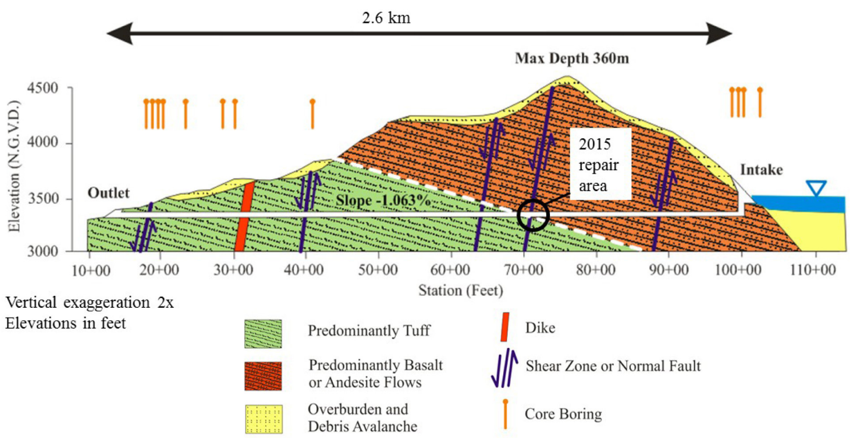


FIGURE 2.10 Geologic profile along tunnel. Left is west; right is east. There are five mapped shear zones shown. The location of the 2015 repair area is shown. This tunnel was deformed at the contact between predominantly tuffaceous and hard rock materials along the Julie and Kathy L. shear zone. SOURCE: Britton et al., 2016a.

FIGURE 2.11 Photo of heave in the tunnel. The tunnel diameter was originally 11 feet. The man is standing on the heaved portion of the tunnel. SOURCE: Britton et al., 2016a.

water. Engineering solutions for the control of water levels in Spirit Lake are discussed in Chapter 5.

Sediment Retention Structure

The USACE completed construction of the SRS in 1989 both to reduce chronic flood risk and to reduce the need for downstream dredging. The 1,888-foot-long (575-m), 185-foot-high (56-m) structure was constructed to trap medium- to coarse-grained sediment in the basin upstream of the dam until 2035, but greater than expected sediment transport in the North Fork Toutle River resulted in sediments burying the SRS outlet pipes earlier than expected. Flow from the North Fork Toutle River has been diverted to the SRS spillway, and some sediment now passes freely over the spillway.

Based on discussions with interested and affected parties during the committee's open session meetings in Kelso, the management of sediments in the region represents a controversy. The valley immediately upstream of the SRS, known as the sediment plain, grew rapidly as sediment accumulated (see Figures 2.12 and 2.13) behind the SRS. The landscape of the valley has been radically altered, and residents of the region expressed concerns about the ecological and economic health of the region. Passage of anadromous fish, for example, is negligible (at best) beyond the SRS.

The committee is not aware of a potential failure mode analysis that may have been conducted for the SRS in light of large volcanic, seismic, or atmospheric events for the region. A limited number of numerical simulations have been published that, for example, consider the effects of catastrophic floods and debris flows on the SRS capacity (e.g., Denlinger, 2011). Those studies, however, may assume no ill effects on the structure itself. The management of the SRS is described in Chapter 3. A limited number of alternatives for future management of the alternatives have been considered by the SRS and these are discussed in Chapter 5.

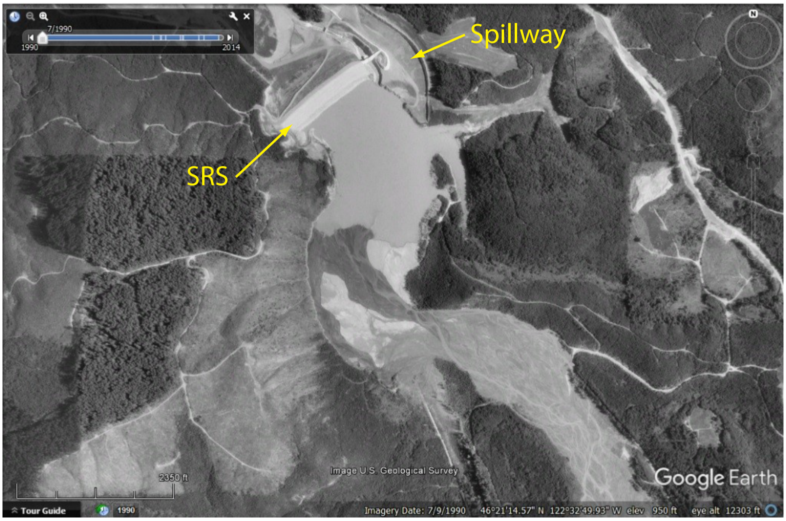
Levees

Communities located along the Toutle and Cowlitz Rivers are protected by flood levees with authorized levels of protection (LOPs) from 118-year (p=0.0085) to 167-year (p=0.006) return periods. Leveed areas along the lower Cowlitz River and property in leveed areas are valued at about $3.65 billion (USACE, 2017); they include portions of Longview, Kelso, Lexington, and Castle Rock (population of approximately 50,000). The most recent comprehensive LOP update was performed in 2009 for the Cowlitz River Levee Systems, 2009 Level of Flood Protection Update Summary (USACE, 2010a). This resulted in updates to the Cowlitz River discharge-frequency curve, stage-discharge relationships, (geotechnical) fragility curves for the levees, and an appraisal of hydraulic and hydrologic uncertainty. Uncertainty in river stage from that study is reported to have a standard deviation of 0.5 to 1.3 feet (0.15 to 0.4 m) along the river comprising natural, model, and sediment (from Mount St. Helens)

(a)
(b)

FIGURE 2.12 The SRS and the sediment plain (a) in approximately 1990 prior to the outlet works reaching their upstream capacity (b) and after reaching capacity. Note that water is now diverted over the spillway in the left of the photo. SOURCE: USACE.

(a)



(b)

FIGURE 2.13 Aerial view of the SRS and sediment plain taken both in (a) July 1990 and (b) July 2014. Note the increase in the size of the sediment plain. The SRS, which is approximately 2,000 feet in length, is the northeast-southwest trending linear structure in the upper center of the figure. SOURCE: Google Earth.

contributions. The part of the uncertainty due to sediments effects, which derives both from channel bed form and high sediment loads during storms, ranges from 0.25 to 0.7 feet (0.08 to 0.21 m), depending on location along the rivers. Sediment from Mount St. Helens deposited in the reaches of the Toutle and Cowlitz Rivers increases bed elevations and decreases discharge capacities of the reaches, raising the stage-discharge curves and thus the stage-frequency relations (i.e., annual exceedance probabilities).

SOCIO-DEMOGRAPHIC AND ECONOMIC SETTING

The socio-demographic and economic characteristics of the region, including those of Native American Tribes in the region, are important to the development of any long-term management plan for at least two reasons. They define the setting against which many of the impacts of engineering and management interventions must be measured, and the knowledge of the history and the current role of various groups and entities facilitates the identification of interested and affected parties who may be participants in plan development.

Mount St. Helens itself is located in Skamania County, Washington, but the concerns that are most central to this report (especially those associated with the Toutle and Cowlitz Rivers) focus primarily on impacts likely to be felt in adjacent Cowlitz County. The area was inhabited by Cowlitz and other Native American Tribes prior to contact with the Pacific Fur Company in 1811 (Cowlitz Indian Tribe, 2016). The indigenous population was forcibly removed from the area in 1855; many were sent to reservations in other parts of the state, but their descendants subsequently returned. Anglo-European settlement in the region, including what is now Cowlitz County, began in the early 1800s and centered primarily on trapping and the fur trade. The Hudson's Bay Company established the first permanent settlement in the area in 1825, but development began in earnest after 1920 when R. A. Long established a sawmill in Longview (Weber, 2012). That business was among a number of entities owned by Long and his Long-Bell Lumber Company, based in Kansas, which was the largest timber operation in the world when it opened in 1924. Longview was originally established to provide housing for workers.

Today, Longview is the largest community in the county, with a population of 37,000, and is the site of the county's major port (U.S. Census, 2016). Kelso, the county seat, is the second-largest community in the county, with a population just under 12,000. The county had an estimated population of 103,468 in 2016. The population is 86% non-Hispanic white, 7% Hispanic, and 2% Native American. About 1.4% of the population is of Asian descent, and 3% claim two or more different racial backgrounds. African Americans make up less than 1% of the population. In 2014, 15% of residents 25 years of age or older had a bachelor's or an advanced degree, compared with 33% of the state population and 30% of the U.S. population.

Major employers in the county include Weyerhaeuser Timber Company, International Paper (formerly Long-Bell Lumber Company), Kapstone Paper (formerly Longview Fiber Company), Alcoa, PacifiCorp (formerly Pacific Power and Light), Peacehealth/St. John's Medical Center, the county government, and the school system. As of 2013, the estimated median household income in the county was $48,417 (compared to a state average of $58,105). In the 1970s, manufacturing accounted for approximately one-third of all jobs in the county; now the proportion is around half that number. For the past 2 decades, unemployment in the county has been about 2% higher than the national average (Bailey, 2016). The median value of owner-occupied housing units in the county for the years 2010-2014 was approximately $175,000, lower than the statewide average of $257,000. Following state and national trends, housing prices in the county improved in 2015. Thirty-two percent of county residents are renters.

The county was hard-hit by the 2008 recession, with job losses particularly marked in the construction and manufacturing sectors. Men were disproportionately affected by the recession because of their high representation in those sectors. Post-recession jobs recovery began slowly, but employment had recovered by 2015. Jobs that have returned, however, are lower-wage than the manufacturing jobs they replaced (Bailey, 2016). Hope for better employment prospects has been spurred by recent plans to build a methanol plant at the Port of Kalama (Luck, 2015). Discussions between committee members and community representatives held during the committee's open session meetings indicate that residents also hope for increases in tourism and recreational travel.

The county's strategic plan for the years 2016 to 2020 (Cowlitz County Department of Emergency Management, 2016) highlights several challenges with respect to residents' overall well-being. The plan describes the population of the county as "older, poorer, and less diverse than the rest of Washington." The proportion of the population living below the federal poverty line is 13.5%. The county ranks high in the need for tenant assistance because of the lack of affordable rental housing, and about 34,000 residents receive Medicaid. The 2016-2020 strategic plan notes that public perceptions regarding the county are not optimistic, owing to such factors as job insecurity, unemployment, and low wages. Census and other data, as well as the appraisals of community residents and leaders, indicate that Cowlitz County has been negatively affected both by general economic trends and by economic forces specific to the region. Residents' views on long-term management options will undoubtedly reflect those concerns.

The Cowlitz Indian Tribe

The Cowlitz Indian Tribe is another influential force within the region. It and other tribes in the region are sovereign nations and therefore important stakeholders in decisions regarding Spirit Lake and the Toutle River system. The Cowlitz Indian Tribe, federally recognized in 2000, is headquartered in Longview, although reservation land is located in nearby Clark County, near the town of La Center. Although no part of the Spirit Lake and Toutle River system crosses reservation lands, the tribe, which retains hunting and fishing rights on its traditional lands, is a party to a memorandum of understanding with the Washington Department of Fish and Wildlife that focuses on the need for cooperation and communication aiming at maintaining the health of the fish and wildlife populations in the region. The Cowlitz Indian Tribe has natural resources and fisheries departments (with the scientific and technical expertise contained therein) within its governing structure that informed a 2014 letter to the USACE from Cowlitz Tribal Council Chairman William Iyall regarding a USACE (2014) report on the long-term sediment management plan and supplemental environmental impact statement (personal communication William Iyall to Jose L. Aguilar, October 23, 2014). The letter expressed concerns regarding, among other issues, the health of fish populations affected by the SRS, fish passage, and flood protection. Importantly, the letter stressed the need for systematic assessments of the success of previous mitigation actions and for more information on how both past actions and future plans will affect tribal interests. Concerns of the Cowlitz Indian Tribe and its relationship to the land and other interested and affected parties are described in Chapter 3.

HOW THE SETTING AFFECTS SYSTEM RISK ASSSESSMENT AND LONG-TERM MANAGEMENT

Information on the regional setting contained in this chapter has a number of implications both for assessing risks and for making decisions about long-term management of the Spirit Lake and Toutle River system. Key among these are the fact that the physical setting is complex and dynamic, that socioeconomic considerations, including tribal concerns, are part of the decision landscape, and that decision making needs to be based on a holistic conceptualization of the region and issues. The next sections summarize those concepts.

A Dynamic Region

The area of interest has been and continues to be shaped both by naturally occurring events and by engineering solutions designed to mitigate the impacts of those events. The most recent disaster that affected the region was the catastrophic eruption of Mount St. Helens in 1980, but that event occurred in the context of ongoing volcanic, seismic, and hydrological processes. Those conditions will be explored in greater detail in subsequent chapters, but a crucial finding from the discussions in this chapter is that management decision making needs to take into account the future effects of multiple hazards on the region. Engineered works do contain some of the adverse effects of the 1980 eruption, but they have also had adverse effects of their own. For example, the SRS has resulted in the trapping of sediments upstream of the structure, changing the landscape of that region and having wide-ranging effects on fish species that are valued by many local stakeholders. The tunnel designed to regulate water levels in Spirit Lake may be vulnerable to natural hazards such as earthquake-related movement. Repairs of the tunnel result in the need to temporarily close the tunnel, leaving the debris blockage vulnerable to rising water levels. Maintenance and repair of the tunnel also puts workers at risk.

Within this dynamic setting are many uncertainties that will have to be taken into account in long-term management decisions. In many cases, uncertainties have been compounded by data gaps, a lack of ongoing monitoring, and failure to consider potential sources of vulnerability. The need for future studies to better characterize hazards and vulnerabilities and to reduce uncertainty is an ongoing theme in this report.

Socioeconomics and Tribal Concerns as Part of the Decision Landscape

Decision making needs to be informed by more than the physical characteristics of the region. Socioeconomic conditions and tribal concerns are also part of the decision landscape. Although economic conditions have improved since the 2008 financial crash, incomes in Cowlitz County are low compared to statewide averages, and overall economic growth has been sluggish. Before the eruption of Mount St. Helens, the region enjoyed the economic benefits of recreational travel centered on fishing, hiking, and other outdoor pursuits, and many local stakeholders hope for a return of those types of recreational opportunities. Timber harvesting remains an important contributor to the region's economy, and the health of the federal, state, and private forests may be affected by management of the Spirit Lake and Toutle River system.

The Cowlitz Indian Tribe represents another set of interested and affected parties that have a special interest in conserving and restoring the region's wildlife and in agency accountability with respect to those concerns. Maintenance of cultural and religious practices is also a major tribal priority. The tribe is unlikely to accept long-term management decisions that do not take these interests into account.

Holistic Conceptualization

An understanding of the regional setting calls for a more holistic conceptualization of that system that should form the basis for long-term decision making. Spirit Lake, the Toutle River, and associated engineered works are elements within a broader regional system that includes many other features such as the Monument, the Cowlitz and Columbia Rivers, and downstream flood protection levees. Elements within that system are managed by different entities—a point that will be emphasized in Chapter 3—and are often considered in isolation from one another. Those facts cannot stand in the way of formulating and implementing a decision framework that accounts for interrelationships and feedback processes within the broader system.

CHAPTER 3

Institutional Setting: Developing a Common Understanding

Ownership of land surrounding Mount St. Helens is both private and public, but the focus of discussion in this report (a decision framework for management of the Spirit Lake and Toutle River system) is largely related to features on publicly owned land. Management of those lands and the waters and ecological features of the region is thus influenced and guided by public agencies that operate under multiple management missions and mandates. The most prominent of the federal agencies in the area are the U.S. Forest Service (USFS) and the U.S. Army Corps of Engineers (USACE). The Washington State Department of Natural Resources (WADNR) owns and administers large parcels of land in the region, and the Washington Department of Fish and Wildlife (WDFW) manages key areas along the North Fork Toutle River. Additional areas in the region fall under tribal, county, or municipal management (see Figure 3.1). There are also a number of individuals, organizations, institutions, groups, and communities who may be directly or indirectly affected by decisions associated with Spirit Lake and the Toutle River.

Understanding the historical and contemporary management contexts (i.e., the institutional setting) of the areas affected by management actions—for example, those involving the Spirit Lake outflow and the downstream sediment retention structure (SRS) on the Toutle River—is

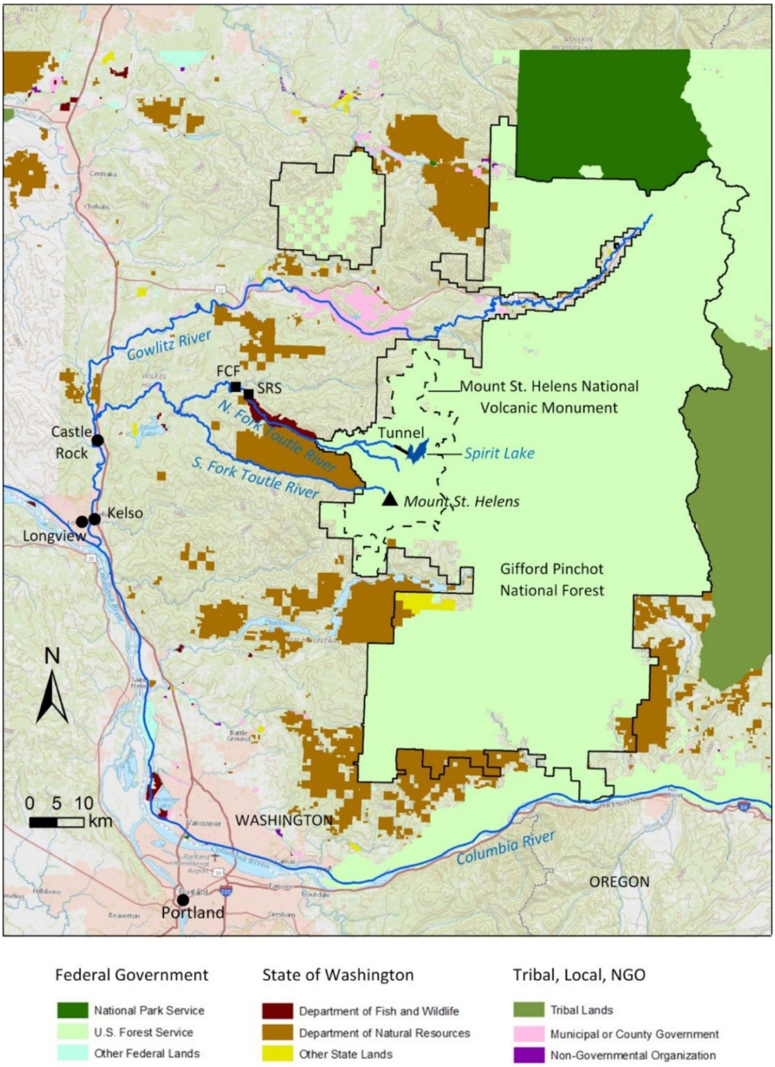


FIGURE 3.1 Areas under public management within the study region. SOURCES: Map by authors; base map: @OpenStreetMap and contributors, including the USGS's The National Map: National Boundaries Dataset, 3DEP Elevation Program, Geographic Names Information System, National Hydrography Dataset, National Land Cover Database, National Structures Dataset, and National Transportation Dataset; U.S. Census Bureau—TIGER/Line and USFS Road Data.

important in the development and implementation of a successful decision framework. The public agencies with roles and interests in the management of Spirit Lake, the existing tunnel, and the potential impacts of management or failure are thus discussed below.

PRE-ERUPTION (1980) MANAGEMENT CONTEXT: SPIRIT LAKE AND MOUNT ST. HELENS

At the time of the May 1980 eruption, Mount St. Helens and the areas immediately surrounding it were located within the boundary of Gifford Pinchot National Forest (GPNF) and managed by the USFS, which is part of the U.S. Department of Agriculture (see Box 3.1). The primary goal of the USFS is to manage national forests to sustain "the health, diversity, and productivity of the Nation's forests and grasslands to meet the needs of present and future generations."[1] The GPNF is managed for a range of purposes, including timber, range, water, wildlife, and outdoor recreation within larger directives associated with the Multiple-Use Sustained-Yield Act of 1960[2] and other federal legislation (GPO, 2011). Following passage of the 1964 Wilderness Act,[3] several areas within the GPNF were designated as Wilderness, which placed constraints on allowable land uses and management activities. Areas within the GPNF boundary serve as the headwaters of more than a dozen significant rivers and streams, including the Toutle and Cowlitz Rivers, which are the focus of this report.

Prior to the 1980 eruption, individual management plans had been established for different management units within the GPNF. Passage of the National Forest Management Act[4] (NFMA) in 1976 mandated that each National Forest implement an improved process for establishing land allocations, management goals and objectives, and standards and guidelines used by land managers, other government agencies, private organizations, and individuals. Two important aspects of NFMA were that it required the

[1]See http://www.fs.fed.us/about-agency.
[2]See http://uscode.house.gov/statutes/pl/86/517.pdf.
[3]See http://uscode.house.gov/statutes/pl/88/576.pdf.
[4]See http://www.fs.fed.us/emc/nfma/includes/NFMA1976.pdf.

BOX 3.1
U.S. Department of Agriculture—Forest Service

In response to concerns about the depletion and declining quality of American forests, the commissioner of agriculture appointed Franklin Hough to the role of special forest agent in 1876 and charged him with "gathering data on forests and forest products, European forestry practices, and on means to preserve and renew the forests" (Bergoffen, 1976: 11). In 1881, this role was expanded into a newly created Division of Forestry that was located within the Department of Agriculture, with Hough appointed as its first chief.[a] In 1891, Congress passed the Forest Reserve Act, which authorized withdrawing land from the public domain as "forest reserves" but charged the General Land Office in the Department of the Interior with their management. Congress subsequently passed the "Organic Act of 1897," which defined the main statutory basis for the management of forest reserves, stating that their purpose was "to improve and protect the forest within the reservation . . . securing favorable conditions of water flows, and to furnish a continuous supply of timber for the use and necessities of citizens of the United States."[b] In 1901, the Division of Forestry was renamed the Bureau of Forestry. The Transfer Act of 1905 transferred management of the forest reserves from the U.S. Department of the Interior to the Bureau of Forestry, which was renamed the U.S. Forest Service, with Gifford Pinchot named as its first chief. In 1907, the forest reserves were renamed National Forests.

[a]See http://www.foresthistory.org/ASPNET/People/Hough/Hough.aspx.
[b]See http://www.foresthistory.org/Education/Curriculum/Activity/activ5/essay.htm.

USFS to use a systematic and interdisciplinary approach to resource management and that it provided for public involvement in preparing and revising forest plans. The GPNF published its first Land and Resource Management Plan (Forest Plan) in 1990. That Forest Plan described resource management practices, levels of resource production and management, and the availability and suitability of lands for resource management.[5] Management of the GPNF has since been further circumscribed by standards and guidelines addressing major issues and management concerns at the

[5]See http://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5444081.pdf.

regional level (e.g., the Northwest Forest Plan).[6] The USFS has also made several amendments to its original Forest Plan since 1990.

The guiding principles of land and forest management that were in place at the GPNF at the time of the 1980 eruption were defined and shaped by more than a century of evolving attitudes regarding public (and private) lands management in the United States. These attitudes, in turn, stemmed from a complex set of viewpoints and ideals concerning the values of nature and wilderness that first coalesced during the early conservation movement of the late 1800s and early 1900s, as exemplified by such figures as George Perkins Marsh, George Bird Grinnell, John Muir, and Gifford Pinchot, among many others. In particular, emerging approaches to public land management that began in the late 1800s with the creation of the first National Parks and Forests were heavily rooted in notions of land and property ownership that had distinctly European bases. These ideas became codified through a century of environmental legislation and laws concerning public lands management, which culminated in passage of several important acts in the 1960s and 1970s central to managing the GPNF, including the Endangered Species Act (ESA), the Wilderness Act, and the National Environmental Policy Act (NEPA).[7]

LAND OWNERSHIP IN THE BROADER TOUTLE RIVER VALLEY CIRCA 1980

Most land in the Toutle River valley outside the GPNF boundary was privately owned prior to 1980. Following the arrival of European trappers in the region in the early 19th century, Fort Vancouver was founded in 1825 on the north bank of the Columbia River near present-day Portland, Oregon, as the first permanent European settlement (Wilma, 2005). By the start of the 20th century, and with the establishment of the Mount Rainier Forest Reserve, miners, loggers, homesteaders, and ranchers had moved into the Toutle River valley and the area surrounding Mount St. Helens to farm in

[6] See http://www.reo.gov/general/aboutNWFP.htm.
[7] See https://www.epa.gov/nepa.

the river valleys and raise cattle and sheep in meadows and prairies.[8] Forests in the area represented some of the best timber in the nation at the time of the eruption, and logging on public and private lands supported a thriving timber industry that in 1978 contributed 44% of the total wages and salaries in Cowlitz County (USACE, 1983). The Weyerhaeuser Company owned much of the land immediately west of the GPNF at the time of the eruption.

Tourism in the valley was strong and centered on hunting (e.g., elk, deer), fishing (especially salmon and steelhead), and other outdoor activities. Spirit Lake itself was a popular tourist destination, with six camps located along its shore and a number of lodges catering to visitors. Towns downstream of the GPNF include Toutle (near the confluence of the North Fork and the South Fork Toutle Rivers); Castle Rock (on the Cowlitz River just below its confluence with the Toutle River); Lexington (on the Cowlitz River approximately 10 miles [16 km] downriver from Castle Rock); and Kelso and Longview (on the Cowlitz River just above its confluence with the Columbia River; see Figure 1.2). The Port of Longview (in operation since 1921) is located at the confluence of the Cowlitz and Columbia Rivers and has had an important role in regional economic development associated with manufacturing and international trade.

POST-EVENT MANAGEMENT RESPONSES TO THE ERUPTION (1980-1989)

The eruption of Mount St. Helens on May 18, 1980, resulted in the greatest loss of life (57 deaths) and was the most economically destructive volcanic event in U.S. history. More than 200 homes, 185 miles (300 km) of highway, 47 bridges, and 15 miles (24 km) of railways were destroyed (Tilling et al., 1990). The immediate environmental effects of the eruption on forests, fish and wildlife, and waters in the blast vicinity, which are detailed in greater depth elsewhere (e.g., Dale et al., 2005a; Major et al., 2009), were extensive. Economically, it has been estimated that the total cost of damage from the eruption amounted to nearly $1 billion in losses to

[8]See http://www.fs.usda.gov/main/giffordpinchot/learning/history-culture.

forestry, agriculture, buildings, and other infrastructure.[9] Long-term management of sediment and flood risk involving costly engineered structures (discussed below) has been ongoing since the eruption.

The relevant management responses with respect to Spirit Lake and the Toutle River system within the first decade following the eruption are reviewed here because they provide context for understanding the current management situation. A number of management actions were taken in the immediate aftermath of the eruption to address perceived threats to human safety and economic concerns. Actions that took place within the first 2 years following the eruption included dredging of downstream rivers, modifications of levees in downstream communities, and establishment of a pumping station to stabilize the level of Spirit Lake. These activities were (1) largely financed by emergency funding and (2) based on limited data and information, as is common in emergency response situtations. Over the rest of the decade, planning focused on solutions for mitigating or managing longer-term issues in the watershed. Most notably, this included the creation of the Spirit Lake outflow tunnel and the SRS (discussed later in the chapter).

Establishment of Mount St. Helens National Volcanic Monument

The 110,000-acre (172-mi^2 or 445-km^2) Mount St. Helens National Volcanic Monument (the Monument) was established in August 1982 by President Ronald Reagan from lands within and adjacent to the GPNF, including areas that had been under ownership by the Weyerhaeuser Company and Burlington Northern Incorporated.[10] The authorizing legislation (P.L. 97-243) explicitly stated that the Monument would be administered as "a separate unit within the boundary of the Gifford Pinchot National Forest" and managed "to protect the geologic, ecologic, and cultural re-

[9] See Washington State Department of Commerce and Economic Development Research Division, as cited by Oregon State University, "Cost of Volcanic Eruptions," http://volcano.oregonstate.edu/cost-volcanic-eruptions (accessed December 4, 2017); see also https://www.usitc.gov/publications/332/pub1096.pdf.

[10] See https://www.gpo.gov/fdsys/pkg/STATUTE-96/pdf/STATUTE-96-Pg301.pdf.

BOX 3.2
Administration of the Mount St. Helens National Volcanic Monument

Section 4 of P.L. 97-243, which authorized the Mount St. Helens National Volcanic Monument, made specific provisions regarding activities permitted within the Monument boundaries. Several of these provisions with potential relevance to the decision framework are excerpted here:

(a) The Secretary acting through the Forest Service shall administer the Monument as a separate unit within the boundary of the Gifford Pinchot National Forest, in accordance with the appropriate laws pertaining to the national forest system, and in accordance with the provisions of this Act.

(b) (1) The Secretary shall manage the Monument to protect the geologic, ecologic, and cultural resources, in accordance with the provisions of this Act allowing geologic forces and ecological succession to continue substantially unimpeded.

(2) The Secretary may take action to control fire, insects, diseases, and other agents that might (A) endanger irreplaceable features within the Monument or (B) cause substantial damage to significant resources adjacent to the Monument.

(3) Nothing in this Act shall prohibit the Secretary from undertaking or permitting those measures within the Monument reasonably necessary to ensure public safety and prevent loss of life and property.

sources, in accordance with the provisions of this Act allowing geologic forces and ecological succession to continue substantially unimpeded."[11] Specific provisions and limitations regarding scientific study and research, recreational and interpretive facilities, timber harvesting, and hunting and fishing were defined, including several with potential relevance to the decision framework outlined in this report (see Box 3.2). Finally, the authorizing legislation stipulated that the secretary of agriculture would submit a detailed and comprehensive management plan for the Monument to the U.S. Senate Committee on Energy and Natural Resources and the U.S. House of Representatives Committees on Agriculture and on Interior and Insular Affairs. The resulting Mount St. Helens National Volcanic

[11] See https://www.gpo.gov/fdsys/pkg/STATUTE-96/pdf/STATUTE-96-Pg301.pdf.

(c) The Secretary shall permit the full use of the Monument for scientific study and research, except that the Secretary may impose such restrictions as may be necessary to protect public health and safety and to prevent undue modification of the natural conditions of the Monument.

(d) In order to protect the significant features of the Monument, reduce user conflicts, and ensure visitor safety, the Secretary is authorized to control times and means of access and use of the Monument or parts thereof: Provided, that nothing in this section shall be construed as to prohibit the use of motorized vehicles, aircraft or motorboats for emergency and other essential administrative services, including those provided by State and local governments, or when necessary, for authorized scientific research.

(e) (1) The Secretary shall provide for recreational use of the Monument and shall provide recreational and interpretive facilities (including trails and campgrounds) for the use of the public which are compatible with the provisions of this Act, and may assist adjacent affected local governmental agencies in the development of related interpretive programs.

(2) Except for roads needed for recreational and interpretive purposes as may be recommended by the comprehensive management plan submitted in accordance with the provisions of subsection (i), roads or other developed facilities within the Monument should be located generally in areas which were developed prior to the 1980 eruption.

Monument FEIS (Final Environmental Impact Statement) Comprehensive Management Plan (CMP)[12] has since been incorporated as a part of the GPNF Forest Plan.[13] Consistent with the CMP, the USFS restricts public access to Spirit Lake and a 30,000-acre (47-mi^2 or 122-km^2) area of the North Fork Toutle River drainage. Off-trail travel is by permit only[14] to protect ongoing and future research opportunities in this most heavily impacted portion of the 1980 blast zone. The Monument has been a venue for research on ecological succession (e.g., papers in Dale et al., 2005a) as well as volcanic and seismic risks associated with Mount St. Helens.

[12]See http://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fseprd500683.pdf.
[13]See http://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5444081.pdf.
[14]See http://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprd3800649.pdf.

Management of Spirit Lake and Its Outflow

As has been described earlier in this report, avalanche and pyroclastic flow deposits from the 1980 eruption blocked the natural pre-eruption outlet of Spirit Lake to the North Fork Toutle River valley, raising concerns about the possibility of an eventual catastrophic breach and flood caused by rising lake levels (e.g., Youd et al., 1981). A chronology of the response to these concerns can be constructed based on USACE (1982), GAO (1982), and Glicken et al. (1989):

1. In the spring of 1982, the USFS organized a task force chaired by John Steward (USFS) and comprised of technical specialists from the USFS, the USACE, and the U.S. Geological Survey (USGS), as well as a member of the Cowlitz County Board of Commissioners. The goal of the task force, which was first convened June 22, 1982, was to evaluate the flood hazards associated with Spirit Lake.
2. On July 27, 1982, the task force issued an interim report recommending that an "emergency schedule condition be declared with respect to the potential natural breaching of the Spirit Lake debris dam" (USACE, 1982: 3).
3. By August 1, 1982, the lake level had risen 54 feet (16.5 m) above that recorded for May 21, 1980, and the lake volume had increased 115%.
4. On August 2-3, 1982, Washington Governor John Spellman declared a state of emergency for the Mount St. Helens area and sent a letter through the Federal Emergency Management Agency (FEMA) to President Reagan requesting that "an emergency be declared for Washington State as a result of the flood threat" (USACE, 1982: 3) and that federal aid be provided (Glicken et al., 1989).
5. In response to another recommendation of the USFS task force, Jeff Sirmon (Regional Forester, USFS Pacific Northwest Region) formally requested on August 4, 1982, that the USACE "assume

the lead role for work related to controlling the water release from Spirit Lake." (USACE, 1982: Inclusion 2).

6. On August 19, 1982, the president declared a federal state of emergency regarding Spirit Lake under the Disaster Relief Act of 1974, directing FEMA to coordinate the federal response to the Spirit Lake emergency and authorizing use of the President's Disaster Relief Fund to assist efforts to lower the lake's level and lessen the flood threat (GAO, 1982). FEMA tasked the USACE with developing both interim and longer-term solutions to stabilize lake levels and address the threat of catastrophic flooding from a breach of the Spirit Lake blockage (USACE, 1982). The emergency declaration for Spirit Lake has long since lapsed under conditions of the 1976 National Emergencies Act (NEA), which prevents open-ended emergencies by stating that actions activated by an emergency declaration expire if the president expressly terminates the emergency or does not renew the emergency annually, or if each house of Congress passes a resolution terminating the emergency. (Note that this later provision was modified in 1985.)

As an immediate response, in early November 1982, the USACE constructed an emergency pumping station that began to transfer water over the debris blockage and into the North Fork Toutle River, which allowed it to regulate the level of Spirit Lake until a permanent, stable outlet could be constructed. During the summer and fall of 1981, the USACE had also constructed outlet channels to control the levels of eruption-created impoundments in nearby Coldwater and Castle Lakes, both of which also drain into the North Fork Toutle River (USACE, 1983).

After the lake level was stabilized by pumping, the USACE assessed several alternatives for a longer-term outlet for outflow from Spirit Lake on the basis of criteria related to location within the Monument, constructability, cost, and the ability to withstand impacts from future volcanic or seismic events due to the proximity of the volcano (Britton et al., 2016a). Alternatives included a buried conduit, an open channel, a tunnel (with several possible alignments, including outlets to watersheds other than the

Toutle), and a permanent pumping facility. The USACE concluded that the preferred alternative for a permanent Spirit Lake outflow was a buried conduit (USACE, 1984a). After consultation with other agencies, however, the eventual decision was to drill a gravity-fed drainage tunnel through Harry's Ridge and into South Coldwater Creek and thence to the North Fork Toutle River. This tunnel option was favored over the buried conduit by a number of parties, including Governor Spellman, the Cowlitz County Board of Commissioners, and the USGS, because of uncertainties at the time concerning the integrity of the Spirit Lake debris dam. It was their opinion, as expressed by Governor Spellman, that: "In view of volcanic and seismic hazards, a tunnel provides greater flexibility and safety than either a buried conduit or an open channel through the debris dam" (USACE, 1984b: 358).

Through terms laid out in a 1984 Temporary Land Use Agreement and a 1986 Interagency Agreement (USFS No. 86-06-59-01), the USFS and the USACE defined responsibilities for the operation, maintenance, and funding of the Spirit Lake tunnel and the Coldwater and Castle Lake outlets. The 1986 Interagency Agreement notes:

> *The Corps of Engineers and the Forest Service recognize and agree that the jurisdiction and management responsibilities for the lands and related features within the Mount St. Helens National Volcanic Monument lie with the Forest Service. It is also recognized and agreed that the Corps of Engineers, having designed and constructed the emergency protective works at Spirit Lake, Castle Lake, and Coldwater Lake, has developed especial operational and engineering knowledge of these facilities.* (2)

The tunnel connecting Spirit Lake and South Coldwater Creek was finished in May 1985. As outlined in the 1986 Interagency Agreement (USFS No. 86-06-59-01), the USACE was charged with performing operation and maintenance activities on the Spirit Lake tunnel and providing inspections and restoration of Spirit Lake project construction areas during the post-construction drawdown and monitoring period (through the end of the 1986 fiscal year). In turn, the USFS agreed to accept responsibility for operation and maintenance of the Spirit Lake tunnel protective works upon completion of the facility and during the post-construction drawdown and monitoring period.

The longer-term management of Spirit Lake and the outflow tunnel was also addressed in the 1986 Interagancy Agreement. Beginning in fiscal year 1987, the USACE agreed to (1) perform for the USFS all operation and maintenance activities, including monitoring and inspection, on the Spirit Lake tunnel and the Castle Lake and Coldwater Lake outlet facilities, and (2) coordinate all extraordinary maintenance activities with the USFS to protect the resources and values of the Monument. In exchange, the USFS agreed to budget and allot funds in successive years to the USACE for all agreed-to services for the operation and maintenance, including monitoring and inspection, of the Spirit Lake tunnel. This arrangement delineates responsibilities, but it has complicated management of the Spirit Lake outflow because the agency with the technical expertise for maintenance and repair is not that which develops the necessary budget.

Sediment Management in the Toutle-Cowlitz River System

The 1980 eruption caused a large movement of sediment into surrounding watercourses, which affected shipping and raised concerns about the threat of flooding in downstream communities. The lahar and pyroclastic flows associated with the eruption raised the level of the Cowlitz River approximately 12 feet (4 m), and sediment filling the Columbia River prevented ships from reaching or leaving Portland for more than a week (USACE, 1983). The USACE was a key participant in emergency response efforts coordinated by FEMA (see Box 3.3) (e.g., USACE, 1981). Under the authority of P.L. 84-99, Flood Control and Coastal Emergencies (33 U.S.C. 701n), the USACE immediately responded to impacts of the eruption by dredging the clogged Cowlitz and Columbia River channels and raising and strengthening levees along the Cowlitz River (USACE, 2012). In an early effort to control sediment from the Toutle River, the USACE constructed small debris retention structures on both the North and South Forks in 1980 to

BOX 3.3
Responsibilities of the U.S. Army Corps of Engineers

The responsibility of the U.S. Army Corps of Engineers (USACE) to respond to the Mount St. Helens emergency stemmed directly from its congressionally authorized mission (Willingham, 2005), which includes "deliver(ing) vital public and military engineering services" and "reduc(ing) risks from disasters."[a] Located administratively within the U.S. Department of Defense, the USACE was created in the late 1700s and has always been involved in both civil public works and military construction. Among other things, they are responsible for surveying and improving the nation's rivers and harbors to benefit navigation; the development of flood control projects, including levees and dams; and the planning and implementation of water resource development and conservation projects on major waterways. Given these tasks, the collective expertise of the USACE in the planning, construction, operation, and maintenance of water resource projects is considerable.

[a]See http://www.usace.army.mil/About/Mission-and-Vision.

limit sediment flow into the main stem Toutle River. The structure on the North Fork Toutle River was intended to be in service through 1985, but of necessity it was breached by the USACE in March 1982 to prevent uncontrolled failure of the structure while the South Fork Toutle River structure was removed in November 1982 to facilitate fish passage (USACE, 2012). In 1983, Congress authorized additional interim protection measures (including more dredging and sediment control structures) for the USACE to maintain at least 100-year flood-risk management levels along the Cowlitz River until an overall solution could be developed and implemented. From the time of the eruption until October 1985, the USACE spent more than $375 million for emergency actions (USACE, 1985).

Recognizing the expense that protracted emergency actions would impose on the federal government, President Reagan requested that the USACE prepare and evaluate alternative management strategies for dealing with the movement of Mount St. Helens–related sediment through the Toutle-Cowlitz system in a 1982 memorandum to the secretary of defense

(USACE, 1984b). From 1983 to 1985, the USACE assessed alternatives for longer-term sediment management, including plans involving dredging, levee raises, and the construction of one or more sediment retention structures. Results of an initial analysis were presented in *A Comprehensive Management Plan for Responding to the Long-term Threat Created by the Eruption of Mount St. Helens* (USACE, 1983); this report was followed by the subsequent environmental impact statement, *Mount St. Helens, Washington, Feasibility Report and Environmental Impact Statement, Toutle, Cowlitz and Columbia Rivers* (USACE, 1984b), and the final decision document, *Mount St. Helens, Washington, Decision Document, Toutle, Cowlitz and Columbia Rivers* (USACE, 1985). Central to the final decision were (1) the development of a sediment budget for the Toutle River system and longer-term estimates of the sediment yields and (2) comparisons of the projected environmental effects and estimated costs of the different alternatives. Of particular importance were calculated threshold values for expected sediment yield that would favor a dredging alternative versus the construction of a single sediment retention structure. It is worth noting that even today there is a relatively high degree of uncertainty regarding future sediment yield from the debris avalanche, in terms of both total yield and variability of yield (Britton et al., 2016b).

Long-term sediment control facilities were authorized under the Supplemental Appropriations Act of August 15, 1985 (P.L. 99-88). A major component of the USACE's long-term plan was the construction of a single SRS upstream of the confluence of the Toutle and Green Rivers to reduce downstream sediment transport and deposition (see Figure 1.2 for location). The lands necessary for the SRS and its sediment retention area were condemned through actions of the Washington Department of Transportation, and the SRS was constructed from 1987 to 1989 on the North Fork Toutle River (USACE, 2012). The USACE retains ownership of the SRS structure itself, but most of the sediment plain behind the dam is under ownership by the State of Washington. Construction of the SRS was just one component of several strategies implemented by the USACE to mitigate the flood risk to downstream communities, as identified in the

1985 *Mount St. Helens, Washington, Decision Document, Toutle, Cowlitz and Columbia Rivers* (USACE, 1985).

Several final points are worth noting regarding USACE involvement in management of the Toutle-Cowlitz system, all of which are discussed in USACE (2012: 1-3). First, continued work on the Mount St. Helens project is accomplished under the existing open construction project that was originally authorized in August 1985 with a 50-year project life. Second, Congress directed the USACE to maintain authorized flood damage reduction benefits for the Longview, Kelso, Lexington, and Castle Rock levees along the Cowlitz River (see also USACE, 1985). Subsequent language in Section 339 of the Water Resources Development Act of 2000 authorized the USACE to maintain these flood damage reduction benefits through the end of the Mount St. Helens project planning period (2035). Finally, the State of Washington is the nonfederal sponsor of the project with cost-sharing requirements that were outlined in a 1986 Local Cooperation Agreement between the Department of the Army and the State of Washington and Cowlitz County diking districts.

ONGOING MANAGEMENT SETTING (1990-PRESENT)

The Toutle River valley has relatively few residents living in the unincorporated communities of Kid Valley, Riverdale, Toutle, and Silver Lake. Downstream of the confluence of the Toutle and Cowlitz Rivers, the population rises to about 50,000 in the communities of Castle Rock, Kelso, and Longview. Efforts taken in the decade following the 1980 eruption to control the level of Spirit Lake and to minimize the downstream impacts of sediment and chronic and catastrophic flood risk have continued through maintenance, minor modifications, and repairs to the same structures over the last 25-30 years. These are documented in the sections below.

