Effects of the Eruptions of Mount St. Helens on Physical, Chemical, and Biological Characteristics of Surface Water, Ground Water, and Precipitation in the Western United States

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By DOUGLAS B. LEE

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PREFACE

The volcanic eruptions of Mount St. Helens in 1980 affected lakes, rivers, streams, the Columbia River Estuary, ground water, and precipitation in the Western United States. Because of the sheer breadth of these effects, studied by hundreds of scientists over a large geographic area encompassing thousands of square miles, the compilation of a source book or review of the available information was needed. The source book covers the myriad of subjects involved in characterizing the physical, chemical, and biological changes in many diverse situations. Data and conclusions from scores of reports and scientific papers are reviewed in this report, which rapidly grew to substantial length because of the wide spectrum of materials. This report, when used in conjunction with the original source documents, provides a retrospective overview of research and accomplishments. In the event of a future eruption, individuals responsible for initiating and recommending new studies will be provided with common grounds for discussion, from which additional questions and problems can be identified. Because of the report's unusual size, some readers perhaps can benefit from suggestions on how best to use this document.

The intended audience is very broad, including scientists with diverse backgrounds and interests. For the benefit of all interested persons, extensive references are cited. In many cases, discussions of original papers may be sufficiently detailed to allow the reader to evaluate the desirability of obtaining either the cited document or its abstract. In a manner of speaking, one might usefully regard this literature review to be a compilation of abstracts and proceed to use it in that fashion.

The first part of this report describes the effects of the eruption on lakes. Those lakes are divided into three categories that define the levels of change caused by the eruptions. The effects of the eruptions on rivers, streams, and the Columbia River Estuary are separate major subdivisions, as are the topics of effects on ground water and precipitation. A collection of detailed discussions on individual lakes or rivers constitutes the bulk of this report. The narratives have been written in a "case-study" format in an endeavor to describe the unique attributes or environmental features of a lake or river. The case-study format was used to facilitate compilation of the different effects impinging on a particular ecosystem.

Most researchers wrote about specialized topics according to their particular discipline and seldom expanded on many different aspects of various phenomena that occurred. The case-study format seeks to consolidate the diverse types of information pertaining to a particular lake or river, so that any relation among the many different facts may emerge. In a few cases, perhaps, an understanding of how empirical observations are related to one another can be reached, to facilitate identifying and defining cause-and-effect relations. At the end of each collection of case studies, a summary of the effects of the eruption on physical, chemical, and biological characteristics of water quality is provided.

Persons who do not need details on any particular lake or river and who may desire only to review phenomena common to a large category of water bodies will probably profit most by turning directly to a summary section. If additional details are desired, the reader of this report might then proceed to the applicable case study in question. A researcher endeavoring to find quantitative data on specific topics might decide to scan various case-study histories in this report to extract the appropriate information and pertinent references. An overall summary and conclusions section, such as might be written for a much shorter document with fewer topics and then placed at the end of that document, was considered impractical for this report and is therefore not included.

Douglas B. Lee

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PLATE [In pocket]

TABLES

CONVERSION FACTORS

[SI, International System of units, a modernized metric system of measurement]

Multiply	By	To obtain
A. Factors for converting SI metric units to inch/pound units		
	Length	
centimeter (cm)	0.3937	inch (in)
millimeter (mm)	0.03937	inch
meter (m)	3.281	foot (ft)
	Area	
hectare	2.471	acre
square meter (m^2)	10.76	square foot (ft^2)
	Volume	
milliliter (mL)	0.001057	quart (qt)
liter (L)	1.057	quart
liter	0.2642	gallon (gal)
	Mass	
gram (g)	0.03527	ounce (oz avoirdupois)
kilogram (kg)	2.205	pound (lb avoirdupois)
	Temperature	
degrees Celsius (°C)	Temp degrees F=1.8 (Temp degree C) +32	degrees Fahrenheit (°F)
B. Factors for converting SI metric units to other miscellaneous units		
	Miscellaneous	
cubic foot per second (ft^3/s)	0.02832	cubic meters per second (m^3/s)
acre	4,047	cubic meter (m^3)
	Concentration, in water	
milligrams per liter (mg/L)	1	parts per million (ppm)
micrograms per liter (μg/L)	1	parts per trillion (ppt)
	Concentration, in tissue	
micrograms per gram (μg/g)	1	parts per million (ppm)
micrograms per kilogram (μg/kg)	1	parts per billion (ppb)
C. Factors for converting inch/pound units to SI metric units		
	Length	
inch	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.09294	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)

Electrical conductivity is measured as specific electrical conductance, in units of microsiemens per centimeter (μS/cm).

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Note: This report uses data and information published by researchers who used many different units of measurements. Because it is advantageous to use a consistent system of units and measures, data measurements reported by authors of the original source documents have been converted to a conveniently consistent system of units. These conversions allow readers to compare data sets from different sources. For example, original measurements published in meters or centimeters have been changed to feet or inches in this report; concentrations published as micromoles per liter have been changed to milligrams or micrograms per liter.

Effects of the Eruptions of Mount St. Helens on Physical, Chemical, and Biological Characteristics of Surface Water, Ground Water, and Precipitation in the Western United States

By Douglas B. Lee

Abstract

This report is a review of literature pertaining to the 1980 eruptions of Mount St. Helens, and to the subsequent effects of those eruptions on physical, chemical, and biological characteristics of surface water, ground water, and precipitation in the Pacific Northwest, Montana, and Colorado.

Scores of studies dealing with the eruption and changes in water quality have been published; however, the data and information are contained in numerous U.S. Government and State government publications, proceedings of symposia, and a myriad of scientific journals. The salient published findings and conclusions on eruption-related, water-quality topics are compiled and categorized here to illustrate the scope of previous investigations. Conclusions, other than those reported by the authors listed in the Selected References, are not presented.

This report contains quantitative information and descriptions of changes in the physical, chemical, and biological characteristics of water quality caused by the volcanic activity of Mount St. Helens during 1980. Lakes that received only ashfall experienced fewer effects than lakes that were within the blast zone. Phenomena occurring in new lakes created by the eruption are unique, and in some cases, had never been observed or documented prior to 1980.

Different lakes are described, using a case-study approach that includes sufficient background information on each lake to put the effects of the eruption in perspective. The changes attributable to the volcanic blast, mudflows, and ashfall varied dramatically from one lake to another—depending on the location of the lake under the ash plume, the distance of the lake from Mount St. Helens, and other physical circumstances. Similarly, the effects on rivers and streams varied in magnitude from barely perceptible changes to profound alterations that virtually created new drainage systems.

Limited literature exists about the effects of the eruption on ground water. Changes in ground-water levels and chemistry are principally associated with the most heavily effected river systems—those which lay in the path of mudflows generated by the volcanic eruption. Potentially toxic chemical compounds, such as phenols, were identified by researchers in several investigations. Ground-water levels in parts of the Cowlitz River system appear to have been raised above historical levels.

Few studies were done about the effects of the eruption on precipitation. Observations from investigations in Colorado and Oregon suggest that physicochemical changes, such as altered specific conductance and pH of rainwater samples, were not long-lived.

INTRODUCTION

One responsibility of the U.S. Geological Survey (USGS) is to investigate and monitor geological hazards. As early as 1975, Mount St. Helens was identified by the USGS as a potentially hazardous volcano. Seismologists from the University of Washington who monitored the volcano over a substantial timespan and USGS scientists such as Dwight Crandell and Donal Mullineaux (1978) considered Mount St. Helens to have the greatest potential for an eruption of all the volcanoes in the Cascade Range.

On March 20, 1980, seismic activity, punctuated by numerous earthquakes of increasing intensity, indicated that an eruption was likely in the very near future. As a consequence, agencies responsible for emergency services were alerted to the possibility of a potentially hazardous explosion. The steps necessary to protect the public were taken, and details of these preparations have been described in the popular press as well as in various agency publications.

Prior to the eruption of May 18, 1980, an extensive network of personnel from applicable State, Federal, and municipal agencies evolved. The plans and procedures necessary to coordinate information and activities for an emergency were essentially in place by the time the explosion actually occurred.

Scientists, as well as lay readers, should refer to "Volcanic Eruptions of 1980 at Mount St. Helens," USGS Professional Paper 1249, by Foxworthy and Hill (1982), a detailed history of Mount St. Helens that includes descriptions of the volcano before, during, and after the eruption of May 18, 1980. USGS Professional Paper 1249 was written with the general public in mind and provides the background for understanding the physical, geological, hydrological, chemical, and biological studies initiated in anticipation of, and in response to, the explosive May 18, 1980, eruption of Mount St. Helens and subsequent eruptive events. In addition to the paper by Foxworthy and Hill (1982), many reports covering an entire spectrum of research topics related to the eruption of Mount St. Helens were published in a compendium of reports edited by Lipman and Mullineaux (1981). "The 1980 Eruptions of Mount St. Helens, Washington," USGS Professional Paper 1250. That compendium contains an extensive list of references for researchers and serves as a companion volume to the 1982 report by Foxworthy and Hill.

Neither aforementioned professional paper, edited by Lipman and Mullineaux or by Foxworthy and Hill, however, focuses on the effects of the eruption on surface and ground water or precipitation. The USGS recognized that a report—which would be a review and summarization of the literature pertaining to various aspects of water quality affected by or which resulted from the eruption of Mount St. Helens—was needed.

This report summarizes investigations—by the USGS, other Federal and State agencies, and individual researchers—that pertain to problems and issues of water quality resulting from the volcanic activity of Mount St. Helens.

This review includes reports published individually or as parts of other collections. By categorizing the results of those reports, a broad overview of diverse topics pertaining to water quality emerges. A primary objective of this report (Part I of the project) is to provide a general framework and summary of facts and information, derived from a variety of sources and publications, describing the effects of the volcanic eruption on the water characteristics of lakes, rivers, streams, ground water, and precipitation. Closely related topics of geochemical processes, which are linked to water quality, also are discussed.

Part II of the project is intended to provide a retrospective look at research completed by scientists. Interviews with investigators will provide insight on the following elements:

(1) If the investigators were to perform the same type of study again, would they utilize a similar approach, or would they add or delete certain elements?

(2) Could the investigators, on the basis of experience gained from the eruption of Mount St. Helens,

  (a) identify priorities of research for possible future eruptions of other volcanos,

  (b) suggest new types of research to be performed, and

  (c) establish criteria to use for allocating available personnel and funds to the best advantage?

(3) If research needs for future work can be identified, can these needs be stated in the form of hypotheses to be tested?

All of these elements, considered collectively, should culminate in the ability to make suggestions on how the USGS and other agencies could respond to a future major eruption. Because each volcanic eruption differs in magnitude and setting, a variety of responses is possible. The common characteristics of such events must be identified, however, so that a reasonable set of hypotheses might be formulated.

EFFECTS OF THE ERUPTION ON LAKES

Pacific Northwest citizens were kept informed of events preceding the Mount St. Helens eruption, and the popular press reported the announcements of agencies monitoring the volcano. As the story began to unfold, interest in the mountain spread throughout the United States. People living in Washington and Oregon were kept abreast of day-to-day and weekly developments through extensive newspaper and television coverage. The mountain and adjacent forests, rivers, and lakes of southwestern Washington provide a popular recreational area for people living in the Pacific Northwest. In addition, thousands of people from all parts of the United States visit Washington and Oregon each year, making the tourist industry a vital part of the regional economy. As a consequence of the volcano's relative proximity to populated metropolitan areas, such as Vancouver in Washington or Portland in Oregon, the mountain soon became a center of attraction. People could easily drive to within viewing distance of the peak, and Mount St. Helens developed into a favorite destination for tourists and others who flocked to the area.

News reporters interviewed many persons living in the immediate vicinity of the volcano. Because these individuals were perceived to be dwelling near a hazard zone, a certain sense of drama began to develop as concern for their safety grew. Spirit Lake, a popular and picturesque body of water, was well known to many people as a vacation spot. One of the permanent "old-time" residents of a lakefront lodge was a colorful gentleman named Harry Truman, and his dogged determination to remain at Spirit Lake despite the danger was the theme of a compelling human-interest story capturing the imagination of many reporters. Truman's tale will not be retold here, but we mention his account because it helps explain why many laymen, as well as researchers, attentively followed studies of the volcano. Citizens who owned recreational properties and homes in the Spirit Lake area, and loggers who made their living in forests lying in the shadow of the volcano, followed announcements of the USGS and other agencies with intense personal interest. By the time the major eruption occurred on May 18, 1980, most people reading news accounts of Mount St. Helens probably knew at least several stories about people who were living or working next to the volcano. The mountain and the people living nearby had become famous.

Spirit Lake was profoundly impacted when the volcano erupted; a substantial section of this report is devoted to describing the effects of the explosion on that lake. Because of the widespread publicity surrounding the blast, many people were immediately aware of the immense impact on Spirit Lake. Thousands of television viewers witnessed the scenes of widespread destruction on the flanks of the volcano. The blast area was even visited, subsequently, by President Jimmy Carter. Moreover, the explosion affected many other lakes that were not as large or well-publicized as Spirit Lake.

Among the researchers who converged upon the mountain and the surrounding area were individual scientists who subsequently studied the effects of the eruption on more than 40 other lakes; these lakes were not necessarily as well known as Spirit Lake to either the public or representatives of the news media. These scientists attempted to classify the magnitude of the blast, and to categorize the lakes according to the type of physical effects to which the lakes were exposed.

The area immediately north of Mount St. Helens, which was directly affected by the actual explosion and other direct effects of the violent outburst, was regarded as the "blast zone" (Dion and Embrey, 1981, p. G3). Bodies of water within this zone were certainly the most impacted by the eruption. Lakes outside of the direct blast zone were affected to a much lesser extent, although the distance in miles away from the mountain was minimal. Although located close to the source of the blast, some lakes escaped major impacts and received only ashfall because the blast was directed away from those lakes. Baross and others (1982) divided the lakes they studied into three groups:

(1) lakes affected by mud or debris flows;

(2) lakes that were in the tree "blowdown" or "scorch" zones; and

(3) lakes and water bodies that received only ashfall, to which the authors compared the effects of the first two categories of lakes.

Wissmar and others (1982b, p. 175) used a system of classification that was slightly more complex, by differentiating the degree to which trees and vegetation were affected. That system included a division between lakes with only scorched vegetation, and lakes that experienced an actual blowdown of trees near the shoreline in combination with heavy ashfall and denuded vegetation.

Plate 1 shows the location of the study lakes reviewed, along with the rivers, streams, and other features discussed in this report.

For purposes of this report, each lake is listed alphabetically and designated as belonging to 1 of 3 main categories (table 1). Listing each lake by category is largely a matter of convenience, and serves as a device for grouping various topics for analysis and discussion. The description of a lake in category I, category II, or category III is as follows:

I. *Lakes outside the blast zone* that received only ashfall: Some of these lakes served as "controls" or reference lakes in a sense, because the observed physical, chemical, and biological effects of the explosion were minimal. These lakes do not actually provide true "baseline data;" however, differences between these reference lakes and those lakes more heavily impacted did allow researchers to make useful comparisons about the magnitude and scope of the eruption and blast effects.

II. *Lakes within the blast zone:* This category can be further subdivided, and details and descriptions of each individual lake and its surroundings are provided. No two lakes were affected by the eruption in exactly the same manner, and each lake should be regarded as a single case study. Each lake in category I also experienced unique effects; but for lakes in categories II and III, the particular attributes of the lake and its environs influenced blast effects to a greater extent than lakes that received only ash. Substantial narrative concerning each lake is presented in order to emphasize differences among the lakes placed within category II.

III. *Newly created lakes*: Some lakes were actually formed as a direct consequence of the eruption of the volcano. Mudflows dammed river basins that in turn flooded and filled with water.

Composition and Effects of Volcanic Ash on Water Quality

The chemical changes observed in category I lakes can be directly attributed to ash falling on the lakes. No consensus about the extent to which ash might be transported by rainfall and erosion from land surfaces seems to exist among authors. Erosion of ash could be affected by numerous factors, such as the surface of the surrounding terrain and the steepness of the slopes adjacent to a lake or river. Information on ash weathering and transport is not available for each lake, and a discussion of those topics is regarded as outside the scope of this report; however, the reader needs to be aware of the potential influence of these naturally occurring processes on the amount of ash available to influence water quality.

Later in the report, when ash effects on the water quality of rivers are discussed, the reader should be aware that observers could not usually distinguish between changes in turbidity caused by ash, or by other materials such as fine avalanche debris, increased sediment or silt. For rivers (such as the Toutle and Cowlitz Rivers), researchers reported the effects as changes in mass of suspended sediment per liter of water and in standard measurements of turbidity, like Jackson Turbidity Units (JTU). In other words, it was generally not possible to report the proportions of the total turbidity that were attributable to ash when compared to total turbidity attributable to silt and sediment, mudflow debris, or other sources. For analyses in this report of category I lakes that received only ash (lakes that received no materials from mudslides or avalanches), however, increased turbidity was considered to be caused solely by ash. Similarly, the source and quantity of components contributing to total turbidity measurements, defined in the controlled "laboratory types" of experiments in which collected ash was added to water, are described later in this report. The effects of ash on the characteristics of the surface waters and ground water are discussed in this report; therefore, some background on the chemistry and distribution of the ash is presented.

The distribution, thickness, and volume of ash resulting from the eruption of Mount St. Helens are documented by Sarna-Wojcicki and others (1980). An isopach map of ash was compiled for the State of Washington, Idaho, and Montana. Isomass and isochron maps, compiled for the same region, graphically depict the quantities of ash that fell on land and water in different parts of the plume.

Table 1. Categories of lakes included in Mount St. Helens studies

[Unless otherwise noted, the lakes are located in Washington. Category I, lakes outside blast zone; category II, lakes within blast zone; category III, newly created lakes]

Name	Category	Description
Amber Lake	I	Unaffected by eruption, deposition of ash
Blue Lake	I	Unaffected by eruption, a "reference lake"
Clearwater Lake	I	Western Montana, Clearwater drainage basin
Coeur d'Alene Lake	I	Eastern Washington: received ashfall. Includes: Gasser Point, Brown's Bay, and Hidden, Round, and Chatcolet Lakes
Fish Lake	I	Oligotrophic lake in Idaho
Indian Postoffice Lake (upper)	I	Oligotrophic lake in Idaho
Indian Postoffice Lake (lower)	I	Oligotrophic lake in Idaho
June Lake	I	"Reference lake" received only ashfall
Lake Alva	I	Western Montana: Clearwater drainage basin
Lake Elsina	I	Western Montana: Clearwater drainage basin
Lake Inez	I	Western Montana: Clearwater drainage basin
Lake Lenore	I	Received ashfall. Alkaline lake in central Washington
Liberty Lake	I	Eastern Washington, received only ashfall
McBride Lake	I	"Reference lake," received only ashfall
Merrill Lake	I	"Reference lake," outside blast zone
Placid Lake	I	Western Montana, Clearwater drainage basin
Rainy Lake	I	Western Montana, Clearwater drainage basin
Salmon Lake	I	Western Montana, Clearwater drainage basin
Seeley Lake	I	Western Montana, Clearwater drainage basin
Soap Lake	I	Outside blast zone; alkaline lake in central Washington
Sprague Lake	I	Unaffected by eruption; ash only
Walupt Lake	I	37 miles northeast of volcano
Warden Lake	I	Unaffected by eruption, ash only
Boot Lake	II	Blowdown or scorch zone
Fawn Lake	II	Blowdown or scorch zone; blowdown timber
Findley Lake	II	Blowdown timber; scorch zone
Hanaford Lake	II	In the blast zone, but "less affected"
Island Lake	II	Blowdown or scorch zone
Meta Lake	II	Blowdown or scorch zone
Panhandle Lake	II	Blowdown or scorch zone
Ryan Lake	II	Blowdown and scorch zone, "moderate impact"
Spirit Lake	III	Heavily affected
St. Helens Lake	II	In blast zone, called by some "less affected"
Venus Lake	II	Blowdown or scorch zone
Castle Lake	III	New lake, affected by mud and debris flows
Coldwater Lake	III	New lake, affected by mud and debris flows

The report by Sarna-Wojcicki and others (1980) describes the methodology and calculations utilized in estimating volumes of distributed tephra (ash, cinders, pumice, and other materials explosively ejected from the volcano); details are presented on the techniques used for determining the weights of material that fell in different locations per unit area of ground.

A variety of studies and reports on the chemistry of ash samples indicate that the ash composition differed from one site to another. Knowledge of the chemical makeup of ash distributed into a particular lake may not have been available to investigators, unless they analyzed ash as part of the study.

Samples of ash collected from the vicinity of Moses Lake, Washington, and from sites in Idaho and Montana were analyzed by Taylor and Lichte (1980, p. 949). The authors reported that physical characteristics of the ash varied from site to site within geographic locations covered by the plume, as the ash was carried by the wind eastward away from Mount St. Helens. Similarly, the chemical composition of ash samples varied according to the distance the ash was transported away from Mount St. Helens, which is related to physical differences in particle size and density. The changes in ash composition, of course, affected the manner and degree to which the composition of various lakes and rivers was changed. Depending on where a lake or river was located in the ash plume, water-quality changes were related to the quantity and type of ash received. Concentrations of constituents such as calcium, chloride, magnesium, manganese, potassium, sodium, and sulfate are given. Moderately high levels of soluble salts were reported by Taylor and Lichte (1980, p. 949), and the molar ratios determined suggested the presence of sodium chloride ($NaCl$), potassium chloride (KCl), calcium sulfate ($CaSO_4$), and magnesium sulfate ($MgSO_4$). The authors leached samples of dry ash with deionized water to show that various ash constituents were soluble and might contribute to precipitation runoff. The following elements were shown to be leachable from the ash: arsenic, barium, beryllium, cadmium, copper, iron, lead, mercury, selenium, and zinc. Analyses of ash leachate indicated the presence of nutrients such as nitrates and phosphates, as well as ammonium and dissolved organic carbon. The availability of these nutrients may be significant, provided that they could be eluted from the ash. Taylor and Lichte (1980, p. 952) speculated that dissolved organic carbon found in the ash was formed as a result of atmospheric condensation of the combustion products created as vegetation near the volcano burned.

Extensive chemical analyses of ash extracts collected from the Missoula, Montana area were performed by Juday and Keller (1984), who used water from numerous lakes. Water from Placid, Alva, and Inez Lakes, as well as distilled water, was used to extract constituents from ash samples collected from the Missoula, Montana area. The authors investigated the effects of deoxygenated and oxygen-saturated water on chemical extractions, and examined the effects of light and dark on the extraction process. Analyses were performed for the following ions: chloride, sulfate, calcium, magnesium, sodium, and potassium. Substantial differences in concentrations of these ions were not detected in the test waters used to perform the extractions, except for changes attributable to mass-action effects. For example, if the water used to perform the extractions already contained appreciable concentrations of calcium and magnesium, the amount of calcium and magnesium extractable from the ash was less than the amount obtained when distilled water was used for extraction. Regardless of the type of water used to extract either sodium, potassium, sulfate, or chloride, no appreciable difference of concentration was found. Juday and Keller (1984, p. 7–8) stated:

> Phosphate levels show a high variability but cannot be ascribed to differences in exposure to light, or oxygen. Nitrate levels are clearly lower in deoxygenated and samples exposed to light. It is well known that under anaerobic conditions bacteria are capable of mobilizing phosphate, iron, and manganese, while using up nitrate. Also, denitrification is enhanced by light. ***One could expect that appreciable amounts of nitrates, phosphate, and manganese and possibly other trace elements would be released to the environment over a period of time.***On the basis of extraction results then, one could expect enhanced productivity of lakes from the fall-out.

Incubation experiments were conducted using ash extracts that were added to flasks containing various species of algae that were being cultivated under controlled-light conditions. Juday and Keller (1984) concluded that the phosphate content of ash might possibly stimulate the growth of algae in lakes, provided that phosphate was a limiting growth factor.

Parker and Gaddy (1983, p. 2) studied the effects of soluble and particulate fractions of the ash on carbon fixation by a diatom and a green alga. *Cyclotella meneghiniana* Kutz (a diatom), and *Cryptomonas ovata* Ehr. (an ovoid flagellate) were exposed to particulate ash and ash filtrate in laboratory experiments using carbon-14-labeled sodium bicarbonate to measure rates of carbon fixation. The ash for these experiments was collected from Pullman, Washington. Parker and Gaddy (1983, p. 16–17) stated:

> There is no evidence that the quantities of ammonium and nitrate found in ash leachate are sufficient to stimulate carbon fixation by nitrogen-starved *Cryptomonas* and *Cyclotella*. To the contrary, *Cyclotella* demonstrated reduced photosynthetic activity in the presence of filtrate, suggesting that soluble toxic materials may be released by ash particles in freshwater. Ash suspensions increased carbon fixation by *Cryptomonas*, but did not affect *Cyclotella* significantly.

The effects of ash on several filter-feeding zooplankton species were studied by Parker and Gaddy (1983, p. 2). Experiments were performed with the particulate ash fraction, to determine its effect upon the ingestion rate, filtration rate, and assimilation efficiency of *Diaptomus ashlandi* Marsh and *Daphnia pulex* Leydig. The organisms were cultivated with growth medium in Erlenmeyer flasks and were fed with radioactively labeled food cells (algae) that had been grown with carbon-14-labeled sodium bicarbonate in the culture medium. According to Parker and Gaddy (1983, p. 17):

> Grazing by *Diaptomus* and *Daphnia* on *Cryptomonas* was not altered significantly by the presence of particulate ash; the same can be said of *Diaptomus* feeding on *Cyclotella*. When fed *Cyclotella*, however, *Daphnia* filtered more medium and ingested more algae at intermediate ash concentrations. Assimilation proved to be highest in the absence of ash, that is, ash interfered with the uptake of carbon-14 from ingested *Cyclotella*.

Extraction experiments on ash were performed by Skille and others (1983, p. 91), who studied the effects of ash on limnological features of the Coeur d'Alene River system and summarized their conclusions regarding chemical effects of the ash as follows:

> The sedimented ash was chemically stable and its potential for contributing ions and nutrients to the water column was low. ***[The] ash layer has had little, if any, effect on the exchange of metals between the sediments and overlying water. Physical and chemical characteristics of water throughout the Coeur d'Alene Lake system were not changed by ashfall.

Considering the large volume of this lake system, it seems unlikely that the ash could have caused changes of a large magnitude. Analyses of the chemical composition of tephra collected at 16 sample sites indicated that the ash was not likely to affect primary production through enhancement of nutrient availability. Skille and others (1983, p. 55) stated:

> Results indicate that the ash has a very low potential for contributing nutrients to the water column. Phosphate, ammonia, nitrate, and nitrites were in low to nondetectable levels (appendix E).

Laboratory studies with volcanic ash were performed by McKnight and others (1981) to determine if ashfall might affect the growth of algal populations in lakes and rivers; experiments were performed on leachate from ash collected from several sites in eastern Washington. The ash collected near Richland, Washington, differed in chemical makeup from that of the ash collected near Moses Lake, Washington. Richland lies east of Mount St. Helens, whereas the Moses Lake site is northeast of Mount St. Helens. The research of McKnight and others (1981) needs to be considered when analyzing biological and chemical effects of ash on the various category I lakes that were considered to be "references" by so many authors. If the ash varied in chemical composition, then another set of variables was introduced when comparing one lake to another.

Some toxic components of the ash were not evenly dispersed in the plume (McKnight and others, 1981) The authors determined, through bioassays utilizing the blue-green alga *Anabaena flos-aquae*, that certain fractions of volcanic ash-leachate could alter the growth characteristics and morphology of this alga under laboratory conditions. McKnight and others (1981, p. F1) showed that:

> [The] leachate derived from ash collected at Richland, Washington, is toxic to the blue-green alga *Anabaena flos-aquae*, whereas leachate from ash collected at Moses Lake, Washington, is not. The difference in the toxicity of the two leachates may be attributable to differences in concentration of cationic-exchangeable, dissolved, organic compounds. *** [The] toxic components of the volcanic ash are non-uniformly distributed over the ashfall area.

The dissolved organic carbon fraction constituted a larger proportion of the entire Richland sample, compared with the Moses Lake sample. The authors concluded that toxic substances were probably not uncomplexed trace metals, but were most likely organic compounds. McKnight and others (1981, p. F11) speculated that such organic compounds might be:

(1) cationic-organic compounds such as amines;

(2) strongly hydrophobic (sparingly soluble) organic compounds such as phenols that interact with and are retained by the resin; or

(3) metal-organic complexes which are retained by interaction of the metal with the cation-exchange resins.

Blue-green algae are important nitrogen-fixers in lakes and ponds, and their relative abundance is one indicator of lake productivity. In lakes where the concentration of nitrogen compounds is limiting or in short supply, the nitrogen-fixation activities of blue-green algae are important. If blue-green algae were adversely affected by toxic substances, the lake's productivity might be altered. The amount of change in productivity would depend on the concentration of the toxic substances in the lake. The magnitude of the effect observed would vary from one lake to another, according to the composition and amount of ash received by the lake. The composition and amount of ash depends on the location of the lake in the plume. McKnight and others (1981) did not state that an effect on productivity was observed in lakes. The authors concluded, however, that their laboratory observations are consistent with the field data collected from lakes in the Moses Lake region. Analyses of Soap Lake and Lake Lenore indicated no changes in summer phytoplankton populations. In the summer of 1980, the blue-green algal bloom in Moses Lake appeared to be normal. This finding is noteworthy, because in terms of the measured quantities of ashfall received, the Moses Lake area in central Washington had one of the heaviest deposits of the study region.

The ash leachates from the Richland and Moses Lake samples were analyzed for calcium, magnesium, strontium, manganese, nickel, lithium, copper, barium, iron, cobalt, and molybdenum. Appreciable differences were found in the amounts of manganese, zinc, and iron that could be leached out of the two sets of volcanic ash samples. McKnight and others (1981, p. F6) stated:

> Several of the measured constituents (manganese, copper, zinc, cadmium, and organic carbon) were present in concentrations high enough to be possibly toxic to algae (see Hutchinson, 1957; Bartlett and others, 1974). Both leachates have high concentrations of copper, cadmium, and zinc.

These are laboratory results from *in vitro* experiments, and the authors did not state that such concentrations were eluted from the ash under actual lake conditions. However, these data suggest that toxic effects might affect other types of algae and may provide one possible explanation for the lack of response to nutrients by the algae in the previously mentioned bioassay experiments.

Case Studies of Lakes Outside the Blast Zone—Category I

Before describing and analyzing each lake in detail, it is useful to briefly review the context in which various category I lakes were studied. The effects of the Mount St. Helens eruptions on selected lakes in the State of Washington was described by Dion and Embrey (1981). The authors studied physical, chemical, and biological effects on what had been virtually pristine, oligotrophic lakes. Category I lakes, according to this classification system, were Walupt, Warden, Sprague, and Amber Lakes. Walupt Lake, approximately 37 miles northeast of Mount St. Helens, did not experience direct blast effects. Warden, Sprague, and Amber Lakes lie many miles east of the volcano, and received varying amounts of volcanic ash. A typical method by which various authors selected lakes for research is illustrated by selection criteria employed by Dion and Embrey (1981, p. G1):

(1) As a consequence of the eruption, a study lake received substantial amounts of ash.

(2) Lakes chosen had been studied prior to the eruption and "baseline" data were available so that comparisons to post-eruption studies could be made.

(3) Lakes considered to be in the immediate proximity of the volcano received deposits of pyroclastic materials, mud, timber, or ash.

(4) The eastern Washington lakes had exhibited moderate productivity levels in regard to both aquatic flora and fauna. The algal populations resident in these lakes also exhibited seasonal succession patterns.

Dion and Embrey (1981) compared the findings on category I lakes to the findings on four category II lakes located in the blast zone: Spirit, St. Helens, Fawn, and Venus Lakes. The two authors later published another report (Embrey and Dion, 1988) that was a continuation and followup to U.S. Geological Survey Circular 850–G.

Baross and others (1982) were primarily concerned with studies on microbial populations in lakes. Research on June, McBride, and Merrill Lakes included investigations on chemical responses of lakes to ashfall. Their data demonstrate dramatic differences between category I and category II lakes affected by mud and debris flows.

Staley and others (1982) utilized the term "control" lakes" in describing their studies of Merrill, McBride, June, and Blue Lakes. The bacteriological investigations demonstrated remarkable differences among the three categories of lakes studied.

Juday and Keller (1984) did not study lakes in the actual blast zone, and their investigations primarily concerned effects of ashfall in lakes located in Idaho and western Montana, downwind from the volcano. Their report includes results of investigations on several oligotrophic, high mountain lakes in Idaho. Their selection of lakes allowed for comparisons between lakes that received markedly different amounts of ashfall, and the authors possessed pre-eruption data describing oligotrophic lakes in Idaho and Montana. The report includes ash-extraction studies and incubation experiments in addition to traditional field data.

Funk (1980) studied the effects of ashfall on lakes in eastern Washington and on the upper Spokane River. A substantial amount of baseline, water-quality data were available for several lakes in this area. Food chain, water quality, and eutrophic indices had been previously well defined for Liberty Lake; Funk's work revealed alterations in the physical, chemical, and biological characteristics of this lake.

Wissmar and others (1982b) studied the chemical changes of lakes outside of and within the blast zone. McBride, June, Merrill, and Blue Lakes were used as reference lakes, because those lakes were located in what Wissmar and others (1982b, p. 175) called a region of light ashfall that was unaffected morphologically. The authors studied biological responses of lakes in the blast zone—with particular emphasis on microbiological phenomena. Baseline data for a variety of factors were available for lakes such as Spirit Lake.

Selected physical characteristics of category I lakes are listed in table 2. Complete morphometric data were not available for all lakes, but additional details about each body of water will be provided in narrative discussions. Because each lake is unique, it is difficult to discuss any one set of characteristics (for example, physical characteristics) in general terms applicable to the entire list of lakes in category I.

Table 2. Physical characteristics of selected category I lakes
[--, data not available from references cited in this report; ~, approximately; <, less than]

Lake	Altitude (feet above mean sea level)	Mean depth (feet)	Area (acres)
Amber Lake	2,160	17	120
Blue Lake	3,937	--	--
Bumping Lake	--	120	1,300
Fish Lake	~7,000	--	--
Indian Postoffice Lake (upper)	~7,546	<33	<5
Indian Postoffice Lake (lower)	~7,546	<33	<5
June Lake	3,231	--	--
Coeur d'Alene Lake	--	--	29,630
McBride Lake	2,828	23	8.9
Merrill Lake	1,555	39	490
Sprague Lake	1,878	11	1,800
Walupt Lake	3,926	176	354
Warden Lake	1,076	27	200

Although many of the lakes of a given category might have experienced similar effects from the eruption, there are enough differences among the individual lakes that attempts to generalize findings could exclude facts pertinent to a particular lake. A case-study approach will be used to describe the physical, chemical, and biological characteristics of individual lakes. A summary is presented for the readers' convenience, so the relative lack of observable effects can be compared easily to the more dramatic impacts documented for category II lakes.

Merrill, McBride, June, and Blue Lakes were a group of relatively unaffected lakes that received small, unmeasured amounts of ash. This group of lakes was used by various authors as reference lakes or "quasi-controls" and are grouped together in this section of the report.

Merrill Lake

Merrill Lake was regarded by Baross and others (1982) to be a lake unaffected by the eruptions; the lake, southwest of the volcano in Cowlitz County, Washington, is at an altitude of 1,555 feet. The lake lies in a forested drainage basin; emersed plants covered about one-fourth of its shoreline prior to the eruption. The lake received a small, unmeasured amount of ash. Although Merrill Lake was considered a reference lake, the analytical data of the authors focused on McBride Lake for comparative purposes. Staley and others (1982) report some bacterial counts for several post-eruption dates. The total microscopic counts of bacteria increased from 5.4×10^5 cells/mL (cells per milliliter) on June 30, 1980, to 1.4×10^6 cells/mL on September 11, 1980. Viable bacteria counts dropped from 1.0×10^3 cells/mL to 2.0×10^2 cells/mL on those respective dates (Staley and others, 1982, p. 666). The authors viewed these numbers to be similar to counts for lakes in western Washington such as Findley Lake, but did not speculate on increases in the total count, which were apparently relatively insignificant. Similar to McBride Lake, post-eruption total and fecal coliform counts for Merrill Lake were fewer than 1 cell/10 mL (Staley and others, 1982, p. 668).

McBride Lake

McBride Lake received only a small amount of ash, and was considered by various researchers (Smith and White, 1985; Baross and others, 1982; and Staley and others, 1982) to be an unaffected reference or "control" lake. McBride Lake is southwest of Mount St. Helens in Cowlitz County, Washington. Smith and White (1985, p. 346) described McBride Lake as a steep basin surrounded by undisturbed conifer forests, and were of the opinion that water flowing into the lake had passed over ashfall. Water flowing out of this basin was relatively free of particles. McBride Lake was considered to be a hard-water eutrophic lake, with calcium, magnesium, sodium, and potassium as the predominant cations. The research of Smith and White will be more thoroughly discussed in conjunction with category II and III lakes.

McBride Lake, as well as June and Merrill Lakes, experienced little chemical alteration and remained well oxygenated (Baross and others, 1982). Physical and chemical characteristics for McBride Lake are presented by Baross and others (1982, p. 50) and are compared to the data for Coldwater, Ryan, and Spirit Lakes—which underwent radical changes.

McBride, Merrill, June, and Blue Lakes were used as "reference lakes" for microbiological studies by Staley and others (1982), who reported a total microscopic count of 6.1×10^5 cells/mL with a viable count of 2.0×10^3 cells/mL on June 30, 1980. Total counts increased by September 11, 1980, to 1.8×10^6 cells/mL, but the viable count was reported as 2.0×10^3 cells/mL on that date. The authors speculated that viable counts were low, because some bacteria could not be cultivated for a variety of reasons. In general, the range of counts reported was considered typical of a western Washington lake. Tests for total and fecal coliform bacteria indicated no detectable cells on September 11, 1980 (Staley and others, 1982, p. 667–668).

Smith and White (1985) studied phytoplankton assemblages in McBride Lake but had no comparable data prior to May 18, 1980. The authors reasoned that because the lake was only slightly impacted by ashfall, the phytoplankton community was not appreciably altered. The authors compared McBride Lake phytoplankton data with phytoplankton data for Castle, Meta, Coldwater, and Spirit Lakes. In summary, McBride Lake data are useful primarily because this lake served as an excellent reference for several groups of investigators.

June Lake

June Lake, considered by Baross and others (1982) to be unaffected by the blast, was used in conjunction with McBride and Merrill Lakes for comparative purposes. June Lake is southeast of the crater and received only ash. The authors primarily were concerned with initial microbiological responses of different lakes, and studied physical and chemical factors relevant to microbial metabolism. For example, June Lake was contrasted to heavily impacted lakes that became essentially anaerobic after the eruption and experienced concomitant rapid increases in growth of heterotrophic bacteria.

Characteristics of volcanic ash, with reference to chemical analyses performed by Fruchter and others (1980), were discussed by Baross and others (1982, p. 50) who stated:

> All the lakes near the volcano have received periodic input of volcanic ash, of dacitic composition, consisting primarily of silica and aluminum oxides, and mainly of sand size.[The volcanic ash was carried, at intervals, into] all the lakes near the volcano.

Leaching experiments, conducted under aerobic conditions, indicate that ash contains nutrients such as sulfate, phosphate, and the trace elements manganese, iron, and molybdenum. According to Baross and others (1982, p. 50), "Most of the constituents of the ash are insoluble in aerobic conditions."

Although June Lake was outside the blast zone, some apparent alterations of dissolved chemical characteristics were reported by Wissmar and others (1982b). [Numerous allusions to the research of Wissmar and others (1982b) will be made throughout this entire report, and it should be noted that this group's chemical data relate to dissolved chemical constituents that pass through a 0.45-micron Millipore filter.] Concentrations of some chemicals appeared to be elevated, in comparison to data presented by other researchers. The authors state that June Lake contained larger post-eruption concentrations of major cations such as sodium, primary nutrients (nitrate-nitrogen), and silica (Wissmar and others, 1982b, p. 177). The authors attributed this increase to effects of erosion and mudflows close to the lake.

Staley and others (1982) designated June Lake a "control" or reference lake. June Lake was sampled on July 16, 1980. The direct microscopic count of bacteria was 1.4×10^5 cells/mL; the viable count was 9.0×10^2 cells/mL. No information on total or fecal coliform bacteria is available for June Lake. Microscopic and viable counts for June Lake were comparable to counts for Findley Lake—considered to be totally unaffected by the eruption. In summary, few conclusions can be made about changes in characteristics of June Lake.

Blue Lake

Blue Lake, a subalpine lake in Cowlitz County, Washington, lies outside the direct blast zone and received a small, unmeasured amount of ash. Blue Lake, along with Merrill, McBride, and June Lakes, was considered to be a "control" lake by Staley and others (1982). Blue Lake was called a U Lake, according to Wissmar and others (1982b, p. 175), meaning: "[It lay in a] morphologically unaffected region with light ashfall, outside the blast zone***." Pre-eruption morphometric information or bathymetric profiles for Blue Lake are unavailable; similarly, pre-eruption data on physical characteristics, such as transparency and specific conductance are lacking. The same lack of baseline data exists for Merrill, McBride, and June Lakes, which are located south of the crater.

Wissmar and others (1982b) compared data collected on June 30, 1980, with pre-eruption information for several lakes, including Spirit Lake. The June 30 samples were from a depth of 0.82 foot below the water surface, and data relate to analyses only for this part of the water column. At the time of sampling, the alkalinity of Blue lake was 136 µeq/L (microequivalents per liter), and the pH was 6.95. After the eruption, the chemical constituents of Blue, Merrill, and McBride Lakes were found to be similar to the pre-eruption chemical constituents of Spirit Lake and other bodies of water in the vicinity of Mount St. Helens. For example, concentrations of nutrients (such as phosphorus and nitrogen), major cations, and trace metals were quite comparable (Wissmar and others, 1982b, p. 175–176). In other words, although pre-eruption chemical data were unavailable for reference lakes, Spirit Lake pre-eruption data were used for comparison. Spirit Lake, before the eruption, was considered by most researchers to be a typical oligotrophic lake. In this manner, characteristics of post-eruption Blue Lake were compared to Spirit Lake conditions prior to May 18, 1980. A slightly higher level of sulfate was reported for Blue Lake, and the concentration of 2.8 mg/L (milligrams per liter) reported in Blue Lake was the highest concentration observed for all the U Lakes. This concentration is three times the pre-eruption concentration of sulfate in Spirit Lake. Similarly, it appears the concentration of chloride was the largest for the U Lakes, and more than twice the level found in pre-eruption Spirit Lake. The 0.34 mg/L concentration of manganese is the largest of the U Lakes, but comparable data for pre-eruption lakes were not available.

The biological responses of various lakes were studied by Wissmar and others (1982a), who compared post-eruption findings to Findley Lake, an oligotrophic lake regarded by Wissmar to be completely unaffected by the eruption. Findley Lake lies in King County, Washington, about 200 miles north of Mount St. Helens and hence could serve as a reference to which Merrill, McBride, June, and Blue Lakes could be compared. Various authors made such comparisons out of necessity, because few baseline data existed for biological characteristics of many lakes in the area. Wissmar and others (1982a) studied the microbiological changes and made various physicochemical measurements. On June 30, 1980, the total bacteria count for Blue Lake (Wissmar and

others, 1982a, p. 179) was 8×10^5 cells/mL, which was regarded to be equivalent to maximum annual counts previously observed for Findley Lake. Viable heterotrophic bacteria counts were 2×10^3 cells/mL. Total coliform and fecal coliform counts were not measured for Blue Lake.

Wissmar and others (1982b, p. 178) measured particulate organic carbon (POC), particulate organic nitrogen (PON), and dissolved organic carbon (DOC), chlorophyll *a*, and adenosinetriphosphate (ATP) levels. For Blue Lake, concentrations of POC, PON, chlorophyll *a*, and ATP were larger than for Findley Lake. These increases in Blue Lake were attributed to higher populations of phytoplankton and invertebrates —not because the lake received ashfall. These observations contrast dramatically to effects described for lakes in the blast zone, such as Spirit Lake.

Total direct microscopic counts of 7.6×10^5 cells/mL, and viable counts of 1.8×10^3 cells/mL (determined by plate counts) were reported by Staley and others (1982, p. 667). These counts were from samples taken on June 30, 1980, and are nearly identical to counts by Wissmar and others (1982a) previously described.

Bumping Lake

Bumping Lake is not a natural lake, but is a storage reservoir located 29 miles northwest of Naches, Washington. The reservoir is on the Bumping River and has been a popular fishing area that contained mountain whitefish and several species of trout. Bumping Lake received about 0.10 inch of ashfall. Some pre-eruption, baseline, water-quality data and biological information was available to researchers. After the eruption, the lake was sampled on June 23, 1980, and in September 1980 by Faulconer and Mongillo (1981).

Faulconer and Mongillo (1981, p. 16–17) reported an increase in conductivity, and a reduction in Secchi-disk transparency after the eruption. The Secchi-disk transparency (a flat disk lowered into water that measures transparency, expressed as the depth at which the disk disappears from sight) changed from 7.6 feet prior to the eruption to 1.8 feet after the eruption. Measurements of chlorophyll *a* as an estimate of the phytoplankton standing crop indicated a decrease in primary production. The authors speculated that the reduction in chlorophyll *a* could be attributed to light attenuation effects caused by suspended ash particles. The authors reported a decrease in zooplankton numbers, and discussed the possibility that ashfall may have contributed to zooplankton mortality. However, there appeared to be little effect on benthic invertebrates. Gill nets were used to collect fish, which were weighed, measured, and sexed. The fish also were checked for gill damage and the general condition of the body. No damage to gills of fish or other physiological effects on fish were noted. The 1980 fishing season generally was considered to be good, in comparison to historical data.

Fish Lake and Upper and Lower Indian Postoffice Lakes

The upper and lower Indian Postoffice Lakes in Idaho County, northern Idaho, received a depth of ashfall estimated to be about 0.25 inch; these are grouped by Juday and Keller (1984, p. 14) with Fish Lake for study purposes. The three lakes were considered to be oligotrophic. Scarcely any morphometric data are available for the Indian Postoffice Lakes; the lakes are high mountain lakes located at an altitude of about 7,000 feet. The upper and lower Indian Postoffice Lakes each have an area of approximately 5 acres; the depth of each lake is less than 30 feet.

Juday and Keller (1984) presented pre- and post-eruption data for nitrate-nitrogen, total inorganic phosphorus, and total phosphate phosphorus, found in the upper and lower Indian Postoffice Lakes and in Fish Lake. The three lakes exhibited ash effects on the chemical constituents. Data of Juday and Keller (1984, p. 115–117) are summarized in table 3, which includes information for Fish Lake.

Fish Lake is located in the Bitterroot Mountains of Idaho, in the Clearwater National Forest. Juday and Keller (1984) included Fish Lake in their studies, largely because of the availability of historical data collected in 1979. Fish Lake had received ashfall, reported by several observers to be approximately 0.25 inch deep, although accurate measurements were not available. Fish Lake is thought to have received about 1 kg/m^2 (kilogram per square meter) of ash, much of which contained substantial quantities of magnetic iron oxide.

Nitrate-nitrogen and total phosphate-phosphorus levels dropped by about 50 percent after the eruption in Fish Lake, and both chlorophyll *a* and phaeophytin concentrations dropped by an order of magnitude at the three depths sampled (see table 3).

Table 3. Concentrations of nitrogen, phosphorous, chlorophyll *a*, and phaeophytin in lakes of Idaho before and after the May 18, 1980, eruption of Mount St. Helens, Washington
[Concentration units are in micrograms per liter; <, less than]

Depth in feet	Nitrate-nitrogen	Inorganic-phosphate	Total-phosphate	Chlorophyll *a*	Phaeophytin
		Indian Postoffice Lake (upper)			
		September 17, 1979			
Surface	<1	1	12	0.4	0.3
9.8	<1	1	10	.3	.3
20	<1	1	16	.3	.3
		August 17, 1980			
Surface	<1	1	10	.7	.4
		August 14, 1981			
Surface	<1	<1	6	1.3	.1
		Indian Postoffice Lake (lower)			
		September 17, 1979			
Surface	<1	2	18	.7	.2
13	<1	2	27	1.5	1.5
		August 17, 1980			
Surface	<1	2	10	1.1	.8
		August 14, 1981			
Surface	2	<1	10	1.2	.05
		Fish Lake			
		July 24, 1979			
Surface	<1	5	13	1.9	1.1
26	<1	3	9	2.2	1.2
52	11	2	11	23.1	13
		July 31, 1980			
Surface	<1	2	4	.3	.1
8	<1	2	4	.3	.1
16	5	2	6	.6	.3

Other chemical constituents appeared to be unchanged. Juday and Keller (1984) state that for these oligotrophic lakes, productivity cycles are affected by the seasonally observed fluctuations in runoff and flooding, which affect nutrient loading in the lakes. The lakes lie at high altitudes, so that the presence of ice cover during winter months profoundly affects photosynthesis and algal productivity. Blooms of algae, which vary in type and duration depending on available nutrient levels and sunlight, may occur as the snow and ice melt. The authors believe that observed post-eruption fluctuations in levels of productivity, estimated by comparisons of chlorophyll *a* values, were difficult to interpret because of the usual seasonal cycling of nutrients. The variations in runoff, flooding, ice and snowcover, and sunlight were characterized as fluctuations in climatological factors.

A comprehensive analysis of algal productivity and effects of climatological factors on productivity is presented by Juday and Keller (1984, p. ii), who concluded that, in general:

> [The ashfall] had virtually no effect on [the] productivity of oligotrophic lakes. Appreciable increases in algal productivity were noted in mesotrophic lakes in 1980 [in contrast to oligotrophic lakes], although these increases were no larger than might be expected from climatological changes or from local logging activity.

Chemical analyses of extracts from ash within this area showed the ash contained substantial amounts of nutrients. These nitrates and phosphates were thought to be capable of enhancing algal productivity, provided they could be released from ash to lake water. This possibility had been examined in the laboratory by Juday and Keller (1984), who had demonstrated nutrients were indeed water-extractable from ash. Furthermore, their laboratory work included tests in which lake water samples were incubated with nutrient extractions from ash. Those tests indicated extracts could enhance algal productivity in lake-water samples, so analogous results might have been expected for the real-world situation. According to Juday and Keller (1984, p. ii):

> Laboratory studies showed that, imitating natural conditions, appreciable amounts of nutrients could be extracted and that the extracts increased algal productivity of incubated lake samples.

The authors concluded, however, that concentrations of nutrients did not increase in lake water because of ashfall.

Coeur d'Alene Lake

Skille and others (1983) studied the Coeur d'Alene Lake and River system to determine the effects of volcanic ash. This lake-river system in northern Idaho is 200–300 miles east of the volcano, well removed from the blast zone of Mount St. Helens. Both the Coeur d'Alene and St. Joe Rivers flow into Coeur d'Alene Lake, and will be included in discussions of rivers later in this report. The Coeur d'Alene Lake and River system provided an opportunity to study ash in sediments and in water columns. Skille and others (1983) investigated chemical and biological composition, and examined benthic, phytoplankton, and zooplankton populations. In this review, Chatcolet, Hidden, and Round Lakes are considered flood plain category I lakes that belong to the Coeur d'Alene system, whereas deep lake samples are those collected from Gasser Point and Brown's Bay in Coeur d'Alene Lake.

All these sampling sites lay in the part of the plume that distributed substantial ash. Although the lakes are many miles from the volcano, this part of Idaho received an ash layer ranging from 0.25 to 0.75 inch in depth. Core samples for the measurement of ash and sediment thickness were taken from the bottoms of the lakes in this part of the plume.

According to Skille and others (1983, p. 15), the thickness of the sedimented ash over the entire lake system averaged 0.22 inch during 1981. By 1982, the thickness had increased to 0.30 inch. The differences in values obtained were attributed to sampling and measurement errors. Significantly, the authors concluded the ash layer formed a distinct layer and did not have a tendency to mix with either old or new lake bottom sediments over the 2-1/2-year period following the eruption. Skille and others (1983, p. x) stated:

> ***[The] ash layer in the lake sediments and throughout the watershed was stable and not easily resuspended or eroded. The volcanic tephra was chemically inert and had no measurable impact on water chemistry or nutrient enrichment. Benthic and planktonic communities were unchanged relative to pre-ash conditions.

In addition to extensive physical and chemical analyses, the authors also performed leachate analyses of the ash. The results indicated this ash did not constitute a significant source of nutrients, as it contained only low to nondetectable levels of phosphate, ammonia, nitrate, and nitrites. According to Skille and others (1983, p. 55):

> This indicates that the sedimented tephra has a negligible effect on primary production in the water column, a conclusion supported by our primary production measurements.

The following is a synopsis of the work and findings of Skille and others (1983, p. 66–90):

(1) No significant changes in pH values were detected as a result of ash deposition.

(2) Conductivity, turbidity, and Secchi-disk transparencies did not significantly change. The very small amount of tephra which resuspends during normal seasonal turnover does not appear to affect the penetration of light or the clarity of the water.

(3) Thirty-four genera of phytoplankton were studied, and investigations on succession patterns were made for the years 1981–82. Skille and others (1983, p. 67) did not detect:

"* * * substantial decreases in algal numbers relative to 1970."

(4) The primary production level in this lake system appears to parallel production levels that were observed during pre-eruption investigations.

(5) Zooplankton densities of cladocerans and copepods, compared with pre-ashfall data, suggest the ash did not significantly alter either the abundance or diversity of zooplankton species. Genera studied included *Daphnia, Alona, Camtocercus, Ceridaphnia, Leptodora, Canthocamptus, Cyclops, Epischura,* and others. (Extensive data were published listing the various species for "pre-ash" and "post-ash" periods for Round Lake, Gasser Point, and Brown's Bay.)

(6) There appeared to be no significant changes in either the abundance or composition of the benthic population of oligochaete or chironomid populations a short time after the ashfall, nor had long-term effects been observed.

(7) According to Skille and others (1983, p. 88–89): "[The sedimented layer of ash did not] alter the vertical stratification pattern of the littoral benthic community." It had been hypothesized that a dense layer of ash could disturb the burrowing patterns of the benthic fauna, thereby changing the vertical distribution of organisms. This did not happen.

In summary, these scientists did not consider the ash to cause any significant physical, chemical, or biological changes in the lakes examined.

Soap Lake

Soap Lake and Lake Lenore are alkaline lakes in the Lower Grand Coulee region of central Washington and are grouped together in this report for that reason. The lakes were studied by Edmondson and Litt (1983). Similar to Lake Lenore, Soap Lake was diluted by a freshwater-irrigation project and was studied prior to the eruption of Mount St. Helens, because its specialized flora and fauna changed in community structure as the salinity decreased. The water-quality characteristics of Soap Lake had been investigated for nearly three decades prior to the eruption. The alkaline, moderately saline water was historically incapable of supporting a population of fish. Edmondson and Litt (1983, p. 2) reported that the ash reaching the lake formed a bottom layer approximately 0.08–0.24 inch thick, and that the ash had settled out rapidly. As in the case of Lake Lenore, after the eruption the population of *Diaptomus sicilis* (a Crustacean of the Order Copepoda) decreased in Soap Lake; but this decrease was considered part of the normal cycle of this organism. A water flea (Cladocera), *Moina hutchinsoni,* was found to increase numbers in its usual seasonal fashion, and this also was considered normal. The layer of ash did not appear to prevent the larvae of midges (Chironomidae), which are aquatic insects, from reconstructing their normal shelters, consisting of tube-like structures held together by salivary gland secretions. The secretions are silklike in texture and are used to fasten together materials found in the insect's environment. On lake bottoms, silt is used to make soft dwelling tubes for the larvae. After the eruption (Edmondson and Litt, 1983, p. 2), "[the midge larvae] were able to burrow up through the ash layer and reestablish their tubes." These herbivorous larvae provide food for fish, which is the primary reason they were included by Edmondson and Litt (1983) in previous predation studies.

Edmondson and Litt (1983) also compared counts of a rotifer to normally observed seasonal cycles studied since 1968. The cycle for *Hexarthra polyodonta* did not appear to be altered. In summary, although the authors did not conclude that data is indicative of effects attributable to ashfall, the information is noteworthy because there appeared to be no harmful effects due to the ash—even though the ash formed a measurable layer on the lake bottom. These observations are particularly significant because data could be compared to historical information spanning several decades. In general, pre-eruption biological information for many of the lakes listed in this report was scarce, even for a few species.

Lake Lenore

Considered by Edmondson and Litt (1983) to possess specialized flora and fauna, Lake Lenore was the subject of many investigations 30 years prior to the eruption of Mount St. Helens. The alkaline lake is considered to be highly productive and is different in this respect from most other category I lakes, which are oligotrophic. Prior to the eruption, the salinity of Lake Lenore changed substantially because of dilution effects from a nearby freshwater-irrigation project

(Edmondson and Litt, 1983). The history of the changes in biota attributable to alterations in the lake's salinity prior to 1980 will not be presented here, but it should be noted that the lake had been incapable of supporting populations of fish. Over the years, attempts to introduce a species of rainbow trout were unsuccessful. Finally, in 1977, a subspecies of cutthroat trout *(Salmo clarki henshawi)* that normally lives in alkaline lakes of moderate salinity, was introduced into Lake Lenore. The stocking of the lake with this fish was regarded to have a significant effect on the biological characteristics of the lake. Within the context of studies done on the effects of introducing this fish, Edmondson and Litt (1983) did their research. Investigations were undertaken to determine predation effects of that fish species on populations of predatory Odonata (damselflies and dragonflies) and salamanders. Concurrent research on the benthos and plankton of this lake also was planned.

Edmondson and Litt (1983) did not evaluate physical or chemical constituents in their study, which was interrupted, from their point of view, by the volcanic eruption. When Mount St. Helens ash fell into Lake Lenore, the continuity of the environmental conditions required for field-study analyses was interrupted. According to Edmondson and Litt (1983, p. 2), the ash, after rapidly settling out, formed a layer 0.08 inch thick in Lake Lenore.

After the eruption, a decline in the numbers of the copepod *Diaptomus sicilis* was observed by Edmondson and Litt (1983, p. 2). However, the authors did not attribute this change to ashfall, because the population of this species changes seasonally as a normal part of its life cycle. Copepods serve as food for different sizes of fish; therefore, the availability and distribution of copepods is important in considering predatory effects of fish. At the same time, the population of the Cladoceran *Daphnia pulex* (a water flea) increased according to its normally observed seasonal cycle. The importance of the Cladocera in predation experiments is recognized, because these organisms are responsible for converting small, freshwater algae into food that carnivorous animals consume. Young fish feed upon Cladocerans, whereas older and larger fish eat insect larvae that feed upon *Daphnia*. Edmondson and Litt (1983) did not attribute changes in *Daphnia* to ashfall; fluctuation in the *Daphnia* population appears similar to the changes observed in previous years. The authors also noted a substantial number of dead amphipods (higher crustaceans, such as scuds) after the ash was deposited on the lake, but regarded their death to be a normal seasonal event. The amphipods increased in number later in the year. Salamander tracks on the ash layer, which are indicative of active survivors, were seen by Edmondson and Litt (1983, p. 2). In general, the authors did not attribute any substantial changes in Lake Lenore to volcanic ash.

Liberty Lake

Liberty Lake, studied by W.H. Funk of Washington State University prior to the eruption of Mount St. Helens, is in Spokane County in eastern Washington—outside the blast zone. The lake was already undergoing eutrophication before May 18, 1980, and had been intensively studied by Funk (1980) for that reason. During these pre-eruption studies, the lake had been monitored by automatic sampling devices and other gaging instruments. Changes in measurements of pH and light extinction coefficients occurring during the period of ash fallout could be noted, because preparations for intensive monitoring had already been made. Importantly, Funk had surveyed biological and chemical conditions only 2 days prior to the eruption, and had investigated zooplankton, phytoplankton, and benthic invertebrate populations. Funk also had conducted studies with carbon-14 assimilation and chlorophyll *a* as a measurement of productivity.

Post-eruption physical characteristics studied by Funk (1980, p. 18–19) included light penetration and transparency readings. His results indicated a decrease in light penetration, measured as a change in vertical extinction coefficients. The effect was most pronounced in the blue wavelengths of light. The decrease in light penetration was not persistent, and values returned to near-normal levels within a month. Within 2 weeks after the eruption, Secchi-disk-transparency readings decreased 50 percent.

The chemical characteristics of Liberty Lake appeared to be substantially altered as a result of ashfall and, according to Funk (1980, p. 18):

> [There was an order-of-magnitude increase in levels of aluminum and silicon, as well as a] quadrupling of Fe [iron] and Mn [manganese] and a doubling of Cu [copper]. Preliminary results of nutrient analyses indicate a decrease of approximately 50 percent in total phosphorus.

Little change in the concentration of other chemical species was observed. The amount of ashfall received by the lake, and which caused the changes, was not measured precisely. Funk's observations on the increase in iron and manganese concentrations in lake water is consistent with analyses of lakes by various researchers.

Profound post-eruption changes in biological characteristics of the lake were reported by Funk (1980, p. 18), who noted: "[A] massive decrease in numbers and volume of phytoplankton immediately occurred." The decrease in the algal population was apparently not long-lived. Less than a month after the eruption, the population numbers returned to within two-thirds of pre-eruption counts. Although the numbers started to return to normal, Funk indicated the variety of species comprising the population may have been altered. Studies with carbon-14 also indicated that the productivity of Liberty Lake dropped to about one-half of the pre-eruption level, and the blue-green algal population nearly disappeared. This finding is possibly consistent with the ash-toxicity data of McKnight and others (1981) previously discussed. The author reported a drop in numbers of each zooplankton group studied, but the relative proportions of each species appeared unchanged. As mentioned previously, Liberty Lake was undergoing eutrophication and, for that reason, apparently had been treated with alum in 1974. Funk (1980) remarked that after the eruption and ashfall, the lake conditions resembled those that existed after the chemical treatment of 1974. The author was unable to determine if changes observed were a consequence of either alterations in chemical water quality or physical effects of ash that might have caused algae to be removed from the water.

The biological changes noted by Funk are significant, because few other researchers were able to perform comparative biological studies of category I lakes.

Liberty Lake had already been observed to be in a stage of eutrophication; therefore, it was not typical of other category I lakes that were used by researchers as reference lakes. It appears necessary to view alterations in Liberty Lake within that context.

Walupt Lake

Walupt Lake was studied by Embrey and Dion (1988) from June through October of 1980 as a comparison lake. Walupt Lake, situated east of Mount St. Helens in Yakima County, Washington, was far removed from the blast zone. Walupt Lake did not appear to exhibit any significant changes in chemical constituents after the eruption, although dissolved manganese slightly increased for a brief period of time.

Some data are presented by the authors regarding phytoplankton and zooplankton communities, but little pre-eruption data for comparisons existed. Numerous species of Chlorophyta, Chrysophyta, Cyanophyta, Cryptophyta, Eugelenophyta, Pyrrophyta, and other groups were identified. Shortly after the eruption of June 23, 1980, one species of Chrysophyceae, *Dinobryon bavericum* (after Imhoff), was dominant (Embrey and Dion, 1988, p. 54, 60). Several months later, there was a more mixed community, and other species were dominant or codominant; the authors drew no conclusions from phytoplankton or zooplankton population data. The authors were hindered by the lack of baseline biological information for most lakes. For Walupt Lake, however, their research contributed a considerable volume of new information.

Amber Lake

Amber, Sprague, and Warden Lakes were grouped together in the studies by Dion and Embrey (1981). The three lakes, located in eastern Washington, constitute a geographical group and are classified here as category I lakes. The lakes were regarded to be unaffected by the explosion, except for the receipt of ashfall. For that reason, these lakes are discussed and grouped together in this report.

Amber Lake was far removed from the volcano's blast zone in Spokane County, Washington, and was downwind from Mount St. Helens. The lake received ash deposits of up to 3 inches in depth. No changes in the configuration of the lake's basin occurred as a consequence of the eruption.

Historical data from 1973 were available for Amber Lake, and water-quality data on Amber Lake were collected by Dion and Embrey (1981, p. G22) on June 26, 1980, and on August 14, 1980. Comparisons of post-eruption data to 1973 data indicate that about a 10 percent increase in specific conductance at a depth of 36 feet may have occurred. Secchi-disk transparency ranged from 9.8 to 18 feet in pre-eruption measurements and ranged from 12 to 17 feet in post-eruption measurements.

The water temperature appeared normal. The long interval between the different sets of information introduces some uncertainty regarding the actual magnitude of difference between values measured. The authors concluded that physical characteristics of this lake were not changed.

Some changes were observed, however, in the chemical characteristics of Amber Lake. Dion and Embrey (1981, p. G18, G22):

> *** suggest that the dissolved iron concentration in the hypolimnion (bottom water layer) of Amber Lake and the dissolved manganese concentration in the hypolimnion of both Warden and Amber Lakes have increased.

These findings did not enable the authors to attribute changes in either iron or manganese concentrations directly to ashfall received by the lakes, because their data for Sprague Lake indicated a decrease in the concentrations of dissolved iron and dissolved manganese. Nonetheless, in pre-eruption data for the lake, dissolved manganese ranged in concentration from 30 to 340 μg/L (micrograms per liter) at depths greater than 30 feet, whereas post-eruption values ranged from 660 to 1,200 μg/L at equivalent depths. Similarly, dissolved iron concentrations in Amber Lake ranged from 40 to 150 μg/L in pre-eruption data, whereas post-eruption concentrations of 980 μg/L were observed.

There was little pre-eruption information regarding biological characteristics of Amber Lake, but information was available regarding concentrations of chlorophyll *a* in the water. The concentration of chlorophyll *a* is related to the productivity of the lake, because this pigment is found in all groups of aquatic algae. Comparisons of the concentrations of chlorophyll *a* revealed no significant changes.

Sprague Lake

Sprague Lake was considered by Dion and Embrey (1981) to be largely unaffected by ash received from the eruption. Sprague Lake is in Adams County of eastern Washington and lies outside of the blast zone along with Warden and Amber Lakes. Sprague Lake received up to 3 inches of ash. Amber, Sprague, and Warden Lakes are considered to be alkaline lakes, compared to the study lakes lying within the blast zone. According to Dion and Embrey (1981, p. G23), the three lakes were more productive than other lakes investigated. The authors published Sprague Lake water-quality data from 1975. The post-eruption data are for June 25 and August 13, 1980.

The specific conductance (microsiemens per centimeter at 25 degrees Celsius [μS/cm at 25°C]) after the eruption may have increased approximately 13 percent at depths ranging from 13 to 15 feet. Apparently, post-eruption concentrations of iron and manganese decreased substantially at two depths (3 and 15 feet). Concentrations for dissolved manganese ranged from 30 to 50 μg/L in 1975, from samples taken on four different dates. During the period June through August of 1980, the manganese concentrations ranged from 0.0 μg/L to approximately 20 μg/L. The concentration of dissolved iron appeared to drop an order of magnitude, from a range of 80 to 340 μg/L at various depths on August 13, 1975, to a range of 10 μg/L to 20 μg/L at a depth of 15 feet on August 13, 1980. The authors considered this information to be at variance with their data for Amber and Warden Lakes, in which post-eruption concentrations for iron and manganese were elevated. Dion and Embrey (1981, p. G18) stated:

> "[Given] this set of seemingly contradictory data, it is difficult to ascribe changes in the water chemistry of the lakes to the eruption with any degree of certainty."

Sprague Lake's post-eruption productivity was studied by Dion and Embrey (1981, p. G23), who used the concentration of chlorophyll *a* as an index. A value of 133 μg/L was noted on August 13, 1980, which is four to five times greater than values obtained prior to the eruption. However, stated Dion and Embrey (1981, p. G23):

> Sprague Lake has a history of summer blooms, and there is no evidence to indicate that the bloom observed on that particular date was a result of ash deposited in the lake.

The authors believe that biological effects were difficult to evaluate because some ash effects might promote the growth of algae, whereas other effects might retard growth. For example, an increase in nutrients or alkalinity might be beneficial, whereas physical changes such as a reduction in transparency and light would have a negative effect on photosynthesis. The authors discuss the difficulties encountered in attempts to perform multivariate analyses on systems in which many changes occur simultaneously and suggest that caution be exercised when attempting to use the data for predictive purposes.

Dion and Embrey (1981) discussed the possibility that leachate from volcanic ash may have possible toxic effects on some algae. McKnight and others (1981) had performed experiments on the leachate from the ash collected from several sites in eastern Washington. Their findings and conclusions, relative to Sprague Lake, will be discussed later.

Warden Lake

Warden Lake is in Grant County, south of Moses Lake, in eastern Washington. The lake, which is outside the blast zone, received 0.4 to 1.2 inches of ashfall. Baseline data were available for Warden Lake prior to May 18, 1980—a principal reason for selecting this lake for study. Dion and Embrey (1981, p. G20) present information on various water-quality constituents for pre- and post-eruption sampling dates. For specific conductance, pH, temperature, dissolved oxygen (DO), and hardness, there were no appreciable changes as a result of the eruption or ashfall. The only chemical constituent that appeared to have changed was manganese, in the lake's hypolimnion. The manganese concentration at a depth of 65 feet was 440 µg/L on June 24, 1980, as compared to the concentration of 290 mg/L at a depth of 62 feet measured on August 18, 1975. Dion and Embrey (1981) did not ascribe this change directly to the eruption.

Summary of Volcanic Effects on the Water Quality of Category I Lakes

Physical Characteristics

In general, substantial data do not exist to indicate that lakes outside of the blast zone underwent appreciable, long-term, physical changes. Certainly, no physical changes in area, volume, configuration, basins, or profiles of these lakes were evident, and no physical changes would be expected. Authors were seldom able to measure the actual amounts of ashfall received by these lakes, although in several cases some estimates were made.

Specific conductance was measured for various category I lakes, and some changes were observed. The apparent increase in specific conductance may have been as great as 13 percent, depending on depth, in several lakes after the eruption; but the magnitude of the changes was not comparable to the increase observed in category II lakes.

The transparency of lake waters, as measured by Secchi disk, might be expected to change, if the amount of ash falling into a lake was appreciable. If the ash remained suspended, the transparency would decrease. Dion and Embrey (1981) found no changes in the transparency of category I lakes that could be attributed, positively, to ashfall. The authors observed a low transparency (3.5 feet) in Walupt Lake on June 23, 1980, but were uncertain about the exact cause of this low reading and stated that it may have been a consequence of ash falling on the lake. Dion and Embrey, (1981, p. G17–G18) speculated that another possible source of suspended sediment may have been ash associated with snow in the drainage basin, because the sampling was performed at a time of:

> ***high runoff and inflow***. The sediment may also have been the result of normal spring runoff, although the minimum transparency value observed prior to the eruption was 20 feet (in 1971).

In any event, it seems reasonable to conclude that in several cases, ash may have contributed to a decrease in lake-water transparency, as a consequence of either direct fallout or from being carried by inflow from basin drainages at a later date.

Reduced transparency in the Coeur d'Alene Lake system was reported by Skille and others (1983, p. 66). The Secchi-disk transparency decreased from 8.2 feet to 1 foot, but the effect was of short duration. The authors stated that once ash settled to the lake bottom, it did not tend to resuspend in sufficient quantities such that light penetration would be affected. Similarly, no changes in turbidity attributed to ash "mixing" during the annual turnover of lake water were reported.

Funk's (1980) report on Liberty Lake reflects the most substantial changes in physical characteristics for a category I lake. Funk reported that light penetration was decreased immediately after the eruption, and changes observed were most pronounced in the blue wavelengths of light. The effect was of short duration; however, Funk reported that within the 2-week period following the volcano's explosion, Secchi-disk transparency decreased 50 percent when compared with pre-eruption values. Regardless of the fact that Liberty Lake is not a typical category I lake because of its history of eutrophication, the physical measurements by Funk constitute compelling evidence of physical changes caused by ashfall in some lakes.

For Soap Lake and Lake Lenore, Edmondson and Litt (1983, p. 2) observed that ash was settling to the bottom of the lakes. The ash did not appear to remain suspended, but settled rapidly to the bottom of these lakes to form an identifiable layer. This ash layer was approximately 0.08 to 0.2 inch thick in Soap Lake, but less than 0.08 inch thick in Lake Lenore.

The observations of Skille and others (1983) corroborate the conclusions of Edmondson and Litt (1983), who reported that ash formed a distinct layer on lake bottoms. Skille and others (1983) conducted research on benthic lake communities and stated that nearly 2-1/2 years after the eruption no discernible mixing of the ash layer was evident with either parent sediments or newly deposited non-ash sediments. According to Skille and others (1983, p. 15): "While doing experiments with the benthic communities on the lake bottom, we found that the ash layer could literally be rolled away like a carpet." The authors concluded that settling of the ash had been rapid, and that the ash layer itself was cohesive with no tendency toward migration or movement. Ash that had fallen on land in the lake basin appeared to be resistant to erosion by rain and surface-water runoff. In addition, during the months after the eruption, there did not seem to be any secondary layers of ash added to the original layer. The authors were of the opinion that, for the Coeur d'Alene Lake Basin, the ash layer was so well consolidated it could be used as a marker for future sediment studies of the deep areas of Coeur d'Alene Lake (Skille and others 1983, p. 15–30).

Chemical Characteristics

In many instances, little pre-eruption data existed for a particular lake, so data on concentrations obtained for any given constituent after May 18, 1980, cannot be compared with true baseline data. For this reason, much of the chemical data in the literature on category I lakes is of most value when it is used to compare analytical results for the category II lakes. The bulk of the information on pH, alkalinity, trace elements and metals, hardness, alkalinity, and gases would fall in this category. Many authors had to use the parallel lake comparisons out of necessity; however, the reader must be conscious of the limitations inherent with this technique. It is risky, at best, to compare data from widely separated lakes without knowledge of seasonal variations. This summary primarily concerns noteworthy or unusual observations presented by researchers. A collection of abstracts of conclusions taken from the case histories is presented for the reader's convenience.

Major Cations: Calcium, Magnesium, Sodium, and Potassium

In most cases, changes of cation concentrations in category I had to be inferred by the use of the parallel lake-comparison technique already described. Wissmar and others (1982b) list concentrations of many cations for their reference lakes, from samples dated June 30, 1980, but pre-eruption data were not available for some of the reference lakes. Data were available for Spirit Lake on April 14, 1980, however, and were used to compare post-eruption data for the category I lakes. Information for pre-eruption Spirit Lake was considered by Wissmar to represent similar, subalpine lakes found in the Cascade Mountains. For example, the concentrations of the dissolved calcium for Spirit Lake prior to the eruption were 2.1 mg/L, but values of calcium found in the category I lakes ranged from 2.2 mg/L to 4.1 mg/L. If pre-eruption data for Spirit Lake waters were to be used as baseline values, the concentration of 4.1 mg/L found in June Lake might be considered elevated. Because the pre-eruption concentration for June Lake was not known, caution should be used to draw conclusions about the actual magnitude of the apparent increase in dissolved calcium concentration. Likewise, the same caution should be used in speculating that concentrations of magnesium, sodium, and potassium were elevated for several lakes in category I that were outside of the blast zone. Similarly, one could note a concentration of Na^{1+} (sodium) of 8.8 mg/L in category I for June Lake, compared to a pre-eruption value of 2.0 mg/L for Spirit Lake (Wissmar and others, 1982b, p. 176). Regarding Merrill, McBride, June, and Blue Lakes, Wissmar and others (1982b) stated that concentrations of major cations and metals in these lakes were comparable to values found for pre-eruption lakes near the volcano. When comparing the effects of the eruption on relatively unaffected category I lakes with category II lakes, however, the post-eruption differences are very striking and will be discussed later.

Dissolved Iron and Manganese

The findings of different research teams indicate that for some lakes in category I, concentrations of dissolved iron and manganese seem to be increased.

These concentrations generally were greater than those measured prior to the eruption of May 18, 1980. It seems reasonable to conclude that the source of these two elements was the ash.

The trace element manganese was found in ash; however, many of the trace elements found were insoluble under aerobic conditions (Baross and others 1982). The experiments of Juday and Keller (1984, p. 8) indicated: "Manganese extraction is also limited largely to the anaerobic extractions as would be expected." This phenomenon is related to the fact that anaerobic bacteria will mobilize iron and manganese, while using nitrate as an energy source. In Amber and Warden Lakes, there seemed to be an increase in dissolved manganese and dissolved iron concentrations in the hypolimnion (see Amber and Warden Lakes, this report). However, the increase of manganese was not seen in Sprague Lake, where concentrations seemed to decrease after the eruption. The results for these three lakes led Dion and Embrey (1981) to state how difficult it was to draw conclusions because of these observed differences. Wissmar and others (1982b, p. 176) found a manganese concentration of 0.034 mg/L for Blue Lake, which was the highest value for their U Lakes (see subsection titled "Blue Lake"). These differences might be explained in part by the fact that many category II lakes became anoxic. Concentrations of iron and manganese in Liberty Lake (a lake experiencing eutrophication problems) were reported by Funk (1980, p. 18) as having quadrupled—these increases are consistent with the other reports.

Sulfate

In Blue Lake, as reported by Wissmar and others (1982b), the concentration of sulfate was nearly three times higher than sulfate concentrations observed for other lakes of this type but much lower than sulfate concentrations for lakes located in the blast zone. This finding may be significant, because Baross and others (1982) indicated that while the ash contained sulfate and phosphate, sulfate was insoluble in aerobic conditions. The lakes outside the blast zone remained oxygenated, for the most part.

Concentrations of sulfate from ash extracts in oxygenated water as high as 29.6 μg/L were reported by Juday and Keller (1984), who investigated the difference between sulfate concentrations from ash extracts in both oxygenated and deoxygenated water that was collected from a variety of sources. There seemed to be less sulfate extracted for several oxygenated samples, but whether or not aerobic conditions prevented appreciable amounts of sulfate from being extracted was not reported (Juday and Keller, 1984). For data regarding Fish Lake, which was oxygenated, the sulfate level did not appear to increase after the eruption. In discussions of methods used to measure sulfate, Juday and Keller (1984) expressed uncertainty regarding the accuracy of their sulfate data, due to some technical problems observed during analytical procedures. In general, it is difficult to conclude that the sulfate concentration of lakes in category I was appreciably affected by ash.

Inorganic Nitrogen and Inorganic Phosphorus

Dion and Embrey (1981, p. G17) stated:

> For the most part, on the basis of chemical and physical characteristics documented in this report, the study lakes in eastern Washington appear to have been unaffected by the volcanic eruption.

W.H. Funk, who reported dramatic changes in other chemical constituents for Liberty Lake, reported no substantial change for orthophosphorus (soluble reactive), total soluble phosphorus, nitrogen (Kjeldahl), nitrate, nitrite, or ammonia-nitrogen after the eruption (Funk, 1980, p. 18). Conversely, Funk reported a substantial decrease in total phosphorus. This change was followed by a decrease in the numbers of phytoplankton, which are discussed later in this report.

Biological Characteristics

Benthic Flora and Fauna

Investigations on benthic organisms after May 18, 1980, were relatively few. Where such studies were made of these populations, it was difficult to draw conclusions because of the lack of pre-eruption data.

A decline in the population of the copepod *Diaptomus sicilis* was observed in studies of Lake Lenore by Edmondson and Litt (1983). However, this change in numbers was considered to be within the range of normal seasonal variation. Similarly, an increase in *Daphnia pulex* was attributed to usual changes in the seasonal cycle. A number of dead amphipods such as scuds were reported, but as in the case for *Daphnia pulex*, such observations could be attributable to seasonal cycles. The authors saw

evidence that resident salamanders survived, because their tracks were seen on the ash layer. In summary, Edmondson and Litt (1983) did not consider the ash to substantially change the fauna of Lake Lenore.

A decline of *Diaptomus sicilis* in Soap Lake was reported by Edmondson and Litt (1983), who considered the decline to be typical of the normal seasonal cycle (see Soap Lake). The water flea *Moina hutchinsoni* increased in numbers, but this also was considered a normal change for the time of year. Significantly, midge larvae (Chironomidae) seemed able to reestablish shelter tubes by burrowing up through the ash layer, which was reported to be 0.08–0.20 inch thick (Edmondson and Litt, 1983, p. 2). The author's counts of rotifers (such as *Hexarthra polyodonta*) revealed no abnormal changes. In general, the work of Edmondson and Litt (1983) indicates that the ash did not appear to alter populations of the species studied. These observations are significant, because Soap Lake and Lake Lenore data could be compared to extensive pre-eruption data.

Dramatic changes in phytoplankton and zooplankton in Liberty Lake were documented by Funk (1980, p. 19). Few details are available regarding populations of benthic invertebrates, but the author mentions that they appeared to be little affected. Funk possessed pre-eruption information on lake biology, and a survey of benthic invertebrates had been made; therefore, his opinion that the benthic invertebrate population was unaffected is significant.

In their studies of the deep parts of Coeur d'Alene Lake, Skille and others (1983) compared their 1981–82 benthic data to some pre-ashfall data reported in 1972. Seasonal changes in oligochaete and chironomid populations were plotted, and the annual variability in the occurrence of population peak densities was examined. Skille and others (1983, p. 84) concluded: "[The] ash has not had a significant long-term effect on the abundance of the benthos in the Coeur d'Alene Lake system." These authors also conducted an experiment in Chatcolet Lake during 1982, using PVC tubes driven into littoral sediment that was representative of microenvironments. The researchers applied an ash-leachate-water solution to the tube cores and compared the effects of leachate on benthic organisms to control cores untreated with ash-leachate solution. The tubes or cores were recovered, and live organisms were separated by sieving. The authors concluded that no changes in abundance or composition of benthic organisms would have occurred in the several days after the lake had received ash. The acute mortality experiments showed no statistically significant differences between test and control tubes, in terms of the survival of live Oligochaetae, Chironominae, or Diptera. In observations concerning the vertical stratification of benthic fauna, Skille and others (1983, p. 88–90) concluded: "[The] sedimented ash layer did not alter the vertical stratification of the littoral benthic community [in Chatcolet Lake]."

Primary Productivity

A comparison of pre- and post-eruption concentrations of chlorophyll *a* in various lake waters is a convenient means of evaluating primary productivity in the lakes. Considerable data regarding this parameter were available for numerous category I lakes. Dion and Embrey (1981) report that for Warden and Amber Lakes, the concentration of chlorophyll *a* was not significantly changed as a result of the eruption. On August 13, 1980, the Sprague Lake concentration of chlorophyll *a* was appreciably larger (133 μg/L) than concentrations observed prior to May 18, 1980. The authors did not attribute this change to anything other than an algal bloom, which had been observed to occur in Sprague Lake in the past. The authors did not consider this post-eruption bloom to be caused directly by ash, but the fact that a large bloom did occur is noteworthy. Other experiments demonstrate the possibility that nutrients could be leached out of ash. These experiments suggest the potential for such nutrients to trigger a bloom, under conditions in which nutrient concentrations were limiting. This is a potential topic for future studies.

In Blue and McBride Lakes, noted Wissmar and others (1982a), concentrations of chlorophyll *a* were slightly larger when compared to the oligotrophic Findley Lake. The authors did not attribute this larger concentration to ashfall effects, but simply considered that Blue and McBride Lakes normally possessed a higher population of phytoplankton than did Findley Lake (see previous sections titled "Blue Lake" and "McBride Lake").

Juday and Keller (1984) had pre-eruption data from July 24, 1979, for comparison purposes. For Fish Lake, the authors stated that the chlorophyll *a* concentration decreased by an order of magnitude at various depths. However, like other researchers,

the authors emphasized that fluctuations in primary productivity were common in these lakes, and that the interpretation of results was difficult due to the influence of climatological factors. In summary (see Fish Lake), Juday and Keller (1984) did not conclude that ash fallout affected algal productivity, in spite of the fact that the presence of nitrates and phosphates in ash was demonstrated.

The most dramatic change in primary productivity was reported by Funk (1980) for Liberty Lake (see subsection titled "Liberty Lake"), in which a decline in numbers of algae occurred shortly after the eruption. Although the numbers declined dramatically, the population returned to within two-thirds of the pre-eruption counts within a month after the eruption. The author also concluded that the community's species composition may have been altered, and that the blue-green algal population greatly decreased to near-extinction levels. This is probably the heaviest impact on any category I lake population reported in the literature being reviewed for this report. Funk's carbon-14 studies also indicated the lake productivity decreased to approximately one-half of the level observed immediately prior to May 18, 1980. Although Liberty Lake is not a typical category I lake because of its history of eutrophication, this finding is especially interesting if it could be correlated with studies by McKnight and others (1981), whose research indicated that some ash contained substances toxic to the blue-green algae *Anabaena flos-aquae*. Funk (1980) also had reported a decrease in light penetration and transparency, however, so it is difficult to determine if changes in productivity and populations of blue-green algae were due to either physical or chemical effects of the ash.

In Walupt Lake, there was a paucity of pre-eruption data for phytoplankton communities. Embrey and Dion (1988) reported population numbers for organisms belonging to the Chlorophyta, Chrysophyta, Cyanophyta, Cryptophyta, Euglenophyta, and Pyrrophyta, and found that immediately after the eruption there was a predominant species, *Dinobryon bavericum* (after Imhoff). *Dinobryon bavericum* (Division Chrysophyta) is a golden-brown algae, which has cells united in free-swimming colonies and is commonly found in the plankton of lakes. The authors did not conclude that changes in the species composition was a direct result of ashfall and stated that after several months the population contained groups of algae other than *Dinobryon*. In spite of the difficulty in drawing conclusions about the cause of events, this is an example where a marked change in an algal population was observed. No reasons were proposed concerning why this particular species came to predominate in Walupt Lake.

A reduction of chlorophyll *a* in Bumping Lake was reported by Faulconer and Mongillo (1981, p. 16–17). The authors attributed this change to a reduction of the photic zone, which was most likely due to light attenuation by suspended particles. The authors had recorded a large reduction in Secchi-disk transparency, from 7.62 feet to 1.82 feet, which was considered to be correlated with a decline in the lake's primary productivity. The authors reported a decrease in zooplankton numbers, which might have been caused by the ashfall.

Bacteria

In their studies on microbiological changes, Wissmar and others (1982a) obtained total and viable counts for heterotrophic bacteria in Blue Lake. The data were considered to be normal in comparison with an oligotrophic lake (Findley Lake) that received no ash. Staley and others (1982) obtained virtually the same results. Bacterial counts reported by the authors for June Lake were considered typical of an unaffected lake. McBride Lake had some apparent increase in total counts, but viable counts did not increase in proportion (see McBride Lake). Staley and others (1982) considered these data to be comparable for lakes that had received no ash. The same situation exists for Merrill Lake.

The bacteriology of category I lakes is unremarkable, and little significance is attached to the slight variations observed in them by various researchers. In that sense, the reference lakes serve their purpose well, because their bacteriological characteristics are in marked contrast to those of the category II lakes discussed in the next section.

Case Studies of Lakes Within the Blast Zone—Category II

In contrast to category I lakes outside the blast zone, many category II lakes within the blast zone were greatly altered. The findings for individual lakes are in some cases voluminous, and there is a greater variation in the physical impacts of the eruption on lakes within the blast zone compared to category I lakes.

Characteristics common to all category II lakes are not easily defined, because the particulars for each lake are unique and are discussed in detail in the case studies. An abbreviated summary follows the case-history section, and a list of available physical characteristics for some category II lakes is presented in table 4. For the location of the lakes, refer to plate 1.

Table 4. Physical characteristics of selected category II lakes within the blast zone
[--, data not available]

Lake	Altitude (feet)	Mean depth (feet)	Area (acres)
Boot Lake	4,643	--	--
Fawn Lake	3,700	22	20
Hanaford Lake	4,134	--	--
Panhandle Lake	4,643	--	--
Ryan Lake	3,340	--	3.95
Spirit Lake[1]	3,198	130	1,300
St. Helens Lake	4,567	--	79
Venus Lake	4,920	47	20

[1]Prior to the May 18, 1980 eruption, which changed all morphometric data.

Venus Lake

Venus Lake, about 10 miles north-northeast of Mount St. Helens, received a substantial deposit of ash. Trees in the lake's vicinity were uprooted and blown down by the volcanic blast and were stripped of branches, leaves, and bark. Compared to other lakes in the blast zone, Venus Lake was considered to be protected from some of the blast effects. Venus Lake did not have logs blown into it, because the blast was deflected by several high ridges lying between Venus Lake and Mount St. Helens. Comparisons of pre- and post-eruption bathymetric maps of Venus Lake indicate no gross physical changes. During July and August 1980, research teams reported that water was draining normally from the Venus Lake outlet.

Light transmission in the water column of Venus Lake was reduced by ashfall and other inorganic and organic debris, according to Embrey and Dion (1988, p. 7), who characterized the water of Venus Lake in July 1980 as: "* * * severely turbid and gray in color from suspended particulate matter." Because of increased concentrations of various constituents in the water, the physical and chemical characteristics of the lake changed greatly. The transparency on September 17, 1971, was 66 feet, whereas on October 16, 1980, the transparency was only 1 foot. Transparency increased to 24 feet by August 19, 1982. In 1974, the lake was described as blue-green in color; immediately after the eruption, in May 1980, the water was olive brown. Gradually, during 1981, the color became gray-green, and then turned green. By 1982, when the transparency had increased to 24 feet, researchers described the water color as blue (Embrey and Dion, 1988, p. 16). Although the recovery process required 2 years, Venus Lake was considered to be one of the fastest recovering lakes in the blast zone.

The specific conductance of the lake water increased after the eruption. On September 14, 1971, the specific conductance was 9 μS/cm (microsiemens per centimeter), whereas the post-eruption value was 233 μS/cm on July 28, 1980. The specific conductance declined to 81 μS/cm by October 16, 1980—still 9 times higher than pre-eruption values. Various groups of investigators performed chemical analyses on the lake after the eruption. Determinations of various chemical constituents are presented in table 5 and are derived from data of Dion and Embrey (1981, p. G18) and Embrey and Dion (1988, p. 10).

Changes in dissolved oxygen in Venus Lake and in other lakes were described by Embrey and Dion (1988, p. 16):

> Before the 1980 eruption, summer profiles of dissolved oxygen (DO) concentrations in Spirit, Fawn, Venus, and Walupt Lakes were higher in the metalimnion (the layer of water between the epilimnion and hypolimnion and characterized by rapidly varying temperatures with increasing depth) than in either the epilimnion or hypolimnion (the cold layer of water near the lake bottom.) This profile shape, or positive heterograde curve, is common in clear lakes of moderate productivity and has been attributed to maximum production of oxygen in the metalimnion by photosynthesizing algae, to thermally related oxygen-saturation differences between the epilimnion and hypolimnion, or to some biological and chemical depletion of oxygen in the hypolimnion.

Table 5. Water-quality data for Venus Lake, Washington, before and after the eruption of May 18, 1980

[From Dion and Embrey (1981, p. G18) and Embrey and Dion (1988, p. 10). µS/cm, microsiemens per centimeter; concentrations are in mg/L (milligrams per liter) unless otherwise indicated; --, data not available; µg/L, micrograms per liter]

	Date of collection			
	9/14/74		7/28/80	10/16/80
	Sample depth (feet)			
Constituent	3	125	3	3
Specific conductance (µS/cm)	9	12	233	--
pH units	--	--	6.3	--
Total alkalinity as $CaCO_3$	--	--	2	9
Dissolved oxygen	9.5	7.2	--	9.4
Nitrate plus nitrite, total as N	.01	.02	0	--
Nitrogen, ammonia, total as N	.04	.03	0	--
Nitrogen, total organic as N	.10	.08	.74	0
Phosphorus, total as P	.00	.01	.16	.10
Iron, dissolved as Fe (µg/L)	--	--	51	30
Manganese, dissolved as Mn (µg/L)	--	--	370	140
Carbon, organic, total as C	--	--	3.1	2.4

Concentrations of dissolved oxygen are normally related to one of several mechanisms:

(1) oxygen maximum produced by photosynthetic algae in the metalimnion;

(2) differences in oxygen saturation between the upper and lower layers, which are related to temperature differences between the layers; and

(3) oxygen depletion in the bottom layer by various biological or chemical processes.

According to Embrey and Dion (1988, p. 16), Venus Lake's post-eruption DO profile resembled that of a eutrophic lake. In a eutrophic lake, the DO profile is a clinograde shape, characterized by a top layer of water containing a relatively higher concentration of oxygen than the metalimnion. The clinograde-shaped curve is characterized by a rapid decrease in dissolved oxygen downward through the metalimnion; when the hypolimnion is reached, little or no dissolved oxygen remains. A change in a lake's DO curve, from positive heterograde to clinograde, can sometimes indicate changes in lake productivity. Other reasons exist, however, which could explain changes in DO curves. For example, a decrease in light transmission, such as that caused by turbidity, can reduce rates of photosynthesis and oxygen production. In other situations, chemically reduced, organic-chemical constituents can fall into the water and cause oxygen to be removed from the hypolimnion. Further discussions on these phenomena will be presented later, when Spirit and Ryan Lakes are discussed.

A pH of 7.07 for a sample taken 0.8 foot below the surface of Venus Lake on June 30, 1980, was reported by Wissmar and others (1982b, p. 176). The authors reported a post-eruption concentration of sulfate of 16 mg/L, compared to a pre-eruption concentration of 0.80 mg/L for Spirit Lake. Wissmar and others (1982b) compared concentrations of sulfate, chloride, and sodium, with pre-eruption Spirit Lake data, because baseline data for Venus Lake were not available for these chemical constituents. The authors considered water-quality data for pre-eruption Spirit Lake to closely represent pre-eruption baseline water-quality conditions of other lakes in this area and compared post-eruption data for lakes, such as Venus Lake, to pre-eruption Spirit Lake data.

The post-eruption concentration of chloride (C l) in Venus Lake was 7.1 mg/L, compared with a pre-eruption concentration of chloride in Spirit Lake of 1.1 mg/L. The post-eruption concentration of sodium in Venus Lake was 5.9 mg/L, compared with Spirit Lake's pre-eruption concentration of sodium of 2.0 mg/L (Wissmar and others, 1982b, p. 176). The concentrations of sulfate, chloride, and sodium were greater in Venus Lake than in lakes outside the blast zone (such as Merrill, McBride, June and Blue Lakes). The data of Wissmar and others (1982b) and Embrey and Dion (1988) indicate that Venus Lake water became a calcium-sulfate-chloride type after the eruption. Prior to May 18, 1980, the lake was regarded to be a calcium bicarbonate water type. As timed passed, Venus Lake water types progressed through calcium-sodium-sulfate-bicarbonate, calcium-sodium-sulfate-chloride, calcium-sulfate-chloride, calcium-sodium-sulfate-bicarbonate, finally, to a calcium-sodium-sulfate type by August of 1982 (Embrey and Dion, 1988, p. 19).

Other researchers demonstrated that volcanic ash contained large concentrations of sodium, chloride, and sulfate, as compared with the amounts ordinarily found in soil or sediments. Taylor and Lichte (1980) regarded ash particles to be a source of chloride and sulfate, because water-soluble salts of these ions had condensed onto the surface of ash particles. The authors suggest that the ions could be leached from ash particles into the water and, therefore, could account for observed alterations in water type.

Pre-eruption data on dissolved manganese and iron, and total organic carbon were scarce; therefore, determining if concentrations of those constituents had changed was difficult. It appears that the manganese concentration was considerably increased, because the reported concentration of 370 μg/L was larger than concentrations ordinarily found in category I lakes that received less ash than Venus Lake. The iron concentrations do not appear significantly different than those reported for various category I lakes. Iron and manganese concentrations were largest near lake bottoms (Embrey and Dion, 1988). Elevated concentrations were correlated with summer months, when the lake exhibited strong thermal stratification. During this period, the concentration of DO found in deep water is small, and water at the lake bottom is essentially anoxic. These observations are consistent with the findings of other researchers, who suggest that iron and manganese are not mobilized from ash in oxygenated water. Embrey and Dion (1988) present data indicating an elevation in the concentration of total organic carbon in the water, but not to the extent reported in Spirit Lake. Data on the biological characteristics of Venus Lake were scarce, but Embrey and Dion (1988) documented possible changes in phytoplankton and zooplankton groups. The authors presented data from 1981 and 1982 and showed that the species composition and relative proportions of organisms was altered. In general, Embrey and Dion (1988) were of the opinion that a greater diversity of phytoplankton species was present in Venus Lake during 1982 when compared with 1981. It is important to note that the authors possessed data on Venus Lake from June of 1980, shortly after the eruption; however, there are no corresponding data prior to May 18, 1980. On October 16, 1980, the phytoplankton assemblage included members of the Chlorophyta (green algae), Cyanophyta (blue-green algae), and other unidentified flagellated forms. The following year, samples taken on five dates from June 25 to September 29, 1981, showed a significant seasonal change; by August 1981, a single species of phytoflagellate, *Chlorochromonas*, was dominant. Large numbers of this organism were found in other blast-zone lakes, and it was dominant or codominant in St. Helens, Coldwater, and Castle Lakes (Embrey and Dion, 1988, p. 27). Other dominant or codominant species were the members of the Chlorophyceae, Anki*strodesmus falcatus* (Smith) and *Dictyosphaerium pulchellum* (Wood). A member of the Chrysophyta, which at times became dominant or codominant, was *Cyclotella*, sp. Kutz. In the Chrysophyceae (yellow-green algae), *Dinobryon sertularia* (Ehrenberg) also was found in addition to *Chlorochromonas*. Among the Cyanophyta, the species *Chroococcus dispersus* (Keissl.) and *Rhabdoerma lineare* (Schmidle and Lauterborn) were found.

By August 1982, the percentage composition of phytoplankton species was altered, and the Chrysophyceae (diatom) population, previously small in 1981, grew to constitute a major component of the total species present in Venus Lake. Similarly, a change in species composition over time was observed in Spirit, St. Helens, and Castle Lakes. Diatoms are characterized by silica frustules and chromatophores containing chlorophyll *a*, chlorophyll *c*, beta carotene, and several unique xanthophylls. The most distinguishing feature of diatoms is their highly silicified cell wall, consisting of overlapping halves. Venus Lake experienced an increased concentration of silica or silicates, and the relation between increased silica and apparent selective reproduction of diatoms might be a question to address in future studies.

A complete listing of species described from 1980 through 1982 is presented by Embrey and Dion (1988, p. 53). The observed changes in phytoplankton are difficult to attribute to the eruption, because the scarcity of pre-eruption data prevented a comparative analysis. Venus Lake was slightly enriched in inorganic phosphorus, iron, and manganese. It is difficult to determine the extent these and other chemical changes were responsible for biological changes. Physical changes such as reduced light of different wavelengths also could have played a major role in changing phytoplankton species.

Communities of zooplankton in Venus Lake were compared by Embrey and Dion (1988) with communities of zooplankton in Walupt Lake, a category I lake. The post-eruption numbers of zooplankton reported in Venus Lake during August

and October of 1980 were two orders-of-magnitude lower than numbers for Walupt Lake. The authors attributed the reduction in numbers to mortality and reduced growth of zooplankton. The cladoceran *Holopedium gibberum* was the dominant species in Venus Lake during the late summer and early fall of 1980. *Holopedium gibberum* is a stenotherm—a term that characterizes species existing only within a narrow water-temperature range. Aside from discussing the preference of *Holopedium gibberum* for a narrow temperature range, the investigators did not report any other unusual zooplankton species exhibiting a preference for atypical trophic qualities. *Holopedium gibberum* also was found to be the dominant species in St. Helens Lake and Deadmans Lake during the late summer and early fall of 1980 (Embrey and Dion, 1988, p. 33, 59). Characterization of species belonging to the Cladocera, Calanoida, Cyclopoida, and Ploima are presented and will not be discussed here.

Wissmar and others (1982a, p. 179) commented on the numbers of phytoplankton found in Venus Lake and other blast-zone lakes, and changes in phytoplankton populations were attributed to limitations of light available for photosynthesis. The authors derived an inverse relation between chlorophyll *a* concentrations and light extinction (a logarithmic expression of the degree to which light intensity is diminished when passing through water containing a solute) for four different lakes, but concluded that no corresponding inverse correlation between chlorophyll *a* and large dissolved organic carbon concentrations existed. According to the authors (Wissmar and others, 1982a, p. 179), "***the lack of any relationship between chlorophyll *a* and either bacterial numbers or ATP suggests little competition for nutrients." These observations were made in reference to all lakes studied by the authors.

The bacteriology of Venus Lake was studied by Wissmar and others (1982b), who concluded that, in terms of total bacterial counts and counts of viable heterotrophs, Venus Lake contained numbers of bacteria comparable to lakes outside the blast zone.

Panhandle Lake

Wissmar and others (1982b, p. 176; 1982a, p. 180) performed most of the research on Panhandle Lake, which is approximately 10 miles north-northeast of Mount St. Helens. Mountain ridges partially shielded Panhandle Lake from the blast. The light extinction coefficient of the lake was 16.38 from samples taken at a depth of 0.8 foot on June 30, 1980, compared with light extinction coefficients ranging from 0.56 to 0.71 for the reference lakes (Merrill, McBride, June, and Blue Lakes). The pH was 7.42. Suspended particulate matter (SPM) was reported to be 132.8 mg/L, which is an order-of-magnitude greater than the concentration in reference lakes. The amount of light available for photosynthesis was reduced. At a sample depth of 0.8 foot, no chlorophyll *a* was detected, and bacterial populations probably accounted for much of the lake biomass. Total microscopic bacteria counts were 7×10^5 cells/mL, and the viable count was greater than 10^4 cells/mL. The ATP concentration was 0.6 µg/L on that date. Wissmar and others (1982b, p. 176) reported elevated concentrations of dissolved chemical constituents (calcium, magnesium, sodium, manganese, iron, sulfate, and chloride), based on comparisons to reference lakes. On June 30, 1980, the sodium concentration was twice as high as in reference lakes; and sulfate and chloride concentrations were an order-of-magnitude larger than those of the reference lakes. The iron concentration did not appear to be elevated.

Boot Lake

Boot Lake is 9.3 miles north of Mount St. Helens in Skamania County, Washington, and was partly shielded from direct blast effects by nearby mountains. The amount of SPM for Boot Lake was the largest of all lakes studied by Wissmar and others (1982a, p. 180). The SPM concentration of 188.8 mg/L from a sample collected June 30, 1980, was larger than SPM concentrations in reference lakes, whose SPM concentrations ranged from 1.23 to 8.17 mg/L. A light extinction coefficient of 14.30 was reported, compared to the largest light extinction coefficient of 0.71 reported for Blue Lake (a reference lake) at the same depth on the same date. The amount of light attenuation appears to correlate with the lack of chlorophyll *a* found in Boot Lake at that time.

Chemical data for Boot Lake was compared by Wissmar and others (1982b, p. 176) to data from category I lakes (Merrill, McBride, June, and Blue Lakes) and pre-eruption Spirit Lake. Analyses of samples taken 0.8 foot below the surface on June 30, 1980, indicate that concentrations of various dissolved chemical constituents had increased greatly as a result of the eruption.

The concentrations reported were as follows: calcium (24.4 mg/L), magnesium (3.0 mg/L), sodium (16.9 mg/L), potassium (3.8 mg/L), manganese (0.46 mg/L), phosphorus (0.04 mg/L), sulfate (70 mg/L), and chloride (32 mg/L). Calcium and manganese concentrations were an order-of-magnitude greater than for the category I lakes; magnesium, sodium, and potassium concentrations were more than double the largest concentrations for those constituents in category I lakes. The concentration of sulfate was two orders-of-magnitude larger than concentrations in pre-eruption Spirit Lake, and when compared to average concentrations for category I lakes, sulfate concentration was more than 30 times larger in Boot Lake. The concentration of chloride was at least seven times larger than the concentration in category I lakes. The concentrations of iron, silicon, nitrate-nitrogen, nitrite-nitrogen, and ammonia-nitrogen were comparable to those found in category I lakes.

The concentration of DOC in Boot Lake was reported by Wissmar and others (1982a) to be 4.98 mg/L on June 30, 1980. The DOC concentration in Boot Lake was twice as large as concentrations in reference lakes, and particulate organic carbon (POC) also was elevated. Particulate organic nitrogen (PON) concentrations were comparable to "controls." Chlorophyll *a* was not detected (Wissmar and others, 1982a, p. 180).

The bacteriology of Boot Lake was studied and compared by Staley and others (1982, p. 665–667) to the four subalpine lakes (Merrill, McBride, June, and Blue Lakes). The reference lakes had total microscopic bacterial counts ranging from 1.4×10^5 to 7.6×10^5 cells/mL on June 30, 1980, which increased to 1.8×10^6 cells/mL by September 11, 1980. Boot Lake's total microscopic counts were only slightly higher (2.9×10^6 cells/mL), but the viable counts appeared to increase with time when compared to the "controls." By September 11, 1980, the viable count for Boot Lake was 1.0×10^6 cells/mL—three orders-of-magnitude higher than for counts recorded for Merrill and McBride Lakes on the same date. By comparison, the viable count of bacteria in the reference lakes ranged from 200 to 5,000 cells/mL. Boot Lake had 45 cells/mL of total coliform bacteria, but no fecal coliforms were reported on September 11, 1980. The authors state that a common species of coliform, *Klebsiella pneumoniae*, was also found in other blast-zone lakes. The organism is a facultative anaerobe (can live either in the presence or absence of oxygen), with the capacity to fix nitrogen. This particular metabolic attribute is important to consider in relation to environments where quantities of dissolved nitrogen compounds available for biological systems are limited. Low concentrations of usable nitrogenous compounds can tend to select for organisms capable of utilizing gaseous nitrogen. More information about *Klebsiella pneumoniae* and its role as a potential human pathogen is presented later in this report.

An ATP concentration of 0.7 µg/L at a depth of 0.8 feet on June 30, 1980 was reported by Wissmar and others (1982a, p. 179–180). The authors thought that dense bacterial communities and large ATP and DOC concentrations were correlated and cited regression data illustrating these relations. See table 6 for selected post-eruption water-quality data.

Hanaford Lake

Hanaford Lake was in the blast-zone region, where timber was blown down and ashfall was heavy. The lake is approximately 8.7 miles north of the volcano and was covered by ice at the time of the eruption (Dion and Embrey, 1981, p. 6). Staley and others (1982) regarded Hanaford Lake to be less affected than other lakes in the blast zone, although the lake is exposed on a ridge above Coldwater Creek. Pre-eruption bathymetric data are not available. The water temperature apparently was not affected, but the lack of pre-eruption data makes it difficult to draw conclusions. According to Wissmar and others (1982a, p. 180), the light extinction coefficient at a depth of 0.8 feet was 4.28 on June 30, 1980, compared to a range of values of 0.56 to 0.71 for reference lakes. The SPM was reported to be 28.36 mg/L compared to the reference lakes, whose SPM concentrations ranged from 1.23 to 8.17 mg/L. It seems likely that the amount of light attenuation was sufficient to adversely affect photosynthesis, as in the case of other blast-zone lakes.

Wissmar and others (1982b, p. 177) stated that Hanaford and Fawn Lakes had the lowest pH values of lakes located in the blowdown area, and considered pH changes caused by the eruption in lakes to be, in general, "* * * minor in comparison to other volcanically influenced lakes [in other parts of the world]." A pH of 6.97 was reported for Hanaford Lake on June 30, 1980. The range of pH values for reference lakes of 6.73 to 7.20 on the same date and sampling depth indicates the pH of Hanaford Lake was not much affected.

Table 6. Selected post-eruption water-quality data for Boot, Hanaford, Ryan, Fawn, and St. Helens Lakes, all of which are category II lakes in Washington

[Refer to case study for sampling details, dates, and references; µS/cm, microsiemens per centimeter; --, data not available; mg/L, milligrams per liter; °C, degrees Celsius; $CaCO_3$, calcium carbonate]

Constituents or properties	Boot Lake	Hanaford Lake	Ryan Lake	Fawn Lake	St. Helens Lake
Specific conductance µS/cm	--	--	--	666–760	150
pH (standard units)	--	6.97	6.46	6.5	6.6
Alkalinity (mg/L as $CaCO_3$)	--	--	--	19–25	9.0
Maximum temperature of water in °C	--	--	25.5	15.7	17.0
Transparency:					
Secchi-disk reading (in feet)	--	--	--	7	1.0
Light extinction coefficient	14.30	4.28	--	3.04	--
Oxygen, dissolved (mg/L)	--	--	3.60	0.6–9.2	2.6–7.0
Sulfate, dissolved (mg/L as SO_4)	69.7	195	79.8	165–180	38–44
Chloride, dissolved (mg/L)	32.1	85.9	27.0	64–71	12–14
Aluminum, dissolved	--	--	--	--	--
Iron, dissolved (mg/L as Fe)	--	--	0.6–2.8	--	0.050–0.150
Magnesium, dissolved (mg/L as Mg)	--	--	2.8	6.2–6.8	1.5
Manganese, dissolved (mg/L as Mn)	.456	.91	.7	--	.330–0.360
Dissolved organic carbon (mg/L)	4.98	4.79	11.0	1.9	2.4–5.3

The alkalinity of Hanaford Lake was 461 µeq/L (microequivalents per liter) on June 30, 1980, and had the largest value for a blowdown lake, but smaller than June Lake, a reference lake. By comparison, the alkalinity for pre-eruption Spirit Lake was 139 µeq/L.