Longer-Term Management of Spirit Lake and the Spirit Lake Outflow

Current management responsibilites for the Spirit Lake outflow tunnel remain divided between the USFS and the USACE and largely reflect decisions and agreements made more than 30 years ago. As per terms of the 1986 Interagency Agreement between the USFS and the USACE (USFS No. 86-06-59-01), the USACE was responsible for tunnel operation and maintenance while the USFS was responsible for budgeting and allotting funds for routine operation and maintenance of the tunnel as well as emergency repairs. In 2013, representatives of the USFS and the USACE signed Interagency Agreement 13-IA-11060300-004, which reaffirmed that

> *The Corps will perform operation and maintenance activities, including monitoring and inspection, on the Spirit Lake protective works . . . and coordinate all extraordinary maintenance activities with the Forest Service in order to protect the resources and values of the Mount St. Helens National Volcanic Monument. . . . The Corps will provide the Forest Service with recommendations on operation and maintenance needs and perform operation and maintenance work that is funded by the Forest Service. If the need arises, the Corps and Forest Service will meet annually or when required to define the operation and maintenance work to be performed by the Corps on the Spirit Lake Tunnel and lake blockages. . . . The USACE is the parent agency having designed, constructed, and maintained the tunnel since its creation. Their continuing involvement is an expedient way for the Forest Service to maintain on-the-ground knowledge for this structure.*

There have been two recurring problems associated with operation of the Spirit Lake outflow tunnel, the first of which has involved the need for tunnel repairs, particularly in the area where the tunnel cuts across what is known as the Julie and Kathy L. shear zone. The USACE has conducted routine annual inspections since the Spirit Lake tunnel was completed in 1985. As described in Chapter 2, these inspections have resulted in several localized repairs to the tunnel (Britton et al., 2016a), but more problems were encountered in 1992 and 2014-2015 (with associated repairs being completed in 1996 and 2016, respectively). Funding for such repairs must be secured by the USFS, while the necessary work must be coordinated with the USACE. Repairs since the tunnel's construction have imposed cumulative costs of roughly $7 million, including roughly $3 million (Britton et al., 2016a) for the most recent 2015-2016 repairs.

The second recurring issue with the Spirit Lake outflow tunnel involves operations and maintenance of the tunnel intake. Spirit Lake contains a significant amount of floating, semi-submerged, and sunken wood debris as a result of the 1980 eruption. High winds can push a raft of floating wood debris such that it collects at the tunnel intake and restricts the only outlet for the lake. If such a blockage were to cause lake levels to rise to an unsafe level, the lake could breach the blockage, resulting in catastrophic flooding downstream. The USACE assessed options for managing wood blockages in the lake, with alternatives being compared on the basis of environmental constraints, material logistics, equipment concerns, long-term maintenance, constructability, aesthetics, risk, and costs (USACE, 2009). The recommended method to manage the debris was to monitor the degree of blockage and periodically remove the debris from the intake channel when data indicate there is a blockage problem.

These two issues (conducting tunnel repairs and maintaining the tunnel inflow) raise an additional concern that is relevant in the decision-making process. Access to the tunnel intake for management activities (including opening and closing the gates as well as conducting wood removal) can be dangerous, particularly during bad weather and the winter months, a concern that was voiced by USFS personnel during the committee's open session meetings held for this project. The resulting operational risk to personnel (or decisions that reduce that risk) needs to be considered as part of the final decision-making framework.

The Toutle River System and Sediment Retention Structure

In 1985, the USACE developed a 50-year plan to manage sediment associated with the 1980 eruption of Mount St. Helens and to maintain authorized flood risk levels along the Cowlitz River (Britton et al., 2016b). The main feature of this plan was the SRS on the North Fork Toutle River (USACE, 1985). When the SRS was completed, flow was initially constrained through an outlet works structure within the SRS; as sediment accumulated behind the SRS, rows of increasingly higher outlet works pipes were buried and closed (USACE, 2012; see Figure 3.2). The outlet works pipes were completely blocked by sediment by 1998 at which point all flow began passing over the spillway. The result was that a significantly larger amount of sediment began passing the structure, the coarser sandy fraction of which was deposited downstream in the Toutle and Cowlitz Rivers where it had the potential to increase flood risk and affect shipping. In response to bathymetric survey data indicating that accumulated sediment had begun to impact the authorized levels of protection for Longview, the USACE dredged the lowest 5.7 miles (9.2 km) of the Cowlitz River from 2007 to 2008 (USACE, 2014). Higher-than-projected sediment accumulation resulted in the SRS beginning to fill by 2012 (USACE, 2012).

Confronted by increased sediment delivery through the SRS, yet authorized to maintain levels of flood protection identified in 1985 for Castle Rock, Lexington, Longview, and Kelso on the Cowlitz River through the year 2035 by the Water Resources Development Act of 2000 (section

FIGURE 3.2 Rows of increasingly higher outlet works pipes on the SRS as seen from the downstream side of the SRS in the late 1980s or early 1990s, prior to the outlet pipes becoming buried on the upstream side of the structure. As the pipes were blocked on the upstream side of the SRS, water and fine-grained sediments passed through successively higher pipes until the SRS reached capacity in 1998. Water now bypasses this structure and flows over the spillway (see Figure 3.3). SOURCE: Paul Sclafani, USACE.

FIGURE 3.3 (Top) Aerial photo showing the sediment retention structure (SRS) and the accumulation of sediment in the sediment plain upstream of the structure in the summer of 2016. The yellow square indicates the spillway location. (Bottom) A close-up of the SRS spillway. The ponded water to the left of the spillway is the location of the original SRS outflow (see Figure 3.2). SOURCES: Imagery © 2017 Digital globe; Landsat/ Copernicus, State of Oregon, U.S. Geological Survey, USDA Farm Service Agency; Map data © Google.

339),[15] the USACE began to evaluate corrective measures for managing sediment. In 2004, the USACE, the USGS, the USFS, and the WDFW began meeting to discuss options for additional sediment control (Dale et al., 2005b). Three alternatives were deemed capable of maintaining the authorized flood risk levels along the Cowlitz River: (1) a single large raising of the SRS, (2) a dredging program in the Cowlitz River, and (3) a phased approach involving three incremental SRS spillway raises coupled with the construction of grade building structures in the sediment plain above the SRS and with dredging on an as-needed basis (USACE, 2011; Britton et al., 2016b). The phased approach was selected as the least costly and most adaptable alternative, and the USACE constructed a 7-foot-high (2.1-m) concrete sill to raise the elevation of the SRS spillway in 2012 (USACE, 2012). The USACE sediment management alternatives would "address the changes to the affected environment that have occurred since the original EIS was written and evaluate the potential environmental impacts of each of the proposed long-term sediment management alternatives" (USACE, 2012: ES-7). An initial Draft Supplemental Environmental Impact Statement (DSEIS) was released for public review and comment on August 22, 2014 (USACE, 2014). Consultation between the USACE and the National Marine Fisheries Service (NMFS) delayed finalizing the SEIS. Finally, in August 2017, the NMFS provided a biological opinion in which it concluded that the USACE needed to improve fish passage at the SRS. The USACE prepared a revised DSEIS to evaluate alternatives for managing sediment as well as improving fish passage; it was released on September 15, 2017, and open for public comment until November 6, 2017 (USACE, 2017) (see also Box 3.4).

The WDFW Fish Collection Facility and Mount St. Helens Wildlife Area

Rivers near Mount St. Helens have been managed by the WDFW and its predecessor agencies for decades, with emphasis on (1) the management of salmon, steelhead, and trout species for sport harvest and (2) assuring

[15] See https://www.gpo.gov/fdsys/pkg/PLAW-106publ541/content-detail.html.

BOX 3.4
Mount St. Helens Long-Term Sediment Management Plan: Revised Draft Supplemental Environmental Impact Statement

The sediment retention structure (SRS) was constructed to trap sediment eroding from the debris avalanche on Mount St. Helens in an effort to reduce flood risk to communities along the lower Cowlitz River. It has been successful in doing so, but enough sediment has accumulated behind the SRS that it currently operates as a run-of-the-river dam, allowing more sediment to be transported downstream. Despite the SRS spillway having been raised by 7 feet (2.1 m) in 2012 to increase its sediment storage capacity, additional management actions have been deemed necessary by the USACE to manage downstream flood risks. To this end, the USACE conducted a limited reevaluation of sediment management alternatives in the North Fork Toutle River, including a "no action" alternative, a dredging-only alternative, a one-time raise of the entire SRS spillway by 43 feet (13.1 m), and a "phased construction" alternative that would involve two incremental raises of the SRS spillway totaling 23 feet (7 m) coupled with dredging in the lower Cowlitz River and the construction of grade building structures within the sediment plain, as needed (USACE, 2014). The latter option was selected as the preferred alternative.

The Draft Supplemental Environmental Impact Statement (DSEIS) was released on August 22, 2014, for public comment, which ran until October 21, 2014. The USACE

adequate reproduction of wild fish stocks, some of which were harvested at sea or in the Columbia River (Bisson et al., 2005) (see Box 3.5). Fish species listed on the ESA are of primary management importance, including threatened and endangered salmon and steelhead species (winter steelhead [*Oncorhynchus mykiss*] and coho salmon [*Oncorhynchus kisutch*]; spring and fall Chinook salmon [*Oncorhynchus tshawytscha*]; and chum salmon [*Oncorhynchus keta*]) (USACE, 2007), as well as eulachon (*Thaleichthys pacificus*), which was listed as threatened for the Southern Distinct Population Segment in 2010.[16] The greatest production of eulachon within the conterminous United States originates in the Columbia River basin, and the major and most consistent spawning runs return to the main stem

[16]See https://www.gpo.gov/fdsys/pkg/FR-2011-04-13/pdf/2011-8822.pdf.

made changes to the content of the DSEIS in response to public comments and to include measures to reduce impacts to species listed under the Endangered Species Act. In response to concerns raised by the National Marine Fisheries Service (NMFS), the USACE evaluated the potential environmental effects of fish conservation alternatives to ensure that the sediment management alternatives do not jeopardize the continued existence of any endangered or threatened species or result in the destruction or adverse modification of designated critical habitat. The Fish Conservation Measure Alternatives considered included (1) constructing a new Fish Collection Facility at the location of the existing facility and establishing a new fish release site or (2) upgrading the existing Fish Collection Facility to meet current design criteria and establishing a new fish release site on Deer Creek, a tributary of the upper North Fork Toutle River upstream of the SRS. Measures considered but dismissed included removing the SRS, the construction of a modified spillway that would facilitate volitional fish passage, and the implementation of measures to maintain or improve conditions for juvenile salmonids to migrate downstream through the sediment plain and over the SRS spillway. The final revised DSEIS (USACE, 2017) was released on September 15, 2017, after this report had been sent for external review; therefore, it was not available during the committee's deliberation, and the committee did not have time to consider or assess the information and cannot make any determination regarding its adequacy and accuracy. Nevertheless, any consideration of management activities related to the Spirit Lake and Toutle River system should be informed by a thorough review of the revised DSEIS.

Columbia River and the Cowlitz River.[17] Management of these species by the WDFW in the Toutle River watershed with respect to the effects of the 1980 eruption has focused heavily on two related issues: (1) the alteration of aquatic habitat by the eruption and (2) the ecological consequences of sediment management, especially construction of the SRS on fish passage.

As described in Chapter 2, environmental changes caused by the 1980 eruption devastated fish populations in the Toutle and Cowlitz Rivers. Small numbers of adult salmon and steelhead managed to navigate and return in 1980 and 1981, but recreational fisheries for salmon and wild steelhead were closed immediately after the eruption and not reopened until 1987 (Bisson et al., 2005). Juvenile salmonids were found in tribu-

[17]See http://www.westcoast.fisheries.noaa.gov/protected_species/eulachon/pacific_eulachon.html.

BOX 3.5
Washington Department of Fish and Wildlife

Tracing its roots to the appointment of the first fish commissioner by Governor Elisha Ferry, the Washington Department of Fish and Wildlife (WDFW) operates under a dual mandate in which it serves Washington's citizens "by protecting, restoring and enhancing fish and wildlife and their habitats, while providing sustainable fish and wildlife-related recreational and commercial opportunities" (Calkins, 2006: 3). To achieve its mission, the WDFW focuses its activities on four goals: (1) conserving and protecting native fish and wildlife species, (2) providing sustainable fishing, hunting, and other wildlife-related recreational and commercial experiences, (3) promoting a healthy economy, protecting community character, maintaining an overall high quality of life, and delivering high-quality customer service, and (4) building an effective and efficient organization by supporting the state's workforce, improving business processes, and investing in technology.[a] Department policy is guided by the Washington Fish and Wildlife Commission, which is composed of nine citizen members appointed by the governor, and department operations are led by a director (appointed by the Fish and Wildlife Commission) and an executive management team.[b]

[a]See http://wdfw.wa.gov/about/mission_goals.html.
[b]*See* http://wdfw.wa.gov/about.

taries throughout the South Fork Toutle River watershed and tributaries of the North Fork Toutle River except those draining the landslide debris flow areas within 5 years of the eruption. Anadromous salmon populations below the SRS have grown due to returns of ocean-rearing individuals that were not affected by the eruption, straying from nearby populations, and reintroduction efforts by the WDFW (Liedtke et al., 2013). Hatcheries have had an important role in maintaining a number of fish populations in the Toutle and Cowlitz Rivers for decades, and salmon and steelhead production in the lower Columbia River subbasin is currently dominated by fish produced in more than 20 salmon and steelhead hatcheries in the region. These fish are produced for sport and commercial harvest, to supplement natural production, and as a conservation bank for severely depleted populations. Current North Toutle Hatchery release goals are 2.5 million sub-yearling fall Chinook salmon, 800,000 early-stock coho salmon smolts, and (from the Skamania Hatchery) 50,000 summer steelhead smolts (USACE, 2017). As habitat and fish populations have recovered, however, debates have arisen over the practice of stocking hatchery-raised fish in the North Fork Toutle–Green River system.[18] Additional information on hatchery-related issues is summarized in Box 3.6 and discussed in greater detail in the Washington Lower Columbia Salmon Recovery and Fish and Wildlife Subbasin Plan (LCFRB, 2010).

The second fish species management issue involves methods used to manage eruption-related sediment. The design of the SRS is too high to include a fish ladder, and the SRS is a barrier to upstream volitional fish passage, preventing migration of species back into the North Fork Toutle River and its tributaries. As defined by the USFWS,[19] volitional means that fish are able to migrate around a dam or structure through an upstream fish ladder or downstream bypass system as opposed to being trapped and hauled around the structure or attempting to move through hydropower turbines where many would be killed. Volitional fishways allow anadromous fish to migrate when they are physiologically ready and to imprint on the streams and river during their migration downriver. Species that have been particularly impacted by the SRS in the Toutle River system include Chinook and coho salmon, steelhead, sea-run cutthroat trout, and nongame species such as minnow and suckers (Bisson et al., 2005).

To mitigate impacts to fish passage from the original construction of the SRS, in the late 1980s the USACE funded habitat enhancements that included construction of a trap-and-haul Fish Collection Facility (FCF) on the North Fork Toutle River 1.3 miles (2 km) downstream from the SRS (see Figure 3.1 for location); the development of off-channel rearing areas for Cowlitz River coho salmon; and hatchery supplementation at the North Toutle Hatchery on the Green River to raise coho salmon and both spring and fall Chinook salmon (USACE, 2007). Adult steelhead and coho salmon are collected by diverting a portion of the river below the FCF

[18]See http://tdn.com/news/local/anglers-protest-state-plan-to-remove-hatchery-fish-from-green/article_7a76805e-7a62-11e3-8ac3-0019bb2963f4.html.

[19]See https://www.fws.gov/yreka/hydrofaqs.html.

BOX 3.6
Hatchery-Raised Fish in the Toutle River System

Discussions concerning the use of hatchery-raised fish as mitigation for obstructions to fish passage and habitat loss go back more than a century, but they could be relevant when implementing the decision framework for actions to be taken in the Spirit Lake and Toutle River system. The WDFW and the National Marine Fisheries Service (NMFS) use information from hatchery and genetic management plans to evaluate hatchery impacts on salmon and steelhead listed under the Endangered Species Act in an effort to devise biologically based hatchery management strategies that provide for sport harvesting while ensuring the conservation and recovery of these species' populations.[a] Both the WDFW and the NMFS are focused on helping stocks of wild fish recover because they are believed to be more resilient than are fish raised in hatcheries. The WDFW formally adopted a Statewide Steelhead Management Plan in 2008 that proposed the development of a network of wild steelhead gene banks, and the North Fork Toutle River and its tributary the Green River have been cited as potential wild steelhead sanctuaries.[b]

As with other conservation-centered issues, the debate over hatchery-raised anadromous fish transcends biological issues to involve cultural and economic values as well as competing political goals, with passionate advocates on both sides.[b] It is even possible to support conflicting values and goals: for example, valuing the intrinsic worth of wild-raised fish as components of natural ecosystems, yet acknowledging that hatchery-raised fish have long been a significant and necessary part of the Toutle River system, particularly following the depletion of native stocks due to unsustainable commercial and recreational fishing more than 50 years ago. In addition, while much has been learned recently about hatchery effects and how to mitigate them (e.g., NRC, 2004, 2012a), there are still many unknowns with regard to preventing adverse ecological and genetic effects of hatcheries, and in many cases, hatcheries may be necessary for managing and maintaining anadromous fisheries. If improved sportfishing in the upper Toutle River is identified as an important goal during the decision-making process, the feasibility and costs of reaching that goal may need to consider not only fish passage and habitat but also the issue of wild versus hatchery raised fish.

[a]See http://wdfw.wa.gov/hatcheries/hgmp/pdf/lower_columbia/ntoutle_types_coho_2014.pdf; http://wdfw.wa.gov/hatcheries/hgmp/pdf/lower_columbia/ssthd_ntoutle_2012_final.pdf; and http://wdfw.wa.gov/hatcheries/hgmp/pdf/lower_columbia/ntoutle_fa_chin_2014.pdf.
[b]See http://tdn.com/news/local/anglers-protest-state-plan-to-remove-hatchery-fish-from-green/article_7a76805e-7a62-11e3-8ac3-0019bb2963f4.html.

into a fish ladder whence they move up into a collection pond. Fish are then moved into tanks on trucks and taken to upstream release locations. The FCF was subsequently turned over to the State of Washington and is operated and maintained by the WDFW.

Although the trap-and-haul program associated with the FCF has allowed wild coho salmon and steelhead populations to persist in the North Fork Toutle River basin, it has had limited effectiveness for roughly a decade because many of the original fish-handling features became inoperable through time due to the high sediment load of the Toutle River and because of limited staffing (Liedtke et al., 2013). The trap-and-haul program has become a labor-intensive operation for the WDFW, and in recent years, WDFW biologists, Cowlitz evaluation program staff, the Cowlitz Indian Tribe, and dedicated local volunteers have operated the facility (AMEC, 2010). A study conducted from 2005 to 2009 and involving the use of radio-tagged fish has recently provided the first empirical data on adult salmon and steelhead behavior and movement patterns in the Toutle River since the 1980 eruption; this study found that (1) the SRS spillway served as a complete migration barrier for all coho salmon and all but 3 of the 23 released steelhead; (2) a large percentage of tagged steelhead released into the SRS sediment plain (69%) could move upstream to potential spawning areas, although success was much lower for coho salmon; (3) the FCF was not efficient at collecting adult salmon; and (4) none of the tagged fish released in the tributaries where trap-and-haul fish were commonly released left those tributaries (Liedtke et al., 2013). These results collectively underscore the challenge that the SRS and its associated sediment plain pose for fish passage into the upper North Fork Toutle River.

Currently, upstream volitional fish passage is blocked downstream of the SRS by the barrier dam at the FCF as well as by the head cut at the base of the spillway channel (USACE, 2017), while upstream migration from the North Fork Toutle River into Spirit Lake is completely blocked by the debris avalanche and the Spirit Lake tunnel. Downstream migration of outgoing smolts has been less frequently addressed, but it is still an issue for young fish hatched upstream of the SRS. For example, the hydraulic design goals associated with the 2012 SRS spillway raise included maintenance of downstream fish passage and the promotion of a separated and vegetated floodplain terrace in the flat sediment plain above the spillway (Britton et al., 2016b). If restoring volitional fish passage in the North Fork Toutle River system is identified as a management objective for this project, then decision makers and managers will need to assess how different actions, either at the SRS or Spirit Lake, affect fish migration.

A number of issues and approaches for restoring or enhancing volitional fish passage at the SRS were discussed in the final revised DSEIS for the Mount St. Helens Long-Term Sediment Management Plan (USACE, 2017) (see Box 3.4). Two basic and relevant conclusions of that report and the NMFS biological opinion that informed it are that (1) future modifications of the SRS spillway would likely be required to facilitate fish passage through the spillway channel to allow individuals to move upstream into the sediment plain and (2) raising the SRS could potentially harm out-migrating juvenile Coho salmon and steelhead because the raise would result in increased sediment storage upstream of the SRS, which would also adversely modify the physical and biological features that contribute to the migratory pathway component of designated critical habitat. Those conclusions and the information used to support them, however, need to be further assessed and validated because the final revised DSEIS was not released in time to inform deliberations for the present report. Furthermore, any actions to restore volitional fish passage all the way to and from Spirit Lake (e.g., through creation of an overland channel) need to consider the full range of impediments to fish passage, including those imposed by the Fish Collection Facility, the SRS, the SRS sediment plain, and the feature used to provide outflow for Spirit Lake.

Apart from operating the Fish Collection Facility, the WDFW manages the Mount St. Helens Wildlife Area (MSHWA), established in 1990 to protect elk winter range on the North Fork Toutle River mudflow that resulted from the 1980 eruption.[20] Most of the 2,744 acres (1,110 hectares) comprising the MSHWA were acquired through a land exchange with the Weyerhaeuser Company, with assistance from the Rocky Mountain Elk

[20]See http://wdfw.wa.gov/lands/wildlife_areas/mount_saint_helens.

Foundation; in exchange, the WDFW traded two parcels in Cowlitz and Yakima Counties for 2,212 acres (Calkins, 2006). More recently, a 2009 land transfer from the Washington State Department of Transportation expanded the wildlife area to its current size. The MSHWA is bordered by Weyerhaeuser lands on the north, WADNR lands to the south, and the Mount St. Helens National Volcanic Monument to the east (see Figure 3.1).

The initial management plan for the MSHWA was drafted in 1990 by a team of WDFW scientists, managers, and enforcement personnel because there were no new additional state funds allocated for management of the new wildlife area. (Note that development of the initial management plan is detailed in Calkins [2006], from which the following summary is drawn.) The 1990 Management Plan stressed two broad objectives: (1) "protecting and improving lands and water habitats to assure optimal number, diversity and distribution of wildlife for the welfare of the people of Washington state," and (2) "providing the highest quality wintering elk habitat in the North Fork Toutle River drainage while allowing public viewing and limited recreation" (Calkins, 2006: 42). Extensive efforts have thus been made to improve elk winter forage, including erosion control, weed control, fertilization and vegetation plantings, and a winter feeding program, when necessary.[21] Furthermore, while the focus of the MSHWA as outlined in the 1990 Management Plan was on the protection and management of elk that spend their winters in the Toutle River valley, the implementation of habitat management measures that contribute to the recovery of fish populations in the Toutle River basin was added as a central management objective for the MSHWA in the 2006 Mount St. Helens Wildlife Area Plan. In particular, recovery of fish species protected under the ESA is a key statewide and regional goal of the WDFW.

INTERESTED AND AFFECTED PARTIES

Management of the Spirit Lake and Toutle River system as defined in this report will necessarily involve consideration of the safety of

[21] See http://wdfw.wa.gov/publications/00480/mt_st_helens_2014update.pdf.

the downstream communities, the protection of the local and regional ecology and economic activities, and other considerations. Because the Spirit Lake and Toutle River system encompasses public and private lands, no single entity is responsible for management of the entire system. Furthermore, as described earlier in this report, public landowners have distinct and sometimes contradictory public service missions and mandates. Members of the public served by those agencies are affected directly or indirectly by the management of the system. They may also have specialized knowledge about the system that might be useful to inform decisions—for example, from their observations of the behavior of fish and other species affected by ecological changes. These people will likely have a wide array of priorities that need to be addressed in some way during the decision-making processes, both to facilitate acceptance and implementation of decisions and to arrive at decisions that take into account all relevant knowledge.

Interested and affected parties are the agencies, individuals, organizations, institutions, groups, and communities that may be making or are affected directly or indirectly by a given set of decisions. Decision makers are also considered interested and affected parties because they, too, have an interest in the results and are affected by the outcomes of their decision. Parties may be affected by various combinations of statutory, legal, and administrative choices, which may in turn raise economic, political, and sociocultural concerns. Moreover, different concerns may be salient for different groups. While the regulatory and management concerns and responsibilities of responsible agencies may be assumed a priori on the basis of their statutory foundations, understanding the range of concerns of other interested and affected parties that need to be considered during decision making requires empirical efforts. Such efforts may include studies to identify the parties' concerns, sometimes called stakeholder analyses; participatory processes that allow the parties to express their concerns directly to responsible agencies; or combinations of these approaches. Consciously seeking to understand the diversity of interests affected by management decisions may allow decision makers to better account for stakeholder concerns and minimize post-decision conflicts.

The two agencies explicitly charged with managing those lands and features of the Spirit Lake and Toutle River system most relevant for this decision-making process are the USFS and the USACE. Their roles are diverse and have been discussed throughout this chapter, but they stem directly from the agencies' responsibilities for managing the Monument, the level of Spirit Lake, the functions of the current Spirit Lake outflow tunnel, the SRS, levees along the lower Cowlitz River, and other aspects of the system related to sediment and water management. With respect to the decision framework addressed in this report (see Chapters 6-8), interested and affected parties include additional public agencies and groups at a range of political scales (federal, tribal, state, and local) as well as stakeholders from the private sector; these are described in the following sections.

Federal Agencies

Federal agencies beyond the USFS and the USACE might be considered interested and affected parties with respect to the management of the Spirit Lake and Toutle River system. The USGS, located within the U.S. Department of the Interior, is a research organization with no regulatory responsibility. Legislation passed by Congress in 1974, however, made the USGS the lead federal agency responsible for providing reliable and timely warnings of volcanic hazards to state and local authorities.[22] Under this mandate and recognizing the need to continue surveillance of Mount St. Helens, the USGS created the David A. Johnston Cascades Volcano Observatory (CVO) in Vancouver, Washington—part of the larger USGS Volcano Hazards Program—to develop and maintain a network to track volcanic and seismic activity.[23] Scientists from the CVO have studied many aspects of the Mount St. Helens system since the 1980 eruption, and they work closely with scientists from other agencies, including the USFS and the USACE, to provide technical advice and hazard warnings to local, state, and federal stakeholders.[24]

[22] See https://pubs.usgs.gov/gip/msh/scientists.html.
[23] See https://volcanoes.usgs.gov/observatories/cvo/cvo_about.html.
[24] See https://volcanoes.usgs.gov/observatories/cvo/cvo_about.html.

Certain management decisions regarding the Spirit Lake and Toutle River system would necessarily involve other federal agencies if they trigger actions under provisions of the Endangered Species Act, the National Environmental Policy Act, or other federal environmental legislation. The act (ESA 16 U.S.C. § 1531 et seq.)[25] was signed in 1973 to protect and recover imperiled species and the ecosystems upon which they depend. It is administered by the U.S. Department of the Interior's U.S. Fish and Wildlife Service (USFWS), which has primary responsibility for terrestrial and freshwater organisms, and the Commerce Department's National Marine Fisheries Service, which has primary responsibility for marine wildlife, including anadromous fish such as salmon and steelhead,[26] both of which are historic components of the Toutle River system. Furthermore, the NEPA (NEPA, 42 U.S.C. 4321 § et seq.),[27] signed in 1970, requires all federal agencies to conduct detailed evaluations (i.e., environmental assessments and environmental impact statements) of the environmental impact of and alternatives to major federal actions significantly affecting the environment.[28] The NEPA process, which is overseen by the President's Council on Environmental Quality and may involve organizations such as the U.S. Environmental Protection Agency, mandates that agencies provide opportunities for public review and comment on those evaluations. Other relevant legislation could include (1) the Magnuson-Stevens Fishery Conservation and Management Act and its amendment; (2) the Sustainable Fisheries Act of 1996, which establishes requirements for essential fish habitat for commercially important fish; and (3) the Fish and Wildlife Coordination Act of 1934, which requires federal agencies involved in water resource development to consult with the USFWS and state agencies administering wildlife resources concerning proposed actions or plans (USACE, 2012).

[25] See https://www.fws.gov/endangered/esa-library/pdf/ESAall.pdf.
[26] See https://www.fws.gov/endangered/laws-policies/index.html.
[27] See https://ceq.doe.gov/laws_and_executive_orders/the_nepa_statute.html.
[28] See https://www.epa.gov/nepa/what-national-environmental-policy-act.

Tribal Nations

Native Americans have lived in and influenced the ecology of the region for more than 6,000 years, hunting and later gathering food and other necessities from the area surrounding Mount St. Helens. The forest's resources allowed larger, more settled populations, and people began to manage the landscape more actively (e.g., by burning) for game and other food.[29] An estimated 6,000 members of the Cowlitz Indian Tribe lived in about 30 villages along the Cowlitz River and its tributaries at the time of their first contact with Europeans and Americans (Wilma, 2005). Native Americans living in the region were familiar with Mount St. Helens and the geological risk it posed, naming it "Lawetlat'la" (the Smoker) and "Loowit" (Keeper of the Fire) (Olson, 2016), and the mountain was important to the indigenous cultural identity of citizens of the Cowlitz Indian Tribe (McClure and Reynolds, 2015). This significance was recognized in 2013 when 12,501 acres (5,059 hectares) of the Monument were officially listed in the National Register of Historic Places for its significance as a Traditional Cultural Property.[30] The Cowlitz Indian Tribe provides services related to housing, health, and transportation to about 4,100 tribal members, many of whom live in southwest Washington, including in areas protected by lower Cowlitz River levees (USACE, 2017).

The landscape surrounding Mount St. Helens was nominated for designation as a Traditional Cultural Property by the USFS and the Cowlitz Indian Tribe because of its significance as a cultural landscape central to the oral traditions, geography, and identity of its native peoples. At the time, Cowlitz Tribal Council Chairman William Iyall said:

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[29] See http://www.fs.usda.gov/detail/giffordpinchot/learning/history-culture/?cid=STELPRDB5172182.

[30] This designation stems from National Register Bulletin 38 (Parker and King, 1990), which presented guidelines for evaluating the eligibility of sites for inclusion in the National Register based on their cultural significance. Criteria were related to the historical and ongoing relationships between the property and the cultural practices, values, and beliefs of the people for whom the property has importance (Smythe, 2009). Perhaps the greatest benefit of Bulletin 38, nationally, has been its role in raising public and agency awareness about the traditional cultural significance of places of importance to Native American Tribes, including landscape features imbued with sacred qualities and tied to tribal histories (Lusignan, 2009; McClure and Reynolds, 2015).

> *The listing of Lawetlat'la as a Traditional Cultural Property honors the long relationship between the Cowlitz People and one of the principal features of our traditional landscape. For millennia, the mountain has been a place where Tribal members went to seek spiritual guidance. She has erupted many times in our memory, but each time has rebuilt herself anew. She demonstrates that a slow and patient path of restoration is the successful one.* (U.S. Forest Service, 2013: 1)

During the committee's open session meetings in Kelso, representatives of the Cowlitz Indian Tribe described distinct aspects of tribal culture likely to influence their positions on long-term management of the Spirit Lake and Toutle River region. One set of beliefs centers on the need to adjust to rather than control natural processes such as volcanic activity and periodic eruptions—inevitable given this particular geologic and geographic setting. Given this familiarity with and respect for the active volcanic history of Mount St. Helens, ancestors of the Cowlitz Indian Tribe developed what Euro-Americans might call a management strategy for "living with the volcano" (see Box 3.7). Related to this tradition is the tribe's views on time horizons, which could affect tribal positions on the definition of "long-term management." The tribe desires protection, conservation, restoration, and promotion of culturally relevant species, including anadromous fish, deer, elk, mountain goats and other species,[31]and landscapes integral to their unique identity. Spokesmen for the tribe have also expressed special concerns about the impacts of the SRS on the environmental conditions of the North Fork Toutle River, particularly with respect to salmon and steelhead populations.

In addition to the Cowlitz Indian Tribe, the Yakama Nation has been interested in the preservation and management of their traditional use lands in the Gifford Pinchot National Forest. The Yakama reservation is located adjacent to the eastern boundary of the Gifford Pinchot National Forest, and the Yakama people continue to engage in ceremonial, subsistence, and commercial fishing for salmon, steelhead, and sturgeon in the Columbia River and its tributaries.[32]

[31] See http://cowlitz.org/index.php/natural-resources-mission-statement.
[32] See http://www.yakamanation-nsn.gov/programs.php.

BOX 3.7
Living with the Volcano

Cowlitz Indian Tribe ecologist Nathan Reynolds raised the concept of "Living with the Volcano" at a stakeholder meeting in Kelso, Washington, on August 3, 2016. As he stated elsewhere, "[S]ome people have described [the 1980 event] as a traumatic eruption that destroyed the mountain, but the indigenous name for the mountain, Lawetlat'la, translates as 'smoker.' So for the Cowlitz people, the eruptive state of the mountain is who She [Mount St. Helens] is, it's what She does."[a] Indigenous people in the region recognized that the dynamic nature of the landscape surrounding Mount St. Helens necessitates flexible responses to eruption impacts, including relocation from impacted areas. In a contemporary context, this might translate into the idea that single solutions are difficult to engineer when a wide range of dynamic processes are at work, thereby necessitating creative and holistic management and planning.

[a]See http://www.opb.org/television/programs/ofg/segment/mountain-goat-survey.

While there is a tendency to focus on the social, cultural, and historical contributions of the Cowlitz Indian Tribe and the Yakama Nation when considering management of the region, members of these groups possess an array of relevant expert knowledge, skills, and capabilities regarding the physical, biological, and environmental aspects of the study system that are relevant to the decision-making framework. As is noted in the USACE's Mount St. Helens Long-term Sediment Management Plan (2017), the Cowlitz Indian Tribe has been particularly active in the North Fork Toutle River watershed, which lies in the heart of the tribe's ancestral lands, where they have conducted fish and habitat research, restored and protected critical salmonid habitat, and assisted in trap and haul efforts at the FCF and worked closely with the WDFW and other stakeholders to protect and conserve resources of the Toutle River. In terms of technical expertise, the Cowlitz and Yakama communities both have highly trained scientists and technicians that perform and publish the results of fundamental scientific research as well as established programs in wildlife, fisheries, range, and vegetation resources management that are engaged in restoration and conservation projects in rivers draining to the Columbia River. These programs receive funding from the Bonneville Power Administration through the Fish Accords.[33]

State Agencies

The role of the WDFW in managing the MSHWA and the FCF has already been described. Given its dual mission of protecting, restoring, and enhancing fish and wildlife and their habitats while also providing sustainable fish and wildlife-related recreational and commercial opportunities, the WDFW has a valid interest in any actions with respect to the management of Spirit Lake and the Toutle River that affect those resources. At the MSHWA, that would especially include a focus on anadromous and resident fish populations as well as elk and their winter habitat along the North Fork Toutle River.

In addition to the WDFW, the WADNR has a stake in the Spirit Lake decision. Created by the state legislature in 1957, WADNR now manages 5.6 million acres (2.3 million hectares) of forest, range, agricultural, aquatic, and commercial lands throughout the state for more than $200 million in annual financial benefit for public schools, state institutions, and county services.[34] In the Toutle River watershed, it manages 37,100 acres (15,014 hectares) of state-owned trust lands immediately west of the Monument between the North Fork and South Fork Toutle Rivers as well as smaller parcels elsewhere in the watershed (see Figure 3.1).

The Washington State Department of Ecology is Washington's environmental protection agency and has a mission "to protect, preserve and enhance the State's land, air, and water for current and future generations."[35] The department is also primarily responsible for the regulation of dams on state and private lands. In the case of work at Mount St. Helens,

[33]See, for example, http://www.yakamafish-nsn.gov and https://www.cowlitz.org/index.php/contacts/15-natural-resources; https://www.ynwildlife.org/aboutus.php.

[34]See http://www.dnr.wa.gov/about-washington-department-natural-resources.

[35]See http://www.ecy.wa.gov/about.html.

the Department of Ecology (in conjunction with the U.S. Environmental Protection Agency) would be involved if construction debris from dam-related projects needs to be disposed off-site. Other state agencies that also may be affected by management of the Spirit Lake and Toutle River system include (1) the Washington State Governor's Office for Regulatory Innovation and Assistance (ORIA), which serves as first point of contact for project planners to help determine which Washington State regulations are pertinent and which state agencies potentially need to be involved; (2) the Washington State Department of Transportation, which would have an interest in understanding the risks associated with management of sediment and water transport in the Toutle and Cowlitz Rivers; (3) the Washington Department of Archaeology and Historic Preservation, which advocates for the preservation of irreplaceable historic and cultural resources, including significant buildings, structures, sites, objects, and districts[36]; and (4) and the Washington State Parks and Recreation Commission, which manages Seaquest State Park and the Mount St. Helens Visitor Center, both of which are near Silver Lake within the Toutle River watershed.

County and Other Local Governments

The Mount St. Helens National Volcanic Monument is an important natural resource and tourist attraction for Cowlitz, Skamania, and Lewis Counties. The communities that would be most directly affected by a catastrophic failure of the Spirit Lake debris blockage are located primarily in Cowlitz County. These are also gateway tourism communities for the west side of the Cascades. The Cowlitz River valley is a major interstate and freight corridor between Portland, Oregon, and Seattle, Washington. Numerous county and local government agencies have responsibilities related to economic development, public safety, and emergency management, including management related to chronic and catastrophic floods. Specific issues of importance to such entities could include life safety, damage to private lands, public facilities and water systems, and critical areas as

[36] See http://www.dahp.wa.gov.

defined under the Washington State Growth Management Act (RCW 36.70A.020[37]) (cf. Granger et al., 2005). Sediment accumulation in the Cowlitz River poses problems for river navigation, particularly shipping associated with the Port of Longview at the confluence of the Cowlitz and Columbia Rivers.

Nongovernmental Organizations, Businesses, and Local Residents

Individuals, businesses, and communities in the region are all potentially affected by Spirit Lake and Toutle River management decisions, so their interests and concerns need to be considered. Many active nongovernmental organizations interested in the region seek to represent these interests and concerns and to speak for subsets of the interested and affected parties. The goals, interests, and objectives of such parties are diverse, however. These include groups focused on environmental education (e.g., the Mount St. Helens Institute), recreation (e.g., the Cowlitz Game and Anglers), economic development and tourism (Toutle Valley Community Association), and conservation (e.g., Gifford Pinchot Task Force), to name just a few. Such groups, many of which were involved in the open session committee meetings in Kelso associated with this report, can help to coalesce the concerns of some of these interested and affected parties, though it should not be assumed that all relevant concerns will be represented by existing organized groups. They can also bring into the process decision-relevant observations of conditions and changes in the system that may not yet have been made by public officials.

A COMMON UNDERSTANDING FOR SYSTEM MANAGEMENT

A complex relationship has developed between the USFS and the USACE around the management of Spirit Lake given the different missions and functions of the agencies. Perceptions regarding the problems requiring

[37] See http://apps.leg.wa.gov/RCW/default.aspx?cite=36.70A.020.

action, management objectives, and management alternatives are influenced by these different missions. Likewise, their respective views will be different when considering the consequences—good and bad—of decisions. Funding and the political climate at any given time further complicates their relationship and the decisions they can make. Management of system elements downstream—for example, in the North Fork Toutle River near the SRS—is even more complex because many federal, tribal, state, local, and private entities have their own responsibilities and interests related to different aspects of the valley. The narrative thus far reflects ad hoc management of each element by the different agencies with modest consideration of how the elements interact.

As described in Chapter 1, the USFS has expressed interest in applying a systems approach to managing water levels in Spirit Lake and in the transport of water and sediment in the Toutle River system. Chapter 2 described how doing so is important and how decision making needs to consider both physical attributes of the system, and also socioeconomic conditions of the interested and affected parties. A holistic conceptualization of the system can be accomplished only if interested and affected parties beyond those with immediate management authority are engaged in meaningful ways. This means engaging the parties in developing shared definitions of the system and shared understandings of the nature of the problem, goals, potential solutions, and feasibility of those solutions. The parties need a shared vocabulary.

Recommendation: Responsible agencies and other interested and affected parties should develop a common understanding of the Spirit Lake and Toutle River system, its features, hazards, and management alternatives.

Improved communication comes from common understanding of region-wide issues and will result in more productive identification of problems and management alternatives. Transparency and regular interaction and information sharing makes developing that common understanding more likely. Differences among interested and affected parties might be transcended through a deliberative and participatory process. This is discussed in Chapter 6.

No single organization understands all aspects of the Spirit Lake and Toutle River system: the USFS does not have the engineering expertise needed for managing Spirit Lake, but the USFS and the USGS conduct joint research in and around Spirit Lake and have developed understanding of environmental and geologic processes. Flood risk management engineers may not appreciate the extraordinary magnitude of lahars and lake breakout floods (see Chapter 4); and geologists, with field evidence of the history of such catastrophes, may have little expertise in practical flood hazard management.

Engaging Interested and Affected Parties

The literature is replete with examples of how interested and affected parties might be involved in decision making, ranging from highly structured elicitation methods to less-structured and informal approaches. National Oceanic and Atmospheric Administration guidance on interested and affected party participation in coastal decision making (2015), for example, identifies more than a dozen ways to obtain input, including workshops, town meetings, public hearings, surveys, focus groups, and the formation of advisory committees. Similarly, Aven and Renn (2010) highlight interested public hearings, roundtables, negotiated rule making, mediation, surveys, and focus groups as mechanisms for gathering information from interested and affected parties. More formal approaches such as that recommended in Chapter 6 of this report specify how interested and affected party values, objectives, and judgments regarding outcomes can be systematically incorporated into decision processes. The National Research Council's report titled *Public Participation in Environmental Assessment and Decision Making* (NRC, 2008) identified principles for effective management of these processes, process design, and integrating science with participation. For example, the process design principles are: "(1) inclusiveness of participation, (2) collaborative problem formulation and process design, (3) transparency of the process, and (4) good-faith communication" (NRC, 2008: 230). The best approach to implement these principles, the report notes, is dependent on context.

Identifying Interested and Affected Parties

The study committee did not conduct a scientific survey of interested and affected parties in the region, nor was an effort made to ensure that those participating in public meetings represented a scientific sampling of the points of view held in the region. The interested and affected parties contacted during the course of this project are summarized in Table 1.1. The committee's open session meetings attracted a diverse group of attendees, including congressional member office staff, scientists and consultants, community leaders, science writers, reporters, and others, and discussions yielded diverse and complicated interests among these parties. Several themes emerged during the discussions, some of which are highlighted below. A common understanding of these and other such themes that come about during future discussions will aid more productive communication and deliberation.

The wide range of interested and affected parties and their respective concerns described in this chapter illustrate how difficult it will be to develop a common understanding of the Spirit Lake and Toutle River system, of the physical and socioeconomic consequences of management alternatives, and of how to reach decisions that will address the diverse concerns. The material offered herein could be considered a starting point for future deliberation among decision makers and other interested and affected parties. A common understanding of issues for the region will improve communication, lead to better identification of problems and alternatives to solve those problems, and might help build trust among agencies and other interested and affected parties by removing unintentional misunderstandings.

Broadening the Range of Potential Benefits to Management

Many decisions made in the wake of the 1980 eruption were reached under emergency conditions, with limited information and when the effects of the eruption were fresh in residents' minds. The future decision process might be more deliberative and better informed with new information, data, and perspectives. In this context, all the participants heard from during open session meetings recognized that any decisions need to incorporate the current and future safety of citizens downstream of the Spirit Lake blockage. There was also support for evaluating a broader range of goals and benefits such as improving recreational opportunities; improving fish habitat and passage; improving habitat for elk and other fauna and flora of the region; reducing the likelihood of both chronic and catastrophic flooding; containing costs associated with long-term management; sustaining emergency response capabilities; helping allay the concerns for residents concerned about floods and other hazards; managing sediment flows through a variety of means; recognizing and honoring distinctive Native American Indian values and cultural practices; having the ability to make repairs to structures such as the Spirit Lake tunnel without increasing flood risk; minimizing the risks to personnel involved in maintaining management infrastructure (e.g., the Spirit Lake tunnel); and maintaining decision-making flexibility in the face of environmental uncertainties going forward.

Greater "Naturalness" and Decreased Reliance on Engineered Solutions

A lack of common understanding regarding the consequences for various management alternatives is apparent among all interested and affected parties, even among those representing federal agencies. Following the eruption, public agencies (especially the USACE) were called to address threats to downstream human safety and economic concerns. A number of participants in the committee's open session meetings echoed variations of sentiments similar to that provided by George Fornes, Habitat Conservation, Protection & Restoration program biologist for the WDFW. He noted that the "WDFW continues to support an approach involving decreased reliance on engineered solutions. We encourage those involved to work toward restoring natural processes" (George Fornes to Sammantha Magsino, August 11, 2016). The desire for a more natural system was based on several objectives, including (a) economic recovery—for example, a desire for a return of tourism in the Toutle River valley centered on outdoor activities such as sport fishing for salmon, steelhead, and trout; (b) ecological restoration, including the recovery of native nongame species, but especially focused on anadromous fish species; and (c) the promotion of intrinsic and aesthetic values, including the historic and cultural significance of the valley for the Cowlitz Indian Tribe. It was not clear, however, that interested and affected parties necessarily agreed on what was meant by "natural," on what a more "natural" valley would be, or on what would be the potential consequences of decisions regarding engineered structures such as the Spirit Lake tunnel or the SRS. Nor was it clear that interested and affected parties understand that the 1980 volcanic eruption (a natural and recurring process) changed the system to create a different natural setting and a "new normal" for the foreseeable future. No measures taken could revert the system back to pre-1980 conditions. The lack of common understanding is a problem explored in other environmental and water sensitive areas, such as the Comprehensive Everglades Restoration Plan (USACE and SFWMD, 1999) and the National Academies report on sustainable water and environmental management of the California Bay-Delta (NRC, 2012a). Chapters 6-8 provide suggestions regarding how to develop a common understanding among decision makers.

Greater Transparency and Involvement in the Decision Process

The NEPA requires that decisions concerning actions to be taken by federal agencies such as the USFS or the USACE that may significantly affect the environment must include opportunities for public comment, and public comments have been elicited in the past. Nevertheless, during the committee's open session meetings private citizens and representatives from a number of interested and affected groups expressed frustration that the participatory processes for previous decisions regarding Toutle River management had been insufficient and non-transparent. Some participants expressed a lack of trust in the decision-making process or the agencies involved. A desire was expressed that public engagement involving the Spirit Lake outflow should not only meet the legal requirements for public input but also seek meaningful engagement with interested and affected parties and build trust where trust is lacking.

Management Complicated by Institutional Situation

As has been described throughout this chapter, the management of Spirit Lake is complex for a number of reasons. First, the jurisdiction and management responsibilities for the lands and related features within the Monument, including Spirit Lake and the tunnel outflow, lie with the USFS, but the USACE performs all operation and maintenance activities on the Spirit Lake tunnel itself, including monitoring and inspection. The SRS is operated by the USACE so upstream decisions that affect sediment flow into the SRS affect the life span of the structure and have implications for downstream flood and sediment management. Similarly, management of the SRS affects fish migration, for example, which necessitates involvement of such organizations as the National Marine Fisheries Service under the auspices of the ESA. The USACE is also authorized by Congress to maintain authorized flood damage reduction benefits for the Longview, Kelso, Lexington, and Castle Rock levees through the end of the Mount St. Helens project planning period in 2035. Various relationships have been authorized between federal and state agencies to accommodate these responsibilities. No mechanisms exist to manage these as a system.

CHAPTER 4

Natural Hazards

Natural hazards drive concerns for risk management in the Spirit Lake and Toutle River system. This chapter summarizes these hazards, discusses the state of knowledge about them, and considers how they integrate within a decision framework. The understanding of these natural hazards, their probabilities of occurring, and their potential magnitude is the foundation for risk management in the region. The literature concerning the hazards is large. The recent report by Grant et al. (2016a) surveys that literature.

Following the 1980 eruption, the initial and pressing concern was the possibility that Spirit Lake might breach its debris blockage and create a cataclysmic, sediment-laden flood in the Toutle River valley and the Cowlitz River plain. This possibility was much in the minds of cognizant agencies and of affected parties. Geologic evidence from ancient eruptions led to the reasonable belief that a breakout flood was possible and with precedence in the geologic record (e.g., Scott and Janda, 1982). The consequences of a breakout flood could be enormous. Furthermore, engineering calculations at the time supported the geologic record, confirming the extent of inundation and the depth of sediment deposition that might be expected from a breakout flood (Swift and Kresch, 1983).

Today, the initial concern over a breakout flood has partially abated given the 35-year history of successful management of Spirit Lake drainage. At least three natural hazards need to be considered, however, in the management of the Spirit Lake and Toutle River system. For these to be explicitly considered in a decision framework (see Chapters 6-8), three issues present themselves:

1. The set of hazards that potentially affect the system and lead to downstream effects;
2. The annual probability of each hazard and its severity; and
3. The potential downstream consequences should a hazard event occur.

The probability of a given hazard affecting the system increases as the time frame of consideration grows longer. Processes with low annual probabilities, but possibly large impacts, become increasingly likely as the planning time frame grows longer. Thus, it is important to define the time frame early in the decision-making process because it affects planning. A great deal of data collection and analysis was performed in the early years following the 1980 eruption. These investigations have continued, but less intensively, and a number of uncertainties remain. Some of these affect risk management and the decision-making framework, as discussed in Chapters 6-8.

Three sources of natural hazards that affect management of the Spirit Lake and Toutle River system are discussed in this chapter as well as the hazards that affect management of the Spirit Lake tunnel and the sediment retention structure (SRS). These are meteorological, volcanic, and seismic. These three could result in or exacerbate any issues related to the management of sediment and water transport in the Spirit Lake and Toutle River system; thus, their probabilities and impacts need to be thoroughly understood to make wise management decisions. Two other natural hazards are considered in the Cowlitz County Hazards Mitigation Plan: landslides and wildfire (Cowlitz County Department of Emergency Management, 2013). Each is of importance as it may affect sediment delivery, runoff, and nutrients. This report, however, focuses on meteorological, volcanic, and seismic hazards because of the greater likelihood of their region-wide impacts. Moreover, because of the 1980 eruption's effect on the location and availability of fuels in the upper Toutle River, fire is not as much of an issue and will not be for some time (USDA Forest Service, 1997).

The first part of this chapter summarizes the natural hazards, risks, and state of understanding associated with meteorological, volcanic, and seismic events and a summary of our understanding of the debris blockage and the catastrophic flooding that could occur as a result of its failure. The adequacy of information related to all these topics is described. The text continues with a discussion of how hazards can be integrated using probabilistic hazard assessments and how a probabilistic assessment fits into a decision framework. Information needs are also discussed. The chapter concludes with a brief discussion related to ongoing monitoring.

METEOROLOGICAL INPUT AND CHRONIC FLOODING

As has been discussed earlier in this report, the Toutle River valley and lower Cowlitz River plain are subject to both chronic and catastrophic flooding. Chronic flooding—the severity of which is affected by a combination of meteorological inputs (e.g., rainfall, rain-on-snow events), sediments already in the system, and management of those sediments—results from the normal hydrological regime. Precipitation falling on the Toutle River basin is large enough to generate large river discharges. Average annual precipitation varies from approximately 50 inches (127 cm) at Castle Rock, elevation 60 feet (20 m), to approximately 120 inches (305 cm) at Mount St. Helens and Spirit Lake, elevation 3,400 feet (1,036 m), averaging about 75 inches (190 cm) over the entire basin (West Consultants, 2002). The U.S. Army Corps of Engineers' (USACE's) flood risk management (FRM) in the Toutle River and Cowlitz River areas addresses chronic flooding. This includes the SRS as well as the extensive system of levees in the lower Cowlitz River plain and intermittent dredging.

More important in the context of chronic flood generation is the precipitation that falls during the wettest years and the combination of warm precipitation on snow, which may accompany those larger storms. Thus, an important determinant of flood potential is the accumulation of water stored in snowpacks. Based on data collected at snow courses in the vicinity of Mount St. Helens, Dunne and Leopold (1981) found that median snow water equivalents on April 1 ranged from 47 inches (120 cm) at an elevation of 3,510 feet (1,070 m) to 118 inches (300 cm) at an elevation of 6,100 feet (1,860 m). In extreme years the maximum storage can rise to as much as 79 inches (200 cm) at lower elevations and 157 inches (400 cm) at higher elevations. Snow depths are subject to rapid melting during warm rainstorms—events known as atmospheric rivers and often referred to as the "Pineapple Express" (see Figure 4.1). As an important flood generation mechanism in the coastal American West, these narrow zones of the atmosphere transport large volumes of warm, moist air from the subtropics over the mountainous watersheds of the Pacific coast, generating heavy rain accompanied by rapid snowmelt.

The post-eruption condition of the Toutle River valley has another important effect on flood hazard in the settled parts of the Toutle River and lower Cowlitz River valleys, namely, as a source of sediment that can settle in the Cowlitz channel and reduce the flood conveyance capacity of the engineered levee system between Castle Rock and the Columbia River confluence (see Figure 4.2). The USACE has periodically dredged these river reaches for the purposes of flood risk management. As has been described earlier, a principal rationale for the construction of the SRS was to retain this sediment load higher in the Toutle River basin.

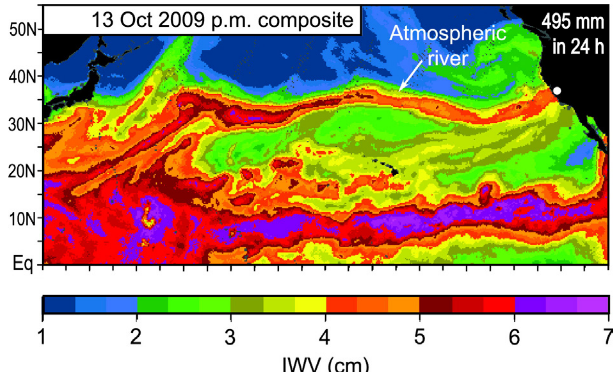

FIGURE 4.1 Satellite observation of water vapor, illustrating a 2009 atmospheric river event circled in the upper middle of the figure. These narrow zones of the atmosphere transport large volumes of warm, moist air from the subtropics over the mountainous watersheds. NOTE: IWV is integrated water vapor. SOURCE: Ralph et al., 2011, © American Meteorological Society. Used with permission.

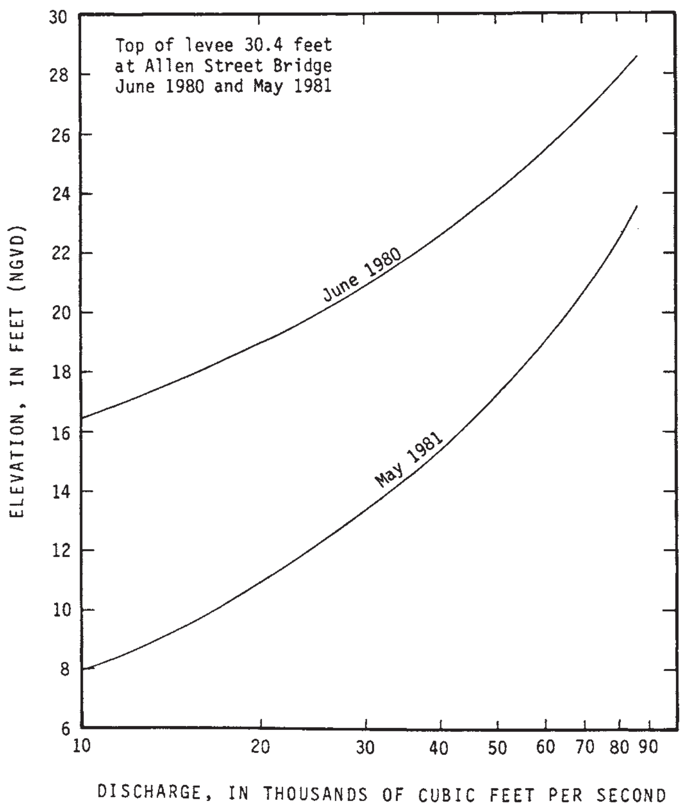

FIGURE 4.2 Elevation-discharge curve for the Cowlitz River and Kelso-Longview, Washington. The June 1980 curve represents the post-eruption but pre-dredging condition of the river. By May 1981, dredging had lowered the bed of the river and correspondingly the elevation of the river surface. SOURCE: Lombard, 1986.

Effect of Changing Climate

Changing global climate adds uncertainty in assessments of flood hazards in this region. An increase in the frequency of flood-generating weather events is likely. While projected changes in precipitation are small, temperatures are projected to increase through the end of the century, leading to a transition of snow to rain and more flooding (Mote and Salathé, 2010). Seasonal cycles responsible for heavy precipitation are also projected to intensify. The expected warming atmosphere will increase atmospheric water vapor, which is projected to increase the frequency of days the most extreme atmospheric rivers are generated by up to 290% by 2100 (Warner et al., 2014).

Impacts of Chronic Floods

The area potentially at risk from chronic flooding extends north from the confluence of the Columbia and Cowlitz Rivers and east along the Toutle River to the confluence of the North Fork Toutle and Green Rivers. The lower reaches of the Cowlitz River include the cities of Castle Rock, Lexington, Kelso, and Longview, Washington, before entering the Columbia River. The area at risk also includes approximately 1.25 miles (2 km) of the Columbia River extending from its confluence with the Cowlitz River to the Columbia River navigation channel.

Populated areas in the region are primarily in Cowlitz County. Managed areas along the Cowlitz River include portions of Longview, Kelso, Lexington, and Castle Rock, with a total population of approximately 50,000 (see Table 4.1). Property in the leveed areas has a value of approximately $3.65 billion (USACE, 2014).

Adequacy of Existing Information

The current level of information on chronic flood hazard in the Toutle and Cowlitz Rivers and on the management of flood risks is similar to that in most river basins managed by the USACE (see Table 4.2). There is uncertainty, however, about the importance of changing climate on the hydrology of the system and its effects on chronic flooding. This uncertainty is likely to be similar to that in other flood-managed basins across the country.

One characteristic of the Toutle River system that makes it unique is the existence of the SRS and the sediments stored behind it. A large magnitude earthquake could change the behavior of the sediments behind the SRS (e.g., as a result of earthquake-induced liquefaction) and change the

TABLE 4.1 Inventory of Levees and Authorized Levels of Protection in the Cowlitz River Plain and Corresponding Annual Probabilities of Floods Exceeding the Level of Protection (LOP)

Levee Location	Owner	Authorized LOP (yrs)[a]	Annual Exceedance Probability of Flooding[a]	Length (miles)[b]	2010 City Population[c]
Castle Rock	City of Castle Rock	118	0.0085	1.5	2,140
Lexington	Lexington Flood Control Zone District of Cowlitz County	167	0.006	2.7	NA
Kelso	Cowlitz County Consolidated Diking Improvement District No. 3 and the Drainage Improvement District No. 1	143	0.007	5.7	11,925
Longview	Cowlitz County Consolidated Diking Improvement District No. 1	167	0.006	2.4	36,648

[a]Data from USACE, 2009.
[b]Data from USACE, 2010b.
[c]U.S. Census Bureau. Settlement of Lexington is not included as an entity in the U.S. Census.

TABLE 4.2 Existing Natural Hazards Information on Chronic Flooding

Existing information	Annual probabilities of fluvial flooding; estimates of impacts from chronic flooding; estimates of sediment yields; assessments of levels of flood protection provided by the levee system.
Strengths	Historical data on flood frequencies and severity in the system are reasonably complete. These assessments follow normal USACE practice for FRM.
Weaknesses	Uncertainty in sediment yields into the Toutle River; some uncertainties regarding impacts of climate change and possibly regarding the impacts of large seismic events on releases from the SRS.

SOURCES: Dunne and Fairchild, 1984; Lombard, 1986; USACE, 2009, 2010a,c.

probability of chronic flooding should a large meteorological event occur. The simultaneous occurrence of a large magnitude earthquake and a large meteorological event is less probable than either event occurring singly, but simultaneous occurrence could result in greater changes in sediment behavior.

VOLCANIC HAZARDS

The geologic setting of the region, including volcanism, is described in Chapter 2. Consideration of volcanic activity in a decision framework has two main components: (1) defining hazards that affect the Spirit Lake and Toutle River system resulting in downstream impacts and (2) defining the annual probability of each. Individual volcanic eruptions can produce multiple hazards processes or types. Some volcanic processes associated with certain types of eruptions may not affect the Spirit Lake and Toutle River system and thus can be ignored. For example, dome building activity similar to the 2004-2008 episode may have no effect on that watershed, and it may not need to be addressed in detail.

Volcanic activity can produce several hazards, each with unique physical impacts on the Spirit Lake and Toutle River watershed and infrastructure within. These may extend downstream as far as the SRS and well beyond. The emphasis here in this discussion is on hazards that could affect management decisions regarding the Spirit Lake drainage and the SRS. The list appears generic in that Mount St. Helens is capable of producing the full range of volcanic hazards. These hazards include

- Tephra fallout, which are deposits produced by direct fallout of particles (e.g., pumice, ash, lithics) from a high-standing volcanic plume ~10-20 miles (~15-30 km). Such deposits blanket the landscape in the downwind direction during an eruption. In the case of the Spirit Lake and Toutle River system, impacts could include choking of the Spirit Lake tunnel intake with pumice floating in the lake and introduction of abundant loose material onto parts of the watershed, which can be remobilized rapidly by surface water flow and dramatically increase the sediment flux to the SRS.
- Pyroclastic flows, which are very hot ash, lava fragments, and gases that are explosively ejected from the volcano, typically at high speeds. They are more limited in extent than tephra fallout are and would most likely form a new fan of unconsolidated deposits on the pumice plain (see Figure 2.7). Some might reach and directly introduce material into Spirit Lake, but assuming no major topographic changes in the area, most would likely contribute to increased sediment flux into the Toutle River and the SRS if flow deposits are remobilized in tributaries of the North Fork Toutle River by alluvial or fluvial processes. Pyroclastic flows could rapidly melt snow from the crater and the pumice plain and evolve into a lahar of a magnitude that could arrive at the sediment plain upstream from the SRS (Denlinger, 2011).
- Lava flows produced by Mount St. Helens during recent eruptive episodes mostly have involved highly viscous magma that formed domes around the vent and flowed only a few hundred meters, as, for instance, during the 2004-2008 eruptive episode. Such lava domes may experience partial collapse, however, which can produce small pyroclastic flows. If basaltic lavas, which are hotter and

less viscous, were to be erupted, however, they could flow several kilometers.[1] Because basaltic lava flows are strongly controlled by the lowest paths across the topography, it is unlikely that one would reach Spirit Lake. Nevertheless, such a flow could disrupt drainages in the pumice plain that feed the Toutle River. Lava flows can also cause rapid snowmelt that in turn can trigger lahars.

- Volcanogenic lahars (volcanic mudflows) could result from emplacement of new tephra fallout, pyroclastic flow, lava flow, or debris avalanche deposits. Materials deposited by these processes can then be remobilized by heavy precipitation or can induce rapid melting of snow and ice, providing water for the flows. Lahars could introduce large volumes of sediment into the SRS. There may also be lahars that are not triggered by volcanic activity, but these are more appropriately thought of as flood or geotechnical hazards.
- Debris avalanches in the Toutle River valley are unlikely until the volcano rebuilds itself from the 1980 sector collapse. Their probability, then, depends upon the time frame of interest. Such flows could introduce large volumes of debris into the Toutle River system.

For any given eruption scenario, annual exceedance probabilities can be defined—and the uncertainty of those probabilities—for the aforementioned hazards and their impacts to the Spirit Lake and Toutle River system. The information can also be used as input for design criteria for any new mitigation structures and as input to a decision-making framework such as the one presented in Chapters 6-8 of this report.

The Probability of Eruptive Events

Table 4.3 summarizes the estimates by Grant et al. (2016a) of the annual probability of future eruptive events at Mount St. Helens. The probabilities

[1]The lavas that formed the Ape Caves on the southern flanks of Mount St. Helens are basaltic.

based on the expert opinion of Grant et al. (2016a) used the geologic record of previous events over a defined timescale to estimate order-of-magnitude hazard probabilities. The values do not include analysis of uncertainties due to incompleteness of that record, to continually evolving knowledge of eruption mechanisms, and to potential future changes of the behavior of the volcano. Nor do the estimated probabilities account for the fact that the past events—even if well recorded in the geologic record—represent a subset of events that the volcano is capable of producing in terms of timing and volume. Other experts might derive different annual probabilities from the geologic record or from additional analysis using numerical modeling, for example. Ultimately, any annual frequency value should account for such uncertainties, which are not included in Table 4.3. Nevertheless, the Grant et al. (2016a) probability estimates can serve as a starting point for more detailed hazard assessments if such are needed, following the approach described below.

Adequacy of Existing Information

Disruptive eruption scenarios can be defined by the eruption processes accompanying any event that could disrupt the Spirit Lake and Toutle River system. For example, an eruption that produces enough tephra fall-out could, as described above, block the Spirit Lake tunnel and ultimately cause breaching of the debris blockage if the tunnel could not be cleared before water levels rise to dangerous levels. It could also introduce enough new sediment into the watershed to impact the SRS. Even relatively minor pyroclastic flows could similarly affect the sediment budget enough to affect the SRS. Disruptive eruption scenarios are not limited to those involving major lateral blasts or debris avalanches. Existing volcanic hazards information and its strengths and weaknesses are summarized in Table 4.4.

SEISMIC HAZARDS

The Spirit Lake and Toutle River system is located in a highly seismic region of the United States with the potential of strong ground shaking

TABLE 4.3 Annual Probability Estimates for Volcanic Hazards Affecting the Spirit Lake and Toutle River System

Eruptive process	Distance <3 miles. Impact within or near crater		Distance 3–5 miles. Impact capable of reaching Spirit Lake		Distance >5 miles. Impact capable of reaching Spirit Lake and beyond	
	Geologic Record	P/yr	Geologic Record	P/yr	Geologic Record	P/yr
Airfall tephra/ash	Multiple explosive eruptions that deposited tephra fallout several inches to more than 3 feet thick	0.01	Multiple explosive eruptions that deposited tephra fallout several inches to more than 3 feet thick	0.01	Multiple explosive eruptions that deposited tephra fallout several inches to more than 3 feet thick	0.01
Lava dome	Pre-1980, extensive dome building activity within past 4,500 years; 1980-2008 two dome complexes	0.01	A lava dome is unlikely to erupt near Spirit Lake, but dome collapses in the crater could generate pyroclastic flows that melt snow and ice and generate water floods or mudflows	<E-5	A lava dome is unlikely to erupt near Spirit Lake, but dome collapses in the crater could generate pyroclastic-flows that melt snow and ice and generate water floods or mudflows	<E-5
Lava flow	Multiple	0.01	Multiple flows affected all flanks in past 2.5k[a]	0.001	Three groups of basalt lava flows from 1.8–2k[a] that traveled more than 8 miles from volcano	0.001

Pyroclastic flow	Multiple; several during 1980 eruptions	0.01	Multiple; several during 1980 eruptions	0.002	Multiple flows, but few on north side that have traveled more than about 5 mi; associated ash clouds could travel >5 mi	0.001
Laterally directed surge (type of highly energetic pyroclastic flow)	3 known: (2) ~A.D. 900 (1) 1980	0.002	3 known: (2) ~A.D. 900 (1) 1980	0.002	3 known: (2) ~A.D. 900 (1) 1980	0.002
Debris avalanche	4 known: (1) ~20k[a] (2) 2.5-3k[a] (1) 1980	0.001	4 known: (1) ~20k[a] (2) 2.5-3k[a] (1) 1980	0.001	4 known: (1) ~20k[a] (2) 2.5-3k[a] (1) 1980	0.001
Mudflow	~40 in Toutle River valley in past 50k[a]	0.1	~40 in Toutle River valley in past 50k[a]	0.1	~40 in Toutle River valley in past 50k[a]	0.01

[a]Estimates based on stratigraphic evidenced and post-1980 monitoring of Mount St. Helens. Uncertainties related to incompleteness in the stratigraphic record and potential eruption mechanisms were not incorporated in the analyses.
SOURCE: Grant et al., 2016a.

TABLE 4.4 Existing Volcanic Hazards Information and Its Strengths and Weaknesses

Existing information	Annual probabilities of volcanic hazards with sources at three different distance ranges from Mount St. Helens (see Table 4.3).
Strengths	Addresses all applicable volcanic hazards and clearly states basis for annual probability estimates.
Weaknesses	Annual probabilities are based on events recorded in the geologic record, and do not have quantified uncertainties.

SOURCE: Grant et al., 2016a.

due to nearby and distant earthquakes. As with other hazards, consideration of seismicity in a decision framework has two principal components: (1) identifying seismic hazard and its potential consequences that could affect the Spirit Lake and Toutle River system and (2) assigning an annual exceedance probability to the seismic hazard and consequences. Individual seismic events produce multiple hazards processes such as strong ground shaking, which can result in earthquake-induced liquefaction and slope instability. These may or may not affect the Spirit Lake and Toutle River system in a way that causes problems downstream.

As described in Chapter 2, the Spirit Lake and Toutle River region is in a zone with multiple sources of seismicity. Earthquakes originating in the locked portion of the Cascadia Subduction Zone, shown in Figures 2.4 and 4.3, are capable of producing large magnitude (M ~9.0), long duration earthquakes (McCaffrey et al., 2007), with a recurrence interval on the order of 200-600 years. The last known occurrence of such an event occurred just over 300 years ago. The Cascadia Subduction Zone is relatively far from the Spirit Lake and Toutle River system and is not necessarily the largest potential contributor to strong amplitude shaking (Czajkowski and Bowman, 2014). But, the corresponding long duration and long period shaking on the order of several minutes exceeds the duration of shaking from other sources. The long duration shaking increases the demand on various systems as well as the potential for liquefaction and slope instability.

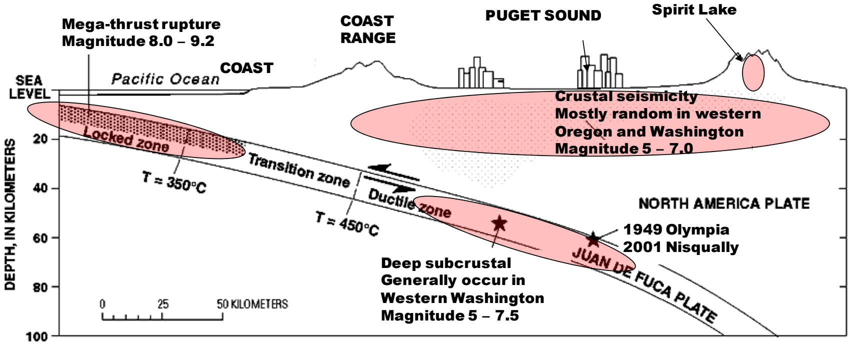

FIGURE 4.3 Schematic map of seismic sources in the vicinity of Mount St. Helens. SOURCE: USACE, 2016b.

Deep and shallow crustal sources of earthquakes (see Figure 4.3) produce earthquakes of magnitudes in the range of M 5.0 to 7.5 and are of shorter duration compared to those generated by Cascadia Subduction Zone earthquakes. These can be closer to Spirit Lake and will likely produce stronger and more damaging shaking than do earthquakes originating from the locked portion of that subduction zone. Earthquakes generated in the north-south trending Mount St. Helens Seismic Zone shown in Figure 2.4 have produced numerous earthquakes of smaller magnitude than have the above two sources, and they can produce shaking very near to Spirit Lake and the SRS and hence potentially be quite damaging to elements such as the diversion tunnel and the debris blockage. The shaking amplitude can be stronger than that generated by the more distant seismic sources. Mount St. Helens is located on a Holocene active seismic zone, with numerous earthquakes with a magnitude greater than 2.0 (Czajkowski and Bowman, 2014). Volcanic earthquakes, discussed in Chapter 2, are localized earthquakes associated with magma movement. They are generally not important from a seismic hazard standpoint, but they are important as indicators of volcanic activity.

Impacts of Seismic Hazards

Seismic activity produces several hazards, each with unique physical impacts on the Spirit Lake and Toutle River system, including on engineered structures in the system. The most important of these impacts are related to ground shaking, fault displacements, landslides, and soil liquefaction, described below.

- Ground shaking—Ground motions and associated accelerations can damage features such as the tunnel and tunnel portals, the debris blockage, and the SRS. This is usually expressed as a horizontal spectral acceleration associated with a given seismic scenario.
- Fault displacements—If an earthquake is generated by rupture along a fault that crosses the Spirit Lake drainage tunnel, for example, displacement of tunnel segments could compromise its performance.
- Landslides—Ground motion during a strong earthquake can destabilize hillsides, causing mass movements that could introduce new sediment into the river system. Landslides can also block tunnel portals thus compromising its performance.
- Liquefaction—Saturated (wet), unconsolidated sediments are susceptible to a process wherein shear seismic waves cause a buildup in the pressure of pore fluids that reduces the strength of soil deposits, causing them to behave in a manner similar to a liquid. Sediment stored upstream of the SRS, for example, could liquefy during an earthquake, which could increase the horizontal load on the SRS or could lead to greater mobility of the sediments and overflow.

These impacts potentially affect all the management alternatives for drainage of Spirit Lake, including the surface channel, buried conduit, other tunnels, and the like (discussed in Chapter 5).

As with volcanic hazards, annual exceedance probabilities of anticipated ground shaking and related hazards can be developed. Analyses to date (Grant et al., 2016a) identify potential seismic hazards from the

Cascadia Subduction Zone, the Mount St. Helens Seismic Zone, and earthquakes (see Chapter 2). These analyses use U.S. Geological Survey (USGS) seismic hazards maps (Petersen et al., 2008) to obtain estimates of ground shaking based on regional geologic mapping.

Adequacy of Existing Information

Detailed probabilistic seismic hazard analysis (PSHA) and engineering analyses of fragility would be required to evaluate seismic hazards and the impacts of these hazards for the region. The level of detail in such studies should be tailored to the decisions being made and to the decision framework adopted (see Table 4.5). USGS hazard maps (Petersen et al., 2008) are useful as an initial screen tool to provide a first order estimate of the anticipated levels of shaking across the region. These maps, however, do not provide the level of resolution required for evaluating seismic hazard for critical infrastructure. Site-specific seismic hazard analysis would be required to provide estimates of anticipated levels of ground shaking at sites with features of interest and of potential fault rupture where fault zones exist.

PSHA studies are a standard part of the seismic evaluation of structures such as the Spirit Lake tunnel, the debris blockage, or the SRS. Many qualified organizations or consultants can conduct PSHAs These studies can then be used to address the behavior of a number of critical elements of the system, for example:

TABLE 4.5 Existing Seismic Hazards Information and Its Strengths and Weaknesses

Existing information	Regional information on contributing seismic sources and estimates of ground shaking.
Strengths	Identifies some of the seismic hazards and their consequences.
Weaknesses	Uncertainties about site-specific ground motions estimates and their probabilities and related hazard, including shaking, ground displacement, and liquefaction. Some analyses based only on qualitative assessments.

1. It is not known if the Spirit Lake tunnel is traversed by a fault that might displace during a seismic event. Even without a fault, ground deformations associated with a Mount St. Helens event might cause enough shaking to collapse the tunnel. A study designed to understand the vulnerability of the tunnel to seismic ground shaking and displacement would allow for seismic hazard to be part of the risk analysis of the tunnel drainage system. At present, tunnel failure modes considered include only qualitative probabilities in the risk analyses.
2. The impact of seismic shaking on potential land sliding and related damage is not known. Slope instability can lead to a blockage of the tunnel inlet or the outlet. Additionally, slope instability of the blockage may weaken the integrity of the debris blockage.
3. The impact of seismic shaking on potential settlement and movement of the debris blockage. Issues that might arise due to land sliding within the debris blockage mass or from nearby landslide debris and hillsides are also not known.
4. The response of the SRS with its impounded highly liquefiable sediments under seismic events is not known (although, during the committee's open session meetings, liquefaction was said to have been observed as a result of the M 6.8 Nisqually Earthquake in February 2001[2]). Analyses conducted thus far are based on outdated information and methodologies. Analyses are needed to evaluate the potential lateral spreading of the liquefied sediments, their impacts on the SRS, and their potential flow over the SRS.

It should be noted that much of the characterization of the region and the design and construction of infrastructure to manage the Spirit Lake and Toutle River region (e.g., the Spirit Lake tunnel and the SRS) was conducted prior to any knowledge of a potential M 9.0 Cascadia Seismic Zone event.

[2]See https://earthquake.usgs.gov/earthquakes/eventpage/uw10530748#executive.

CATASTROPHIC FLOODING AND THE SPIRIT LAKE DEBRIS BLOCKAGE

The Spirit Lake debris blockage, which can be thought of as a natural dam, is a unique feature representing an unusual management challenge. The debris blockage, being a natural element of the environment, illustrates that a natural hazard is affected by the meteorological, volcanic, and seismic events already described. The integrity of the debris blockage is vulnerable to rise in lake level, volcanic eruption, and seismic shaking. If the debris blockage were breached as a result of failure of the engineered lake-level control system; piping due to a critical hydraulic head gradient in the groundwater; or erosion working headward up the debris barrier from the remnant drainage channel system of the North Fork Toutle River valley north of the volcano, it would represent a primary source of potential catastrophic flooding downstream.

Potential Failure Modes

Shortly after the 1980 eruption, rising Spirit Lake levels impounded by the unconsolidated debris blockages there and at tributary junctions downstream at Coldwater and Castle Lakes led to concerns that overtopping or the partial settling or collapse of the blockage might lead to rapid erosion and widening of a breach. Such a sequence of potentially hazardous events would allow the lake to drain within hours and create damaging floods. Youd et al. (1981) performed an initial geotechnical stability analysis of the blockage. This study assumed that hydraulic overtopping was the principal mode of failure of the blockage. Based on the original study, pyroclastic deposits were concluded to be considerably more erodible than thought earlier. As a result, the bottom elevation of the pyroclastic materials was taken to be the critical lake elevation for breaching (see Chapter 5). The USGS and the USACE conducted drilling in the blockage to identify the elevation of the contact between the avalanche deposit and the pyroclastic materials.

Calculations of likely filling times and discharges of either mudflows or muddy floods at various locations along the Toutle River (Dunne and

Leopold, 1981; Swift and Kresch, 1983; Dunne and Fairchild, 1984; Kresch, 1992) were used to estimate the probability of some form of catastrophic failure and flooding in the cases of the rising lake levels in Coldwater Creek and later at Spirit Lake unless the lakes were stabilized. Reinforced outlet channels were constructed for the impoundments at Coldwater Creek and Castle Creek in the early 1980s.

Some detailed studies have since been made of mechanisms for the breaching of the Spirit Lake debris blockage (Swift and Kresch, 1983; Sager and Chambers, 1986) and stability analysis at Castle Lake (Roeloffs, 1994). The post-1980 water level was 3,406 feet (1,038 m), and geometric interpretations of ground conditions suggested that water levels higher than 3,475 feet (1,059 m) could result in erosion and potential breaching of the blockage. The techniques applied were simple. The development of piping in the debris blockage was the only failure mechanism considered. Blockage-scale analyses for seepage force and effective stress failures were not conducted. These would have required more detailed data on geologic, hydrologic, and morphologic conditions than were available at the time or are available now.

Studies on the stability of the Castle Lake blockage (Roeloffs, 1994) indicate that if the groundwater level were to increase by approximately 50 feet (15 m), that blockage would become saturated. In that case, an earthquake of M 6.0 would likely cause failure of the blockage. The updated numerical simulation Roeloffs employed was a steady-state two-dimensional saturated groundwater flow model to assess the stability or factor of safety of the debris dam. No stress field computation was made. The factor of safety was defined by the upward critical gradient to the computed gradient. In such analysis, the actual shear strength of the debris materials was not considered. Measured water table fluctuations for the years 1991 and 1992 were used to constrain the model. Upward seepage caused a low factor of safety for the debris blockage. Geologic, geotechnical, and geophysical surveying of the blockage may be needed to determine the potential piping development over the past 36 years as well as the stress field-based factor of safety analysis.

A potential failure modes analysis (PFMA) was conducted in 2016 principally by a team from the USACE but also comprising personnel from the U.S. Bureau of Reclamation, the U.S. Forest Service (USFS), and the USGS. The present study committee did not have direct access to the results of the PFMA; it relied on a summary of those results by Grant et al. (2016a). Eleven potential failure modes were reported to have been identified by which drainage of Spirit Lake could be interrupted, with the consequence of a rising lake level eventually reaching a critical elevation against the blockage. More information about the PFMA is provided in Chapter 5.

Catastrophic Flood Magnitudes

The hydraulic analysis of a plausible Spirit Lake catastrophic breakout by Swift and Kresch (1983) indicated peak mudflow discharges of approximately 2.65 million cubic feet per second (cfs) (7.5×10^4 m^3/sec) 18 miles (29 km) downstream from the lake near the terminus of the debris avalanche deposit, decreasing to approximately 1.14 million cfs (32,000 m^3/sec) at the Cowlitz River confluence and 1 million cfs (283,000 m^3/sec) at the confluence with the Columbia River. The calculations also predicted depths of inundation of 60 feet (18 m) in Castle Rock and Lexington, and 30-40 feet (9-12 m) in Toutle, Kelso, and Longview. Swift and Kresch (1983) calculated that warning times for the first arrival of the lake-breakout flood were about 4 hours at Toutle village, 10 hours at Castle Rock, and 16 hours at Kelso-Longview.

The calculated boundaries of the mudflow throughout the Toutle River and Cowlitz River valleys as far as Castle Rock are consistent with those mapped by Scott and Janda (1982), although the peak discharge of the calculated flood in the middle Toutle River valley (2.55 million cfs) was significantly below the 7-10 million cfs (200,000 to 285,000 m^3/s) of the lake breakout that occurred 2,500-3,200 years ago as estimated by Scott (1988a,b). Consequently, the flow magnitudes, inundation depths, and geographical extent of the estimated lake-breakout flood suggested the need for stabilizing the level of Spirit Lake considerably below an elevation that might trigger a breach of the impoundment.

Groundwater Regime of the Debris Blockage

Chapter 2 summarizes the groundwater regime within the debris blockage. The stability of debris blockage was not considered in the original Spirit Lake drainage options of buried conduit, tunnel, open channel, and permanent pumping in the comprehensive plan to manage sediment (USACE, 1983), thus leading to the decision to use the tunnel for routing the water from Spirit Lake. The comprehensive plan did not extensively consider geologic and hydrologic information, including the impact of lake level on groundwater and stability and lake sediment thicknesses. The existing groundwater regime in the blockage and in the North Fork Toutle River valley was characterized by a series of borings in the aftermath of the eruption and, more recently, by geophysical studies taken from the surface. There have been few, if any, downhole data collected since the 1980s. The result is that changes in the groundwater regime since the 1980s are poorly characterized, as is the current state of the groundwater. The recent geophysical surveys suggest that the changes since the 1980s may be modest, but the groundwater regime is of such importance to the geotechnical performance of the blockage that it would be prudent to have more up-to-date information. Such up-to-date information might shed light on whether internal erosion was taking place within the blockage and whether groundwater seepage continues to move toward Spirit Lake rather than draining away from it. There seems no reason for immediate concern other than that few recent groundwater data have been collected.

Understanding the North Fork Toutle River valley groundwater flow regime since the eruption would provide the needed scientific basis for assessing potential failure mechanisms for debris dam, surficial erosion processes, and water balance in Spirit Lake. It would also provide hydrogeologic information necessary to consider alternatives, for example, related to the control of Spirit Lake water levels.

Catastrophic Floods and the SRS

Denlinger (2011) evaluated the impact on the SRS of catastrophic floods and debris flows originating from Castle Lake and from the crater of Mount St. Helens. In each case, numerical modeling suggests that a structurally sound spillway at the SRS is capable of passing large floods without the risk of overtopping the dam itself. Large debris flows originating from these two sources never reached the SRS, instead filling graded channels upstream. While an important finding, catastrophic floods from these two sources would be small (but not negligible) in comparison to that originating from a catastrophic breakout of Spirit Lake itself. The study concludes that the valley leading to the SRS is large enough to absorb a transient peak discharge of 40,000 cubic meters per second without overtopping the SRS—about half the discharge predicted for a breakout of Spirit Lake.

Grant et al. (2016a) note that the principal current basis for predicting catastrophic flood discharges and inundation areas is the modeling work done shortly after the eruption and as compared with Holocene lahars:

> *But some things have changed since the 1980s which justify another look at the downstream effects of a breakout flood. The topography of the North Fork Toutle River valley has evolved considerably since the eruption and subsequent downstream delivery of sediment. Construction of the Sediment Retention Structure and its operation and filling over the past few decades has potentially changed the way lahars might behave.* (Grant et al., 2016a: 110-111)

Further downstream, flood levees have been built and later raised, which may affect the extent and level of inundation. Three decades have passed and there are now better flood routing models and better understanding of floods and sediment. As Grant and others (2016a: 111) concluded, "a more informed reanalysis seems warranted."

The early model-based estimates of potential peak flows were not based on detailed characterizations of valley topography, and though their magnitude was roughly confirmed with field evidence, there is room for refinement of the estimates if such refinement ever becomes necessary for public policy decision making. Topographic changes that have occurred in the North Fork Toutle valley since 1980, however, are unlikely to have diminished the estimation of a debris flow, with the peak flow rate and especially of the volume and duration of a flow likely to result from drainage of Spirit Lake. The geologic evidence of prehistoric lahars in the vicinity of the SRS is that debris flows that required the release of volumes of water commensurate with a lake breakout recurred several times in multiple eruptive periods of the volcano and left evidence of reaching catastrophically high levels where the SRS stands. The peak rate, density, viscosity, and abrasive potential of these flows are many times higher than for which the SRS and its spillway were designed.

Adequacy of Existing Information

Existing information on catastrophic flooding is summarized in Table 4.6. The potential for such flooding and its corresponding consequences are reasonably well known. Geologic evidence from the early lahars off Mount St. Helens supports the modern analyses. The weaknesses in current information have to do with the fragility of the debris blockage and its corresponding vulnerability to seismic hazards, the current state of groundwater conditions, and details of current geotechnical conditions.

ONGOING MONITORING

Since the 1980 eruption much has been learned about the character of the natural hazards existing in the Spirit Lake and Toutle River system. Some informational needs remain, particularly about the engineering performance and fragility of the system when exposed to hazard events. Immediately following the eruption, there was a great expenditure of effort and resources in the 1980s to better understand the physical features of the system, but monitoring has been far less intense in recent years even given the complex and dynamic nature of the system, scientific insights, the changing priorities of interested and affected parties in the region, and

TABLE 4.6 Existing Catastrophic Flooding Information and Its Strengths and Weaknesses

Existing information	Potential failure modes analysis of failures of the lake drainage system
	Extensive 1980s data on geology of debris blockage
	Extensive hydrological data and analysis of runoff into Spirit Lake
Strengths	Extensive analysis of what can go wrong with drainage schemes
	Relative certainty about the critical level of Spirit Lake
Weaknesses	Seismic loading on the blockage during a Cascadian earthquake
	No recent geotechnical studies or analyses of blockage stability
	No recent geotechnical studies or analyses of possible piping
	No regular monitoring of present conditions and changes in ground water within the blockage
	Design quality understanding of the geotechnical properties
	Understanding the effect of a breakout flood from Spirit Lake on the SRS and the possible mobilization of sediments in the sediment plain behind the SRS

changes in engineering practice that have taken place. The adequacy of information available to quantitatively inform any decision making is questionable. Monitoring capabilities and data collection programs need to be reexamined and updated and analytic capabilities need to be reevaluated in light of the information needs of all interested and affected parties. Those key physical variables that impact decision making need to be identified through a process in which those with management authority engage each other and other interested and affected parties in the region (as will be discussed in greater detail in Chapters 6-8). New scientific insights—for example, that related to the probability of a Cascadia Seismic Zone event affecting the region—warrant greater examination on how such an event might affect the region and therefore management decisions for the region.