Wissmar and others (1982b, p. 176) stated that Hanaford Lake had larger concentrations of major cations and metals than other lakes in the blast area, and appeared to have experienced a "* * * greater direct input from the lateral blast." Data collected from 0.8 feet below the water surface on June 30, 1980, in Hanaford Lake and in the reference lakes indicate that concentrations of dissolved calcium and sodium are an order-of-magnitude larger than concentrations recorded for reference lakes (Merrill, McBride, June, and Blue Lakes). The concentration of dissolved potassium in Hanaford Lake was 24 mg/L, an order-of-magnitude larger than the 0.30 to 1.6 mg/L concentration ranges reported in reference lakes. The sulfate concentration in Hanaford Lake was 195 mg/L—nearly two orders-of-magnitude larger than in the "control lakes," where sulfate concentrations ranged from 6.69 to 2.8 mg/L. Hanaford Lake's chloride concentration of 86 mg/L was more than an order-of-magnitude larger than chloride concentrations for lakes outside the blast zone. For further comparison, the pre-eruption concentration of chloride in Spirit Lake was 1.1 mg/L on April 4, 1980. The concentration of dissolved manganese in Hanaford Lake was 0.91 mg/L—more than an order-of-magnitude larger than the 0.0022 to 0.034 mg/L range of dissolved manganese concentration reported for comparison lakes.

The concentrations of nitrogen as nitrate, nitrite, or ammonia did not appear changed. The level of phosphorus may have been slightly elevated. However, according to Wissmar and others (1982b, p. 177), Hanaford and Fawn Lakes had the largest concentrations of nutrients for blowdown area lakes studied by these authors. Without pre-eruption data for Hanaford Lake, it is difficult to determine the degree to which nutrient availability was changed.

On June 30, 1980, the DOC concentration in Hanaford Lake was 4.79 mg/L (Wissmar and others, 1982a, p. 180). That concentration was more than two times the largest DOC concentration reported for the reference lakes. Chlorophyll *a* was present at about the same levels as in the reference lakes, indicating that algae still constituted a part of the biomass in surface waters. The ATP concentration in Hanaford Lake was equivalent to the ATP concentration in other blowdown lakes.

After the eruption, the numbers of viable bacteria in Hanaford and Fawn Lakes changed dramatically, according to Staley and others (1982, p. 666). Hanaford Lake contained 4.0×10^3 cells/mL on June 30, 1980; but only 16 days later, the number of viable bacteria had increased almost two orders-of-magnitude to greater than 4×10^5 cells/mL. At that time, the total microscopic count was 1.8×10^6 cells/mL, which was greater than numbers reported for reference lakes. The total coliform and fecal coliform counts in Hanaford Lake were 20 and 10 cells/mL, respectively, on September 11, 1980. The authors reported *Klebsiella pneumoniae* to be the dominant total coliform species, as in the case of many other blast-zone lakes.

Embrey and Dion (1988) cite research by the State of Washington Department of Game (WDG), showing that live fish were found in Hanaford Lake during the autumn of 1980 and spring of 1981. In addition to eastern brook trout, the lake also had a population of cutthroat trout. According to Embrey and Dion (1988, p. 38):

> [These fish were considered to be in] good condition and had been feeding on terrestrial insects and, to a lesser extent, on midge larvae and free-living (caseless) caddisflies.

See table 6 for selected post-eruption water-quality data.

Ryan Lake

Ryan Lake is 11.8 miles north of Mount St. Helens and was in the tree blowdown area of the blast zone. The lake was a typical subalpine oligotrophic lake prior to May 18, 1980. Maximum depth was reported to be 23 feet. Wissmar and others (1982b) regarded Ryan Lake to be partially shielded from the eruption by nearby mountain ridges. According to Dahm and others (1983, p. 1634), ashfall depth in the area of the lake was estimated to be 3.9 to 7.9 inches. Prior to the eruption, Ryan Lake was surrounded by old-growth Douglas Fir forest, whose foliage was pyrolized (chemically altered by heat) by the blast. Dahm and others (1983, p. 1636) reported that a blast of heat in excess of 250°C reached the lake area (estimates made from the deformation melting point of parking-light plastic lenses on a truck parked at the lakeside). The heat wave was of short duration, however, and persons camping at the lake were relatively unharmed. Wissmar and others (1982a) reported a temperature in the lake of 25.5°C at a depth of 0.8 feet on June 30, 1980, which was presumably above the normal temperature for that time of year. Because no pre-eruption temperature data exits, the actual rise in temperature was not known.

Dahm and others (1983, p. 1637) measured pH changes over time and reported: "[The] lake pH was consistently below 7, with a minimum of 6.46 measured on 10 August 1980." Wissmar and others (1982a, p. 180) indicated the amount of light available for photosynthesis was reduced. No chlorophyll *a* was detected in samples collected at a depth of 0.8 feet, but the reported ATP concentration of 3.6 µg/L was correlated with high counts of bacteria, which accounts for the biomass.

During the summer and early autumn of 1980, the water was light brown to black in color as a consequence of the high levels of sulfide and DOC (Baross and others, 1982, p. 51). The authors sampled Ryan Lake extensively and reported physicochemical data for various depths. According to Wissmar and others (1982a, p. 180), the concentration of DOC in Ryan Lake was 10.97 mg/L on June 30, 1980, which was more than five times the largest concentration in reference lakes. Dahm and others (1983) also reported high DOC concentrations, particularly in samples collected at the surface. The authors reported a drop in DOC values by September 11, 1980, due to the diluting effects of rainwater and runoff.

DO concentration was 3.60 mg/L from a sample taken at 0.8 feet on June 30, 1980, reported Wissmar and others (1982a, p. 180). At that time, oxygen was present in the epilimnion. Vertical profiles taken at later dates throughout the summer by Baross and others (1982, p. 50) indicated there was no oxygen below the surface, and the lake had large concentrations of methane and carbon dioxide gases at various depths. The authors reported a carbon dioxide concentration of 238 nanomoles later in the summer and stated that the odor of hydrogen sulfide gas was noticeable in most water samples. Reduced iron (Fe^{2+}) was detected at all levels of the water column. Dahm and others (1983, p. 1634) reported: "[By] August 1980, Ryan Lake had a 3.3- to 6.4-foot-aerobic epilimnion with an anaerobic hypolimnion." Extremely supersaturated levels of carbon dioxide and methane gas existed throughout the water column, and especially high concentrations were found near the lake bottom. According to Wissmar and others (1982a, p. 180): "These observations indicate the potential for development of dense chemolithotrophic microbial communities."

Baross and others (1982, p. 51) remarked:

> [The] presence of dissolved gases and the microbial activities in the water suggest that nitrogen cycle processes, including nitrogen fixation, nitrification, and denitrification, are important***. Dissolved organic nitrogen (DON) concentrations remained low, due to the low C/N [carbon to nitrogen] ratio of the conifer remains blasted into the lakes.

In general, conifer material is rich in carbon, but relatively poor in nitrogen. Different parts of Douglas Fir trees have carbon-to-nitrogen (C/N) ratios that range from 60 to 500.

According to Dahm and others (1983, p. 1636):

> Overall, C [carbon], S [sulfur], metals, and, to a lesser extent, P [phosphorous], were enriched in Ryan Lake, whereas the relative input of N [nitrogen] by the eruption was not comparable with the other nutrients.

Wissmar and others (1982b, p. 176), in comparing Ryan Lake to the lakes outside of the blast zone, reported elevated concentrations of dissolved calcium, magnesium, sodium, potassium, manganese, and iron for samples taken June 30, 1980. Samples taken from 0.8 feet below the water surface had a calcium concentration of 27.8 mg/L, compared to a maximum value of 4.06 mg/L reported for Merrill, McBride, June, and Blue Lakes. The magnesium concentration of 2.8 mg/L was nearly twice as large as the largest value in June Lake (1.5 mg/L), and the sodium concentration of 17.6 mg/L was two to six times the concentrations reported for reference lakes. The concentration of manganese was 0.70 mg/L, compared to concentrations ranging from 0.0022 to 0.034 mg/L for reference lakes. The concentration of iron was 0.57 mg/L, and was more than five times the concentration found in McBride Lake. The sulfate concentration in Ryan Lake was 79.8 mg/L, compared to a range of 0.69 to 2.8 mg/L reported in "control" lakes. Concentrations of phosphorus, and the concentration of nitrogen (as nitrate, nitrite, or ammonia-nitrogen), were little changed on June 30, 1980. The concentration of chloride was 27.0 mg/L, while concentrations of chloride in the reference lakes ranged from 1.2 to 4.5 mg/L. Dahm and others (1983, p. 1637) reported markedly increased concentrations of dissolved iron (Fe^{2+}) as depth increased; on August 10, 1980, the iron concentration was 2.8 mg/L at a depth of 20 feet.

According to Dahm and others (1983, p. 1638):

> Ryan Lake contained low concentrations of all forms of N on 10 August 1980. DON was highest in concentration, although the available portion of this pool for microbial growth was probably only a small fraction of the total. Measurable quantities of NO_2^- + NO_3^- occurred only in the oxygenated surface waters***.

Ward and others (1983, p. 243) sampled Ryan Lake on September 11, 1980, and on July 22, 1981. The authors identified *Anabaena* Bory, *Microcystis* Kutzing, *Tribonema* Derbes and Solier, *Navicul*a Bory, *Nitzschia* Hassall, microflagellates (cryptomondads), and other organisms during 1980 and reported total algal numbers of 6.1×10^4 cells/L (cells per liter). One-third of the organisms were microflagellate species. In 1981, the population changed substantially, and *Schroederia ancora* G.M. Smith was the dominant organism (77 percent of the total), along with *Tribonema* and *Cosmarium* Corda. *Navicula* and *Fragilaria* species constituted 2 percent of the total population, whose average density numbered 9.4×10^5 cells/L. The authors regarded genera identified both years to be typical algae found in small eutrophic lakes. According to Ward and others (1983, p. 243), who also counted protozoans during sampling:

> [The] numbers indicated that microflagellates and ciliated protozoans played important roles in the initial post-anaerobic conditions in these lakes. The maximum numbers reported here (greater than 10^5/L) are among the highest reported from various lakes and reservoirs worldwide.

High concentrations of protozoans typically occur in eutrophic lakes, and the bacteria on which protozoans feed were found in extremely high numbers in Ryan Lake. In turn, protozoans serve not only as food for the macrozooplankton but also constitute an important link in the aquatic food chain.

Extensive microbiological investigations were conducted on Ryan Lake by several groups. Wissmar and others (1982a, p. 180) reported a total microscopic bacteria count of 1×10^7 cells/mL on June 30, 1980. The viable heterotrophic bacteria count was 3×10^3 cells/mL. The authors reported a total coliform count of 60 cells/100 mL. These bacterial populations were correlated statistically with high DOC and ATP concentrations. The authors attributed high ATP concentration to bacterial growth—rather than algal growth—because the chlorophyll *a* concentration remained low.

Baross and others (1982) reported bacteria counts throughout the summer of 1980 and sampled the lake during August and September 1980. Total microscopic counts as high as 3.0×10^8 cells/mL were reported for the littoral zone of Ryan Lake. Total microscopic counts at the surface and at depths of 10 and 20 feet ranged from 6.4×10^6 to 3.0×10^7 cells/mL. Densities of manganese sulfur oxidizing bacteria as high as 2.0×10^6 cells/mL, at a depth of 20 feet, were reported by Baross and others (1982, p. 52). Denitrifying bacteria were present in all parts of the water column, except for the oxygenated surface water. According to Baross and others (1982, p. 52):

> The manganese sulfur oxidizing bacteria were the most abundant denitrifying bacteria, but unlike most stratified and meromictic lakes, where the metal-oxidizing bacteria are detected only at the oxycline, in Mount St. Helens Lakes the denitrifying metal oxidizers oxidize throughout the anaerobic water column and thus resemble estuarine sediment denitrifiers.***[The] significant nitrification was limited to the oxygenated zone at Ryan Lake with greatest activity in the littoral zone, apparently associated with the nitrogen-fixing cyanobacteria.

Staley and others (1982, p. 664) recovered high numbers of viable bacteria from Ryan Lake and stated:

> [The] high numbers of bacteria and the efficacy of the viable enumeration procedure are evidence that the lakes have been transformed rapidly from oligotrophy to eutrophy due to the eruption and its aftermath. Organic material leached from the devastated forest vegetation is thought to be responsible for the enrichment of heterotrophs.

Staley and others (1982, p. 666) reported:

> Ryan and Castle Lakes, which had the highest microscopic counts initially, had the lowest viable counts of all the blast-zone lakes. However, viable bacterial numbers increased dramatically*** to more than 10^6 cells/mL by 11 September 1980.

This group's research indicates the necessity of sampling over a substantial time period with different types of plating media. The low initial viable counts were correlated with water conditions that had not yet deteriorated to eutrophic condition. As time passed, the lake changed from an oligotrophic to a eutrophic state. The population of bacterial species in the lake changed, and the number of bacteria that can be cultivated varies from one growth medium to another. The authors speculated that other factors could have affected the recovery of viable bacteria shortly after the eruption. Staley and others (1982, p. 669) stated:

> A probable explanation is that these bacteria were microaerophillic or anaerobic and thus did not grow on the medium under the aerobic conditions used.*** It is conceivable that the lakes may have become anaerobic immediately after the eruption.

Data show that on June 30, 1980, Ryan Lake's oxygen concentration was below saturation. In any event, many bacteria present shortly after the eruption were noncultivatable on the media utilized, as evidenced by the extremely high total microscopic counts. The description of growth media and plating techniques by the various research groups suggests that for future studies it might be useful to utilize a variety of plating media and growth conditions—such as reducing media or anaerobic incubation procedures.

Dahm and others (1983) reported that the total bacterial counts made on August 10, 1980, which ranged from 6.4×10^6 to 3.0×10^8 cells/mL, were comparable to those reported by other investigators. According to Dahm and others (1983, p. 1638–1639):

> Chemosynthetic bacteria capable of growth on reduced Mn or S, or both, were particularly abundant. Viable counts of Mn-S oxidizing bacteria constituted from 0.3 to 31 percent of the total counts. Anoxic waters were particularly rich in bacteria capable of chemosynthetic growth. Also, N fixation, both aerobic and anaerobic, was an important attribute of the microbial population. *** Addition of new nitrogen, through fixation, was a major response of the microbial population in Ryan Lake.

The authors performed microscopic examinations of water samples taken from various regions of the lake, and identified *Anabaena* sp., cyanobacteria, and diatoms in surface littoral waters. These organisms were not found in deep water.

Dahm and others (1983) identified two zones of maximum nitrogen fixation, and presented a very detailed analysis of bacterial metabolic activities and related phenomena in their report. According to Dahm and others (1983, p. 1641–1642):

> [The] evidence of extensive anaerobic microbial activity included active ebullition of methane and H_2S [hydrogen sulfide gas] emanating from the sediments. Any disturbance of the littoral sediment at Ryan Lake resulted in extensive degassing. [The authors commented upon the importance of nitrogen fixation in successional phenomena, and reported] extraordinary rates of both aerobic and anaerobic fixation. [The] potential planktonic aerobic N_2 fixation (algal and bacterial) rate measured in the afternoon of 10 August 1980 exceeded all previously reported values in North American Lakes.

According to Dahm and others (1983, p. 1642) nitrification in the lake took place only in oxygenated waters of the littoral zone and surface water. The nitrification rates were equivalent to rates observed in eutrophic lake systems.

Dahm and others (1983, p. 1642) postulated that low concentrations of nitrate in the lake during the summer of 1980 were correlated with the presence of denitrifying bacteria. The extremely high rate of denitrification in anoxic deeper waters was recorded as evidence of this population growth. The manganese-sulfur oxidizing group of denitrifying bacteria were abundant throughout the anaerobic water column of Ryan Lake. The presence of this type of bacteria at various depths contrasts with the situation in most other lakes—where the bacteria that oxidize metals during denitrification are generally found in oxygenated water. See table 6 for selected post-eruption water-quality data.

Fawn Lake

Fawn Lake is approximately 9 miles north-northwest of Mount St. Helens and received a heavy deposit of ash. The lake is exposed high on a ridge overlooking Coldwater Creek and was directly affected by the lateral volcanic blast of the explosion. Ashfall depth in the vicinity of Fawn Lake ranged from 0.4 to 1.2 inches. Trees adjacent to the lake were knocked down and uprooted, and had been stripped of leaves, branches, and bark. According to McKnight and others (1984), Fawn Lake was covered with ice at the time of the eruption and, perhaps, was not as severely affected as lakes that were farther away from Mount St. Helens but were unprotected by ice. A comparison of pre- and post-eruption bathymetric maps indicated that Fawn Lake was not appreciably altered, although substantial amounts of ash had been deposited. Dion and Embrey (1981, p. G17) published water-quality data derived from samples taken September 14, 1974. Order-of-magnitude changes in values for specific conductance were observed after the eruption. On September 14, 1974, specific conductance values had ranged from 30 to 46 µS/cm, at depths of 3 and 72 feet, respectively. On August 27, 1980, the specific conductance was 666 µS/cm at a depth of 3 feet, and 760 µS/cm at 50 feet. Transparency was 7 feet on August 27, 1980, as compared to 21 feet recorded September 14, 1974; however, the transparency increased to 12 feet by October 28, 1980. Wissmar and others (1982a, p. 180) reported a light extinction coefficient of 3.04, compared to values of less than 1.0 for category I lakes sampled on the same date.

Embrey and Dion (1988, p. 17–18) compared DO profiles of Fawn Lake to data from 1974 and concluded that the DO profile had changed from a positive heterograde shape to a clinograde shape (see subsection titled "Venus Lake" for a discussion of the terms "heterograde" and "clinograde"). This change in DO profiles was observed for most blast-zone lakes. In August 1980, the DO content of samples taken at progressive depths through the metalimnion decreased, until at a depth of 50 feet conditions were essentially anoxic. The DO profile continued to change substantially, and by October 1980, oxygen at metalimnion depths had recovered to near pre-eruption concentrations.

According to Embrey and Dion (1988, p. 19), Fawn Lake changed into a calcium-sulfate (Ca-SO_4) water type; whereas the water was previously a calcium-bicarbonate (Ca-HCO_3) type, according to other researchers. Dion and Embrey (1981, p. G17) reported dissolved sulfate concentrations of 170 mg/L at a depth of 3 feet, and 180 mg/L at a depth of 50 feet, on August 27, 1980. These sulfate concentrations were larger than those observed for category I lakes in this area, whose maximum post-eruption concentrations were less than 70 mg/L.

Fawn Lake was compared to category I lakes by Wissmar and others (1982b, p. 176), who inferred that substantial changes in the chemical characteristics of Fawn Lake had occurred. Compared to the category I lakes, Fawn Lake had large, increased concentrations of calcium, magnesium, sodium, potassium, sulfate, and chloride. On June 30, 1980, the largest concentration of calcium for category I lakes was 4.06 mg/L, whereas Fawn Lake had a concentration of 62.7 mg/L. For magnesium (Mg^{++}), the maximum concentration recorded in unaffected category I lakes was 0.82 mg/L, but Fawn Lake had a value of 6.2 mg/L. Concentrations of magnesium, sodium, and potassium were an order-of-magnitude higher in Fawn Lake, and the concentration of manganese (1.1 mg/L) was two order-of-magnitude larger than in unaffected category I lakes (0.034 mg/L). Sulfate and chloride concentrations of 165.0 mg/L and 64.0 mg/L respectively, were elevated compared to maximum concentrations of sulfate (2.8 mg/L) and chloride (4.5 mg/L) reported in category I lakes. Data by Wissmar and others (1982b, p. 176) for sulfate and chloride agree with the data of Dion and Embrey (1981). Wissmar and others (1982b, p. 176) summarize these findings and make parallel comparisons of the chemical compositions of 16 different lakes. The authors regarded location of affected lakes to be a major factor when accounting for differences in concentrations of various chemical constituents among these lakes. As a consequence of location and exposure on a ridge, Fawn Lake may have been chemically altered to a greater extent than were lakes in adjacent, blowdown timber areas. The trajectories of the blast cloud and the subsequent placement of deposits are directly related to the lake site and to the topography of adjacent terrain.

Wissmar and others (1982a) were of the opinion that Fawn Lake possessed a diverse algal community. Embrey and Dion (1988, p. 34–37) studied phytoplankton and zooplankton of Fawn Lake shortly after the eruption. The lack of pre-eruption biological data made it difficult to ascertain what changes, if any, took place. From August to October 1980, the phytoplankton community decreased. In late August 1980, the community was dominated by members of the Chlorophyta (green algae), which constituted about 80 percent of the total; members of the Cyanophyta, Bacillariophyceae, and others made up less than 20 percent of the community. By October 28, 1980, the percentage composition had changed radically, and members of the Cyanophyta (blue-green algae) constituted approximately 70 percent of the total population. Unidentified flagellated forms, and some green algae and diatoms, made up the remainder of the community. Determining if this pattern of change is normal for Fawn Lake is not possible, because historical data regarding successional patterns are unavailable. Embrey and Dion (1988) showed that the zooplankton density decreased from August to October 1980, and the percentage composition of different species changed from a predominance of Cladocerans (over 90 percent) to Rotifera (over 90 percent) by late October 1980. When compared to the absence of rotifers in other lakes, the presence of rotifers in Fawn Lake was unique. Walupt Lake was the only other lake with a population of rotifers during 1980. The distribution of rotifers changed by 1981, when rotifers were found in all lakes studied by Embrey and Dion (1988).

Wissmar and others (1982a) reported total bacteria counts of approximately 2×10^6 cells/mL, compared to total microscopic bacteria counts of 10^5 cells/mL for category I lakes. Total coliform counts were 20 cells/100 mL, and fecal coliform counts were 5 cells/100 mL. Total coliform and fecal coliform bacteria were also found in Hanaford, St. Helens, Boot, Ryan, Castle, and South Coldwater Lakes; none were reported for category I lakes. Staley and others (1982) reported greatly increased bacterial counts and a lag period of almost 2 months before peak counts were attained. For example, on June 30, 1980, total bacterial counts were 5.0×10^3 cells/mL, but 2 weeks later, counts had increased two orders of magnitude. By September 11, 1980, however, numbers had declined but still exceeded levels observed in reference lakes. Staley and others (1982) report that the coliform species *Klebsiella pneumoniae* was commonly found in different blast-zone lakes.

Escherichia coli was found in Fawn Lake (Staley and others, 1982, p. 666–669). Further discussion about circumstances accompanying these counts is presented later in this report.

No quantitative data exist for higher organisms such as fish, frogs, or tadpoles in Fawn Lake. After the eruption, the WDG determined that live fish were found in Fawn Lake, in contrast to Spirit and St. Helens Lakes. Most of the fish sampled, which were caught using baited gill nets, were eastern brook trout. This trout species was also the dominant fish species in Panhandle, Tradedollar, Hanaford, and Elk Lakes. See table 6 for selected post-eruption water-quality data.

St. Helens Lake

St. Helens Lake lay within the blowdown area of the volcanic blast; and although it was not in the path of pyroclastic flows, the lake was heavily impacted. St. Helens Lake is about 6 miles north of Mount St. Helens. McKnight and others (1984) reported that the lake was covered with ice on May 18, 1980. Wissmar and others (1982b) regarded the lake to have been partly shielded from the blast by the nearby mountain ridges. St. Helens Lake received a heavy layer of ash nonetheless, and gases of the volcanic blast scorched timber in the blowdown area. After the eruption, most of the lake's surface was covered by logs that either had been blown into the water or had slid or rolled down into the lake from the steep, surrounding slopes.

The pre-eruption area of the lake was 79 acres. The lack of pre-eruption bathymetric data makes it impossible to determine effects of the eruption on the lake's depth or profile. After the eruption, a bathymetric map was made, and Embrey and Dion (1988, p. 7–9) reported a maximum depth of approximately 280 to 285 feet. Investigators reported that the lake's outlet was not plugged or otherwise affected. Embrey and Dion (1988), visited St. Helens Lake in July 1980 and stated that water flowed out of the lake in an apparently normal fashion. The lake's outflow is eastward into Spirit Lake, whereas inflow is considered to originate from the north-northeastern edge.

Few pre-eruption data exist for physical, chemical, or biological characteristics of St. Helens Lake. Most investigators compared their findings to pre-eruption data for lakes in similar geographic locations, such as Merrill and Spirit Lakes. Researchers generally agreed that the transparency of St. Helens Lake was substantially decreased because of suspended ash and mud. Dion and Embrey (1981, p. G15–G16) reported the water color as grey-brown on August 28, 1980. Secchi-disk transparency was only 1.0 foot, far less than Spirit Lake pre-eruption readings that seasonally ranged from 23 to 46 feet. Pre-eruption transparency readings in category I lakes ranged from 1.8 to 32 feet, depending on the time of year. While a comparison of transparency readings for St. Helens Lake to pre-eruption Spirit Lake might indicate the transparency of St. Helens Lake was diminished by an order of magnitude, such conclusions cannot be made with certainty, because pre-eruption readings of less than 2 feet were commonly observed in category I lakes. The transparency of St. Helens Lake remained at 2.3 feet or less until August 1982 and was substantially less than transparencies observed in most other lakes studied by Embrey and Dion (1988). According to Embrey and Dion (1988, p. 16):

> [By] August 1982, the color had changed to yellow-green and the transparency had increased to a depth of only 2.5 feet***. This lake, which showed the least improvement in transparency, has the longest estimated water exchange time (5.4 years) of the study lakes***.

On June 6, 1980, littoral waters of St. Helens Lake had a specific conductance of 150 µS/cm (Dion and Embrey, 1981, p. G16). Interpretation of data is difficult, because some category I lakes commonly had pre-eruption values of specific conductance ranging from 25 to over 600 µS/cm. For example, Warden Lake had readings of 660 µS/cm on May 27, 1975. Dion and Embrey (1981, p. G16) summarized their findings by stating:

> A comparison of pre-eruption water-quality conditions in Spirit Lake***with post-eruption water-quality conditions in St. Helens Lake***suggests that the changes brought about by the volcano were similar to those observed in Spirit Lake, but not as great. This generalization is usually true for characteristics such as dissolved solids, specific conductance, hardness, metals, phosphorus, sulfate, and chloride. The concentrations of silica and DO in the epilimnion may have decreased, whereas the nitrogen, iron, and manganese may have increased.

The conclusions of Dion and Embrey (1981) appear to be substantiated by Wissmar and others (1982b, p. 176), whose post-eruption data show calcium, sodium, manganese, iron, sulfate, and chloride concentrations to be elevated, compared to category I lakes and to pre-eruption Spirit Lake. Concentrations of nutrients such as nitrogen and phosphorous compounds did not appear substantially altered. According to Embrey and Dion (1988, p. 20), "* * * inorganic nitrogen was still essentially at the detection level, and dissolved phosphorous concentrations were only slightly above detection levels." These observations were important when analyzing algal growth changes in freshwater-lake systems, because it was generally recognized that a lake's primary production is usually limited by availability of phosphorus. Embrey and Dion (1988) did not regard primary production in St. Helens Lake and many other category II lakes to be limited by available nutrients. The authors regarded primary production to be more affected by other factors, such as reduced available light for photosynthesis and competition with bacteria for available nutrients. Wissmar and others (1982a) attributed low phytoplankton numbers in various blast-zone lakes to attenuated light and did not regard competition to be a major factor in reducing primary production. Wissmar and others (1982a) observed an inverse relationship between chlorophyll *a* concentrations and available light, as measured by light extinction coefficients. These authors emphasized that although photosynthesis apparently was affected negatively, the total amount of living matter present in the lake actually had increased. Wissmar and others (1982a) attributed the increase in the amount of living matter to bacterial growth.

The post-eruption DO profile of St. Helens Lake was a clinograde curve (see Venus Lake), with high levels of dissolved oxygen in the epilimnion (Embrey and Dion, 1988, p. 17–18). As measurements were made through the metalimnion, DO decreased rapidly and was very low or absent in the hypolimnion. The authors noted lower dissolved oxygen concentrations near the bottom of the lake in 1982 than in 1981. Embrey and Dion (1988) speculated that a longer-than-usual mixing period during annual lake turnover may have occurred in 1981, because ice covering the lake melted earlier in 1981 than in 1982. Bacterial activity and chemical-oxidation reactions, the authors speculated, created the higher oxygen demand during 1982. According to various authors, other possible explanations for the changes were a reduction in photosynthesis, and an influx of reduced chemicals that caused oxygen in the hypolimnion to become depleted.

Prior to the eruption, the water type was probably a calcium-bicarbonate type. After the eruption, St. Helens Lake was characterized as a calcium-sulfate type, which probably reflects the lake's close proximity to the volcano. In general, most investigators thought the concentration of ions distributed in water increased the closer a lake was to the volcano (Embrey and Dion, 1988, p. 20–23). Wissmar and others (1982b, p. 176) reported a concentration of sulfate of 37.9 mg/L on June 30, 1980. Reference lakes in the unaffected zone (Merrill, McBride, June, and Blue Lakes) had a range of sulfate concentrations from 0.69 to 2.8 mg/L. Similarly, the chloride concentration of 14.5 mg/L in St. Helens Lake is larger than concentrations observed in the reference lakes, where concentrations of chloride ranged from 1.2 to 4.5 mg/L.

In St. Helens Lake, post-eruption concentrations of manganese and iron were elevated, according to Wissmar and others (1982b). Iron and manganese concentrations were most likely mobilized under anoxic conditions. Many blast zone lakes exhibited anoxic conditions in the hypolimnion during the time period in which they were studied. The anoxic condition was particularly prevalent during summertime periods of thermal stratification that are normally observed in such lakes. As time passed, the concentrations of iron and manganese in these lakes decreased.

Similar to other blast-zone lakes, there was a marked increase in the concentration of DOC and TOC in St. Helens Lake. Wissmar and others (1982a, p. 180) measured DOC shortly after the eruption and reported a 2.42 mg/L DOC for St. Helens Lake. By comparison, category I lakes had a DOC concentration range of 0.65 to 2.29 mg/L, and pre-eruption Spirit Lake had a concentration of 0.83 mg/L DOC. Embrey and Dion (1988, p. 20) attributed the large influx of organic material to pyrolization of conifer trees that were adjacent to the volcano. McKnight and others (1984, p. 11) cite a pre-eruption DOC concentration of 1.0 mg/L in Merrill Lake on May 1, 1980, and a pre-eruption DOC concentration of 0.8 mg/L in Spirit Lake. Both values agree with the reports of other investigators.

Most researchers did not attribute increases in DOC for these lakes to increased phytoplankton growth. Wissmar and others (1982a, p. 178) stated that increased DOC was accompanied by a drop in the concentration of chlorophyll *a*. The authors reported chlorophyll *a* was undetectable in St. Helens Lake on June 30, 1980. Embrey and Dion (1988, p. 24) reported concentrations of chlorophyll *a* of 3.0 to 4.0 μg/L in samples taken during August and October of 1980. In general, the concentration of DOC in heavily impacted category II lakes decreased during winter and spring due to dilution by rain and snowmelt. According to McKnight and others (1984, p. 11), the concentration of DOC decreased from 3.0 mg/L to 1.5 mg/L between September 1980 and the summer of 1981.

Dissolved organic material found in blast-zone lakes was analyzed by McKnight and others (1984, p. 11), who found that most of these compounds were hydrophobic and hydrophilic acids. The two classes of acids generally were found in many lakes where adjacent timber had been blown down, but relative concentrations of the acids varied considerably, particularly in St. Helens Lake. These acid constituents are discussed later in this report.

Although most authors reported a low level of light transmission in St. Helens Lake, its phytoplankton population did not appear significantly smaller than populations in other lakes. Embrey and Dion (1988, p. 41) reported densities of algae during 1981 and 1982:

> [Densities,] ranging from 110 to 1,090 million organisms per cubic meter, were not substantially different from the other lakes. The phytoplankton communities in the existing blast-zone lakes in late summer 1980 were composed primarily of green and blue-green algae.*** After the eruption, concentrations of zooplankton in Spirit, St. Helens, and Venus Lakes were more than 100 times less than populations in Walupt Lake and 1,000 times less than those in Fawn Lake. ***St. Helens Lake generally had the smallest (less than 70 organisms per cubic meter).

The authors reported the absence of rotifers in St. Helens Lake after the eruption, as was the case for other lakes in the blast zone.

Bacterial counts, from samples taken 0.8 feet below the water surface on June 30, 1980, were reported by Wissmar and others (1982a, p. 180). Total bacterial counts were 1×10^6 cells/mL, viable bacterial counts were greater than 10^4 cells/mL, total coliform counts were 20 cells/100 mL, and fecal coliform counts were 0 cells/100 mL. Staley and others (1982, p. 666) reported that *Klebsiella pneumoniae*, which was the most common total coliform species in other blast-zone lakes, was not found. *Serratia liquefaciens*, however, was identified in St. Helens Lake as another coliform species.

Embrey and Dion (1988, p. 38) stated that no live fish were found by the WDG after the eruption. No other biological information on higher biological taxa is available. At the time of the publication of their report, Embrey and Dion (1988, p. 39) estimated that St. Helens Lake was recovering very slowly, and that due to the estimated water-exchange rate of 5.4 years: "It may be decades before St. Helens Lake returns to near pre-eruption conditions." See table 6 for selected post-eruption water-quality data.

Spirit Lake

The largest and most famous blast-zone lake studied, Spirit Lake, was profoundly affected by the eruption of Mount St. Helens. Located only about 5 miles north-northeast of the volcanic crater, Spirit Lake received the full impact of the lateral blast. According to Franklin and others (1988, p. 12):

> The impact of the blast and debris avalanche temporarily displaced much of the lake from its bed; lake waters were sloshed in a wave extending to 260 m [850 feet] above lake level on the mountain slopes along the north shore of the lake.

Huge quantities of debris-avalanche materials, pyrolized trees, and other forest plants, ash, and minerals of various origins were deposited in Spirit Lake. The volume of material was so great that the surface area, depth, and volume of Spirit Lake were completely altered—virtually creating a new lake.

The lake's surface elevation was raised approximately 197 feet by the influx of debris, and the resultant surface area was about 80 percent larger than before the eruption. Researchers offer varying estimates on how much the lake's level was raised and the extent that surface area increased. According to Dion and Embrey (1981, p. G3):

> The surface area of the lake increased from 1,300 acres to about 2,200 acres. Soundings of the east bay of the lake on October 16, 1980, indicated that the depth at the midpoint of the east bay, originally 190 feet, was less than 50 feet. ***

The rise in lake level, estimated to be about 240 feet, is due to the blockage of the North Fork Toutle River, floods from melting snow on the volcano, and partial filling of the lake with debris (Youd and Wilson, 1980).

Dahm and others (1982, p. 116) stated:

Physically, Spirit Lake is a large lake set in a basin with a comparatively small drainage network when compared to other lakes in the region. Recharge for the Lake from rainfall and snowmelt will occur more slowly than [for] other lakes in the debris flow. Also, the immensity of the sediment input that elevated the lake surface by 74 m [243 feet] will be a vast reservoir for organic and inorganic nutrients for many years.

Because the lake was covered with logs after the eruption, researchers were prevented from immediately making a post-eruption bathymetric map. However, such maps were made several years later and could be compared to pre-eruption maps made by Bortleson and others (1976). The maps and aerial photographs taken before and after the eruption bear little resemblance to one another. Embrey and Dion (1988, p. 7) stated:

[The] maximum depth of the lake decreased from 190 feet to about 110 feet as a result of the eruption, and that the lake volume remained nearly the same [although the area was altered greatly].

The natural outlet of the lake was completely blocked by debris (Rosenfeld, 1980; Kerr, 1980), and the hydrologic balance of the basin became extremely unstable. The debris dam created a closed system, and various agencies, particularly the U.S. Army Corps of Engineers (COE), were concerned that the dam eventually would be breached. Continual water inflow caused the lake's volume to increase in the months following the eruption. A tunnel, connecting Spirit Lake to the North Fork Toutle River via South Coldwater Creek and designed to drain accumulated water, was constructed during 1984 and 1985 by the COE. The tunnel helped alleviate concerns regarding the breach of the debris dam. See Larson and Glass (1987) for references on COE activities in this regard. The present report is restricted to water quality phenomena caused by natural forces.

Fairly complete pre-eruption water-quality data are available for Spirit Lake, because Wissmar and others (1982b) performed various chemical and physical analyses on April 4, 1980, at the onset of volcanic activity. Their data, in conjunction with information compiled by other researchers in 1974, provide a description of the pre-eruption water chemistry. A comprehensive, two-volume report by Larson and Glass (1987) reviews most literature dealing with Spirit Lake over a 5-year timespan. The report includes research by Larson and Glass and cites material from scores of related reports.

On May 19, 1980, the temperature of Spirit Lake at the water surface was 32.7°C (Dion and Embrey, 1981). The high temperature was a result of pyroclastic flows, heated volcanic debris, and geothermal waters deposited into the lake. According to Dahm and others (1982), a typical surface temperature during the month of May would be approximately 10°C. Dethier and others (1980, p. 15), who sampled sites on the southeast, northeast, and northwest arms of Spirit Lake on June 8, 1980, reported temperatures ranging from 25.5–27.0°C. On June 30, 1980, Wissmar and others (1982a) reported a temperature of 22.4°C from a sample taken 0.8 feet below the water surface. According to Dion and Embrey (1981), the temperature dropped to 12.2°C by October 16, 1980, which was approximately the temperature recorded in Spirit Lake at that time of year during 1974. However, it seems certain that the temperature of Spirit Lake was increased substantially for a period lasting 4 to 5 months. Spirit Lake is the only lake known, with any degree of certainty, to have experienced an increase in water temperature that was caused by eruptions.

Prior to the eruption, Spirit Lake was known for its exceptional water clarity. According to Pereira and others (1982, p. 392), much of the lake surface was covered by logs after May 18, 1980:

[The transparency of Spirit Lake was very] greatly reduced by the introduction of partially degraded lignin molecules and other pyrolized (chemically changed by heat) organic material.

According to Embrey and Dion (1988, p. 11):

Water transparency depth as measured by Secchi disk was 46 feet in September 1974, but only 2.5 feet in late 1980, and never exceeded 3.5 feet through September 1981.

According to Larson and Glass (1987, p. 40–93), the post-eruption Secchi-disk transparency was only about an inch. In summary, the transparency was reduced to a fraction of the original value shortly after the eruption. Various research groups reported gradual increases in transparency, however, and Embrey and Dion (1988, p. 11) reported a transparency of 14 feet in August 1982.

After the eruption, the water in Spirit Lake was nearly black, which slowly changed to a shade of brown that resembled strong tea (Embrey and Dion, 1988, p. 11). According to McKnight (D.M. McKnight, written commun., 1993), "the color was due to the dissolved humic material formed from the leaching of pyrolized organic material." According to Larson and Glass (1987, sec. 4, p. 100):

> [The] principal sources of this discoloration are the lake's vast quantities of floating and submerged logs, which continue to leach some dissolved organic materials into the lake. Additionally, inflows from geothermal seeps and overland runoff also contribute to lake water discoloration.

The discoloration of lake water remained through 1985.

The pre-eruption DO profile of Spirit Lake was a typical positive heterograde curve during summer months, when DO concentrations were highest in the metalimnion. The heterograde profile was totally changed after the eruption, and DO was rapidly depleted. On June 30, 1980, Wissmar and others (1982a) reported a DO concentration of 2.35 mg/L at a depth of 0.8 feet, which is less than 40 percent of saturation. The authors thought that the small amount of oxygen resulted from wind-driven aeration in surface waters. Dahm and others (1982, p. 104) stated: "[The] deeper waters were certainly anaerobic. Lakes in the debris and avalanche area were particularly affected by the intense microbial oxygen demand." According to Dion and Embrey (1981, p. G14):

> On October 16, 1980, the DO concentration in the epilimnion (top layer) of Spirit Lake was only 0.8 mg/L; on October 9, 1974, before the eruption, the DO concentration in the epilimnion was 9.2 mg/L.

Larson and Glass (1987, sec. 3, p. 13) stated: "[After the eruption,] however, the lake became completely anoxic and remained so until at least 21 October 1980." According to Dahm and others (1982), the anaerobic condition of the lake permitted only growth of facultative or obligate anaerobic microorganisms. Baross and others (1982, p. 51) stated: "Heterotrophic microbial activity coupled with the decreased solubility of oxygen at the elevated temperatures quickly consumed the available O_2."

Numerous researchers monitored the recovery of Spirit Lake to an oxygenated condition. Embrey and Dion (1988, p. 17) reported:

> [By] mid-July 1981, Spirit Lake had become thermally stratified and the DO profile had assumed a clinograde shape with a maximum observed DO concentration of 5.4 mg/L in the epilimnion, whereas the hypolimnion was anoxic.

The reader is referred to reports by Embrey and Dion (1988) and by Larson and Glass (1987) for further details on recovery processes.

After the eruption, an unusual phenomenon was observed and reported by Dion and Embrey (1981, p. G4):

> When visited on September 4, 1980, the surface of the lake was emitting large quantities of gas, some of it in 'boils' 2 to 3 feet in diameter and some of it in almost continuous 'streamers of gas bubbles.' During an October 1980 visit, the gas activity of Spirit Lake was considerably less. According to Rasmussen, more than 50 gases have been identified, including H_2S (hydrogen sulfide), CS_2 (carbon disulfide), and CS (carbonyl sulfide). Many of the gases identified are toxic, and some are flammable. *** Rasmussen also reported that there is a large amount of chlorine gas present [R.A. Rasmussen, Oregon Graduate Center, oral commun. to Dion and Embrey, October 10,1980].

Certainly, the metabolic processes of microbes leading to the evolution of many gases is related to the influx of large concentrations of dissolved organic carbon compounds described by McKnight and others (1984). Dissolved organic carbon compounds are discussed later in this report.

Wissmar and others (1982a, p. 180) stated:

> The pronounced odor of hydrogen sulfide was strongly evident in most water samples. These observations indicate the potential for development of dense chemolithotrophic microbial communities.

In studies undertaken in 1981, Dahm and others (1982, p. 111) report extensive methanogenesis, which was attributed to microbial processes, from sediments of Spirit Lake. At that time, methane concentrations at lower sample depths exceeded 0.80 mg/L, which exceeded normal saturation values. Dahm and others (1982, p. 111) stated:

> [By] late June, the profile indicated that methane oxidation had begun, primarily at depths below 49.2 feet. This was the zone of the oxic-anoxic interface ***. By August, the interface had been displaced to near 16.4 feet depth. Again, evidence of active methane oxidation was apparent. Methane oxidation, possibly linked to dissimilative nitrogen cycle

reactions, was a significant source of dissolved oxygen depletion in Spirit Lake.

Wissmar and others (1982b) reported a substantial change in the pH of Spirit Lake, from 7.35 on April 4 to 6.21 on June 30, 1980. According to Wissmar and others (1982b, p. 176): "[The alkalinity changed from 139 μeq/L on April 4, 1980 to 3,010 μeq/L on June 30, 1980, a] 22-fold increase in total alkalinity." Dion and Embrey (1981, p. G15) reported pH values ranging from 6.0 to 6.8 during the period June 6, 1980, to July 28, 1980. The pH 6.0 value was recorded for littoral zones on June 8, 1980. Historically, a pH 6.2 was recorded during September 1974; therefore, it is not possible to say with certainty that the eruption caused a record minimum pH value.

The data of Dion and Embrey (1981, p. G15) show an order-of-magnitude change in total alkalinity expressed as $CaCO_3$, (calcium carbonate) from values ranging from 11 to 16 mg/L in samples from 1974, to a range of 110 to 190 mg/L during June and July 1980. The alkalinity of water is related to its buffering capacity and its capacity to neutralize acid. According to Larson and Glass (1987, sec. 4, p. 24), the lake was weakly buffered prior to the eruption. Larson and Glass (1987, sec. 4, p. 25) observed:

> [The post-eruption acidic pH was caused by] large quantities of carbon dioxide (CO_2) [that] were generated during in-lake decomposition of organic materials. Ensuing hydration of CO_2 yielded carbonic acid (H_2CO_3) which, together with other weak, microbially derived acids such as hydrogen sulfide (H_2S), lowered the lake water pH.

In summary, although the lake had a greater post-eruption buffering capacity due to increased alkalinity, the water became slightly more acidic. The authors reported that the pH of the lake water returned to a pre-eruption level by 1981.

Pre-eruption Spirit Lake was characterized as a calcium-bicarbonate water type. The inorganic chemistry of the lake was profoundly altered by the eruption; by October 1980, Embrey and Dion (1988, p. 23) characterized the lake as a calcium-sodium-bicarbonate type. Spirit Lake remained a calcium-sodium-bicarbonate type through August 1982. Embrey and Dion (1988, p. 23) stated:

> [Such changes reflect the] composition of volcanic materials and debris introduced into the lakes at the time of eruption and the subsequent chemical and biological processes in the lake. Similar to lakes outside of the blast zone, salts of chloride and sulfate had been condensed onto ash particles, and were distributed to lake waters when leached from the ash by water.

Citing research by Wissmar and others (1982b), Larson and Glass (1987, sec. 4, p. 26) stated:

> [Within a matter of days,] sulfate had become the most common ion in Spirit Lake, reaching concentrations that were 150 to 160 times greater than pre-eruption levels.

It should be noted that in leaching experiments on volcanic ash, the ion found in largest concentration was sulfate. Larson and Glass (1987, sec. 4, p. 30) stated:

> Once Spirit Lake had become anoxic, however, sulfur-reducing, anaerobic bacteria proceeded to deplete the lake's accumulated sulfate. By late October 1980, surface concentrations of sulfate had fallen to 70 mg/L (Larson and Geiger, 1982). This process of microbial sulfur reduction generated considerable amounts of toxic hydrogen sulfide, which were distributed throughout the lake.

Dissolved iron concentrations of from 1,300 to 3,600 μg/L for various sites in Spirit Lake during early June 1980 were reported by Dethier and others (1980, p. 22). Dissolved manganese concentrations at that time ranged from 4,800 to 5,000 μg/L. According to Dion and Embrey (1981, p. G14):

> The concentrations of dissolved iron and manganese are greatly increased, although the iron concentration had decreased by June 8, 1980. Significant increases also were noted in the concentrations of [the elements] ***(calcium, magnesium, sodium, and potassium), nutrients (nitrogen and phosphorus), sulfate, chloride, and silica.

In table 7, the range of pre-eruption concentrations of chemical constituents from June 27 to October 9, 1974, are compared to post-eruption data. The post-eruption data are expressed as a range of concentrations on the sampling dates on June 6 and June 8, 1980, and July 28, 1980.

According to Larson and Glass (1987), the post-eruption total hardness of the lake water was greatly increased, as a consequence of the increase in calcium, magnesium, and other cations. Larson and Glass (1987, sec. 4, p. 26) stated:

> Lake water hardness during the summer and fall of 1980 was 20 to 30 times greater than pre-eruption hardness values*** [and reflect] the abundant presence of hardness-related metals in the lake.

Wissmar and others (1982b, p. 176) reported data on chemical constituents from April 4 and June 30, 1980 (all samples taken from a depth of 0.8 feet). Concentrations of the following constituents were either elevated or raised to the level of analytical detection (if they had been undetectable prior to the eruption): copper, zinc, lead, arsenic, chromium, aluminum, antimony, silicon, silicon oxides, and phosphorus.

Table 7. Water-quality data for Spirit Lake, Washington, before and after the eruption of May 18, 1980

[From Dion and Embrey (1981, p. G15). Concentrations are in milligrams per liter unless otherwise indicated; --, data not available; µg/L, micrograms per liter]

	Date of collection	
	6/27/74–10/9/74	6/6/80–7/28/80
	Sample depth	
Constituents	3 feet	Littoral
Calcium, dissolved (Ca)	5.0	54–130
Magnesium, dissolved (Mg)	0	12–13
Sodium, dissolved (Na)	1.8	68–78
Potassium, dissolved (K)	.4	15
Carbon dioxide (CO_2)	0.1–5.6	85
Sulfate, dissolved (SO_4)	1.3	150–160
Chloride, dissolved (Cl)	1.3	83–86
Silica, dissolved (SiO_2)	11–12	46–50
Nitrate plus nitrite, total as N	0.00–0.02	.07
Nitrogen, ammonia, total as N	.01	0.00–0.19
Nitrogen, total organic, as N	0.10–0.13	1.2–1.5
Phosphorus, total, as P	0.00–0.01	.34–1.8
Phosphate, ortho dissolved (PO_4)	0	--
Iron, dissolved, (µg/L)	20–230	420–8,800
Manganese, dissolved, as Mn (µg/L)	0–10	4,800–5,000
Carbon, organic, total, as C	1.4–2.7	40

The concentrations of several dissolved constituents were greatly increased. For example, the pre-eruption concentration of aluminum was 0.010 mg/L; post-eruption concentration was 0.30 mg/L. The concentration of potassium was 0.40 mg/L before the eruption and 16.0 mg/L after the eruption. The pre-eruption concentration of magnesium was 0.48 mg/L; post-eruption concentration was 13.2 mg/L.

Changes in trace-metal concentrations in Spirit Lake were discussed by Larson and Glass (1987, sec. 4, p. 77–81), who compared the scant pre-eruption data concerning trace metals to post-eruption information. Larson and Glass (1987) regarded trace-metal concentrations in the lake to be changing, and related reported concentrations to permissible standards set by agencies such as the U.S. Environmental Protection Agency (EPA) for toxic metals. According to McKnight (D.M. McKnight, written commun., 1993), organic complexation of metals is important at higher levels. This could be the case, and the topic could be an area for future study.

Data of Wissmar and others (1982b) show post-eruption concentrations of dissolved phosphorus and orthophosphate were greatly increased. Larson and Glass (1987, sec. 4, p. 48) discussed whether or not the volcanic ash contributed appreciably to the amount of phosphorus in the water. Larson and Glass (1987, sec. 4, p. 48) attributed much of the post-eruption increase in dissolved phosphorus to: "*** bacterial decomposition of organic matter deposited in the lake." The authors presented a detailed analysis of changes in phosphorous concentration in Spirit Lake, and discussed hypotheses which would explain these changes. There appears to be no consensus among researchers about what water-quality changes resulted as a consequence of ash-derived phosphorus.

According to Larson and Glass (1987, sec. 4, p. 37):

> [The] concentration of nitrogenous compounds in Spirit Lake prior to the 1980 eruption was extremely low.***This scarcity of nitrogen restricted the production and growth of aquatic plant life, thus maintaining the lake in an oligotrophic state.

Agreeing with reports by Dion and Embrey (1981), the data of Wissmar and others (1982b) showed increases in concentrations of organic nitrogen and ammonia-nitrogen after the eruption. However, according to Larson and Glass (1987, sec. 4, p. 37–39):

> The post-eruption chemical enrichment of Spirit Lake did not include nitrogen. *** For instance concentrations of particulate organic nitrogen, although they increased by about 50 percent, from 0.047 to 0.070 mg/L between 4 April (pre-eruption) and 30 June 1980 *** were still very low. The demand for nitrogen in Spirit Lake was strong because extraordinary heterotrophic microbial activity during summer 1980 quickly depleted the lake's supply of nitrogen. Consequently, microorganisms capable of fixing molecular nitrogen (N_2) proliferated, succeeding bacteria without nitrogen-fixing capability. *** By mid-summer 1980, neither NO_3-N [nitrate] and NO_2-N [nitrite] were detected in Spirit Lake.

Ammonia-nitrogen was abundant in Spirit Lake primarily as a consequence of heterotrophic microbial decomposition of organic matter (Larson and Glass, 1987). The ammonia-nitrogen producing processes most likely occurred in the hypolimnion under anaerobic conditions. Larson and Glass (1987, sec. 4, p. 39) also regarded geothermal seeps to be contributors of ammonia-nitrogen to lake water.

Chemical changes, for samples collected on June 30, 1980, were reported by Wissmar and others (1982a, p. 180) as follows:

(1) The concentration of DOC was 39.9 mg/L, compared with a DOC concentration of 0.8 mg/L in April 1980 in reference lakes.

(2) The POC concentration was 570 µg/L, compared with POC concentrations ranging from 197 to 565 µg/L in reference lakes.

(3) The PON for Spirit Lake was 70 µg/L, compared with PON concentrations ranging from 15 to 62 µg/L in reference lakes.

(4) The concentration of ATP was 4.3 µg/L in Spirit Lake, compared with ATP concentrations that ranged from 0.6 to 3.7 µg/L in reference lakes.

The authors correlated the relatively high ATP concentrations and DOC values with greatly increased populations of bacteria.

The origin of the dissolved organic material to be found in various lakes after May 18, 1980, was discussed by McKnight and others (1984, p. 1). Soil and plant material had been incorporated into mudflows and deposits of debris and avalanche materials. This material, as well as blowdown timber, was swept into the lakes as a consequence of the eruption. According to McKnight and others (1984, p. 1):

> [The] resulting major increase in the concentration of dissolved organic material was one of the most significant changes in the water chemistry of surface waters of the blast zone.

In general, lakes such as Spirit Lake were the recipients of pyroclastic, mudflow, or debris-avalanche deposits and had larger concentrations of DOC than category I lakes. Organic materials leached from the ash and other dead plant materials also contributed to a small proportion of the total amount of DOC.

In continuing studies, McKnight and others (1984, p. 8–10) reported several trends in concentration changes of organic carbon in blast-zone lakes:

> First, DOC concentrations were much greater than SOC [suspended organic carbon] concentrations; these are typical for freshwaters other than large rivers. Second, throughout the summer of 1981, the DOC and SOC concentrations generally were greater in the hypolimnia of these lakes than in the epilimnia. *** These data indicate that a major source of dissolved organic material was anaerobic decomposition of organic material in the volcanic deposits covering these lake bottoms. Rapid aerobic biodegradation or chemical reactions, such as photolysis, in the epilimnion also may be responsible for the lesser DOC values in the epilimnion. The third major trend in DOC data for Spirit [and other] Lakes is that the epilimnetic DOC concentration did not change much in these lakes during the summer of 1981.

McKnight and others (1984) stated that the lake volume remained nearly the same during the summer, so that chemical constituents were only slightly diluted. However, they were of the opinion that the distribution of organic solutes between different classes of compounds varied within the lake's water column. The organic solutes, found mostly in the epilimnion, were different from those in the hypolimnion. McKnight and others (1984, p. 10) concluded:

> The constancy of the epilimnetic DOC concentrations further indicates that most of the dissolved organic material was in the form of relatively refractory substances that were not being utilized as a substrate by microorganisms at a significant rate. This conclusion is further supported by data*** which shows that the majority of the dissolved organic material could be characterized as humic material.

According to McKnight and others (1984, p. 12), the DOC in Spirit Lake was composed largely of hydrophobic and hydrophilic acids fractions, which were found in nearly equivalent amounts in the epilimnion. Hydrophobic acids, which are predominantly aquatic humic substances characterized as high molecular-weight organic acids that are aquatic fulvic acids, soluble at low pH, and yellow in color, were dominant. In general, hydrophobic aquatic fulvic acids are refractory, compared to other dissolved organic compounds. The aquatic fulvic acids were found predominantly in the epilimnion.