Recommendation: Agencies engaged in risk management in the Spirit Lake and Toutle River region should develop a coordinated and targeted monitoring system to track changes in factors that affect risk. Data and analyses should be shared and made available to all.

Because the Spirit Lake and Toutle River system is continually changing in response both to the forces of nature and to human intervention, information about the system needs to be regularly updated. Current characterization of the Spirit Lake debris blockage; the behavior and location of groundwater in the blockage; current and future meteorological trends; a quantified characterization of the types of risks posed by volcanic activities on Spirit Lake levels and elsewhere in the region; and the seismic response to local and regional seismic activity of the debris blockage and other parts of the system are all examples of factors that may affect the understanding of risk associated with management alternatives that might be considered. For the purposes of planning and decision making, the large body of knowledge on natural hazards needs to be integrated in a consistent way. Given modern trends in policy analysis and hazard management, that integration needs to occur through a process of systematic risk analysis.

CHAPTER 5

The Engineered Landscape

A sense of urgency pervaded public and official response to the 1980 eruption of Mount St. Helens. As a result, an engineered landscape was created in the Spirit Lake and Toutle River system to protect people and property downstream from the natural hazards associated with water and sediment. A landscape is engineered based on the values and perceptions of risk held by interested and affected parties. Such perceptions and values are not static, but change with time. Although it has been one-third of a century since the original decisions about hydraulic infrastructure in the system were made and implemented, management approaches in the region do not seem to have evolved commensurate with changes in values and risk perception. This chapter considers the engineered landscape, approaches to managing that landscape today, and the information needs associated with it. Nonengineering (i.e., nonstructural) measures have also been implemented, but these are not included in this discussion.

An assemblage of hydraulic infrastructure was planned and built in the 1980s, including provisions to maintain water levels in Spirit Lake by boring a drainage tunnel, modifications to Coldwater and Castle Lakes, changes in the North Fork Toutle River channel, the addition of the sediment retention structure (SRS) to capture sediments before they could enter the Toutle and Cowlitz Rivers, and flood levees farther downstream. The infrastructure reflected risk perception and values of the time as well as the best judgment of responsible authorities. Management strategies to date have focused principally on expedient engineering solutions rather than a systems approach. Decades past the initial response, values such as those related to provision of ecological services and recreational benefits have gained currency in stakeholder perceptions. The dangers posed by hydrology, volcanism, and seismicity have not abated, but they have been lived with for 35 years, including by a generation that knows no other way of life. In the minds of many interested and affected parties, the hazards may not rival other consequences of the engineered landscape in importance.

The approach to choosing among alternatives for managing the region is described in the decision framework of Chapter 6. When considering alternatives, it is advantageous to consider the broad physical and social system within which they function and to recall long-standing principles of design practice for achieving reliability and safety. Whereas the committee recommends a systems approach to management of the region that considers both physical and social systems and solutions, such an approach has not been taken to date. Given the importance of both physical and social systems, discussion of the hydraulic infrastructure and decisions related to it are described separately in this chapter. Integrating risks associated with all these elements in a probabilistic risk assessment (PRA) is addressed at the conclusion of this chapter.

SPIRIT LAKE WATER LEVELS AND RISK OF CATASTROPHIC FLOODING

Long-term management of Spirit Lake is of major concern because control of the lake level is instrumental in avoiding massive flooding downstream caused by breaching of the debris dam impounding the lake. Chapter 4 summarizes potential breaching flood hazards as modeled by Swift and Kresch (1983), Dunne and Fairchild (1984), and Kresch (1992). The conclusion was that the consequences of a dam-breach flood from Spirit Lake would be catastrophic. An estimate of fatalities was not made; rather, the extent and depth of inundation were estimated, but there would be fatalities—possibly many. The reports and analyses of the period (USACE, 1983) reflect this emphasis on danger.

In response to concerns about rising Spirit Lake water levels, and as described in Chapter 3, the U.S. Army Corps of Engineers (USACE) stabilized lake levels on a short-term emergency basis in 1982 with barge-mounted pumps. Subsequently, four long-term alternatives to control water levels were considered: a buried conduit through the blockage, a surface channel over the blockage, a drilled tunnel through rock (with several possible alignments), and permanent pumping. Although the USACE initially identified the buried conduit as the preferred alternative (USACE, 1983), the 8,600-foot (2,600-m) tunnel through Harry's Ridge was ultimately selected, which drained Spirit Lake water to South Coldwater Creek and then to Coldwater Lake, which by that time had itself been stabilized with a drainage channel across a natural bedrock sill. The capacity of the tunnel was designed to accommodate a p=0.01 annual chance (i.e., 100-year return period) flood followed by the Probable Maximum Flood (PMF) (see Box 5.1). The tunnel became operational in May 1985, and ownership of the tunnel was transferred from the USACE to the U.S. Forest Service (USFS). The geologic conditions, design, and subsequent performance of the tunnel are summarized by Grant et al. (2016a). The tunnel is the sole means of controlling water levels in Spirit Lake. Failure of the tunnel or its

BOX 5.1
What Is the Probable Maximum Flood (PMF)?[a]

The Probable Maximum Flood (PMF) is developed based on the Probable Maximum Precipitation (PMP). The PMP is the greatest amount of precipitation for a given storm duration that is theoretically possible for a particular geographic location. The PMF is the flood that may be expected from the most severe combination of critical meteorological and hydrologic conditions that are reasonably possible in a particular drainage area. Dams are usually designed to safely pass what is termed the Spillway Design Flood (SDF) or Inflow Design Flood (IDF), which typically ranges from the 100-year flood to the PMF. The selection of an SDF or an IDF is usually based on the hazard category of the dam and the potential for loss of life or property damage that would result from a dam failure during a given flood.

[a]Adapted from the Association of State Dam Safety Officials (ASDSO; www.damsafety.org).

long-term closure would leave the lake vulnerable to water level rise that, in turn, could lead to catastrophic failure of the debris blockage.

The tunnel is shut off and inspected annually. In the 1992 inspection, swelling and distress were observed within a 100-foot (30-m) section where the tunnel crosses a wide shear zone (see Figure 2.11). The tunnel was closed for repair in 1995 and 1996, during which time a stronger support system was installed within the affected section. There has been no sign of continued squeezing in the repaired section (Britton et al., 2016a), but squeezing has been observed in adjacent sections. Following the annual inspections of 2014 and 2015, the conclusion was drawn that another major repair is required. The committee is not aware if the deformation in the shear zone has been sufficiently characterized to determine if it is the result of heave or of movement along the fault. Similarly, the committee is not aware if there is potential for movement or deformation along the several other mapped shear zones or how such movement might affect the tunnel. Long-term operation and maintenance of the tunnel need to be informed by such analyses and also by analyses of the response of the tunnel to seismic shaking, to a large flood event that would fully pressurize the tunnel, and to other tunnel collapse scenarios.

Future Spirit Lake Management Alternatives Under Consideration

The USACE, in cooperation with the U.S. Forest Service (USFS), the U.S. Geological Survey (USGS), and the U.S. Bureau of Reclamation (USBR), conducted a potential failure modes analysis (PFMA) of four conceptual alternative Spirit Lake outlet strategies, which are listed in Table 5.1. The alternatives and the PFMA process are summarized by Grant and others (2016a). Among the goals of the analysis was identification of uncertainties and risk drivers. It appears that the best available scientific and engineering information was used for the specialized purpose of identifying the potential failure modes of five drainage concepts: the existing tunnel, the tunnel and its possible repair, a shallow conduit, pumping, and an open channel. Protocols followed during the analysis

TABLE 5.1 PFMA Alternatives for Managing Water Levels at Spirit Lake

Alternative	Hydraulic Release Capacity
1. Existing condition of Spirit Lake outlet project	3' gate opening
2. Major rehabilitation of Spirit Lake outlet project	4' gate opening
3. Permanent pumping facility	Same hydraulic capacity as full open tunnel
4. Deep buried conduit across debris blockage	Same hydraulic capacity as full open tunnel
5. Riverine channel across debris blockage	Unknown

SOURCE: USACE, 2016a.

were developed by the USBR and the USACE within the context of the federal dam safety initiative. The committee did not have direct access to the PFMA, and information about and conclusions drawn regarding the PFMA are based on summaries provided by Grant and others (2016a) and discussion with those authors during open sessions of committee meetings. The following text from Grant and others (2016) summarizes the procedures used in the PFMA.

> *The risk assessment includes a consideration of the likelihood of breaching of the blockage and an uncontrolled release of Spirit Lake as well as potential consequences should breaching occur. The likelihood of a release of lake water is a function of the likelihood that the posited loading process will occur, the likelihood it will cause the outlet to fail and allow the lake level to rise, and the likelihood that an intervention to prevent breaching of the blockage will be unsuccessful. After estimating the joint probability of this chain of events for each potential failure mode, the*

> *likelihood that a failure (lake release) will occur was broadly categorized. The team also assigned a level of confidence to the failure likelihood.* (82)

The committee interprets the PFMA process to have been based on scientific and engineering judgment rather than on quantitative modeling and analyses.

A PFMA is intended to identify possible modes of engineering failure of constructed dams but was applied in this case to determine modes of failure of the Spirit Lake debris blockage. The PFMA involved only conceptual-level designs, however. No specific engineering designs were evaluated that would require quantitative engineering data, and no quantitative risk analysis was done that would require quantitative data on engineering performance. A full quantitative risk analysis would require broader and more detailed information. Because the PFMA did not include a formal quantitative analysis of the probabilities of failure modes, it is thus not a probabilistic risk assessment in the sense that the term is normally used in federal practice (NRC, 1994). Four significant uncertainties that drive risk for the tunnel option were identified, as was a qualitative description of the likelihood of failure for each of the drivers (see Table 5.2).

The probabilities of the drainage failure modes were judged on a seven-step ordinal scale from "remote" to "failure observed." These are failure modes of the drainage system, not of the blockage. With respect to a breaching failure of the blockage, two breakout scenarios were identified: (1) seepage through the blockage leading to internal erosion and (2) knickpoint erosion undermining the blockage and creating a channel (see Figure 5.1). These were not assigned probabilities: the presumption is that if the lake level achieves a critical elevation, breakout will occur. The committee did not have direct access to the results of the PFMA; instead, it relied on the summary by Grant and others, on discussions with some of those who participated in the PFMA, and on limited unpublished materials provided by the USACE in response to specific requests for information.

Alternate drainage directly to the North Fork Toutle River by means of pumping had been used before the tunnel was constructed in 1985, and it has been proposed as an alternative for the future either by constructing

TABLE 5.2 Potential Significant Risk Drivers for Existing Tunnel

Potential Significant Risk Driver	Failure Likelihood (confidence)
Probable maximum flood event overtops intake structure and leads to tunnel failure. Lake rises to elevation of contact between debris avalanche and overlying ashcloud deposit. Seepage erosion within ashcloud deposit leads to failure of debris blockage.	Remote (low)
Earthquake leads to significant displacement along faults crossing tunnel, which leads to tunnel blockage or failure. Lake rises to elevation for internal seepage erosion.	Remote (moderate)
An eruption triggers a lahar that flows into Spirit Lake and produces a debris-laden wave that damages intake structure and blocks flow into tunnel. Lake rises to elevation for internal seepage erosion.	Remote (moderate)
Extended closure during major tunnel repair leads to precarious lake level followed by significant hydrological event that results in uncontrolled flow into the tunnel. Tunnel subsequently fails.	Moderate (low)

SOURCE: Grant et al., 2016a.

a conduit (alternative 4 in Table 5.1) or an open channel from the south side of the lake (alternative 5) or by perpetual pumping (alternative 3). Changing the outflow works at Spirit Lake—for example, by shifting more or all the drainage now flowing into South Coldwater Creek to the North Fork Toutle River—could change the pattern and volume of erosion and thus the amount of sediment transported to the SRS. The current outflow of Spirit Lake averages about 300 cfs (cubic feet per second) (8.5 cms) with a target of 400 cfs (11.3 cms) under optimum conditions. This discharge

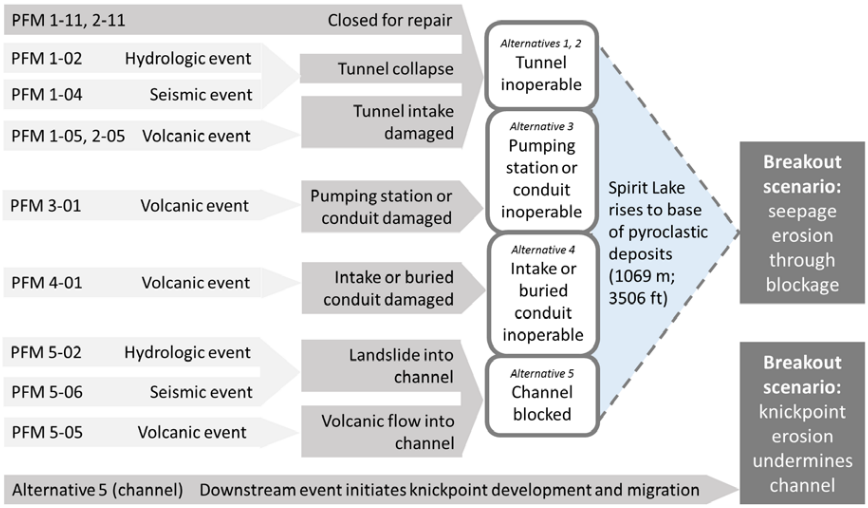

FIGURE 5.1 Schematic depiction of potential failure modes, outcome of failure mode on infrastructure, and ultimate potential consequence of outlet system failure. SOURCE: Grant et al., 2016a.

TABLE 5.3 Summary of Natural Hazard Events for Managing Spirit Lake Drainage

Hazard	Examples
Hydrologic hazards	Typical wet season, atypical wet season, PMF-type extreme event
Seismic hazards	Shallow crustal earthquakes, deep intra-slab earthquakes, megathrust earthquake
Volcanic hazards	Lahars, tephra fallout, pyroclastic flows, lava flows
Geomorphic hazards	Landslides (shallow and deep), channel avulsion across debris deposit, channel incision, knickpoint development, sediment transport

flows into Coldwater Creek, on a hard surface with minor erosion and sediment generation, and then into Coldwater Lake.

Each of the alternatives assessed during the PFMA was evaluated in consideration of the same hydrologic, seismic, and volcanic loadings. For example, from a hydrologic perspective, the analysis considered whether or not the drainage tunnel could safely pass the PMF. The PFMA also considered annual probabilities of maximum reservoir stage. No new data were gathered specifically for the PFMA, and no site-specific seismic analysis was conducted. Grant and others (2016a) note that the PFMA was informed by numerous completed regional studies that related to the Mount St. Helens Seismic Zone since the original tunnel was designed and constructed. The alternatives considered in the PFMA were not expanded beyond those considered in the 1980s. The performance of the engineered infrastructure is driven in large part by the hazards affecting management of Spirit Lake as identified by Grant and others (2016a), as summarized in Table 5.2 and as described in Chapter 4. These hazards affect human use of the landscape by influencing catastrophic and chronic flooding, sediment impacts, most ecological processes, and recreational values.

Uncertainties Regarding the Outlet Tunnel

A number of uncertainties were identified by Grant and others (2016a) with respect to the management of the Spirit Lake tunnel. One of these is hydrological, relating to a need for better characterization of the PMF draining into the lake (see Box 5.1). The USACE has recently conducted a great deal of work to improve the characterization of the PMF (USACE, 2016a). This work seems an adequate reflection of the current state of the art with respect to hydrology. The other uncertainties are geotechnical, having to do with the geometry, material properties, groundwater conditions, and seismic performance of the tunnel and the blockage. A summary of information needs with respect to the outlet tunnel is shown in Table 5.4.

In contrast to the amount of work done on the hydrology of Spirit Lake, up-to-date information on the geometry, geotechnical properties, and groundwater conditions of the blockage confining Spirit Lake need

TABLE 5.4 Geotechnical Information Needs Related to the Spirit Lake Outlet Tunnel

Type	Description	Justification
Engineering geology	Detailed geologic mapping of the tunnel. Stabilization of slopes at tunnel inlet and outlet portals.	Extending the life of the tunnel for the next 100 years will require an upgrade of the tunnel lining. Detailed engineering geology mapping is required to decide feasibility and to develop plans to improve the tunnel lining. Long-term stability, including seismic stability of the portals, is important for extending the design life of the tunnel.
Fault geology	Mapping of faults and shear zones crossing the tunnel and evaluating their aseismic and seismic deformation potential.	Understanding potential fault displacement is necessary when considering the repair and long-term operation of the tunnel. The current information of the shear zones crossing the tunnel alignment may not be adequate.
Mount St. Helens Seismic Zone	Detailed evaluation of the source zone, potential extent of fault displacement, and strength of shaking.	This is necessary to evaluate the seismicity in this area and potential impact of fault rupture on the tunnel and debris blockage.
Site-specific seismic hazard analysis	A detailed seismic hazard analysis, including estimates of fault rupture and ground motion shaking, is needed as part of the rehabilitation of the existing outlet tunnel.	Generic data on seismicity in the region are insufficient for engineering safety evaluation of the tunnel.

to be updated. Little information on geotechnical conditions has been gathered since the 1980s. While it is possible—and perhaps even likely—that the groundwater conditions have changed little since the 1980s, and although geophysical studies have been conducted since, it is essential to verify current geotechnical conditions to serve as the basis for quantitative analysis.

Uncertainties Regarding the Debris Blockage

A site characterization program was undertaken in the 1980s and is described in Chapter 2. An important finding of the characterization work was that the overlying ash deposits (see Figure 2.6) are likely to be susceptible to internal erosion and piping. Reducing uncertainties related to the geotechnical properties and behavior of the blockage is mostly a matter both of obtaining better and more recent in situ data and of performing more extensive engineering analyses (Wynn et al., 2016).

The groundwater regime does not appear to have changed significantly in the intervening years based on geophysical testing conducted in 2016 (Wynn et al., 2016; see Figure 2.9); however, the extent of site characterization in the 1980s using borings as well as that in the 2000s using geophysics is limited. Considerable uncertainty appears to remain about groundwater, pore pressures, and seepage within the blockage. The blockage is the linchpin in the Spirit Lake system. Were it not for the blockage, the concern over a breakout flood from Spirit Lake would be moot. Therefore, while the blockage appears to be stable, and while there have been few indicators in recent years of its mis-performance, prudence nonetheless indicates that an assurance of its current condition be confirmed.

To evaluate the possibility of using a surface channel to drain Spirit Lake, information is needed on the current geotechnical properties of the blockage and of the groundwater regime; the geometry that such a channel would require (e.g., it was suggested in the committee's meetings that this channel would be too steep to accommodate fish passage or a sandy bottom); and the maintenance requirements necessary to maintain such a channel. Much of this information was presumably considered in the 1980s at the time of the original drainage decisions, but such information would need to be updated, and economics studies (i.e., benefit-cost analysis) would probably need to be updated as well. There is nothing particularly difficult about collecting such information and making the related engineering and economic decisions, yet little modern engineering information has been collected since the 1980s.

A summary of information needs with respect to the debris blockage is shown in Table 5.5.

Other Alternatives

Applying traditional principles of reliability and safety (see Box 5.2) is good engineering practice, and such principles were recognized in the PFMA process as reflected in the following passage from Grant and others (2016a):

> *During the risk assessment process and at other junctures, the question was raised as to whether there should be redundant or backup mechanisms for getting water out of Spirit Lake. By this view, adoption of any new alternative for releasing water other than rehabilitating the existing tunnel would include maintaining the existing tunnel as a backup should the new design fail.* (112)

The principle of redundancy of reliable design, however, was not accepted based on cost:

> *This option was not rigorously analyzed. While superficially an attractive option, a problem with this approach is that maintaining dual infrastructure could double the amount of repair and maintenance required in order to keep both outlets functioning. Since the overarching objective of the risk assessment is to identify alternatives for safely draining the lake which require less intervention, having to maintain two facilities instead of one appears impractical.* (112)

TABLE 5.5 Information Needs Related to the Debris Blockage

Type	Description	Justification
Geology	Accurate and precise mapping of the contact boundary between debris avalanche and overlying pyroclastic deposits. High-resolution delineation of the contact between boundary of debris avalanche and underplaying rock.	Important in confirming critical elevation for breakout flood calculation and whether changes have occurred since the 1980s. Critical boundary for groundwater seepage and debris blockage stability analysis.
Geomorphology	Detailed mapping of the landscape evolution of the debris blockage since the 1980 eruption.	Critical in identifying current condition of surface erodibility for open channel and buried conduit alternatives should these be reappraised.
Hydrogeology	Detailed observation and description of the water table configuration and its evolution since the 1980 eruption to within modern margins of error for groundwater surveys.	Critical for identifying current conditions of permeability structure, piping development, debris blockage stability, and open channel and buried conduit alternatives.
Geomechanics	Detailed characterization of the heterogeneity of debris blockage (pyroclastic, deposits, debris avalanche, and underlying rock) in shear strength and erodibility.	Critical in assessing current conditions of piping development, debris blockage stability, and open channel and buried conduit alternatives.

BOX 5.2
Principles of Reliability and Safety

Decisions about alternatives for Spirit Lake and the Toutle River system depend importantly on the safety provided by them. The comparison of alternatives needs to recognize a number of traditional principles that enhance reliability and thereby safety. The more important of these are redundancy, diversity, segregation, defense-in-depth, fault tolerance, and fail-to-safe condition (described below). Incorporating these in decisions about alternatives helps ensure safety and motivates the search for additional alternatives.

Redundancy means that there is more than one way to achieve safety. Should one way not work there is another as a fallback.

Diversity means that there are different ways to achieve the same protection. Should one way not work it would not preclude another way from working.

Segregation is the separation of redundant features by space or by barriers to prevent all or most from failing in the event of a common hazard. It means that output is served from different directions, thus attaining redundancy.

Defense-in-depth means that there are large margins of capacity over demand. The factor of safety against adverse performance in any mode that performance might occur is large.

Fault tolerance means that a single fault will not cause loss of system function. This should include tolerance to human reliability where relevant.

Fail-to-safe-condition means that if the system does fail, it will be rendered to a harmless state. The consequences of a failure, should it occur, are minimal.

Despite this view, the committee heard from various interested and affected parties in attendance at the committee's information gathering sessions, including some USFS staff, that redundancy in protection was desirable. Any trade-off of safety (or other desired outcome) against financial cost is one that should be engaged within a transparent decision process involving interested and affected parties. The process may determine that the cost of redundancy is too high to be practical, but that is a trade-off to be made and quantified during application of a decision protocol. Guidance for making those determinations is provided in Chapters 6-8. It is also within the context of the decision framework that engineering and nonengineering solutions could be considered together to offer redundancy, where possible. Whatever solutions are ultimately considered, it needs to be remembered that if a reduction to a specific risk level by a given date is the desired outcome, then the specific actions in their appropriate sequence and estimated costs will need to be incorporated into the analyses of alternatives (discussed in Chapter 7).

As part of its task (see Box 1.1), the committee was asked "to identify possible alternatives for long-term management" of the Spirit Lake and Toutle River system. Considering other alternatives is consistent with the traditional principles of reliability and safety. The study sponsor, the USFS, understood that the committee would not provide a comprehensive list of alternatives nor would the committee assess the viability of any options. The purpose of the request was to inject potentially new ideas into future decision-making processes, the viability of which would be quantified in future efforts by the USFS and other agencies with management authority in the region. The next sections summarize some of the ideas generated during the committee's brainstorming exercises. They are rough ideas, however, based on limited data, and therefore do not represent recommendations.

Lowering the Level of Spirit Lake

Spirit Lake is a large body of water capable of producing catastrophic losses given catastrophic failure of the debris blockage. By maintaining a lower lake elevation and thus reducing the volume of water, the probability and consequences of risk in terms of loss of life and property could be lowered. The operating elevation of the lake is set at 3,440 feet (1,049 m), although it rises annually to about 3,448 feet (1,051 m) (see Table 5.6). This is a management decision, the justification for which is described in Grant

TABLE 5.6 Key Elevations Related to Spirit Lake

	Elevation (m)	Elevation (ft)
Crest of debris dam	1,079	3,540
Maximum operating level of lake	1,055	3,460
Safe operating level of lake	1,049	3,440
Gate bottom elevation	1,030	3,379
Depth of lake	56	185

SOURCE: Britton et al., 2016a.

and others (2016a). Briefly, it is determined that the "effective dam crest elevation," representing the contact between the debris-landslide deposit and the overlying pyroclastic deposits is located at approximately 3,490 feet (1,064 m). This contact elevation is relevant because of the erodibility of the pyroclastic materials. Water above that elevation could rapidly erode the pyroclastic materials. It was further assumed that both debris-avalanche and pyroclastic deposits would eventually consolidate, which would lower the contact point by as much as 15 feet (5 m), to an elevation of 3,475 feet (1,059 m). A piping analysis conducted by the USACE suggested that piping failure could occur with a sustained lake level above 3,460 feet (1,055 m) (USACE, 1983; Sager and Chambers, 1986). This elevation was thus chosen to be the safe lake level. To provide for short-term storage capacity to cope with potential hydrologic and volcanic events, a freeboard of 18 feet (6 m) was deemed necessary. Thus, the safe operating elevation was set at 3,440 ft. The elevation of the tunnel control structure is at 3,475 feet (1,059 m). That elevation is important not only because of the presumed interface between the more competent and permeable strata of the debris blockage but also because the tunnel becomes fully pressurized above that level and may suffer damage.

There appears to be no engineering reason why the lake could not be drawn down to further reduce risk. It is possible, however, that reducing storage by lowering the operating lake elevation could increase flood heights in the Toutle River downstream. Additionally, Spirit Lake provides recreation and ecosystem services (e.g., aquatic habitat), and lowering the operating lake level may reduce these benefits. These potentially adverse consequences, of course, would need to be incorporated into the decision process.

Multiple options for lowering the lake level exist with corresponding trade-offs in cost, vulnerability to seismic loading, vulnerability to volcanic disturbance, and impact on sediment downstream. Most immediately, the entrance to the existing tunnel (see Figure 2.10) might be modified to lower the pool elevation by 36 feet (11 m). The USACE originally designed a drop structure at the entrance such that the bottom of the gate is located at 3,436 feet, while the invert of the tunnel is at 3,430 feet. According to the USACE, this drop was included in the design precisely to provide an option for modifying the tunnel entrance elevation if the need to lower the lake arose because of the blockage becoming unstable (email from C. Budai, USACE, to S. Magsino, November 29, 2016).

Dry Emergency Spillway

A dry emergency spillway could be constructed over the debris blockage in the event of an uncontrolled increase in lake level due to tunnel failure or major renovation, among other reasons. Unlike the open channel alternative (alternative 5 in Table 5.1), the emergency spillway would not carry flow from Spirit Lake except under emergency conditions. Its headworks and the entire spillway can be constructed at a higher elevation than the tunnel inlet resulting in lower construction and maintenance costs than for a non-dry operating channel. Additionally, because the spillway would divert water only when the lake is at or near maximum safe elevation, no gates are required at the entrance. The operation of the spillway is entirely passive.

Such a spillway provides redundancy to the existing tunnel-based lake level management strategy. It adds diversity in that the two outlet options represent different technologies and operating modes. To the extent that the emergency spillway and the existing tunnel are physically separated, the resulting segregation reduces vulnerability to some kinds of volcanic or tectonic events.

To perform all these functions, the emergency spillway must remain structurally sound and free of blockages over time, despite the possibility of various volcanic and tectonic events. This requirement is the same as that applying to any form of open channel discharge. In the absence of a Spirit Lake water level emergency, though, the spillway is either dry or subject only to ephemeral flows (local drainages). Therefore, inspection and repairs should be easier to accomplish than in the case of an open channel that handles the entire lake drainage. Its effects on the debris blockage and rates of downstream sediment transport need to be considered during the decision-making process.

Second Drainage Tunnel

During the committee's open session meetings in Kelso, Washington, the committee heard from some participants about a desire for redundancy in protection. There was concern that having only a single means of controlling water levels leaves the region vulnerable should issues arise with the tunnel. Construction of a second tunnel, located on the east side of Spirit Lake, would offer such redundancy, and it could offer other advantages as well. Foremost are reducing the impacts of geologic hazards and providing flexibility in the management of lake level and sediments in the system. While not inexpensive, a second tunnel could allow those with management authority greater flexibility to work toward a range of long-term objectives—from reducing the hazard of debris blockage overtopping to being able to restore more natural drainage conditions less dependent on engineering interventions. A second tunnel intake placed at a low enough elevation could allow for full control of lake levels. If that is achieved, it is conceivable that future management of the system could include a free-overflow surface channel through the debris blockage. Such a channel might be created in a controlled manner to re-create the pre-1980 flow patterns from Spirit Lake to the North Fork Toutle River.

A tunnel could be constructed along alignments A, B, or D, as shown in Figure 5.2. These were alternate alignments suggested during the original tunnel planning. The east side of the lake is farther away from debris

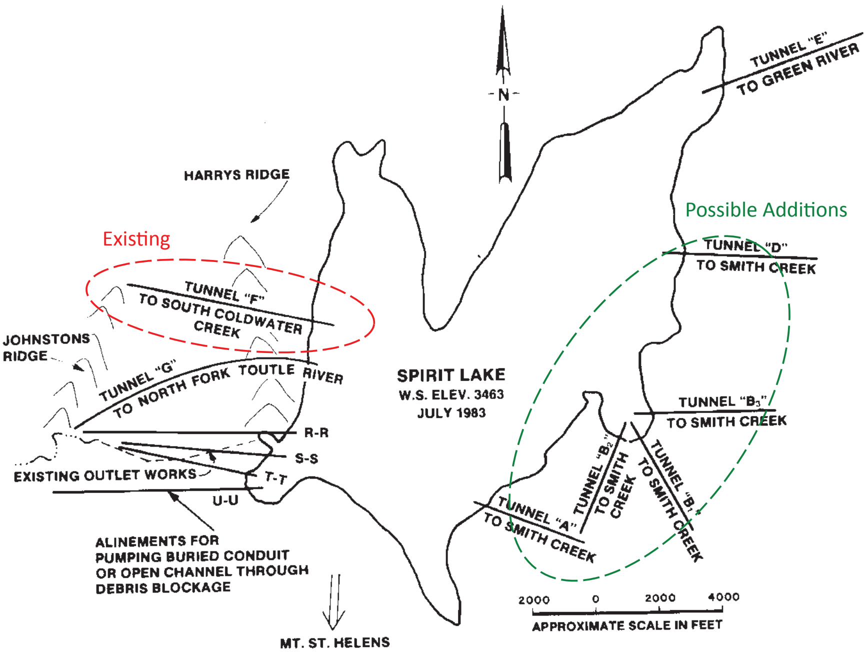

FIGURE 5.2 Original suggested tunnel alignments. Existing tunnel alignment (circled in red) drains Spirit Lake to the west, through Harry's Ridge toward South Coldwater Creek. Possible tunnels might drain to the east, toward Smith Creek. SOURCE: Modified from USACE, 1983.

blockage, active geologic faults, and extensive surface erosion. A new tunnel could be located within competent bedrock with minimum faults and seismic effects. Since the difference in elevation between the lake water level and nearby streams or creeks east of Spirit Lake that drain into the Lewis River is about 1,200 feet (400 m), the tunnel could be gravity-fed, open-channel, or pressurized. The impact of routing water to the existing hydroelectric power reservoir system could be minimal, but it would need to be explored. If designed appropriately, the flow from the second tunnel could be used to generate electric power.

The second tunnel might remove nearly all risks of the identified potential failure modes in the proposed alternatives of the PFMA. If installed, the existing tunnel could then be thoroughly rehabilitated without concern about uncontrolled rise in the lake level. It could also be possible to convert the Harry's Ridge tunnel to a pressure tunnel or construct a lower intake level to allow for further lowering of the lake (as described earlier). Two working tunnels provide multifold flexibility in water routing, tunnel maintenance, lake water control, and sediment control. In the event of a potential eruption of the volcano, the water level in Spirit Lake could be drained to a desired state. The discharge of Spirit Lake water can go either southeastward or northwestward as needs dictate. The current Toutle River system will still exist, but with a discharge downstream of the Coldwater Creek confluence diminished by 300-400 cfs (8-11 m^3/sec). The reduction in discharge could have negative impacts that would need to be explored. If the reductions were temporary until more natural flow patterns could be established, the long-term benefits might outweigh the short-term consequences. These are considerations that would have to be worked out through the decision-making process.

MANAGING SEDIMENTS

As described in Chapter 3, the USACE developed a 50-year plan to manage sediment associated with the 1980 eruption so as to maintain authorized flood risk levels along the Cowlitz River (USACE, 1985). Table 5.7 provides a timeline of events related to sediment management in the region. The USACE designed, built, and began operation of the 1,888-foot-long (575-m) and 184-foot-high (56-m) SRS on the North Fork Toutle River (see Figure 2.9) to capture medium- to coarse-grained sediments and allow finer particles to flow downstream in suspension to the Columbia River and out to sea.

The history of the SRS involves three phases (USACE, 1985). In Phase I (1989), sediments reached the level of the spillway, the pipe outlets were closed, and water began spilling over the spillway. Storage at this date was approximately 45 my^3 (34.4 mm^3). This followed expectations, more or less. The fine fraction of the sediment load (silt, clay, and sand finer than 0.125 mm) remains in suspension when it reaches the Cowlitz

TABLE 5.7 Timeline of Events and Sediment Management Actions by the USACE with Respect to the SRS from 1980 to Present

Year	Event or USACE Action
1980	Eruption—More than 3 billion cubic yards of material displaced
1980-1983	Emergency responses
1985	Decision document finalized (original plan laid out)
1989	Sediment Retention Structure constructed
1993	Fish Collection Facility operated/maintained by State
1998	Top (and last) row of pipes closed at the SRS
2005	Cowlitz River sediment build-up at mouth; increased flood risk
2007-2009	Dredging in Cowlitz River at mouth
2009	Castle Rock Levee Cut-Off Wall
2010	Pilot Grade Building Structures constructed
2012	SRS Spillway Crest raised
2010-2015	Update to Long Term Plan with final draft SEIS
2016	Draft Biological Opinion received

SOURCE: Kuhn and Sclafani, 2016.

River and is flushed to the Columbia River. In Phase II (1998), a wedge of additional storage formed at low gradient on top of the Phase I sediment plain. Storage in this wedge was approximately 145 my^3 (110 mm^3). An increasing percentage of larger sediment fractions washed over the spillway and was transported downstream. In the 2010s, grade building structures were placed in the sediment plain to encourage the development of the wedge. In Phase III, upstream bed becomes coarser as more sand fraction is washed over the spillway, and the slope of the plain steepens. Phase III storage is an additional approximately 68 my^3 (52 mm^3) (USACE, 2012).

By 2007, 4 to 5 million tons of sand had been transported from the Toutle River valley into the Cowlitz River (Biedenharn Group, 2010), where sand tends to settle and reduce flood conveyance capacity. This sand supply will increase in high-flood years and whenever the sediment fill approaches the spillway elevation. In 2006, it was concluded that flood protection provided by the levees along the lower Cowlitz River had been degraded by these sedimentation processes (USACE, 2006). To respond to its commitment to provide certain levels of flood protection to the communities in the Cowlitz River floodplain (see Table 4.1) the USACE dredged the mouth of the Cowlitz River channel in 2007-2009 and improved the Castle Rock levee. In the absence of dredging, the observed trend of diminishing channel capacity was expected to continue and spread upstream, further reducing protection levels (USACE, 2006). Evaluation of such a plan required a new evaluation of the likely trajectory of sediment supplies from the Toutle River valley.

The strategies adopted for reducing impacts of this sediment load on downstream channel stability and flood conveyance capacity have included temporary check dam structures to capture a portion of the sediment within the North Fork Toutle River valley, raising and strengthening engineered flood levees along the lower Cowlitz River, and dredging the lower Cowlitz River to maintain navigation and flood conveyance capacity as necessary.

Sediment Budget and Management of the SRS

The flow of sediments into the SRS since 1980 is shown in Figure 5.3. Sediment flow may be slowing; but, based on communication with technical experts during the course of the study, that conclusion does not seem unanimous. Projections of future sediment yield have been lowered (Kuhn and Sclafani, 2016). The annual mean rate of sediment accumulation behind the structure is about 5 million cubic yards (3.8 million m^3), but there have been spikes up to 20 million cubic yards (15 million m^3). Large volumes of sediment are still expected to move off the Mount St. Helens debris avalanche for many years, and sediment deposition in the lower Cowlitz River remains a concern (USACE, 2014). About 80% of the volume of sediments accumulated to date originates in the debris avalanche.

Many uncertainties affect management decisions with respect to the SRS. The first is the future sediment yield off the debris avalanche. The sediment yield is related to volcanic activity at the mountain, but it is also related to hydrologic events. Conclusions from recent scientific studies vary: some predict persistently high sediment loads (Major, 2004;

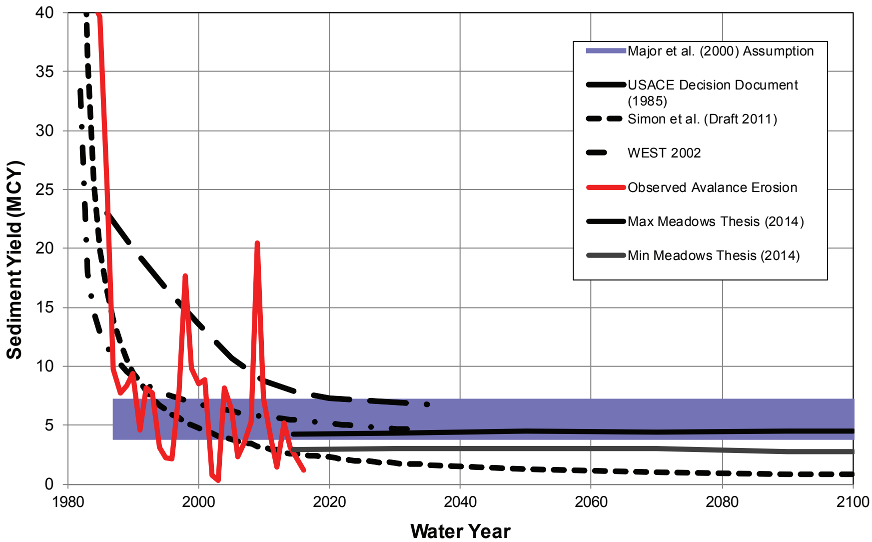

FIGURE 5.3 Flood debris avalanche sediment load. SOURCE: Kuhn and Sclafani, 2016.

Meadows, 2014), while others predict a reduction of the loads (Simon and Klimetz, 2012).

Based on these studies, the USACE reevaluated management options for sediment control for the authorized planning horizon to 2035 (USACE, 2010a). The analysis confronted two contrasting projections: one argued that sediment supplies are declining (Simon, 1999; Simon and Klimetz, 2011); the other argued that there is no evidence that sediment supplies are declining (Major, 2004; Grant et al., 2016a). Direct measurement of sediment loads throughout the post-eruption period led Major (2004) to conclude that "persistent, extraordinary suspended sediment yields from severely disturbed channels indicate that mobile supplies of sediment remain accessible, and those supplies likely will not be exhausted for many more years or possibly decades." A more recent review of empirical records to 2009 supports a similar conclusion (Grant et al., 2016a).

The USACE commissioned a new study of the post-eruption sediment budget of the Toutle-Cowlitz river system with projections of sediment loads to 2035 (Biedenharn et al., 2010; Biedenharn Group, 2010). This study, the most thorough and multifaceted one to date, was based on a combination of post-eruption records of both erosion and sediment transport and on empirically calibrated hydraulic and statistical modeling. It separated the behavior of different grain sizes of sediment, which is important for assessing which sediment escapes from the SRS and which settles in the Cowlitz River channel.

The Biedenharn Group (2010: 149) concluded that evidence for a decline in the rate of debris-avalanche erosion over the past 20 years is not a sufficiently reliable base from which to project into the future. They estimated that the most likely sediment loading from the avalanche deposit by 2035 was 233 million tons (± 25-40%); they further estimated that after the SRS filled to the spillway elevation in 1998, approximately 80% of the sediment supply to the Toutle River mouth consisted of output from the SRS, with the South Fork Toutle River catchment providing another 13%. The study also concluded that between 2008 and 2035, with no changes made to the SRS, the most likely sediment load at the Toutle River mouth was 173 million tons—but with a range from about half to two times that value and a more likely uncertainty range of about one-third (Biedenharn Group, 2010). These projections assume no volcanic-, seismic-, or extreme-weather-related disruptions of the watershed.

These and other forms of evidence collected in their own sediment budget investigation led the USACE (2011) to adopt the more conservative interpretation of future sedimentation outcomes and to design an adaptive approach to managing the sedimentation risk for the remainder of the planning period to 2035. The adaptive management plan (USACE, 2014) involved three components: (1) A two-stage elevation of the spillway of the SRS, which would minimize cost and include the second increment only if necessary before 2035. The new spillway heights would be 7 feet (2.1 m) (completed in 2015) and then as high as 23 feet (7 m) as necessary above the original level. (2) Adaptable, incremental installation of grade building structures to increase flow length and resistance in the sediment plain upstream of the SRS to reduce transport capacity and increase deposition. (3) Continued dredging of the lower Cowlitz River channel as needed.

The reduction in spillway capacity caused by raising the spillway was considered conservative because: First, any conceivable mudflow that might be generated by a breakout of Castle Lake, or from a volcanic event in the Mount St. Helens crater, would result mainly in deposition upstream of the spillway and not tax the spillway capacity (Denlinger, 2011). But the current spillway would not accommodate a Spirit Lake breakout. Second, a reevaluation of the PMF for the location, based on updated methodology and gauged information, reduced the PMF by almost 50% (USACE, 2011).

The seismic behavior of the SRS and the sediment plain it retains is also uncertain. The peak ground acceleration associated with a maximum considered earthquake (MCE) as used in design is 0.61g (Britton et al., 2016a). This is relatively large. Assuming the sediment plain liquefies during this earthquake, the embankment is computed to have a factor of safety against instability of FS=1.3 (Britton et al., 2016a). That means that the resistance of the SRS structure to the loads imposed on it in such an event are 30% greater than the loads; thus, the SRS is considered stable under earthquake loading—even if the impounded sediments lose their strength (liquefy) during the event.

With the filling of the SRS to the spillway, larger grain size sediment is again flowing down the Toutle River. Without action, the USACE estimates that 20 to 70 million cubic yards (15 to 54 million m^3) of sediment will flow into the Cowlitz River by 2035 (Stepankowsky, 2009), some of which will accumulate there. As a point of reference, the corresponding total load after the 1980 eruption was about 30 million cubic yards (23 million m^3). Intensive dredging was required in the Cowlitz and Columbia Rivers as a result.

The USACE is considering four alternatives for future flood risk management in the Cowlitz River sediment plain in the wake of the spillway rise in 2012. These are described in detail in USACE (2014) and are only listed here:

1. No action to manage sediment and maintain the established levels of protection (LOPs).
2. Lower Cowlitz River dredging only.