With respect to the epilimnion, McKnight and others (1984, p. 12) stated:

> [The] proportion of organic material in the different fractions was remarkably constant from September 1980 to August 1981. This result is consistent with the characterization of the major fractions, organic acids, as refractory aquatic-humic substances.

In contrast, rather than being refractory:

> [Hydrophilic acids] include many organic acids readily utilized by bacteria and other heterotrophic microorganisms, such as hydroxy acids and low molecular weight fatty acids, and may also be precursors in the formation of aquatic fulvic acids [McKnight and others, 1982, p. 86].

The distribution of the hydrophobic and hydrophilic acids in the water column was not uniform, but was affected by the amount of oxygen in the water. By the summer of 1981, the epilimnion of the lake was partially oxygenated. In this portion of the water column, aquatic fulvic acids constituted a large proportion of the DOC.

In continuing studies, McKnight and others (1984, p. 12) examined the hypolimnion of Spirit Lake in late August 1981. In the hypolimnion, where water was essentially anoxic, there was a greater proportion of hydrophilic acids than hydrophobic acids. The authors cited the work of Dahm and others (1982), which indicated there was active methane produced by bacterial decomposition of organic materials during this time period. According to McKnight and others (1982, p. 12):

> In this sample, hydrophilic acids were a larger fraction than hydrophobic acids, which may be characteristic of the production of dissolved organic material from anaerobic degradation of organic material in the underlying volcanic deposits.

The fulvic acids in the epilimnion of Spirit Lake described by McKnight and others (1984, p. 22) had a high sulfur content during the summer of 1980, but the amount of sulfur contained in the fulvic acids decreased over time. To account for the amount of sulfur associated with the fulvic acids, McKnight and others (1984, p. 14) suggested that sulfur dioxide from volcanic gases could have somehow been incorporated into organic materials. Another possible explanation is that anaerobic waters contained dissolved hydrogen sulfide formed during microbial metabolism—and the hydrogen sulfide subsequently might have reacted with organic material. McKnight and others (1987, p. 190–192) summarized their findings, and stated:

> [There] was a 50 percent decrease in the sulfur content between 1980 and 1981, and a progressive decrease in the phenolic hydroxyl content to a value of 0.2 MEQ/G [milliequivalent per gram] in 1983, which is extremely low compared to other aquatic fulvic acids.
>
> * * * * * * *
>
> [There was a] decrease in the concentration of some strong copper-binding sites. All these changes indicate that the material underwent significant oxidative change as a result of exposure to sunlight and oxygenated conditions in Spirit Lake.

For a complete discussion on the contribution of organic acids to alkalinity, and pH effects in Spirit Lake and other lakes, the reader is referred to Wissmar and others (1990).

McKnight and others (1984) concluded that volcanic ash deposited in the watershed was carried into the lake by rain and snowmelt. The authors regarded the influx of ash and leachate into the lake to be a contributing source of low molecular-weight organic compounds, such as fatty acids, dicarboxylic acids, and aromatic acids. However, low molecular-weight compounds constituted a relatively minor proportion of the total DOC. For a list of organic compounds identified by the authors in lake waters and volcanic ash, the reader is referred to McKnight and others (1984). At least one of the organic compounds found in Spirit Lake after the eruption is known to be toxic, according to Larson and Glass (1987, sec. 4, p. 87), who reported:

> Phenol concentrations, which had been less than 1 μg/L before the 1980 eruption (Thurman, 1986), reached 680 and 780 μg/L in August and October 1980, respectively (Larson and Geiger, 1982).***Phenol concentrations in Spirit Lake have diminished considerably since 1980, however, averaging less than 10 μg/L during the present study ***. These values are higher than phenol concentrations typically found in natural waters, which are less than 2 μg/L***.

Larson and Glass (1987, sec. 4, p. 87), and other researchers, considered the source of phenol to be forest and other organic debris in the lake, which underwent decomposition.

Pereira and others (1982, p. 392–393) analyzed water samples from Spirit Lake and stated:

> [Fatty] acids, dicarboxylic acids, phenolic acids, and benzoic and benzeneacetic acid derivatives, various phenols and cresols were identified***. Two tricyclic diterpenoid resin acids were also identified in the acid fraction of Spirit Lake ***. These two compounds were also found associated with volcanic ash. These two resin acids have been identified previously in Kraft Mill wastes ***.

Pereira and others (1982, p. 393) also reported: "*** [the] presence of three insect juvenile hormones in the acid fraction of Spirit Lake." The hormones have been isolated by other researchers from conifer trees, and the authors speculate on their efficacy as ovicides and juvenile hormones. The reader is referred to the report by Pereira and others (1982) for discussion of these and other compounds found in acid and neutral fractions, and for the bibliography dealing with various compounds identified and their possible toxic effects on fish and invertebrates.

Pre-eruption data on phytoplankton in Spirit Lake is sparse, and earlier studies alluding to diatoms and green algae are of limited value in evaluating post-eruption changes. Staley and others (1982, p. 666) stated:

> ***algae were affected adversely. Algal biomass, as determined by chlorophyll *a* concentrations, declined in Spirit Lake after the eruption and was low or undetectable in other blast-zone lakes***.

According to Dahm and others (1982, p. 116), who studied Spirit Lake during 1981:

> Algal activity as measured by light ^{14}CO [carbon-14 carbon dioxide] uptake was negligible. One early sign of lake recovery will be the reappearance of algae in the surface waters of the lake. Presently, microbiological processes overshadow other biological components in Spirit Lake.

Phytoplankton populations of five lakes during 1982 were studied by Smith and White (1985, p. 359), who stated:

> There are no records of phytoplankton assemblages from the lakes prior to the eruption of Mount St. Helens, therefore the origin of the phytoplankton populations that have developed must remain speculative. Spirit Lake received heavy ashfalls during the May 18, 1980 eruption and the lake bottom was raised some 197 feet by avalanche debris and pyroclastic material. The phytoplankton in Spirit Lake and the newly formed Castle and Coldwater Lakes were most probably inoculated from other lakes.

However, other groups of researchers reported finding algae during 1980.

Ward and others (1983, p. 242–244) sampled Spirit Lake on August 11, 1980, and identified colonial blue-green algae, *Cyclotella* Kutzing, *Melosira* Agardh., *Cocconeis* Ehrenberg, and *Nitzschia* Hassall. *Cyclotella* and *Melosira* were dominant. The authors reported an algal population density of approximately 2.6×10^5 cells/L. The authors inoculated water samples into reduced inorganic media, and were able to isolate *Nitzschia* sp. and *Chlorella* Beijerinck. Although the *Chlorella* and other small, unicellular green algae were not detected in the quantitative microscopic counts, Ward and others (1983, p. 242–244) were of the opinion:

> [These small cells may have been] hidden within the detrital particles or on the sides of the particles and therefore [may] not [have been] visible through the microscope.

The authors speculated that the microscopically undetectable but viable unicellular algae were most likely inactive due to the anaerobic conditions. However, the following summer on June 29, 1981, the authors reported:

> Small unicellular green algae made up the largest percentage (43 percent) of the phytoplankton in the sparse numbers observed by microscopy in Spirit Lake***.

The algal numbers were low at this time (7×10^2 cells/L), and included blue-green algae and some possibly heterotrophic forms of microflagellates. *Pseudoanabaena* Lauterborn, and *Navicula* Bory species made up approximately 58 percent of the total number of algae reported in 1981.

Using a helicopter, Larson and Geiger (1982, p. 377–378) collected a surface-water sample on October 21, 1980. The authors compared water-quality data to information collected in August 1980, and concluded that some changes had occurred over a 2-month period. The water contained a smaller concentration of soluble iron, and there were reductions in the total hardness and in specific conductivity. Larson and Geiger (1982, p. 378) reported the following species of diatoms: *Cyclotella stelligera, C. Kutzingiana, Stephanodiscus astraea v. minuta, S. astraea, Fragilaria construens* Venter, *F.leptostauron, Melosira distans, M.italica, Achnanthes minutissima, A. microcephala, Asterionella formosa, Synedra rumpens, Cocconeis placentula*, and Chrysophyte statospores.

The species in greatest abundance were *Cyclotella stelligera, Stephanodiscus astraea minuta,* and *Fragilaria construenes* Venter. Larson and Geiger (1982, p. 378) reported a total density of approximately 2.6 × 10^5 organisms/L, which they regarded as low, "*** [and] comparable to diatom densities reported for oligotrophic Crater Lake." The authors regarded the species composition to be representative of a eutrophic lake. According to Smith and White (1985, p. 347):

> The findings of Larson and Geiger (1982) indicated that populations of highly tolerant planktonic diatoms had reestablished in Spirit Lake and they suggested that lake recovery was underway despite the limnological disorder caused by the eruption and subsequent pyroclastic flows.

Embrey and Dion (1988, p. 26) reported a concentration of phytoplankton of 11.5 billion organisms/yd^3 (organisms per cubic yard) in October 1980. According to the authors, *Rhabdoderma lineare*, a blue-green alga, was virtually the only species in the phytoplankton population. The same species was identified in subsequent years, and the density of this organism decreased with time. According to Embrey and Dion (1988, p. 27–28):

> By late August 1981 the blue-green algae that had dominated Spirit Lake since late 1980 declined and the green and yellow-green algae, including the diatoms, became more prevalent.

Phytoplankton in Spirit Lake were studied during August 1982 by Smith and White (1985, p. 350), who found diatoms and other organisms and reported a total of 20 species from their samples. The authors reported that *Cyclotella meneghiniana, Mallomonas crassiquama, Cryptomonas* sp., and other flagellates were mostly found, and *Cryptomonas* sp. constituted 57.9 percent of the total community. The authors (Smith and White, 1985, p. 352) stated:

> [*Cyclotella meneghiniana* is often] found in slightly saline waters. The Spirit Lake waters had an enhanced sodium concentration ***, due to the quantity of avalanche debris and pyroclastic material deposited in the lake.

In comparing their data to the work of Larson and Geiger (1982), Smith and White (1985, p. 359) concluded:

> [The different assemblage reported in this study is most probably due to seasonal changes or succession due to the changing chemistry of the lake water. The only genus found in common was *Cyclotella*.

Several research groups continued studies of the phytoplankton assemblages in Spirit Lake in subsequent years, and the reader is referred to the report by Larson and Glass (1987) for additional references and details on species composition. The divergent results presented by the various researchers may reflect the different sampling techniques or sites.

There is little pre-eruption data on zooplankton in Spirit Lake. Wissmar and others (1982a, p. 181) reported on species collected from the surface waters on April 4, 1980, which included: *Bosmina, Daphnia, Diaptomus*, and cyclopoid copepods. Embrey and Dion (1988, p. 33) investigated zooplankton communities in August and October of 1980, and stated:

> ***[Zooplankton communities] were more than 100 times smaller than the community in Walupt Lake and 1,000 times smaller than that in Fawn Lake. The smaller numbers may indicate some mortality during the eruption in lakes close to the volcano. During the period of study, however, zooplankton concentrations increased markedly in Spirit Lake from 7 organisms/m^3 [organisms/1.3yd^3] in May 1981 to about 12,000 organisms per 1.3 cubic yards.

The composition of the zooplankton communities in 1981 consisted largely of the class Crustacea, and included Arthropods, primarily Copepods and Cladocerans. Among the Cladocerans found in October 1980, *Bosmina* sp. Baird, and *Ceriodaphnia* sp. Dana were dominant. Although no rotifers were found in 1980, by 1981 Embrey and Dion (1988) identified the rotifers *Keratella cochlearia, Kellicottia logispina, Keratella quadrata,* the protozoan *Vorticella,* and members of the Cyclopoida. Embrey and Dion (1988, p. 58) stated:

> In general, community compositions of zooplankton in the lakes varied in samples collected during each sampling period and may reflect changes in the dominant species or groups because of seasonal succession or food supply.

Prior to the eruption, Wissmar and others (1988, p. 181) found the rotifers *Asplanchna* and *Kellicottia.* After the eruption, the authors reported finding *Keratella, Filinia*, and *Hexarthra*. Larson and Glass (1987, sec. 4, p. 120) commented that *Keratella* sp., a rotifer which had been found in large numbers, feeds

primarily on bacteria that were abundant after the eruption. This is a good example of a situation in which a researcher was able to correlate the incidence of a zooplankton species with newly created environmental conditions. The reader is referred to the report by Larson and Glass (1987) for further details on changes in zooplankton populations in 1982, 1983, and subsequent years.

Extremely high levels of bacteria in Spirit Lake were reported by Dahm and others (1982, p. 99) and:

> Massive quantities of organic carbon, sulfur, and metals were loaded into the lakes. Heterotrophic microbial processes, stimulated both by elevated nutrient concentrations and temperature, rapidly consumed the available dissolved oxygen. Widespread anaerobiosis was prevalent within most lakes throughout the blast zone from July to October of 1980. Anaerobic conditions stimulated bacterial species capable of utilizing alternate sources of electron acceptors. Denitrifiers, capable of oxidizing sulfur, manganese, iron, and reduced gases, utilized nitrate as an electron acceptor to carry out oxidative reactions. These chemolithotrophic bacteria were found to represent a significant portion of the microbial flora in lake water. In total, microbial processes resulted in bacterial numbers routinely exceeding 10^8 organisms per milliliter of water in these lakes.

Although there were no pre-eruption bacterial enumeration data for Spirit Lake, certain guidelines exist for evaluating the status of blast-zone lakes. In general, researchers seem to agree that typical oligotrophic lakes have bacterial densities of approximately 10^5 cells/mL. Comparisons of bacterial counts were made with reference lakes. Dahm and others (1982, p. 104) stated that because of the abundance of organic carbon, increased levels of nutrients, and raised temperature of the lake, heterotrophic bacteria rapidly increased in numbers. The metabolism of heterotrophs is oxidative, and as a consequence of their activity, the little oxygen remaining in the lake was soon depleted. Certainly, the lake was essentially anaerobic by August 1980. Dahm and others (1982, p. 104) suggested:

> The widespread anaerobiosis also stimulated the leaching of metals and sulfur from the sediment and inorganic particulate matter due to microbial reduction reactions involving heterotrophs, methanogens, and sulfate reducers. Iron, manganese, and sulfur were solubilized. These elements in their reduced chemical state, can be used as sources of energy by chemosynthetic microorganisms.

Direct microscopic and viable counts of bacteria from samples collected June 30, 1980, were reported by Staley and others (1982, p. 667). The authors reported a total microscopic count of 4.9×10^6 cells/mL, corresponding to a viable count of greater than 10^4 cells/mL. The total counts gradually decreased during the summer of 1980, but the number of recoverable viable bacteria increased slightly. Vertical profiles of bacterial density showed that the total microscopic counts varied little from surface samples to depths of 32 feet, during early September 1980. The same uniformity of counts at various depths was reported by this group during April and June of 1981. Baross and others (1982) reported total microscopic counts as high as 4.2×10^8 cells/mL for the summer months of 1980 and total counts of manganese-sulfur oxidizing bacteria of 5.0×10^6 cells/mL. According to Baross and others (1982, p. 51):

> The manganese-sulfur oxidizing bacteria were repeatedly detected in excess of 10^6 per mL, a value comparable with the total bacterial counts in eutrophic lakes which generally range from 10^6 to 10^7 [cells]/mL.

On September 11, 1980, total coliform counts of 15 cells/100 mL and a fecal coliform count of zero were reported by Staley and others (1982, p. 668). In 1981, these investigators found total and fecal coliform bacteria, but the fecal coliforms were not detected until June 29, 1981. It should be noted that previous investigations had not detected fecal coliforms. According to Staley and others (1982, p. 666): "On 11 September 1980 the most commonly encountered total coliform species was *Klebsiella pneumoniae* * * *." This bacterium is a lactose-fermenting, gram-negative rod, which is ordinarily included in the list of coliform species. Staley and others (1982, p. 669) further stated:

> The prevalence of this bacterium was not altogether unexpected inasmuch as this organism has been associated with vegetation and, more specifically, with trees in the Pacific Northwest. In addition, it occurs in pulp mill ponds, habitats that may not be too different from these lakes after the eruption in terms of the types of organic materials present. It should be noted that *K. pneumoniae* is a nitrogen-fixing bacterium, and there is good evidence that active nitrogen fixation is occurring in at least some of these lakes.

Various serotypes of *K. pneumoniae* were isolated from vegetables, seed samples, and living white fir trees by Brown and Seidler (1973, p. 900). Some serotypes from these "natural environmental sources" were similar to serotypes previously isolated from human respiratory and genitourinary tract infections. Other researchers have described *K. pneumoniae* in association with insects and turtles. According to the authors, this organism has been associated with lobar pneumonia in humans, from a classical clinical viewpoint.

Klebsiella pneumoniae was subsequently reclassified as *K. oxytoca*, a species of *Klebsiella* commonly reported in association with human infections. The dual species designations of the genus *Klebsiella* will be used interchangeably in this report, because both names are utilized in the literature. Regardless of species name, this potentially pathogenic organism is a cause of septicemia (an infection of the bloodstream) in pediatric wards and also is responsible for a form of bacterial pneumonia in adults—particularly if the individual has a compromised upper-respiratory tract. The bacterium is destructive to lung tissue (Boyd and Marr, 1980 p. 363).

The species of *Klebsiella oxytoca, Enteropexies cloacae, Enterobacter aerogenes,* and *Escherichia coli* were found on April 30, 1981, by Staley and others (1982, p. 668). *Enterobacter* species and *E. Coli* were reported from depths of 66 feet. The authors stated:

> The lakes have been transformed rapidly from oligotrophic subalpine and montane lakes to eutrophic lakes, based upon the numbers of viable bacteria and total and fecal coliform bacteria.

Baross and others (1982, p. 49) stated:

> Within weeks of the eruption, the impacted lakes became anaerobic, ultraeutrophic and developed extensive populations of bacteria, some of which were not common to those environments. By August 1980 both assimilative and dissimilative nitrogen cycle reactions were regulating the extent of chemosynthetic, photosynthetic and heterotrophic activities***.

A number of investigators reported finding other potential human pathogens, and the occurrence and characterization of these species in subsequent years drew the attention of agencies concerned with public health. The pathogens include *Legionella* species, and *Pseudomonas aeruginosa.*

Pseudomonas aeruginosa was found in Spirit Lake in 1983 (Larson and Glass, 1987, sec. 5, p. 27). This bacterium was present in low numbers, or about 0.3 cells/100 mL. Commonly found during procedures used to isolate members of the Enterobacteriaceae, pseudomonads are common in both water and soil. *Pseudomonas aeruginosa* is often associated with hospital-acquired (nosocomial) infections and can multiply in a variety of body tissues. The organism was found in greater numbers in other lakes and streams, such as Coldwater Creek and the Toutle River, and are discussed later in this report.

High numbers of *Legionella* bacteria in lakes affected by the eruption were reported by Dahm and others (1981) and Tison and Seidler (1983). The initial reports of this organism prompted other researchers to continue sampling lakes and rivers of the blast zone for a considerable period of time after the eruption, because of the public health concerns related to the potential pathogenicity of *Legionella.* According to Tison and Seidler (1983, p. 1):

> Research personnel exposed to aquatic environments in the Mount St. Helens blast zone reported illnesses with 'flu-like' symptoms throughout the summer of 1980 and again early in the spring of 1981. The similarity of the reported symptoms to the 'Pontiac Fever' syndrome caused by *Legionella pneumophila* and the nature of the aquatic environments produced by the cataclysmic eruption prompted*** a study to determine the density and distribution of *Legionella sp.* (the etiologic agents of Legionnaires' Disease and Pontiac Fever) in the blast zone of Mount St. Helens.

The COE required data on bacteriological water-quality characteristics, because of the COE tunneling operation to discharge Spirit Lake water to the North Fork Toutle River via South Coldwater Creek. The tunnel was designed to prevent excess water from exceeding the safe and stable storage capacity of the lake basin. It was essential for the COE to determine if receiving waters might be degraded by the discharge of Spirit Lake water. Numerous sites were chosen for sampling analysis, and the reader is referred to the report of Larson and Glass (1987) for further information.

Larson and Glass (1987, sec. 5, p. 77) worked in conjunction with the State of Washington Department of Social and Health Services, which conducted extensive bacteriological surveys for *Legionella* species.

The authors stated:

> Among the sample sites within the eruption impact area, Spirit Lake had the lowest frequency of positive samples; nevertheless, 52 percent of the samples were found to contain the organisms. These frequencies (of culture positive samples) are far greater than frequencies generally found in environments which are not associated with disease outbreaks.

Larson and Glass, (1987, sec. 5, p. 77) reported:

> Of the *Legionella* types found, *L. pneumophila* was the most prevalent. Seventy-four percent of all positive samples contained at least one serogroup of this species. *L. pneumophila* is also the species most frequently associated with human disease, accounting for 80 to 90 percent of the Legionnaires' disease reported (Reingold and others, 1984). The next most common isolate in positive samples was *L. gormanii* (55 percent) and *L. longbeachae* (52 percent). These organisms are also known human pathogens.

Extensive analysis of the incidence of *Legionella* were performed by Larson and Glass (1987, sec. 5, p. 36), who stated that from 1983 through 1985:

> Fifty-two percent of the 92 samples examined from Spirit Lake were positive for *Legionella*. There was no significant difference in the proportions of positive samples between the East Bay and the West Bay sites, and no differences between sampling depths ***. The rate of positive samples has also remained constant over the years of the study. [However,] significant differences were found between seasons, with 85 percent of the samples collected during the winter and spring positive compared to positive findings on only 35 percent of the samples collected during the summer.

The extent to which pathogenic *Legionella* species found in natural reservoirs are responsible for causing human disease is uncertain. The organism, in addition to causing Legionnaires' Disease and Pontiac Fever, generally has to be present in high density, and is normally carried to susceptible persons by aerosols. Larson and Glass (1987, sec. 5, p. 78) stated:

> [In a natural environment,] aerosols are frequently produced where waters flow over rocks, obstructions, and waterfalls. Whether these conditions are sufficient to produce disease is uncertain.

It was reported that some researchers had antibodies in their blood for *Legionella*, which is evidence that these scientists had been exposed to the organism. There were reports of persons with respiratory problems, and at least one scientist was hospitalized with a "strange pneumonia" (D.M. McKnight, written commun., 1993). The scientists who became ill were not medically confirmed as having Legionellosis, although this organism seems to be the pathogen likely responsible for some of the illnesses described.

Bacteriological studies in various blast-zone lakes during 1981 and 1982 were continued by Tison and others (1983, p. 345–348). On April 30, 1981, the authors reported the *Legionella pneumophila* concentration was 1.3×10^7 cells/L in Spirit Lake, and continued to be present in detectable numbers through July 22, 1981. The authors reported that of all sites studied, the concentration of *Legionella* sp. was most dense in Coldwater and Spirit Lakes. The two lakes receive water from thermal seeps, and the number of cells per liter of *Legionella* species of bacteria was two orders-of-magnitude larger than in lakes and creeks not fed by thermal seeps. According to the authors, the hydrothermal seeps in the drainage area serve to enrich the aquatic niches. In some of these seeps that had temperatures above 65°C, DOC concentrations as large as 900 mg/CL (milligrams of carbon per liter) were reported. Seeps with lower temperatures had smaller DOC concentrations. Tison and Seidler (1983, p. 9–10) suggested that the carbon-enriched thermal waters may act as a source of *Legionella*, and that the organism might rapidly reproduce in nonthermal waters of the lakes, provided favorable conditions are present.

Few data exist regarding changes in invertebrates or higher organisms in Spirit Lake. Embrey and Dion (1988, p. 38) stated:

> Conversations with other researchers and subjective field observations made at the times of lake sampling provided limited information concerning the higher organisms. The high temperatures and low DO concentrations observed in Spirit Lake after the eruption most likely killed all fish in the lake.***Numerous midge and mosquito larvae were observed in the open-water zone of Spirit Lake, but closely associated with the floating logs that cover much of the surface of the lake. The logs may provide a suitable habitat for numerous organisms.

B. A. Crawford, Washington State Department of Game, sampled Spirit Lake between May 1980 and August 1985. Pre-eruption Spirit Lake had a fish assemblage that included rainbow trout *(Salmo gairdneri),* cutthroat trout *(Salmo Clarki)* and brook trout *(Salvelinus fontinalis),* and had last been stocked in 1979. However, after the eruption, Crawford (1986, p. 293) stated that Spirit Lake, and several other lakes, "* * * appeared to have lost their fish populations as a result of the May 18, 1980, eruption."

Summary of Volcanic Effects on the Water Quality of Category II Lakes

In contrast to the subtle changes exhibited by category I lakes, category II lakes underwent alterations in water-quality characteristics which, in many cases, were quite dramatic. Some effects noted for a particular lake may be peculiar or unique to that lake because of singular physical characteristics or surroundings. Such an effect cannot be considered to be "common" to all category II lakes. The summaries emphasize characteristics for which adequate comparative data exist, and can be readily contrasted to category I lakes. The reader is advised to refer to case histories for references, additional details, and particulars.

Physical and Chemical Characteristics

Temperature, pH, and Alkalinity

Spirit Lake appeared to be the only lake having a documented change in temperature directly attributed to the eruption. Most likely, Spirit Lake's surface temperature of greater than 32°C was an increase of about 20°C over the normal seasonal temperature. The situation for Spirit Lake is, however, extraordinary due to the influx of pyroclastic flows, heated volcanic debris, and geothermal waters. Ryan Lake was thought to be slightly warmed after the eruption. It is unlikely that the temperature of other category II lakes was appreciably affected.

Changes in pH were slight, if observed at all. Hanaford and Fawn Lakes had slightly lower pH values after the eruption, but lack of baseline data makes comparisons difficult. Category I lakes had pH values ranging from 6.73 to 7.20 after the eruption, so that a 6.97 pH reported for Hanaford Lake reflects little change. Ryan Lake may have exhibited a pH change; and the post-eruption pH was less than neutral, with a minimum 6.46 pH recorded nearly 2 months after the eruption. Spirit Lake, in contrast, definitely experienced a drop in pH, and minimum post-eruption values of 6.0 to 6.2 were reported. This change is greater than 1 pH unit and is atypical of category II lakes, most of which were not subjected to such complete changes as Spirit Lake.

Various authors regarded pH changes in category II lakes to be minor, and attributed the lack of change to the buffering capacity of these lake waters. Prior to the eruption, many of the lakes were characterized as the calcium-bicarbonate water type. Volcanic eruptions in other parts of the world have caused lakes to change in pH more noticeably. Other phenomena affecting pH were the production of carbon dioxide and hydrogen sulfide by microbial processes. Carbon dioxide can be hydrated to carbonic acid, which could contribute to buffering capacity; and organic acids contribute to surplus alkalinity. Hydrogen sulfide could contribute to acidity. Depending on the particular lake, therefore, changes in pH were related to "competing processes" of increased alkalinity and the production of acidic compounds.

Measurements of alkalinity were not made for all category II lakes, but there were reports of changes in several lakes. Hanaford Lake had a post-eruption alkalinity of 461 μeq/L, contrasted with a pre-eruption Spirit Lake alkalinity of 139 μeq/L. June Lake, a reference lake, had an alkalinity greater than Hanaford Lake. Spirit Lake had an order-of-magnitude increase with post-eruption values of 3,000 μeq/L or greater.

Light Transmission, Extinction Coefficients, Color, and Suspended Particulate Matter

Most category II lakes exhibited reduced light transmission due to ashfall, other organic debris, and humic substances. Chemicals, such as partially degraded lignin molecules and other burned organic matter, contributed to the changes. In some cases, diminished transparency was persistent and of several years duration. Decreased transparency was pronounced in some cases, and several lakes became virtually opaque, with transparencies reduced to 1 foot or less. Previously known for its water clarity, Spirit Lake was an extreme example—post-eruption Secchi-disk transparency was only about an inch. A large range in the pre-eruption transparency readings for category I lakes (1.8 to 32 feet) indicates a need for caution in drawing conclusions for lakes lacking true baseline data—particularly for lakes that appeared to exhibit fairly subtle changes.

Many lakes underwent profound color changes, from the transparent water of oligotrophic lakes to colors creatively described by various authors. For example, Venus Lake changed from a pre-eruption color of blue-green to a post-eruption color of olive-brown. Ryan Lake was described as light-brown to black; St. Helens Lake became grey-brown; and Spirit Lake was nearly black after the eruption.

In lakes for which measurements of SPM were made, significant changes were observed as a result of the eruption. Boot Lake had an increase in SPM of two orders of magnitude (post-eruption value was greater than 188 mg/L). By comparison, category I lakes had concentrations of SPM ranging from 1.23 to 8.17 mg/L. In Panhandle Lake, the reported SPM concentration of greater than 132 mg/L was an order-of-magnitude larger than for category I lakes. Similarly, Hanaford Lake apparently had an increase in SPM, which was related to increases in observed light attenuation.

Specific Conductance

Some changes occurred in specific conductance for most category II lakes; in several cases, that increase was substantial. For Venus and Fawn Lakes, values of specific conductance changed an order-of-magnitude. For some lakes, such as St. Helens Lake, the amount of change in specific conductance was difficult to document, because post-eruption values could only be compared to reference lakes that ranged from 25 to over 600 μS/cm.

Dissolved Oxygen

Pre-eruption summer DO profiles of several lakes were characterized as heterograde curves, typical of moderately productive lakes. After the eruption, DO profile changed to clinograde curves, more characteristic of eutrophic lakes (see Venus Lake for discussions of heterograde and clinograde curves). Altered DO profiles, which may have persisted several years, were documented for Venus, Fawn, and St. Helens Lakes. Ryan Lake DO characteristics changed greatly, and in the late summer of 1980 the lake became anoxic. Concentrations of DO in Venus Lake were lower after the eruption, and these changes persisted until 1982. The changes in oxygen for Spirit Lake are complex and linked with unusual microbial processes; the reader is referred to the section of this report dealing with that topic and the summary on DOC. Essentially, Spirit Lake was anoxic at times, and its pre-eruption heterograde DO curve was completely altered.

Carbon Dioxide, Hydrogen Sulfide, and Methane Gases

Some category II lakes contained unusual concentrations of gases related to various chemical and microbial processes. In Ryan Lake, a concentration of carbon dioxide greater than 230 nanomoles was reported; the odor of hydrogen-sulfide gas was noticeable in water samples. Spirit Lake emitted gases in "boils" that broke the water surface in bubbles; many gases, including hydrogen sulfide, carbon disulfide, carbonyl sulfide, and chlorine were identified. Methane concentrations in excess of saturation values were reported at lower depths; some of the other gases were regarded to be toxic.

Water Type, Chloride, Sulfate, and Major Cations

Most category II lakes heavily impacted by the eruption underwent changes in water type. Most of the lakes were classified as calcium bicarbonate water types before the eruption, but underwent fairly major changes in ionic composition. Examples are Venus, Fawn, and Spirit Lakes. Shortly after the eruption, Venus Lake was characterized as a calcium-sulfate chloride water type, Fawn Lake a calcium-sulfate type, and Spirit Lake a calcium/sodium-bicarbonate type.

In Boot and Hanaford Lakes, the concentrations of sulfate were increased compared to pre-eruption Spirit Lake and other reference lakes, whose typical pre-eruption values for sulfate ranged from 0.69 to 2.8 mg/L. Sulfate concentration in Boot Lake was more than 30 times the average for the reference lakes. Changes in sulfate concentration in Hanaford Lake were an order of magnitude. In Fawn Lake, dissolved sulfate concentrations ranged from 170 to 180 mg/L, depending upon depth. These sulfate concentrations were larger than those observed for category I lakes in this area, whose maximum post-eruption concentrations were less than 70 mg/L.

Most category II lakes had a change in the concentration of chloride ion; Boot Lake, for example, had a post-eruption chloride concentration seven times larger than the average category I lake. Other examples are Spirit and Fawn Lakes. Various researchers had demonstrated that volcanic ash was a probable source of sodium, chloride, and sulfate.

Generally speaking, lakes within the blast zone had increased concentrations of calcium, magnesium, sodium, and potassium as a result of the eruption. Changes ranged from nonsignificant to several orders of magnitude, depending upon the cation species and the lake investigated. Refer to Wissmar and others (1982b) for tables of physical and chemical information, that facilitate comparisons of data for different lakes within and outside of the blast zone.

Iron and Manganese

A lack of baseline data for some of the category II lakes hinders an analyses of iron and manganese concentrations; nonetheless, it is apparent that changes occurred. Comparisons were usually made with category I lakes whose manganese concentrations ranged from 0.0022 to 0.034 mg/L. Manganese concentrations in the category II lakes of Venus, Boot, Panhandle, Hanaford, Ryan, St. Helens, and Spirit Lakes had increased when compared with category I lakes. The relative amount of increase varied from lake to lake, and in some cases were an order of magnitude larger.

Comparisons with category I lakes indicate category II lakes, such as Panhandle, Ryan, St. Helens, and Spirit Lakes, had increased concentrations of iron. Depending upon the lake, increases in concentrations of iron were as great as five times the concentration reported for reference lakes.

In general, iron and manganese concentrations were largest near lake bottoms and during summer months. Researchers generally agree that iron and manganese were mobilized from ash under anaerobic conditions by the action of various bacteria in the hypolimnion of category II lakes.

Nitrate, Nitrite, Ammonia, Organic Nitrogen, and Phosphorous Compounds

Generalizations about changes in the concentrations of nitrate, nitrite, or ammonia-nitrogen are difficult to make; the situation for each category II lake is fairly unique. Some of the lakes did not appear to be changed in nutrient concentrations. In Boot Lake, post-eruption nitrate, nitrite, and ammonia-nitrogen concentrations were comparable to those found in category I lakes. For Venus Lake, nitrate plus nitrite nitrogen appear little changed, as was the case in Hanaford and St. Helens Lakes. Some authors consider several lakes to have been slightly enriched in inorganic phosphorus after the eruption. For Spirit Lake, the topic of nutrient levels is complex, and the reader is referred to the case history for details.

Some of the category II lakes experienced increases in total organic nitrogen. Venus and Hanaford Lakes had increased concentrations. However, Ryan Lake was low in dissolved organic nitrogen. Depending on the lake and the author, a variety of conclusions and hypotheses explaining observations are found in the literature. Because physical, chemical, and microbial processes are unique for each body of water, the broad spectrum of conclusions reported in the literature may merely reflect the many different observations—rather than differences of opinion among authors.

It is evident that Spirit and Ryan Lakes exhibited intense levels of microbial activity, such as denitrification; rapid changes occurred in levels of compounds such as nitrate. The type and rate of change depends on different stages of microbial succession attained. In Spirit Lake, nitrate and nitrite were difficult to detect by midsummer of 1980, whereas ammonia-nitrogen was abundant. Further complicating the analyses were changes, in some lakes, of populations of nitrogen-fixing organisms like blue-green algae and heterotrophic bacteria. In summary, it may be difficult to study nitrogen compounds in lakes on anything but a case-by-case basis.

Changes in concentrations of phosphorous compounds were observed in several lakes, but generalizations are difficult to make. Phosphorus increased slightly in Venus Lake, but did not change appreciably in St. Helens Lake. Researchers appear divided in opinions on whether or not phosphorous concentrations changed in Ryan Lake. A large increase in concentrations of dissolved phosphorus and orthophosphate occurred in Spirit Lake.

Dissolved Organic Carbon

According to some authors, the concentration of DOC increased in many blast-zone lakes in excess of 50 times the pre-eruption levels. In some cases, such as Boot Lake, researchers were able to correlate high DOC levels with bacterial populations and elevated levels of ATP. Elevated ATP levels were considered indicative of bacterial growth, rather than of phytoplankton growth (phytoplankton levels were usually estimated by measurements of chlorophyll *a*). St. Helens Lake had an increase in DOC, apparently unrelated to chlorophyll *a*. Ryan Lake exhibited

similar DOC-to-ATP relations. The concentration of DOC in Hanaford Lake was double the concentration found in any reference lake; DOC concentrations in Spirit Lake were more than 15 times the concentrations found in category I lakes. Dissolved organic carbon mostly consisted of hydrophilic acids and fulvic acids. The DOC post-eruption concentrations in category II lakes fluctuated during winter and spring seasons, probably from dilution by rain and runoff.

Biological Characteristics

Bacteria

Extreme bacteriological changes took place in several blast-zone lakes, particularly those that became anoxic or virtually anaerobic after the eruption. The most heavily impacted lakes developed bacterial populations quite uncommon to lake environments. By the autumn of 1980, the activities of bacteria came to dominate many aspects of lake metabolic processes. Particularly important were bacteria associated with assimilative and dissimilative nitrogen-cycle reactions; metal- and sulfur-oxidizing bacteria; and anaerobic and facultatively anaerobic organisms. Ryan and Spirit Lakes were particularly affected by changes in bacterial populations; these lakes grew bacteria to densities seldom observed in natural aquatic settings. Various authors found correlations between the density of bacterial populations and the concentrations of DOC and ATP.

In several cases, populations of potentially pathogenic organisms such as *Klebsiella pneumoniae,* were found as a dominant total coliform species. Other members of the coliform group of bacteria, such as *Serratia liquefaciens,* were identified. Total coliform and fecal coliform bacteria were found in Hanaford, St. Helens, Boot, and Ryan Lakes, compared to none for category I lakes. In Spirit Lake, *Pseudomonas* sp. and *Legionella pneumophila* were isolated. Detailed information on microbiological phenomena are detailed in the sections of this report on Ryan Lake, Spirit Lake, and newly formed lakes.

Phytoplankton and Zooplankton

Various authors reported apparent changes in phytoplankton and zooplankton populations after the eruption, with types and relative numbers of different species continuing to change throughout 1981 and 1982, as the lakes began to recover. Zooplankton densities in the lakes that were impacted most heavily were lower than zooplankton densities in reference lakes. Some authors attributed the lower zooplankton concentrations to mortality—particularly if the lake was in close proximity to the volcano. In general, green and blue-green algae comprised most of the phytoplankton in category II lakes during the summer months of 1980. Collectively, most category II lakes had few diatoms in the first year after the eruption; however, the relative proportions of diatoms in the population had increased by 1982.

In Venus Lake, phytoplankton species changed throughout 1982, and, whereas phytoflagellates were dominant in 1981, diatoms became dominant in 1982. In Ryan Lake, there were initially many post-eruption microflagellates. The number of microflagellates and ciliated protozoans found in Ryan Lake was considered extraordinary, for they are more typically found in eutrophic lakes. In the initial post-eruption, near-anaerobic conditions, the ciliated protozoans were numerous in Ryan Lake. The increased numbers of protozoans were related, quite likely, to the dense bacterial populations which provide food for macrozooplankton.

In Fawn Lake, phytoplankton densities decreased after the eruption; by late August 1980, green algae became dominant. Rotifers were found later in Fawn Lake; but during 1980, few lakes in the blast zone had members of the Rotifera, an observation considered unusual by researchers. In St. Helens Lake, the phytoplankton population appeared relatively unchanged, but zooplankton species were greatly diminished. The apparent negative effect of the eruption on zooplankton also was observed in Spirit and in Venus Lakes. Spirit Lake had low phytoplankton densities by fall 1980. The species composition of Spirit Lake after the eruption was considered to be similar to a eutrophic lake, if such a eutrophic lake was located in the Oregon portion of the Cascade Range.

Wissmar and others (1982a) attributed changes in phytoplankton populations to limitation of light available for photosynthesis. The authors derived an inverse relation between chlorophyll *a* concentrations and light extinction for different lakes.

Fish

Fish survived blast effects in some category II lakes; not all lakes were surveyed for fish, so generalizations about their survival are difficult to make. In the autumn of 1980, eastern brook trout and

cutthroat trout were found in Hanaford Lake and were thought to be feeding on terrestrial insects and surviving midge larvae and caddisflies. No live fish were reported for St. Helens Lake after the eruption; and fish populations appear to have been destroyed in Spirit Lake.

Case Studies of Newly Created Lakes—Category III

The eruption of Mount St. Helens created a number of new lakes by damming streams. Several lakes are large and have evolved for more than a decade with substantial changes in characteristics. Smaller impoundments also were created, but had a short life span and no longer exist. It is important to understand that after the eruption, many of the water bodies formed were variously called lakes or ponds by different authors. Some of these short-lived lakes were studied by different researchers, who may have designated a given lake by a name that differed from the name assigned by another author.

This part of the report is confined primarily to descriptions and analyses of two "newly created" lakes existing at this time (1992). The new lakes represent completely atypical situations, and discussions regarding them are grouped together whenever possible. References have been chosen to reflect data collected within 1 to 2 years after the creation of the new lakes. A long-term analysis of changes occurring in new lakes is outside the scope of this report.

Coldwater Lake

North and South Coldwater Lakes were created by landslide-debris flows which dammed Coldwater Creek, a tributary of the North Fork Toutle River. In this report, a reference to Coldwater Lake is understood to mean North Coldwater Lake, rather than South Coldwater Lake, unless otherwise stated.

Baross and others (1982, p. 50) were among the first researchers to describe Coldwater Lake and its seep. According to the authors, Coldwater Lake lies 6.8 miles from the crater and had a depth of 112 feet in the summer of 1980. The surface area of Coldwater Lake was reported to be 247 acres.

According to Dahm and others (1982, p. 124):

> The drainage network which feeds North Coldwater Creek includes much of the Mt. Margaret and Mt. Whittier area. The rapid growth of the lake during the winter and spring of 1981 required the construction of an oveflow channel to mitigate flood dangers to downstream communities from a sudden downcutting of the debris dam. The overflow channel has now [1981] stabilized the elevation of the lake surface. Maximum depth of the lake is about 40 meters [131 feet].

Coldwater Lake was studied from June 1981 to August 1982 by Embrey and Dion (1988, p. 6), who reported that after channel construction and stabilization of the lake, the lake's altitude was 2,480 feet above sea level. The lake's surface area was 900 acres. Lake volume was 70,000 acre-feet and maximum depth was 190 feet—considerably greater than in 1980. A bathymetric map made in November of 1981 is included, with details of Coldwater Lake's evaporation, in the report by Embrey and Dion (1988). The map was drawn after the outflow channel had been constructed. During this time, water flowed into both ends of the lake, while the outflow was from the southwestern part.

According to Baross and others (1982, p. 51), oxygen was present at the surface of Coldwater Lake (1.61 mg/L) during the summer of 1980. However, by August and September of 1980, the authors reported no oxygen at a depth of 0.7 feet in the lake. Coldwater Lake was virtually anaerobic below the surface layer, although the surface layer may have contained some oxygen. Baross and others (1982, p. 51) stated: "***Heterotrophic microbial activity coupled with the decreased solubility of oxygen at the elevated temperatures quickly consumed the available O_2." The authors reported that the lake's pH of 6.21 was substantially more acidic than post-eruption Spirit Lake.

According to Baross and others (1982, p. 51):

> During the summer and early autumn of 1980***water at all sites was light brown to black in color due to high levels of sulfides and DOC***. The sediments were actively degassing, giving off methane and other gases, so that in some lakes, such as North Coldwater, the entire surface was continuously bubbling. The bubbles in the lake and at isolated puddles at North Coldwater were collected and analyzed and found to consist of approximately 50 percent CH_4 [methane], 50 percent CO_2 [carbon dioxide] and trace levels of H_2 [hydrogen gas], CO [carbon monoxide] and N_2O [dinitrogen oxide].

The authors suggested that low dissolved organic nitrogen levels in Coldwater Lake during this time period favored organisms involved with nitrogen cycle processes. The authors reported extraordinarily high rates of phototrophic nitrogen fixation and anaerobic dark nitrogen fixation. Baross and others (1982) reported anaerobic dark N_2 fixation in Coldwater Lake's surface water at rates that may have exceeded 200 nanomoles per liter per hour, a rate more than an order-of-magnitude higher than previously reported. Baross and others (1982, p. 52) concluded:

> [Nitrogen fixation] was a major source of reduced nitrogen to the lakes in the blast zone of Mount St. Helens. [The authors state that] high levels of CO [carbon monoxide], H [hydrogen gas], and N [nitrogen gas] were also detected in all impacted lake waters.

According to Baross and others (1982, p. 51), the concentration of hydrogen gas found in Coldwater Lake was one to two orders-of-magnitude larger than in post-eruption Spirit Lake. The concentration of methane was at least double the concentration found in post-eruption Spirit Lake at that time.

Chemical characteristics reported by these authors for the seep of North Coldwater Lake are extraordinary. Coldwater Lake seep had a pH of 5.35 and a DON of 4.20 mg/L. The DOC in the seep was 4,285 mg/L, which was approximately five times the amount of DOC in post-eruption Spirit Lake. Pre-eruption Spirit Lake had a DOC of 0.83 mg/L—a concentration nearly four orders-of-magnitude lower than that of the seep.

Coldwater Lake was sampled in September 1980 by McKnight and others (1984, p. 19), who stated:

> [Coldwater Lake was] not as enriched in dissolved organic carbon (15 mg C/L) as Coldwater Creek (150 mg C/L), and only seven neutral organic compounds were identified. ***Four of these compounds were terpenes, including cineole, fenchone, and terpinene-4-ol. No [low molecular weight] organic acids were identified in Coldwater Lake in September 1980.

The authors sampled Coldwater Lake again on April 30, 1981, and found that the chemistry of the lake had changed. McKnight and others (1984, p. 19) reported finding numerous organic acids in this 1981 sample:

> [Fatty] acids, dicarboxylic acids, and their derivatives***and aromatic acids [were found]. *** As was true in South Fork Castle and Spirit Lake, most***of the organic acids present on April 30, 1981, in Coldwater Lake also had been found in volcanic ash. ***This again supports the conclusion that leaching of volcanic ash was an important source of low molecular-weight organic compounds in blast-zone lakes during the spring snowmelt.

Post-eruption Coldwater Lake had a larger concentration of iron, but approximately the same concentration of manganese, when compared to post-eruption Spirit Lake (Baross and others, 1982, p. 51). The concentration of total phosphorous was nearly the same for both Spirit and Coldwater Lakes, but there was more dissolved nitrogen and dissolved organic carbon in Coldwater Lake (DON = 0.690 mg/L and DOC = 114 mg/L).

McKnight and others (1984, p. 10–11) reported that during the summer of 1981:

> DOC and SOC concentrations were not consistently greater in the hypolimnion*** than in the epilimnion. The failure of dissolved organic material to accumulate in the hypolimnion probably was related to the continued presence of dissolved oxygen at depth until late August. Dahm and others (1982) concluded that biodegradation of organic material in the volcanic deposits underlying the lake probably was comparable to biodegradation in Spirit and South Fork Castle Lakes, based on similar rates of methane production. Leaching and decomposition of the logjam covering Coldwater Lake also may have contributed organic material to the surface water of the lake.

Coldwater Creek, which was dammed by landslide debris and from which Coldwater Lake was formed as a consequence, was analyzed by Pereira and others (1982, p. 388). The authors reported large amounts of dissolved organic materials in Coldwater Creek, which may have been the origin of many organic compounds identified in Coldwater Lake. The authors considered pyrolization of forest, vegetation, and soil materials to be a source of various chemical compounds. Such could be the case with the other lakes discussed in this report. In many blast-zone areas, trees which had been blown down also were burned. Charred trees were buried in ash and hot mud, and the net effect was a "retorting" of chemical compounds derived from the burned vegetation. According to Pereira and others (1982, p. 388):

> North Coldwater Creek is now significantly contaminated by resinous and tar-like organic material. These 'pockets' of burned vegetation that are buried in the high-temperature muds and ash are *'in situ'* steam distilling from the wood, seeping to the surface, and mixing with surface water.

The authors also reported a black, tarry substance in the creek water.

Hindin (1983, p. 73) analyzed Coldwater Lake in September 1981, more than a year after the eruption, but did not find the black, tarry substance—in either the epilimnion or the hypolimnion—which Pereira and others (1982) had reported finding. Hindin detected a nonquantifiable concentration of phenol, and found measurable amounts of 2,4,6-trichlorophenol in both the epilimnion and the hypolimnion. According to Hindin (1983, p. 59–60, 73):

> The hypolimnion also contained 2,4-dichlorophenol. Low molecular weight polycyclic aromatic hydrocarbons, i.e., anthracene and phenanthrene were found in both water layers. The terpenes, beta-cymene and alpha-terpineol were found in both layers. In addition, alpha-pinene, and terpinene-4-ol were found in the hypolimnion. The dissolved organic carbon content was about the same for each layer (epilimnion, DOC = 6.4 mg/L; hypolimnion, DOC = 7.3 mg/L).

The authors reported finding haloforms (chloroform and dichlorobromomethane), in addition to phenolic compounds, polycyclic aromatic hydrocarbons, and terpenes.

Water from Coldwater Lake was inoculated to growth media by Ward and others (1983, p. 242–243), who isolated various small, unicellular green algae in 1980. Analogous to investigations in Spirit Lake, viable algal cells were perhaps hidden by, or associated with, detrital particles and were not detectable by the phase contrast microscopic technique utilized for quantitative counts. Low light conditions reported by various researchers were a factor in explaining the slow development of phytoplankton species shortly after the eruption. Coldwater Lake was one of the most turbid lakes examined and had, a year after the eruption (Ward and others, 1983, p. 243), "***only 1 percent of surface light available 1 meter [3.3 feet] below the surface in June 1981."

By August 1980, the lake was considered to be totally anaerobic and was dominated by bacterial metabolic processes. Conditions began to change during spring of 1981, however, and the lake was oxygenated throughout the spring season. Thermal stratification processes, nevertheless, caused the hypolimnion to become anaerobic in subsequent months. Ward and others (1983, p. 246) speculated that large manganese concentrations may have adversely affected algal growth. The authors considered net phytoplankton productivity to be immeasurable during 1980 and 1981.

Coldwater Lake was sampled for bacteria during the summer and the early autumn of 1980 by Baross and others (1982, p. 51). During that period, the authors reported total bacteria counts ranging from 3.4 to 7.0×10^7 cells/mL at the lake surface, and the total number of sulphur/manganese oxidizing bacteria present was 3.0 to 4.0×10^5 cells/mL. In addition to bacteria, the presence of algae and diatoms also was reported by the authors.

Baross and others (1982, p. 51) discussed the potential productivity of Coldwater Lake during 1980, and cited carbon/nitrogen ratios in the 150–250 range. According to the authors:

> [The] nitrogen concentrations, relative to carbon, phosphorous and sulphur, suggested a nitrogen limitation. Such a notion was supported by the high rates of phototrophic N_2 [diatomic nitrogen] fixation and anaerobic dark N_2 fixation.

Baross and others (1982, p. 51) reported levels of anaerobic dark N_2 fixation in surface waters of Coldwater Lake, which were historically among the highest levels ever reported. According to the authors, nitrogen fixation was a primary source of reduced nitrogen for this lake. Ward and others (1983, p. 240), in reference to reports by Baross and others (1982), concluded that anaerobic nitrogen fixation, fermentation, methanogenesis, sulfate reduction, and chemosynthesis were the dominant biological processes during 1980. By 1981, bacterial denitrification processes also were important.

One year later, during the spring and summer of 1981, high numbers of bacteria in Coldwater Lake were reported by Dahm and others (1982, p. 124–128), who stated:

> [The] abundance of particles for bacterial attachment increased the density of microbes. The total bacterial counts on June 29, 1981 ranged from 1.3×10^8 to 3.7×10^8 organisms per milliliter. Microbial processes dominated the biological activity in North Coldwater as in Castle Creek and Spirit Lakes.

Castle Lake

Castle Creek, a tributary of the North Fork Toutle River, lies northwest of Mount St. Helens. The pre-eruption basin was a marsh, but blast-debris avalanches and mudflows dammed Castle Creek and formed Castle Lake. Wissmar and others (1982b) allude to separate Castle Lakes: West Castle Lake and East Castle Lake. The larger water body is West Castle Creek Lake and was also called Castle Lake, South Fork Castle Lake, or Castle Creek Lake by different authors. Unless otherwise stated, West Castle Lake will be known throughout this report as Castle Lake.

According to Wissmar and others (1982b, p. 176), Castle Lake (West Castle Lake) has an elevation of 2,428 feet and is 5.6 miles from the crater. Castle Lake's surface area was 82 acres, and its depth was 36 feet during the summer of 1980. According to McKnight and others (1984, p. 3):

> Aerial photographs of South Fork Castle Lake [Castle Lake] clearly show that the lake greatly increased in size from November 11, 1980, to March 1, 1981. The volume of South Fork Castle Lake [Castle Lake] increased by about 14 times from 1,100 acre-feet on September 30, 1980, to 14,960 acre-feet on May 27, 1981***.

During the summer and fall of 1981, the rate of increase in the volume of the lake decreased. McKnight and others (1984, p. 3) reported: "[The] lake surfaces were partly covered with floating logs from the summer of 1980 through the fall of 1981."

Wissmar and others (1982a, p. 180) sampled the water in (West) Castle Lake on June 30, 1980 at a depth of 0.8 feet and reported a light extinction coefficient of 12.4. Embrey and Dion (1988, p. 15) reported that a year later, during May and June 1981, water transparency improved from 4 to 11 feet, although the water remained amber stained at that time. Wissmar and others (1982b, p. 177) reported low pH values for South Coldwater and West Castle Lakes 6.61 and 6.17, respectively, and stated: "The two lakes also had very high total alkalinities (1,520 and 4,500 μeq/L, respectively) and major cation concentrations." Embrey and Dion (1988, p. 15), who performed various analyses on water from the lake from 1981 to 1982, determined that Castle Lake was a calcium-bicarbonate water type from the time it was formed and that it remained so in subsequent years.

According to Wissmar and others (1982a, p. 180), the lake was oxygenated after its formation. The authors reported 3.00 mg/L of dissolved oxygen at a depth of 0.8 feet on June 30, 1980. According to McKnight and others (1984, p. 12), oxygen-saturated rain and snowmelt during the spring of 1981 caused the water to become increasingly saturated with oxygen. However, Dahm and others (1982, p. 116) reported that DO concentration decreased during the period from April 30 to August 31, 1981. By late June 1981, the water below 33 feet was anoxic. The anaerobic condition of the hypolimnion persisted during the summer months of 1981. Dahm and others (1982, p. 116) stated:

> Dissolved oxygen concentration in Castle Creek Lake decreased steadily throughout 1981. ***Anaerobiosis in the deepest waters was measured in late June and was maintained throughout the summer. However, anaerobic conditions were limited to depths below 33 feet in Castle Creek [Castle Lake]***.

Embrey and Dion (1988, p. 17) stated:

> Coldwater and Castle Lakes developed clinograde DO profiles in 1981 and 1982. The hypolimnia in both lakes became depleted of oxygen during the summer of both years, probably due to a substantial biological and chemical oxygen demand from the breakdown of organic materials supplied by the newly inundated land, and to logs and other debris contributed to the new lake basins [created] by the eruption.

According to Wissmar and others (1982a, p. 180) the water temperature on June 30, 1980, was 20.0°C (all samples from 0.8 feet). Castle Lake had 46.36 mg/L of SPM, and the concentration of particulate organic carbon was 5,925 μg/L, the largest concentration for lakes studied by Wissmar and others (1982a). The concentration of particulate organic nitrogen of 1,305 μg/L was two orders-of-magnitude larger than that found in reference lakes with PON concentrations ranging from 15 to 60 μg/L. The concentration of chlorophyll *a* was 0.6 μg/L, which was comparable to reference lakes; however, the ATP concentration was 15.2 μg/L, the largest concentration reported for any of the lakes studied. The ATP concentration was related to large numbers of bacteria in the lake on that date.

Dissolved chemical characteristics of Castle Lake for samples taken 0.8 feet below the surface on June 30, 1980, were reported by Wissmar and others (1982b, p. 176). The authors report a concentration of calcium of 94.3 mg/L, compared with concentrations in Merrill, McBride, June, and Blue Lakes ranging

from 2.17 to 4.06 mg/L. McKnight and others (1984, p. 6) reported a calcium concentration of 74.3 mg/L on September 11, 1980. On April 30, 1981, the calcium concentration was 21.4 mg/L.

According to Wissmar and others (1982b, p. 176), the magnesium concentration for Castle Lake was 21.2 mg/L, compared to the range found in reference lakes of 0.42 to 1.5 mg/L on June 30, 1980. McKnight and others (1984, p. 6) reported a magnesium concentration of 16.7 mg/L on September 11, 1980, which decreased to 14.4 mg/L by April 30, 1981.

Wissmar and others (1982b, p. 176) reported a sodium concentration of 112 mg/L, compared to a range of 2.6 to 8.8 mg/L for the reference lakes. By comparison, the sodium concentration of pre-eruption Spirit Lake was only 2.0 mg/L. McKnight and others (1984, p. 6) reported a sodium concentration of 82.3 mg/L on September 11, 1980, which decreased to 18.6 mg/L by April 30, 1981.

According to Wissmar and others (1982b, p. 176), the potassium concentration in Castle Lake was 40.0 mg/L, compared to a range of 0.30 to 1.6 mg/L for the reference lakes on June 30, 1980. The authors reported a concentration of aluminum that was two orders-of-magnitude greater than observed for Spirit Lake prior to the eruption. The manganese concentration of Castle Lake was 5.4 mg/L, compared to a range of 0.0022 to 0.034 mg/L for "controls." McKnight and others (1984, p. 6) reported a manganese concentration of 4.6 mg/L on September 1, 1980, which decreased to 1.1 mg/L by April 30, 1981.

According to Wissmar and others (1982b, p. 176), the iron concentration of 15.7 mg/L was about three orders-of-magnitude larger than for reference lakes that had iron concentrations ranging from 0.0022 to 0.027 mg/L on June 30, 1980. The concentration of iron in Castle Lake was the largest of all the lakes studied by Wissmar and others (1982b). McKnight and others (1984, p. 6) reported an iron concentration of 1.97 mg/L on September 11, 1980, which decreased to 0.640 mg/L on April 30, 1981. Dahm and others (1982, p. 116–117) who analyzed the lake for both ferrous iron and methane production during the period from April 30 to August 31, 1981, reported:

> [The] concentrations of reduced iron were particularly high, approaching 3 ppm [parts per million]. Methane production from the sediment was somewhat less than in Spirit Lake, assuming the bottom sample concentration in each lake reflects methanogenesis in the sediment. Methane concentrations were generally one-third or less than those at the bottom sampling depth in Spirit Lake.

According to McKnight and others (1984, p. 6) copper, lead, zinc, and strontium were present in concentrations of 28, 38, 38, and 373 μg/L respectively, on September 11, 1980. By April 30, 1981, the concentration of copper and strontium had fallen substantially, but the amounts of lead and zinc were diminished only slightly.

According to Wissmar and others (1982b, p. 176), silicon and phosphorous concentrations were larger than for reference lakes. Nitrite nitrogen was 0.13 mg/L compared to a range of 0.0009 to 0.002 mg/L for "controls," whereas nitrate-nitrogen was within the range for the reference lakes. Dahm and others (1982, p. 121) noted an important difference between the nutrient chemistry of Castle Creek and Spirit Lakes, and stated:

> ***Spirit Lake was phosphate rich but contained almost no inorganic nitrogen ***. The converse was true in Castle Creek. The cause for the distinct differences in lakes a few miles apart is unclear.

According to Wissmar and others (1982b, p. 176), the concentration of sulfate was 120 mg/L—two orders-of-magnitude larger than reference lakes with sulfate concentrations ranging from 0.69 to 2.8 mg/L. The concentration of chloride was 142 mg/L, compared to a range of 1.2 to 4.5 mg/L for reference lakes. The chloride concentration of pre-eruption Spirit Lake was 1.1 mg/L. The authors discuss the availability of chemical constituents, formed by weathering and hydrothermal processes upon new deposits of pyroclastic flows and debris materials from avalanches.

> ***Coldwater Lakes [stated Wissmar and others, 1982b, p. 177] had high concentrations of most constituents because of their proximity to new mineral deposits.*** The relative order of abundance of dissolved constituents***suggests the possible solubility of elements in the new deposits.

The dissolved inorganic chemical constituents were greatly diluted by snowmelt and rainfall, according to McKnight and others (1984, p. 6), who stated:

> For example, the data for major cations and trace metals in South Fork Castle Lake on September 11, 1980, and on May 1, 1981, show that the concentration of most of these constituents decreased by about four fold***.

The volume of the lake increased by about 14 times during this interval, which indicates that dissolution of volcanic deposits in the watershed continued to be a source of dissolved inorganic constituents.

According to Dahm and others (1982, p. 116):

> The blast placed a large amount of terrestrial vegetation into the lake and DOC concentrations in 1980 were the highest measured in any lake in the blast zone.

Wissmar and others (1982a, p. 180) reported a DOC concentration of 148.7 mg/L on June 30, 1980, which was about two orders-of-magnitude greater than in the reference lakes, which had DOC concentrations ranging from 0.65 to 2.28 mg/L. McKnight and others (1984, p. 3, 6) also stated that in Castle Lake (South Fork Castle Lake), "***the major source of dissolved organic material* * * has been pyrolized plant and soil material in volcanic deposits that cover the lake bottoms."

According to the McKnight and others (1984 p. 6–7):

> During the summer of 1980, DOC concentrations were greatest in South Fork Castle, Coldwater, and Spirit Lakes. For example, on September 11, 1980, the DOC of South Fork Castle Lake was 135 mg C /L (milligrams carbon per liter). The DOC concentrations were also affected by the dilution of the lakes by snowmelt; the DOC of South Fork Castle Lake on May 1, 1981, was 10 mg C/L. Comparison of this data with the 14-fold increase in lake volume indicates that there were no major new sources of dissolved organic material in the snowmelt.

More DOC was hydrophilic acid than hydrophobic acid during 1980 in Castle Lake, report McKnight and others (1982, p. 86), who stated:

> The molecular weight and functional group content of South Fork Castle Lake and Spirit Lake fulvic acids are in the range of fulvic acids isolated from other aquatic environments.

McKnight and others (1984, p. 9) reported a trend in the DOC distribution found in the water column. In general, both DOC and SOC concentrations were greater in the lake's bottom layers than in the epilimnion during the summer of 1981. The authors performed extensive organic chemical analyses of lake water containing aquatic humic substances. According to McKnight and others (1984), the amount of phenolic groups contained in fulvic acids was related to the oxygen concentration in the water column. During September 1980, the amount of phenolic groups was largest when there was little dissolved oxygen; however, the next year, in 1981 when the lake contained more oxygen, there was a decrease in the phenolic group content of aquatic fulvic acids. Aquatic fulvic acids found in Castle Lake had a large sulfur content that decreased during the later part of 1980 and 1981. Other than changes in sulfur contents, stated McKnight and others (1984, p. 15):

> ***elemental compositions of the aquatic fulvic acids in the lakes did not change during the year. Also, they were very similar to the elemental composition of fulvic acid from Merrill Lake.

McKnight and others (1982 p. 92) concluded that aquatic fulvic acids constituted a major proportion of the DOC. The chemical constituents are closely related to the possible recovery of the lakes in the blast zone, because the DOC concentration in these lakes most likely will be gradually diluted by rain and seasonal snowmelt—rather than being diminished by biological degradation. McKnight and others (1982, p. 92) stated:

> In fact, microbial degradation of organic bottom material will probably act as a continuing source of dissolved organic material in lakes and streams of the blast zone.

The watershed, according to the authors, contained a great quantity of organic material and dead trees, that may constitute another possible continuing source of DOC materials to streams and lakes in the area.

The role of pyrolization in the enrichment of surface waters was emphasized by McKnight and others (1982, p. 86), who stated:

> Phenols and cresol, well-known products of pyrolysis of wood and plant material, were generally more than a thousand times more concentrated in South Fork Castle and Spirit Lakes than in lakes in the blowdown zone that received only directed blast deposit.*** It is probable that organic acids in the surface waters with extremely high DOC concentrations (South Fork Castle Lake***and Spirit Lake) were derived from pyrolytic flow, mudflow, and debris-avalanche deposits.

In 1980, the hydrophobic and hydrophilic acids were the most important constituents of DOC materials; on September 11, 1980, concentration of DOC materials was 135 mg C/L (McKnight and others, 1982, p. 86). An analysis of the DOC showed that 63 percent of the DOC was hydrophilic acids. The concentration of phenol was 910 µg/L, and the concentration of cresol was 95 µg/L at this time.

McKnight and others (1984, p. 12) concluded that the relative proportions of chemical compounds in DOC were changing by May 1981, and the concentration of hydrophobic acids was increasing. The increase in the hydrophobic acid fraction (fulvic acid), according to McKnight and others (1984, p. 12), "***may have been caused by chemical processes occurring as the lake water became saturated with dissolved oxygen during the spring snowmelt." The proportions of hydrophilic and hydrophobic acids in the epilimnion and hypolimnion of South Fork Castle Lake were similar in 1981. By contrast, at that time Spirit Lake had little or no oxygen below a depth of 26 feet. By comparison, Castle Lake had some dissolved oxygen in the hypolimnion, which may have accounted for the hydrophobic acids found. No consensus exists among the different researchers about the oxygen concentration in the bottom layers of the lake in 1981.

> To summarize [stated McKnight and others, 1984, p. 15], the general characterization data show that fulvic acids from blast-zone lakes were chemically changed, as the lakes were aerated and diluted by rain and snowmelt during the winter and spring of 1981.

Scores of organic compounds in Castle Lake, including neutral organic compounds and organic acids, were identified by McKnight and others (1984, p. 15–18). During the summer of 1980, the authors reported finding phenol; phenol, 2-methoxy-; and phenol,-methyl-isomer; however, only phenol,2-methoxy- remained a year later, in May 1981. The authors speculated that as the water became oxygenated, the phenolic compounds would be either degraded biologically or be utilized in oxidative-coupling reactions. The authors reported that phenol,2-methoxy, appeared to be persistent, and the compound continued to be added to the lake, perhaps along with the seasonal snowmelt. McKnight and others (1984, p. 18) emphasizing that phenol,2-methoxy was a very small percentage of the total DOC, stated:

> [In general,] some organic compounds entered the lake with rain and snowmelt*** [and this is] consistent with the conclusion that the dissolved organic material, mainly aquatic fulvic acid and hydrophilic acids behaved conservatively and that there were no major new inputs of dissolved organic material.

McKnight and others (1984, p. 18–19) identified various ketonoles in the September 1980 sampling, including cyclopentanone, 3-methyl-; ethanone, 1-phenyl-; and ethanone,1-(methylphenyl)-. The authors were of the opinion that 1 ketone (1 H-inden-1-one,2,3-dihydro-ketone) was carried into the lake with snowmelt contacting volcanic ash in the watershed, because this compound had been reported by Pereira and others (1982) in volcanic ash. The compound was not found in the March 1981 sample, but was present in a May 1981 lake water sample collected after the snowmelt.

McKnight and others (1984, p. 22–24) stated:

> In South Fork Castle Lake, many organic compounds found in September 1980 including terpenes, resin acids, and phenolic compounds, persisted in the lake at detectable concentrations until March 27, 1981, but were not detectable by May 1, 1981.

The authors speculated that dilution by the spring snowmelt may have been the reason phenolic compounds were not detected during May 1981. McKnight and others (1984, p. 18) found organic sulfide compounds, including Trisulfide,dimethyl and Disulfide,1,1-dimethylethyl-methyl was reported in September 1980 and early 1981, but was not detectable by May 1981. The authors state that by May 1981, the water was well oxygenated; however, Trisulfide,dimethyl, was still present at this time. Most organic compounds found by the authors during 1981 in Castle Lake were fatty, dicarboxylic, and aromatic acids associated with volcanic ash. Examples include derivatives of butanedioic, pentanoic, pentanedioic, benzoic, heptanoic, octanedioic, benzenedicarboxylic, and cyclohexanecarboxylic acids. According to McKnight and others (1984, p. 18):

> ***leaching by rain and snowmelt of the large quantities of volcanic ash deposited in the watersheds was a significant source of low molecular weight organic compounds.

However, the percentage of the dissolved organic material that consisted of such low molecular weight organic compounds was very small.

During August and September 1980, algal surveys were conducted in Castle Lake by Ward and others (1983, p. 244), who reported an extremely low density of phytoplankton. In August 1980, 5×10^2 total cells/L was reported, and density increased in Castle Lake to 2.8×10^5 cells/L in June 1981. During the first year, the phytoplankton assemblage consisted mainly of diatom fragments and the phytoplankton *Gomphonemaeria* Kutzing and *Gomphonema* Agardh, but by 1981, the population was predominantly

composed of cryptomonal microflagellates and pennate diatoms. *Vorticella* stalks also were present in 1981. The low numbers of phytoplankton during 1980 were correlated with reported low chlorophyll *a* concentrations.

Smith and White (1985, p. 350–352) conducted phytoplankton surveys during August 1982, and by that time, the species composition included many genera. The authors attributed the phytoplankton assemblage in Castle Lake to inoculation from other lakes. They reported high numbers of *Synedra, Fragilaria, Rhizosolenia,* and statocysts from a species of chrysophytes, such as *Chrysococcus* sp. and *Dinobryon cylindricum.* A smaller percentage (7.5 percent) of the community consisted of unidentified unicellular green algae. The authors reported a total of 11 species, and a total phytoplankton density of 2.17×10^3 cells/mL. Large blooms of diatoms and chrysophytes occurred during August and were correlated with reductions in soluble silicon in the lake water. Smith and White (1985, p. 359) stated:

> [The] chrysophyte statocyst from Castle Lake*** is tolerant of high base metal concentrations (e.g., calcium, magnesium, potassium), and of medium organic pollution. A bloom of the vegetative stage of this chrysophyte probably preceded the diatom bloom which included *Fragilaria crottonensis, Synedra delicatissima* var *angustissima* Grunow and *Rhizosolenia eriensis.*

McKnight and others (1984, p. 7), stated:

> Extensive bacterial populations and anaerobic conditions developed within weeks after the May 18, 1980, eruption in the most severely impacted lakes. Dense bacterial populations (as many as 2×10^7 cells/mL) were correlated with high DOC, manganese, sulfur and iron concentrations as anaerobic degradation of organic material and oxidation of reduced metals were the major energy sources.

Staley and others (1982, p. 666–667) reported direct microscopic bacteria counts ranging from 1.7 to 2.3×10^7 cells/mL during the period of June 30, 1980, to September 11, 1980. The viable bacteria counts during the same period ranged from 3.0×10^3 to 1.0×10^6 cells/mL, with the highest counts occurring in September 1980. Although Castle Lake had some of the highest total microscopic counts initially observed, the initial viable counts were the lowest. However, data show that viable bacteria counts increased rapidly during the summer of 1980 and remained high through 1981. Staley and others (1982, p. 666) stated:

> Vertical profiles of Spirit and Castle Lakes indicated that the bacterial numbers were quite uniform from surface to bottom, as determined by our microscopic and plating procedures.

Castle Lake had the largest total and fecal coliform indices of all the lakes studied, and on September 11, 1980, the authors reported a total coliform count of 1,330 cells/100 mL, and a fecal coliform count of 70 cells/100 mL. *Klebsiella pneumoniae* was the most common total coliform bacterium. The authors reported finding *Klebsiella pneumoniae, K. oxytoca,* and *Escherichia coli.* at various depths of the lake (to 49.2 feet) on April 30, 1981. *Enterobacter cloacae* was found at a depth of 49.2 feet. Staley and others (1982, p. 666) reported finding a spirillum (unidentified species) in Castle Lake on May 1, 1981. This organism was present in high numbers, but its density decreased over the summer of 1981. The numbers of Spirilla present were correlated with total microscopic and viable counts, and the authors concluded they had been successful in cultivating the most predominant Spirillum species present. In general, the authors considered the composition of bacterial species in Castle Lake to be rapidly changing and evolving.

Dahm and others (1982, p. 121) studied the bacteriology of Castle Lake during 1981, and reported total bacterial counts as large as 2.4×10^8 cells/mL on June 29, 1981. The number of viable manganese/sulfur oxidizing bacteria ranged from 1.5×10^3 to 8.0×10^4 cells/mL. According to Dahm and others (1982, p. 121):

> Oxygen was present at all depths, although at very low concentrations at 49.2 feet. Bacterial numbers, nitrification rate, and denitrification rate all peaked at 49.2 feet. *** With nitrogen at a maximum at 49.2 feet total autotrophic and heterotrophic bacteria also were highest.

During the summer of 1981, the concentrations of reduced metals increased in deep water, which was coincident with high bacterial numbers reported. According to Wissmar and others (1982a, p. 179), high total bacterial counts and high ATP and DOC concentrations were correlated. The authors speculated that labile DOC compounds may have included primary products that were derived from metabolism of pyrolized and "retorted" vegetable and soil matter available to bacteria.

Summary of Water-Quality Characteristics of Category III Lakes

The creation of Coldwater and Castle Lakes by the eruption of Mount St. Helens afforded scientists a truly unique opportunity to study the development of lake ecosystems. Most previous studies on lake aquatic environments established by volcanic activity have been performed on lakes centuries old, long after chemical and biological transformations had been stabilized. Some of the characteristics previously discussed in summaries of category I and II lakes are recapped and are compared to the changes in newly created lakes. However, phenomena peculiar to the new lakes, which have seldom been documented in the literature, are emphasized.

Shortly after their creation, the two new lakes differed slightly in their DO characteristics. The availability of oxygen, of course, profoundly affected the genesis of different biological and chemical processes. The surface water of Coldwater Lake was oxygenated during the summer of 1980; but by August 1980, anaerobic conditions had been established below depths of 0.7 feet. Castle Lake, in contrast to Coldwater Lake, remained oxygenated for many months after its formation. During the spring of 1981, the oxygen content of Castle Lake increased after runoff from snowmelt entered the lake. By June 1981, however, anoxic conditions below 10 m (33 feet) were recorded. Both Coldwater and Castle Lakes developed clinograde DO profiles during 1981 and 1982.

During the summer of 1981, an acidic pH of 6.21 was recorded in Coldwater Lake—one of the lowest pH values reported for any lake in this report. Coldwater Lake's sediments soon were actively degassing; methane, carbon dioxide, carbon monoxide, and dinitrogen oxide were reported by researchers. The production of methane gas was observed in Castle Lake from April 30, 1981, to August 1981. The gas production in both lakes was the consequence of high levels of microbial metabolic activity.

In Coldwater Lake, low dissolved nitrogen levels were present originally—a condition favoring organisms capable of fixing nitrogen. Researchers reported extraordinary levels of phototrophic and anaerobic dark nitrogen fixation by bacteria that were the major sources of reduced nitrogen available for biological processes during this period. In Castle Lake, however, there existed large concentrations of particulate organic nitrogen (PON) shortly after formation of the lake. A reported PON of 5,900 μg/L was more than two orders-of-magnitude larger than that of reference lakes, in which PON from 15 to 60 μg/L. In Castle Lake, nitrite nitrogen was 1.3 mg/L compared to 0.0009 to 0.002 mg/L for reference lakes. Nitrate-nitrogen concentrations were in the same range as post-eruption reference lakes.

In Coldwater Lake, the early post-eruption concentration of dissolved organic carbon (114 mg/L) was larger than that found in post-eruption Spirit Lake. Castle Lake had one of the largest concentrations of particulate organic carbon of all the lakes listed in this report and a high DOC concentration of 148 mg/L. Similarly, the ATP concentration of 15.2 μg/L also was one of the largest values reported for lakes and relates to the numbers of bacteria found in the lake at that time.

Concentrations of iron were larger than in post-eruption Spirit Lake; manganese concentrations were about the same as in post-eruption Spirit Lake. The iron concentration in Castle Lake was 15.7 mg/L, which is three orders-of-magnitude greater than that of reference lakes that had iron concentrations ranging from 0.002 to 0.26 mg/L. Castle Lake's manganese concentration was greater than 5.4 mg/L, compared to a range of 0.002 to 0.034 mg/L for reference lakes. In Castle Lake, remarkable concentration levels of several cations were reported. The calcium concentration was greater than 80.0 mg/L, magnesium concentration was 21.2 mg/L, and sodium concentration was 112 mg/L. These concentrations are orders-of-magnitude greater than those of reference lakes.

In Coldwater Lake, sulfate reduction processes by bacteria were important. In Castle Lake, the sulfate concentration of 200 mg/L was two orders-of-magnitude greater than in reference lakes that had sulfate concentrations ranging from 0.75 to 2.8 mg/L. The chloride concentrations in Castle Lake were reported as being more than an order-of-magnitude greater than in reference lakes, where chloride concentrations ranged from 1.2 to 4.5 mg/L.

Changes in neutral organic compounds were identified in Coldwater Lake in 1981. Organic acids not detected in 1980, including fatty, dicarboxylic, and aromatic acids, were detected during 1981. Phenol and haloforms also were reported in 1981, in addition to polycyclic aromatic hydrocarbons and terpenes. In Castle Lake, much of the DOC consisted of both

hydrophobic and hydrophilic acids, including aquatic fulvic acids that presumably were derived from microbial degradation of organic materials. Large concentrations of phenol, phenol derivatives, and cresol were found in Castle Lake, as in the case of Spirit Lake, along with neutral organic compounds.

Bacteria dominated chemical and geochemical processes. Coldwater Lake had total bacterial counts as high as 10^7 cells/mL; and sulphur/manganese oxidizing bacteria were present in the 10^5 cells/mL range. Levels of anaerobic dark nitrogen fixation in surface water were at historical world record levels. Fermentation, methanogenesis, sulfate reduction, and chemosynthetic processes were occurring. By June 1981, total bacterial counts in Coldwater Lake were in the 10^8 cells/mL range. Much the same situation existed in Castle Lake, where the number of viable manganese/sulfur-oxidizing bacteria were in the high 10^4 cells/mL range. In both Coldwater and Castle Lakes, coliform bacteria, such as *Klebsiella pneumoniae* and *Enterobacter cloacae*, were reported at various depths. The bacterial species composition changed and evolved rapidly in both lakes.

High turbidity limited the amount of light available for primary productivity in Coldwater Lake, but small unicellular algae were reported during 1980. In general, researchers regarded the development of phytoplankton to be fairly slow and attributable to low light availability. In Castle Lake, the situation was somewhat different, and algal surveys conducted in late summer 1980 indicated that low densities of phytoplankton were present at the 10^2 total cells/L range, which increased to the 10^5 cells/L range in June 1981. In Castle Lake, the original phytoplankton community consisted mainly of diatoms and *Gomphonemaeria* and *Gomphonema*; by the next year, the assemblage was composed largely of cryptomonal microflagellates and diatoms. By 1982, many phytoplankton species were reported, including diatom and chrysophyte blooms, and phytoplankton biomass was greater than in most category II lakes.

EFFECTS OF THE ERUPTION ON RIVERS, STREAMS, AND THE COLUMBIA RIVER ESTUARY

The different rivers and drainage systems will be treated individually, although their geographic areas are not so clearly defined as those of the lakes.

The Toutle River and Cowlitz River Drainage Systems

Cummans (1981, p. B4) described the Toutle and Cowlitz River drainage systems:

> Both the North and South Forks of the Toutle River originate on the slopes of Mount St. Helens ***. Prior to the eruption, the two streams drained a combined area of about 15 square miles from the slopes above 4,000-feet elevation.
>
> The North Fork flows in a westward direction away from Mount St. Helens. At its confluence with the South Fork, the North Fork drains 303 square miles, of which 132 square miles is drained by the Green River, a major tributary to the north.
>
> The South Fork of the Toutle River originates on the western slopes of Mount St. Helens and drains 129 square miles above its junction with the North Fork.
>
> The Toutle River, formed by the junction of the North and South Forks, flows in a generally westward direction into the Cowlitz River. At its mouth, the Toutle drains 512 square miles. The Cowlitz River flows south into the Columbia River, and several miles of its lower reach,*** are affected by tides in the Columbia River.

Warren and others (1982, p. 181) described the Cowlitz River flood plain prior to the eruption as:

> ***narrow, [and] generally less than 1-mile wide from river mile 20 at the mouth of the Toutle River downstream to Kelso at river mile 5. Near the Columbia River at its maximum the flood plain is 5 to 6 miles wide ***. On both sides, the flood plain quickly gives way to foothills and mountains climaxing in the Cascades and Mount St. Helens some 35–40 miles to the east.

According to Warren and others (1982, p. 182), the pre-eruption natural channel capacity was described as follows:

> The patterns of the Cowlitz River vary from year to year but runoff is likely to peak with the heavy rain of midwinter. Rain and rapid snow melt in the spring can also cause the rivers to rise and allows them to carry more sediment to spread over that portion of the river channel that is only occasionally physically occupied by the river—the flood plain. Thus slowed by shallower depth, lesser gradient, and obstructions, they deposit layers of sediment and organic materials.

Occasionally, the cutting power of the stream in flood will excavate a new channel. When the stream recedes the new channel may continue to be occupied while the former channel is at least temporarily abandoned. The former channel now is a low area, a catchment for organic and sedimentary debris, and a rich habitat for plants and wildlife.

Lombard and others (1981), Cummans (1981), Dinehart and Culbertson (1982), Janda and others (1982), Haeni (1983), Klein (1984), and Meyer and Janda (1986) described physical processes that affected the Toutle and Cowlitz Rivers following the eruption. The reader is referred to their reports for details of the mudflow chronology and studies related to sediment deposition. This report briefly reviews these subjects; certainly, the mechanical processes related to the mudflows and sedimentation phenomena are directly related to physical, chemical, and biological changes in water-quality parameters. The North and South Forks of the Toutle, the Toutle, and Cowlitz Rivers are discussed both individually and collectively, because the phenomena occurring in them were so closely interrelated. An overview of eruption effects in the Toutle River Basin and the Cowlitz River Basin systems is presented first.

According to Jones and Salo (1986, p. 2):

> A massive landslide-debris flow, resulting from the largest slope failure known during the earth's recorded history, traveled 13.5 miles down the North Fork Toutle Valley.

Haeni (1983, p. K1) stated:

> Mount St. Helens erupted, sending billions of cubic yards of mud, ash, rock fragments, and debris down the North and South Forks of the Toutle River, the Cowlitz and Columbia Rivers, and other streams. A total of 35.6 million cubic yards of mudflow material was deposited in the lower Cowlitz (downstream from the Union Pacific Railroad bridge) and Columbia Rivers.

According to Phinney (1982, p. 295):

> An estimated 174 billion liters [0.23 billion cubic yards] of melted glacial ice mixed with overflow from Spirit Lake and an estimated 1.4 billion cubic yards of volcanic ash, mud, and debris flowed off the mountain into the North and South Forks of the Toutle. *** The upper North Fork Toutle was buried to a depth of 443 feet and the Cowlitz to 16 feet.

According to Martin and others (1982, p. 239):

> The massive debris avalanche and associated mudflows buried the North and South Forks and mainstem of the Toutle River including the lower reaches of tributary streams. The channels in the affected streams were obliterated and the fluvial processes of channel formation have begun to develop a new river and in some cases new tributary streams. Streams in new channels are unstable, and have a high concentration of suspended sediment.

According to Hindin (1983, p. 2):

> The valley of the North Fork of the Toutle River was filled with a combination of ash, landslide material, large blocks of rock ejected from the volcano, and pyroclastic material. The fill resulted in a relatively flat surface rising to a maximum of about 200 feet above the old valley floor. The new valley floor in the blast zone contained new bodies of water.

Cummans (1981, p. B1), describing the volume of material deposited in the North Fork Toutle River valley, stated:

> Approximately 3 billion cubic yards of material, including rock, ash, pumice, snow, and ice was deposited directly north of the mountain in the upper 17 miles of the valley.

Klein (1984, p. 18) reported:

> The headwaters of the Toutle River drainage were altered beyond recognition by volcanic debris deposits and pyroclastic flows from the May 18 [1980] eruption. The downstream reaches of the Toutle and of the lower Cowlitz below its confluence with the Toutle River were devastated by massive flooding and mudflows.

An overall summary is presented by Meyer and Janda (1986, p. 71), who stated:

> The 0.67 cubic miles rockslide-avalanche deposit of 18 May 1980 buries 23 square miles of the upper North Fork Toutle River valley to an average depth of 148 feet. This deposit consists of a noncohesive mixture of about 15 percent silt and clay, 45 percent sand and 40 percent gravel and cobbles with occasional coherent blocks *** [scores of feet] in diameter (Voight and others, 1981; U.S. Army Corps of Engineers, 1984). Additionally, a high velocity, laterally directed blast (pyroclastic surge) destroyed the forest and deposited 0.03 to 4.9 feet of slowly permeable silt, sand and fine gravel in 181 square miles of the Toutle River Basin

> (Moore and Sisson, 1981; Waitt, 1981; Hoblitt, Miller, and Vallance, 1981). Most of the 110-square-mile drainage area contributing runoff to the debris avalanche deposit was affected by the blast.
>
> An additional 3.0×10^7 cubic yards of noncohesive, poorly sorted sand and gravel were deposited along the South Fork, North Fork and main stem of the Toutle River by two major lahars*** [that] shoved most woody debris and riparian vegetation to the edge of the inundated area, destroyed the pool-and-riffle bed configuration, and buried the stable cobble and boulder stream bed with sandy material. ***The net effect was to leave a narrow, hydraulically smooth channel in which post eruption stream velocities and flood peak discharge are higher than during comparable pre-eruption conditions (Orwig and Mathison, 1981).

Various authors described the series of mudflows in the river basins, which accompanied the eruption. The mudflows were caused by melting of glaciers and ice fields on the flanks of Mount St. Helens and displacement of a large volume of water from Spirit Lake caused by the massive influx of material and debris. According to a description by Cummans (1981, p. B1):

> [Mudflows are] masses of water-saturated debris of various sizes that flow downslope as a result of gravity. Mudflows commonly resemble masses of wet concrete or mortar, and indeed, these terms were used by several observers to characterize the mudflows in the Toutle River system.

According to Lombard and others (1981, p. 693):

> [The eruption triggered mudflows in the North and South Forks of the Toutle River, which] were especially significant because of their immense magnitudes and consequent destruction. The two mudflows deposited large volumes of sediment in the North Fork and South Fork Toutle Rivers; and in the Toutle, lower Cowlitz, and Columbia Rivers. In the lower Toutle and Cowlitz River valleys, as much as 15 feet of mud and debris were deposited in the river channels, and as much as 10 feet on the adjacent flood plains.

Janda and others (1982, p. 163) stated:

> The most voluminous lahar originated by slumping and flowing of water-saturated parts of the debris avalanche in the headwaters of the North Fork Toutle River. This lahar, which had the characteristics of mudflow, modified more than 74.6 miles of channel, including the main Toutle River and sections of the Cowlitz and Columbia Rivers.

The South Fork Toutle River was impacted by two mudflows on May 18, 1980. The first mudflow contained large amounts of debris, and observers reported the force of the flow was sufficient to knock down and carry trees. Cummans (1981, p. B6–B7) stated: "[The mudflow traveled] 27 river miles, from the mountain to Camp 12, in 90 minutes." The second mudflow was smaller and of shorter duration than the first mudflow. The water level at the Toutle River gaging station at Silver Lake (located one-quarter mile below the Highway 504 bridge) reached 23.5 feet, which was the highest stage reached in the history of the site. At times, the entire surface of the river was covered with floating logs. When the mudflow entered the Cowlitz River, the river stage at the Castle Rock Bridge, which is 2.7 miles downstream from the mouth of the Toutle River, rose 3.15 feet above its normal 10-foot stage. The water level probably peaked in the Cowlitz River by late afternoon, and observers reported logs in the water. Cummans (1981, p. B7) reported:

> Water temperature was 10.6°C and turbidity remained at its normal level of 4 JTU's (Jackson Turbidity Units). However, between 8:00 and 8:30 p.m., the turbidity abruptly increased to 420 JTU's, and the treatment-plant water intake had to be closed.

According to Cummans (1981), the mudflow had been contained within the valley walls of the river, with little overbank flow except above the confluence with the North Fork.

According to Lombard and others (1981, p. 695):

> At about the same time (1330 on May 18 [1980]) that the first mudflow peaked at Castle Rock, a second larger mudflow was developing on the massive debris-avalanche deposit in the devastated upper part of the North Fork Toutle River valley. ***This massive and highly destructive mudflow moved more slowly than the South Fork mudflow, with the peak stage at Castle Rock *** occurring at about midnight on May 18 [1980]. The peak stage of the second mudflow was 49.5 feet, 16.1 feet higher than the first mudflow. The North Fork mudflow spilled over the lower Cowlitz River flood plain, leaving deep deposits of sand, volcanic ash, and gravel-sized pumice on the flood plain and in the channel.

The mudflows altered the flow capacity and channel configuration of the lower Cowlitz River. Cummans (1981, p. B13) provided a summary of the changes and stated:

> Cross-sectional measurements of the Cowlitz River channels at both Kelso and Castle Rock reveal that deposits of sediment and debris raised the average elevation of the channel bottom about 15 feet at both locations. Prior to the mudflows, the maximum carrying capacity of the Cowlitz River at Castle Rock (at the flood stage of 23.0 feet) was 76,000 cubic feet per second [ft^3/s]. As of July 1980, the channel capacity was about 7,300 ft^3/s. At that time, the river could carry less than 10 percent of its former capacity without flooding the surrounding valley.

According to Haeni (1983, p. K11):

> The effect of the mudflows on the lower 2 miles of the Cowlitz River was to fill in the navigation channel with 10 to 20 feet of material and to deposit a large pile of stumps and log debris near the confluence with the Columbia River. ***. Several sections near the mouth of the Cowlitz River were deeper after the mudflow than before, indicating that the mudflows eroded bottom materials in places.

Haeni (1983, p. K13) reported on the volume, thickness and texture of the mudflow material in the lower Cowlitz River, and stated:

> The deposited material averages 7 feet, reaches a maximum of 20 feet, and is confined mainly to the former dredged channel. ***A minimum of 0.4 million cubic yards of material was eroded from the Cowlitz River by the mudflows, but the deposition of this eroded material is unknown. Most, however, was probably redeposited in the Columbia River near Longview, Washington, along with the greater part of the mudflow material. ***The deposit in the Cowlitz River was generally fine grained, consisting of silt, very fine sand, fine sand, and small pieces of charred wood fragments and a trace of coarse angular rock fragments.

For a detailed description of the effect of the mudflows on the channels and flood plains of the Toutle and Cowlitz Rivers, refer to reports by Cummans (1981), Haeni (1983), and Lombard and others (1981).

The eruption caused major changes in the sediment-discharge characteristics of rivers and streams in affected basins. An analysis of the altered sediment-carrying capacities of rivers and streams has been thoroughly discussed in numerous reports (Moore and Reese, 1982; Meyer and Janda, 1986; Dinehart and Culbertson, 1982).

After the May 18, 1980, eruption, the USGS collected data at numerous sites in the Toutle River Basin. Dinehart and Culbertson (1982, p. 149) reported:

> About 20 million tons of suspended sediment were delivered to the Cowlitz River from the Toutle River Basin during the 3-month period, October through December 1980, 70 percent of that load being delivered in 10 days. Measured peak suspended-sediment concentrations ranged from 99,000 mg/L on the South Fork Toutle River during the November 7, 1980, flood to greater than 400,000 mg/L on the Toutle River at Highway 99 bridge near Castle Rock during the February 19, 1981 flood.***[These] measurements show rather extreme deposition of the Toutle River sediment in the Cowlitz River downstream from the mouth of the Toutle.

Disturbances in land surfaces and vegetation of drainage areas characterized by steep hillslopes caused erosion effects far downstream from the disturbed sites, and according to Meyer and Janda (1986, p. 68):

> [Streambank erosion] extends for at least 29.8 miles from the North Fork Toutle debris-avalanche deposit and annually amounts to at least 2.5×10^5 cubic yards per mile of channel; 4.1×10^4 cubic yards per square mile of drainage area. This erosion is a consequence of the $2.6–3.9 \times 10^7$ cubic yards of sand and gravel annually delivered to the North Fork Toutle River by channel erosion and streamside landslides on the***debris avalanche deposit that buries 23.2 square miles of the upper North Fork Toutle River valley.***Virtually all of the sediment in the study reach is derived from streambank and channel erosion, about 50 percent of the eroded material is pre-1980 alluvium and lahar deposits.

Sedimentation changes for water years 1981–83 were summarized in the report by Meyer and Janda (1986), which contains an extensive bibliography pertaining to this subject. In regard to the Toutle River, Stober and others (1981, p. 41) stated:

> [The] suspended sediment concentrations exceeded 300,000 mg/L in the upper North Fork during fall rainfall events [during 1980]. *** Concentrations observed in the lower North Fork ranged to 12,522 mg/L.

In addition to materials deposited in the Toutle River by mudflows and debris avalanches, there was a continued influx of sediment to the Toutle River Basin by erosion of tephra from hillslopes in drainage basins of the North Fork Toutle, South Fork Toutle, and Green Rivers. The tephra, which includes ash, lapilli, pumice, bombs, and other materials ejected during the eruption, was eroded at greatly varying rates depending on the (1) surface cover, (2) gradient, and (3) thickness and texture of the tephra (Collins and others, 1982, p. 82). Calculations of the amount and rates of erosion were made by researchers studying sedimentation, flood control, stream habitat, and related phenomena. Collins and others (1982, p. 82) estimated:

> [Thirty-one] percent of all sediment eroded from hillslopes was trapped in lakes impounded by the debris avalanche that filled the North Fork Toutle River valley on 18 May 1980. Of the remaining 8.0×10^6 tons of sediment that entered streams of the Toutle River system, 36 percent were clay and silt, 58 percent were sand, and 6 percent were gravel.

Lakes that trapped much of the sediment included Coldwater, Castle, Spirit, and Jackson Creek Lakes. Collins and others (1982, p. 93) calculated 3.52×10^6 tons of sediment were impounded by lakes and were of the opinion that: "*** sediment eroded from hillslopes was not stored at the base of hillslopes nor in stream channels ***."

A massive dredging effort was initiated, soon after the eruption, to excavate the infill and to restore the flood-carrying capacity of the Cowlitz River. According to Willis (1982, p. 210), 33 million cubic yards of material was removed during 1980, and work continued until, by September of 1981, a total of 56 million cubic yards of sediment had been dredged. Naturally, the ongoing dredging activity affected water quality and must be considered in conjunction with eruption effects.

A brief description of COE activities in the North Fork Toutle River Basin is essential background for understanding the whole picture of water-quality changes. Major projects were undertaken after the eruption to stabilize the surface elevation of Spirit Lake and to prevent water overtopping the debris dam formed by the eruption. In addition to pumping operations of approximately 20 months duration, the COE built an outlet tunnel connecting Spirit Lake to the Toutle River drainage system. The tunnel connected Spirit Lake to the North Fork Toutle via South Coldwater Creek, a tributary of the North Fork Toutle River. The tunnel was 8,500 feet long, and was constructed during the period June 1984 to April 1985 (Larson and Glass, 1987, sec. 1, p. 5). The discharge of water from Spirit Lake affected the water quality of the Toutle River system; but, because these effects are due to manmade events occurring long after the eruption, an analysis of these effects is not included in this report. (See Larson and Glass, 1987, for a complete analysis of the effects of discharging Spirit Lake water into the Toutle River system.)

The COE built several retaining structures to impede the flow of debris and mud in the North and South Forks of the Toutle River. The debris-retaining structures served as settling basins to catch some of the sediment and ash. The debris dam on the North Fork Toutle at river kilometer 32 was completed in November 1980 (Lucas, 1986, p. 279). Extensive studies on water quality, focusing on water released from the retaining structures, were performed. According to Hopman (1982, p. 137), who reported elevated iron and manganese concentrations:

> Concern about the projects becoming pools of contaminated water lessened considerably in late November 1980, when the North Fork impoundment filled with sediment. At that time, monitoring was discontinued because it was found that the projects were having little or no effect on water quality in the Toutle River.

Lucas (1986, p. 279) describes how the dam built by the COE was breached and repaired after its completion. The author stated, that at times, fish were able to migrate upstream as a consequence of these changes. In addition to the phenomena associated with the debris-retaining structures, Coldwater and Castle lakes were breached by the COE in 1981 to alleviate flooding concerns.

Stober and others (1981, p. 57) sampled the North and South Forks of the Toutle River from July to November 1980, and from March to August 1981. The authors reported pH values ranging from 6.2 to 7.7 in the upper part of the North Fork Toutle River. The authors reported concentrations of DO ranging from 5.9 to 11.4 mg/L in the upper reach of the North Fork Toutle River. In the middle and lower parts of the

North Fork Toutle River, the DO concentrations ranged from 5.9 to 11.4 mg/L and from 4.8 to 11.6 mg/L, respectively. The concentration of filterable solids during this time period was in excess of 18,000 mg/L in the upper reach of the North Fork Toutle River, compared to 2,700 and 1,690 mg/L in the middle and lower reaches of the North Fork Toutle River, respectively. The concentration of filterable solids is far in excess of any other maximum value for other rivers sampled. According to Stober and others (1981, p. 56):

> There is little evidence that low dissolved oxygen concentrations persisted at any of the stations sampled. A temporary minimum of 4.5 mg/L occurred at the upper North Fork Toutle River station immediately downstream of the massive avalanche debris. The pH was circumneutral at all the stations monitored and the eruption did not appear to cause major changes. The conductivity of the water in the North Fork Toutle River was increased substantially above other stations ***. This probably resulted from the leaching through the debris material in the upper valley.

Lucas (1986, p. 279), citing U.S. Forest Service data, reported:

> In the North Fork [Toutle River], more than 20 miles ***from the crater, water temperatures were in excess of *** 37.3°C *** on the day of the eruption.***The North Fork Toutle [River] and most tributaries had been extensively logged before the eruption, but additional loss of vegetative canopy due to the eruption sent stream temperatures soaring [in the months after the eruption].

According to Stober and others (1981, p. 49–50), who compared temperatures in the Toutle and Cowlitz River systems, temperatures in the Toutle River were higher than in the Cowlitz River by 5–10°C by July 1980, which the authors attributed to the loss of riparian vegetation and possible effects of increased concentrations of suspended materials. Martin and others (1982, p. 241–242) reported water temperature in various reaches of the North Fork Toutle River during the period from June through September 1981, and discuss the effects of devegetation of stream banks. Martin and others (1982, p. 241–242) reported that water in most of the study streams exceeded optimal temperature ranges for the growth and survival of juvenile coho salmon and stated:

> [The] maximum temperatures in Elk, Wyant, Herrington, and Bear Creeks equal or exceed the upper lethal level. Based on temperature criteria, the temperature regime present in the affected streams, excluding Deer Creek, is considered to be hazardous to fish.

The authors attribute some of the devegetation effects to logging practices, in addition to blast effects.

Stober and others (1981, p. 59–60) reported average concentrations of nutrients for the North Fork Toutle River during the spring of 1981. Nutrient concentrations were presented as phosphate, silicate, nitrate, nitrite, and ammonia. Phosphate (PO_4) concentrations ranged from 0.105 ppm (parts per million) in the Upper North Fork Toutle River to 0.228 ppm at the confluence of the Green River. Silicates (SiO_4) ranged from 17.90 to 36.91 ppm. Nitrate (NO_3) concentrations ranged from 0.00 to 2.62 ppm, and nitrite (NO_2) ranged from 0.00 to 0.06 ppm. Ammonia (NH_4) concentrations ranged from 0.01 to 0.08 ppm. The authors (Stober and others, 1981, p. 59) stated: "The eruption appears to have increased the available PO_4 and SiO_2 in the North and South Forks of the Toutle River."

According to Campbell and others (1982, p. 2), sediments taken from the Cowlitz and Columbia Rivers after the eruption were shown to contain phenolic compounds, when the sediments were subjected to elutriate analysis by the COE. Phenolic compounds were detected at the inlets and outlet of Spirit Lake, where decomposing logs were presumed to be the source of phenols. According to Campbell and others (1982, p. 2):

> [Various researchers voiced the opinion that] chlorinated phenolics were not likely to be present in the Toutle River, and stated that high background levels (100 to 200 ppb [parts per billion]) of total phenolics are characteristic of the Pacific Northwest due to the logging industry and thus not a cause for concern.

In conjunction with the USGS Water Quality Laboratory, Stober and others (1981, p. 56–58), analyzed samples taken from the middle North Fork Toutle River during 1981 for DOC compounds and phenols. Dissolved organic carbon concentrations ranged from 1.1 to 3.5 mg/L during the period from March 18 to July 10, 1981. The authors reported total phenol concentrations of less than 1.0 μg/L during this period. Dissolved organic carbon and phenol concentrations were at acceptable ranges, and according to Stober and others (1981, p. 57–59):

It was concluded that these rivers were not significantly contaminated in the spring of 1981 with organic compounds leached from pyrolized organic matter entering upstream from the blast zone. Unfortunately, water was not analyzed for phenolic content throughout the 1980 field season and the potential presence of phenols cannot be completely discounted as an influence on fish mortality.

Phenol concentrations as high as 140 μg/L in the North Fork Toutle River and 134 μg/L in the South Fork Toutle River were reported on November 25, 1980 (Larson and U'ren, 1982). However, these values are within the normal background range, 100–200 μg/L associated with the Pacific Northwest and its logging industry. These concentrations exceeded the 1976 EPA guidelines of 1 μg/L and are on the low end of the range currently recommended for a variety of phenolics (i.e. 0.03–500 μg/L, EPA 1980).

Hindin (1983, p. 64–73) sampled the North Fork Toutle River for organic compounds at two locations. At river mile 21, the author reported finding 4.5 μg/L of phenol, various terpenes (1.8 μg/L alpha-pinene, 3.0 μg/L of beta-cymene, 2.1 μg/L of terpinene-4-ol, and 4.6 μg/L of alpha-terpineol), haloforms (6.4 μg/L of chloroform, 1.3 μg/L of dichlorobromomethane), and 1.5 mg/L of DOC on June 3, 1982. Hindin sampled an upstream station 3 months later, and reported finding a low level of phenol, and low levels of phenanthrene and fluoranthene. Alpha-terpineol (2.7 μg/L) was reported, in addition to haloforms, which were found in higher concentrations than observed at the downstream sample location. The concentration of DOC was 2.6 mg/L at this site.

Hindin (1983, p. 74) sampled Alder Creek, a tributary of the North Fork of the Toutle River on August 31, 1982, and stated:

> [This tributary had] unusual heavy iron hydroxide precipitate on the rocks in the stream. Phenol in a nonquantifiable concentration was present. The terpene, terpinene-4-ol, was found in measurable concentration in the water. The dissolved oxygen concentration was substantially higher than that in the North Fork Toutle River.

Campbell and others (1982, p. 14) performed studies in 1982 to determine if harmful concentrations of phenolic compounds could be detected in the tissues of fish resident in the Toutle River system and to characterize background levels of phenolic compounds in water. The authors detected pentachlorophenol in tissues of fish collected from Deer Creek, a tributary of the North Fork Toutle River. However, no pentachlorophenol was detected in the water samples, although the presence of this compound was confirmed in the tissues of fish in subsequent analyses.

Fuste' (1981, p. H1–H2) studied eruption effects on the benthic fauna of the Toutle and Muddy Rivers and on the Pine Creek drainage basin. In anticipation of the eruption the USGS predicted, USGS surveys were made from March 28–30, 1980, to document pre-eruption conditions. The sampling stations on streams examined by Fuste' were characterized as gravel-armored streambeds with fairly stable banks. The riparian vegetation was dense coniferous forest. The stream gradients varied from low to very steep, and the author describes pre-eruption sites in these watersheds as being highly diverse. Fuste' (1981, p. H1) stated:

> The mayflies were most common in the third-order streams, and the chironomid larvae were most common in first- and second-order streams.***The volcanic eruption of May 18 [1980] destroyed most, if not all, of the benthic fauna present at the sites sampled.***Of the remaining sites, a very simplified community was found in July, composed primarily of midges and blackfly larvae (98–100 percent of the total number of organisms collected.

Some of the pre-eruption stations established by Fuste' on the North Fork Toutle River were destroyed by the eruption. The author sampled a sufficient number of undisturbed stations, however, to enable him to evaluate the consequences of the eruption. Fuste' reported that pyroclastic flows and mudflows had essentially destroyed living vegetation in the headwaters, and algae and mosses growing on rocks in the streams were scoured away. In reference to a site near Kid Valley, Fuste' (1981, p. H11–H13) said:

> Although no numerical estimates are available, the fauna in the North Fork Toutle River near Kid Valley retained a higher degree of structural complexity than the other sites sampled in the post-eruption surveys. Because of the presence of mature nymph stoneflies *(Calineuria californica* and *Pteronarcys princeps),* whose large bodies could easily have been crushed by the exceedingly high bedload transported downstream, it is most likely that these organisms drifted downstream from tributaries outside the blast zone. This is supported by the fact

> that *Pteronarcys* normally takes 3 to 4 years to reach the adult stage. The presence of the other organisms at three downstream stations is probably due to a combination of downstream drift and aerial oviposition (egg laying) by adult forms. Adults of aquatic insects were conspicuous at all sites visited in July [1980].

Fuste' (1981, p. H7–H13) had established a sampling station (no. 7) on Castle Creek, a tributary of the North Fork Toutle River. Prior to the eruption, this station had a very rich faunal community, with 53 taxa identified. In March 1980, 62 percent of the taxa were mayflies, including members of the families Ephemerellidae, Leptophleblidae, Baetidae, and Heptageniidae. Members of the family Baetidae were most numerous, with *Baetis sp.* predominant. There were also numerous stoneflies of the families Taeiopterygidae, Nemouridae, and Chloroperlidae. Waterfleas, primarily of the family Lebertiidae, and various aquatic earthworms (Oligochaetes) were identified. The eruption created a hot mudflow, which traveled down the Castle Creek drainage basin and caused trees to be uprooted and vegetation to be stripped away. The post-eruption fauna was greatly affected, and representatives of the orders Ephemeroptera, Plecoptera, and Trichoptera were not found. Members of the Diptera (midges) were virtually the only survivors (99.1 percent).

Martin and others (1982, p. 242, 252) collected macroinvertebrate drift samples during the summer of 1981 to determine if surviving fish would have food-supply problems. The authors found fish-food organisms in Alder, Wyant, Devils, Elk, Upper Deer, Lower Deer, and Bear Creeks, all of which are tributaries of the North Fork Toutle River system. The density of the organisms varied between sampling dates, and the affected streams were shown to have lower densities than unaffected streams. In general, the authors were of the opinion that the eruption did not appreciably alter the relative rates at which food-supply organisms recovered in various streams.

Karlstrom (1986), reported on the recovery of amphibians in the North Fork Toutle River debris-avalanche area, and studied various species found in the "Elk Rock Ponds" that were formed after the eruption. The lack of pre- and post-eruption data was described by Karlstrom (1986, p. 334), who stated:

> Published references to the survival of or early immigration of amphibians and reptiles in the impacted zones have been limited to incidental observations. MacMahon (1982), Franklin and others (1985) reported sightings of amphibian and other aquatic species as early as the summer of 1980 in the high ashfall area north of the summit. MacMahon (1982) observed transforming larvae of the salamanders *Ambystoma gracile* and *A. macrodactylum* as well as those of the western toad, *Bufo boreas*. James Seddell studied streams in the same general area and came up with an impressive list of invertebrates, fishes and other riparian amphibians native to the area (reported in MacMahon, 1982).

On the basis of information from various sources, Karlstrom (1986) proposed an amphibian population consisting of 16 species for the river basin. Some authors speculated that aquatic forms may have survived in areas of ice cover, in underground hibernation sites, or in sediments, depending upon the microenvironment of the river basin. According to Karlstrom (1986, p. 337), on the basis of the area he studied:

> What appears clear is that the various geologic episodes of 1980 virtually destroyed all existing animal life in this part of the valley of the North Fork. The subsequent recovery of amphibians would appear to be from refugial sites along more protected draws and streams tributary to the main river and for the Elk Rock Ponds, locally from the north side. Up-valley and down-valley migration from areas of the North Fork also is possible. Only sketchy observations of early post-eruption amphibian life are available for the upper North Fork.

Karlstrom (1986), who reviewed sightings of western toads in 1981 and of other organisms during 1982 and 1983, tentatively concluded on the basis of this very limited data that a species of Hyla (treefrog) may have been breeding in one section of the valley in 1982. A discussion of studies on post-eruption recovery of amphibians during the periods 1981 through 1986 is outside the purview of this report; refer to Karlstrom (1986) for a review of these subjects and applicable references.

According to Lucas (1986, p. 276), the pre-eruption Toutle River and its tributaries had supported anadromous fish runs, which included sea-run cutthroat, winter steelhead, coho, and fall chinook. These fish were self-sustaining runs. Of lesser importance were spring chinook and summer steelhead. According to Lucas (1986, p. 276):

> Resident rainbow and cutthroat trout, peamouth chum, northern squawfish, mountain whitefish, Pacific lamprey, torrent sculpin and several other unidentified sculpin species were also native to the Toutle drainage.

In addition to the more dramatic changes wrought by pyroclastic flows and mudflows, Phinney (1982, p. 295) stated:

> Gravel was scoured away in the forks and main river and replaced by heavy deposits of fines. Gravel in areas not scoured, such as Green River and North Fork tributaries, was heavily infested with fines from ashfall. ***Watersheds of both forks of the Toutle River and most major tributaries were impacted. ***All three salmon culture facilities operated by WDF [Washington Department of Fisheries] were damaged***.

Losses in the hatcheries of juvenile coho and chinook salmon numbered in the millions. Martin and others (1982, p. 239) reported finding salmonid survivors in mudflow-impacted areas, such as the North Fork Toutle River below the debris dam and the South Fork Toutle River. However, streams which had channels across the landslide debris flow, such as the upper North Fork Toutle River, Coldwater Creek and Jackson Creek, did not have survivors.