3. Raise the SRS spillway one time by 43 feet (13 m) and the SRS dam by 30 feet (10 m) without additional dredging.
4. Phased construction with two incremental raises of the SRS spillway totaling 23 feet, additional grade building structures in the sediment plain, with dredging as needed.

The USACE identified this alternative as its preferred and recommended plan.

The USACE (2014) indicates that the preferred alternative would have major adverse effects on fish in the upper North Fork Toutle River area. Sediment deposition in fish habitat and a temporary rise in water temperatures would result from post-construction water impoundment. Mitigation would be implemented, but the current preferred alternative of a spillway raise does not include a mechanism for fish passage. A summary of information needs with respect to the SRS is shown in Table 5.8.

TABLE 5.8 Information Needs Related to the SRS

Type	Description	Justification
Engineering characterization of the sediments	A detailed investigation is needed to evaluate the engineering properties of the SRS sediments, including strength, stiffness, and shear wave velocity.	No information is currently available on these sediments to evaluate their engineering behavior during a seismic event.
Site-specific seismic hazard analysis	A detailed seismic hazard analysis, including estimates of fault rupture and ground motion shaking, is needed as part of the rehabilitation of the existing outlet tunnel.	Generic data on seismicity in the region is insufficient for engineering evaluation of the SRS.

MANAGING CHRONIC FLOOD RISK

As has been described, the lower Toutle River and the lower Cowlitz River floodplain are subject to chronic flooding from the Toutle River as a result of the increased sediment in the river channels. For example, in the flood of February 8, 1996, the Toutle River watershed (drainage area 496 square miles [1,285 km^2]) contributed 61,800 cfs (1,750 m^3/sec) of the 112,000 cfs (3,171 m^3/sec) peak flow passing the Castle Rock gauge on the reservoir-regulated Cowlitz River (drainage area 2,238 square miles [5,796 km^2]) on the same day (USACE, 2014). Flows from the upper Cowlitz River north of the confluence of the Toutle and Cowlitz Rivers are mostly controlled by the Mayfield and Mossyrock Dams operated by Tacoma Power. The current levels of authorized flood risk reduction in the lower Cowlitz River, for which the levee system is sized, are listed in Table 4.1. These are provided by levee projects at Castle Rock, Lexington, Kelso, and Longview, the locations of which are shown in Figure 5.4. The authorities for these LOPs are granted in P.L. 99-88 (1985) and are specifically to "provide flood protection for developed areas along the Cowlitz River and navigation on the lower Columbia and Cowlitz Rivers"; they are likewise granted in Section 339, Water Resources Development Act of 2000,[1] which "clarified that the [USACE] maintain levels of flood protection specified in 1985 Decision Document." The river channels that drain the Mount St. Helens area consist of broad alluvial reaches with moderate to low gradients (0.005 to 0.03), whereas the gradient in the lower Cowlitz River drops to 0.0008 (Janda et al., 1984), which can contribute to sediment deposition and flooding. With time, LOPs in the lower Cowlitz River will decrease due to this settlement accumulation (see Figure 5.5).

Four possible engineering solutions were considered by the USACE to manage sediments (and therefore chronic flooding) in the Toutle and Cowlitz Rivers. There are other engineering and nonengineering

[1]P.L. 106-541.

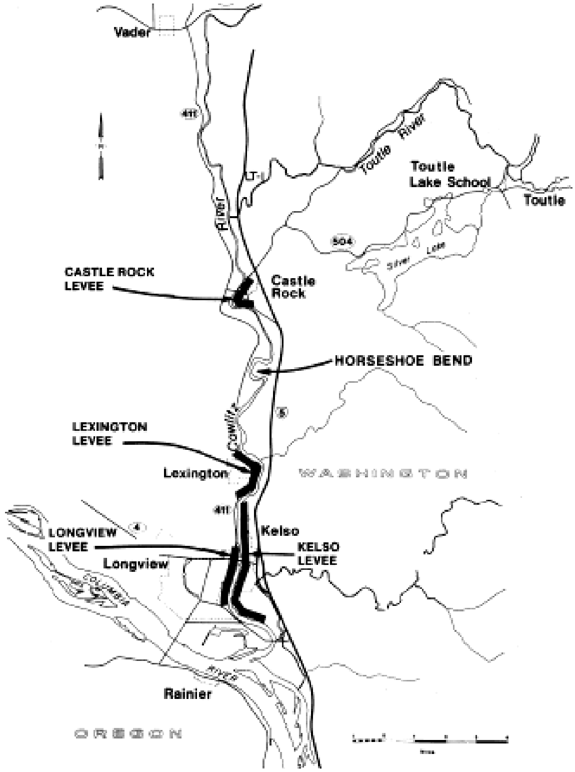

FIGURE 5.4 Locations of levees on the lower Cowlitz. SOURCE: USACE, 2010b.

alternatives[2] for flood-risk reduction in the lower Cowlitz River floodplain that are not considered in current planning and that are not necessarily mutually exclusive. They might involve, for example, creating a wider floodplain by removing structures and creating levee crevasses or reoperation of Mossyrock Dam, which feeds water to the upper Cowlitz

[2]Some nonengineering solutions might include restricting new development to the current 500-year (p=0.002) floodplain or expanding the purchase of flood insurance or enhancing emergency management plans for both routine and catastrophic events. These and other nonengineering solutions could be done in lieu of or in concert with engineered solutions. Chapter 7 provides guidance on how alternatives with combinations of structural and nonstructural solutions can be compared.

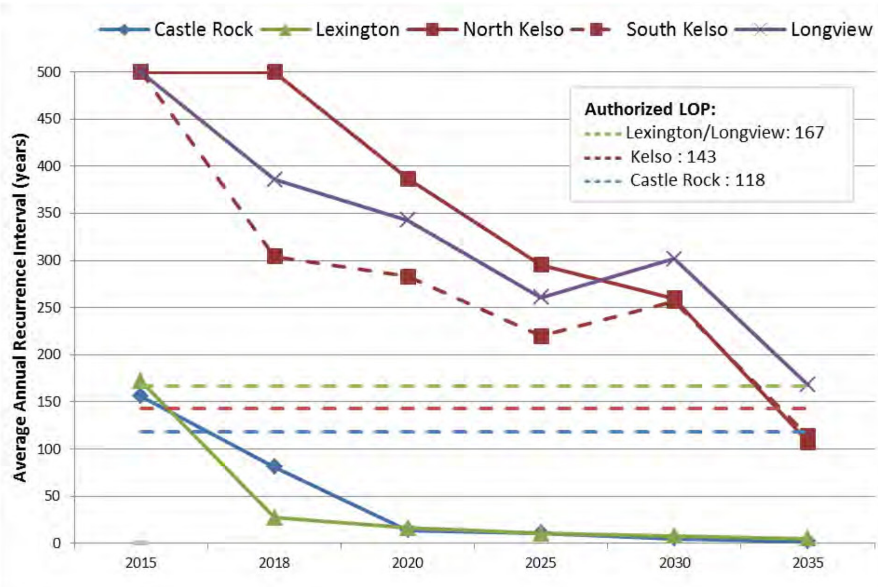

FIGURE 5.5 Authorized levels of protection (LOPs) for Lexington-Longview, Kelso, and Castle Rock are shown in dashed line. LOPs for Longview and Kelso remain above authorized until 2035, but those of Castle Rock and Lexington depend on the 2014 Plan. LOPs for lower Cowlitz decrease into the future due to settlement accumulation if the actions adopted under the 2014 Sediment Management Plan are not enacted. SOURCE: USACE, 2014.

River. Interim actions to address current sediment management requirements to maintain flood damage reduction benefits while the long-term sediment management plan is updated have been undertaken.

Flood Levees

The levees originally were built using a range of materials, some poorly suited to levee construction and having the corresponding impacts on stability and protection that would be expected under such circumstances. LOPs are variable. The levees have been improved several times, including nonengineered and temporary improvements. In 2010, the USACE evaluated whether the safe water levels (SWLs) for the levees were below authorized LOPs. The SWL is the highest flood that the levee can reliably withstand without geotechnical distress or overtopping. Based on this analysis, the USACE determined that LOPs were met for the North Kelso and Longview levees, but were below authorized levels for Castle Rock, Lexington, and South Kelso (USACE, 2010b). Levee heights are variable and dip below the SWL at multiple locations (see Figure 5.6). The determination that the Longview levee meets the LOP is based on an assumption that the diking district can temporarily raise the levee to meet the LOP during high-water events. It is worth noting, however, that all levee heights are above the 1996 flood elevation.

At the lower Kelso levee, the SWL was lowered by the USACE because seepage on the landward slope can lead to sloughing of the cohesionless sand that forms the foundation of the levee (USACE, 2010c). Material below the Castle Rock levee ranged from “well to poorly graded sand, with silt or gravel, and occasional clayey sand. The compactness of the foundation soil ranges from loose to very dense” (USACE, 2010b). Conversely, the SWL was lowered on some levees (i.e., Kelso levee south of Olive Street) because dredge spoils had been removed from the riverside of the levee, which could lead to seepage during high-water events. Thus, the geotechnical stability of the levees is variable and dependent on the local diking districts managing the levees during high-water periods.

The Lexington and Castle Rock levees are particularly vulnerable to the flooding impacts associated with sediment loads. Since these are areas where losses are lowest from a regional perspective, however, the analysis of viability of nonstructural alternatives, such as relocating these communities, may be inadequate. Similarly, analysis of the combinations of structural and nonstructural alternatives has not, to the knowledge of the study committee, been conducted. As stated in the USACE external review of the Sediment Management Plan, “the effectiveness of the final array of alternatives in addressing sediment transport beyond the year 2035 could potentially show different economic and environmental results than if only the period until 2035 was considered. This could alter the selection of the recommended plan” (Batelle, 2014).

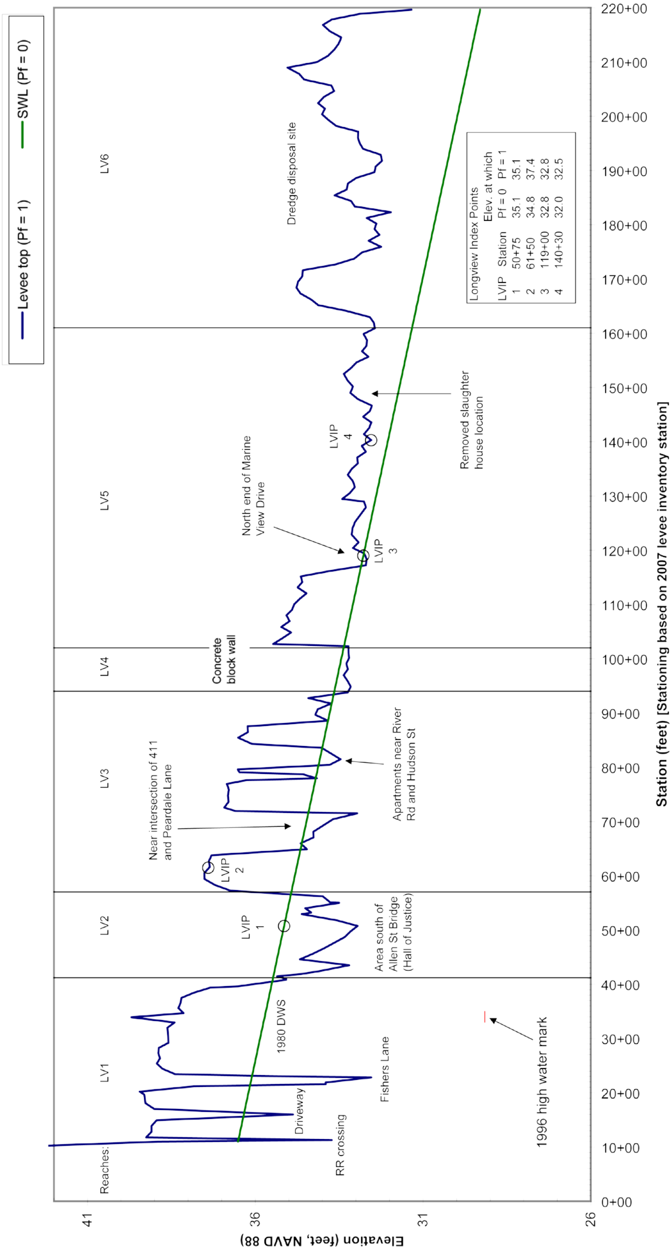

FIGURE 5.6 Longitudinal top of levee and Safe Water Level for Longview levee. SOURCE: USACE, 2010c.

The transport of sediment, including debris flow events, from the Mount St. Helens area can significantly increase the flood hazards. Debris flows are initiated by mobilization of landslides, volcanic melting of snowpack, and flood surges, with the most damaging flood events associated with the entrainment of sediment during large flood surges (Major et al., 2005). The USACE has yet to forecast how much future sediment buildup would reduce flood risk protection in the Cowlitz River, although interim actions as noted above have been undertaken. A cut-off wall was also added to the levee reaches in Castle Rock to alleviate potentially destabilizing underseepage. The principal uncertainties have to do with the volume and timing of future sediment releases over the SRS and the consequent amount of bed elevation in the Cowlitz River channel, especially in the vicinity of the three riparian municipalities.

Information needs with respect to flood risk reduction in the lower Cowlitz River are more modest than are those with respect to other aspects of the management of the system. The main uncertainties that require better information are those related to the potential for nonstructural strategies of a flood risk reduction and those related to the rate of future sediment accumulation in the lower Cowlitz. A summary of information needs with respect to the levees and flood risk reduction is shown in Table 5.9.

SHORT- AND LONG-TERM MANAGEMENT

Although authorization for management of various elements of the Spirit Lake and Toutle River system extend through 2035, the need for active risk management of the Spirit Lake and Toutle River system does not end at some arbitrarily authorized date. Management decisions need to be planned with a long-term perspective, irrespective of the vagaries of current political pressures. Agreeing on a management time horizon, however, needs to be done in the context of a decision protocol because the interests and needs of different interested and affected parties may only be met given specific time frames. Identifying a time horizon may result in institutional and social conflict given the different strategies that might be required for

TABLE 5.9 Information Needs Related to Levees and Flood Risk Reduction

Type	Description	Justification
Evaluation of nonstructural strategies for reducing flood losses	Data and analyses supporting nonstructural strategies, including relocating communities, is lacking.	Information needed to judge whether nonstructural solutions are viable is not now available. Nonstructural solutions alone or in combination with structural solutions might provide optimal alternatives to management.
Evaluation of future sediment accumulation	The USACE has yet to forecast how much future sediment buildup would reduce flood risk protection in the Cowlitz River, although interim actions have been undertaken.	The principal uncertainties have to do with the volume and timing of future sediment releases over the SRS and the consequent amount of bed elevation in the Cowlitz River channel, especially in the vicinity of the three riparian municipalities.

the different time frames. Factors affecting the choice of time frame are discussed in Chapter 6.

Recommendation: Alternatives for managing the Spirit Lake and Toutle River system should be judged over both short and long time frames to ensure consideration of the range of the concerns of interested and affected parties.

Engineered elements such as the tunnel, the SRS, and levees are part of the Spirit Lake and Toutle River system and have a finite engineering design life. The choice of time frame for risk management decisions related to their design, construction, and management is critical and therefore must be explicit. Legislated time frames, however, such as the 50-year open construction period for the SRS—typical for many infrastructure projects—may preclude consideration of system management activities such as restoration. Choosing among alternatives given consideration of management over a single time frame may limit flexibility in management over the long term and may, in fact, increase long-term costs. Furthermore, the longer-term risks and financial burdens left unaddressed in a given time frame will become the responsibility of future residents and taxpayers. Active assessment of alternatives given multiple time frames can inform the selection of both the most appropriate alternatives and the time frames given the impacts and trade-offs associated with either.

OPERATIONAL RISK

The evolving landscape of the Spirit Lake and Toutle River region is now dominated by the engineering conducted within it since the 1980 eruption of Mount St. Helens. The engineered landscape was originally created to protect those living in the Toutle and Cowlitz River basins from natural hazards resulting from the eruption, but that engineering has had large-scale and important effects on the ecology, geomorphology, and landscape values of the region. Federal, state, and local responsibilities for managing this system are inevitably complex, expensive, and indefinite. Engineering needs to adapt to both the evolving natural environment and the preferences and needs of interested and affected parties. Any thought of a natural, unmanaged environment is unrealistic.

The engineering itself introduces risk beyond those caused by natural events. Such risks are caused by the operation of the engineered facilities; historically, operational risks to, for example, dam safety may be large (Leveson, 2011; Hartford et al., 2016). Operational risks may result by policy and procedures, by instrumentation and supervisory control and data acquisition (SCADA) systems, by inaccessibility to the site at a time of urgency, by human errors, or by many other factors (Leveson, 2011). Operational risks in a complex system such as the engineered landscape of the Spirit Lake and Toutle River region may exceed risks due to natural hazards, engineering design, or other factors that more commonly appear in risk assessments (Regan, 2010).

Large rises in Spirit Lake water levels have been associated with periods of extended tunnel closure for maintenance or repair (Grant et al., 2016a), for example, as in 1996 and 2016 (see Figure 5.7). The associated hazard is that if the tunnel remains closed, lake levels may rise uncontrollably. Even though precautions are taken to prevent such an operational risk, the risk still exists. The possibility of a dramatic and quick rise in lake levels during tunnel closure has led to an operational bias of avoiding tunnel closure more than was necessary. Occupational safety and health risks may also be introduced by operational factors. Access to the tunnel intake for management activities (including opening and closing the gates and wood removal), for example, can be dangerous, particularly during bad weather in winter months. This concern was voiced by USFS personnel to study committee members during the committee's open session meetings. It is necessary to recognize operational risk explicitly when considering engineering reliability; thus, operational risks to personnel (or decisions that reduce that risk) need to be considered as part of the final decision-making framework.

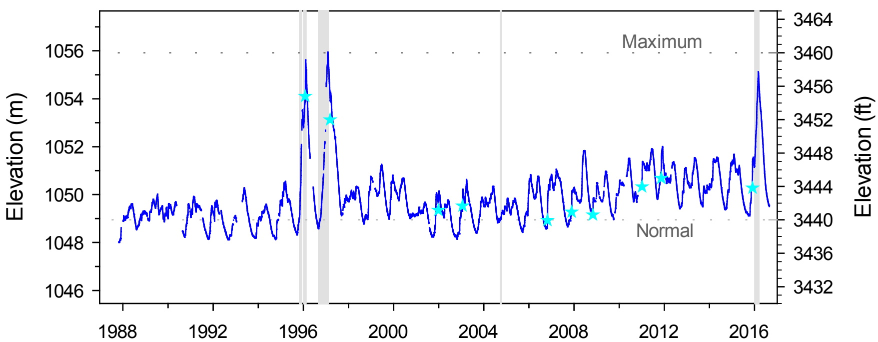

FIGURE 5.7 Daily water-surface elevation of Spirit Lake from October 1987 through September 2016 from the U.S. Geological Survey gauge at Tunnel at Spirit Lake, Washington (14240304), with normal operating level and maximum elevation for safe operation. Gray vertical bars indicate periods of extended tunnel closure, and stars indicate the timing of the 10 largest 1-day inflows during the period of record. SOURCE: Grant et al., 2016b.

Operational risks arise in many aspects of the risk management plan for the Spirit Lake and Toutle River system. This is true irrespective of the drainage alternative used for the lake—be it a tunnel, surface channel, conduit, or pumping—or for any infrastructure put in place in the system. All of these involve operations and consequently operational risk, although the levels of operational risk associated with the various alternatives are not all the same. They all involve the vagaries of weather, human operators, sensors, SCADA systems, and other practical factors. It may be that the larger risks posed by the system derive from these operational factors rather than from natural hazards and extreme events alone (Hartford et al., 2016). Given that the Spirit Lake and Toutle River system is an engineered system, it needs to be managed and operated by a cognizant authority. As such, the risks that attend it arise not only from natural hazards but also from the human operations that direct it.

Recommendation: Operational risk should be explicitly considered when evaluating alternatives for management.

INTEGRATION USING PROBABILISTIC RISK ASSESSMENT

The effectiveness of the engineered landscape is today commonly appraised by the use of a probabilistic risk assessment, or PRA. This approach is common to most modern infrastructure studies as well as to the evaluation of natural and technogenic hazard mitigation: for example, as applied to dam and levee infrastructure (see NRC, 2012b). Modern approaches to risk management are increasingly based on PRAs that address the capability of a system to withstand extreme loads. A PRA is especially useful in appraising design and rehabilitation decisions and which design loads and corresponding factors of safety must be chosen. Assessing operational risk involves considering the vagaries of weather, human operators, sensors, SCADA systems, and other operational factors. It may be that the significant risks posed by the system derive from these operational factors rather than from natural hazards and extreme events alone.

The incorporation of natural hazard risks in a decision framework is now common in public policy planning and infrastructure risk management. The uncertain occurrence of hydrologic, volcanic, and seismic hazard events in the Spirit Lake and Toutle River region is typically described in annual exceedance probability curves of their magnitude. Operational risks as discussed above are also important to infrastructure risk management. A PRA provides the platform for integrating the many hazards affecting the Spirit Lake and Toutle River system and for combining those hazards and their potential consequences within a formal decision protocol as discussed in Chapters 6-8. Without a quantitative analysis of these risks it is not possible to balance the opportunities and investments to achieve the most advantageous outcomes. The implementation of a PRA for the Spirit Lake and Toutle River system is not difficult given the current level of understanding of the system, the history of evidence-based analysis of the natural conditions of the basin, and the foundation of data already acquired. Methods of conducting a PRA in common practice in such closely related fields of science and engineering as volcanology, civil engineering, and actuarial science provide a well-exercised basis for applying this methodology.

Probabilistic Risk Asessment

A PRA is a systematic approach to evaluating risks associated with complex engineered systems such as the Spirit Lake and Toutle River system. A PRA addresses the types and magnitudes of hazardous events that might load a system, the performance of that system under these loads, and corresponding adverse consequences that might result. A PRA is an essential component of modern public policy decision making, especially in the context of complex engineered infrastructure (Yohe, 2010) and is a necessary input to the decision framework of Chapters 6-8. The decision framework recommended in this report cannot be fully leveraged without a quantitative understanding of the risks presented in the system.

The common modern convention for a PRA in closely related fields is the threat-vulnerability-consequence (TVC) model, shown schematically in Figure 5.8. "Threat" (or hazard) is quantified in the probability

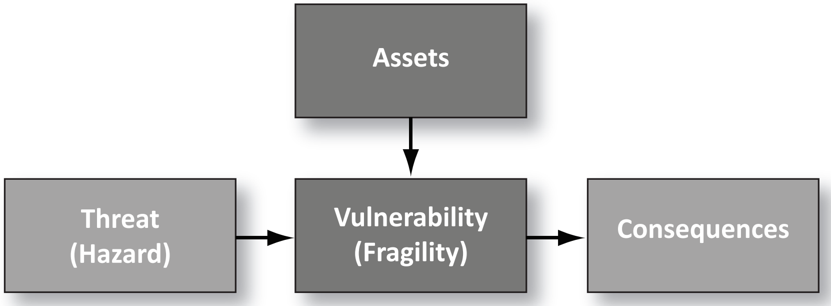

FIGURE 5.8 Threat-vulnerability-consequence model of probabilistic risk assessment.
SOURCE: Adapted from Grossi and Kunreuther, 2005.

of load events occurring against the system. "Threat" is a term commonly associated with man-made or malicious actions, while "hazard" is a term commonly associated with natural processes, as in the case of the Spirit Lake and Toutle River system. "Vulnerability" is the expected performance or damage to the system given a load event of certain description. In structural, earthquake, geotechnical, and dam safety engineering, vulnerability is usually replaced by the term "fragility," which is the conditional probability of adverse performance (e.g., failure) of the system given a load event of certain description. "Consequences" are typically quantified in economic costs, environmental impacts, and loss of life.

A hazard in the present context is any real or potential element that may result in adverse performance of the system leading to undesirable consequences. Hazards are identified by historical review of past events, by functional analysis of modes in which a system can fail (e.g., PFMA), or by expert appraisal (Kumamoto and Henley, 1996). In some applications, design and construction flaws are also treated as hazards, but that is outside the normal TVC paradigm. Those who will use the results of any PRA for decision making will need to be involved in deciding how such factors should be counted in the PRA. The vulnerability of a system is the damage expected for a given hazard load. The fragility is the chance of failure or adverse performance for a given hazard load. The concepts are related, and for the most part, the terms are used in similar ways. Both vulnerabilities and fragility curves can be assessed in the normal engineering ways: from empirical data, modeling, or expert judgment (Rossetto et al., 2014).

The chance of hazardous events occurring is expressed probabilistically. The aggregate risk is calculated as expected loss, that is, the sum-product of the probabilities of the prospective hazards and their corresponding consequences. These probabilities and consequences—the aggregate risk—serve as necessary input to the application of the decision framework discussed in Chapters 6-8.

Adequacy of the Current Risk Analysis

The decision framework outlined in Chapters 6-8 is predicated on a quantitative assessment of the hazards, vulnerabilities, and consequences attending infrastructure decisions and the management of risk in the Spirit Lake and Toutle River system. This is not now available in a comprehensive form. A well-intentioned and competent precursor of a quantitative risk analysis was performed in the context of the PFMA of the Spirit Lake drainage situation. This PFMA provides a journeyman analysis of the potential failure modes associated with each alternative drainage option for the lake. It provides a firm foundation for a PRA. It does not go sufficiently far, however, to associate probabilities and potential consequences with the respective failure modes. This will be needed among a more extensive analysis for the risks associated with the lake, its drainage, and other issues to be fully understood. Such a quantitative risk analysis is recommended for fully leveraging the decision framework of Chapters 6-8.

The probabilities of the major natural hazards affecting the system—hydrologic, seismic, and volcanic—may be known imperfectly or qualitatively, but they are characterized to some extent. Probabilities associated with the vulnerabilities of the built environment, specifically the drainage alternatives for Spirit Lake and the performance of the SRS, have not been evaluated. The same is true in large part for the quantification of the downstream consequences of these hazards. Thus, for the present, a quantified understanding of risk is not available.

A PRA seeks to assess hazards, performance, and consequences in quantified units of probability and cost. Probabilities express how likely something adverse is to happen; costs express consequences in dollars, lives, and environmental measures. The PRA answers three questions (Kaplan and Garrick, 1981): (1) What can happen? (i.e., What can go wrong?); (2) How likely is it that it will happen? and (3) If it does happen, what are the consequences?

Event Tree Representations as Information for the Decision Framework

Event trees are now commonly used to represent the components of a PRA for civil infrastructure systems, particularly for dam and levee safety (USBR and USACE, 2012). They have also been widely used to analyze risks associated with volcanology. The USACE has been a pioneer in the application of PRA methods to civil infrastructure systems, particularly to issues in water resources engineering. Thus, the expertise for such studies is demonstratively available and straightforward to apply, and there is extensive documentation of such applications to similar natural systems involving volcanology, seismology, and dam safety reported in the literature. This device may be used for any of the hazards discussed above—particularly to integrate these hazards within a common framework.

Construction of event trees involves establishing probabilities for the various uncertain events that might affect the system. For instance, given an eruption with its associated annual probability, what is the probability of a pyroclastic flow of a certain volume, and if it occurred, what damage might it cause? Such probabilities can be based on events from the historical or geologic record; on additional data, such as geophysical imaging of the volcano's plumbing; on numerical models of specific processes; or on expert opinion elicitation (O'Hagan et al., 2006). Expert judgment can be obtained through the work of individual scientists or small teams of scientists, or from a formal expert elicitation process wherein a panel representing a diverse range of expertise is provided with all relevant information (e.g., Aspinall, 2006; Coppersmith et al., 2009).

The event tree in Figure 5.9 is a simple example of a generic volcanic hazard. Moving from left to right, first the probability of a given eruption scenario occurring during the time frame of concern is specified. Then the probabilities of particular eruption phenomena that might be associated with that scenario are assigned, followed by probabilities of particular magnitudes (such as lahar volume). This approach can be carried forward to include vulnerabilities and consequences of any type in the Spirit Lake and Toutle River system. An important first step in any analysis is defining the time frame of interest (e.g., a design lifetime of the SRS), and, in the case of this example, the eruption scenarios of interest. Note that the time frame of interest needs to account for the interests of all interested and affected parties involved in decision making. Choosing the time frame is best done in a collaborative analytic process that includes stakeholders, as is discussed in Chapter 6.

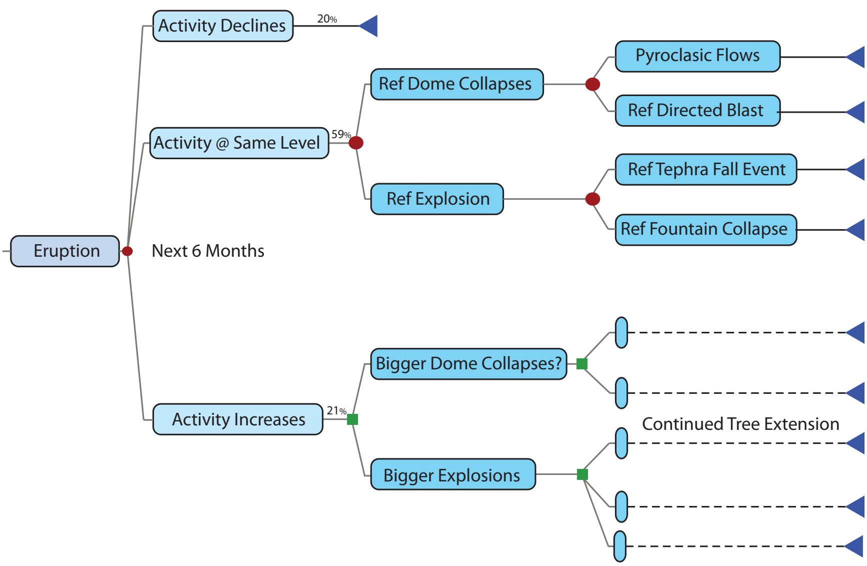

FIGURE 5.9 Example of a partial volcanic hazards event tree for the Montserrat Volcano. SOURCE: Modified from Baxter et al., 1998, in consultation with Monserrat Volcano Observatory.

An event tree is simply a systematic way to organize and describe the possible outcomes of a hazard and its consequences. It is an input to the decision framework in Chapters 6-8. Event trees represent the possible outcomes of a random process. At each node in the event tree the emanating events are appraised as mutually exclusive and collectively exhaustive, so their respective probabilities add up to 1.0. Assessing the consequences of future natural hazards requires integration of our understanding of potential hazards, as discussed above, and engineering aspects of the debris blockage, the Spirit Lake tunnel or other drainage scheme, and the SRS. The consequences downstream can be estimated in measures deemed important through the decision framework (see Chapter 6), including impacts on environmental health, fish populations, and sociological factors. The probability-weighted consequences provide a quantitative measure of risk and its uncertainty.

LEVERAGING RESOURCES AND EXPERTISE

The study committee has noticed an apparent insularity of expertise among those involved in management of elements of the Spirit Lake and Toutle River system. Whereas great expertise resides within those agencies, relying almost solely on that expertise can stifle the generation of new ideas and can result in a propagation of assumptions based on incomplete assumptions. The federal and state agencies involved in managing the system have a number of resources available to them from other parts of their respective organizations. For example, the USACE operates a Risk Management Center for dam and levee safety, which could be leveraged to a much greater extent in the future than it has been in the past. Similarly, the USFS and the USGS have agency resources that might be more fully brought to bear on the planning for Spirit Lake and the Toutle River. The mobilization of these important resources needs to be encouraged throughout analytic processes, the results of which inform decision making. Likewise, external review of analytical processes needs to be encouraged to identify how and where analysis might be strengthened.

CHAPTER 6

Choosing a Decision Framework and Identifying the Decision Problem

Long-term management of risks in the Spirit Lake and Toutle River system conducted in a way that is responsive to safety as well as to the multiple values and points of view of interested and affected parties in the region is challenging, but not impossible (Rittel and Weber, 1973). The process of identifying and comparing alternatives to manage both routine and catastrophic risk in the Spirit Lake and Toutle River system is made more difficult due to

- Analytical uncertainty resulting from incomplete or outdated information;
- Analytically irreducible uncertainty associated with low-probability moderate-intensity events and very low-probability but potentially catastrophic events;
- Competing values and interests across multiple interested and affected parties;
- Lack of agreement on the appropriate time horizon for planning;
- Overlapping decision authorities with separate but interdependent responsibilities and budgets;
- Low trust among agencies and the public;

- Lack of a single solution that is likely to completely satisfy all agencies of governments and other interested and affected parties; and
- Inadequate budgets for implementing potentially desired alternatives.

The committee's statement of task (see Box 1.1) calls for recommendation of a systematic process to identify, explore, and illuminate choices in the face of complexity and uncertainty given these many challenges. The decision framework includes the steps required for interested and affected parties to formulate a problem and to organize the identification of issues, alternatives, and consequences in light of available information and existing constraints of budget and authority.

The framework also guides the identification of those who should be involved at different levels in the decision-making process, which is especially important in the case of decisions that affect many parties with potentially conflicting values and interests. Table 6.1 describes the different and potentially conflicting missions and authorities of the different agencies in the region. Finally, the decision framework guides the process for comparing alternatives. Decision making as described in the next chapters contrasts sharply with the ways in which management decisions for the Spirit Lake and Toutle River system have been made in the past (see Box 6.1).

This chapter includes discussion regarding the choice of a decision framework and provides guidance on how the decision problem is defined (including who leads the decision process, and in what ways, and who participates) and on the relevant spatial and temporal scales of decision making.

CHOOSING A DECISION FRAMEWORK

The decision framework recommended in this report embodies two overarching elements. First, the decision framework is based on an analytical-deliberative process (NRC, 1996). Broad public input is

TABLE 6.1 Examples of Responsible, Interested, and Affected Entities and Their Objectives

Entity	Responsibility	Management Objectives
Federal		
U.S. Forest Service (USFS)	Caretaker for Mount St. Helens, Spirit Lake, and surrounding lands; funds operation and maintenance of Spirit Lake tunnel; funds emergency repairs on tunnel.	Sustain health, diversity, and productivity of the nation's forests and grasslands for multiple purposes (including timber, range, water, wildlife, and outdoor recreation); maintain wilderness in designated areas; involve public in preparing forest plans; operate in compliance with applicable environmental legislation.
U.S. Army Corps of Engineers (USACE)	Operate and maintain Spirit Lake tunnel; own and manage sediment retention structure on the North Fork Toutle River; maintain flood protection for downstream communities; stabilize level of Spirit Lake; operate and maintain Castle Lake and Coldwater Lake outlet facilities; coordinate extraordinary maintenance with the USFS.	Survey and improve nation's rivers and harbors to benefit navigation; develop flood control projects; plan and implement water resource development and conservation projects on major waterways.

continued

TABLE 6.1 Continued

Entity	Responsibility	Management Objectives
Mount St. Helens National Monument (administered by the USFS)	Manage the Monument area.	Protect the geologic, ecologic, and cultural resources while allowing geologic forces and ecological succession to continue substantially unimpeded; conduct scientific study and research; allow for recreational and interpretive facilities and for the Cowlitz Indian Tribe and Yakama Nation to continue to use the mountain for cultural purposes.
Tribal		
Cowlitz Indian Tribe and Yakama Nation	No federally recognized management responsibility.	Protect environment and natural resources through technical expertise; provide housing, transportation, and health services for their peoples as well as spiritual guidance and other cultural resources consistent with their duties as sovereign nations.

TABLE 6.1 Continued

Entity	Responsibility	Management Objectives
State		
Washington State Department of Fish and Wildlife (WDFW)	Manage Mount St. Helens Wildlife Area along the North Fork Toutle River.	Protect habitats to assure optimal number, diversity, and distribution of wildlife; optimize wintering elk habitat; support recovery of fish, especially endangered species; operate fish collection facility on the North Fork Toutle River.
Washington State Department of Natural Resources (WADNR)	Manage land in the study area, including along the South Fork Toutle River. Manage public trust lands to provide continuous revenue through activities such as harvesting timber and other forest products and other activities.	Manage trust lands to earn income for state beneficiaries, protect water and habitat for native plant and animal species, and provide diverse recreation opportunities.
Local		
County, local governments; private landowners	Manage their parcels in the area.	Various.

BOX 6.1
Past Decision Processes in the Region

Decisions regarding flood risk and sediment management in the Spirit Lake and Toutle River system are made more complex because of how regulatory and budget decisions are dispersed and poorly coordinated across the physical system and multiple agencies. Decisions made by one agency can have implications for others. For example, dredging of sediment to reduce downstream flood risk might disturb habitat of aquatic organisms and upstream fish migration. Broad public participation needs to be fully incorporated into environmental assessment and decision-making processes (NRC, 2008), and therefore needs to include the full spectrum of parties, beginning in the early problem-formulation stages of the planning process. Input received by the study committee during its information gathering open session meetings indicates that the number of interested and affected parties and the breadth of their interests are broader than Table 6.1 suggests.

The practices recommended in this chapter contrast with the standard practice of agencies in this region. In effect, Congress defined the problems (to manage the catastrophic and chronic flood risks) and authorized the USACE to formulate alternatives to manage them. With respect to Spirit Lake water levels, the USACE was expected to formulate alternatives to minimize the likelihood of a catastrophic breakout. This resulted in the proposal of alternatives, including the tunnel. The USACE then solicited written comments from agencies and any interested and affected parties that were motivated to provide input. Based on input, the USACE chose the tunnel. Any informal interagency communication that may have taken place is not part of the formal public record.

A similar process led to the construction of the sediment retention structure (SRS). In that case, Congress defined the problem as assuring a defined level of protection for the levees that lined the river and that were built prior to the eruption. The USACE formulated alternatives designed to keep sediment from filling the river cross-section between the levees and compromising protection levels. Other agencies were asked to provide written comments on the alternatives. In consideration of these comments, and in consideration of cost-effectiveness analyses required by the U.S. Army's assistant secretary for civil works, the USACE chose the SRS as its preferred alternative. The same process continues today with the planning to raise the SRS spillway.

incorporated throughout the process to both influence and be influenced by technical analysis. Second, the decision framework explicitly calls for use of decision analysis techniques to properly account for the multiple objectives and multiple values of interested and affected parties.

Recommendation: Adopt a deliberative and participatory decision-making process that includes technical considerations; balances competing safety, environmental, ecological, economic, and other objectives of participants; appropriately treats risk and uncertainty; and is informed by and responsive to public concerns. Dialogue among interested and affected parties and technical experts should be iterative, begin with the formulation of the problem, and continue throughout the decision process.

A number of decision-making approaches incorporate these elements; Keeney and Raiffa's (1993) PrOACT framework is useful as a point of reference both because of its organizing structure and because it has been used successfully in complex water management contexts.

The general steps of the PrOACT framework as described by Keeney are

- Clarify the decision **Pr**oblem.
- Identify the decision **O**bjectives and ways to measure them.
- Create a diverse set of **A**lternatives.
- Identify the **C**onsequences.
- Clarify the **T**rade-offs.

The structure outlined by these bullets represents a process of exploration for an acceptable solution, and it is discussed step-by-step throughout this and subsequent chapters. Alternatives are assessed through a variety of metrics and in consideration of the various trade-offs (or compromises) required of different interested and affected parties until agreement is reached. Once solutions are envisioned, they can then be reconciled with agency authorities, jurisdictions, and funding. This may require revisiting the chosen solution, a normal procedure in a fundamentally iterative process. Successful implementation of a deliberative process such as that recommended in this report requires expertise that may not be contained within the agencies and organizations involved.

There are many ways to integrate technical analyses and participation of interested and affected parties in a deliberative process, and various principles and procedures have been developed for doing so (e.g., NRC, 2008). Applications of a PrOACT-like process have addressed the relicensing of hydroelectric dams. Gregory and others (2012) mention roughly 30 relicensing studies in British Columbia, Canada. Runge and others (2015) review the application of decision analysis techniques in a Glen Canyon Dam study. Others have considered topics such as the ecological recovery of the Missouri River basin (USACE, 2016b). A related planning protocol—Shared Vision Modeling—has been applied to water quantity management in the Apalachicola-Chattahoochee-Flint and Alabama-Coosa-Tallapoosa basins (Georgia, Alabama, Florida); to water allocation in the Rappahannock River (Virginia); and to the development of an integrated resources plan for the Los Angeles Urban Watershed.[1] Conroy and Peterson (2013) include a water management example in their set of case studies. A multiyear effort by the Missouri River Recovery Implementation Committee also uses a PrOACT-like process (USACE, 2016b).

Even among superficially similar applications, the planning efforts vary greatly in scale. An effort to study removal of nonnative fish from below the Glen Canyon Dam did not contemplate any structural changes, but it did involve multiple interested and affected parties, including various government agencies and Native American Tribes (Runge et al., 2011). That application was limited, however, to operational changes at one specific location and was also able to utilize an existing working group. Consequently, it was possible to walk through all PrOACT steps in two meetings, with several weeks of modeling work between the first and second meeting. It is likely to require more than two meetings just to form the decision group and agree on a protocol to address the Spirit Lake and Toutle River system.

[1]Palmer et al. (2013) review these applications of Shared Vision Planning, as well as 17 others.

A more complex effort was required to develop the Bridge Seton Water Use Plan in British Columbia (Mattison et al., 2014). That study was undertaken against a background of pending lawsuits involving federal agencies and First Nations (Indian Tribes of Canada). The plan required consideration of complex multiple-agency overlaps as well as a complex multiple-reservoir hydroelectric system, although no new physical works were planned. The investigation required 13 main committee meetings over 2 years, plus an additional 25 meetings on technical issues such as fish, flooding, wildlife, recreation, and First Nations' interests.

Applying the recommended decision framework to multi-stakeholder environmental management issues has led to the development of a variety of engagement tools discussed in the remainder of this report. Some describe the result as "structured decision making" (SDM; Gregory et al., 2012). Others, focusing on the collaborative aspect of the analytics, consider the decision framework part of a broader category of computer-aided dispute resolution (CADRe) techniques (Bourget, 2011). Given their similarities, this text treats all of these as variants of the PrOACT process.

In this report, the committee uses the PrOACT model as the basis for its own recommended decision framework. Major sections of this and Chapters 7 and 8 are named for each of the steps listed above and offer general descriptions of those steps, their importance in the analytical-deliberative process, and the relationship of each step to past or future decisions made in the Spirit Lake and Toutle River system. Recognize, however, that Keeney's PrOACT framework is focused on a single decision maker's approach to multi-objective problems. Additional guidance has been developed as the approach has been applied to decisions made with multiple decision participants and the broader issues that arise. As noted in the preceding paragraph, this broader practice has become known as "structured decision making" (Gregory et al., 2012). The remainder of the report draws on both sets of experiences.

THE DECISION PROBLEM

A decision problem is that issue—or, as in the case of a system like Spirit Lake and the Toutle River, the set of interconnected issues—about which a management decision needs to be made. The statement of task for this study embodies a broad definition of the decision problem: determining a long-term solution for managing water and sediment transport in the Spirit Lake and Toutle River system. A more precise problem definition may be challenging to articulate; therefore, developing a list of characteristics that describes the decision problem to the extent possible is a critical preliminary step.

Each step of the analytical-deliberative process requires iterative discussions among a lead responsible for implementing the decision framework and the participants in the process. The EPA provides an extensive list of considerations for building public participation into complex decision problems (EPA, 2017). Some key questions to be asked during problem formulation include

- Who leads the process?
- Who is involved, and what is their role?
- What types of solutions can be considered?
- What is the geographic scope under consideration?
- What is the time frame being considered for this decision problem?

Who Leads the Process?