Lucas (1986, p. 279) considered that tributaries above Bear Creek were capable of supporting steelhead and stated:

> [A] moderate number of steelhead [were] spawning in the main-stem North Fork before the eruption***. [Alder, Bear, and Hoffstadt Creeks were] heavily utilized by steelhead for spawning and rearing.

After the eruption, Hoffstadt Creek was scoured out by a logjam, and most of the anadromous zone of Bear Creek was buried by mudflows. According to Lucas (1986, p. 279):

> Alder Creek probably has the finest spawning and rearing habitat in the entire Toutle Basin. With the exception of mudflow deposits in the lower reaches, Alder Creek was not measurably impacted by the eruption.

Lucas (1986, p. 279) stated that in the North Fork:

> All major tributaries above the mouth of Alder Creek were nearly destroyed by the combined impacts of the mudflow and blast. *** Portions of many tributaries were completely enveloped by sediment, and water backed up forming numerous lakes as these tributaries rose, attempting to overtop the debris avalanche.

The author was of the opinion that fish exposed to high temperatures associated with the May 18, 1980, mudflows were killed outright, but that some survivors might be found in unaffected tributary streams. Electrofishing surveys confirmed this hypothesis, and the author found live adult summer steelhead in the North Fork Toutle River in August 1980. According to Hopman (1982, p. 136):

> [The Washington State Game Department officials who made surveys in the Green River drainage, a tributary of the North Fork Toutle River,]***encountered significant numbers of steelhead that could only have originated from Columbia River waters in the intervening period. This is especially significant because turbidity levels were still in the neighborhood of many thousand JTU's and up until this time, those levels had been reported as fatal to anadromous fish species.

During 1981, Lucas (1986, p. 281) found sparse numbers of adult fish in Miners Creek, another tributary of the Green River.

Lucas (1986, p. 281) collected juvenile steelhead and cutthroat in Elk Creek on June 18, 1980. Elk Creek is a tributary of the Green River; the Green River merges with the North Fork Toutle River. Located within the blast zone, Elk Creek was characterized by Lucas as a streambed with heavy accumulations of ash and as a creek with turbid water conditions. The author described erosion in gill filaments of fish, which he attributed to the abrasive action of ash particles. On the same day, the author found juvenile steelhead and coho in Devil's Creek, a tributary of the Green River; Devil's Creek is outside the blast zone. The surveys by Lucas (1986) provided hard evidence that juvenile fish survived in tributary streams, despite losses in the main parts of the river.

The North Fork Toutle River had difficulty establishing a permanent channel after the eruption, because the wide flood plain allowed the river to "wander back and forth," stated Lucas (1986, p. 279). The suspended-sediment discharges were as large as 2.8×10^7 metric tons per day during the period October 1980 to September 1981. Equivalent order-of-magnitude discharges were observed during the periods October through September of 1981–82 and 1982–83. Lucas (1986) was of the opinion that only tributaries of the North Fork drainage system could serve as suitable spawning and rearing habitats and cited Alder Creek as the most likely candidate. Alder Creek was little affected by the eruption and still

possessed substantial stream canopy provided by zones of old-growth timber. Water temperatures in Alder Creek were lower than in tributaries that experienced elevated stream temperatures at least through 1981.

Lucas (1986, p. 282) reported that adult fish could reach the spawning streams by swimming up the Cowlitz and Toutle Rivers—a significant finding, even though he already possessed proof that fish had survived in tributaries. The mainstream rivers were choked with ash, and it was not known if migrating fish could endure such adverse conditions. In August 1980, Lucas found an adult summer steelhead. However, the author reported that many adult fall chinook, which are "large river spawners," had little success in finding suitable spawning and rearing habitats. Many fish perished on their migration upstream, and Lucas (1986, p. 282) stated: "Their carcasses, still full of eggs and milt, littered the streambanks." According to Martin and others (1982, p. 236):

> Last fall (1980) returning adult salmon were observed dead and unspawned along the [Toutle] riverbanks, apparently as a result of stranding in an effort to swim up the shallow braided channels in the river.***Coho followed in October and were somewhat more successful. Although many died, a few found sanctuaries for spawning in tributaries of the South Fork Toutle [River].

Lucas (1986, p. 282) reported finding steelhead redds in Alder and Wyant Creeks of the North Fork Toutle in 1981, and the success of steelhead redds in Alder Creek further improved during 1983 and 1984. Other investigators determined that smolts could successfully migrate to the sea, in spite of the adverse environmental conditions. Some proof was provided by Martin and others (1982), who recovered coho smolts that had been released far upstream in Alder Creek, above the mouth of the Toutle River.

For a long-term analysis regarding the recovery of anadromous fish in the Toutle River system, refer to reports by Lucas (1986), Martin and others (1982), and Phinney (1982).

South Coldwater Creek

South Coldwater Creek is in the North Fork Toutle River Basin; however, it is discussed as a subsection of this report, because its water quality was affected by numerous post-eruption events and activities. South Coldwater Creek had been transformed by the eruption into a muddy, organically enriched, bacteria-laden stream. The COE elected to utilize South Coldwater Creek as receiving water for Spirit Lake water releases through an engineered tunnel 8,530 feet long (see Spirit Lake). The tunnel connected the west arm of Spirit Lake to the headwaters of South Coldwater Creek. Discharge of Spirit Lake water to South Coldwater Creek was carefully monitored by several agencies in subsequent months. Because of the poor water quality of Spirit Lake, there was concern that water of the North Fork Toutle River, and hence the Toutle River, would be degraded in the process of lake drawdown. For that reason, much of the most intense sampling of South Coldwater Creek occurred many months after the eruption but was nevertheless essential to understanding water-quality changes throughout the whole system. A short summary of information gathered during late post-eruption studies follows. According to Larson and Glass (1987, p. sec. 6, p. 2):

> The South Coldwater drainage basin had an area of 6 square miles. At the tunnel's proposed outlet, the drainage area was 1.2 square miles. Average annual discharge of South Coldwater Creek was 5 ft^3/s *** at the outlet and less than 100 ft^3/s *** at the mouth. *** The basin was virtually destroyed by the May 1980 eruption. The lateral blast completely denuded the watershed and removed much of the soil from the hill slopes. Much of the debris avalanche was deposited in the upper basin. The pre-eruption outlet of the South Coldwater watershed was plugged by the debris-avalanche deposit. Consequently, South Coldwater Creek drained through North Coldwater Lake.

The authors describe three reaches of South Coldwater Creek in detail, along with effects of the tunnel discharge on channel characteristics and water quality. South Coldwater Creek empties into Coldwater Lake at the site of the mudflow dam caused by the eruption. Coldwater Lake discharges to the North Fork Toutle River by an overflow channel constructed by the COE in 1981. In summary, after completion of the tunnel and outlet channels, water from Spirit Lake flows downstream to South Coldwater Creek to South Coldwater Lake, from which it empties into the North Fork Toutle River. Water-quality changes in any part of this system were greatly affected by manmade and post-eruption activities that complicated interpretation of the data collected on these basins.

Larson and Glass (1987, sec. 6, p. 19–24) reported 40 water-quality constituents for the North Fork Toutle River and compared data from November 1980 to subsequent years through 1986. The authors regarded the North Fork Toutle River to be diluted by water flowing out of Coldwater and Castle Lakes. According to the authors, concentrations of nitrogen, phenols, and some trace metals were increased by post-eruption releases from Spirit Lake and in part by water releases from Coldwater and Castle Lakes. Larson and Glass (1987, sec. 6, p. 19) stated:

> Considering the 40 water-quality variables *in toto*, waters released through the Spirit Lake outlet tunnel have, overall, improved the chemical quality of North Fork River waters. Improved, or diluted, readings have been noted for 32 variables, and degraded, or more concentrated, readings for the remaining six or eight variables***. Additionally, at Stations 6 and 7, only concentrations of arsenic, mercury, elemental phosphorus (P), manganese, and iron greatly exceed water quality standards, water quality criteria, or recommended safe levels for municipal drinking water supplies.***Even so, values of nearly all monitored chemical constituents in the North Fork Toutle River are still well above pre-eruption levels.

Larson and Glass (1987) performed extensive bacteriological analyses on many sites in this part of the basin because of the possibility that pathogenic bacterial species (see Spirit Lake) might degrade the water quality of the Toutle River when Spirit Lake water was discharged via the tunnel to Coldwater Creek. The authors reported mean standard bacteriological plate count densities for three sites on Coldwater Creek and numerous other locations on the Toutle and Kalama Rivers. An analysis of their findings on the different river systems is not presented in detail, and the data was gathered several years after the eruption, during the period 1983 to 1985. However, some data for Coldwater Creek are discussed to illustrate the scope of research by Larson and Glass (1987).

According to Larson and Glass (1987, sec. 5, p. 16):

> [During 1983, the] Coldwater Creek bacterial densities [standard plate count] ranged between 10^1 and 10^2 organisms per milliliter***. [The] highest densities were found in the summer and fall months, the lowest during the winter and spring.

For total coliform densities, the authors reported that the overall mean for Coldwater sites was 38 cells per 100 mL, and densities peaked during the summer and fall of 1983 (Larson and Glass, 1987, sec. 5, p. 22). Mean fecal coliform densities of less than 1 organism/100 mL were reported during the period 1983 to 1985, and no trends related to time were evident.

According to Larson and Glass (1987, sec. 5, p. 24–25), 9.4 percent of the 64 samples tested positive for *Klebsiella pneumoniae* in Coldwater Creek during 1983, and for comparative purposes:

> Outside of the impact zone, *K. pneumoniae* were present in 39 percent of the stream samples from the Kalama River and 29 percent of the samples from the Lewis River.

The potential pathogen, *Pseudomonas aeruginosa* was identified in about 10 percent of the samples. The density of *Pseudomonas aeruginosa* peaked during summer and fall months and ranged from 0.7 to 4.7 cells/100 mL in samples from Coldwater Creek. According to Larson and Glass (1987, sec. 5, p. 29), the following conditions existed in 1983:

> In Coldwater Creek samples, densities of *Ps.aeruginosa* differed significantly between sample sites. Twenty-six of 35 samples (74 percent) from the Coldwater Gaging Station were positive, with a mean density for all samples of 4.8 organisms per 100 mL. ***Coldwater samples also varied significantly with the season. The frequency of positive samples increased from 29 percent during the winter and spring, to 58 percent during the summer and 73 percent during the fall. The mean density at the Coldwater Gaging Station increased from 1.2 per 100 mL in the winter and spring, to 3.4 per 100 mL during the summer, and peaked at 18.3 during the fall months.

Larson and Glass (1987, sec. 5, p. 57–59) performed analyses for *Legionella* over a period of 3 years, starting in 1983. According to the authors, 88 percent of the 77 samples they examined from the Coldwater sites tested positive for *Legionella* species. According to Larson and Glass (1987, sec. 5, p. 57):

> The highest rate was at the Gaging Station, where 94 percent of all samples were positive for *Legionella*. *Legionella* were found in the samples from the Coldwater Creek Outlet site and 73 percent of the samples taken at the Inlet. Samples were collected from the Inlet during 1983 only;

the other two sites were sampled all years. There was no difference in the positive rate between study years.

According to Larson and Glass (1987, sec. 5, p. 59): "There was a significant difference in the positive rate between seasons, however." The number of positive samples was largest during winter and spring. During the summer and fall, positive rates were lower, and average numbers differed substantially between sampling sites. The authors report *Legionella gormanii* was the most frequent isolate, which was found at more than three-fourths of the Coldwater sampling sites. On the other hand, *Legionella pneumophila* gr6 and gr3 were found in less than 20 percent of the Coldwater sites, in contrast to other river basins, where it was the most common isolate. For a detailed analysis of the occurrence of pathogenic species of bacteria, refer to the monograph by Larson and Glass (1987).

South Fork Toutle River

The South Fork Toutle River was less affected than the North Fork, because the South Fork Toutle River experienced only mudflows—rather than a combination of mudflows and blast debris (Hopman, 1982, p. 136). Nonetheless, the eruption effects were substantial. Stober and others (1981, p. 41) reported a large suspended sediment concentration of 11,900 mg/L in the South Fork Toutle River during 1980, which altered the water's physical and chemical characteristics. Stober and others (1981, p. 57) reported the South Fork Toutle River had DO concentrations ranging from 6.1 to 12.0 mg/L and pH values ranging from 6.5 to 7.8 during July–November 1980, and March–August 1981. Similar to changes observed in the North Fork Toutle River, levels of phosphate and SiO_4 apparently increased after the eruption.

Ample pre- and post-eruption water-quality data exist for several sampling sites on the South Fork Toutle River. Data from Turney and Klein (1982) illustrate some changes in chemical constituents.

Information about the South Fork Toutle River (below Disappointment Creek near Spirit Lake) and the South Fork Toutle River at Toutle is contained in table 8. Pre- and post-eruption data for the same site are not available. For comparisons of data with other sites on the South Fork Toutle River, refer to Turney and Klein (1982).

According to Klein (1984, p. 20), who sampled the South Fork Toutle River on March 30 and on June 6, 1980, "***there was a major increase in chloride composition and sulfate increases were negligible. Only minor cation changes were observed."

Concerns for possible water-quality changes caused by the debris-retaining structures constructed by the COE were addressed by Larson and U'ren (1982, p. 198), who sampled water from below the spillway of the structure during October and November of 1980. According to Larson and U'ren (1982, p. 198):

> The data collected revealed no evidence of hazardous chemical contamination, as had been originally feared. ***Moreover, of the nearly 40 constituents tested, including those in sediment eluates, most were either near or below minimum detection limits, or were well within guidelines recommended by the Environmental Protection Agency. Concentrations of iron and manganese were markedly higher than levels normally encountered in surface waters, but this was typical, perhaps, for water from a volcanically disturbed watershed.

According to Hindin (1983, p. 74):

> The South Fork of the Toutle River had a lower suspended solids content and visually appeared of a higher quality than the North Fork of the Toutle River on June 3 and August 31, 1982. Water samples collected from the South Fork of the Toutle River on those 2 days showed nondetectable concentrations of phenols, polycyclic aromatic hydrocarbons, terpenes, and a nonexistent haloform potential. The dissolved organic carbon was low, averaging 0.9 + 0.1 mg C/L [carbon per liter]. [The author reported finding] nonquantifiable quantities of phenol in Bear Creek, which is a tributary of the South Fork of the Toutle River***[and] terpenes were found in measurable concentrations. The dissolved organic carbon concentration and haloform potential were high compared to that found in the South Fork of the Toutle River.

According to Fuste' (1981, p. H4), riparian vegetation of pre-eruption South Fork Toutle River was sparse; the consequence of heavy logging activity in previous years. The river valley is narrow, and streams of the basin had steep gradients that ordinarily limited upstream migration of adult salmon in tributaries of the South Fork Toutle River.

Table 8. Water-quality data for the South Fork Toutle River below Disappointment Creek near Spirit Lake, Washington, and Toutle, Washington, before and after the eruption of May 18, 1980
[From Turney and Klein (1982, p. 117–121). mg/L, milligrams per liter; µg/L, micrograms per liter]

Constituent	Location: Below Disappointment Creek near Spirit Lake, Washington — Date: March 29, 1980	June 6, 1980	Toutle Washington — July 30, 1980
Magnesium, dissolved (mg/L)	1.00	1.60	2.30
Sodium, dissolved (mg/L)	3.2	7.6	7.3
Potassium, dissolved (mg/L)	.6	1.6	1.5
Carbon dioxide, dissolved (mg/L)	.4	.9	2.6
Sulfate, dissolved (mg/L)	1.6	5.9	8.2
Chloride, dissolved, (mg/L)	2.1	6.1	11.0
Nitrogen, nitrate + nitrite, total as N (mg/L)	.06	.01	.02
Nitrogen, ammonia total as N (mg/L)	.01	.04	.02
Nitrogen, total (mg/L)	.32	.33	2.1
Phosphorus, total as P (mg/L)	.03	.08	6.00
Phosphorus, dissolved (mg/L)	.02	.01	.40
Aluminum, total recoverable (µg/L)	510	100	49,000
Aluminum, suspended as Al (µg/L)	480	60	49,000
Aluminum, dissolved (µg/L)	30	40	110
Arsenic, total as As (µg/L	0	2	9
Arsenic, suspended total as As (µg/L)	0	1	7
Arsenic, dissolved as As (µg/L)	0	1	2
Barium, total recoverable as Ba (µg/L)	200	0	200
Barium, suspended recoverable as Ba (µg/L)	200	0	200
Barium, dissolved (µg/L)	10	8	7
Boron, total recoverable as Bo (µg/L)	90	50	120
Boron, suspended recoverable, (µg/L)	70	0	100
Boron, dissolved (µg/L)	20	70	20
Iron, total recoverable (µg/L)	560	1,200	36,000
Iron, suspended recoverable (µg/L)	460	990	36,000
Iron, dissolved (µg/L)	100	210	47
Lead, total recoverable (µg/L)	54	6	20
Lead, suspended recoverable (µg/L)	54	4	0
Lithium, total recoverable (µg/L)	0	10	40
Lithium, suspended recoverable (µg/L)	0	2	30
Lithium, dissolved (µg/L)	5	8	10
Manganese, total recoverable (µg/L)	30	150	880
Manganese, suspended recoverable (µg/L)	10	40	750
Manganese, dissolved (µg/L)	20	110	130
Nickel, total recoverable (µg/L)	0	6	42
Nickel, suspended recoverable(µg/L)	0	6	39
Nickel, dissolved (µg/L)	2	0	3
Zinc, total recoverable (µg/L)	20	250	100
Zinc, dissolved (µg/L)	4	<3	<3

Pre-eruption samples of other organisms in these tributaries were mainly composed of members of the families Baetidae (*Baetis sp.*) and Chironomidae. However, the author's sampling site was divided into two channels after the eruption, so post-eruption data was reported for the new channels—one of which carried a high suspended-sediment load, while the other channel was clear. Small numbers of the families Baetidae, Heptageniidae, Tipulidae, Simuliidae, Chironomidae, Empididae, Hydrophilidae, and others were found in the clear channel, while only eight organisms could be recovered in a sample from the muddy channel. The few organisms consisted of only two taxa, Baetidae and Chironomidae (Fuste', 1981, p. H10).

The density of aquatic food chains in the South Fork Toutle River tributaries varied, depending upon the location of the tributary. According to Lucas (1986, p. 285):

> Invertebrate populations in many streams out of the eruption zone were in excellent condition. These streams, through downstream drift of insects, provided a source for recolonization of impacted streams.

The author described the fairly rapid recovery of insect populations in the South Fork Toutle River as turbidity returned to near normal levels but observed that there was a lack of leaf litter for certain invertebrates.

Toutle River

Post-eruption water-quality data in the Toutle River necessarily reflects a large number of manmade activities initiated after the eruption. Willis (1982, p. 213) describes recovery operations undertaken in the Toutle River drainage, including the excavation of eight sediment-stabilization basins. The basins were operated until September 1981, and 7.5 million cubic yards of sediment was removed from the basins.

According to Hopman (1982, p. 135):

> On 19 May [1980], it has been established that at the mouth of the Toutle River where it enters the Cowlitz River approximately 50 miles from the base of the mountain, temperatures were in the neighborhood of 32.2°C. Turbidity levels were nearly immeasurable.

Klein (1984, p. 18) reported that prior to the eruption, the normal specific conductance of the Toutle River at the Castle Rock sampling site was about 90 μS/cm at 25°C. The author was not able to collect samples on May 18, 1980, but states that on May 19, 1980, the conductance of the mudflows was 1,200 μS/cm. On May 20, 1980, the first water samples collected after the eruption had a specific conductance of 560 μS/cm. Turney and Klein (1982) reported data for the Toutle River near Castle Rock, Washington, which is presented in table 9.

Table 9. Water-quality data for the Toutle River near Castle Rock, Washington, before and after the eruption of May 18, 1980

[From Turney and Klein (1982, p. 127). μS/cm at 25°C, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter]

	Date of collections		
	April 22, 1980	May 27, 1980	June 23, 1980
	Time (2400 hours)		
Constituents	**1450**	**1350**	**1355**
Specific conductance (μS/cm at 25°C)	36	290	150
pH field (units)	7.5	7.4	7.7
Temperature, water °C	9.0	10.0	15.6
Total (nitrate + nitrite)	.19	.01	.03
Nitrogen (mg/L as N)			
Total ammonia	.080	.430	.040
Nitrogen (mg/L as N)			
Total phosphorus (mg/L as P)	.030	5.40	.730
Dissolved orthophosphate (mg/L as P)	.010	.020	.010

The order-of-magnitude change in specific conductance agrees with data reported by other authors. Post-eruption concentrations of ammonia-nitrogen and of total phosphorus were increased; within a month, the concentration of phosphorus was two orders-of-magnitude larger than pre-eruption values. Klein (1984, p. 26), summarized changes in the Toutle and Cowlitz Rivers:

> High concentrations of total nitrogen and total organic nitrogen were observed in post-eruption water samples. In all cases, the high nitrogen concentrations were associated with high levels of turbidity, and the greater proportion of the nitrogen was organic. The high concentrations of organic nitrogen probably resulted from pyrolysis of the forest within the blast zone. It is envisioned that the vaporized organic products immediately attached to volcanic ash particles and were then transported to points of deposition.

Calcium and bicarbonate were the major pre-eruption chemical constituents in the Toutle River near Castle Rock. Klein (1984, p. 18–19) stated:

[Post-eruption water samples had an] entirely different chemical composition ***, with dissolved sulfate and chloride abruptly becoming the dominant anions. The June 24 sample suggested a trend of the river back to its pre-eruption composition; however, the July 22 sample showed another large increase in the chloride concentration, indicating that some upstream activity is continuing to alter the chemistry of the river water***.

According to Klein (1984), water-quality changes in the Toutle and Cowlitz Rivers were persistent due to the influx of chemical constituents leached from sediments on a continual basis. Representative values for iron, manganese, and aluminum are presented in table 10. Klein (1984, p. 24–26) stated:

Total concentrations of iron, manganese, and aluminum increased greatly over pre-eruption levels, up to 100 to 500 times in the Toutle and Cowlitz Rivers compared with 5 to 50 times at the reported sites east of the mountain. The elevated total concentrations of these metals have tended to persist in the Toutle and Cowlitz Rivers; whereas, those in the ash-affected streams quickly returned to pre-eruption levels.

According to Klein (1984), concentrations of suspended metals were generally much larger than concentrations of dissolved metals because of the large suspended-sediment concentrations.

Bonelli and Taylor (1981, p. 262) sampled the Toutle River near Castle Rock on May 20, 1980, and June 24, 1980, and stated:

The chemical changes observed *** indicate a greater persistence and variability of change due to continuing influx and leaching of sediments in devastated headwater areas. In addition, the total concentrations of Fe, Mn and Al [aluminum] increased greatly over pre-eruption levels. There appeared to be no persistence of dissolved inorganic trace constituents that would constitute any known hazard to human health. However, a large amount of organic material (trees, plants, soil) trapped in the hot, wet volcanic debris is decomposing rapidly to form a variety of organic degradation products and gas (methane, carbon dioxide, hydrogen sulfide).

Lucas (1986, p. 285) reported that the aquatic food chain in the Toutle River was severely affected by the eruption, and invertebrates were killed when ashfall and mudflows buried stream substrates. According to Lucas (1986, p. 285):

Ash filled interstices between rocks. Many invertebrates were denied access to preferred habitat underneath rocks and out of the current. Although caddisflies (Trichoptera) and black flies (Simuliidae) could attach to exposed rock, the extremely turbid water, shifting bedload and lack of food made for a tenuous existence. Turbid river conditions precluded sunlight penetration to the streambed preventing growth of algae. Leaf litter, another food source for invertebrates, was in short supply because of the near absence of riparian vegetation.

According to Phinney (1982, p. 294):

Salmon losses in the Toutle River included all fish at two Washington Department of Fisheries (WDF) salmon culture

Table 10. Variation of trace elements in the Toutle River at Highway 99 Bridge near Castle Rock, Washington, before and after the eruption of May 18, 1980

[From Klein (1984, p. 24). Concentrations expressed as micrograms per liter]

	Iron		Manganese		Aluminum	
Date	Dissolved	Total recoverable	Dissolved	Total recoverable	Dissolved	Total recoverable
3/29/80	70	230	20	20	40	200
5/20/80	95	22,000	1,000	1,300	310	20,000
5/27/80	110	78,000	490	2,000	25	57,000
6/19/80	240	33,000	290	290	40	20,000
6/24/80	210	19,000	290	680	140	100,000

facilities and virtually all rearing juveniles throughout the river that were progeny of naturally spawning segments of the populations. A small number of adult spring chinook were also in the Toutle [River] and were killed.

The author remarks on the good fortune experienced by the major part of the large Cowlitz spring chinook run, which had already passed to safety and were above the mouth of the Toutle River on May 18, 1980. Hopman (1982, p. 136) reported:

> The initial high temperatures caused in the Toutle and Lower Cowlitz Rivers by the eruption of 18 May, immediately resulted in the killing of essentially all fisheries resources in those portions of the Toutle and Cowlitz Rivers impacted. Temperature readings of above 32.2°C were recorded the day after the eruption in the Lower Toutle River and near that figure in the Lower Cowlitz River. Although those temperatures subsided rapidly in following days, damage had already been done and fishery resources were essentially eliminated. [However, late] in the summer and early fall of 1980, the fall and coho run from the ocean up the Columbia River also proved to be near record proportions and the runs entered the Cowlitz and moved upstream to the Toutle River in large numbers.*** The apparent lack of impacts on the anadromous fish species in the Toutle and Cowlitz Rivers was a pleasant surprise for nearly all concerned. It demonstrated that those species generally could cope with the high suspended-sediment and turbidity levels and the large number of dredging plants working in the stream.

Stober and others (1981, p. 2) studied the tolerance of anadromous fish to suspended-sediment concentrations in the Toutle and Cowlitz Rivers. The authors monitored water quality and used laboratory static bioassays, live-box testing, and artificial streams. Juvenile (presmolt and smolt), adult coho salmon *(Oncorhynchus Kisutch)*, and chinook salmon smolts *(Onchryhyncus tshawytscha)* were studied for 13 months, in conjunction with geological studies of sediment-stabilization rates. Stober and others (1981, p. 139–142) summarized their findings:

> It is apparent that the smolt stage of both coho and chinook was less tolerant of suspended sediment than presmolt coho salmon in the field. However, coho smolts were found most tolerant in comparable static tests***[and] it is unknown whether coho salmon smolts are actually more sensitive in the field.
>
> *　*　*　*　*　*　*
>
> The high sensitivity of fall chinook salmon smolts in the field appear to be consistent with the smaller size of this species. *** Complete and partial mortality occurred consistently with coho presmolts in the Toutle and lower Cowlitz Rivers, respectively, during the summer following the May 18 [1980] eruption. Live-box tests [Live-box tests utilize test fish contained in open screened cases suspended in the river water.] during the spring of 1981 showed partial mortality only in the lower Toutle, North Fork Toutle and Green Rivers. Survival was not affected in the South Fork Toutle and lower Cowlitz Rivers in 1981. The increase in survival of fish exposed in live-boxes in 1981 was directly related to the decline in suspended sediment concentration.
>
> *　*　*　*　*　*　*
>
> The laboratory testing has shown that juvenile chinook and coho salmon are very tolerant to high suspended concentrations and low water velocities under controlled conditions. However, the tolerance may be reduced considerably when fish are exposed to suspended sediment in combination with other factors in the field.*** Tributaries unaffected by high sediment concentrations are expected to continue to produce where incubation and rearing can be successfully completed.

Brannon and others (1981) conducted experiments in October of 1980, using male chinook salmon *(Oncorhynchus tshawytscha)* that had returned to the University of Washington's College of Fisheries hatchery on the Lake Washington Ship Canal, Washington. The studies tested effects of suspended ash on the chinook salmon's preference for one water source or another. The question of whether the ash might reduce homing ability was raised, and experiments were designed to study the phenomenon of straying to spawn in nonnatal rivers or tributaries. For example, a salmon spawning in the Toutle River first enters the Columbia River on its journey to the spawning grounds.

At the confluence of the Cowlitz River with the Columbia, the salmon would need to choose to enter the Cowlitz. Subsequently, at the junction of the upper Cowlitz River with the Toutle River, the fish meets another bifurcation and needs to make another choice. After the eruption, turbidities at these junctions were very high. According to Brannon and others (1981, p. 23–24), mean concentrations of suspended ash and sediment in the Cowlitz River were over 1,200 mg/L. During the fall of 1980, concentrations of suspended ash and sediment of over 3,000 mg/L were recorded in the Toutle River, and these levels were regarded by the authors to be in the lethal range.

The experiments of Brannon and others (1981, p. 5–6) were carried out at the Lake Washington Ship Canal; collected ash was suspended in y-mazes—concrete raceways designed to give fish a choice of clear or suspended-ash water channels. For details of these unique experimental methods, refer to the original report. Brannon and others (1981, p. 23) concluded:

> [The] changes in the migratory behavior of adult salmon may occur at sublethal turbidities. Consequently, there are likely to be significant amounts of straying of salmon presented with a choice between home water containing ash suspensions and clear, nonnatal water.

It was found that some fish strayed, whereas others may delay migration through water containing ash; in any event, the experiments predicted that substantial numbers of fish may have strayed during the high-turbidity conditions encountered in the Columbia, Toutle, and Cowlitz Rivers. In summary, stated Brannon and others (1981, p. 24): "If there is significant straying from natal, ash-laden streams, there may be negative effects on the populations in streams receiving these fish." The authors concluded that ash effects on the behavior of salmon possibly could be persistent, if ash levels remained high.

Cowlitz River

A major factor affecting the water-quality of the Cowlitz River was the continued transport of sediments into the Cowlitz from the Toutle River. According to Vanoni (1986, p. 401):

> Measurements of sediment discharge and aggradation in the Cowlitz River show clearly that the river is not capable of transporting the sediment delivered to it by the Toutle River. Apparently, the heavy washload that is so effective in increasing sediment transport capacity in the Toutle River is decreased drastically in the Cowlitz through dilution. There appears to be no reason to expect any reduction in deposition and consequent aggradation until the high yield of the Toutle is reduced.

According to Warren and others (1982, p. 88):

> [The debris avalanche on the North and South Forks of the Toutle River provided a major source of sediment for the Cowlitz,] although additional material originated from the * * * banks, bed, and flood plain along the Toutle and the Cowlitz [Rivers].

After performing sediment physical and chemical analyses on the Cowlitz River from May 20 to November 25, 1980, Moore and Reese (1982, p. 254) stated:

> [The sediments were] within the sand and gravel grain size range, contained approximately 20 percent ash, and did not contain excessive levels of the contaminants analyzed. An exception was elutriate, total phenolic compound numbers which were higher than would normally be expected given the other sediment and water-quality findings. These high levels were determined by this study and others to be from nonpoint source discharges and widespread in the drainage basin.

The authors were of the opinion that suspended sediments responsible for high levels of turbidity would persist many years, because ash and mudflow material in the blast area would continually be eroded. Although the authors detected phenolic compounds, they concluded that the overall impact was slight, relative to 1980 EPA water-quality criteria. Stober and others (1981, p. 56–59) cited COE studies, which reported a phenol concentration of 3 μg/L on October 6, 1980, and a concentration of 4 μg/L on November 12, 1980. By 1981, the concentration of total phenols was less than 1.0 μg/L.

According to Turney and Klein (1982, p. 133), the turbidity of the Cowlitz River at Kelso, Washington, was 3.7 NTU's (nephelometric turbidity units) on April 16, 1980. Post-eruption turbidities ranged from 72 to 650 NTU's at Kelso, whereas upstream at Castle Rock, turbidities as high as 2,700 NTU's were reported. Turbidity returned to near pre-eruption levels by August 1980.

Stober and others (1981, p. 57) reported data for five Cowlitz River sites, including the Interstate I–5

bridge, Castle Rock, Lexington, Kelso, and Longview, during July–November 1980 and March–August 1981 field-sampling periods. Average concentrations of DO ranged from 9.6 to 10.4 mg/L; there were no minimum concentrations less than 6.4 mg/L. Average pH values during this time ranged from 6.9 to 7.0 for the five sites, although minimum values low as 6.1 were occasionally recorded. Average conductivity ranged from 48 to 71 μS/cm.

Long-term pre-eruption physical and chemical data for the Cowlitz River for sites at Castle Rock and Kelso were available, so the impact of the volcanic activity on water quality could be evaluated. The observed chemical-composition changes closely resembled those reported for the Toutle River. Klein (1984, p. 19–20) presented data from April 1978 to August 1980, and stated:

> The largest variations occurred in the concentrations of sulfate, dissolved solids, total and organic nitrogen, and turbidity. High concentrations of sulfate and chloride were observed in late May and June, although maximum values for both ions were below those in samples collected monthly during the previous 2 years. However, the mudflows had a drastic effect on the levels of total organic nitrogen, total nitrogen, and turbidity ***. Samples collected in late May and early June showed turbidity values well above the normal values observed at this station, and, as before, these increases were accompanied by major increases in total nitrogen concentration, with most of the increase due to total organic nitrogen.

Data that indicate the changes in concentrations of iron, manganese, and aluminum are contained in table 11 (Klein, 1984). According to Klein (1984, p. 21–23):

> [The] post-eruption concentrations of dissolved iron, manganese, and aluminum increased and the increases persisted owing to continued leaching from the debris and mudflow deposits. ***Total concentrations of these metals at the Toutle and Cowlitz stations increased 100 to 500 times over pre-eruption values***.

The author attributed the persistence of changes in the Cowlitz and Toutle Rivers to leaching of elements from sediments deposited in severely impacted headwaters.

Turney and Klein (1982, p. 133–137) reported an increase in concentration of 50 percent or greater (comparing data from April 16, 1980, to post-eruption data during the period May through August 1980) for the following chemical constituents at the Cowlitz River at Kelso site: total phosphorus; dissolved organic carbon; suspended organic carbon; total arsenic; dissolved and total recoverable barium; total recoverable and suspended recoverable cobalt; total recoverable and suspended recoverable copper; total recoverable, suspended recoverable, and dissolved lead; total recoverable mercury; total recoverable, suspended recoverable, and dissolved nickel; and total recoverable, suspended recoverable, and dissolved zinc. Concentrations of other constituents may have increased after the eruption, but the lack of pre-eruption data makes it difficult to verify if appreciable changes did occur.

Table 11. Concentration of trace metals in the Cowlitz River at Kelso, Washington, before and after the eruption of May 18, 1980

[After Klein (1984, p. 24). Concentrations are in micrograms per liter; --, data not available]

	Iron		Manganese		Aluminum	
Date	Dissolved	Total recoverable	Dissolved	Total recoverable	Dissolved	Total recoverable
			Pre-eruption			
4/16/80	50	400	5	10	--	--
			Post-eruption			
5/30/80	24	12,000	110	350	120	29,000
6/12/80	90	10,000	90	290	80	10,000
6/17/80	70	45,000	110	900	20	39,000
6/25/80	80	8,000	70	230	60	10,000

Elements included in this "uncertain" category are boron, lithium, molybdenum, strontium, and vanadium. Concentrations of selenium and silver appear unchanged. The authors performed analyses for the Cowlitz River at Castle Rock, but pre-eruption data for comparative purposes were not available. The reader is referred to Turney and Klein (1982) for detailed tables of chemical and physical analysis for Castle Rock and numerous other sites on the Cowlitz River. Moore and Reese (1982) extensively sampled sediments from the Cowlitz River, and information on chemical data for sediments is available in their report.

After the eruption, the Cowlitz River was sampled extensively for organic compounds by Hindin (1983, p. 71–72). Two major sampling sites were the intake and outflow to the Longview, Washington, water-treatment plant. The sites are about 10 miles downstream from the confluence of the Toutle River with the Cowlitz River. In addition to Hindin's sampling, water-treatment-plant personnel routinely monitored water quality, and data from this site should have identified any post-eruption water-quality changes in the lower Cowlitz River. According to Hindin (1983, p. 33–38), no pentachlorophenol was reported for intake water on August 19, 1981, but 6.9 µg/L of pentachlorophenol was detected on March 19, 1982. The pentachlorophenol concentration dropped to 3.1 µg/L on April 7, 1982, and was not detected on June 3, 1982. Various terpenes in the base- and neutral-enriched extract were reported; the concentration ranges of terpenes from August 19, 1981, to June 3, 1982, were as follows: alpha-pinene (1.0–1.5 µg/L), beta-cymene (1.0–1.6 µg/L), terpinene-4-ol (1.0–1.3 µg/L), and alpha-terpineol (1.8–2.7 µg/L). During the same time period, haloforms were detected by Hindin in the following concentration ranges: chloroform (4.3–6.5 µg/L), dichlorobromomethane (1.0–1.5 µg/L), and total haloforms (4.3–7.7 µg/L). DOC concentrations were in the range 0.6–1.3 mg/L during this period. According to Hindin (1983, p. 71):

> [The average concentrations of DOC were considered to be] relatively low for a surface water receiving a multitude of tributary inflows. Similarly, the haloform potential was low.

Hindin's data on finished water from the Longview treatment plant indicated the plant was capable of removing phenols and pentachlorophenol. On September 15, 1981, however, Hindin (1983, p. 36) reported finding 1.4 µg/L of 2,4,6-trichlorophenol in finished water. This particular constituent was never reported in intake water, and Hindin (1983, p. 71–72) speculated that the compound was formed from a precursor during the chlorination processes of water treatment. The treatment plant successfully removed terpenes, but the concentration of DOC was reduced only slightly. According to Hindin (1983, p. 36):

> [The organics remaining were capable of] exerting haloform potential***. An unusually high dissolved organic carbon concentration and high haloform potential was noted [on June 3, 1982].

In addition to a nonquantifiable concentration of 2,4-dichlorophenol, there were numerous nonidentifiable constituents in the acid fraction extract. According to the author, the number (16) of nonquantifiable constituents is considered to be a substantial increase in the number of compounds—compared to intake water that did not contain as many constituents.

According to Phinney (1982, p. 294–297), there was considerable concern for hatchery-raised juvenile salmon scheduled for 1980 release because of live-box tests performed by the Washington Department of Fisheries (WDF) immediately after the eruption. The eruption events, subsequent dredging, and construction projects, continued to create extreme turbidity problems in the Cowlitz River downstream from the mouth of the Toutle River. The live-box tests indicated that juvenile chinook salmon could suffer 100-percent mortality rates within hours, as a consequence of severe gill abrasion resulting from the abnormal concentrations of suspended solids. The level of concern was sufficient to cause the WDF to truck the juvenile hatchery salmon to alternate downstream sites in the Columbia River in order to avoid the turbidity in the lower Cowlitz River. According to Phinney (1982, p. 294):

> All salmon and other fish and aquatic life in the Cowlitz River below its confluence with the Toutle was undoubtedly eliminated. Again, these were mostly juvenile chinook and coho salmon with a small number of adult spring chinook. Fortunately, the main portion of the large Cowlitz spring chinook run was already safely above the mouth of the Toutle at the time of the eruption.

According to Phinney (1982, p. 297):

> WDF was concerned about the ability of adult salmon returning to Cowlitz hatchery to survive the trip upstream through the lower Cowlitz with the water quality conditions that prevailed.*** Radio-tagging experiments by WDF and National Marine Fisheries Service show a slower rate of migration of chinook salmon in the lower Cowlitz River than previously observed in other areas. A lab study showed [,however,] that ability of salmon to 'home' or return to their stream of origin was apparently not impacted by high sediment levels in the water. Live-box tests with adult salmon during the fall in the Cowlitz River showed that adult salmon displayed a greater tolerance to the suspended sediment than juveniles, but other impacts on adults were notable. For example, there apparently was a higher than usual rate of straying to other areas of Cowlitz/Toutle-origin returning adult salmon to avoid the marginal quality water in the Cowlitz possibly as a result of some small effect on homing ability or a purposeful avoidance of the prevailing conditions. An unknown number died in the lower Cowlitz River—a problem exacerbated by the dredging activity. There should have been at least 10–15,000 adult coho return to Toutle hatchery alone, but few were observed in the vicinity.

Studies by Stober and others (1981, p. 139–141) revealed a disparity between results of live-box and static tests used to determine tolerance of fish to suspended sediments. Caution is necessary when interpreting results of such studies. For example, data showed that fish exhibited a fairly high tolerance to elevated levels of suspended sediments in static tests by coho and fall chinook smolts, in comparison to live-box (in river) tests. Histological studies of gill tissue from salmon appeared to show that during live-box and static bioassays for suspended-sediment-related gill histopathology, little or no gill damage was found. This finding illustrates difficulties inherent in performing live-box tests. Related studies by Brannon and others (1981, p. 24), using adult chinook salmon exposed to 650 mg/L of volcanic ash in a static system for 1 week, showed that the fish did not exhibit visible damage to their olfactory sensory epithelium—nor was their homing ability affected.

In related investigations, Redding and Schreck (1982, p. 300–301) performed controlled laboratory tank tests to examine the effect of ash on fish gill and epithelial tissues and other physiological responses indicative of physiological stress. The effect of volcanic ash, characterized by the contents of silicate glass particles, was compared to tests utilizing other types of suspended materials such as topsoil and kaolin clay. Redding and Schreck (1982, p. 300–301), "[did not] observe consistent histological effects on gill tissue ***." The authors did note elevated corticosteroid and hematocrit levels in juvenile steelhead trout. These clinical-chemical reactions were considered to be indicative of a sublethal stress reaction in the fish.

According to Stober and others (1981, p. 66):

> Returning adult salmon were found dead in the lower Cowlitz River during fall 1980. These individuals presumably could not tolerate the suspended sediment concentrations encountered in the lower Cowlitz River, and did not elect to avoid the high suspended sediment concentrations encountered.

The immediate losses to the fish resources in the Cowlitz and Toutle Rivers were estimated to number in the millions of juvenile coho and chinook salmon. The year class of these fish likely would have contributed hundreds of thousands of adult salmon in subsequent years. According to Phinney (1982, p. 295):

> No losses have been calculated for future years but this onetime loss level could extend well into the future as an annual loss, depending upon the recovery rate of the affected watersheds.

In contrast to the situation described for 1980, Phinney (1982) reported that the 1981 adult spring chinook migration was essentially normal, and the returns to the hatchery seemed unaffected.

Changes in the reported number of winter steelhead caught in the Cowlitz River were reported by Lucas (1986, p. 283):

> [The number] declined precipitously from a pre-eruption mean of 15,605 to 4,101 post-eruption. ***As with the summer run, most winter fish wandered into the Kalama and Lewis Rivers.

The high turbidities at the mouth of the Cowlitz River caused these fish to stray into other Columbia River tributaries to spawn. Ordinarily, few fish stray from their native streams, but abnormally high numbers of migrating fish found their way into new spawning grounds after the eruption. The steelhead that avoided the Cowlitz River because of turbidity spawned in other tributaries. According to Lucas (1986, p. 288):

> [The offspring of these stray fish, however, presumably would] provide a seeding source to rebuild Toutle stocks [in subsequent migrations. That is, new offspring fish hatched in the Kalama or Lewis Rivers might stray in subsequent years into the Toutle River (where their parents originated), when the water quality of the Toutle River improved. These fish can act as a] seeding source to rebuild Toutle stocks. Strays into the Toutle also provide genetic diversity.

In summary, the straying process was a mechanism which may have ultimately helped preserve the fish stocks.

Complete and partial mortality occurred with coho presmolts in the lower Cowlitz River during the summer of 1980 (as in the case of the Toutle River), according to Stober and others (1981, p. 140–142), who reported:

> [The] rapid reduction in the suspended sediment concentrations over one winter season suggest that juvenile salmon may be able to survive passage through most of the system, although high suspended sediment loads may prevent salmonid reproduction for a considerable time due to excessive gravel sediments in the affected rivers.

According to the authors, concentrations of suspended sediment actually had declined within one winter season, to the extent that emigrant smolts should not have been endangered. By 1981, such was the case in the lower Cowlitz River. Phinney (1982, p. 297) stated: "The 1981 migration of adult spring chinook was unaffected as returns to the hatchery and success of the Cowlitz River sport fishery were normal."

Because of earlier reports of phenolic compounds in the water, several investigators performed analytical studies of fish tissue to determine if such compounds might have been assimilated by fish. Campbell and others (1982, p. 10) detected phenol in a sea-run cutthroat trout from the mouth of the Cowlitz River, collected on September 11, 1981. The specimen had a tissue phenol concentration of 35 ng/g (nanograms per gram) of tissue. Several samples of eulachon (smelt) were collected from the Cowlitz River on January 19, 1982, with an average concentration of 172 ng/g. The smallest fish contained the largest concentrations of pentachlorophenol. According to Campbell and others (1982, p. 3), the concentrations of phenol and pentachlorophenol were not likely to be a cause for concern, relative to EPA standards published at the time and calculations performed by the authors. It was not possible to establish the source of the phenol; in the case of pentachlorophenol reported in Deer Creek, the water from which the fish containing pentachlorophenol were taken did not appear to contain the chemical. The authors presented data for other fish species, which contained neither phenol nor pentachlorophenol. No evaluation of the chemical effects on fish at concentrations reported was presented.

Cispus River

The Cispus River flows into the Cowlitz River near Randle, Washington, and is discussed in conjunction with the Cowlitz River as a separate subsection. Cushing and Smith (1982, p. 529) sampled the Cispus River and its two tributaries, Camp Creek and Yellowjacket Creek. The sampling site on the Cispus River was 15.5 miles upstream from the point of discharge into the Cowlitz River, and at that point, the Cispus River is approximately 66 feet wide, with a mean annual flow of 1,345 ft^3/s. Camp Creek is about 6.6 feet wide and flows into the Cispus River approximately 1.2 miles upstream from the point where Yellowjacket Creek joins the Cispus. Yellowjacket Creek is about 49 feet wide. The Cispus drainage basin received up to 2 inches of ashfall, and the authors compared effects in this basin to the Klickitat drainage, which received substantially less ash.

A hypothesis studied by Cushing and Smith (1982) was whether nutrients, such as nitrate-nitrogen leached from ash, might have a fertilizing effect on streams such as Camp and Yellowjacket Creeks. The authors attempted to define correlations between possible changes in water chemistry caused by the ash and changes in algal and caddisfly populations. Periphyton, seston (living plankton and nonliving particulate matter), and caddisfly larval samples were collected during 1980. Pre-eruption hydrographic and water-quality data existed for the sample sites, and some eruption effects could be identified. Cushing and Smith (1982, p. 530) stated:

> [The water chemistry indicated a] small, transient increase of dissolved inorganic nitrogen in the Cispus, but not as much as for total phosphorus which remained slightly elevated into the following winter.

Nitrate-nitrogen did not appear to increase in concentration, even though there had been substantial ashfall in the basin. Cushing and Smith (1982) possessed no data for dissolved organic nitrogen, so eruption effects

on this parameter could not be determined. However, turbidity in the Cispus River increased significantly and, according to the authors, was a consequence of the flushing of ash after the eruption.

The Cispus River is normally turbid, and differences in the algal populations (as evidenced by comparisons of periphytic chlorophyll *a* concentrations) in the Cispus and the Klickitat Rivers were attributed partially to the effects of turbidity. The turbidity decreased the penetration of light, which would limit the growth of algae. No algae, such as *Cladophora, Nostoc,* or *Nitella,* were observed in the Cispus River or in Camp or Yellowjacket Creeks, as was the case in the Klickitat River.

Cushing and Smith (1982, p. 538) emphasized: "[This] study did not allow us to distinguish between normal disruption by high water runoff and the specific effects of Mount St. Helens tephra." However, the authors describe a number of biological phenomena which could, at least in part, be attributed to ashfall. According to the authors, significant changes in macroinvertebrate populations may have occurred, although caddisfly populations normally fluctuate seasonally at Camp and Yellowjacket Creeks. Normally, the numbers of Trichoptera are low in the spring and early summer months and grow in number during the summer and early fall. Cushing and Smith (1982, p. 537) noted:

> [Hydropsyche is normally a common inhabitant of the Cispus River; after the eruption, Hydropsyche] appears to have been nearly eradicated. *Brachycentrus occidentalis* and *Dicosmoecus gilvipes* were also impacted by the ashfall.

Arctopsyche grandis larvae, as well as members of the *Rhyacophila acropedes* group, were apparently unaffected. The following description by Cushing and Smith (1982, p. 537) summarized their findings:

> Basically, we found that following the deposition of tephra (ash + pumice) from Mount St. Helens in the Cispus River, Camp Creek, and Yellowjacket Creek in spring 1 980, some common dominant species of Trichoptera were extremely reduced or eliminated. There was an immediate decrease in caddisfly numbers. Scraping forms (e.g., *Glossosoma*) and collector-filterers (e.g. *Hydropsyche*) decreased significantly. Fall emerging *Neophylax* species were obviously affected during the first year and showed no signs of recovery during the second. Spring emerging *Neophylax* species may have been affected; however, they normally occur in small numbers and low populations may be normal.

The Columbia River Drainage System and the Columbia River Estuary

Much research on the eruption effects of Mount St. Helens on the Columbia River and Columbia River Estuary deals with physical phenomena associated with the huge influx of sediment to both. Certainly, the inclusion of the Columbia River Estuary in this section of the report interjects discussions of a saltwater environment into the midst of a section dealing with freshwater rivers; however, rather than placing the estuary in a separate subsection, it is discussed in conjunction with the Columbia River, because effects on the estuary are inextricably bound to those in the river.

The mudflows impacting the Toutle and Cowlitz Rivers contributed to the sediment load in the Columbia River. Ultimately, some of this material reached the Columbia River Estuary—nearly 70 miles downstream from the mouth of the Cowlitz River, which discharges into the Columbia River near the City of Longview, Washington. Of paramount concern to agencies such as the COE was the blockage of navigation channels in the Cowlitz and Columbia Rivers. The blockage necessitated immediate emergency dredging operations to allow resumption of ship traffic. Thirty-one ships were trapped upstream of the mouth of the Cowlitz River after the eruption; the economic consequences of blocked river traffic, if prolonged, could have rapidly reached catastrophic proportions. An analysis of the economic impacts of the eruption is outside the scope of this report—suffice it to say that the urgency with which dredging activities were initiated served to mobilize people and equipment very rapidly.

Columbia River

The COE maintains the navigation channel from the mouth of the Columbia River to Portland, Oregon, at a 40-foot depth and 600-foot width. The Toutle and Cowlitz Rivers deposited an estimated 45 million cubic yards of sediment in the Columbia River, and it

was estimated that about 14 million cubic yards of this material filled in parts of the navigation channel (Willis, 1982, p. 210). Hydrographic surveys by the COE showed that the 40-foot channel depth was reduced to approximately 15 feet, and a 9.5-mile shoal was created. According to Haeni (1983, p. K1): "[The deposit was] in an area 7 miles upstream and 2 miles downstream from the junction of the Cowlitz and Columbia Rivers." According to Hubbell and others (1983, p. J1), most of the sediment ranged in size from clay-sized particles to 0.50-inch gravel.

The flow of the Columbia River is influenced by daily tidal cycles. During this cycle, there are periods when the river stands and periods when the flow is reversed in an upstream direction. The bulk of the sediment loads carried by the Cowlitz River reached the Columbia River during a period of reduced, or possibly reversed, flow. Although the reverse flow effect is thought to extend only as far upstream as river mile 52, much of the sediment was deposited upstream from the mouth of the Cowlitz for 7 miles. Much of the 45 million cubic yards of sediment was a consequence of the mud and debris flows; however, some of the material was derived from the Cowlitz River bed, when the lower one-half mile of the Cowlitz River was scoured by a surge of water moving downstream on May 19, 1980. According to Haeni (1983, p. K1):

> A minimum of 0.4 million cubic yards of material was scoured from the Cowlitz River bed and subsequently redeposited in the Columbia River before the 1.3 million-cubic-yard delta was formed.

Needless to say, the topography of the Columbia River was greatly altered, and the reader is referred to Haeni (1983) for details on bathymetric changes in portions of the Columbia River near the mouth of the Cowlitz River. To summarize, much of the Columbia River bottom in this part of the river basin was smoothed out, and the depressions and holes were filled in.

Less than a week after the eruption, some trapped vessels were able to proceed downstream by passing through an emergency channel dredged by the COE. The ships utilized this "window," which was created during periods of high tide and provided additional depth, to affect passage. The COE expanded the blocked channel in the Columbia River to a depth of 25 feet and a width of 200 feet by May 29, 1980, which permitted navigation. Ship movement was supervised by the U.S. Coast Guard. By November 30, 1980, traffic was opened to an unrestricted navigation channel (Willis, 1982, p. 210).

The COE sampled the mudflow deposits and was able to obtain a general picture of the characteristics of the mudflow materials by analyzing dredged samples. According to Haeni (1983, p. K13), a USGS scientist:

> Most sediment in the Columbia River was coarser than that in the Cowlitz River and consisted of fine to coarse sand and rock fragments with some silt and wood fragments. Gravel and rock fragments as large as 2 inches in diameter were reported in many of the sediment samples. In general, the deposit was coarser grained on the bottom and finer grained on the top. (Mount St. Helens debris explorations, explanation and shell bucket sample logs. U.S. Army Engineering District, Portland, Oregon, May 1980).

According to Moore and Reese (1982, p. 257), who collected sediments from many sites on the Columbia River May 28, 1980:

> [The sediments] contained up to 20 percent fine ash at the mouth of the Cowlitz. *** The 27 to 29 May and 3 to 4 June physical samples indicated that sediments tended to become progressively coarser from the mouth of the Cowlitz River upstream.

The authors concluded that increases in turbidity were a concern and that the high levels of suspended sediments would be expected to remain for years. On June 18, 1980, turbidity in the Columbia River, depending upon the reach, ranged from 4 to 21 NTU's.

Subsequent studies by the USGS were performed to obtain information on new sediments delivered to the rivers during a 9-day period in mid-August 1980. According to Hubble and others (1983, p. J1):

> [Discharge measurements of the suspended sediment] indicated that material is being scoured from the reach of the Columbia River directly seaward from the Cowlitz River at Columbia River mile (CRM) 68.0, and that some of the scoured material is redeposited between CRM 63.8 and CRM 54.0. Most material in transport is of silt and clay size.

According to the authors, there was a random distribution of pumice particles, which were larger than 2.0 mm in diameter in bottom sediments. The bed material above the mouth of the Cowlitz River was larger, generally, than the material from bottom sediments—taken seaward from the mouth—that had a mean size averaging less than 2.0 mm. For information and an analyses of suspended-sediment-discharge data, particle-size distribution of suspended

sediments and surficial bed material, vertical and longitudinal distributions of suspended-sediment discharges, and specific gravity of sediment materials, refer to Hubbell and others (1983, p. J1), who stated:

> On the basis of this information, corrections for unusual sediment properties are not necessary in sediment-transport or dredging-earthwork computations for the Columbia River.