Given the overlapping responsibilities and jurisdictions of agencies in the region, it is difficult and potentially contentious to identify who the "decision maker" is. The overall goal for the participants using the recommended framework is to search for and identify an effective and defensible solution that can be mutually supported. Participants decide to engage in a constructive search for effective and acceptable solutions through a joint problem-solving process because they recognize doing so is to their benefit (Bourget, 2011). But, if the planning framework is to be utilized to manage the region as a system, there must be, at every stage, a lead individual or entity responsible for organizing and managing the decision-making process. This is not necessarily an entity with authority over a given piece of infrastructure. Ideally, the lead would be a new system-level entity or a formal consortium of existing agencies. This would provide a central focus for congressional mandates and appropriations, ensure collaboration across agency and jurisdictional boundaries, and maintain continuous engagement by all interested and affected parties. Such an arrangement has many advantages, but it would likely require congressional action that may or may not occur.

Recommendation: Create a system-level entity or consortium of agencies to lead a collaborative multiagency multi-jurisdictional effort that can plan, program, create incentives, and seek funding to implement management solutions focused on the entire Spirit Lake and Toutle River system. This effort should also be open and accountable to interested and affected parties involved in management decisions.

There are a number of examples of system-level entities, including those that apply PrOACT-like decision frameworks. The Glen Canyon Dam Study (Runge et al., 2011), described above, closely followed a PrOACT-like framework and was led by a system-level, interagency working group. Nevertheless, it may take time for such an entity to be authorized and put in place. In the absence of a system-level entity, the planning framework can be managed in other ways. Federal, tribal, and state entities involved might agree on an informal consortium-like arrangement in which, by agreement, one agency serves as lead throughout the planning process. Or, since authorizations and funding are usually specific to certain components of the system (e.g., the Spirit Lake drainage tunnel, the SRS, etc.), the administrative lead may change from time to time as planning progresses through different topics and issues. In this case, the lead might be assigned to the agency most involved with implementing the management actions under review (e.g., the USACE might be the administrative lead when considering issues associated with sediment retention).

The critical feature of this latter arrangement is that all parties agree in advance to utilize the same planning framework. Although the lead may change, and certain decisions may be taken sooner or later, it is possible to maintain the same deliberative and participatory decision-making process throughout. The overall effort, while incorporating all relevant technical considerations and appropriately treating risk and uncertainty, can still seek to balance the competing objectives of participants and be responsive to public concerns. In this way, the decision framework serves the purpose of imposing a systems perspective on analysis and decision making and on integrating and coordinating the otherwise disparate components of an overall solution. Without the decision framework, agencies will likely decide on and implement actions as they have in the past: with insufficient collaboration with other agencies and minimal engagement with other interested and affected parties.

The decision framework is described in this report so that it is neutral with respect to who actually implements it. The text can be read as assuming that the U.S. Forest Service (USFS) acts as a lead, setting up and implementing the decision framework. But the framework would work just as well if applied correctly by the USACE. Effective management of a participatory process when competing views are involved, however, requires the lead to be perceived as neutral. A single agency lead for all or part of the planning process may work (or be perceived to work) at cross-purposes with the broader goals of participation, responsiveness, and public support. Any agency considered as a candidate for lead may also be viewed by other participants with skepticism if a multiparty process is to be implemented using the lead's internal resources. The diverse skill sets needed to serve as a decision lead and the challenges faced by those providing neutral facilitation services are described by Conroy and Peterson (2013).

A lead could approach the problem of neutrality by creating two distinct roles for the agency in the decision process:

1. A neutral support team to implement the framework. This team brings with them:

- Engagement skills to identify and engage interested and affected parties;
- Facilitation skills to navigate difficult topics, interest-based discussions, and value trade-offs (e.g., compromises) in groups of up to approximately 25 people;
- Deep technical and modeling knowledge to help participants build and test "if-then" predictive models of how different management alternatives might impact the system and the consequences for participants; and
- Decision analysis skills to help incorporate human elements (uncertainty, risk aversion, and decision biases), together with technical modeling aspects, into the decision-making process. (Risk aversion is the behavioral trait of people to minimize uncertainty even if actions taken means sacrificing certain benefits.)

2. The "agency voice"—a non-neutral role within the core group of decision participants that represents the agency as one of the interested and affected parties, advocating for the agency's objectives in value-focused discussions.

It may be the case that the lead does not possess all the skills outlined above for the neutral support team. This is most likely to occur if the lead is assigned to an agency predominately staffed by scientists, technical specialists, and engineers. In that case, the lead can hire any missing skills externally: for example, from consulting firms, nonprofit organizations, or universities. Regardless of whether the neutral team is sourced from within or outside of the lead organization, parties will be more willing to participate if they see the process as neutral and fair. This perception and the resulting enhanced participation will likely facilitate equal access to analytical support, transparency in modeling, and the ability to have meaningful input into both the analysis and deliberation. Great care is needed to maintain the independence and neutrality of the team supporting the process and participants.

Who Is Involved?

As described in Chapter 1, interested and affected parties include, but are not limited to, those who will experience safety, economic, cultural, or quality of life impacts as a result of management activities. They may have history of engagement with regional issues, or they may have specialized knowledge of some type of potential impact (e.g., environmental). Efforts to attend to and systematically incorporate the views and knowledge of interested and affected parties into decision making have long been recognized as critical to risk management (NRC, 1996). Participation in decision making by interested and affected parties may be particularly important when (a) the problems addressed and decisions required are complex and can be appropriately viewed from different perspectives; (b) no single entity has overriding jurisdiction or the resources needed to make and implement a decision; (c) the decisions required have the potential to be controversial; and (d) the actions being considered are novel and significant rather than incremental (NRC, 1996; NOAA, 2015). These attributes aptly describe the kinds of decisions associated with the long-term management of the Spirit Lake and Toutle River system.

Involving interested and affected parties in decisions such as those being addressed by the USFS and the USACE is desirable for other reasons. When conducted appropriately, engagement activities can reveal the values that serve as the basis for decision making, enhance the credibility of the information that is used in making decisions, improve the quality of decisions, increase public trust and confidence in decision making, increase institutional transparency, help to resolve disputes, and gain legitimacy for actions that are subsequently undertaken (Yosie and Herbst, 1998; NRC, 2008; NOAA, 2015; Nuclear Energy Agency, 2015). Input from interested and affected parties is needed at all phases of decision making, from setting the context in which decisions will be made to specifying the values and objectives involved and identifying alternatives and trade-offs (Gregory and Keeney, 1994). The process of engaging interested and affected parties, however, must be managed well to achieve the kinds of positive outcomes listed above. Engagement cannot be undertaken merely for the sake of satisfying bureaucratic requirements, as doing so could ultimately undermine the legitimacy of the effort if parties conclude that their input was sought but then ignored.

Individuals participating in the decision-making process may do so on their own behalf or on behalf of some group or entity. The lead is responsible for making sure all interested and affected parties are identified and for ensuring that the full spectrum of interests is considered in the process. A list of interests and concerns to be represented during deliberation needs to be generated—perhaps initially by the lead—and confirmed with participants early in the process. Having broad participation beyond those with funding and project authority means this list may include a similarly broad range of interests and concerns.

How Are They to Participate?

The International Association for Public Participation (IAP2)[2] defines levels of public participation ranging from "Inform" to "Empower" (see Table 6.2). This spectrum is similar to the USACE's "Degrees of Collaboration" matrix (Dedekorkut-Howes, 2004). Based on discussions with USACE staff and other interested and affected parties in the region, the level of engagement with the public by the USACE in the aftermath of the 1980 eruption appears to align with the "Inform" or "Consult" levels in the spectrum. An integrated and iterative analytical-deliberative process as recommended by the NRC (1996) and in this report pushes engagement beyond this level.

Recommendation: Broaden and deepen the participatory decision-making process from its earliest stages to include and assimilate the knowledge and interests of affected groups and parties whose safety, livelihoods, and quality of life are affected by management decisions.

[2]See www.iap2.org.

TABLE 6.2 The International Association for Public Participation Spectrum

Increasing Level of Public Impact →

	Inform	Consult	Involve	Collaborate	Empower
Public Participation Goal	To provide the public with balanced and objective information to assist them in understanding the problems, alternatives, and/or solutions.	To obtain public feedback on analysis and/or decision.	To work directly with the public throughout the process to ensure that public issues and concerns are consistently understood and considered.	To partner with the public in each aspect of the decision including the development of alternatives and the identification of the preferred solution.	To place final decision making in the hands of the public.
Promise to the Public	We will keep you informed.	We will keep you informed, listen to and acknowledge concerns, and provide feedback on how public input influenced the decision.	We will work with you to ensure that your concerns and issues are directly reflected in the alternatives developed and provide feedback on how public input influenced the decision.	We will look to you for direct advice and innovation in formulating solutions and incorporate your advice and recommendations into the decisions to maximum extent possible.	We will implement what you decide.

	Inform	Consult	Involve	Collaborate	Empower
Example Tools	• Fact sheets • Websites • Open houses	• Public comment • Focus groups • Surveys • Public meetings	• Workshops • Deliberate polling	• Citizen advisory committee • Consensus building • Participatory decision making	• Citizen juries • Ballots • Delegated decisions

SOURCE: International Association for Public Participation (www.iap2.org).

There are inherent compromises between the breadth of engagement and the depth to which individual participants can deliberate in the decision process. This is necessarily true because the lead's budget to support a decision process will be limited and because not all interested and affected parties have the same willingness, ability, or capacity to participate. Moreover, while erring on the side of broader inclusivity may appear to be more acceptable, broad inclusive participation could be used to shut down meaningful public participation by avoiding the in-depth and iterative discussions required in any PrOACT-like framework (Gregory, 2016).

To work around some of these dilemmas, participation can be stratified into "tiers," with participants at different tiers being engaged at different depths and frequency. There are multiple ways to organize such tiers: for example, as "circles of influence" (Werick and Whipple, 1994). The broad spectrum and number of interests to be addressed, however, may be smaller than the number of interested and affected parties and also the number of participants. There is an important difference between the framework described here and circles of influence (Werick and Whipple, 1994). In the decision framework described in this chapter, some nonagency interested and affected parties could be part of the tier working through the highest level of deliberation and analysis. Werick and Whipple (1994) describe the highest tiers of deliberation as consisting solely of technical experts, with stakeholders being at a less involved level. The present report recommends a framework that emphasizes deep public participation throughout a decision process.

The decision framework described in this report draws on the work of Gregory and others (2012) and Conroy and Peterson (2013) wherein a small group of participants—up to approximately 25—is selected to represent the broad spectrum of interests. It may include, but is not limited to, key regulatory agencies. This small group explores the in-depth technical discussions, model building, and value trade-offs inherent in the PrOACT process during multiple (e.g., 6 to 10) sessions. The small group concept has been applied to aid collaborative toolmaking within the realm of public water management decisions (Bourget and Bingham, 2011).[3] This tier of deep involvement would also be supported by extensive involvement of the neutral support team that would bring their technical and modeling expertise into the PrOACT steps.

Assigning a small group of participants to address the details of the decision process may result in a sense of lost legitimacy among some of the broader set of interested and affected parties—in particular, those that expressed an interest in the proceedings but that were not included in the small group deliberations. A deliberate engagement effort is needed whereby conclusions reached by the smaller group can be shared and tested with a broader group. This could allay concerns about legitimacy while also providing opportunity to validate the conclusions. As an example, when the broad spectrum of interests is canvassed, several people may identify interest in the impacts of management decisions on hunting and fishing. If one of those individuals is chosen to work in the small group, that person could communicate regularly with his or her broader constituency and then inform the more detailed discussions within the small group, possibly refining the analysis to be conducted. Further, the lead could build links between tiers of participation. This will increase engagement given that members of different tiers will also be members of other organizations. The lead will have to ensure that outreach and engagement activities connect the broader but less organized general public with the in-depth decision process. Methods for broad outreach and engagement are described in the literature (see Conroy and Peterson, 2013).

A decision is reached when the small group of decision participants conducting the in-depth analyses is able to support a proposed solution. Due to overlapping and unclear regulatory boundaries, decision making might be difficult and contentious. Treating the decision process as a multiparty negotiation provides the ability to defer a potentially divisive exploration regarding which agency has final say over which aspects of the

[3]The 2011 book *Converging Waters: Integrating Collaborative Modeling with Participatory Processes to Make Water Resources Decisions* (Bourget, editor) is a collection of papers focusing on computer-aided dispute resolution (CADRe). The process aligns closely with the PrOACT approach used for organizing this chapter, albeit with different emphasis placed on certain aspects.

outcomes. The process begins by defining a problem, understanding the participants' decision objectives, and then looking for mutually acceptable and defensible sets of actions that address the objectives. The principle is to conceive of the solution before attempting to reconcile that solution with agency authorities, jurisdictions, and funding. This may require revisiting the chosen solution—a normal procedure in a fundamentally iterative process.

Designating consensus among the decision makers as an aspiration rather than a requirement is a useful decision rule for multiparty collaborative processes (Gregory et al., 2001). This allows the process to be used to explore possible, but perhaps at first unpopular, alternatives and may encourage participants to moderate their views as the process nears its end. Responsible agencies may be better able to identify alternatives that will have widespread support. If the parties involved work through a decision framework and arrive at, for example, a mutually acceptable long-term strategy for flood risk and sediment management, then each party, based on its exiting authorities and responsibilities, is more likely to implement its parts of the strategy.

Knowing when to continue or end deliberating is an important part of the terms of reference for participants. This is addressed later in Chapter 8. If a mutually acceptable solution is not found, then participating parties can search for agreement within smaller coalitions of participants or, in the extreme case, fall back to their own legal and regulatory decision-making authorities. And while the participating agencies could ultimately choose to implement a set of actions considered but not supported through the analytical-deliberative process described here, they would at least know which other interests (if any) are supported by their actions as well as the value trade-offs (discussed in Chapter 8) inherent in pursuing that course of action.

The remainder of this chapter will focus on the work of this smaller group of participants.

What Is the Geographic Scope?

While the initial motivation for this current study was related to long-term performance and maintenance of the Spirit Lake drainage tunnel, the geographic scope of the committee's charge is far broader and extends to long-term management of risks of the entire Spirit Lake and Toutle River system (statement of task; see Box 1.1). As such, adequate long-term risk management of the system depends on system-level analysis of risk. An understanding of the interconnections and interdependencies among subsystems—both natural and engineered—is essential. This approach differs from current widespread practice in the region. Analysis tends to focus on agency-specific responsibilities and interests and on issues at specific locations or features over short time frames. The geographic scope for the broader study, however, is dependent on how much of the system needs to be considered in the decision-making process to fully account for the physical risks and for the interests and values of the participants.

Recommendation: Engage in system-wide thinking when making decisions about management objectives, approaches, and alternatives for the Spirit Lake and Toutle River system. Depending on the issues being considered, the system may include the Cowlitz River or extend beyond it.

Management intervention in any part of the system could have implications both downstream and upstream of the intervention (see Chapter 1). Responsibilities and concerns among interested and affected parties are also connected in ways that become clear only with system-level analysis. Nevertheless, the geographic scopes of individual problems may differ. After consideration of an individual problem, participant objectives, and various consequences of potential solutions, it may be determined that the geographic scope needs to be broadened or narrowed. For example, management decisions related to the Spirit Lake debris blockage could have consequences that extend to the Cowlitz River or beyond; some decisions related to the SRS may be found to have consequences only downstream, but others may have implications for management of Spirit Lake; certain decisions related to anadromous fish passage could conceivably have implications all the way to the Pacific; or decisions related to a small stream feeding into the Toutle River may be found to have more geographically limited consequences. Similarly, consideration of the other lakes in the region impounded by Mount St. Helens may be important in many of the decisions to be made.

Early agreement among participants on both the definition of the system and the geographic scope is important so that objectives can be identified, allowing alternatives and consequences to be appropriately analyzed.

What Alternatives Can Be Considered?

In the immediate aftermath of the 1980 eruption, multiple alternatives to manage flooding and sedimentation on the Toutle River system were considered. While the original USACE effort to address those hazards contained both flood mitigation and related sediment control alternatives, the solutions to what is a system-wide problem were considered in an ad hoc manner and independently (USACE, 1983), a pattern that continues today among all parties. At least some interested and affected parties attending the committee's public meetings, however, did view the Spirit Lake and Toutle River system as a whole and discussed potential system-wide solutions.

It is important to have an early and explicit discussion with participants about the scope of the process. This helps to identify differences in expectations between the agencies—and between agencies and the public—to ensure alignment between what the participants want to achieve and what the agencies are willing and able to deliver (NRC, 2008). For example, to control a catastrophic breakout of Spirit Lake, it might be decided to consider alternative lake water levels; alternatives to manage sediment at the SRS and above; and downstream alternatives that reduce risk to populations such as levee construction or improvement, rezoning, and resettlement. All these alternatives may be considered, but in practice there may be disagreement regarding the scope: for example, because of limitations on agency authorities. Such limitations need to be clarified and, if necessary, challenged. All parties need to have a shared understanding of the scope early in the problem formulation process.

Box 6.2 describes some of the first decisions likely to be made using elements of the recommended decision framework: decisions regarding management of Spirit Lake water levels.

What Is the Planning Time Frame?

Interactions with agency representatives and other interested and affected parties during the course of this study revealed a diverse set of views regarding appropriate planning time frames. While those asked during the meetings agreed with the need for long-term planning, their definitions of “long term” varied widely. Because different planning time frames can lead to radically different management strategies, choosing a time frame can represent an institutional and social conflict associated with management of the Spirit Lake and Toutle River system.

Overly long time frames may cause planners to overlook short-term solutions to immediate problems or not to anticipate changes in the physical system that might occur during a long time frame. For instance, a long enough time frame will also make it a near certainty that a low-probability but high-consequence event (e.g., a geologic or hydrological event) will occur that would disrupt whatever management activities are implemented.

Planning based on short time horizons, on the other hand, may be appealing because they favor alternatives that promise solutions to existing problems. Time frames that are too short, however, may preclude otherwise desirable capital-intensive projects thereby narrowing the range of alternatives that might be considered. They may also understate the importance of various low-probability but high-consequence events that could have substantial effects on different infrastructure elements of the Spirit Lake and Toutle River system.

Arbitrary time frames that are not meaningful for the decisions under consideration can hamper appropriate consideration of management alternatives. For example, the congressional authorization for the SRS was 50 years (i.e., 1985-2035; USACE, 1985). This authorization excludes

BOX 6.2
Managing Spirit Lake Water Levels: Who Is Involved and How?

The first set of decisions to be made using the decision framework in this report will likely be related to management of Spirit Lake water levels. The USFS, given its responsibility for the Spirit Lake drainage tunnel, will likely initiate a decision process and serve as its administrative lead in at least its earliest stages. This is likely to occur prior to the full implementation of recommendations in this report, but many of the principles of the decision framework presented herein may still be applied. Through the process the USFS initiates, it will be determined who is involved and with what roles in decision making, the geographic scope of the problem, time frames to be considered, and the types of solutions to be considered. To identify the participants in the decision process, the USFS may want to convene a small group of those with management authority in the region. This group may include federal, tribal, state, and local agencies. They will need to identify overlapping or even conflicting jurisdictional issues so that the scope of the process can be negotiated. Some alternatives for managing lake levels may give other agencies a certain amount of leverage when alternatives are ultimately considered. For example, potential solutions regarding the debris blockage may increase sediment migration downstream and impact the SRS, which may give the USACE some amount of leverage. Some alternatives may or may not facilitate fish migration into and out of Spirit Lake, which might indicate the Washington Department of Fish and Wildlife or the National Marine Fisheries Service (NMFS) may have roles in decision making.

It may become apparent after a cursory assessment of internal staffing resources that the USFS has neither the internal capacity nor the expertise to carry out the multiple functions of facilitator, decision analyst, technical data analyst and modeler, and stakeholder engagement specialist as described in this report. The USFS would need to assemble a team of external resources (the neutral support team described previously) early in the process to carry out the bulk of decision process tasks while the USFS maintains the administrative lead of the process. The expertise contained within the neutral support team could be augmented with expertise found locally: for example, that within agencies such as the USACE and the NMFS. They may help to develop the analysis methodologies and acquire data to ultimately compare decision alternatives.

Once the internal organization is established and the process team is in place, interested and affected parties need to be identified. Table 1.1 provides a good starting point for identifying such parties. The region's tribes, various state and local agencies (including emergency management and natural resource management agencies), representatives of business interests, and other interest groups in the region would be included among these. A hired specialist with expertise in stakeholder engagement (part of the neutral support team) may hold open houses to identify interests and those that should represent those interests as well as to develop a preliminary list of issues that will need to be considered when comparing decision alternatives. It might become more apparent through these engagements just how decisions made at Spirit Lake do ripple downstream and vice versa. This discovery process helps to set the bounds for the geographic scope of the decisions to be made.

Ultimately, the USFS and its neutral support team will build a diverse group of up to approximately 25 people representing the broad spectrum of federal, tribal, state, and local interests and management authorities that are willing to commit to the decision process (called the decision participants). Note that some organizations—for example, the USACE—could have staff in two functions; some staff would be part of the decision participants that represent USACE values. These will participate in value-based discussions. Different USACE staff might contribute to the neutral support team, providing unbiased technical assistance to the group of interested and affected parties as deliberations proceed. The neutral support team works at the behest of the decision participants, answering the questions, accessing data, and building models to aid the comparison decision alternatives by the group of 25. This two-way deliberation between the technical and the value-focused spheres is key to this process.

These early discussions to identify who should be involved in what ways is recommended so that the result is a better understanding of the interconnectedness of elements in the Spirit Lake and Toutle River system. This will help the decision participants appropriately define the scope and types of management actions that could be considered, including simultaneous changes to different elements of the built environment in the region (e.g., the tunnel, levees, the SRS), ongoing management actions (including dredging), and nonstructural actions (e.g., zoning changes).

consideration of the impacts of any management alternatives beyond 2035. Moreover, the USACE may only begin to consider such alternatives and their impacts in 2030. This planning horizon fails to identify how current decisions affect management and decommissioning impacts beyond 2035. The long-term risk and financial and other burdens to future residents and taxpayers may be left unaddressed (see Box 6.3 for greater detail). This issue was raised by an independent evaluation of the SRS project:

> *Using 2035 as the end year of analysis in the [USACE Mount St. Helens limited Re-evaluation Report] does not address the uncertainty surrounding sediment transport in the basin for the period beyond 2035 and may affect the economic and environmental results of alternative evaluations. . . . The Panel believes that the physical life of the project is of primary importance when considering the long-term effectiveness and the environmental consequences of the project. Therefore, discussion and evaluation of the alternatives for the period beyond 2035 should be provided for a more complete understanding of the longer term economic and environmental aspects of the alternatives and to support the selection of the recommended plan.* (Battelle, 2014: 6)

The USACE did investigate expanding the planning horizon beyond the authorization of the SRS to 2060 to identify how the decision process might change if the authorized lifetime of the project was extended (USACE, 2010a). The committee is not aware that such action has been taken.

Early on in the process, the decision participants described in Box 6.2 will need to consider time frames associated with the decision process itself (i.e., the time needed to gather necessary information); time frames associated with different natural hazards and processes; and time frames associated with infrastructure life cycles. They could be informed, for example, by presentations from experts in volcanic and seismic hazards to learn the probability of cataclysmic volcanic or seismic events over short and long time horizons. They may want to consider the time horizons that the chances of such events rise to near certainty and "reset" the system, as described in Box 6.3. Other

BOX 6.3
Additional Principles to Consider When Choosing a Time Frame

Explicitly identifying the planning horizons that affect interested and affected parties, and working toward a decision process that acknowledges and integrates the most essential of those planning horizons, will benefit the management process. In addition to those issues already described, the following are also worthy of special consideration:

- **The impact of decisions on future generations (intergenerational equity).** End-of-life plans for assets such as the SRS need to be included in the comparison of alternatives so that the financial, social, and environmental impacts on future generations are not overlooked. As an example, the lack of planning for the long-term removal of more than 1,300 aging dams in the United States has burdened current taxpayers by hundreds of millions of dollars (O'Connor et al., 2015). The largest of these cost $310 million to remove. If some alternatives in the Spirit Lake and Toutle River system add to or subtract from this retirement cost, then these impacts need to be captured in the comparison of alternatives. Retirement funds (Palmieri et al., 2003) might address this issue.
- **Short-term planning with long-term consequences (consideration of path dependency and reversibility).** Infrastructure planning often fails to include consideration of how decisions made today may affect or limit future alternatives or produce irreversible outcomes. Failing to properly value the ability to be flexible in the future while making decisions may result in the future inability of a major capital project to be responsive to change. Short-term actions affect long-term solutions, but long-term planning and adaptive management can be both financially and politically expensive.
- **Disturbances "resetting" the system.** Establishing planning horizons around the return frequencies of disruptive events large enough to completely "reset" the physical landscape may be appropriate in the Spirit Lake and Toutle River region. These natural events (e.g., volcanic or seismic) are so severe that they could destroy some or all the risk mitigation infrastructure in the basin. At this point, prior planning is irrelevant; a new plan, considering new alternatives, must be developed to reflect post-event conditions. From a decision process standpoint, the distinction between management alternatives becomes smaller as the likelihood of such events occurring in the time frame becomes more certain.

presentations could highlight which decisions need be made given asset life spans and other considerations. Explicit recognition of the trade-offs associated with the choice of different management time frames will also need to be presented.

Chapter 7 discusses the next steps of the decision process, which include identifying and choosing among the various priorities and objectives of interested and affected parties and the generation of potential sets of alternative actions.

CHAPTER 7

Identifying Decision Objectives and Alternatives

Once interested and affected parties have been identified and the smaller set of participants willing and able to work through a decision process has been established (as described in Chapter 6), the next task in the decision process is to clarify and structure a set of decision-specific objectives. Table 6.1 highlights the overlapping responsibilities and management objectives of agencies in the Spirit Lake and Toutle River system. Stated goals of the participants, however, do not align. In fact, when compiled, those goals may create a messy list of process concerns, positions, vaguely stated broad aspirations, and underlying interests. This chapter describes how the priorities and objectives of the different interested and engaged parties may be identified and organized and how metrics to forecast expected performance of those potential alternatives against those objectives may be derived. The discussion then leads to how the decision participants might start formulating a wide range of alternatives across the system to meet specific objectives.

THE OBJECTIVES

Decision objectives are the identified goals that are to be attained or accomplished through decision making (Keeney, 1988). They are always phrased as verbs with a direction—for example, to maximize economic well-being, or to minimize adverse environmental impacts—but they are only qualitatively defined until some metric (called an attribute in the language of decision theory) is assigned for their measurement. Objectives are linked to fundamental interests (Fisher et al., 2011) and provide the underlying motivations for participant positions on different management alternatives. Part of the process of identifying objectives is developing a common understanding of the motivations and priorities of decision participants. For instance, an objective that the committee heard repeatedly during public session meetings in Kelso was restoring the "naturalness" of the system. Like improving "sustainability" or "ecological health," restoring naturalness seems a worthy goal, but naturalness means different things to different people. The term sometimes seemed to refer to the ability of fish to migrate past the sediment retention structure (SRS) and into Spirit Lake. At other times the term seemed to be an appeal for "pristineness" in the Mount St. Helens National Volcanic Monument (the Monument) or to management solutions that require little human intervention. Since the term "naturalness" seemed to be an important issue cared about by many, further discussions to define the elements of a "natural" system are warranted to help ensure that decision participants share a common understanding of the term. Furthermore, this common understanding should be adequately reflected in the objectives hierarchy (discussed later) in a way that can be useful for comparing alternatives.

People often refrain from generating or considering important decision objectives if not prompted through a careful and structured elicitation (Bond et al., 2008). At the same time, broad conversations with the public might lead to an unmanageably large list of overlapping concerns that are a mixture of potential solutions, process concerns, or issues not related to the decision at hand (Gregory et al., 2012). The decision process should result in development of a complete, compact, and structured set of decision objectives that includes all the objectives identified by the agencies and other interested and affected parties. This list will serve as the basis for exploring trade-offs among decision alternatives later in the decision process. Since participants in these processes often do not come into the discussion with clearly defined values, the decision process should help participants iteratively construct and refine their values over time. The list of decision objectives will then need to be organized and structured.

Explicit elicitation of the participants' decision objectives helps to build trust in the process on the part of all participants. The subsequent sections provide guidance as to how a small group of interested and affected parties might develop a set of decision objectives related to managing catastrophic and chronic flood risk as well as sedimentation in the region.

Drafting Decision Objectives

If the purpose of developing a list of decision objectives is to help compare alternatives for managing flood risk and sedimentation, the planning objectives used in the U.S. Army Corps of Engineers' (USACE's) original plan (USACE, 1983: IV-11) might work as a starting point for discussion. Management alternatives could be compared based on how they impact

- Flood control, including both the risk of a catastrophic breakout of Spirit Lake and the chronic flood risk arising from sedimentation and high seasonal flows;
- Navigation;
- Water quality;
- Erosion;
- Fish and wildlife; and
- Maintenance of cultural resources.

Based on comments received from interested and affected parties during the committee's public meetings, this preliminary list might be elaborated to include

- Ecosystem services (e.g., reestablishing the pre-eruption landscape of the Toutle River);
- Cost, including both the expected cost to implement an alternative and the cost risk arising from an alternative not performing as expected; and

- Safety, including the operational safety of workers inherent in the different alternatives.

A list such as this could be a starting point for discussion, although its format is not useful for comparing management alternatives.

Ultimately, identifying a widely acceptable solution requires that each participant observe that his or her concerns are reflected in the group's decision objectives. Each agency should be able to trace some subset of the group's decision objectives developed within this process back to its own overall management objectives (i.e., such as those listed in Table 6.1). Similarly, nonagency participants should be able to do the same when reflecting back on their respective goals stated early in the process. From a process perspective, this provides a formal check that concerns are being heard and considered. The process requires consideration of each participant's concerns and objectives; it does not assume adoption of each participant's proposed solution.

The Objectives Hierarchy

The bulleted list of decision objectives above could be a starting point for discussion. As dialogue continues among the decision participants, however, a more refined and structured set of decision objectives should be developed. Decision objectives can be nested within an "objectives hierarchy" (Keeney, 1996), a method of organizing the objectives into a manageable format. An objectives hierarchy allows decision participants to better understand the relationships between specific goals. Participants create an objectives hierarchy by deciding which objectives represent the highest-level goals (i.e., minimize adverse impacts of erosion of the debris blockage) and which represent more detailed goals that are necessary to reach the highest-level objectives (e.g., minimize cost, minimize risk of a Spirit Lake breakout, minimize adverse impacts to downstream residents). Each of those subgoals can be further broken down into more subgoals. The relationship between objectives can be illustrated in a hierarchy such as the example in Figure 7.1. This committee developed this figure based

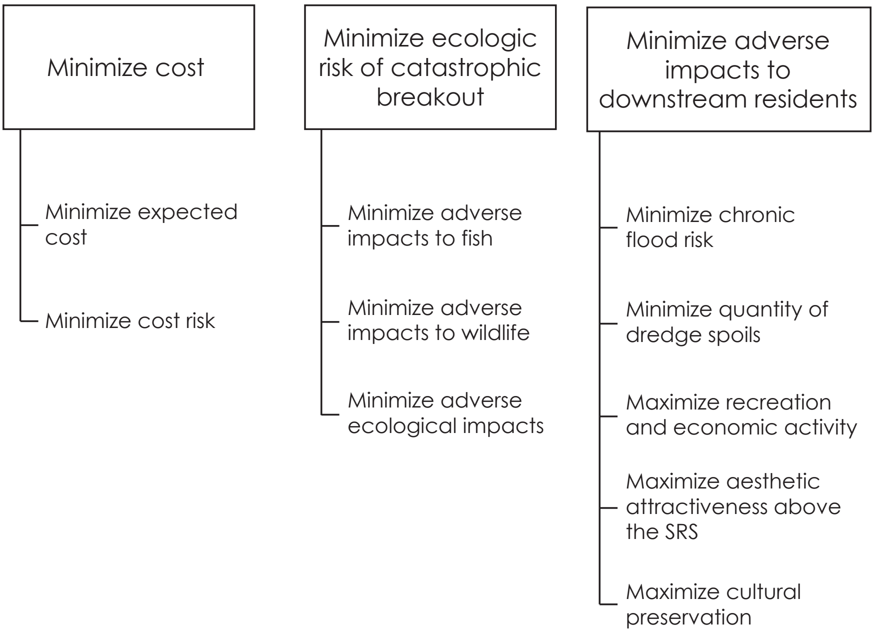

FIGURE 7.1 Example of a simplified partial objectives hierarchy. NOTE: This is only an example that might be developed and does not represent a recommendation from the committee. The objectives hierarchy resulting from an actual discussion will be different.

on individual opinions expressed during its public meetings in Kelso and on information published by the USACE: for example, see USACE, 1983 (section IV, 11-12). It represents only a small subset of high-level objectives and therefore should be considered rough and incomplete. The objectives in it, however, might be similar to those of a hierarchy developed for decisions related to control of water levels in Spirit Lake and the implications for erosion management.

The decision objectives are phrased and organized to clarify both the preferred direction of change (e.g., decreasing) and the subject of concern (e.g., cost risk). Tension may arise among participants because not all these objectives can be reached at their minimum or maximum levels, but the diagram could be used in later discussions about management alternatives and their consequences to determine how well those consequences align with decision objectives. This should aid the identification of a preferred alternative. More specificity can be included in the objectives hierarchy to differentiate how alternatives align with the various objectives. It might be desirable among the decision participants to include goals related to different fish species or specific impacts to fish above and below the SRS. Doing so may help participants understand how different decision alternatives will require certain trade-offs among the objectives.

Developing an objectives hierarchy is an iterative process. The exact wording of the objectives in the hierarchy will evolve with greater understanding of the relationships between management alternatives, their consequences throughout the system, and the objectives that matter to people. It is important to avoid premature comparisons of decision objectives because priorities among objectives are likely to shift as management alternatives are better understood. It is more useful to focus on creating a complete and compact set of clearly worded objectives and sub-objectives. While the objectives need to be designed with an eye toward highlighting future trade-offs, the comparison of objectives will be more productive when trade-offs associated with choosing among decision alternatives and consequences are explored (discussed later).

A structured objectives hierarchy needs to be organized into categories relevant to the decision at hand and meaningful to participants. Each participant's (and agency's) decision objectives should appear somewhere in the hierarchy and should be presented so as to be meaningful to all participants. Doing so is an important trust-building measure. The objectives hierarchy developed by the small group may be different in some respects from what would emerge from a benefit-cost analysis or other agency planning processes. Reconciling the results of this proposed objectives hierarchy and the objectives hierarchies used by other agencies is discussed briefly at the end of this chapter. Box 7.1 describes how decision objectives might be established for managing water levels at Spirit Lake.

BOX 7.1
Managing Spirit Lake Water Levels: Setting Decision Objectives

As the scope of the decision problem is defined, the U.S. Forest Service (USFS) and the facilitator and decision analyst on the neutral support team can begin to work with decision participants to develop a list of decision objectives. The decision participants may use the example of a simplified partial objectives hierarchy in Figure 7.1 as a starting point for discussion and consider whether such an objectives hierarchy could be used to compare system-wide alternatives for managing water levels at Spirit Lake. It might be agreed that the cost elements of the decision problem are adequately represented in Figure 7.1. All participants might agree that, all other things being equal, a less expensive alternative is preferable. The USFS member among the decision participants, however, might also want cost risk to be part of the decision framework because although their budget can be adjusted to fund different alternatives, once funding is in place it is difficult to obtain additional funds for unanticipated costs (e.g., emergency repairs). Therefore, the USFS may be interested in seeing alternatives less likely to require future emergency repairs.

The decision participants might also recognize that different outlet alternatives from Spirit Lake and different management regimes give rise to a whole host of issues in and around the lake and downstream (including downstream of a second tunnel, as discussed in Chapter 5, if that alternative is to be considered). Figure 7.1 would need to be amended to represent other hierarchies associated with those issues. Subgroups among the decision participants could be tasked with exploring these issues and developing a set of objectives and sub-objectives. Decision participants—led, perhaps, by local environmentalists and the U.S. Fish and Wildlife Service (USFWS)—might want to modify the middle column of Figure 7.1. For example, careful consideration of preliminary alternatives could lead the group to focus on an objective related to upstream fish passage. With technical input from the neutral support team, the decision participants might come to understand that upstream passage is only a means to a more fundamental interest of successful spawning, which itself is a means to the more underlying interest of overall fish survival and recovery.

When Is a Set of Objectives Complete?

Identifying the right number of discrete objectives is challenging, and there are no exact rules for doing so. It is possible to consider too few or too many objectives. Each decision process will result in a different number of objectives, and the objectives and their number will evolve as information is gathered and viewpoints are explored. The completeness of an objectives hierarchy might be gauged by considering a preliminary list of decision alternatives to the decision problem. When comparing alternatives, if no new decision objectives are raised by the interested and affected parties, then the list may be adequate. If new decision objectives are revealed, then additional work is needed to include the newly raised objectives into the hierarchy.

Choosing Metrics to Predict Performance Against Objectives

To define objectives properly, there is a need to determine by what means those objectives would be measured. Performance metrics can be chosen to measure the degree to which objectives are expected to be attained. Establishing such metrics gives decision participants a means to quantify a desired outcome so that expected progress toward or away from those outcomes can be modeled. Measuring expected progress is challenging, however. Metrics used by physical scientists and engineers to assess, for example, projected infrastructure performance will not necessarily measure progress with respect to decision objectives. Keeney and Raiffa (1993) note that there are many types of metrics and care is needed to select the appropriate metrics for each objective. Consideration of what is measured, where, and over what time frame is partially subjective and so requires both technical and nontechnical considerations. This allows easily overlooked links to be revealed and tested against the management alternatives and their impacts. Moreover, a deeper and more concrete understanding of what the pursuit of an objective may lead to can stimulate the search for new and creative solutions. This underscores the importance of using an iterative and broadly collaborative process. Metrics developed in isolation by technical experts may miss key elements relevant to decision participants.

Metrics used in performance forecasts need to capture what is expected to happen as well as the uncertainty associated with those expectations. The latter is usually expressed as a probability distribution over the scale of the metric. For instance, given one option, models might forecast that 500 fish of a specific species might migrate past a physical barrier in a specific amount of time—this is the expectation. The range of fish passing, however, may be 300 to 700 and expressed as a probability distribution over the scale of the metric.

When beginning to develop metrics, a deliberative discussion with participants could consider different kinds of metrics and how they perform under different scenarios that may be of interest. These discussions are both technical in nature and driven by the concerns of decision participants. Metrics need to be developed with explicit consideration of how they do or do not incorporate risk and attitudes toward risk.

Some metrics directly measure the consequences of interest in their own terms. These are considered measurements of "natural attributes" in decision science literature (e.g., Keeney, 1996). Reliance on natural attributes versus other types of metrics is, to the extent possible, desirable. As used here, the term "natural attributes" should not be confused with what natural scientists might use for characterization; rather, it refers to attributes that can be measured using the same units as those with which the objective might be expressed. An obvious natural metric for the maintenance cost of an alternative, for example, is dollars because there is a direct link between the metric (dollars) and the underlying objective (minimizing maintenance cost). Even in this example, however, care is needed since apparently "obvious" natural attributes might actually include hidden assumptions about participant values and priorities (NRC, 1996).

Using natural attributes as metrics tends to separate causal links from participants' values (Slovic, 2010). It is seldom the case, however, that all the important objectives have natural metrics. More typically, metrics are best stated as proxies (also known as indicators or correlates) for the consequences of an alternative, and still others might be represented on a constructed scale (see Box 7.2). For example, the area (e.g., acres or hectares) of accessible fish spawning habitat might be a useful proxy for

BOX 7.2
Ordinal and Constructed Scales

There are many cases in which metrics are needed but neither natural nor proxy measures are feasible. Generic ordinal scales (e.g., high-medium-low measures or 1-5 Likert scales) are too often used under these circumstances. Generic ordinal scales might be useful during early stages of deliberation when participants' understanding of the system is in development and diverse ideas are still being screened. Ordinal scales, however, are not sufficient for in-depth comparison or final selection of management alternatives. They fail to force the clear thinking and communication required to develop appropriate metrics, and they do not admit the common mathematical operations (e.g., addition and multiplication) required to apply decision weights (see the Chapter 8 discussion of trade-offs). As a result, opportunities are lost to build common understanding and insight both into how the system might respond to different management alternatives and how those responses align with what people value.

A more robust, albeit challenging, solution to capture hard-to-quantify impacts is to use constructed scales, so-called because they are constructed for the problem at hand. More specifically, a discrete level constructed scale would look like ordinal scales (e.g., high-medium-low, or 1-5), but the impacts for each level of the scale are defined with a succinct narrative that is relevant to the decision makers. As such, the qualitative details of what the different levels mean require in-depth discussion with participants and, potentially, subject matter experts.

Failing and others (2012) document a complex water management problem in British Columbia, Canada, where a set of constructed scales were developed to compare hydroelectric operations. Incorporating the values of the local indigenous peoples in the comparison of management options was critical. The constructed scales were based on the impacts to what Failing and others (2012) defined as learning, cultural quality, resource stewardship,

fish abundance since it is easier to measure area and that measurement is tied more directly to management alternatives. In another example, the probability of a catastrophic breakout of Spirit Lake might be a useful proxy for reducing various downstream impacts. This value might be more meaningful to participants and might be easier to measure while exploring management alternatives than to determine the myriad of downstream consequences that would arise from a breakout—even given that the downstream impacts may be what really matter to people in the area. Deliberaand other values. In that case, resource stewardship was broadly defined as a responsibility to manage the ecological health of the river system in a way that is sustainable and takes into account future generations. A discrete five-point scale was developed with decision participants that could help discriminate among the different solutions being considered:

Poor	*One or more of the key parties are not included in active participation and stewardship opportunities are limited.*
Fair	*All of the key parties are involved but stewardship opportunities are limited.*
Good	*All key parties are fully involved, and there are moderate opportunities for active stewardship by key parties and affected communities.*
Very Good	*All key parties are fully involved and there are significant opportunities for active and collaborative stewardship, but with limited long-term financial and institutional commitment.*
Excellent	*All key parties are fully involved, there are significant opportunities for active and collaborative stewardship, and there is a commitment to active and on-going oversight, monitoring, and capacity building.* (Failing et al., 2012: 5)

In the Spirit Lake and Toutle River region, interested and affected parties described a desire to restore "naturalness" in the system, but naturalness is defined differently by different individuals. A constructed scale could be developed and applied to measure the anticipated effects on naturalness of the different decision alternatives under consideration. Constructed scales such as these may be useful when comparing options that use difficult-to-measure decision objectives.

tive discussion among participants regarding proxies is vital; it is necessary to determine whether proxy metrics meet the needs of those comparing the alternatives. Deliberative discussion also stimulates the search for new and creative solutions.

Some metrics, such as flood damage, might be monetized. Flood damage may be translated from inundation depth and the number of structures impacted to an aggregated dollar amount. It may be desirable during a later step in the decision process to convert other impacts into dollars.

This would be done with input from the interested and affected parties and to the extent that this translation is found to be useful for comparing alternatives (see the later discussion of trade-offs).

Finally, progress toward certain decision objectives may be best tracked via constructed scales. Topics that arose during the committee's public meetings suggest that some people would compare management alternatives in ways that would be difficult to measure. For example, it is likely to be difficult to determine the extent to which management alternatives protect the "naturalness" of the Monument or the degree to which they may improve or promote collaboration among agencies.

Additional Considerations When Defining Metrics

Various issues that will likely require metrics were raised by interested and affected parties during the committee's open session meetings. Some are described briefly below. Many more topics will probably be raised during future decision making.

Restoring "naturalness." As already described, "naturalness" is defined differently by different interested and affected parties in the region. Participants will need to agree on a meaningful definition that is grounded in cause-effect logic. The definition will need to be expressed so as to be linked usefully to decision objectives and metrics. This might link naturalness to modeled or quantifiable estimates of fish and wildlife abundance, or it might develop a constructed scale.

Cost uncertainty. While expected costs have been used to characterize built management alternatives, cost uncertainty (also called cost risk) may also need to be addressed. A wide range of beliefs has been aired related to the future performance of the Spirit Lake tunnel (and therefore the need for and size of repairs) versus an open channel alternative (see Chapter 5). Decision participants may find that cost risk is an issue because of institutional barriers—sudden and unexpected repairs stress the USFS budgeting process. Deeper exploration of metrics might yield better understanding of the consequences of management alternatives, which, in turn, could inspire more imaginative management approaches to more directly address decision objectives.