A limited amount of data exists regarding water-quality characteristics in the Columbia River. Sampling of the Columbia River before, during, and after the eruption of May 18, 1980, was not routinely done at any one physical sampling site. As a consequence, conclusions regarding possible changes in river chemistry attributable to the eruption must necessarily be made with caution. The U.S. Geological Survey (Fuhrer and Rinella, 1983) performed a cooperative study with the COE between May and December of 1980 to provide reconnaissance data for determining the potential short-term effects of dredging operations on water quality in various rivers and estuaries. The program had not been designed to monitor changes caused by the volcanic eruption; however, data from the reconnaissance program provides some post-eruption information, although extensive historical baseline data are lacking.

Some pre-eruption, native-water samples had been gathered on May 14, 1980, from the Columbia River at CRM 32.7 and were from a midriver location. Although post-eruption data at the CRM 32.7 site were not available, several other upstream sites were sampled at CRM 65.8 and CRM 70.8 from May 21 to May 28, 1980. CRM 65.8 is downstream from the mouth of the Cowlitz River, and CRM 70.8 is upstream from the mouth of the Cowlitz River. Concentrations of dissolved chemicals found in native water samples from these two sites are presented in table 12 and illustrate some post-eruption water-quality characteristics of the Columbia River. Information relating to CRM 32.7 site also is included in table 12 and represents water-quality characteristics, at a downstream location, prior to the eruption.

After the eruption, Moore and Reese (1982, p. 254) performed *in situ* water-quality testing, reported on the physical parameters and chemical constituents of the Columbia and Cowlitz Rivers, and concluded: "***that oxygen, pH, temperature, and oxidation reduction potential were within the ranges suitable for survival of salmonids."

Table 12. Water-quality characteristics of the Columbia River during May 1980

[From Fuhrer and Rinella (1983). CRM, Columbia River Mile; CRM 32.7 is downstream from the mouth of the Cowlitz River but is not on plate 1; CRM 65.8 is downstream from the mouth of the Cowlitz River; CRM 70.8 is upstream from the mouth of the Cowlitz River. μg/L, micrograms per liter; --, data not available; mg/L, milligrams per liter; μS/cm, microsiemens per centimeter]

	Sites		
	CRM 32.7	CRM 65.8	CRM 70.8
	Sampling Dates		
Constituent	May 14, 1980	May 21, 1980	May 28, 1980
Barium (μg/L as Ba)	<100	<100	<100
Cyanide (μg/L as Cn)	4	--	3
Nickel (μg/L as Ni)	<1	--	1
Nitrogen, ammonia + organic (mg/L as N)	1.8	--	.4
pH (Units)	7.8	7.6	7.9
Specific Conductance (μS/cm)	143	139	124
Phosphorus (μg/L as P)	47	--	34
Orthophosphate (μg/L as P)	12	<10	21
Iron (μg/L as Fe)	19	37	20
Manganese (μg/L as Mn)	30	16	<10
Mercury (μg/L as Mn)	<.1	--	<.1
Carbon, Organic (mg/L as C)	2.4	--	3.2
Nitrogen, Ammonia (mg/L as N)	.04	.01	.03
Phenols	4	12	--

The sediment loads carried to the Columbia River from the Toutle and Cowlitz Rivers created a plume that extended all the way to the Columbia River Estuary. The initial eruptions of the volcano occurred while important salmonid fish species were migrating seaward. The National Marine Fisheries Service (NMFS) was concerned that juvenile Pacific salmon *(Onchohynchus* spp.*)* and steelhead trout *(Salmo gairdneri)* might be affected by ash (Newcomb and Flagg, 1983, p. 7–8). The concern prompted studies by NMFS and the COE on the potential effects of ash, utilizing several bioassay systems. The agencies evaluated three juvenile salmonid stocks, spring and fall chinook salmon from hatcheries, and wild-stock sockeye salmon (*O. nerka*) smolts. The fish were tested at a NMFS laboratory located at the Bonneville Dam.

The fish were acclimated to Columbia River water and tested in varying concentrations of ash and water-soluble components of ash by static and simulated river condition tests. The reader is referred to Newcomb and Flagg (1983) for experimental details and methodology. Columbia River water was used, in conjunction with ash that fell near a collection facility on the Snake River. The ash particles ranged in size from 5 to 100 µm and consisted mainly of angular materials.

Newcomb and Flagg (1983) determined that in very large concentrations, airborne ash delivered to still waters could cause mortality to juvenile spring chinook salmon. In static bioassays, concentrations considered lethal were in the 10- to 25-percent per volume range (volume of ash to volume of water), with exposure time inversely related to ash concentration.

However, according to Newcomb and Flagg (1983, p. 10–11):

> Volcanic ash insults of 5 percent and below by volume were not harmful to juvenile spring chinook salmon within 24 hours. Since 5 percent by volume is equivalent to 6 inches of ash falling over a 10-feet water column, most airborne volcanic ashfalls should not cause acute mortality to salmonid stocks in still water.

Fish were tested by Newcomb and Flagg (1983) to assess the danger of suspended ash in river systems. The authors concluded, through dynamic bioassays using suspended ash, that lower concentrations of ash (less than 0.5 g/L [grams per liter]) were not lethal to the juvenile salmonids when the fish were exposed for 36 hours. Higher concentrations (greater than 6.1 g/L) of ash were considered hazardous to these fish and would be equivalent to concentrations occurring in river systems carrying a high suspended load of ash. In other terms, mortality modeling showed the LC_{50} equaled 6.1 g/L at 36 hours at 15–17°C. The LC_{50} concentration is the concentration of material that will cause a 50 percent mortality in the fish population exposed to the constituent being tested. High concentrations of ash (greater than 34.9 g/L) were considered to be catastrophic to fish. It is not likely that such high concentrations of ash occurred in the Columbia River system.

Newcomb and Flagg (1983) attributed fish mortality, observed in their experimental bioassays, to blockage of osmoregulatory surfaces by ash and mucus. The authors also performed autopsies on the salmonid fish that died during the course of experiments utilizing high suspended volcanic ash concentrations. According to Newcomb and Flagg, (1983, p. 11):

> The gills of dead fish were uniformly coated with ash particles and mucus, and live fish in the high ash concentrations appeared lethargic. There was no gross evidence of abrasion or hemorrhage of the gill filaments. *** This suggests impaired oxygen exchange as the primary cause of death.

The authors speculated that under experimental conditions the particles of ash caused problems for fish—rather than the soluble chemicals associated with the ash. The authors monitored the Toutle-Cowlitz and lower Columbia River systems and stated that potentially harmful concentrations (6.1 g/L) may have occurred for an undetermined length of time shortly after the major volcanic eruptions. The Toutle River, on the other hand, most likely experienced prolonged exposure to such concentrations of ash (see subsection titled "Toutle River").

Columbia River Estuary

The volumes of mud and ash delivered to the Columbia River system raised concerns that associated trace elements could adversely affect aquatic organisms in the Columbia River Estuary. Brzezinski and Holton (1983) reported that in the estuary, volcanic debris was deposited in a layer ranging from 0.2 to 4.5 inches deep. In the shallow water, the debris depth averaged 1.8 inches. Hubbell and others (1983, p. J3) cite mass-balance computations, based on radioactivity measurements, which indicated that before the eruption extremely fine materials could become permanently deposited in the estuary. About 30 percent of such sediment material consisted of particles finer than 0.002 inch. According to Hubbell and others (1983, p. J3–J4):

> [The] current and bottom-sediment transport patterns suggest that little, if any, sand or coarser sediment leaves the estuary, except possibly during extreme upland-flow or storm events***.

The authors thought the massive post-eruption influx of debris and sediment could have had important ecological consequences in the estuary. Several groups of researchers addressed these concerns by studying trace metals in estuarine waters and by investigating the possible declines in primary production rates.

A scarcity of pre-eruption chemical data for soluble and seston-associated trace metals for post-eruption sampling sites in the estuary made it difficult to draw definitive conclusions about eruption effects; however, several reports deal with these topics.

The Columbia River Estuary was sampled from May 21 to May 30, 1980, shortly after the eruption, by Riedel and others (1984, p. 340). The authors considered their samples fairly representative of the whole estuary, although the samples were taken from sheltered environments rather than from channels. The authors considered that effects of wind and current, coupled with the generally brief residence time of estuarine waters, would lead to a fairly thorough mixing of water in the estuary. Riedel and others (1984, p. 344) reported that soluble manganese concentrations ranged from 8 to 170 µg/L in the estuary after the eruption. Suspended concentrations of manganese, during the same period, ranged from 6 to 252 µg/L. The distribution of soluble manganese in the estuary was related to salinity, and the largest concentration (170 µg/L) was associated with a salinity of 2.6 ppt (parts per thousand). Depending upon the location of the sampling station, salinities recorded during the sampling period ranged from 0.0 to 13.1 ppt; this observation agrees with the findings of mid-estuarine enhancement of manganese by other researchers. According to Riedel and others (1984, p. 344), "*** the highest concentrations reported here are about twice the highest values ever reported for the Columbia River Estuary***." Compared to reports of manganese concentrations in the ash, sediments, and freshwaters, this finding is consistent. The authors attributed the increased estuarine manganese concentrations to leaching from materials delivered to the Cowlitz and Columbia Rivers, based on observations and laboratory experiments performed on leaching chemical elements from volcanic ash.

Concentrations of soluble iron in the estuary ranged from 5.7 to 35.5 µg/L, reported Riedel and others (1984, p. 344–345). At that same time, concentrations of suspended iron ranged from 0.3 to 14.1 µg/L. According to the authors, the concentration of iron in the estuary decreased with increasing salinity, which is comparable to data reported for other estuaries. The range of iron concentrations reported by the authors was not considered elevated or unusual for the Columbia River Estuary. This data, at first glance, appears to be contrary to information concerning iron concentrations in ash and freshwater; however, the largest concentrations of iron in freshwaters were reported in conjunction with anaerobic conditions, which helps explain differences between freshwater and saline-water data.

In the estuary, post-eruption concentrations of soluble copper ranged from 0.8 to 2.0 µg/L, and post-eruption concentrations of suspended copper (after acid digestion) ranged from 1 to 43 µg/L (Riedel and others, 1984, p. 344). Compared to manganese concentrations that correlated with salinity, copper concentrations were not as dependent on saline concentration. According to Riedel and others (1984, p. 344), "[The copper concentrations were only] somewhat higher than those previously reported for the Columbia River Estuary ***." As in the case of manganese, the authors attribute increased estuarine concentrations of copper to leaching from debris deposits.

Seston is the plankton group of tiny plants and animals that float, drift, or swim in the water column. The term also includes living plankton and inanimate particulate matter found suspended in the water column. The authors measured concentrations of seston and correlated concentrations of chemical elements within the seston. Estimates of the concentration of seston ranged from 10 to 490 mg/L, based on quantitative techniques related to concentrations of suspended particulate aluminum (Riedel and others, 1984, p. 345). In addition, an unknown quantity of materials affecting the estimates was probably deposited in the estuary, after being carried there as bed load from the Columbia River. Comparing their data to mean elemental compositions of Mount St. Helens ash, mean continental crustal abundance, and pre-eruption values reported for Columbia River Estuary seston and sediments, the authors concluded that the elemental composition of estuarine seston resembled airborne-volcanic ash and the mean-continental crust. Riedel and others (1984, p. 345) stated:

> [The elemental composition is, therefore,] distinct from previously reported sediments and seston from the Columbia River Estuary [during this sampling period].

The authors did not find elevated soluble concentrations of iron, zinc, nickel, cadmium, or lead in the water, although they report high levels of these constituents in seston. According to Riedel and others (1984, p. 347):

> [The] trace-metal concentrations present in the Columbia River Estuary in the period following the eruption of Mount St. Helens posed no serious threat to the estuary ***.

Manganese concentrations the authors observed have been considered to be nontoxic in other estuaries. The elevated copper concentrations might have been inhibitory to phytoplankton at reported levels if complex-forming organics were absent. However, such organics are found in the estuary, so the toxic effect should not have been of a magnitude inhibitory to phytoplankton.

The sand, ash, and volcanic debris carried to the Columbia River Estuary caused an enormous increase in turbidity. Upstream from the estuary, millions of cubic yards of material had been deposited in the Cowlitz and Columbia Rivers. Water contacting this material, it was estimated, would have reached the estuary in 2 days or less. According to Riedel and others (1984, p. 347), who used various USGS data in making their calculations, the flow of the Columbia River ranged from 6.5×10^4 to 4.3×10^5 cubic feet per second during the period of increased light attenuation. Riedel and others (1984, p. 347) calculated that water flowing downstream to the estuary in the Columbia River "* * * had interacted with approximately 40 g/L of volcanic debris." According to Frey and others (1983, p. 213), the entire estuary contained greatly elevated concentrations of suspended-particulate material.

Frey and others (1983) studied the estuary's pre-eruption water-column primary production during April 9–11, 1980, and conducted post-eruption investigations during May 22–24, 1980, and July 22–24, 1980, which enabled the authors to estimate effects of the eruption on primary productivity rates. Frey and others (1983, p. 213), had:

> *** shown that light attenuation in the water column is one of the most important factors in determining the amount of primary production taking place in the water column.

The decreased depth of light penetration in the estuary affected photosynthetic rates of phytoplankton during the period of abnormally high turbidity, which lasted approximately 5 weeks. According to the authors, light attenuation caused by SPM reduced the rate of photosynthesis by about 75 percent. Frey and others (1983, p. 213) made this estimate by comparing:

> *** measured and estimated rates of carbon assimilation with and without the post-eruption turbidity*** [through calculations of primary production rates obtained by measuring carbon-14 uptake].

Primary biomass was assessed by a variety of techniques, and the reader is referred to the report by Frey and others (1983) for information regarding the authors' methodology and assumptions.

Information and estimates on the following parameters were available to Frey and others (1983) when making their calculations and drawing conclusions: light attenuation coefficients, 1-percent light depth, chlorophyll *a*, concentration of total seston, inorganic seston, organic seston, particulate carbon, and particulate nitrogen. The mean pre-eruption 1-percent light depth was 10.2 feet, whereas the mean post-eruption 1-percent light depth during May 22–24, 1980, was 1.6 feet. The mean pre-eruption concentration of chlorophyll *a* was 4.8 mg per cubic yard, whereas the mean post-eruption concentration was 9.6 mg per cubic yard during May 1980, and 9.0 mg per cubic yard in July 1980. According to Frey and others (1983), despite a greatly diminished rate of primary production in the estuary, the total amount of particulate carbon available in estuarine water remained high due to the influx of phytoplankton from the Columbia River. Frey and others (1983, p. 217) stated:

> That chlorophyll *a* concentrations were not depressed in May–July 1980 is a result of the large biomass present in the water imported from the Columbia River and the relatively short residence time of phytoplankton in the estuary. That there was not a phytoplankton population crash induced by high levels of turbidity below river mile 68, is evidence that phytoplankton biomass concentrations in the Columbia River Estuary are mostly a function of import from the Columbia River, rather than a function of *in situ* production.

The authors suggested that primary food supplies were not greatly reduced, because lost carbon production on any given day was estimated to be only 2 percent of the total carbon flux. The estimate was based upon calculations involving concentrations of organic seston, chlorophyll *a*, particulate carbon, and particulate nitrogen values. According to Frey and others (1983, p. 217), the concentrations of these various constituents were larger immediately following the eruption on May 18, 1980, compared to data from earlier and later cruises. The authors considered the observed concentrations as evidence that the eruption added suspended sediment containing large amounts of organic matter to the estuary.

According to the authors, the greatly increased suspended-particle load might have had unknown or unidentified effects on the estuary's higher trophic levels or on the mobility and movements of chemical constituents within the food chain.

Increases in turbidity during the fall and winter of 1980 were not observed (Frey and others, 1983, p. 217). During this period, heavy rains might have been expected to add suspended sediment to the river. The sediments would have been derived from eroded material deposited by the eruption. The lack of historical data for turbidity in the estuary made it difficult to assess the effects of runoff; however, the authors stated that data indicate no increase in turbidity comparable to that observed immediately after the eruption.

Because of its importance as a nursery area for various marine organisms, there were concerns that ash influx and increased sedimentation in the Columbia River Estuary might adversely affect fish reproduction and hatching or the survival of larval fish. Boehlert and others (1983, p. 2–5), who were cognizant of these possible detrimental effects, focused research on the effects of suspended ash upon early life stages of the Pacific herring *(Clupea harenqus pallasi)*. This fish species has important commercial value and also provides food for other fish. Pacific herring have a wide range and spawn in Oregon and Washington estuaries from January through early May. The Pacific herring is a normal inhabitant of the Columbia River Estuary; after hatching, larvae feed and develop in the estuary through the juvenile stage. There were concerns that delicate larval tissues of such fish might be affected by increased sedimentation or ash. The loss of salmonids in the Toutle River and in other rivers due to various effects has been documented and is discussed elsewhere in this report. Researchers regarded larvae to be even more susceptible than adult fish to suspended ash or sediment. In addition to tissue damage, other more subtle effects might ultimately affect fish survival. Such effects might include behavioral factors such as habitat selection or feeding and avoidance behavior.

Factors affecting the survival of fish eggs and larvae were discussed by Boehlert and others (1983, p. 2–5). The Pacific herring deposits adhesive demersal eggs in the lower Columbia River Estuary. (A demersal egg is a heavy egg which tends to sink. The adhesive demersal egg is typical of fish spawning in estuaries.) Adult fish and eggs were obtained from Yaquina Bay, and laboratory fishery-spawned fish were used in experiments. Volcanic ash from Moses Lake, Washington was used, and estuarine sediment was collected from Yaquina Bay, Oregon. The reader is referred to the report by Boehlert and others (1983) for details on experimental methods, specimen collection and maintenance, and volcanic ash; the report contains an extensive discussion of different facets of the experiments conducted. For the sake of brevity, only the conclusions are presented in this report.

According to Boehlert and others (1983, p. 61), in static experimental systems where suspended solids were allowed to settle upon eggs, the mortality of eggs was related to suspension concentrations. Mortality approached 100 percent at high concentrations. The authors attribute mortality of eggs to smothering effects and a lack of dissolved oxygen. In these experiments, Boehlert and others (1983, p. 61) observed a general lack of development, and "grey, particulate yolk, and cessation of growth of the embryos." However, increasing concentrations of sediment or ash did not result in deformed, hatched, larvae. The authors considered environmentally realistic concentrations of suspensions of either ash or sediment to have the most potential for damage to the egg stage. The possibility of smothering might have led to a higher mortality in the lower Columbia River Estuary.

Dynamic experiments, which minimized smothering effects by maintaining suspensions of ash or sediment, showed that egg development or mortality was not a function of suspension concentration. According to Boehlert and others (1983, p. 62):

> [The data] suggests that abrasion was not a problem for the egg chorion, which is generally thick in species with demersal eggs and therefore resistant to mechanical damage.

Such was the case, even though the eggs had been covered by a fine layer of either sediment or ash.

Based on these dynamic experiments, Boehlert and others (1983, p. 67) concluded that for the Columbia River Estuary, "[it is unlikely that] significant smothering and resultant embryo mortality will occur with the exception of very localized dredging areas."

Developing embryos did not appear to be affected more by ash than by sediment, in terms of abrasion of tissues. As long as the water remained well-oxygenated, mortality rates of developing embryos, which were attributed to either abrasion or gas exchange, did not appear to be related to concentrations of either ash or sediment.

The work of Boehlert and others (1983, p. 64), on newly hatched yolk-sac larvae of the Pacific herring, was unique because there was little or no published research on the effects of either sediment or ash on histological features of these young fish. According to Boehlert and others (1983, p. 64):

> [Research does] show that epidermis [at the fin fold] is in significantly poorer condition, apparently from abrasion, in both dorsal and ventral areas for volcanic ash and in the dorsal area only for estuarine sediment.

This damage could be seen in larvae exposed for 24 hours to suspensions of materials and subsequently moved to clear water after the 24-hour-exposure period. The damage appeared to be greater with ash than with estuarine sediment. Although sediment could cause such histological changes, Boehlert (1984, p. 113) stated: "[The] effects of volcanic ash, however, occurred at lower concentrations and were of greater magnitude than those of sediment." According to the author, during the first 24 hours of exposure, no differences in mortality were exhibited when the presence or absence of a heartbeat was utilized as a criterion of survival. Only after larvae had been moved to clean water and observed for several days could tissue changes be seen. Boehlert (1984, p. 124) stated:

> Since all of the larvae were alive at the time of preservation, the damage noted probably represents a sublethal effect which would probably have resulted in later mortality.

The author discussed the concept of the critical period for small larvae related to their poor swimming ability and inability to find food. High densities of food are required for young larvae, and turbidity could affect critical visual orientation perceptions necessary for survival. Boehlert and others (1983, p. 65–66) reported a unique and somewhat surprising finding:

> In both semi-static and continual suspensions of both estuarine sediment and volcanic ash, low suspension levels actually increased feeding rates *** and the percentage of larvae feeding. ***We believe that this result is based upon the enhanced visual contrast allowing the larvae to better visualize the prey.***
>
> It is significant to note, however, that relatively high levels of ash or sediment were necessary to reduce the feeding to levels observed in the controls.

In summary, according to Boehlert and others (1983, p. ii): "Overall, the effects of volcanic ash and estuarine sediment were not severe upon herring larvae at environmentally realistic suspension concentrations." However, Boehlert (1984, p. 113) stated: "In upriver locations characterized by higher suspended particulates, delicate larvae of other species may suffer epidermal damage."

The Lewis River Drainage System

According to Cummans (1981, p. B4):

> [The Muddy River system drains] most of the eastern slope of Mount St. Helens before flowing into the Lewis River 1 mile upstream from the [Swift] reservoir. Pine Creek heads on the southeast summit of Mount St. Helens, and flows southward into the Lewis River, entering about one-half mile upstream from Swift Reservoir.

Collectively, the Muddy River, Pine Creek, and other tributaries flowing to Swift Reservoir drain about 10 square miles from higher elevation slopes of Mount St. Helens. The Lewis River system drains a total of 480 square miles at Swift Reservoir.

After the eruption, upper stream valleys of the Muddy River were scoured by mudflows that had moved down Smith and Pine Creeks. In the stream valley of the Muddy River's lower reaches, some trees survived; but hundreds of logs choked much of the river. The mudflows, stated Cummans (1981, p. B4), "deposited about 11,000 acre-feet of water, mud, and debris in Swift Reservoir." Average inflow to the reservoir was estimated to be as great as 60,000 ft^3/s; during this period the reservoir's water surface rose 2.6 feet.

According to Franklin and others (1988, p. 19), floods helped clear out large amounts of debris in some rivers; however, in the case of the Lewis River and the Muddy River drainage basin, reservoirs prevented transport of debris out of the system. Swift reservoir impounded logs and other organic debris drifting down Smith and Pine Creeks and the Muddy River. Opinions differed regarding the necessity to remove debris, because in terms of providing habitat diversity, some scientists regarded debris to be useful—particularly for salmonids.

Pre-eruption surveys conducted during Fuste's (1981) investigations on benthic invertebrate samples included sites on the Muddy River and Pine Creek drainage basins. The Muddy River, which merges with the Lewis River, was designated by Fuste' (1981) as a first-order stream. Muddy River has a gravel-armored streambed and possesses a medium gradient (characterized as slopes between 0.038 feet and 0.049 feet). At a sampling site located on the Muddy River near the confluence of Smith Creek, streambanks were characterized as fairly stable. Riparian vegetation in this area consisted of dense coniferous forest. Unfortunately, other pre-eruption Muddy River stations sampled by Fuste' during March 1980 were no longer usable after the May 18, 1980, eruption, because they had received excessive amounts of fine suspended sediment.

Some water-chemistry analyses were conducted, and changes in the Muddy River included increased suspended fractions of sulfate, chloride, aluminum, manganese, boron, and iron (Fuste', 1981).

Research on benthic invertebrates was performed in the Muddy River, and during pre-eruption sampling (March 28–30, 1980) 21 taxa were identified from the total of 795 organisms collected. The pre- and post-eruption relative abundances of various benthic invertebrates for the Muddy River are shown in table 13.

The pre-eruption population consisted mainly of genera belonging to the orders Ephemeroptera (mayflies) and Diptera (two-winged flies). The mayflies were mainly species of the genus *Baetis,* in the family Baetidae. In contrast to populations at other sampling stations distributed throughout the study area, such as the Pine Creek station (51.1 percent of the pre-eruption population were members of the Ephemeroptera), there were few representatives of the genus *Iron.* The members of the Diptera were predominantly larvae of the family Chironomidae (midges). After the eruption, the surviving population was small, and the few organisms collected belonged to only two taxa. Pre- and post-eruption populations varied substantially from one stream site to another. The reader requiring comparative data should refer to the report by Fuste' (1981). The information in table 13 is an example of one data set for Pine Creek, at a location just above the confluence of Pine Creek with the Muddy River.

According to Fuste' (1981, p. H11), the pre-eruption Muddy River sample site was characterized by a succession of pools and riffles. After the eruption, however, the stream had more riffles and a large concentration of suspended sediment accompanied by substantial quantities of fine bed material. Such changes in the stream's physical characteristics were typical of sites studied by Fuste' (see subsection titled "Toutle River"). According to Fuste' (1981, p. H11), the average thickness of bed material transported downstream in Muddy River ranged from 3 to 9 inches, "*** making the stream-bottom substrate extremely unstable for a person to stand in the middle of the stream." Such conditions were generally unfavorable for benthic invertebrates; because the turbidity adversely affected the growth of algae on rocks, quantities of the usual food source for benthic organisms decreased. Fuste' (1981, p. H11) speculated that it may be years before the altered streambeds return to pre-eruption conditions:

> [and] successful recolonization of the stream benthos will depend principally on substratum stability followed by improvement of the chemical quality of the stream water.

Table 13. Relative abundance of benthic invertebrate populations in the Muddy River and Pine Creek before and after the eruption of May 18, 1980
[From Fuste' (1981, p. H8). --, not detected]

Order	Relative abundance (percent)			
	Muddy River		Pine Creek	
	Pre-eruption (March 1980)	Post-eruption (July 1980)	Pre-eruption (3/28/80–3/30/80)	Post-eruption (7/27/80–7/29/80)
Ephemeroptera	14.2	--	51.1	1.1
Plecoptera	.6	--	2.3	--
Trichoptera	.6	--	5.7	--
Diptera	76.9	100.00	33.3	98.6
Acari	.2	--	1.3	--
Others*	.1	--	6.3	.7

* Includes Cladocerans (water fleas), flatworms, snails, and roundworms

Empirical field observations of the eruption's ecological effects prompted investigations on the influences of ash transport and deposition on benthic algal biomass, on benthic invertebrates, and on the disruption of relations in the food chain. Such research utilized experimental simulations in addition to field studies. A synopsis of the research performed by Milligan and others (1983, p. 1) is presented in conjunction with these discussions regarding the Muddy River, because it closely relates to the research and conclusions of Fuste'.

Milligan and others (1983) recognized the importance of detritus to the community structure of lower order streams like the Muddy River, because such small headwater streams usually derive much of their energy source from allochthonous inputs of organic matter like leaf litter. Fuste', recognizing limitations of the continuum concepts of stream ecosystems, nonetheless commented that headwaters are typically dependent on such terrestrial inputs of coarse particulate organic matter (CPOM). The author described CPOM-feeding invertebrate organisms, such as shredders and detritivores, and considered these collectors to be the most plentiful macroconsumers (Fuste', 1981, p. H5).

Milligan and others (1983, p. 120) conducted field and laboratory research designed to study effects of volcanic ash on stream microhabitats and primary and secondary production in streams. In controlled laboratory experiments, the authors (Milligan and others, 1983, p. 120) determined that catastrophic and chronic low-level infusions of ash to streams, "*** initially suppressed attached benthic algae standing crops and chlorophyll '*a*' levels." When insects characterized as leaf-shredders, such as stoneflies (*Pternonarcys californica*) and caddisflies (*Hesperophylax occidentalis*), were subjected to simulated post-eruption ash suspension levels for periods lasting 2 weeks, the insects reduced their food consumption by one-half. According to Milligan and others (1983, p. 120–122), other findings included:

> Simulated ash injection into the experimental channels at levels comparable to the May 18 [1980] volcanic deposition in northern Idaho caused a catastrophic increase (4 times) in insect drift and a moderate to large decrease in standing crop at or near the point of impact. ***The mean density of the principal insect species during the 3 weeks of the impact test was reduced to approximately half that in the control channel. Within 1 week following the simulation test, overall numbers of drifting insects were similar in the test and control channels. However, the settle-out rate from drift in the impacted channels was substantially reduced (one-third) compared to the control channel. After 3 weeks, the settle-out rate in the impacted channel had returned to normal. ***The results obtained clearly indicate catastrophic influences of volcanic ash on attached benthic algae biomass and the dislocation of invertebrates and interruption or inhibition of food chain relationships. While the extreme presence of suspended ash was only apparent for a few weeks in natural streams the depositional presence was apparent much longer.

Although the authors described moderate to severe impacts on selected populations, they emphasized that various principal species tested exhibited substantial resilience and could recover over a period of time. Examples cited include the stonefly *Pteronarcys californica*, and the caddisfly *Hesperophylax occidentalis.* According to Milligan and others (1983, p. 121):

> One can infer that single, catastrophic events***did not cause the demise of primary and secondary production elements normally characteristic of healthy community structure, but produced a pronounced, albeit short-term oscillation over time.

The authors were of the opinion that minimal long-term effects on the stream ecosystem could be expected. No complete consensus regarding the possible duration of eruption effects existed among the various researchers.

One year after the eruption, Milligan and others (1983, p. 120) studied the natural effects of ash on streams by sampling the Palouse River in Washington. The sampling reach had received ashfall and would presumably have exhibited changes in biological populations. The authors found that algal and aquatic insect populations were diverse and abundant and:

> [were] distributed in a manner indicative of streams in the region unimpacted by the May 18 [1980] eruption. We conclude that 1 year after the catastrophic eruption, the stream environment in the reach studied had nearly fully recovered from the event [Milligan and others, 1983, p. 120].

Algal communities of streams and springs were studied after the eruption by Rushforth and others (1986, p. 129), who sampled the Muddy River on October 21, 1981. The authors attempted

to characterize eruption effects upon aquatic floral assemblages and to describe the succession of organisms colonizing (or recolonizing) impacted streams. The authors employed various statistical techniques to determine patterns of species distribution and association. Many of the streams contained few visible algae during 1980 and 1981, and diatoms were the dominant algal forms. Collectively, for all streams sampled, the authors reported 24 algal taxa excluding diatoms, whereas a total of 132 diatom taxa were identified. Samples collected from the Clearwater and Muddy Rivers and from Ape Creek were representative of areas with complete or nearly complete destruction of the surrounding terrestrial environment. All were in the blast zone. Reference sites that received ash but were not considered to be in the blast zone were located on Elk, Clear, Lake, and Yellowjacket Creeks. In terms of estimated algal abundance, the Muddy River was considered similar to the upper and middle reaches of the Clearwater River and Elk, Yellowjacket, and Ape Creeks. In terms of the relative density of diatoms, the authors grouped the Muddy River with the Clearwater River and with Elk Creek. Similar groupings based upon the presence or absence of diatom taxa emerged. The Muddy River's dominant diatom taxa included the species *Achnanthes minutissima, Achnanthes lanceolata,* and *Cymella minuta.* Other research cited by Rushforth and others (1986, p. 134) characterized *Achnanthes minutissima* as a species often dominating the flora of disturbed stream sites, whereas *Achnanthes lanceolata* seemed to dominate undisturbed sites. The recolonization of streams involving *Alchnanthes minutissima* was also reported; generally, a pattern of algal succession was initiated by diatoms and followed by various blue-green algae or perhaps some green algae. When the authors returned to sample the Muddy River in October 1981, the stage of diatom recolonization had been developing. However, according to Rushforth and others (1986, p. 135):

> Although the diatom recolonization stage was well developed at many Mount St. Helens sites following the eruption, later successional stages noted by other authors were generally absent. Neither the reference or blast-zone sites demonstrated a diatom-green algal and/or diatom blue-green algal association similar to that reported following some weeks of succession by others. The majority of the sites were dominated by diatoms and contained few other types. *** Such conditions likely represent an early seral stage of succession.

The authors observed that algal cells colonized streams and communities developed, provided that appropriate substrata were available. According to Rushforth and others (1986, p. 136):

> [Stream segments with substrates composed of] shifting tephra and debris [were essentially] inhospitable to algal colonization ***. Continual perturbations from scouring and stream channel instability resulted in the establishment of more or less truncated pioneer communities.

In general, the authors concluded that the algal communities in the Mount St. Helens streams studied were poor in the number of species, especially nondiatom algae. The species *Achnanthes minutissima* found in the Muddy River was typical of most streams.

The Klickitat River and Yakima River Drainage Systems

The Klickitat and Yakima Rivers are tributary to the Columbia River and lie east of Mount St. Helens. The two rivers and their respective tributaries received varying amounts of ashfall, and Klein (1984) related the magnitude of observed effects on these rivers to patterns of ashfall. According to the author, dilution from tributaries receiving little or no ash was a major factor affecting changes in chemical constituents of the river. For discussion purposes, Klein (1984) grouped river systems according to a river's location and distance from the volcano. Ahtanum Creek, a tributary of the Yakima River, and the Klickitat River are located in areas that received heavier ashfall than the Yakima River. The Yakima River lies farther east of the volcano and received a smaller volume of material. The author described progressively diminished eruption effects when analyzing rivers and streams farther away, in an eastward direction, from Mount St. Helens.

Klickitat River

Klein (1984, p. 4) compared data from two stations on the Klickitat River: one near Glenwood, Washington (upstream station), and another near Pitt, Washington (downstream station). The station near Glenwood is near the headwaters of the Klickitat River, which according to Cushing and Smith (1982, p. 527) received about 0.8 inch of ash. At the Glenwood site, the amount of ashfall received was not diluted by downstream tributaries—as was the case

for the station near Pitt. There was ample pre-eruption data for these sites, and Klein obtained post-eruption samples during the period May 18 to September 17, 1980, from the Klickitat stations. The author described changes in chemical concentration as a function of time after the eruption. For the Klickitat River near Glenwood (upstream station), Klein reported relatively minor changes in the cations sodium, calcium, and potassium. After the eruption, the concentrations of bicarbonate, carbonate, sulfate, and chloride were appreciably increased (Klein, 1984, p. 6). The elevated concentrations of the anions were of relatively short duration, and by May 29, 1980, the chemical composition of the water had returned to pre-eruption levels.

Data from the Pitt station was particularly useful, because the station's long history as a sampling site enabled Klein to construct time-series plots covering a 3-year span. The chemical composition of Klickitat River water at the downstream Pitt station was not altered on May 18, 1980, and changes in composition were not detected until the following day. According to Klein (1984, p. 10), the pH of water at the Pitt station historically ranged from 6.5 to 8.3. The author reported a decrease in the pH after a March 27, 1980, eruption that caused a small amount of ash to be distributed in the basin. The pH 6.5 observed after the minor eruption was a pronounced change from the pH values greater than 7 recorded before the ashfall —a unique case in which river system data directly reflected a change in pH attributable to ashfall. However, the decrease in pH was of short duration, and pH rapidly returned to pre-eruption values.

On May 19, 1980, Klein (1984, p. 6) reported an increase in concentrations of chloride and sulfate. According to Klein (1981, p. 724):

> The increase in sulfate, although significant, did not exceed previous high concentrations. The chloride increase noted in the May 19 [1980] sample was notably greater than in pre-eruption and other post-eruption samples.

According to the author, the increased concentrations correspond to ash that provides a source of soluble chloride and sulfate compounds. The increase in chloride and sulfate was short-lived, and according to Klein (1984, p. 6–7):

> [By] May 20, [1980,] the anion composition had shifted back toward the normal pre-eruption percentages, and subsequent samples confirmed that the composition returned to the normal ranges.
>
> The cation composition failed to vary to any measurable extent, probably because the percentage composition of soluble cations in the ash***was not substantially different from that of the native waters.

Time-series plots by Klein (1984, p. 6–7) show increases in total nitrogen, total organic nitrogen, turbidity, and specific conductance. The post-eruption samples contained concentrations of these characteristics well above those observed during the 2 preceding years. According to Klein (1984, p. 9), there appeared to be a correlation between nitrogen and particulate material in the water, based on observed nitrogen and turbidity values. Further evidence of this relation between nitrogen and turbidity was provided, when peaks in concentrations of organic and total nitrogen occurred June 12–13, 1980. Another minor eruption of the volcano at that time dispersed more ashfall, and water turbidity at Pitt station rapidly increased. Total nitrogen concentration increased and peaked during the same time period. Cushing and Smith (1982, p. 530) stated that the concentration of dissolved inorganic nitrogen briefly increased after the eruption of June 12, 1980—which agreed with the findings of Klein (1984).

The total recoverable concentrations of iron, manganese, and aluminum increased, according to Klein (1984, p. 23–24), "***5 to 50 times at the ash-affected stations on the Klickitat River and the North Fork Ahtanum Creek." The concentrations of dissolved and total recoverable iron reached maximum levels on May 19, 1980, when 70 μg/L of dissolved iron and 4,200 μg/L total recoverable iron were measured. The concentrations of dissolved and total recoverable manganese peaked on the same date. Similarly, on May 19, 1980, the concentrations of dissolved and total recoverable aluminum reached maximum levels (70 μg/L and 3,100 μg/L, respectively). According to the author, the length of time that increased metal concentrations were observed varied greatly, depending upon the river system studied. The Klickitat River station at Pitt was affected only by ashfall, and periods during which metal concentrations were elevated were brief. In contrast, elevated levels of total-metals at the Toutle and Cowlitz River stations, which had been affected by mudflows, persisted until the end of June 1980. In summary, Klein (1984, p. 25) stated:

> In the ash-affected basins east of Mount St. Helens, the observed river quality changes were short lived and, in general, decreased in magnitude with distance from the volcano.

According to Cushing and Smith (1982, p. 530–533), the Klickitat River exhibited increased concentrations of dissolved organic nitrogen, correlated with increased turbidity, after the May 18, 1980, and June 12, 1980, eruptions. According to Klein (1984, p. 9–10), organic nitrogen was most likely related to the pyrolysis of forest materials that generated vaporized organic compounds. Klein proposed that vaporized organic compounds subsequently condensed and became attached to particles of ash, which were dispersed in the plume of ash. Klein (1984, p. 10) stated:

> Organic carbon concentrations in ash samples tend to confirm this. For the short term, organic nitrogen conveyed by ash into water would stay attached to ash particles. With time, dissolution, mineralization, and nitrification of this nitrogen would shift the nitrogen species dominance toward dissolved nitrate.

The elevated concentrations of nitrogen and increased turbidity were of short duration in the Klickitat River at Pitt station and returned to historically normal values by July 1980.

Cushing and Smith (1982) studied the impact of varying amounts of ashfall on lotic algae and caddisflies (Trichoptera) in the Klickitat River system. The author compared findings in the Klickitat River to findings in the Cispus River system. (See Cispus River, this report.) The Cispus River system received more ashfall than the Klickitat River. In other words, the author sought differences in productivity attributable to varying amounts of ashfall, and the Klickitat River represented a control system, which should not have been affected as much as other streams in the study. After the eruption, the author sampled the Klickitat River about 6.2 miles upstream from its mouth (the Klickitat River merges with the Columbia River near The Dalles, Oregon).

According to Cushing and Smith (1982, p. 537), the filamentous green alga *Cladophora,* which normally forms floating masses, was plentiful on rocks in the Klickitat River. By August of 1980, the *Cladophora* could still be found, but stones in the river also were colonized by species of *Nostoc* and *Nitella*. However, a lack of related baseline chemical data, such as information on concentrations of transport (seston) chlorophyll *a* and periphyton chlorophyll *a*, made it difficult to interpret algal responses to chemical effects of ash. According to Cushing and Smith (1982), the macroinvertebrate populations of caddisflies were larger in the Klickitat River than in the Cispus River. In August and July of 1980, samples of caddisflies represented a varied species composition, with abundant numbers of individuals comprising each species. Cushing and Smith (1982, p. 537) stated:

> The most common species were *Hydropsyche occidentalis, Dicosmoecus gilvipes, Brachycentrus occidentalis,* and *Rhyacophilia valuma.* These organisms did not appear to be adversely impacted by the ashfall.

In general, the author considered the level of productivity in Klickitat River to be greater than in the Cispus River.

Yakima River

The Yakima River Basin is the major river system of central Washington. According to Faulconer and Mongillo (1981, p. 2):

> The Yakima River arises in the Cascade Mountains at an elevation of 2,448 feet above sea level and flows southeasterly for about 215 miles into the Columbia River near Richland, Washington. It drains an area of about 6,000 square miles.

The Yakima River Basin received large amounts of ashfall, and according to Faulconer and Mongillo (1981, p. 1), ash depth in the Yakima and Ellensburg area ranged from 0.12 to 0.75 inch. The Yakima area received an average of 0.50 inch of ash, which is equivalent to 10.3 tons per acre.

Two sites on the Yakima River, Union Gap and Kiona, were studied by Klein (1984, p. 11–13). Long-term pre-eruption data for the two stations were available, "[and the sites were selected for additional] intensive sampling to document water-quality changes caused by volcanic activity." Changes in water chemistry at Union Gap were not as pronounced as changes reported for North Fork Ahtanum Creek, a tributary receiving more ashfall. Klein (1984, p. 11) attributed the diminished chemical effect at the Union Gap and Kiona sites to dilution by tributaries draining areas that received little ash and stated:

> Sulfate, chloride, and dissolved solids concentrations varied sharply over a short period of time, and the changes were small when compared with seasonal variations; however, they are detectable ***.

Although the anion concentrations did not change appreciably, Klein (1984, p. 12) stated:

> By contrast, the total nitrogen and organic nitrogen concentrations and turbidity values ***increased dramatically. Of further interest, the total nitrogen concentration was primarily organic nitrogen immediately after the eruption, whereas in preceding years, organic nitrogen constituted only about 50 percent of the total nitrogen concentrations.

According to Klein (1984, p. 112–113), the water-chemistry changes for the Yakima River at Kiona, although apparent on time-series plots, were somewhat delayed and short in duration. The author reported dramatic changes in turbidity, total nitrogen concentration, and a significant elevation in the dissolved chloride concentration. The maximum turbidity was recorded June 19, 1980; however, the concentration of dissolved solids had decreased by this time. Klein (1984, p. 14) proposed that precipitation dilution effects, in conjunction with the erosion of ash from areas adjacent to the river, might have accounted for these observations. Post-eruption concentrations of total nitrogen increased, but organic nitrogen levels were lower than levels reported at other sites. Prior to the major eruption on May 18, 1980, the total nitrogen component already had begun to increase, and the concentration did not reach a maximum level until June 25, 1980—more than a month after the eruption. Klein (1984, p. 14) speculated: "[This nitrogen] component may have a lag time in this river system." The author also reported increased concentrations of dissolved sulfate and dissolved solids; however, the peak levels were lower than previously reported maxima for the Kiona station.

Klein (1984) discussed water chemistry in the North and South Forks of Ahtanum Creek, a Yakima River tributary that lies farther east of Mount St. Helens than the Klickitat River. Chemical changes in North Fork Ahtanum Creek near Tampico, Washington, resembled changes observed in the Klickitat River. Concentrations of sulfate and chloride increased on May 18, 1980. The shift in anion composition occurred earlier than the shift observed in the Klickitat River. Klein (1984, p. 10) attributed this time difference to:

> [The] ***closer proximity of Ahtanum Creek to the heaviest ashfall area*** and to a shorter time of travel of water from within the watershed to the sampling site. The degree of change in composition over normal values was also greater because the entire drainage received substantial ash.

According to the author, similar but smaller shifts in the concentrations of sulfate and chloride were correlated with a minor eruptive event that occurred June 17, 1980. After this minor eruptive event, sulfate and chloride shifts occurred from June 24–28, 1980.

According to Bonelli and others (1980, p. 44), there were few changes in cations at the North Fork Ahtanum Creek near Tampico, Washington. Bonelli and others (1980, p. 44) stated:

> In the ash-affected basins east of Mount St. Helens, the observed water-quality changes were generally short-lived and had a tendency to decrease in magnitude with distance from the volcano.

Faulconer and Mongillo (1981, p. 2–4) studied three trout streams in the Yakima Basin for which pre-eruption data existed regarding fish, aquatic invertebrates, and water quality. Two of these trout streams, Naneum and Wenas Creeks, flow directly into the Yakima River. The third is Cowiche Creek, a Naches River tributary. The Naches River flows into the Yakima River. These three creeks were sampled during August 1980 after the eruption; data collected were compared to data from August 1978 samples.

Naneum Creek, considered to be free of irrigation influence, received about 0.1 inch of ashfall. This creek originates in the foothills north of Ellensburg, in Kittitas County, Washington. Naneum Creek contained rainbow trout *(Salmo gairdneri),* brook trout *(Salvenlinus fontinalis),* and limited numbers of cutthroat trout *(Salmo clarki).*

The authors presented the physical parameters of the stream as follows: length = 29.8 miles; approximate average flow = 58 ft^3/s; total drainage area = 70 square miles; range of rainfall per year = 9 to 26 inches; lower elevation = 1,726 feet.

Wenas Creek originates west of Yakima, Washington, discharges to the Yakima River near Selah, Washington, and is considered to be a year-round creek. Wenas Creek received 0.25 to 0.50 inch of ashfall. As in the case of Naneum Creek, the upper drainage of Wenas Creek is considered to be free of irrigation influences; however, the creek is dammed about 15 miles upstream from the point where it flows into the Yakima River. The creek has populations of rainbow and cutthroat trout in its upper reaches, and the WDG planted rainbow trout at 2- to 3-year intervals.

The authors presented the physical parameters of the stream as follows: length 21.7 miles; approximate average flow = 25 ft^3/s; total drainage area = 192 square miles; range of rainfall per year = 9.8 to 43.3 inches; lower elevation = 1,138 feet.

Cowiche Creek, originating in the mountains west of Yakima, Washington, received up to 4.7 inches of ash. North Fork Cowiche Creek is dammed, and irrigation water is diverted from the creek to adjacent agricultural lands. According to the authors, there is good riparian vegetation in the canyon through which the lower part of the creek flows. Fish species include rainbow trout, mountain whitefish *(Prosopium williamsoni)*, and a few steelhead. Faulconer and Mongillo (1981, p. 2) viewed Cowiche Creek as: "[an] ***important spawning stream for rainbow trout and possibly steelhead." Samples were taken from both North and South Fork Cowiche Creek.

Faulconer and Mongillo (1981, p. 5) sampled the creek by electrofishing and performed population studies designed to estimate the number of fish, and the pounds of fish per acre (lbs/acre). The authors calculated "condition factors" for fish captured in August 1978 and August 1980, in order to compare findings for individual sites each year. Faulconer and Mongillo (1981, p. 5) stated:

> [We] used condition factors for comparison because it allowed us to group fish of all sizes and would not be affected by changes in the age structure of the population.*** Length frequency histograms were plotted for each species of fish for each stream to see if the age structure of the population had changed.

The condition factors were assumptions and statistical techniques applied to the analyses that permitted the authors to group fish of all sizes when making comparisons, although there may have been fish of different ages in the populations examined. For further details on the assumptions and statistical methods used by the authors, see Faulconer and Mongillo (1981).

The number of rainbow trout in Naneum Creek increased 17 percent from 1978 to 1980, reported Faulconer and Mongillo (1981, p. 7). The total weight of rainbow trout per acre decreased during this period. The average length of individual rainbow trout decreased from an average of 7.1 inches in 1978 to 6.6 inches in 1980. Mean weight of rainbow trout decreased from 2.38 ounces in 1978 to 1.95 ounces in 1980. The total weight of brook trout per acre decreased from 10.9 lbs/acre in 1978 to 9.0 lbs/acre in 1980. The mean length of brook trout decreased from 6.6 inches in 1978 to 5.6 inches in 1980; the mean weight decreased from 2.4 to 1.5 ounces. The authors noted that a weak year class in 1978 could account for the decrease in mean lengths and weights and cited increased competition for space and food as factors affecting the fish. Faulconer and Mongillo (1981, p. 7) concluded: "When condition factors were compared for Naneum Creek, a significant difference occurred for brook trout while the difference for rainbows was not significant." The authors suggested the brook trout might have been more affected than rainbow trout by the ash, through various mechanisms. For example, Faulconer and Mongillo (1981, p. 13) noticed a great impact upon the area's terrestrial insect population. The authors observed numerous insects that were distressed or dead; this would have decreased the amount of food available to some fish. Faulconer and Mongillo (1981, p. 13) stated: "This is significant since allochthonous material is an important food source in many streams."

By August 1980, only traces of ash could be seen in the riffles and pools of Naneum Creek, and none of the three sample sites had significant deposits of ash. Physical examinations of rainbow and brook trout indicated that both species of fish appeared to be healthy and were free of gill damage. Comparisons of turbidity and total suspended solids data for 1978 and post-eruption months during 1980 showed little change in those physical parameters that might account for the lack of observable biological effects.

Faulconer and Mongillo (1981, p. 8) studied invertebrate populations and reported that average total numbers of invertebrates per unit area increased at three different sampling sites. For Naneum Creek, total invertebrates were reported at a population density of 133 organisms per square foot in 1978. By August 1980, the density had increased to 200 organisms per square foot. Insect orders reported included Trichoptera, Plecoptera, Ephemeroptera, Diptera, Coleoptera, and others. The orders comprising the largest percentages of the sample were the Trichoptera, Ephemeroptera, and Diptera. The largest percentage change was noted in the order Ephemeroptera, which in 1978 was 53.6 percent of the sample population. In August 1980, the Ephemeroptera comprised 29.4 percent—a 24.2 percent decrease from 1978. By August 1980, benthic organisms were abundant; however, Faulconer and Mongillo (1981, p. 14) speculated that short-term effects immediately after the eruption may have affected the number of organisms in some unexplained fashion.

Increases in the number (64 percent) and in the total weight of the fish in Wenas Creek were reported (Faulconer and Mongillo, 1981). However, the mean lengths and weights of the fish captured had decreased. Faulconer and Mongillo (1981, p. 14) report no significant variations in condition factors for these fish, which seemed to be healthy. The decrease in mean length and weight was attributed to a depressed age 1+ year class in 1978. The authors reported a 116 percent increase in the number of benthic invertebrates from 1978 to 1980 and concluded that the ashfall minimally affected aquatic invertebrates in Wenas Creek. Although some ash was found in riffle areas and mixed with pool sediments in Wenas Creek, water quality was considered good.

Cowiche Creek experienced a 48 percent decrease in the population of the fish from 1978 to 1980 and a concomitant increase in the average length and weight of the fish. Although the numbers of fish declined, the total weight of the population per unit area increased. In addition, the proportion of large fish was greater than that of 1978. Faulconer and Mongillo (1981, p. 15) attributed these differences to age composition of the captured population, explaining that in 1978, there was a large proportion of "young-of-the-year" fish. In 1980, few fish of this age category were in the population. The authors considered the most significant change in Cowiche Creek to be a reduction in the number of young-of-the-year fish. According to Faulconer and Mongillo (1981, p. 15):

> The stream received more ash than either Naneum or Wenas Creek, and it appeared to be somewhat heavier and more abrasive than that found in other streams. Young fish were about ready to emerge from the gravel on May 18 [1980]. During this critical stage of development, they would be susceptible to the effects of volcanic ash or any other fines.
>
> On June 16, 1980 severe thunderstorms occurred in the watershed of Cowiche Creek. We believe accumulated ash on the ground made the soil less permeable and was responsible for the higher than normal runoff that occurred.*** The ashfall coupled with high flows shortly thereafter could explain the possible high mortality of the young-of-the-year fish.

The authors further explained the existence of statistically significant differences in the condition factors between 1978 and 1980, and that they had observed fish trapped in pools due to low flows in August 1980. During this time, however, invertebrate populations did not appear to be adversely affected, and there was an increase in production. A relative scarcity of food or space was suggested as a reason for the lower condition factors. In contrast to Naneum and Wenas Creeks, state Faulconer and Mongillo (1981, p. 15), "***substantial deposits of ash were found in pools [of Cowiche Creek]."

The St. Joe River and Coeur d'Alene River Drainage Systems

The research of Skille and others (1983) was discussed earlier in this report in the section on Coeur d'Alene Lake. Coeur d'Alene Lake is fed by the Coeur d'Alene and St. Joe Rivers, which drain the western slopes of the Bitterroot Mountains of Idaho. Lake Coeur d'Alene is drained by the Spokane River at Coeur d'Alene, Idaho. The lower Coeur d'Alene and St. Joe Rivers and deltas were presumed to act like catchment or settling basins for ash runoff from the river drainage systems. The two rivers, in conjunction with the lake, constitute a major water system in northern Idaho. The lake and tributary rivers are about 250 miles east of the volcano and lay within the plume of ash fallout, where ash depth varied from 0.25 to 0.75 inch. The sites described by Skille and others (1983) are (1) Coeur d'Alene River miles 133 and 138, (2) St. Joe River miles 8, 13, and 17, and (3) the respective deltas of each river. The authors attempted to calculate the amount of volcanic ash in sediments and to describe effects of sediments and suspended ash on aquatic populations.

At the start of their research, Skille and others (1983, p. 15) speculated that ash would tend to accumulate in deltas and in lower reaches of the rivers. Apparently this did not occur, and Skille and others (1983, p. 30):

> ***determined that the lower rivers and deltas did not have a significantly greater ash concentration***. The river bottoms tend to be void of ash because the fallout was moved downstream and was unable to settle out.

According to Skille and others (1983, p. 16), the St. Joe and Coeur d'Alene Rivers were in the annual runoff stage when the eruption occurred; however, other parts of the lake system—with less discharge or no water—experienced some settling of ash. For example, at Coeur d'Alene River mile 133, the depth of ash recorded during the fall of 1981 was 0.21 inch; in the fall of 1982, the ash layer was 0.25 inch thick.

The depth of new sediment measured at river mile 133 was 4.42 inches during the autumn of 1981 and 1.5 inches during the autumn of 1982. In summary, data indicate the ash layer was rapidly buried by sediment. According to Skille and others (1983, p. 30): "The well consolidated ash layer provides an excellent benchmark from which future measurements of sedimentation can be made."

The authors described the accumulation of ash and sediment in the St. Joe and Coeur d'Alene River deltas, which experience annual variations in the amount of sediment deposited. The Coeur d'Alene River normally carries a large burden of sediment that is ultimately transported to the lake's west shore. Data indicate that the delta's ash layer was covered with as much as 8 inches of sediment during the first 2 post-eruption years. For the St. Joe River delta, a 2-year accumulation of sediment over the ash layer was about 7.1 inches thick. Both rivers typically exhibit scouring and sediment deposition in various reaches, and outside bends and straight stretches of the river were scoured and devoid of new sediment. According to Skille and others (1983, p. 32):

> Deposition of post-ash sediment only occurred on inside curves where water velocity slowed and allowed sediment to sink. *** Ash counts indicated that very little ash was deposited in the new sediment and that there were negligible amounts of ash entering the system and settling out each year.