Types of cost. Metrics for expected costs may require discussion among decision participants. Some interested and affected parties may place more importance on aggregate costs, while others may think in terms of present value costs. Because different agencies have different budgets allocated for different parts of the system (or different budgets for different mitigation drivers in the same part of the system), division of costs of various management alternatives among parties (and how they are tied to the intended mitigation) might also be of interest.

Adaptive choice. Metrics based on expected costs may be misleading if conditional choices are to be made over time. For example, it might be desirable to compare today's cost of raising the SRS spillway to the cost of a more adaptive approach such as dredging as needed until sediment loads reach a certain threshold before the spillway is raised. Comparing the expected cost of dredging versus a spillway raise without the application of appropriate metrics that capture the expected cost of the dynamic dredging options—using, perhaps, a decision tree, for example—will not capture alternative values of the dredging strategy and would also ignore the regret value of raising the SRS in advance of need.

Fish abundance. Objectives related to fish survival and recovery were repeatedly raised by interested and affected parties. These include the impacts of dredging on fish migration; potential for upstream migration past the SRS, through the sediment plain, and even into Spirit Lake; access to spawning areas (including tributaries that may or may not be cut off from the main stem through sedimentation); and possibilities for downstream migration through the sediment field. It is not apparent, however, that a system-wide assessment of the fish populations and the factors that affect them has been performed, let alone been translated into metrics useful for comparing alternatives. In a similar approach to that presented in Table 7.1, a first step would be to identify factors that impact fish survival and recovery on a system-wide basis and assemble them to compare management alternatives. This would require deeper deliberation to develop common understanding regarding the different dimensions of "fish abundance" (i.e., different individuals might equate population size, population productivity, or aggregate health of individual fish in a population as defining characteristics of fish abundance). If trade-offs are complex because there are different impacts in different locations for multiple management alternatives (e.g., raising the SRS spillway avoids dredging and therefore the associated negative impacts on fish downstream, but it blocks passage and inundates side channels above the SRS), then further work is needed to aggregate the impacts into one summary statistic that

TABLE 7.1 Screening Table for Alternatives and Their Associated Uncertainties.

	Closed Conduit (Alternatives 1-4)	Open Channel (Alternative 5)
Known engineering design and performance	Yes	No
Potential for mechanical failure	Yes	No
Outflow scales with inflow	No	Yes
Vulnerability to principal regional hazards		
Hydrologic	High	Moderate
Seismic	Low[a]	High
Volcanic	Low[a]	High
Geomorphic	None	Moderate to High
Time scales of recession post-hydrologic event	Weeks to months	Days
Time scale for intervention in the event of failure	Weeks to months	Hours to Days
Passes fish	No	Yes

[a]There are subtleties associated with a buried conduit that increase vulnerability to these hazards.
SOURCE: G. Grant, personal communication (November 1, 2016).

allows a comparison of management alternatives based on their overall system-wide impact on fish. This is likely to be a highly technical exercise (e.g., comparing the importance on overall fish abundance of spawning, rearing, and migration life stages). But this is also likely to be a value-laden exercise (e.g., determining which fish matter more and where). Care will be needed to structure the interaction between the technical analysis and the decision participants.

Wildlife habitat. Habitat above the SRS was frequently mentioned but rarely quantified. There are several countervailing trends, including loss of habitat due to the steady accumulation of sediment, the natural re-vegetation of areas impacts by the events of 1980, and the possible revegetation of portions of the sediment plain. Furthermore, habitats suitable for different categories of species (e.g., large mammals, birds, rodents) can be differently affected by decisions. Useful metrics would be species category–specific and would isolate the effects of management alternatives as opposed to natural trends.

THE ALTERNATIVES

The third step in a PrOACT-like process addresses alternatives. The goal is to craft multiple and diverse alternatives to address the management decisions at hand. This section will look at how this can be accomplished and describe how future management efforts might build on previous efforts. Management alternatives should be complete packages of actions or policies (i.e., a full system-wide strategy) put together in a way that addresses all the possible individual actions and policies available to decision participants within the scope of decisions being addressed.

A common mistake in decision making is to construct alternatives from a too narrow subset of possible actions, thus failing to represent a full range of possible solutions (Bond et al., 2008). One effect of constraining alternatives in this way is the tendency to miss interdependencies. This mistake is reflected in past decision documents in the Spirit Lake and Toutle River region. For example, as mentioned earlier, the original USACE plan (1983) included alternatives to manage Spirit Lake levels as well as alternatives to manage sedimentation in the system. While it was recognized that these two management levers could be interdependent (USACE, 1984a), analyses presented in the documents treated them as independent; each set of alternatives was treated separately. The opportunity to formulate and evaluate management alternatives recognizing interdependence was missed. It is often the tendency of individual agencies to concentrate on actions that are possible within their respective authorities whereas representatives of the Cowlitz Indian Tribe, the community residents, and other interested and affected parties may be interested in a more holistic management of the challenges that affect the entire system, as expressed during the committee's open session meetings in Kelso.

Possible actions and policies should be bundled into system-wide alternatives so that their full impact and interrelationships can be assessed. Such an approach will capture the important impacts of, for example,

- Spirit Lake water level management alternatives on the risk of catastrophic breakout through the debris field;
- Spirit Lake water level management alternatives on sedimentation rates at and below the SRS;
- Spirit Lake, SRS, and dredging alternatives on fish survival and recovery; and
- Spirit Lake and SRS alternatives on wildlife from Spirit Lake to the Cowlitz River.

This list captures some issues that are apparently secondary to the primary issue of preventing a catastrophic breakout of Spirit Lake. It might be argued that the prevention of a Spirit Lake breakout is so overwhelmingly important as to make connections to secondary issues irrelevant. Even so, it is helpful to include these secondary issues to avoid derailing decision processes when participants feel that their concerns are being ignored and potential solutions to address them are being dismissed. Inclusion of apparently peripheral issues creates a means for agencies to engage with interested and affected parties on the "primary" issues being addressed.

Broad inclusion of interested and affected parties when creating decision alternatives potentially improves decision quality (NRC, 2008), avoids an overly narrow scoping of alternatives (which can preclude buy-in from a broad audience), and possibly contains and resolves debate over the feasibility of alternatives so that outcomes are mutually satisfactory.

It is useful at this stage of the decision process to be deliberate about why various alternatives are being considered. Broad and creative thinking imposes a process burden (e.g., time and other resources) on the decision lead and participants, and pushback can be expected if alternatives seem unrealistic. Nevertheless, systematically and inclusively identifying alternatives can, at different phases in the decision process,

- Build trust among participants;
- Inform all engaged about modeling processes and system behavior given different management alternatives;
- Help participants better understand the relationship between participants' decision objectives and what is possible to change through management; and
- Drive participants toward a solution.

Just as it is important to collaboratively identify decision objectives and their metrics, it is important to develop the list of alternatives through a collaborative process for many of the same reasons. A level of engagement consistent with the "involve" or "collaborate" levels of participation explicitly includes a commitment to incorporate other participants' ideas in the generation of alternatives.

Generating Common Understanding About Alternatives

The need for common understanding of the decision problem and objectives extends into the next phase of the decision-making process. For example, the expressed desire for a "more natural" way to manage Spirit Lake water levels may be at odds with potential engineering solutions for the control of water in Spirit Lake as described in Chapter 5. Some participants at the committee's open session meetings discussed their understanding of the benefits of the open channel alternative to control Spirit Lake water levels. There seems to be a divergence between what advocates believe a functional, reliable permanent open channel solution would look like (i.e., a "natural" part of the landscape) and the possible reality of a less maintenance-intensive and more robust solution with predictable performance (i.e., an engineered spillway). There is a substantive knowledge gap regarding practical design issues that needs to be resolved before trade-offs can be considered between the open channel alternative and other alternatives. A concerted effort is required to create common understanding and agreement about performance characteristics and design goals (e.g., a more natural landscape). There may even be trade-offs to consider among high-level goals. This may require a smaller deliberative process to design one (or several) open drainage alternative(s) that then informs system-wide considerations.

A Broad Range of System-Wide Alternatives

A system-wide approach for making decisions is described and recommended in this report. This involves thinking about how all the natural and built elements of the Spirit Lake and Toutle River region might contribute to or be affected by any given alternative. Different kinds and possibly combinations of coordinated management actions and policies may result in the most realistic, cost-effective, and sustainable solutions. When considering any decision in the system, it is important to consider all components of a system-wide solution and to generate alternatives that include

- capital works (multiple and perhaps redundant ways to manage water levels at Spirit Lake);
- operational changes (including lowering Spirit Lake, different approaches to dredging);
- emergency response plans (including a road to ensure full-time access to drainage works, automating gate operations, enhancing downstream emergency management systems); and

- mitigation measures (e.g., levees, managing dredge spoils, property buyouts).

No single agency can shoulder the responsibility for all the management actions required, so explicit consideration of what agency or organization will be responsible for what actions needs to be made.

Alternatives Over Time

A systems approach also requires understanding system response over time. When generating alternatives, consider whether actions are necessary only once or are more dynamic and adaptive and based on a sequence of conditional decisions. When the SRS was first planned, the USACE chose a staged approach to future management (USACE, 1983). A sequence of spillway raises was not originally part of the plan, but that possibility became feasible when the probable maximum flood was downscaled in the early 2000s. Such an adaptive approach (given that the existing plan is truly adaptive and responsive to conditions) should also be considered among the alternatives for current and future spillway raise decisions at the SRS, where low-cost dredging alternatives might be explored before undertaking the next spillway raise—given the cost and likely irreversibility of the decision. Note, however, that these alternatives have implications across the system and across steps in the decision process. Where there are dynamic, adaptive management steps that can be taken, taking the expected value of the criteria must account for dynamic choices. Ignoring this modeling requirement means that the expected values will miss alternative value (the benefit of delaying a decision) and regret value (the lost benefit from making a decision too soon) and potentially lead to the wrong policy conclusions.

The Number of Alternatives

Taking a systems approach to management requires developing strategies that consist of one or more actions, addressing multiple goals, and considering all beneficial and adverse effects, both individually and in aggregate. Whereas thinking creatively about all aspects of the system at once can lead to creative solutions, it may also lead to an unmanageable proliferation of alternatives. There are constructive ways to limit this process, and collaborative deliberation guided by a decision analyst can help to negotiate these. Examples are provided below.

- A collaborative participatory process may, in a purposeful manner, screen those alternatives that are obvious nonstarters for participants. The fatal flaws associated with those alternatives need to be carefully communicated so the reasoning behind their removal is understood.[1] A mistake here is to prematurely eliminate alternatives best dealt with during later deliberations of trade-offs.
- Deliberation might reveal those specific actions or policies that could be decided on independently of other choices. These can then be added back into discussions as constants across system-wide alternatives.
- Strategy tables (Gregory et al., 2012), such as the hypothetical example shown as Table 7.2, are visualization tools that can be used to effectively manage the number of possible solution sets when there are a large number of decision elements.
- A careful review of decision objectives can be useful in guiding the generation of alternatives.

There is a tendency for alternatives to be adjusted from some base case or starting point. This may preclude consideration of some viable alternatives that are substantially different from that starting point. In the behavioral decision literature, this is called the anchor-and-adjustment bias (Kahneman and Tversky, 1982). On the other hand, alternative creation can stall when it becomes a mechanical working through of all possible permutations and combinations of decision elements. Using decision ob-

[1]In its review of the raising of the SRS, Battelle [2014] noted that it was not clear why some alternatives were eliminated from consideration.

TABLE 7.2 Hypothetical Example of a Strategy Table[a]

Spirit Lake Levels	Other	Spirit Lake Drainage Alternatives	SRS Alternatives	Dredging Alternatives	Other
Maintain current operating regime	Build access road to intake	Rehab tunnel	Remove	Dredge in Toutle as needed to maintain current flood protection	Raise levees at XX, YY
Reduce max height to XX	Automate gates	Covered conduit	Lower spillway by 7′	Dredge in Columbia as needed to maintain shipping	Do ZZ with emergency management system
Reduce max height to YY	Clear logs from lake	Open channel	Maintain current spillway elevation		
Permanently drain Spirit Lake	Reinforce log boom by intake	Alternate drainage tunnel	Raise spillway by 13″		
		Pumping station	Remove upstream migration impediment for salmon		
		Pumping station on standby			

NOTES: Blue squares represent a primary set of alternatives associated with one possible strategy; red squares represent the alternatives associated with a second strategy. Contents of table represent examples and not recommendations.

[a]In its review of the raising of the SRS, Battelle [2014] noted that it was not clear why some alternatives were eliminated from consideration.

jectives to drive the creation of alternatives can help navigate between these two extremes. Referring back to the examples of draft decision objectives described in the previous section, this process could consider

- A solution that minimizes the risk of a catastrophic breakout from Spirit Lake;
- A solution that minimizes overall cost;
- A solution that maximizes the "naturalness" of the system (if this decision objective is carried forward by decision participants);
- A solution that minimizes the negative impact of sediments; and, perhaps,
- A solution that maximizes the abundance and diversity of fish and wildlife populations.

While this set of alternatives may not contain the solution settled on ultimately by decision participants, these might serve as preliminary bounds for an otherwise almost limitless decision space, constraining the search for the best solution and perhaps yielding surprising insights that can be built upon to create a final, broadly acceptable solution. Box 7.3 provides a list of questions that decision participants should consider as a group when developing their list of alternatives.

In a strategy table (e.g., Table 7.2), one alternative might address the desire for a more "natural" solution by selecting an open channel and a lower SRS spillway level. This alternative is a package of all these alternatives—that is, the various actions required throughout the system to implement a specific strategy—selected at once, as shown by the blue solid circles above. A second strategy (highlighted with red boxes) could be minimizing sediment migration. In this case, Spirit Lake is drained to a lower level, an alternate drainage tunnel is chosen that does not discharge into the Toutle River system, and current dredging practices are continued in the lower river. Whether or not this idea is acceptable depends on how this package of alternatives, as modeled for the combined impacts across the whole system, compares to the performance of other packages of alternatives given the chosen decision objectives and metrics.

BOX 7.3
Creating Alternatives for Managing Spirit Lake Water Levels: Questions for the Decision Participants

Decision participants will move from creating objectives, objective hierarchies, and metrics to forecast performance against those objectives toward considering what actions across the system can be taken to meet those objectives. Experts in decision analysis, stakeholder engagement, and group facilitation who are part of the neutral decision support team (see Chapter 6) might help the decision participant group assess the appropriateness of their alternatives through questions such as:

- Do the alternatives, as a collective set, address the objectives of interested and affected parties? New and innovative alternatives may be derived through consideration of the decision objectives. Has each interested and affected party seen its interests addressed to at least some degree in at least one alternative?
- Were the alternatives developed with input from interested and affected parties? Deeper levels of engagement include opportunity for input from interested and affected parties during creation of alternatives. This increases levels of trust, enhances the development of a complete set of alternatives, and encourages buy-in of the final decision among interested and affected parties.
- Do the alternatives strategies consist of full and complete sets of solutions for the system (as opposed to individual actions taken on system elements)? Does each clearly specify what is (or is not) to be implemented in all areas of the system where changes could be made? A strategy table (e.g., Table 7.2) is useful to encourage system thinking and completeness.
- Have interdependent elements of the system been identified and included together as sets (e.g., if an objective is to encourage fish passage to Spirit Lake, have options that enhance passage past the SRS and options that include fish passage into Spirit Lake been linked)? Similarly, have independent elements of the decision (e.g., the ones whose implementation would not move toward or away from the stated objectives) been separated to simplify analysis?
- Have any alternatives that are dynamic (i.e., dependent on system response over time) been adequately described?

A strategy table is a useful tool for creating a mental model to compare the individual actions required to implement a given strategy with the actions embodied in other strategies. The table provides a visual image that may be helpful for narrowing strategies. A strategy table applied in a real-world setting would probably include more elements than appear in Table 7.2 and, as such, is likely to be more practical once the number of alternate strategies to be considered has been reduced.

CHAPTER 8

Decision Consequences and Trade-Offs

Following the development of a suite of alternatives, it becomes necessary for decision participants to develop a complete understanding of the impacts of those alternatives and then to begin the process of determining which set of alternatives provides the best solution that is supportable at some level by all decision participants. This chapter begins with a discussion of understanding consequences, capturing uncertainties, avoiding over-conservatism, and using a tool called a consequence table. The second half of the chapter discusses how the alternatives can be negotiated through, for example, identifying those that best meet stated objectives, refining metrics to better understand consequences, and clarifying the rules of decision making. By the end of the chapter, the reader will be at least familiar with the analytical-deliberative process. The chapter concludes with a brief discussion of PrOACT-like (Problem, Objectives, Alternatives, Consequences, Trade-offs) processes as compared to existing agency processes.

WHAT ARE THE CONSEQUENCES?

Consequences are the impacts of alternatives as measured by performance metrics. Each measurement reflects a with/without assessment (the value of each performance metric with the alternative, minus its value in the absence of the alternative). In many cases, the performance metric is defined such that it has a zero value when the alternative is not implemented.

Care is needed in eliciting information and opinions regarding relationships between underlying physical processes and performance of different policy alternatives. Relationships may be misstated due to individual perceptions and potential mistrust among agencies and interested and affected parties. There may be a wide range of beliefs concerning a number of key underlying physical processes such as

- limiting factors for fish abundance and
  - the ability of fish to migrate past the sediment retention structure (SRS),
  - the ability of fish to pass through the sediment field above the SRS, and
  - the impacts of dredging on aquatic habitat and fish migration;
- limiting factors for increased dredging capabilities, including
  - where spoils can be put,
  - acceptance of local residents to the placement of spoils,
  - impact of dredging on listed species migration, and
  - the ability to secure environmental permits in a timely manner;
- long-term performance of the tunnel, including
  - seismic withstand, and
  - the ability of tunnel to perform given the underlying geologic composition and dynamism of the surrounding rock;
- operational risk arising from tunnel repair closures;
- volume of material transfer from debris field, including whether the long-term trend of sediment migration is constant or declining;
- susceptibility of an open channel solution to downcutting from erosion;
- calculations of a Probable Maximum Flood (PMF); and
- magnitude of the 100-year flood.

Resolving the list of uncertainties in an environment where some participants cite low trust in other participants is daunting. Nevertheless, scientific complexity is not a barrier to a successful participatory process. Increasing the participatory nature of processes adds to the quality of the analysis (NRC, 2008).

Influence diagrams, developed through discussion with decision participants, can clarify cause-and-effect relationships among the issues being considered. An influence diagram lays out how the system works. For example, the U.S. Army Corps of Engineers (USACE) highlighted "erosion" as a planning objective (USACE, 1983). Figure 8.1 is a simple influence diagram that shows how the rate of sediment production might be linked to other factors. An influence diagram is an outline of the "physics" of the system that clarifies the cause-and-effect pathways.

Capturing Uncertainty

Alternatives identified on the left-hand side of the influence diagram in Figure 8.1 cascade to a spectrum of potential outcomes or consequences on the right-hand side. To be useful in decision making, the consequences on the right-hand side must be measured along the scales of the metrics

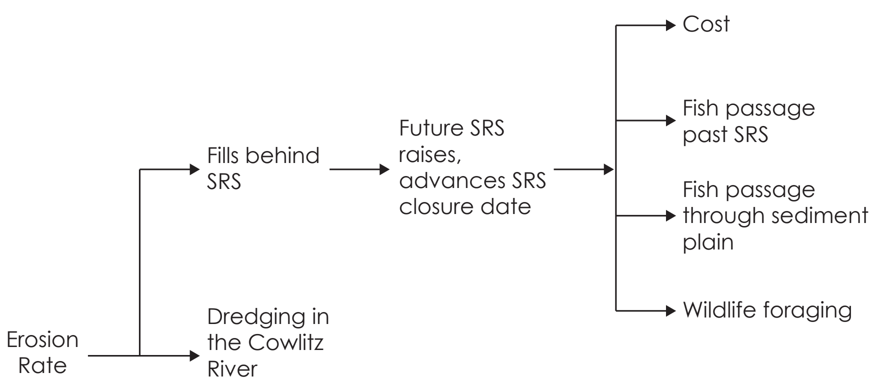

FIGURE 8.1 A simple influence diagram showing how the erosion rate of sediment might be linked to specific phenomena. Detail in this example is provided for only one phenomenon; others would also have to be diagrammed. NOTE: This diagram does not represent a recommendation; the resulting diagram following an actual discussion may be different.

associated with the chosen objectives. The predictions of these consequences within the context of the influence diagram are usually uncertain; therefore, they are expressed as probability distributions. For each of the decision alternatives there is a set of probabilistic forecasts expressed over each of the metrics associated with each of the objectives. These uncertain but quantitative forecasts of consequences related to each of the many objectives form the basis for decision.

A standard approach for capturing uncertainty (Morgan and Henrion, 1990) involves

- Modeling consequences using midpoint or best estimates to start;
- Identifying parameters (or hypotheses) that drive uncertainty and varying these in a sensitivity analysis to understand which uncertainties may significantly affect the decision. This will highlight where work to reconcile conflicting expert opinions is needed (Gregory et al., 2012);
- Testing the impact of key uncertainties, perhaps through analysis of scenarios created jointly with participants, so that the range of uncertainties is captured. These might include expected conditions, a 100-year inflow, a PMF, a moderate seismic event, and a moderate volcanic event; and
- Developing probability distributions for a manageable number of key uncertainties, either through historical data, modeling, or expert elicitation (Burgman, 2015), and building these into a model to show the relevant distribution of possible outcomes. This will highlight the key uncertainties and decision drivers.

Table 7.1 is an example of the first steps of this process where the robustness of alternatives is explored qualitatively against individual hazards (Grant, personal communication, November 1, 2016).

Where deviation from the expected case is large enough to rearrange the ranking of alternatives, additional work is needed to model the uncertainty and to characterize it in ways that assist the participants in understanding trade-offs. In particular, Table 7.1 indicates that additional work is needed to aggregate different sources of risk into one overall measure that captures overall risk of a Spirit Lake breakout. The general public, decision participants, and policy makers will not have the technical background to combine these different sources of risk. Yet this information is critical to developing an understanding of how the different alternatives perform in preventing a catastrophic breakout. It is up to technical specialists working with the decision participants to finish this task.

Avoiding Over-Conservative Assumptions

It is a common mistake to build an element of risk aversion into analyses by using "conservative" modeling assumptions. Such assumptions may take the form of using the worst plausible case for negative outcomes as has been done where the USACE assumes a "no decay" time path of sediment erosion—the highest rate of erosion from several possible hypotheses (Britton et al., 2016b). Others may advocate the use of "safety margins" or engineering judgment to exaggerate possible negative consequences. The use of conservative modeling assumption should be avoided because

- Attitudes toward risk vary among individuals, and building risk aversion into the modeling step requires value judgments to be made on behalf of other participants. These may not be transparent or appropriate for all interested and affected parties.
- Attitudes toward risk can be thought of as the willingness to trade off more certainty for less certainty. Because of this, these attitudes are best captured in assessing trade-offs.
- Being "conservative" along one dimension (e.g., a more robust infrastructure design to improve safety) often means being profligate along another dimension (e.g., higher cost). Again, this trade-off needs to be highlighted and examined, not made implicitly and invisibly during the modeling process.

Using Consequence Tables

In an iterative, collaborative, and deliberative process, it is useful to list and organize each management alternative and each decision objective in a manner that allows the performance of the objective to be seen. A tabular display of this relationship is called a consequence table. Table 8.1 is an example of such a table, adapted from a water management study in British Columbia, Canada (Gregory et al., 2012). In the illustrated case, decision participants sought a solution for conflicts among decision objectives related to generating power, avoiding floods, and enhancing ecological values. This table is likely to have more compact than would a consequence table developed for the Spirit Lake region for comparing system-wide alternatives for managing water and sediment.

Development of a consequence table is a key milestone in the decision process. Because it is built jointly through deliberation among decision participants (who are themselves interested and affected parties), it becomes an important element of a valuation framework. Building a consequence table is an iterative process, and early versions may require heavy revisions to capture information properly. The ultimate goal is a table that is noncontroversial—that is, participants should see their decision objectives, measured in ways that are both rigorous and meaningful to them and, perhaps, used to evaluate alternatives they helped to develop. The process of developing a consequence table helps the group create legitimacy of subsequent decisions among themselves and with a broad group of interested and affected parties. Box 8.1 provides examples of past communication of comparison of management alternatives for the Spirit Lake and Toutle River region. The methods used may not always have been conducive to public support for management decisions.

Comparison of alternatives remains difficult, however. Developing a colored, interactive consequence table can be helpful. Important to this is the concept of Minimum Significant Increment of Change (MSIC) (Gregory et al., 2012). MSIC refers to a pragmatic estimation of the precision of each measurement approach used to populate a consequence table. For example, if the precision of financial models does not allow distinguish-ing among estimates that are within $1 million, then the MSIC for those financial measures will be $1 million. Alternatives within that range will be considered as equivalent.

The color scheme in Table 8.1 is not a simple high-medium-low risk ranking; rather, the color indicates a relative measure of the different alternatives with respect to the alternative being used as a point of comparison. The point of comparison is indicated in blue. Red cells in a particular row indicate alternatives with measures that are worse than the blue point-of-comparison cell; conversely, green cells indicate alternatives with measures that are preferable. A cell with no color indicates those alternatives with measures that are roughly equivalent (within the MSIC) to the blue cell. An "H" in the "Direction" column indicates that higher numbers (in this particular case) are preferable for a particular measure. "L" indicates lower numbers are preferable. (An interactive spreadsheet allows this basis of comparison to be changed during discussion.) This interactive visual tool is an excellent aid for exploring how management alternatives align with the decision objectives of the participants. This information may be used to rule out alternatives and criteria that are not key to the decision so that the group can focus on the main decision drivers.

It is important to have a technical discussion about the precision of data being used early in the decision process. The discussion is meant to focus participants on data that potentially drive decisions rather than on data differences that are inconsequential from a technical point of view. The discussion should be neither a value discussion nor a judgment on the importance of the decision objective to which the data relates. The relevance of this discussion becomes more clear later in the decision process when metrics (and decision objectives) that have similar measurements (i.e., within the MSIC) across alternatives can be set aside since they do not help to distinguish among alternatives. This early technical discussion can help to discourage later value-laden heated discussions over differences that are inconsequential from a technical point of view. It also provides a solid basis of understanding for discussions regarding the trade-offs across consequences among wider groups of interested and affected parties.

TABLE 8.1 An Example Consequence Table for Comparing Options[a]

Objective	Performance Measure	Units	Dir	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 8
Minimize Flooding									
@Lower Bridge River	Flood Frequency	# days/yr	L[b]	1	1	0	0	0	0
@Seton Reservoir	Flood Frequency	# days/yr	L	6	6	6	6	6	6
Maximize Fish Abundance									
@Carpenter Reservoir	Fish Index	1-100	H[c]	69	70	41	41	29	29
@Downton Reservoir	Fish Index	1-100	H	42	71	48	69	65	69
@Lower Bridge River	Fish Index	1-100	H	100	100	100	90	25	10
@Seton Reservoir	Fish Index	1-100	H	66	66	66	66	33	10
Maximize Water Quality									
@Seton Reservoir	Water Suspended Solids	Tonnes/yr	L	94	89	77	84	108	78

Maximize Vegetated Area									
@Downton Reservoir	Weighted Area	Hectares	H	223	231	322	313	295	300
@Carpenter Reservoir	Weighted Area	Hectares	H	759	522	758	520	602	600
Maximize Power Benefits									
Maximize Power Revenues	Revenues	Levelized $M/yr	H	141	145	146	149	144	145

[a]Blue represents the point of comparison; red indicates alternative measures significantly worse than blue; green indicates alternative measures significantly better; no color indicates no significant difference.
[b]L indicates lower numbers are preferable.
[c]H indicates higher numbers are preferable.
SOURCE: Modified from Gregory et al., 2012.

BOX 8.1
Communication of Management Alternative Comparison in the Toutle River Region

Comparisons of management alternatives for the Spirit Lake and Toutle River system have been presented in a variety of ways, and there is a need for significant improvement in communicating alternatives and consequences to interested and affected parties. Several examples illustrate this point:

- The matrix used to compare alternatives for managing Spirit Lake water levels in the original management plan (USACE, 1983) was formatted with alternatives as row headers and criteria as column headers. The estimated impacts were reported on a 1-6 scale (including estimated implementation costs), however, leaving some key calculations incomplete (e.g., total cost, total risk of breakout). Interestingly, a different approach was used when alternatives were compared in an alternatives strategy document (USACE, 1983). The 1-6 scoring system in the matrix was replaced with paragraph-length descriptors for each entry.
- Comparison of alternatives was not done in a multiple-objective matrix format in the comprehensive plan to manage sediment (USACE, 1983). Despite the report explicitly highlighting a number of planning priorities, only the costs of the sediment retention were highlighted when comparing different strategies to manage sediment transport. The sensitivity of those costs, however, was presented in a table format.
- Alternatives for raising the SRS spillway were presented using a prose discussion of impacts (USACE, 2014) describing good and bad features. Comparison of consequences was difficult. For instance, the presentation of costs separately made it difficult to ascertain the incremental cost for incremental sediment capture between any two alternatives.
- The 2016 potential failure mode analysis described by Grant and others (2016b) explains alternative strategies for managing Spirit Lake water levels and also presents alternatives using extended prose descriptions of good and bad features, again making it difficult to apply the decision objective metrics across alternatives. (Note that Table 7.1 was not part of the 2016 report but was presented to the committee during an open session.)

Representing Uncertainty in Consequence Tables

Decision analysis practitioners have not developed a comprehensive approach to representing uncertainty in a consequence table (Gregory and Keeney, 2017). If a key trade-off decision hinges on a risk-return consideration, a quick shortcut is to use the expected outcomes (e.g., the 50th percentile measure of a forecast impact) and some statistic of a downside outcome (e.g., the 10th percentile statistic of a forecast impact) as different line items in a consequence table. In the hypothetical example shown as Table 8.2, alternative 2 appears to deliver a much larger amount of habitat, on average, than does alternative 1. According to the chosen statistic, however, alternative 2 also delivers much less spawning habitat once every 10 years. Choosing between alternatives 1 and 2 requires considering the relative importance of average versus downside impacts. Presenting this type of trade-off and talking about sensitivity to downside risk could be an important line of inquiry in a deliberative process. This discussion can improve understanding about why different parties hold different views on the alternatives; about how susceptible the decision objective in question is to the occasionally poor outcome; and, perhaps, about how to identify ways to modify the otherwise preferred alternative to mitigate these rare occurrences.

TABLE 8.2 A Hypothetical Example of Higher Cost Versus Higher Certainty Trade-off

Objective	Sub-Objective	Metric	Alternative 1	Alternative 2
Maximize Fish Abundance	Maximize expected usable Spawning habitat	Ha[a] (P50)[b]	100	200
	Maximize spawning habitat in low water years	Ha (P10)	50	20

[a]Ha = hectare.
[b]P is the annual probability.

This approach is a substitute for generating a higher-quality inquiry. But it does not fully represent uncertainty because it only looks at two parts of a broader distribution. Alternative 2 may also have a large but unlikely upside potential that is ignored by this shortcut. Gregory and Keeney (2017) correct this theoretical gap by developing, for each decision participant, a single certainty equivalent that reflects that individual's risk preference. The certainty equivalent is the guaranteed amount that an individual would consider equivalent to a given distribution of uncertain amounts. The certainty equivalent differs from the expected value of the distribution according to the risk preference of the individual. A risk-seeking person would have a certainty equivalent greater than the expected value, while a risk-averse person would have a lower certainty equivalent (Raiffa, 1997).

Participants develop the certainty equivalent through a structured discussion. Clemen and Reilly (2014) take this a step further by estimating, through a structured gamble exercise, a risk-aversion parameter for each individual so that uncertain outcomes can be translated mathematically into a certainty equivalent. These more theoretically consistent approaches suffer a similar drawback, however. They greatly increase the process burden, as each decision participant must develop a unique consequence table tailored to reflect his or her unique attitude toward risk. Whether or not this incremental level of effort is warranted depends on the situation.

Helping decision participants collaboratively explore multiple alternatives when there is significant uncertainty across multiple objectives is inherently challenging. Attempts to fully incorporate uncertainty can easily lead to an unwieldy and contentious set of deliberations. Nevertheless, upfront transparency regarding the available tools, coupled with an explicit effort to match the techniques to the needs of the participants, can only add legitimacy to the process.

WHAT ARE THE TRADE-OFFS?

Identifying and closely considering trade-offs is the last step of the decision process. It is useful at this point to recall that the overall purpose of the process is not to find some objectively defined optimal solution, but to find the best solution that is supportable at some level by all the decision participants. In most cases, this support hinges on participants' awareness and acceptance of various trade-offs. Box 8.2 provides illustrative examples of some trade-offs that might be considered in the Spirit Lake and Toutle River region. As noted earlier, a common mistake in collaborative decision making is to prioritize objectives too early in the process (Keeney, 2002). Attempts to do so before decision objectives and their metrics are clarified and consequences are calculated will result in discussion at a level that is too high to uncover and resolve differences. For example, asking a participant in the Bridge River water management process highlighted in

BOX 8.2
Examples of Trade-Offs That Might Be Considered for Management of the Spirit Lake and Toutle River System

Based on input received by the committee during public session meetings, some anticipated trade-offs might be

- Downstream sedimentation versus the "naturalness" of the drainage system;
- Cost versus catastrophic flood risk, particularly if the decision process includes consideration of multiple and redundant engineering solutions to managing Spirit Lake water levels;
- Sediment retention versus fish recovery;
- Sediment retention versus wildlife recovery;
- Fish populations downstream of the SRS versus fish populations upstream of the SRS (but only if participants see this as an important trade-off instead of seeing the abundance of the aggregate fish population being of primary importance);
- Short- versus long-term actions and consequences, particularly if it turns out that the system is likely to "reset" itself every few decades (e.g., through seismic or volcanic activity). Some management interventions may look different over shorter time frames but similar over longer time frames.

This list is illustrative only, put here to demonstrate the type of trade-offs that could surface at this point of the decision process.

Table 8.1 to prioritize too early among flooding, water quality, and wildlife habitat on the Carpenter Reservoir would have generated an answer, but one that was not grounded in any substantive knowledge of those issues in that particular decision context.

An effective decision process is based on the recognition that people develop their decision objectives and priorities as they deliberate and learn in a complicated, novel context (Slovic, 1995). People do not know at the outset how their values interact with what can be changed on the system nor how changing the system leads to intended and unintended impacts to the things they care about. The trade-off step is about exploring that decision space; looking for insights into how values are affected by the way in which the system reacts to changes; and looking for mutually advantageous solutions or, at least, solutions where important gains for some decision participants can be found without too much sacrifice of the interests of other participants.

Developing consequence tables was discussed in the previous sections. The next sections describe practical steps through which decision participants may be led to ultimately highlight the important trade-offs among a small number of alternatives so that a decision may ultimately be made.

Eliminating Dominated Alternatives

Pairwise comparisons of all the alternatives can show how they perform against each other. If an alternative is dominated—that is, not better than any other alternative with respect to all metrics, and worse with respect to at least one metric—it can be eliminated from further consideration. The application of this principle highlights the importance of including all relevant and significant metrics in the consequence table, lest an alternative be dropped prematurely.

Refining Consequence Metrics

Entries in a consequence table should reflect the best available knowledge and science. An early consideration of trade-offs in an iterative deliberative process, however, can focus attention on greatest additional data needs.

Early in the process, before substantial investigation into all the performance metrics and consequences, some metrics will likely be based on judgment. These might have been represented in the consequence table with "yes-no" or "high-low" entries. If there are comparisons between alternatives where most consequences point to a dominant relationship except for one or a few judgmental entries, then the possibility of refining those entries must be considered. Even a modest refinement, such as replacing a "high-low" scale with "high-medium-low," may allow the alternatives to be ranked. If so, there may be no reason to seek further refinement of the ordinal scale. Otherwise, the process must iterate back to the development of more substantive and quantified metrics to better inform what is being gained or given up in the trade-off. Even well-researched and quantified metrics may need to be refined if deeper questions regarding those metrics surface during trade-off discussions. Again, this would lead the group to iterate back to refining the metrics and reestimating the consequences.

It is important that any revision of metrics and consequences be entirely transparent and based on either newly available data or a more intensive analysis of existing data. Revision of prior judgmental metrics is generally to be avoided, as it may be viewed as self-serving or strategic on the part of the agency or the individual responsible for the judgment. This can quickly lead to an erosion of trust among the participants.

Eliminating Uninfluential Criteria

Some consequences brought forward by the decision participants may turn out to be of little importance for the decision at hand. The MSIC value (defined earlier) may be an indication of whether a particular metric can be ignored in decision making. Note the important process implications here: a decision objective and metric were put into the consequence table because one or more of the decision participants believed they were important factors when comparing alternatives. A careful consideration of the underlying impacts, however, could reveal that those factors, while still important to some participants in a general way, can be set aside because they no longer help distinguish among alternatives. An example of this is in the colored consequence table (see Table 8.1). Because the consequences for power generation are roughly equivalent across all alternatives in that table, the group can conclude that this factor is not relevant to the decision. It must be emphasized that this is not a value judgment, but rather a technical one. Yet this technical judgment can reframe the problem in a powerful way, perhaps even helping to unlock a potentially deadlocked set of deliberations.

There is also an important communication element here. If this issue was important to the decision participants, then it is likely that it will be important to those outside the process as well. Communications regarding the process and its conclusions will need to include a careful justification for excluding the metric: explanation as to why it was initially included and what changes occurred that led to its later removal.

Monetizing Metrics

If after eliminating alternatives through the steps above it is still not possible to unambiguously rank alternatives, the next step could be to monetize certain impacts. In the example consequence table (see Table 8.1), only the power benefits are defined in monetary units. Some metrics in the table may not be amenable to monetization, but this is not always the case. For example, there are well-established methods for monetizing flood damage or recreation experience, and doing so may be a helpful way to simplify the consequence table and to clarify the comparison of alternatives to allow ranking.

Monetization methods include market-based valuation (e.g., travel cost analysis, hedonic price analysis), nonmarket valuation (e.g., contingent valuation, conjoint analysis), and benefit transfers. Yet, any valuation of this type should be performed carefully using the best available methods and data. Valuation techniques inject uncertainty into a process that is already characterized by considerable uncertainty. The analyst must be aware of the trade-off between additional information and increased uncertainty.

The move to monetize some impacts is suggested late in the decision process. Retaining the consequences in their natural units as long as possible is important in a decision process such as PrOACT for two reasons. First, monetization of consequences can be controversial, and doing so before mutual trust has developed may undermine the legitimacy of the decision process. Second, leaving consequences in their natural units until consideration of trade-offs increases the opportunity to align understanding of consequences and participants' decision objectives. This can lead to the development of new and creative alternatives. Aggregating consequences into a monetized sum of costs or benefits too early may derail this learning opportunity (Gregory et al., 2012).

Comparing and Combining Objectives

Recall that the goal of this exercise is not to find a single best solution but a solution that is widely acceptable to the decision participants. A collaborative participatory process that includes building a consequence table and applies a structured approach to explore value trade-offs can often identify such a solution. Some have likened this final step to multiparty negotiation (Bourget, 2011). New insights may be used to refine alternatives and generate large gains to one set of interests with only small losses to other interests. Presumably, participants will agree to an outcome if there are greater benefits to doing so than not agreeing. Successful application of these ranking and weighting methods can occur only when a high level of trust exists—whether present at the outset of the process or as a result of the process.

In certain cases, it is possible that a thorough qualitative examination of trade-offs does not generate an obvious mutually acceptable solution. There still may remain a large number of alternatives or trade-offs across a large number of objectives with no single dominant alternative. In these cases, a more structured method may allow participants to think more rigorously about the relationships between their objectives and the alternatives. A structured elicitation and application of decision weights built on a multiple attribute utility theory (MAUT)—for example, swing weighting[1]—has been used in other applications to break a deliberation impasse and reach a mutually agreeable solution (Keeney, 1988). While the swing weighting approach is built on and consistent with the theory of consumer choice as found in any microeconomics textbook, it is not an optimization process that generates the best answer based on objectively defined decision weights. Rather, it is a values-insight exercise that elicits decision "weights" from each individual. There is no need to reach agreement on these decision weights; each individual's weights give rise to an individual's rank ordering of the remaining alternatives. Based on these, the search for a commonly supported alternative can continue. Table 8.3 presents the same information shown in Table 8.1, but it highlights the range (from worst to best) across which the decision objectives are affected by the alternatives under consideration. Presented with the information in this way, a decision participant may move from a positional approach for comparing alternatives and instead may focus on their underlying interests. As an example, the participants can see that the effect of the various alternatives is that flooding in the lower Bridge River may range from zero to one day per year. This information could make it easier to prioritize among their decision objectives.

Individuals' decision weights are tied to their personal values. As such, there is no "correct" answer, and weights are likely to vary from person to person. Guidance can help people construct their values around these difficult and novel considerations. For instance, when considering how to trade off X million dollars against some benefit (say, reduction of flood risk, or improvement of riparian habitat), a useful threshold question to ask is whether similar benefits can be achieved at a lesser cost through action in other parts of the system. A useful comparison question to ask is how other people value similar trade-offs. A useful substitute question to ask

[1]Swing weighting is one of several methods for deriving weights for objectives, allowing performance against multiple objectives to be aggregated and management alternatives to be ranked. Weights for each objective are derived based on the range of worst to best outcome (the "swing") across the alternatives. Following a process of normalization and determination of the relative value of the swings, weights are assigned to the objectives, where the objective with the potential to produce the greatest increase in overall value receives the largest weight (Belton and Stewart, 2002).

might be regarding other benefits that could be "purchased" with that same amount of money—either through different management options within the Toutle River system or through considering hypothetical options across society writ large.

If uncertainty is an important component of understanding trade-offs, it will also need to be addressed in this. This could be done by translating uncertain consequences into their certainty equivalents: for example, by using approaches described by Gregory and Keeney (2017), Clemen (1996), or Runge and others (2015). A unique set of consequence tables like Table 8.1 would be developed for each decision participant and the swing weighting could be carried out for each individual to help rank alternatives. As with all these tools, it is necessary to maintain communications with all decision participants to explicitly test whether the extra process burden is worth the resulting insights it could reveal.

It is important for participants to know that these valuation tools do not supplant decision making; rather, they help participants gain additional insights into their decision objectives that otherwise might be obscured by the multiple-objective decision making in a complex management system. Hobbes and Horn (1997) demonstrated how a divergence between "gut" level choices and those derived through swing weighting can be a source of additional value-insight. Building this exploratory step into the process could enhance the legitimacy of surprising swing weighting outcomes should they occur.

While the decision framework is described in a linear way, it can be iterative when insights gained at one step lead to revisiting previous steps. The need to revisit previous steps might be recognized when participants recognize data gaps as they try to balance consequences across management alternatives, when they recognize certain metrics need to be refined before consequences can be prioritized, or when they conclude that more creative thinking needs to be put into developing alternatives. Being able to answer the questions found in Box 8.3 positively is a good indication that the process is sufficiently mature. Given that the decision processes have to be completed in a finite time, however, it is important to have a common understanding of when deliberation can continue and when a final drive for

TABLE 8.3 Consequences, Swing Weighted from Worst to Best

Swing Weighting								
Sub-Objective-Level Swing Weighting								
Objective	Sub-Objective	Performance Measure	Units	Dir	Worst	Best	Rank	Weight
Minimize Flooding								
	@Lower Bridge River	Flood frequency	#days/yr	L	1	0		
	@Seton Reservoir	Flood frequency	#days/yr	L	6	6		
Maximize Fish Abundance								
	@Carpenter Reservoir	Fish index	1-100	H	29	70		
	@Downton Reservoir	Fish index	1-100	H	42	71		
	@Lower Bridge River	Fish index	1-100	H	10	100		
	@Seton Reservoir	Fish index	1-100	H	10	66		

Maximize Water Quality								
	@Seton Reservoir	Water suspended solids	Tonnes/yr	L	108	77		
	Maximize Vegetated Area							
	@Downton Reservoir	Weighted area	Hectares	H	223	322		
	@Carpenter Reservoir	Weighted area	Hectares	H	520	759		
Maximize Power Benefits								
	Maximize Power Revenues	Revenues	Levelized $M/yr	H	141	149		

SOURCE: Gregory et al., 2012.

BOX 8.3
Negotiating Trade-Offs for Decisions Related to Managing Spirit Lake Water Levels: Questions for Decision Participants

The ability to negotiate trade-offs and compromises will be due, in large part, to the success of the neutral decision support team to make sure that a shared understanding exists among all decision participants of the information and ideas that have been discussed to date. Being able to answer the following questions positively will set up the decision participants to come to a decision that represents the best solution that is at least somewhat agreeable to all parties.

- Are the positive and negative aspects of each alternative adequately highlighted?
- Have the trade-offs among alternatives been portrayed in a way that is understandable and useful to interested and affected parties (e.g., by using a colored consequence table [see Table 8.1])?
- Does the process appropriately explore the value trade-offs (i.e., compromises) inherent in choosing one alternative over another? Has the role of individuals' values been explored explicitly in this consideration?
- Was adequate time allotted in the decision process to use insights gained through exploration of value trade-offs to cycle back to
    - Develop new and better alternatives?
    - Focus additional data gathering in the short term?
    - Structure longer-term data gathering?
- If there are complex trade-offs that include multiple options and multiple conflicting decision objectives, has a structured approach such as swing weighting been used to help interested and affected parties construct their values around these complex and novel trade-offs?

a solution should be made. It is at this point that decision rules developed early in the decision process become important.

Clarifying Rules of Decision Making

Clarifying the rules of decision making in advance is an important early process design step (NRC, 2008). Deliberation until consensus is reached is sometimes stated as a decision rule., but this may give too much sway to holdouts or extreme views as discussions move toward closure. A decision rule might be adopted that does not allow a single dissenting view to block closure but does allow two or more to do so. An alternative approach is to have consensus as a goal, but not a requirement. In absence of consensus, participants (agencies and nonagency participants) can fall back to smaller coalitions (or to themselves in the most extreme example) and the statutory powers they hold. Failing and others (2012) have found that this decision rule can be useful for contentious, multiparty water management issues. In their case, participants were asked to rate the final alternatives via the following scale:

- Endorse (participant fully supports the alternative)
- Accept (the alternative meets participant's minimum needs, but with the following reservations…)
- Block (the alternative does not meet the participant's minimum needs)

Failing and others defined "consensus" as an alternative that was not blocked by any participant. Agencies, in particular, may still block an alternative as required by their individual regulatory or legislated roles. Short of blocking an alternative, however, this format allows participants to state their concerns and reservations without standing in the way of reaching an agreed-upon outcome. In fact, these formally stated reservations may form the basis of discussion regarding monitoring, adaptive management triggers, and the conditions of future reviews.

COMPATIBILITY OF A PROACT-LIKE PROCESS WITH AGENCY PROCESSES

Determining whether the decision framework recommended in this report is better than another framework, or no framework at all, requires that the framework be decomposed into its overarching elements of organized participation and the integration of science. An examination of public participation in environmental assessment and decision making (NRC, 2008) found empirical support for application of certain basic principles. With respect to organizing participation, inclusiveness of participation, collaborative problem formulation and problem design, transparency of processes, and good-faith communication were all found to be important. Whereas the committee recommends more inclusiveness in participation than has occurred in the past in this region, it also suggests there is a practical upper limit to inclusiveness. This suggestion expands beyond the principles as described by the NRC (2008). With respect to integrating science into the process, the NRC (2008) found support for iteration between analysis and broadly based deliberation dependent on the availability of decision-relevant information; explicit attention to facts and values; explicitness about analytic assumptions and uncertainties; independent review; and reconsideration of past conclusions. The committee's recommendations are consistent with these principles.

Whether a process similar to PrOACT is better than some alternative for structuring the analytic content of public participation is difficult to assess. The decision process described in this report draws on real-world experience as well as current understanding of how people make decisions in complex and unfamiliar situations. It is designed to avoid common errors in decision making such as overlooking relevant facts, failing to properly communicate analytical results to all participants, or failing to account for the role of participants' values in interpreting analytical results. A PrOACT-like process recognizes the potential for such errors and provides ways to avoid them.

A second line of evidence could be whether a PrOACT-like process outperforms other types of decision frameworks. There is some experimental evidence to show that a value-focused approach for managing environmental risks (in this case, water management decisions) leads to better outcomes than do approaches that are driven from simply comparing alternatives without a PrOACT-like framework (Arvai et al., 2001).

There is a broad alignment between the steps laid out in a PrOACT-like process, those in a USACE planning process, and a document prepared to comply with the National Environmental Policy Act, with perhaps a bit more granularity given by the five steps of the PrOACT framework. Given these similarities, following the recommended decision framework will not preclude also satisfying individual agency planning processes. Moreover, the information generated through the early steps of a PrOACT-like process can be used to support very dissimilar approaches. For instance, the information contained in a consequence table would also be collected at an interim step through a traditional benefit-cost analysis, where the impacts of the different alternatives would be tracked to the end points of interest.

CHAPTER 9

Applying the Decision Framework

The preceding chapters focus on the distinctive characteristics of the regional and institutional settings that make long-term management decisions for the Spirit Lake and Toutle River system challenging and then describe a framework for decision collaborative and analytically informed decision making that could be applied in the region. Chapter discussions describe hazards within the region and their potential effects on engineered works, downstream communities, and regional ecologies. The committee describes good management and decision-making practices and synthesizes key requirements for implementing those practices in boldface statements, each labeled "recommendation." Box 9.1 lists those recommendations. As required by the statement of task (see Box 1.1), the committee also identifies management alternatives and describes gaps in existing data. This final chapter focuses on how the committee's recommendations might be implemented in a way that fully addresses current and future challenges.

The recommendations in Box 9.1 highlight the need to account for system-wide impacts of both short- and long-term management decisions rather than focus on just one element of management (e.g., Spirit Lake water levels) or a particular engineered work (e.g., the drainage tunnel or the sediment retention structure [SRS]). The report recommends that agencies and other interested and affected parties develop a shared understanding of the broader system, the alternatives for managing the system, and the ways in which those alternatives can be expected to affect the system. Additionally, the report suggests broadening and deepening the

BOX 9.1
Report Recommendations

The committee's Statement of Task (see Box 1.1) calls for the recommendation of a framework for making decisions about the long-term management of the Spirit Lake and Toutle River system. A decision framework has been detailed in Chapters 6-8. In addition to recommending a decision framework, the committee synthesized the many findings and conclusions found throughout this report into eight recommendations, listed below in the order in which they appear. They are described more fully in the chapters indicated parenthetically following each recommendation.

> Recommendation: Responsible agencies and other interested and affected parties should **develop a common understanding** of the Spirit Lake and Toutle River system, its features, hazards, and management alternatives. (**Chapter 3**)
>
> Recommendation: Agencies engaged in risk management in the Spirit Lake and Toutle River region should **develop a coordinated and targeted monitoring system** to track changes in factors that affect risk. Data and analyses should be shared and made available to all. (**Chapter 4**)
>
> Recommendation: Alternatives for managing the Spirit Lake and Toutle River system should be **judged over both short and long time frames** to ensure consideration of the range of the concerns of interested and affected parties. (**Chapter 5**)
>
> Recommendation: **Operational risk should be explicitly considered** when evaluating alternatives for management. (**Chapter 5**)

processes through which all interested and affected parties can participate in decisions regarding future management options—processes that must take into account engineering constraints and issues, stakeholders' competing interests, and public concerns. Robust monitoring systems and the sharing of data among parties with a stake in the management of the system are recommended so that management decisions are informed by a common understanding of the factors that affect the system. Whereas many may view these recommendations as "common sense," they do not

Recommendation: **Adopt a deliberative and participatory decision-making process** that includes technical considerations; balances competing safety, environmental, ecological, economic, and other objectives of participants; appropriately treats risk and uncertainty; and is informed by and responsive to public concerns. Dialogue among interested and affected parties and technical experts should be iterative, begin with the formulation of the problem, and continue throughout the decision process. (**Chapter 6**)

Recommendation: **Create a system-level entity or consortium of agencies to lead a collaborative multiagency, multi-jurisdictional effort** that can plan, program, create incentives, and seek funding to implement management solutions focused on the entire Spirit Lake and Toutle River system. This effort should also be open and accountable to interested and affected parties involved in management decisions. (**Chapter 6**)

Recommendation: **Broaden and deepen the participatory decision-making process from its earliest stages** to include and assimilate the knowledge and interests of affected groups and parties whose safety, livelihoods, and quality of life are affected by management decisions. (**Chapter 6**)

Recommendation: **Engage in system-wide thinking** when making decisions about management objectives, approaches, and alternatives for the Spirit Lake and Toutle River system. Depending on the issues being considered, the system may include the Cowlitz River or extend beyond it. (**Chapter 6**)

represent how elements of the Spirit Lake and Toutle River system have been managed in practice.

A certain sense of urgency regarding the Spirit Lake outflow tunnel exists given the present need for further repairs. The committee recognizes that some management decisions, such as those related to the tunnel, may need to be made before all the recommendations in this report can be fully implemented. Whereas the decision framework provided in this report is intended to be applied to future decisions for the entire system, early decisions can still be consistent with the general principles underlying the framework. Specifically, consideration can be given to how various management alternatives may affect present and future management of Spirit Lake as well as other parts of the system. As such, a two-phase process for implementing the recommendations can be envisioned. The initial phase involves a focus on the immediate challenges associated with Spirit Lake. This focus would include identifying and engaging interested and affected parties to inform and be informed by the analytic and decision-making processes suggested in Chapters 6-8. The decision-making group put together for this first phase of decision making might be a nascent form of the decision participant group that later fully realizes the implementation of the decision framework. The second phase would be focused on system-wide decision making and fully take into account upstream and downstream conditions, potential impacts, and affected parties.

CHANGING MIND-SETS

The volcanic, seismic, and meteorological setting of the Spirit Lake and Toutle River system has created a region subject to steady and rapid physical change punctuated by periodic cataclysmic events such as the 1980 eruption of Mount St. Helens. That eruption created a new physiographic normal for the people and wildlife in the region. Such cataclysmic events are recurring phenomena for the region, even if unknown to the region's European-American settlers before 1980. The huge volumes of materials deposited as a result of the eruption dammed Spirit Lake with the debris blockage and literally reshaped the Toutle River and downstream river valleys. Residents today grapple with the risk of a catastrophic breakout of the debris blockage and of more regular flooding caused by increased sediments in the system. These risks are consequential—potentially affecting life and safety—and cannot be truly "fixed." The probability of a catastrophic event related to one of these hazards in the future is non-negligible.

Management of the region since the 1980 eruption was first guided by emergency response and then by disaster mitigation. Whereas the dangers posed by natural hazards still exist, other consequences—such as those related to ecological conditions, economic interests, or recreational opportunities—also concern the community. If there is a desire to be responsive to the priorities of the region's interested and affected parties, than those other priorities cannot be ignored. Recognizing the various risks and their relationships to community priorities may be a first step in understanding the Cowlitz Indian Tribe's concept of "living with the volcano" (see Box 3.7). Quantifying risks, assigning metrics to values, and developing a common understanding of all this information could help those in the region develop a mind-set that allows them to learn how to live with the volcano, the river, local and regional seismicity, and other hazards. Looking forward, it will need to be determined whether engineered interventions applied to date offer enough protection to justify the benefits and consequences obtained.

Elected officials have delegated the authority, mechanisms, and resources to manage the individual elements of the Spirit Lake and Toutle River system to different agencies. Few of those authorities, mechanisms, and resources have been granted in a manner that allows coordinated management among them, even when several elements are managed by the same agency. Management is often at cross-purposes with the needs and priorities of at least some interested and affected parties. The analytical-deliberative decision process described in previous chapters provides guidance on how beneficial and broadly acceptable management actions might be identified and agreed to.

Decision participants, with the help of their neutral decision support team (Chapter 6), can use the decision process to identify, collect, and analyze the data needed to quantify risks, identify system problems, identify multiple objectives of interested and affected parties, as well as find sets of actions that could address the many elements of the system. The consequences of those sets of actions can be analyzed. With that information, the necessary trade-offs made by those with different resources and priorities can be agreed upon and a set of alternatives chosen. The alternative actions may be in the form of new infrastructure or changes to existing infrastructure; they may be operational (e.g., lowering lake levels or dredging); and they may be nonstructural (e.g., buyouts and zoning requirements). Given that infrastructure has been built that has itself wrought substantial changes in the environment, a systems approach will likely involve a combination of all these types of actions. Many decisions applying the framework can be carried out through existing authorities and resources. All the same, other decisions will likely require action by elected officials. In the latter case, convincing evidence will have been collected as a result of the framework and can be presented to elected officials to support requests for authorities or resources. Because the decision process is largely evidentiary and based on analyses of data, it provides a comprehensive body of evidence to support decisions made at legislative levels.

SYSTEM THINKING

There is no returning the Spirit Lake and Toutle River system to a "natural" condition as long as people choose to live in the region and use the region's resources. Given the choice to live there, decisions were made to manage sediments and the debris blockage, inevitably reducing the "naturalness" of the system. Rising recognition of the multiple objectives and additional priorities beyond safety means that management decisions become increasingly complex. Decisions about different elements in the system can no longer be made in a geographic and policy vacuum: the impacts to the whole system of management activities in any one part of the system must be understood. Moreover, those impacts must be understood over a variety of timescales of interest.

It could be argued that the choice of constructing the Spirit Lake tunnel and the SRS merely delayed the inevitable transfer of sediment from the headwaters of the Toutle River at Spirit Lake through the Toutle River to the Cowlitz and Columbia Rivers and that perhaps a different mind-set than has heretofore been applied is required to manage sediments. Long-term management solutions might seek to facilitate an orderly transfer of sediment through the entire system in ways that also promote desirable long-term ecologic conditions, economic goals, and public safety. Meeting the long-term goals may require considering those issues needing short-term solutions as well as recognizing that different interested and affected parties may have different planning time horizons in mind. Well-trained, skilled facilitators might help decision participants work through these differences. Trade-offs will always be necessary, but fewer benefits will be realized if changes are made absent a common understanding among interested and affected parties about how the system operates at many geographic and temporal scales. Developing strategy tables (e.g., Table 7.2) are useful for comparing multiple combinations of actions and can be modified to represent activities over space and time.

FIRST STEPS

A first step in the recommended decision-making process described in Chapters 6-8 is to identify the lead party responsible for initiating a formal decision process (see Chapter 6). For purposes of this discussion, the committee assumes that the U.S. Forest Service (USFS) will lead the earliest stages of the process given the agency's authority over Spirit Lake, the tunnel, and the surrounding area. The USFS will need to liaise with relevant agency and government bodies to explain the decision process and generate enthusiasm for it. This may mean one-on-one work with these other organizations to walk through the proposed decision process and could include a demonstration of how a PrOACT-like (Problem, Objectives, Alternatives, Consequences, Trade-offs) process operates, how it fits with overlapping regulatory responsibilities, and how it leads to better decision making for the system. The participation of a decision analysis facilitator in these early meetings would be beneficial. Whereas the USFS will likely be the agency to initiate the process, as decision making evolves and matures, the role of lead for any specific decision should be decided collaboratively.

For a decision process to be perceived as legitimate by interested and affected parties, the lead must be accepted as an "honest broker" whose interest is in seeing a fair, even-handed process implemented in a technically competent manner. The lead should not be seen as dominating the process. This implies, among other things, that the lead has knowledge and experience in the practical application of the decision analysis concepts needed to coordinate the implementation of the decision framework in an objective, transparent, and disinterested fashion. These skills may be present in the lead agency, or an outside agent may be identified to serve as an independent coordinator as part of the neutral decision support team (also described in Chapter 6). Important but perhaps not obvious areas of expertise that need to be included as part of the neutral support team are provided in Box 9.2.

As described in Box 6.2, the USFS, with the help of the neutral support team, will assume initial responsibility for identifying and convening the group that represents both agency and nonagency interests and concerns for the entire system and over time. This is the group of up to approxi-

BOX 9.2
Selected Skills of the Neutral Support Team

The success of any planning effort depends on the skills of the cadre of individuals who direct, organize, and carry out the various activities that result in the final plan. The lead agency will need to assemble a number of distinct skill sets as it prepares to walk through the decision framework as recommended in the preceding chapters. Along with specific technical skills, other necessary skills include:

- Decision analysis capabilities. This includes expertise with the standard set of analytic tools in the field as well as a successful record of working with diverse groups of people from a variety of backgrounds—from agency technical experts to laypeople.
- Facilitation skills. Any value-based discussion that includes balancing competing interests across parties requires a skilled facilitator at the front of the room to handle impassioned participants. Ideally, the same person will have both the "soft" people skills and the "hard" decision analysis skills, but often these sets of expertise need to be hired separately and their work efforts coordinated carefully.
- Stakeholder engagement skills. These include the ability to identify various interested and affected parties, to engage with them, and to find a way to satisfy the broad need for information sharing while addressing the narrower need to populate and run a number of smaller but more in-depth discussion sessions. There may be up to a dozen such sessions over the span of several years depending on the ultimate scope of the decision problem adopted.

mately 25 decision participants discussed in Chapter 6. This group may be established to make the initial decisions regarding control of lake levels, but it may also be similar to the group that will make future decisions for the system as a whole. With input from other interested and affected parties, the lead will cast a wide net in seeking parties to participate in this earliest implementation of the decision framework. Box 6.2 provides guidance about determining who might be involved in what ways.

With input from the newly convened group and its neutral support team consisting of those with appropriate technical, facilitation, stakeholder engagement, and decision analysis skills, the lead should decide on the best means for applying the decision framework to the problem at hand (e.g., Spirit Lake), with consideration given to the priorities of all interested and affected parties (see Box 7.1); to hazards inherent in the system (see Chapter 4); and to an understanding of the system-wide consequences and operational risks of the various management alternatives considered (see Chapter 5). For these early considerations, the lead will need to compare the relative urgency of the problem to the amount of time needed to understand potential solutions in deciding how best to apply the decision framework. It may be most informative, for example, to conduct workshops designed to elicit input from interested and affected parties.

While this report has highlighted a number of information gaps, it is not envisaged that a large data collection effort is needed in advance of initiating the decision process. The experience of generating and comparing alternatives and their consequences, highlighting value trade-offs, and interacting with interested and affected parties can be expected to refine and augment data needs. On the other hand, however, some data needs are fundamental to any planning process (e.g., monitoring data). These collection efforts should be started early enough so that the results are available when needed.

Estimating Cost

Planning management actions using any planning protocol has a cost; therefore, early in the process some idea of planning cost will need to be considered. Costs of technical analyses represent one type of estimating problem, while costs of managing a participatory process are another. Calculating cost if the entire effort can be performed "in-house" is different from calculating cost when contractors are used for some or all activities. Combined with the lack of advance knowledge of the exact structure of the planning effort and its scope, these factors argue against an attempt to develop a budget based on a detailed cost estimate of the planning process.

Alternatively, one could investigate the cost of comparable planning activities: ideally, those that have used PrOACT-like processes, or at least analytical-deliberative approaches. Still, it is difficult to find directly comparable applications. The Spirit Lake and Toutle River system is similar to the applications of PrOACT-like processes described in Chapter 6 in that there are multiple agencies with overlapping jurisdictions; other interested and affected parties with lesser decision-making influence; large, but perhaps not completely defined, geographic boundaries for the problem; and multiple ways of defining the scope of the problem needing to be addressed. But the Spirit Lake and Toutle River system is notable for the number and extreme magnitude of the natural hazards as well as for the potential diversity of capital works as solutions to the decision problem. These are important distinctions even without considering which efforts have been performed in-house or with contractors.

An approach that might be taken to develop budget estimates for a Spirit Lake and Toutle River application is to assume programming on a level-of-effort basis—that is, budget estimates will be made for the activities expected for the first year to get the initial level of effort. That budgeted effort may then be adjusted from year to year as the work progresses.

IMPLEMENTING THE FRAMEWORK

This report has noted that long-term management of the regional system encompasses a complex set of interrelated issues over time, for which there may be no single "best" solution and about which no single entity has the authority to make decisions. The USFS and the U.S. Army Corps of Engineers have jurisdiction over parts of the system, while tribal, state, and local entities have their own authorities, and the private sector and public at large also have a stake in decisions made in the broader region. Safety, ecological, cultural, and quality-of-life issues for current and future residents are among the important factors.

Several caveats are needed at the outset of the decision process. First, it will be necessary to identify funding as soon as possible to initiate decision-making activities. The most pressing issues will require funding more immediately, and continued funding will be needed to support longer-term decision making associated with system management. Detailed discussion of levels and sources of funding, however, is beyond the scope of this report. Second, as indicated throughout the report, a number of data needs must be addressed, and doing so should begin as soon as possible if the viability of long-term management strategies is to be analyzed in the near future. Third, it is likely that some type of interagency agreement will be needed to overcome what the committee sees as policy impasses regarding system management. An interagency agreement will help ensure continued active participation of relevant agencies going forward.

The dispersion of decision authority in the region is a fundamental challenge to implementing the recommended decision framework. Given the lack of an explicit governance structure for management of Spirit Lake and the Toutle River basin as a system, no single federal agency has the budget, authority, or capability to lead a system-wide planning and decision-making process as described. Similarly, no single agency can be solely responsible for implementing any of the preferred system-wide management alternatives. Some coordinating mechanism is needed among responsible agencies to identify management strategies that allow agencies to effectively carry out their respective missions and to engage with the concerns of other interested and affected parties in the region. Without some sort of long-term external influence to encourage and compel the needed coordination, individual agencies may not be able to manage the system in a coordinated manner. Thus, the committee recommends the creation of a system-level entity or consortium to lead the effort. This entity would be responsible for managing a collaborative, multiagency, multi-jurisdictional process than can plan, design a program, create incentives, and seek funding to implement management solutions. The planning effort should also be open and accountable to all interested and affected parties. Such a body might inform and influence existing authorities and political leaders of the need to fund, coordinate, and develop system-wide risk management programs and plans, and then be responsible for regularly reporting about management decisions and the decision-making process to all interested and affected parties and members of Congress.

Establishing such an entity requires resources and authority beyond that held by any existing agency with management responsibility in the region. Authority for such an entity would likely have to come from Congress. Lack of such an entity, however, does not preclude the implementation of the decision framework recommended in this report. With or without such an entity, those with decision-making authority may still apply the principles of collaborative engagement to inform an analytic-deliberative process.

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APPENDIX A

Biographical Sketches of Committee Members

Gregory B. Baecher (NAE) is the Glenn L. Martin Institute Professor of Engineering in the Department of Civil and Environmental Engineering at the University of Maryland, College Park. His primary area of expertise is in infrastructure protection with particular concern to waterways. His research also focuses on geoenvironmental engineering, reliability and risk analysis, and environmental history. Dr. Baecher has served on various National Research Council committees, including the Committee on Water Security Planning for the Environmental Protection Agency and the Committee on Science and Technology for Countering Terrorism. He is a past member of the Water Science and Technology Board. He was elected to the National Academy of Engineering in 2006. He received his B.S. in civil engineering from the University of California and his M.S. and Ph.D. degrees in civil engineering from the Massachusetts Institute of Technology.

John Boland is an engineer and economist and is professor emeritus in the Department of Geography and Environmental Engineering at Johns Hopkins University. His fields of research include water and energy resources, environmental economics, benefit-cost analysis, and public utility management. Dr. Boland has studied resource problems in more than 20 countries, has published more than 200 papers and reports, and is a coauthor of two books on water demand management and three more on environmental management. He has served on several National Academies of Sciences, Engineering, and Medicine committees and is a founding member and past chair of the Water Science and Technology Board. Dr. Boland received his B.S. in electrical engineering from Gannon University, his M.S. in governmental administration from The George Washington University, and his Ph.D. in environmental economics from Johns Hopkins University.

Thomas Dunne (NAS) is a professor of geomorphology and hydrology at the Bren School of Environmental Science and Management at the University of California, Santa Barbara. He conducts field and theoretical research in fluvial geomorphology and in the application of hydrology, sediment transport, and geomorphology to landscape management and hazard analysis. He has worked in many parts of the world, including Kenya, where he studied the effects of land use on hill-slope erosion and river-basin sedimentation and how climate and hydrology affect long-term hill-slope evolution. At the University of Washington, he focused on land sliding and debris flows as well as tephra erosion and debris-flow sedimentation resulting from the eruption of Mount St. Helens. The resource management issues he studied in the Pacific Northwest include the impacts of gravel harvesting on river channels and floodplains and the impacts of timber harvesting on erosion and sedimentation. Since joining the Bren School in 1996, Dr. Dunne has studied erosion in the Andes and hydrology, sediment transport, and floodplain sedimentation in the Amazon River basin of Brazil and Bolivia and in the Central Valley of California. He earned a B.A. in geography from Cambridge University and a Ph.D. in geography from Johns Hopkins University.

Youssef Hashash is the William J. and Elaine F. Hall Professor of Civil and Environmental Engineering at the University of Illinois at Urbana-Champaign. After receiving his undergraduate and graduate degrees, he worked in Dallas, Texas, and San Francisco, California, on a number of underground construction projects in the United States and Canada. Dr. Hashash joined the faculty of the Department of Civil and Environmental Engineering at the University of Illinois at Urbana-Champaign in 1998. He has taught courses in geotechnical engineering, numerical modeling in geomechanics, geotechnical earthquake engineering, tunneling in soil and rock, and excavation support systems. His research focus includes deep excavations in urban areas, earthquake engineering, continuum and discrete element modeling, and soil-structure interaction. He also works on geotechnical engineering applications of visualization, augmented reality, imaging, and drone technologies. He has published more than 200 articles and is coinventor on four patents. His research group developed the software program DEEPSOIL that is used worldwide for evaluation of soil response to earthquake shaking. He received his B.S., M.S., and Ph.D. degrees in civil engineering from the Massachusetts Institute of Technology.

John Kupfer is professor and chair in the Department of Geography and senior associate faculty in the Environment and Sustainability Program at the University of South Carolina, Columbia. As a landscape ecologist and biogeographer, he conducts research that couples fieldwork with spatial analysis and modeling using geographic information systems to explore the interactive effects of landscape transformation, nonnative species, and disturbances such as flooding, fire, and hurricanes on plant and animal communities. His broad research on ecosystem types includes montane conifer forests in Idaho and Arizona; ecological transition zones in northern California; coupled human-natural systems in Central America; and riparian systems in the Midwest, Southeast, and Southwest. He has published more than 60 papers, chapters, and reports in a diverse range of outlets, among them top journals in geography, biogeography, geomorphology, and ecology. His research often has direct applications to ecosystem management, and he works regularly with scientists at Congaree National Park where he has aided their understanding of the interactions among flooding, sedimentation, and floodplain forests. Dr. Kupfer earned his B.A. in geography/biology from Valparaiso University and his M.A. and Ph.D. in geography from the University of Iowa.

APPENDIX A

Ning Lu is a geotechnical engineer and hydrologist with 25 years of experience in industry consulting, government research, and academia. He is presently a professor at the Colorado School of Mines, Golden, where his research focuses on the coupling between hydrological and mechanical processes in both natural and engineered environments such as hillslopes, embankments, and levees. These coupled processes play vital roles in the occurrence of such natural and man-made geologic hazards as rainfall-induced landslides and the instability of earth dams and sediments. He is the senior author of two widely used textbooks: *Unsaturated Soil Mechanics* and *Hillslope Hydrology and Stability*. Dr. Lu earned his B.S. in geotechnical engineering from the Wuhan University of Technology and his M.S. and Ph.D. in civil engineering from Johns Hopkins University.

Basil Stumborg is BC Hydro's decision analysis expert in energy planning and economic development (finance). He joined BC Hydro in 2000 and has worked on a number of projects across the company assisting BC Hydro in structuring its decision processes where decisions are complex and outcomes are uncertain. In particular, Mr. Stumborg helped structure and implement the water use planning program that rebalanced competing interests at Hydro's dams; the processes for long-term provincial energy planning; and BC Hydro's Business Case Requirements and litigation strategies. Most recently, he is supporting British Columbia's efforts in reviewing the Columbia River Treaty. Mr. Stumborg created and hosts BC Hydro's internal training on structured decision making to assist staff in implementing the business case requirements for complex projects and process changes. Before joining BC Hydro, Mr. Stumborg did graduate work in economics at the University of Wisconsin–Madison and McGill University, and psychology at Cornell University. He taught at the University of Victoria and consulted in the private and public sectors. The core focus of all his activities has been decision making under uncertainty and multiple-objective decision analysis—a discipline now known as behavioral economics. He received his B.A. in political science and M.A. in economics from McGill University.

Kathleen Tierney is a professor of sociology and director of the Natural Hazards Research and Applications Information Center at the University of Colorado Boulder. The Hazards Center is housed in the Institute of Behavioral Science, where she holds a joint appointment. Dr. Tierney's research focuses on the social dimensions of hazards and disasters, including natural, technological, and human-induced extreme events. With collaborators Michael Lindell and Ronald Perry, she published *Facing the Unexpected: Disaster Preparedness and Response in the United States*. This influential compilation presents a wealth of information derived from theory and research on disasters over 25 years. Among Dr. Tierney's current and recent research projects are studies on the organizational response to the September 11, 2001, World Trade Center disaster, risk perception and risk communication, the use of new technologies in disaster management, and the impacts of disasters on businesses. She received her B.A. in sociology from Youngstown State University and her M.S. and Ph.D. in sociology from The Ohio State University.

Desiree Tullos is an associate professor of water resources engineering at Oregon State University, Corvallis. Her research team investigates the interactions between river engineering and the physical and biological processes of rivers. Projects focus on questions that range from the particle to basin scale with the emphasis on the sustainable management of water resources. Example projects include (a) physical and biological responses to river engineering, including dam removal and reintroducing large wood; (b) impacts of climate change and reservoir operations on flood risk reduction, water supply, hydropower generation, and environmental flows; (c) analysis of uncertainty in water resources; (d) effects of hydropower development in China and flood management in the Himalayas; (e) turbulence and habitat of flow around vegetation and wood in rivers; and (f) sustainable flood risk management and infrastructure. In addition, she currently serves on the Independent Scientific Review Panel for Bonneville Power Administration's Northwest Power and Conservation Council and the board of directors for the Natural Heritage Institute. Her teaching emphasizes design-based learning in her primary classes: river engineering, hydraulic engineering, and ecological engineering. She earned her B.S. in civil engineering from the University of Tennessee, Knoxville, and both her M.S. in civil engineering and her Ph.D. in biological engineering from North Carolina State University, Raleigh.

Greg A. Valentine was a member of the technical staff at the Los Alamos National Laboratory from 1987 to 2007. During this time, he conducted research on explosive volcanic processes, subsurface radionuclide transport, and basaltic volcanism. Dr. Valentine was group leader for the past 10 years of his tenure at Los Alamos, coordinating the research of 60-75 permanent technical staff members on a variety of topics related to environmental, energy, and defense-related problems. He was technical lead and manager for disruptive events (volcanism and earthquakes) on the Yucca Mountain Project, which focused on performance assessment of a permanent geological repository for high-level radioactive waste. Dr. Valentine joined the Department of Geology at the University at Buffalo, The State University of New York system, in 2008 where he teaches and conducts research in volcanology and natural hazards and directs the Center for Geohazards Studies. Dr. Valentine has published more than 80 peer-reviewed papers and book chapters ranging from numerical modeling of eruption processes to experiments on explosive volcanism and fundamental processes of volcanic fields. He initiated vhub.org, a major online cyberplatform for collaborative volcanology and currently leads a major National Science Foundation–funded, multi-institutional project that integrates geology, geophysics, social science, and statistics in order to improve resilience to persistent volcanic unrest. He earned his B.S. in geological engineering and geology at the New Mexico Institute of Mining and Technology and his Ph.D. in geological sciences at the University of California, Santa Barbara.

APPENDIX B

Meeting Agendas

Committee on Long-Term Management of the
Spirit Lake/Toutle River System in Southwest Washington
National Academies of Sciences, Engineering, and Medicine
Meeting 1, June 21-23, 2016

Red Lion Hotel Kelso-Longview
510 Kelso Drive
Kelso, Washington 98626

Day 1 – Tuesday, June 21, 2016

OPEN SESSION
8:45 a.m. – 4:30 p.m.

8:45 Welcome, introductions, overview of the Statement of Task
Gregory Baecher, NAE, Committee Chair

9:00 Presentations from U.S. Forest Service and staff of the Washington State Congressional Delegation
Gina Owens, USFS, Gifford Pinchot National Forest, Forest Supervisor
Tedd Huffman, Mount St. Helens National Monument, Monument Manager
Congressional Staff (TBD)

9:50	Break

Historical overview, the federal perspective

Presentations and discussions:

10:00	Synopsis of the 1980 Eruption Jon Major, USGS
10:30	Hydrologic and Geomorphic Perspectives: Useful for Understanding the Spirit Lake/Toutle River Issues Gordon Grant, USFS
11:00	Geomorphic Response to the Eruption Jon Major, USGS

Working lunch will be served at or around 12 noon (Plenary and small group discussions)

1:00	Implementation of Projects to Manage Water and Sediment Christine Budai, USACE
2:00	Break
2:15	Ecological Response to the Eruption Charlie Crisafulli, USFS
3:00	Discussion of committee information needs
4:00	Open floor: Invitation for input from meeting participants
4:30	Adjourn open session

Day 2 – Wednesday, June 22, 2016

FIELD TRIP
Spirit Lake/Toutle River Drive
8:00 a.m. – 7:30 p.m.

8:00	**Kelso Red Lion – Personnel Pick-Up** Safety briefing and overview of the itinerary by USFS staff
8:30	Depart for Castle Lake Viewpoint Pat Pringle, Centralia College, provides interpretive overview of 1980 eruption, resulting mudflow, and flooding
9:15	Castle Lake Viewpoint Welcome to the Gifford Pinchot National Forest & landscape overview Gina Owens, Forest Supervisor, and Tedd Huffman, Monument Manager
9:45	**Depart for Johnston Ridge Observatory (JRO)**
10:00	**Johnston Ridge Observatory Amphitheater**
	Break
10:45	**15 min talks with additional time in between for questions & discussion** Hydrological considerations (Jon Major, USGS), 15 mins Protection works and the built environment (Chris Budai, USACE), 15 mins Natural environment (Charlie Crisafulli, USFS PNW Res Stn), 15 mins

	FS management of [a] tunnel in a National Volcanic Monument (Tedd Huffman), 15 mins
12:15	**Depart JRO**
12:30	**Spirit Lake Tunnel Outlet** Chris Strebig, USFS, and Chris Budai, USACE
12:45	**Depart Tunnel Outlet**
1:00	**Hummocks Trail** Pat Pringle, Centralia College, and Charlie Crisafulli and Peter Frenzen
2:15	**Depart Hummocks Trail**
2:30	**Coldwater Lake Recreation site (bathrooms), discuss engineered outlet**
3:00	**Depart for Sediment Retention Structure**
3:45	**Sediment Retention Structure (SRS)** Jon Major, USGS, and Chris Budai and Paul Sclafani, USACE
5:00	**Depart Sediment Retention Structure**
5:45	**Coweeman Levee** Chris Budai and Paul Sclafani, USACE
6:15	**Coweeman Levee**
6:30	**Arrive at Red Lion Inn**

Committee on Long-Term Management of the Spirit Lake/Toutle River System in Southwest Washington
National Academies of Sciences, Engineering, and Medicine
Meeting 2, August 3-5, 2016

Red Lion Hotel Kelso-Longview
510 Kelso Drive
Kelso, Washington 98626

Day 1 – Wednesday, August 3, 2016

OPEN SESSION
9:00 a.m. – 5:30 p.m.

9:00 Welcome and introductions and plan for the day
Greg Baecher, NAE, Committee Chair

9:15 Summary of Statement of Task and setting the stage
Sammantha Magsino, Academies Staff

9:20 Introduction by the USFS study sponsor
Jim Peña, Regional Forester, USFS

9:30 Decision support frameworks—how a framework might look
Basil Stumborg and John Boland, Committee Members

10:00 Break

Panel Discussions (with parties interested and affected by management of Spirit Lake and the Toutle River): Concerns and Priorities for Management

10:15	Panel #1 – regional and local Moderator: Basil Stumborg • Joe Gardner, Cowlitz County Board of Commissioners • Ashley Helenberg, Port of Longview • Ernie Schnabler, Cowlitz County Emergency Management • Greg Drew, Drew's Grocery, Toutle
12:00-1:00	Lunch
1:00	Panel #2 –Non-profit Moderator: Kathleen Tierney • TBD, Gifford Pinchot Task Force • Gene Crocker, Cowlitz Game and Anglers Club • Ray Yurkewycz, Mount St. Helens Institute • Claudia Hunter, Toutle Valley Community Association
2:45	Break
3:00	Stakeholder Panel #3 – State, tribal, and land management Moderator: John Kupfer • Nathan Reynolds, Natural Resources Department, Cowlitz Nation • Steve Ogden, Pacific-Cascade Region, WA Department of Natural Resources • Dave Howe, Regional Habitat Program, WA Department of Fish and Wildlife

OPEN SESSION – TOWN HALL MEETING
6:30 p.m. – 9:00 p.m.
Light refreshments served

6:30 Introduction and welcome
Greg Baecher and Sammantha Magsino

6:40 The Academies – An Introduction
Sammantha Magsino

6:45 Open comment period – Sign-up required
**Signup is required and comment time is limited to 3 minutes. Total number of speakers limited to approximately 50.

Day 2 – Thursday, August 4, 2016

OPEN SESSION
8:30 a.m. – 1:45 p.m.

8:30 Welcome and introductions and plan for the day
Greg Baecher, NAE, Committee Chair

8:45 Summary of Statement of Task
Sammantha Magsino, Academies Staff

8:50 **Panel Discussion: Spirit Lake Outlet Risk Assessment**

Each of the panelists will make a 10-minute presentation describing the most important lessons learned from years of monitoring and infrastructure management and will highlight from these experiences those issues that need the most attention moving forward.

General overview of PFMA process,
Jeremy Britton, USACE
PFMA Specifics/Details, David Scofield, USACE
PFMA Hydrology, Angela Duren, USACE
Tunnel Hydraulic Design, Sean Askelson, USACE

9:50 Questions and answers with the panelists

10:05 Break

10:20 **Panel Discussion: Mount St. Helens Long-Term Sediment Management**
General Overview, Tim Kuhn, USACE
Long-Term Sediment Management Study Details,
Paul Sclafani, USACE
Long-Term Sediment Management Geotechnical Details, Jeremy Britton, USACE

11:20 Questions and answers with the panelists

12:15-1:45 Working Lunch
Discussion with all: Consequences associated with the various alternatives

Committee on Long-Term Management of the
Spirit Lake/Toutle River System in Southwest Washington
National Academies of Sciences, Engineering, and Medicine
Meeting 3, October 31-November 2, 2016

Cowlitz Regional Conference Center, Cowlitz & Columbia Room
1900 7th Avenue, Longview, Washington

Monday, October 31, 2016

OPEN SESSION
10:15 a.m. – 2:45 p.m.

10:15 Welcome, introductions and plan for the day
Greg Baecher, NAE, Committee Chair

10:25 Summary of Statement of Task
Sammantha Magsino, Academies Staff

10:35 Questions and answers regarding recently released document
Gordon Grant, USFS
Jon Major, USGS

11:45-12:45 Working Lunch—small group discussions

12:45 Follow-up questions with USACE
Jeremy Britton, USACE
David Scofield, USACE
Angela Duren, USACE
Sean Askelson, USACE
Paul Sclafani, USACE
Jeremy Britton, USACE

1:45	Discussion with USFS study sponsors—expectations from report given Information gathered during all open sessions
2:15	Public comment period (2-minute limit)
2:45	Adjourn open session

APPENDIX C

Board Rosters[1]

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JAMES M. ROBERTSON, Wisconsin Geological and Natural History Survey, Madison
JAMES SLUTZ, National Petroleum Council, Washington, DC
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[1]The boards serve as oversight and liaisons to the ad hoc study committee.

APPENDIX C

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APPENDIX C

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Committee on Geological and Geotechnical Engineering

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APPENDIX D

Congressional Request Letter

Congress of the United States
Washington, DC 20515

September 24, 2015

The Honorable Tom Tidwell
Chief
U.S. Forest Service
1400 Independence Ave, SW
Washington, DC 20250

The Honorable Jo-Ellen Darcy
Assistant Secretary of the Army (Civil Works)
U.S. Army Corps of Engineers
108 Army Pentagon
Washington, DC 20310-0108

The Honorable Suzette Kimball
Director (Acting)
U.S. Geological Survey
12201 Sunrise Valley Drive
Reston, VA 20192

Dear Chief Tidwell, Assistant Secretary Darcy, and Director Kimball,

Thank you for the response from your agencies dated July 13, 2015, regarding our serious concerns with the state of the Spirit Lake Tunnel located on the Gifford Pinchot National Forest. The tunnel, which provides the only outlet for Spirit Lake, is in need of significant renovation and repair due to ongoing damage resulting from seismic activity in the dynamic geologic landscape of Mount St. Helens.

Although we are pleased to learn that funding has been secured and interim tunnel repairs are scheduled to occur later this year, we are concerned that your response failed to provide clear direction on developing a long-term, cost effective solution for stabilization of the lake level. Given the possibility of significant downstream impacts in the event of tunnel failure, we believe that a solution must be sought during the window of time that will be provided by the interim repair measures.

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Subsequently, we request that the U.S. Forest Service fund and develop a report in cooperation with the U.S. Army Corps of Engineers and U.S. Geological Survey that will review and analyze an array of options for a long-term plan that removes the threat of catastrophic failure of the tunnel and takes the unstable nature of the surface geology into account. We believe it is imperative that the agencies use all available resources from academia to local and state emergency management personnel to national laboratories and others who can provide expertise and information toward the development of the best possible solution.

Due to the limited timeframe that will be provided by the interim measures, it is critical that the recommendations be developed and a report provided to us within the next 18 months. The report should address the following points:

- Review a minimum of three options and provide a recommended solution.
- Provide a data analysis and cost estimate for each option, including estimates on long-term maintenance costs.
- Explore and answer the following questions:
  - Should the existing tunnel be repaired and renovated? If not, should it be decommissioned?
  - Are there alternatives that can establish a more natural and sustainable outlet that works with the natural system and takes the dynamic landscape into account?
  - Are there options that require less human intervention, and that provide less risk of hazard exposure to maintenance personnel?
  - What are the risks to downstream communities for each option?
  - What agency(s) will be responsible for the construction and management of the recommended solution?
  - What legal authorities are in place to carry out the recommended solution? Are additional authorities needed and would these require regulatory or legislative action?
  - What are the funding resources needed by the agency(s) to carry out the recommended solution?

We are committed to working with your agencies throughout this process as the region seeks a solution to this pressing need. In keeping with this commitment, we request quarterly briefings with our staff and local stakeholders in order to foster information sharing and to keep us apprised of progress on the report. Please provide us with a contact list of the personnel that will take part in this effort as well as an outline of the process that will be pursued to complete the report within 30 days of the date of this letter.

Thank you for your assistance on this matter. We look forward to your timely reply.

Sincerely,

Jaime Herrera Beutler
Member of Congress

Patty Murray
United States Senator

Maria Cantwell
United States Senator

cc: Jim Peña, Regional Forester, USFS
Brigadier General Scott A Spellmon, Division Commander, USACE
Max Ethridge, Regional Director, USGS