Contrary to early assumptions, the organic carbon content of river delta waters did not increase substantially, based upon measurements made throughout the water column during summer and autumn of 1981 and during spring, summer, and autumn of 1982. Skille and others (1983, p. 36) stated: "There was slightly more organic carbon in the water system in 1981 than in 1982, but this was probably due to annual variations in algal production." The new sediment consisted of 9.3 percent ash in 1981 and only 1.2 percent by 1982. The researchers speculated that by the beginning of 1982, no significant amounts of ash were carried from land surfaces to the rivers. The authors reported that, in general, sampling sites with recently deposited sediments that contained the largest proportion of ash were found in the following order: (1) deltas, (2) rivers, and (3) lakes. According to Skille and others (1983, p. 42):

> [The] thickness of the terrestrial ash layer has not changed significantly since it was deposited and is further evidence that the stable and cohesive nature of the ash prevents erosion from the watersheds.

Dissolved oxygen, pH, temperature, conductivity, turbidity and Secchi-disk transparency were measured during various pre-eruption studies from 1960 to 1971; therefore, comparisons to post-eruption samples taken during 1981 and 1982 could be made—although data for some intervening years were not available. According to Skille and others (1983, p. 66), comparisons of pre- and post-eruption average DO concentrations show little apparent change, although during 1960, a recorded concentration of over 11 mg/L was greater than average concentrations observed during the post-eruption summer months of 1981 and 1982. During those months, the DO concentration ranged from 8 to 9 mg/L. However, a lack of data prevented the authors from determining either the timing or the reasons for the drop in DO levels.

Skille and others (1983, p. 66) observed no significant change in pH values caused by the eruption and report "average annual" pH values in the range 6.9 to 7.1 for the Coeur d'Alene and St. Joe Rivers. Average water temperatures in 1981 were 3.6°C warmer, but variations in temperature due to weather, rainfall, runoff, and other factors were observed from one year to another. The authors did not attribute the change in average temperatures directly to ashfall (Skille and others, 1983, p. 66). The annual average conductivity in the Coeur d'Alene River (mile 133) was 97 µS/cm during the pre-eruption years 1970–71. Average annual conductivities were 84 µS/cm and 81 µS/cm in 1981 and 1982, respectively. In the Coeur d'Alene River delta, one set of pre-ash data cited by the authors reflected an average annual conductivity of 46 µS/cm, whereas average conductivity during 1981 was 84 µS/cm. The observed increase in conductivity declined during 1982, when the annual average conductivity was reported to be 54 µS/cm. A lack of data for the periods 1972 to 1980 made interpretation of these changes difficult; the authors do not attribute fluctuations in average annual conductivities to ashfall.

In the St. Joe River, at river miles 8, 13, and 17, annual average turbidities were little changed. Apparently, the post-eruption mean annual average turbidities for the three sites may have been slightly less during 1981, than for pre-eruption values. The mean Secchi-disk transparency reading was 7.5 feet for Coeur d'Alene River mile 133 during 1970, but transparency appeared to be slightly less during 1981 (6.2 feet) and 1982 (5.2 feet). In the Coeur d'Alene

River delta, the pre-eruption 1970 average Secchi-disk transparency was 9.2 feet, whereas in 1981 the reading decreased to 5.9 feet. The 1982 transparency value was 9.5 feet. Similar slight fluctuations were observed at St. Joe River mile 9. Skille and others (1983, p. 66) reported a short-lived reduction in Secchi-disk transparency in Coeur d'Alene Lake, but the effect was considered to be transient. The authors speculated that ash settling to the lake bottom did not resuspend in quantities sufficient to affect either turbidity or light penetration.

Phytoplankton communities in the Coeur d'Alene Lake system were studied by Skille and others (1983, p. 67–69), who identified 34 genera of phytoplankton. The authors compared seasonal changes in phytoplankton abundance in the Coeur d'Alene and St. Joe Rivers and deltas and superimposed historical (1970) algal succession patterns on composite-water-sample data from post-eruption years 1981 and 1982. The number of algae did not decrease relative to the year 1970, according to the authors. Normal seasonal changes in phytoplankton communities were observed in this lake-river system, but the authors observed apparent maxima and abundance peaks of algae in the Coeur d'Alene River and its delta during the summer. Blooms in the Coeur d'Alene River and delta characteristically involve species of *Anabaena, Ankistrodesmus,* and *Nitzschia*. During the autumn of 1981 and all of 1982, Skille and others (1983, p. 67): "***found a significant increase in phytoplankton abundance at Coeur d'Alene River mile 133 ***." The authors reported no algal blooms in the St. Joe River or delta and considered *Navicula* to be the dominant species of algae in this system.

Skille and others (1983, p. 67–69) speculated that increased algal density in the Coeur d'Alene River and delta was, possibly, "*** linked to the reduction in sediment and water column heavy metal concentrations over the past decade." However, a discussion of heavy metal pollution from upstream mining activities is outside the scope of this report. In general, the authors considered pollution control measures to have decreased the amount of metal loading to this river system. A corollary question might be raised regarding the possible effects of ash on metal concentrations (lead, zinc, and cadmium) in sediments of this river. The metal concentrations in sediments of this river have been regarded, historically, to be at pollution levels that are potentially toxic to benthic invertebrates. Concentrations of the metals in the water column are related to sediment concentrations. Indeed, according to Skille and others (1983, p. 58):

> Heavy metal concentrations in the water column are lower than previously reported ***. St. Joe River zinc concentrations and lead and cadmium concentrations from all 3 sites presently occur at levels below detection limits. Zinc concentrations have decreased from 2.70 to 0.73 mg/L and 0.40 to 0.25 mg/L in the Coeur d'Alene River and Coeur d'Alene Lake, respectively.

However, in general, the authors attributed decreased concentrations of zinc to upstream pollution control measures, and stated: "[The] ash layer has had little, if any, effect on the exchange of metals between the sediments and overlying water."

Skille and others (1983, p. 71) had expected that primary productivity might have been affected by tephra as a consequence of reduced light penetration. The authors studied primary productivity during 1981 and 1982 and plotted post-eruption seasonal trends. A comparison of their findings to Wissmar's historical data led Skille and others (1983, p. 71) to conclude:

> [The] plots illustrate that production has not been adversely affected by the presence of ash in the water.*** [The] post-ashfall primary production in the Coeur d'Alene Lake system parallels pre-ashfall productivity levels.

The authors speculated that ash did not resuspend during times of lake turnover and that little or no ash was carried into the system by erosion from the adjacent watersheds.

Post-eruption seasonal changes in zooplankton abundance were compared by Skille and others (1983, p. 74) to data from 1970. According to the authors, the dominant copepod in the system was *Cyclops bicuspidatis thomasi.* Other copepods included *Cyclops varicans rubellus, Diaptomus ashlarji, D. novamexicanus, D. pygmaeus*, and *Epischura nevadensis. Cladocerans* belonging to the genera *Bosmina, Cerriodaphnia, Daphnia, Diaphanosoma, Alona,* and *Camptocercus, Leptodora, Pleuroxus, Polyphemus, Scapholeberis,* and *Sida* were identified. Details on species composition and diversity can be found in the report by Skille and others (1983), which includes extensive appendices. In the St. Joe River, the estimates of zooplankton abundance indicated that peak numbers during the summer and early fall of 1981 and 1982 were smaller than during the same months in 1970.

According to Skille and others (1983, p. 74), "[however,] abundance estimates over most of the season are similar." Conversely, peak post-eruption zooplankton abundance numbers in the Coeur d'Alene River (mile 133) during 1981 were slightly greater than during 1970. However, during the succeeding post-eruption year (1982), the numbers of zooplankton were fewer than observed in 1970. Skille and others (1983, p. 77) summarized their findings:

> Given the similarity of pre- and post-ashfall cladoceran communities, we do not believe that the deposition of ash in the Coeur d'Alene Lake system has significantly altered the species composition of the zooplankton.

Benthic invertebrates in the Coeur d'Alene Lake system were studied by Skille and others (1983, p. 81), who reported a low invertebrate biomass and abundance in the Coeur d'Alene River. In particular, during the autumn of 1981 and 1982, no organisms could be found. The Coeur d'Alene River delta, however, had a substantial invertebrate population. Skille and others (1983, p. 81):

> ***attribute this phenomenon to heavy metal [trace element] pollution in the Coeur d'Alene River. As the river meets the lake, the toxicity of the metals is reduced by dilution, causing increased invertebrate production in the Coeur d'Alene River delta.

Most of the benthic macroinvertebrates in the system were either oligochaetes or chironomids. The authors listed representatives from the Coelenterata, Nematoda, Hirudinea, Crustacea (Ostracoda, Isopoda, Amphipoda and Hydracarina), Insecta (Plecoptera, Ephemeroptera, Odonata, Trichoptera, Coleoptera, and Diptera), Gastropoda and Pelecypoda (Skille and others (1983, p. 81). The diversity of macroinvertebrates was similar to that described by other scientists in 1971–72. The authors compared 1981–82 data to pre-eruption 1971–72 data for four sites in the system and concluded that no substantial changes in density occurred within that timeframe. Although specific seasonal differences in abundance were noted, according to Skille and others (1983, p. 84), variations were:

> ***attributed to annual variability in the timing of abundance peaks. *** [We] conclude that the ash has not had a significant long term effect on the abundance of the benthos in the Coeur d'Alene Lake system.

The Big Creek and Gedney Creek Drainage Systems

The effects of volcanic ash on benthic invertebrates in the Big Creek and Gedney Creek Basins of northern Idaho were studied by Frenzel (1983, p. 2). Big Creek is a fourth-order, southward-flowing stream that merges with the St. Joe River; Big Creek Basin received about 0.6 inch of ash after the eruption. The study site was northeast of Calder, Idaho, at a gaging station located on the creek 3.4 miles upstream from its juncture with the St. Joe River. The drainage area is about 40.5 square miles, and the adjacent terrain above the gaging station is steep and covered with forest or scrubland. The altitude of the study reach is 2,379 feet; and at the sampling reach, the stream channel is 39- to 49-feet wide. The stream gradient is moderate, with a substrate consisting of cobble. Riparian vegetation consists of deciduous brush and perennial grasses. During 1980, the peak discharge of the stream occurred in late April; at the time of the eruption and ashfall, stream discharge was still high. Frenzel (1983, p. 2) reported:

> [Ash] sank quickly in streams and accumulated in pools and slack water. Some ash was intercepted by vegetation. Minor amounts of ash may have reached the stream as wind and rain removed ash from the vegetation.

The bulk of the ashfall in the area was thought to have remained on adjacent hillsides.

In a companion study, Frenzel (1983) conducted experiments on the effects of ash on water quality and benthic invertebrates in Gedney Creek—another fourth-order, southward-flowing tributary of the Selway River. The study basin lies southeast of the Big Creek Basin and was regarded to be a reference basin, because it had not received ash fallout. The Gedney Creek Watershed drains an area of 48 square miles, and the terrain is steep and forested. Similar to Big Creek, the Gedney Creek Basin is regarded to be minimally impacted by human activities.

Frenzel (1983, p. 4) collected 26 soil samples to estimate the amount of ash in the Big Creek Basin, but concluded: "[It was] not possible to determine exactly how much ash had been transported out of the basin." However, it was estimated, using calculations based on mean, dry-ash weight, that the basin contained about 412,260 tons of ash. Frenzel characterized dry, uncompacted ash as being easily transported by wind.

Compacted ash retained water but had little tendency to move downslope. "In sparsely vegetated areas," Frenzel (1983, p. 5) stated, "ash formed a thin, cement-like crust."

Ash was transported in streams as bedload and suspended sediment, and the observed peak concentration of suspended sediment was 5 mg/L. However, the author was of the opinion that higher concentrations had previously occurred during peak discharge levels. Frenzel (1983, p. 5) stated: "Ash, whether moved as suspended load or bed load, probably is stored in bed material." Sediments in Big Creek contained only a small percentage of fine-grained sediments; similarly, the concentration of suspended sediment was low.

Water-chemistry analyses of Big Creek during the period December 1980 to December 1981 indicated that barium, chloride, sulfate, and zinc were present in small concentrations. These constituents had been determined by Fruchter and others (1980) to be present in substantial quantity in ash, along with 80 percent glass (SiO_2). In general, the water contained small concentrations of dissolved constituents, as was the case in Gedney Creek. Frenzel (1983, p. 8) reported:

> Dissolved oxygen concentrations were always at or near saturation. Concentrations of fecal coliform and fecal streptococci were generally low (less than 10 colonies per 100 milliliters), except during late summer and early autumn, when concentration of fecal streptococci increased.

The pH values ranged from 6.9 to 7.6.

Dip-net collections of benthic invertebrates were made in Big Creek from May 5 to December 1, 1981, and in Gedney Creek from May 1981 to November 1981. The author considered individual collections to be separate entities, rather than representative of random samples taken from a large population. The sampling method was described as being strictly qualitative, and 80 invertebrate taxa were identified in Big Creek. The number of invertebrate taxa in single collections ranged from 20 to 40. The following taxonomic categories were represented: Insecta (Coleoptera, Collembola, Diptera, Ephemeroptera, Hemiptera, Plecoptera, and Trichoptera); Hirudinea; Oligochaeta; and Turbellaria. Frenzel (1983, p. 13) found only the following three taxa common to all samples collected from Big Creek: "two caddisflies, *Brachycentrus americanus* and *Lepidostoma* sp., and a riffle beetle, *Optioservus* sp." In Gedney Creek, 68 taxa were collected. In comparison to Big Creek, stated Frenzel (1983, p. 13):

> [The three taxa, common to all samples, were] a mayfly, *Baetis tricaudatus*; a caddisfly, *Hydropsyche* sp.; and as in Big Creek, the riffle beetle, *Optioservus* sp.

The author classified organisms according to functional groups and calculated indices for diversity and evenness, and the details are delineated in the report.

Two experiments with volcanic ash in Gedney Creek, which lay outside the ashfall plume, were done by Frenzel (1983). One set of experiments was designed to test effects of ash on colonization of substrates by benthic invertebrates. The author employed artificial substrate samplers consisting of wire-mesh baskets filled with ceramic balls, chosen to provide uniformity of substrate size and shape. Ash collected from northern Idaho was dried and sieved prior to being used, experimentally, to cover the artificial substrates. The ash was applied to the substrate in a paste form, and the baskets containing the substrate were lowered into the stream. The author described a number of factors that may have affected the experiment. Such factors included ash-retention time on the substrate, and the influence of test system, predator species on structure and diversity of organisms colonizing the substrate. According to Frenzel (1983, p. 22):

> Collectors-gatherers dominated communities in all three substrate series***. Total detritivores (collectors and shredders) accounted for 83–90 percent of the collections, compared with 71 percent detritivores in a lumped ***qualitative collection***.

The functional category "scrapers" was negatively affected by ash on the substrate but was not as abundant on treated substrates as on untreated ceramic balls. It was proposed that clean ceramic balls provided a more stable attachment surface for the periphyton, which would attract scrapers. A second set of experiments tested effects of ash on invertebrate communities already established in the stream system. According to Frenzel (1983, p. 25):

> Ash-covered substrates were more effective than controls in retaining fine-grained sediment and detritus, and invertebrates were more numerous on ash-covered substrates than on controls. ***Addition of volcanic ash to artificial substrate samplers may increase detritus-trapping efficiency and, consequently, may offer a more suitable microhabitat for benthic invertebrates.

In summary, Frenzel (1983) described an abundant and diverse population of benthic invertebrates in Big Creek, which was characteristic of similar forested headwater streams normally receiving terrestrial inputs of organic material. The author described no anomalies in such populations attributable to ash, nor were there significant changes in either physical or chemical characteristics of water. According to Frenzel (1983, p. 1), experimental data indicated:

> ***a small quantity of volcanic ash was not detrimental to invertebrate communities. ***Addition of volcanic ash to artificial substrate samples may increase detritus-trapping efficiency, and consequently, may offer a more suitable microhabitat for benthic invertebrates.

The author speculated that for streams receiving only small amounts of volcanic ash, there might even be a beneficial effect for organisms living in such streams. A more favorable habitat might have been provided by enhancement of the detritus-trapping ability of the substrate.

Summary of Volcanic Effects on the Water Quality of Rivers, Streams, and the Columbia River Estuary

As in the different lake categories, there was a spectrum of eruption effects on rivers and streams, depending on the river's proximity to the volcano. Overnight, a few river basins that were in the path of debris avalanches or mudflows changed completely; some tributaries were virtually obliterated. The North Fork Toutle and Cowlitz Rivers were examples of heavily affected systems, with certain reaches totally transformed. Other rivers and streams that only received ashfall were changed to a much lesser extent; and in many cases, the effects were subtle, if at all perceptible. Like category I lakes, the St. Joe River and the Coeur d'Alene River systems lay outside the blast zone, were far removed from the volcano, and were marginally affected by the eruption. Similarly, the Klickitat River received only ash and was not affected by blast effects, avalanches, or mudflows. Analyses of eruption effects is complicated because several of the rivers and streams lay partly inside of, and partly outside of, blast-effect areas. The wide range in levels of effects creates difficulties when identifying factors common to all rivers and streams; however, selected findings are summarized with some examples but without citing bibliographic references, for the sake of brevity.

The most heavily impacted rivers experienced greatly increased concentrations of filterable solids, suspended sediments, and increased specific conductivity. In the upper portion of the North Fork Toutle River, concentrations of filterable solids exceeding 18,000 mg/L were recorded. Suspended-sediment concentrations of 11,880 mg/L were reported in the South Fork Toutle River. Changes in specific conductance were as great as an order of magnitude or more, such as occurred in the Toutle River. The Toutle River had a pre-eruption specific conductance at Castle Rock of about 90 μS/cm; but several days after the eruption, the water at the same site had a specific conductance of 560 μS/cm.

Turbidities in some rivers were dramatically increased, in some instances by more than an order of magnitude. The Cowlitz River is such an example. Pre-eruption turbidity at Kelso was 3.7 NTU's, whereas post-eruption turbidities ranged from 72 to 650 NTU's. Other streams had turbidities greater than 2,500 NTU's. The duration of changes in turbidity varied from river to river, because suspended sediments continued to be eroded from mudflow materials in blast area rivers, thus maintaining the high levels of turbidity. In contrast, for minimally affected areas like the Coeur d'Alene River delta, turbidity increases were relatively transient. After the eruption, Secchi-disk transparencies were slightly decreased from a pre-eruption 9.2 feet to 5.9 feet in the Coeur d'Alene River Delta. Transparency changes at Coeur d'Alene River mile 133 were even less. Such changes were short-lived, and apparently ash did not resuspend in quantities sufficient to affect turbidity or light penetration once the ash had settled to the river bottom.

In isolated cases, drastic changes in temperature were caused by the influx of heated and pyroclastic materials; some temperature effects were brief; other increases may have lasted weeks or more, perhaps due to the loss of riparian vegetation and streambank shading and increased amounts of suspended materials. Some streams, such as those tributary to the North Fork Toutle River, experienced temperature increases that equaled or exceeded the limits normally regarded harmful—or possibly lethal—to fish. In the lower Toutle River, temperatures as high as 32.2°C were recorded the day after the eruption; during the same period, temperatures nearly that high also were reported in the lower Cowlitz River.

There were no examples of rivers experiencing prolonged changes in DO concentration, and in most rivers post-eruption DO concentrations ranged from 4.5 to 11 mg/L. Similarly, some minor pH effects were observed; but with few exceptions, these were usually of short duration. In rivers such as the North and South Forks of the Toutle River, post-eruption pH values ranged from 6.2 to 7.7. Some changes observed were slightly lowered pH readings; the most extreme changes were on the order of less than one-half pH unit and were temporary.

Regardless of the river system investigated, most researchers did not regard observed pH changes in rivers to be a major effect. Various researchers reported changes of inorganic chemical constituents in not only rivers impacted heavily but also in rivers less affected by the eruptions. Notable increases in concentrations of sulfate and chloride ions were reported, particularly in the Toutle River system. Alterations in the relative proportions of anions and cations caused the most heavily affected rivers to be changed in water-type classification; in most rivers in the immediate vicinity of the volcano, calcium and bicarbonate were the major pre-eruption chemical constituents. The duration of changes in water type varied greatly from stream to stream. For instance, the Klickitat River was affected only by ash, and the anion composition shifted back towards normal several days after the eruption. In the Klickitat, anions like bicarbonate and carbonate also increased. In other streams, such as the Yakima River, shifts in sulfate and chloride concentrations were observed, but these changes were less than typically observed seasonal variations. An analogous observation was made in the Yakima River after a minor eruption in mid-June 1980, when ashfall distributed in the basin could be correlated with an increase in sulfate and chloride concentrations within several days after the ashfall event. Similar to lakes that were geographically removed from the blast zone, rivers that received only ashfall experienced relatively short-lived changes in chemical constituents; these changes generally decreased in magnitude as the distance from Mount St. Helens increased.

Post-eruption concentrations of major cations, such as sodium, calcium, and potassium, were slightly increased in rivers receiving ash, such as the Klickitat River. Concentrations of trace elements such as iron, manganese, and aluminum were increased to varying degrees, as was the case for the lakes. Examples are the Toutle and Klickitat River systems. The increased metal concentrations were sometimes greatly elevated —up to hundreds of times the pre-eruption concentrations. For some rivers, these changes were more persistent than in others, presumably due to leaching of elements from ash and ash-containing debris. In the Toutle-Cowlitz River systems, elevated concentrations of some metals persisted through the end of June 1980. In the Klickitat River, post-eruption levels of 70 μg/L of dissolved iron and 4,200 μg/L total recoverable iron were recorded. Dissolved and total recoverable aluminum reached maximum levels of 70 μg/L and 3,100 μg/L, respectively, in the Klickitat River. In the South Fork Toutle, concentrations of total recoverable manganese increased over a pre-eruption value of 30 μg/L, to 150 μg/L. Other constituents, such as arsenic, mercury, and boron were increased in some rivers and streams. However, such trace elements and other chemical constituents are best reviewed on a river-by-river basis, due to great variations in the type and amount of data reported by many authors. In general, suspended-metal concentrations tended to be higher than dissolved metal concentrations. For the reader who requires detailed, element-by-element tables of data for many different rivers and streams, including those not covered herein, the report by Turney and Klein (1982) will be valuable. Nearly four dozen sampling sites covering many rivers and their respective tributaries are listed.

As was the case for the lakes, information on post-eruption concentrations of various nutrients varies, depending on the author and the river system. In the North Fork Toutle River, concentrations of nutrients such as nitrate, nitrite, and ammonia appeared to be present at typical, average-annual levels; however, available phosphate and silicate concentrations apparently increased in both forks of the Toutle River.

Increases in dissolved and total organic nitrogen were observed in several rivers and usually could be correlated with abnormally high turbidity levels. Most researchers generally regard the dissolved and total organic nitrogen to have originated by the burning of organic materials, such as trees and forest vegetation.

In general, most rivers did not have changes in DOC concentrations when compared to changes in DOC concentrations evident in some lakes. However, some data did show increases in DOC concentration, for instance, Cowlitz River data.

The presence of phenolic compounds was reported in several rivers, such as the Cowlitz River and certain reaches of the Columbia River, after the eruption. A lack of pre-eruption data hindered comparisons. Phenolic compounds were detected in the North Fork Toutle River in 1981, but levels reported were regarded by authors as fairly typical of background levels for rivers in proximity to logging operations—particularly in the Pacific Northwest. Mudflow deposits also contained low levels of phenols. For a detailed survey of the occurrence of phenols, chlorophenols, terpenes, and other organic compounds in surface and ground waters, refer to Hindin (1983).

Changes in populations of benthic invertebrates in rivers ranged from no perceptible effect to catastrophic changes. Few generalizations could be made, and the eruption impacts on benthic invertebrates were best studied on a river-to-river, stream-to-stream, or reach-to-reach basis. In the St. Joe and Coeur d'Alene Rivers and deltas, no short- or long-term changes in either the species or numbers of benthic invertebrate communities in the lake system were reported; although various fluctuations in numbers were sometimes observed. Researchers studying these basins concluded, essentially, that the distribution patterns of benthic organisms in sediments were unaltered. For tributaries of the Yakima River Basin, short-term effects were difficult to explain, and apparently there was an increase in the population densities of several insect orders in Cowiche Creek. However, data indicate that members of the Ephemeroptera decreased in number when compared to pre-eruption data.

In the Toutle and Muddy Rivers, and the Pine Creek drainage basin, fairly clear-cut changes in benthic invertebrate populations were reported. The eruption virtually destroyed most, perhaps all, benthic fauna at some sampling sites. Many phenomena affecting such organisms included completely modified topography and watersheds, the scouring of riparian vegetation, and changes in stream substrates. In some sites with surviving benthic invertebrates, there was a simplified post-eruption community, consisting mainly of midges and blackfly larva. Some authors reported diminished quantities of leaf detritus; other usual food sources for benthic organisms may have been less plentiful, because turbidity affected algal growth on rocks. The relative scarcity of food might then adversely affect the surviving benthic invertebrates. Few generalizations on food supplies for different organisms, including fish, can be made; data is probably applicable only for reaches sampled and on a case-by-case basis.

Eruption effects on fish in the Toutle and Cowlitz River Basins were, for the short-term, catastrophic; some major tributaries were literally destroyed. Besides the changes wrought by mudflows and pyroclastic materials, gravel was scoured away from other river reaches and tributary streams and fines were deposited, all of which affected spawning grounds. In some instances, fish were killed by various physical effects; in some cases, high temperatures may have been a factor contributing to mortality. Depending on the stream reach surveyed, some fish, such as steelhead, were found alive shortly after the eruption.

Different authors described various causes of mortality for different species, and many post-eruption experiments were conducted to determine the effect of ash on fish. Significantly, researchers determined that some adult fish managed to reach spawning grounds and to swim up the Cowlitz and Toutle Rivers after the eruption. Most of the Cowlitz River spring chinook run survived, because the fish had already reached their spawning grounds above the mouth of the Toutle River before the May 1980 eruption. According to some authors, other fish, such as adult fall chinooks, were not successful in reaching spawning grounds; many died attempting passage upstream. Observations by various researchers differ considerably, and their conclusions regarding eruption effects on fish mortality vary, depending on the stream being discussed. Some scientists reported that the fall chinook and coho runs in late summer and autumn of 1980 were at record proportions and stated that there were few effects on anadromous fish runs in both the Toutle and Cowlitz Rivers. Coho salmon that swam upriver later in October were largely successful in reaching spawning grounds.

On the basis of a variety of experiments, some researchers concluded that suspended ash might possibly have affected the homing ability of anadromous fish. Unable to find the correct mouth of their home stream, migrating fish might have strayed from their native spawning streams while swimming upriver. Experimental observations suggest that fish can suffer physiological problems when subjected to extremely high concentrations of ash; oxygen exchange could be impaired. It is not certain whether or not such high concentration levels of ash, which were associated with the damage incurred by fish during experiments,

were attained in different river systems. Some authors attribute mortality largely to the brief but greatly elevated temperatures in reaches of several drainage systems. In short, besides the possibility that ash may have been harmful physically to the fish, high turbidities may have adversely affected survival, reproductive behavior, or homing ability of migrating fish.

Volcanic debris from the eruption of Mount St. Helens was deposited in the Columbia River Estuary in a layer ranging from 0.2 to 4.5 inches deep, with an average depth in the shallows of 1.8 inches. A large increase in the turbidity of the estuary was caused by the influx of sand, ash, and volcanic debris carried from the Cowlitz and Columbia Rivers. Levels of SPM were greatly elevated.

Sampling for dissolved and suspended concentrations of trace metals by Riedel and others (1984, p. 340) indicated that soluble concentrations of the trace elements cadmium, iron, nickel, lead, and zinc were not appreciably elevated. The concentrations of manganese and copper were slightly elevated; post-eruption concentrations of soluble manganese ranged from 8 to 170 μg/L, and suspended manganese concentrations ranged from 6 to 252 μg/L. According to the authors, manganese concentrations in the Columbia River Estuary were nearly double those previously reported. Experimental data by the authors pointed to volcanic ash as the source of the manganese. Similarly, soluble copper concentrations were somewhat elevated. Concentrations of manganese were related to levels of salinity; however, copper concentrations were not as closely linked to saline concentration.

The increased turbidity caused light attenuation in the water column and likely affected photosynthetic rates of phytoplankton for more than a month (Frey and others,1983). Despite the reduction in photosynthesis, phytoplankton biomass was not greatly affected, because a large amount of the biomass in estuarine water is derived from the Columbia River—although the estuary itself is also a site of phytoplankton production.

Laboratory experiments conducted with the Pacific herring *(Clupea harenqus pallasi)* show that the egg stage of the organisms could possibly be affected by smothering effects caused by the settling of suspended solids, provided the solids were in high enough concentration. Such smothering effects were considered unlikely except in localized areas of dredging.

EFFECTS OF THE ERUPTION ON GROUND WATER

The eruption of Mount St. Helens attracted the attention of agencies and researchers concerned with possible effects on ground water. Some issues arose as a consequence of obvious impacts to municipal wells. For example, the well supplying Toutle, Washington, and its entire water-treatment system was literally buried under mud and ash after the eruption of May 18, 1980. Other problems were more subtle, and there was speculation that the ashfall in some drainage basins might affect stream runoff. According to Datta and others (1983, p. 3–4):

> Runoff is related, in addition to precipitation, to baseflow occurring as recession from ground-water storage, which is fed by infiltration from previous storms. Infiltration is dependent, in turn, on the permeability of the soil.

According to the authors, large amounts of ashfall on parts of the drainage basin areas may have reduced the infiltration capacity of the soils, because the ash tended to form a fine, almost impermeable material, thereby preventing normal infiltration of rainfall. This effect might have been expected to be more pronounced in parts of a watershed where ashfall covered clearcut or blast-affected areas. Conversely, where ash fell into undamaged forests that had litter and understory vegetation, the infiltration capacity of the soil would not be affected.

Another hypothetical problem area was related to the possibility that ash leachate containing toxic chemical compounds or trace metals might percolate down to the ground water over a period of time. This question was raised by environmental engineers, who speculated that large quantities of ash disposed of in landfills might react with acidic materials to release toxic metals. Similarly, depending on the amount of ash falling in an area, preexisting springs and wells were thought to be possibly affected by ash or ash leachate, which led to increased analyses of water from such sources. Early reports by various researchers about chemicals such as phenolic compounds gave these investigations a sense of urgency, and concerns beyond the aesthetic problems of odor or turbidity gave an impetus to investigations on ground-water quality. This report summarizes findings reported in the literature; however, there is a relative scarcity of reports related to effects on ground water, compared to extensive references dealing with effects on surface water.

Formation of Depression Ponds

A phenomenon related to ground water involved the formation of depression ponds after the eruption. The upper North Fork Toutle River valley was virtually transformed into a barren landscape devoid of vegetation by the debris avalanche. Rosenfeld and Beach (1983, p. 70–71) described the ground surface in this region as consisting of: "* * *erratically distributed accumulations of rock, ash, ice, snow, and other debris." Hundreds of depressions created on this terrain began to fill with water. Water was derived in part from the melting of snow and blocks of glacial ice that had been carried down the mountain with the debris avalanche and mudflows. The authors, however, regarded the principal source of water for the ponds to be surface runoff and subsurface water. Where the ground-water level intersected the lower parts of the depressions in the ground, ponds formed. Subsurface water flow created and in many cases helped maintain the ponds. Many of the ponds were ephemeral and would dry out during the summer months when precipitation was low. Ponds with a relatively large surface area generally were perennial. According to Rosenfeld and Beach (1983, p. 72):

> [The] areas having a preponderance of depression ponds are located within Elk Rock narrows (N 1/2, Sec. 7, T9N, R4E), and southwest of Coldwater Lake (Sec. 2 and 11, T9N, R4E).

Changes in Ground-Water Levels

In April 1986, Federal, State, and local agencies formed an interagency group to study ground-water-related problems in the sanitary-sewer systems of Kelso, Lexington, and Castle Rock, Washington. A rise in ground water was seen as a possible contributing factor to the formation of "collapse holes" above sewer lines in those locales. The collapse holes damaged roadways and in some cases were associated with plugged sewer lines. The interagency group investigated the cause of elevated ground-water levels and the associated collapse holes and endeavored to determine whether there was any association between these phenomena and eruption-related mudflows along the Cowlitz River.

After the eruption, most damaged sewer pipes lay beneath the water table during part of each year. Ground-collapse events seemed partly correlated with a short-term rise in the ground water during the winter, when heavy rainfall increased the water-surface height in the Cowlitz River and the level of ground water. The implied relation between ground-water and surface-water systems in this area led to the formation of several hypotheses. One hypothesis was that, since May 18, 1980, a sustained rise in ground-water levels may have taken place in alluvial aquifers adjacent to the Cowlitz River. If such a sustained rise in ground-water levels could be documented, the cause for that rise may have been dredge spoils that had been stored on the flood plains of the Cowlitz River after the eruption. Other possible causes of a sustained ground-water rise included (1) above-normal precipitation and (2) the effects of low-permeability-mudflow deposits in the Cowlitz River, which could have altered the relation of ground-water flow to the Cowlitz River. After the eruption, mudflow and debris material had been deposited in the Toutle River drainage and carried into the Castle Rock-to-Longview reach of the Cowlitz River, thereby raising the Cowlitz River bed. Ensuing changes in flow and stage characteristics and in channel geometry were linked by the investigating interagency group to alterations in the ground-water system of the Cowlitz River Valley and possibly to the collapse holes. The investigation by this interagency group prompted examination of the association between eruption-related events and historical changes in the relation between surface water and ground water. As a consequence of the ensuing studies, eruption effects on ground water in the Castle Rock to Longview-Kelso study area were delineated. The following discussions and analyses pertain to studies performed by U.S. Geological Survey scientists (F.A. Packard, U.S. Geological Survey, written commun., 1990).

A brief description of the study area's physiography and drainage is presented here as background; however, thorough descriptions of bedrock stratigraphy, unconsolidated deposits, and detailed patterns of ground-water flow are omitted for the sake of brevity. The study, located along the flood plain of the Cowlitz River in southwestern Washington, emphasizes unconsolidated aquifers beneath the flood plain extending from the Toutle River downstream to the Columbia River at Kelso-Longview. Boundaries of the study region extend short distances beyond the Cowlitz River flood plain into Tertiary bedrock hills bordering the Toutle and Columbia Rivers.

In the study area, the width of the Cowlitz River flood plain ranges from 0.5 miles at the Toutle River confluence to 1.5 miles at Kelso. At Kelso, the Cowlitz River crosses the Columbia River flood plain and flows an additional 6 miles to merge with the Columbia River. Along the 19-mile study reach, the flood plain altitude drops about 50 feet. The Coweman River, which flows into the Cowlitz River approximately 1 mile upstream from the confluence of the Cowlitz River with the Columbia River, also affects ground water in the study area. In addition, drainage canals along the borders of the city of Longview affect the ground-water system and add to the complexity of analyzing ground-water movement.

Mention of alluvial aquifer in this report refers to 40 to 60 feet of Holocene fluvial materials underlying the Cowlitz River flood plain, the major aquifer in this river valley. Underlying the flood plain of the Columbia River are fluvial deposits about 200 feet thick that overlie bedrock formations of sandstone and siltstone. Available lithologic information is not complete, but the Cowlitz River is in contact with permeable aquifer materials within the alluvial aquifer—allowing easy passage of water to and from the river. As a consequence, changes in river stage should correlate with changes in ground-water levels near the river. Regardless of seasonal lows and highs in ground-water levels, the general patterns of ground-water movement and of stream gain and loss are as follows. In the upper reach of the Cowlitz River, between the confluence of the Toutle River and Beacon Hill-Lexington area, the normal movement of ground water is from the alluvial aquifer into the river (gaining reach of the river.) The converse situation exists in the reach of the Cowlitz extending from Beacon Hill-Lexington south to the Columbia River. Here, (losing reach of the river) water from the Cowlitz and Columbia Rivers move into the alluvial aquifer, thereby charging the ground-water system. At Longview, ground water moves towards and discharges to local drainage canals. At Kelso, ground water generally moves eastward, away from the Cowlitz River, and westward from the Coweman River towards drainage channels and sloughs in the flood plain between these two rivers. Water in these drainage channels is periodically pumped back into the rivers (F.A. Packard, written commun., 1990).

From April 1986 to June 1987, water levels in the alluvial aquifers were correlated with seasonal recharge caused by rainfall and fluctuations in river stages. The frequency of sampling was such that hydrologists could document rapid changes in ground-water levels. The highest ground-water levels occurred in early December 1986 and early February 1987. Lowest ground-water levels were recorded in August 1986. Data indicate that the highest ground-water levels correlate with the maximum river heights of the Columbia and Cowlitz Rivers. On a seasonal basis, these high levels of ground water occur from December through March (F.A. Packard, written commun., 1990).

Historical and recent data provided evidence of changes in ground-water levels in the study area caused by events associated with the eruption of Mount St. Helens. North of Kelso and after the eruption, ground-water levels rose during the period from mid-June to early September 1980. The rise in ground-water level was as high as 7 feet during this period and occurred immediately after bed levels and the stage of the Cowlitz River rose due to the mudflows. During this period of ground-water and river-stage rise, rainfall and discharge were at the low levels typically seen during summer months. Conversely, between September 1980 and June 1981, the ground-water levels fell. This decline in the ground-water level took place during seasonal heavy rain and runoff periods. The decline also corresponded to the period when dredging activities in the Cowlitz River were undertaken to remove deposits of mudflow, debris, and sediments. However, later hydrographic data from 1986 show that ground-water levels had once again risen to above the May-to-June 1980 levels (F.A. Packard, written commun., 1990).

It was essential to determine if any sustained post-eruption rises in ground-water levels had occurred to be able to relate collapse-hole phenomena to the eruption. Pre-eruption water-level measurements in several piezometers installed along the lower Cowlitz River by Gibbs and Olsen, Inc., in 1970, were available. In addition, the USGS had installed 42 piezometers in the Cowlitz River valley in the summer of 1980 just after the eruption, and these provided information from the date of their completion until June 1981. Although many of these piezometers were destroyed or buried during the dredging of mudflow debris in the Cowlitz River, nearly half of the sites remained intact when 1986–87 measurements were made. In conjunction with the interagency study, an additional 58 shallow piezometers were installed on the flood plain reach in 1986, enabling mass measurements of both ground- and surface-water levels.

Essentially, evidence that ground-water levels rose on a sustained basis was obtained from data derived from both private well logs and the USGS wells (F.A. Packard, written commun., 1990).

Changes in the Cowlitz River bed and in river stage since 1980 could have caused ground-water levels to rise; evidence indicates this is the most likely hypothesis for explaining the sustained rise observed. Fifty cross sections of the Cowlitz River channel were surveyed before the eruption and periodically until 1986. These surveys show that the riverbed was higher in 1986 than in pre-eruption 1980. Hydraulic models were used, in conjunction with the sections surveyed, to provide estimates that the stage of the Cowlitz River at Kelso was 3 to 4 feet higher than pre-eruption levels and, at Castle Rock, about 6 to 9 feet higher than pre-eruption levels. These hydraulic-model-generated estimates of surface-water changes correspond to observed changes in ground-water levels where observations were available (F.A. Packard, written commun., 1990).

Another less likely hypothesis, advanced to explain sustained ground-water rises, is that annual rainfall and associated recharge increased substantially above normal, seasonally observed levels since 1980. Yearly precipitation data before and after 1980 show no such significant change, however, so it is unlikely the sustained ground-water rise could have been caused by precipitation.

An increase in recharge through dredge spoils was not considered likely, although this hypothesis was tested. In general, the dredging spoils, though extensive in places and piled up to 15 feet thick, are not so widely distributed that they could be the major cause of differences in the recharge of ground water.

The last hypothesis suggests that lower vertical-hydraulic conductivity of a mudflow layer along the bed of the Cowlitz River could have caused the sustained rise in ground water. The mudflow layer consists of particles and material having different permeability characteristics than normal river sediments, and the flow of water through this layer would be impeded. If a layer of this material lined the riverbed, then presumably either side of the gaining reach of the river would experience a rise in ground-water level as a consequence of the reduced hydraulic conductivity of the riverbed. Current dredging data indicate that 1980 mudflow material does not exist as a continuous layer along the Cowlitz River bed, although some localized deposits may still be present.

For a variety of reasons, it is unlikely that small isolated lenses of the Mount St. Helens mudflows above the Cowlitz River bed have caused sustained ground-water-level rises along any part of the lower Cowlitz River Valley (F.A. Packard, written commun., 1990).

In conclusion, it seems that the sustained ground-water rise since 1980 in this reach was caused in large part by rises in the Cowlitz River bed and stage, which was caused by the accumulation of eruption sediment. The sediments would differ from mudflow materials in composition and permeability characteristics. According to Packard (F.A. Packard, written commun., 1990):

> It is reasonable to conclude that in February 1986 the combination of an annual ground-water rise to cyclic winter levels, the sustained rise due to elevation of Cowlitz River bed and surface-water levels, and a short-term rise due to the 75-year occurrence rainfall event were closely correlated to the collapse-hole activity. To the extent that ground-water levels are responsible for the collapse, the sustained ground-water rise since 1980 increased the risk of collapse.

Effects on Wells

The eruption affected the municipal wells supplying Toutle, Washington, a small town approximately 26 miles northwest of Mount St. Helens. Prior to the eruption, the Toutle River was not a reliable municipal source of potable drinking water because of highly variable quality, high flows, and floating debris—particularly during the month of December (Svinth, 1982, p. 365). The Toutle River had a tendency to meander, rather erratically, back and forth across the Toutle River valley. This tendency in turn made locating water intake pipes a problem. For this reason, the municipal well supplying Toutle at the time of the eruptions had been drilled through riverbed sands and gravel to tap ground water. This shallow, high-capacity well was completed in 1974. The top of the well, located in the riverbed, extended above the predicted high water level and had been protected by fill. However, the well and adjacent treatment facility were buried by the mudflows caused by the eruption. While water was hauled to the town as a temporary emergency measure after the eruption of May 18, 1980, survey work was performed to locate new sources of water.

A brief historical background on wells in the area around Toutle, Washington, is presented to place water-quality problems related to the eruption in context. Historically, according to Sweet and Edwards (1983, p. 146–148), principal sources of ground water near Toutle were Pleistocene terrace deposits and Recent alluvium. The Pleistocene terrace deposits had a low hydraulic conductivity and provided marginally adequate volumes of water from wells that were dug or drilled. For that reason, the town of Toutle used the shallow, high-capacity well that had been drilled in the Recent alluvium of the Toutle River.

In terms of water quality, historical concentrations of iron and manganese in water from both Pleistocene terrace and Recent alluvial aquifers were large and imparted an unpleasant taste to the water—although there was no actual health hazard. The taste problems required water treatment to make the water more palatable. Historically, the iron concentrations in water from the alluvium and in terrace deposits ranged from 0.3 to 11.0 mg/L and from 3.1 to 16.0 mg/L, respectively. Similarly, historic manganese levels in the Recent alluvium ranged from 0.05 to 3.0 mg/L, and from 0.3 to 1.1 mg/L in terrace aquifers (Sweet and Edwards, 1983, p. 146–147). An iron-removal plant that had been an integral part of the treatment system prior to the eruption was destroyed by mudflows.

After the eruption, a new well for Toutle was drilled in Pleistocene terrace sediment near the sewage plant. This initial backup well was eventually considered unsuitable as a long-term municipal well because of insufficient discharge. This initial backup well had not provided an adequate volume of water, and iron concentrations in the water great as 13 mg/L had caused filtration problems. The search for other sources of water continued.

According to Sweet and Edwards (1983, p. 145), field reconnaissance work indicated that several proposed new sites along Outlet Creek were not adequate, so two test wells were drilled near the site of the old, buried well. Through drawdown and recovery tests, it was determined that each new well had a sustained yield of 200 gal/min (gallons per minute). However, water from the well caused complaints by residents of Toutle. After chlorination, water from well 29acc2 was said to possess a medicinal taste and an unacceptable odor. The taste and odor problems persisted in spite of the temporary treatment plant's ability to remove the large concentrations of iron and manganese. Originally, these problems were attributed to buried organic material that was penetrated by drilling. Analysis of this well water revealed that it contained up to 80 μg/L total phenols (Sweet and Edwards, 1983, p. 149). According to the authors, the presence of phenolic compounds in water was not unusual in areas where substantial decomposition of vegetation occurs. Phenol levels in the Cowlitz River had been reported by the USGS. The authors speculated that warm mud, which buried and mixed with vegetative debris after the eruption, accelerated normal processes of decomposition by providing heat. Sweet and Edwards (1983, p. 149) stated:

> [The] phenol rich, saturated, mud unit was slowly dewatering into the Recent alluvial aquifer and the Toutle River***. The phenol concentrations found in the wells completed in the recent alluvium (29acc1, 2, 3) were being directly affected by this dewatering mechanism.

Substantial levels of phenols in mudflow deposits were reported by the EPA and, on a dry-weight basis, were shown to be present in concentrations of over 10,000 μg/kg (Sweet and Edwards, 1983, p. 149). Water-quality problems associated with these wells required treatment by processes such as activated-carbon filtration. According to Svinth (1982, p. 370): "***one of the new wells, which was constructed next to the river, was totally abandoned because of a heavy woody taste and high iron content. This problem was also present in the other wells but to a lesser extent."

According to Svinth (1982, p. 370), the old, original well that had been buried was uncovered and salvaged. It was placed into operation once again, and produced about 120 gal/min. Svinth (1982, p. 370) stated:

> The water quality from this well has changed somewhat since the eruption and it consistently has a higher iron and phenol content. The turbidity of the raw water varies slightly but is consistently higher than before.

In summary, Svinth (1982, p. 373) suggested that evidence existed:

> ***to show that the mudflow has changed the composition of ground water in the vicinity of the river and that this may continue to be a problem during the foreseeable future.

Water from wells that were in operation had not previously exhibited either the taste or odor typical of phenols (Hindin, 1983, p. 3). In addition, post-eruption concentration levels of iron and manganese were increased compared to pre-eruption levels. According to the author, the ground-water changes observed could be attributed to various phenomena, which may or may not be directly related to eruption effects. One explanation was that phenols, formed and trapped in deep aquifers eons ago, somehow may have been released by eruption effects when confining beds were fractured. Through this mechanism, water containing preexisting phenolic compounds might have seeped into previously uncontaminated aquifers. Another possibility is that phenolic compounds, formed by pyrolized vegetation, subsequently mixed with mud-ash deposits and were then carried downwards into upper aquifers—the mechanism proposed by Sweet and Edwards (1983). Hindin (1983, p. 4) summarized the situation:

> In the final analysis, it does not make much difference as to the age of the phenol [or the mechanism that explains the occurrence of phenols] in respect to the city's water-supply problem. They are present now and had not been prior to May 18, 1980.

To some extent, studies on organic contaminants had been given impetus by the work of Pereira and others (1982), whose research in the north Clearwater River Basin had identified about 350 different organic chemicals, some of which had been categorized as being hydrophilic. Hindin (1983, p. 3), citing the work by Pereira and others, stated:

> [Because] of the hydrophilic nature of the organic compounds, they found the potential exists for groundwater contamination by the organics. However, well water samples in the area between the Cowlitz and Columbia Rivers showed no evidence of groundwater contamination at that time.

In followup studies, municipal well water from the City of Toutle was analyzed during August of 1981 and April of 1982 (Hindin, 1983, p. 45–48). On August 31, 1981, water from the municipal well was found to contain: 3.5 μg/L of phenol, 2.0 μg/L pentachlorophenol, 2.5 μg/L chloroform, 1.0 μg/L dichlorobromomethane, and 4.7 mg/L DOC. Subsequent testing of the well on April 7, 1982, indicates that the concentration of phenol had dropped to 1.8 μg/L, but the concentration of pentachlorophenol had reached a level of 5.0 mg/L. Similarly, the concentration of chloroform reached its highest recorded level of 5.0 μg/L, while the DOC concentration was relatively unchanged from the 1981 reading. The levels of phenol and pentachlorophenol diminished throughout 1982 but on August 31, 1982, the concentration of total haloforms (chloroform and dichlorobromomethane) was still 5.8 μg/L.

Water from the City of Toutle standby well that was analyzed during 1982 contained levels of phenol and pentachlorophenol and continued to contain concentrations of chloroform ranging from 4.8 to 13.8 μg/L. Dichlorobromomethane concentrations ranged from 1.0 to 2.0 μg/L. The levels of both haloforms gradually diminished, however, although these constituents remained within the detectable range on August 31, 1982. The DOC concentration ranged from 7.0 to 11.4 mg/L.

According to Hindin (1983, p. 69), declines in the concentration of phenol in the municipal well indicated that: "***phenols were not entering the ground water from some ancient source." A clearly defined trend for phenol in the standby well was not apparent. The pentachlorophenol reported could have originated from several sources. Pentachlorophenol is a compound widely utilized in the Pacific Northwest as a wood preservative. In other words, the compound could enter ground water from some unknown source as an artifact derived from its common use as a commercial product. Another possibility exists. Under certain unusual but natural conditions, pentachlorophenol can be formed when phenol is chlorinated. Hindin (1983, p. 1) describes events accompanying the eruption as a possible mechanism for the formation of pentachlorophenol. When Mount St. Helens erupted, vertical and near-horizontal blasts resulted in a cascade of extremely hot, gas-charged ash being discharged down the side of the mountain. This blast of ash and gas, called a nuée ardente, was estimated by scientists to have a temperature of over 530°C. The velocity of this nuée ardente was most likely over 200 miles per hour, and the mountainside experienced several of these heat-wave blasts on May 18, 1980. Hindin speculated that such extreme and extraordinary conditions may have been sufficient to form pentachlorophenol from phenol and chlorine-containing compounds.

The author did not, however, report detectable concentrations of polycyclic aromatic hydrocarbons in Toutle wells. The absence of these constituents was confirmed by other scientists, who also reported finding the haloforms described by Hindin (1983). Hindin (1983, p. 81) stated:

Polycyclic aromatic hydrocarbons, due to their hydrophobic character and affinity for adsorption on the muds, do not appear in the ground waters.

Contamination and Chemical Changes in Ground Water

Extensive post-eruption surveys of ground water from sources other than Toutle wells were conducted by Hindin (1983, p. 5), who also performed surveys of surface water that were discussed earlier in this report. Hindin's research was aimed at determining the extent to which biohazardous compounds existed in the area's ash and water, and the question of whether ground water might be contaminated by these compounds. As in the case of the Toutle wells, he determined levels of phenolic, polycyclic aromatic, and terpene compounds in ground water, surface water, and ash. Hindin also investigated the leaching of polycyclic aromatic hydrocarbons and phenols from mudflow material. The author's level of analysis, using gas chromatography, was conducted at minimum detection limits of 1.0 µg/L. For dissolved organic carbon, Hindin's minimum detectable limit was 0.2 mg/L; a concentration of 0.5 mg/L as a baseline level was utilized when analyzing the dissolved organic carbon content of wells inside and outside of mudflow plains.

Overall, Hindin's studies encompassed a 505-square-mile area of the middle and lower portions of the Cowlitz River Basin. Large parts of the study area were forested and lay within the boundaries of the Gifford Pinchot National Forest; other sections included agricultural lands, as well as the cities of Longview-Kelso, Washington. To facilitate data collection, the author elected to obtain ground-water samples from existing operating wells and springs. However, Hindin had to contend with the fact that many wells and springs in the eruption's impact area and mudflow paths were put out of operation, or covered, by the eruption. The author sampled sites outside of the October 1980 restricted red zone and also received samples from Weyerhaeuser Corporation's wells located within the restricted area.

A particularly interesting set of findings was obtained by Hindin (1983, p. 25) through the use of field interviews. Residents in the study area were asked whether they experienced any unusual water-quality or water-quantity problems during the time seismic activities were recorded at Mount St. Helens. For example, prior to the major eruption on May 18, 1980, during the period from early February 1980 through May 17, 1980, various residents reported increased silt and turbidity in rural wells. These particular residents lived in the area south of Toutle, Washington. Hindin (1983, p. 25) cited one particularly dramatic example that occurred early in the day on May 18, 1980. At that time, one family reported observing an actual "surge of water" in their well, which according to Hindin (1983, p. 25), "[was] followed by a drop in the water level, and finally the well became dry for several minutes." When water returned to the well, it contained considerable silt and was a "rusty color." After a period of time, the silt and turbidity cleared. However, the water remained rust colored.

A number of wells and springs outside the mudflow plain were sampled throughout 1981 and 1982, and the reader is referred to the report by Hindin (1983) for a list of sites and analytical data. Although most of the constituents were not detected at the analytical limits (discussed above) of Hindin's methodology, the chemical constituents studied are presented for the use of the reader, who may need information on the compounds in the analytical list:

(1) phenolic compounds: 2-chlorophenol; 2-nitrophenol; phenol; 2,4-dimethylphenol; 2,4-dichlorophenol; 2,4,6-trichlorophenol; 4-chloro-3-methylphenol; 2,4-dinitrophenol; and pentachlorophenol;

(2) polycyclic aromatic hydrocarbons: anthracene; benzo (a) anthracene; benzo (a) pyrene; benzo (e) pyrene; chrysene; fluoranthene; perylene; phenanthrene; pyrene; and triphenylene;

(3) terpenes: camphene; alpha-pinene; beta-cymene; terpinene-4-ol; and alpha-terpineol;

(4) haloforms: chloroform; dichlorobromomethane; dibromochloromethane; total haloforms; and

(5) dissolved organic carbon.

Hindin (1983, p. 69) summarized his findings on wells outside the mudflow plain by stating that, with few exceptions, the wells did not contain detectable levels of dissolved organic carbon. Such wells, Hindin (1983, p. 69) further stated, "***did not contain detectable concentrations of the specific organic compounds being analyzed or of the haloform precursors."

Hartz and others (1984, p. I-28) evaluated the possibility that ash dumped in municipal landfills after the eruption might have contaminated the ground water. Many towns and cities lying within the ashfall plume discarded the ash collected during cleanup activities in landfills and dumps. Leachate from landfills is generally acidic, in large part due to the production of organic acids by the anaerobic microbial decomposition of solid wastes. As water infiltrates through long-established landfills, it can encounter zones of leachate with acidic pH values attributable to the organic acids. Historically, even without the presence of volcanic ash, there have been concerns about the pollution of ground water by water leaching various chemicals from landfills. It was soon recognized that the volcanic ash may be a source of potential contaminants such as trace metals, and it was hypothesized that the low pH and conditions characteristic of a landfill might lead to increased leaching of trace and heavy metals from the ash. An ancillary question was related to the ability of subsoils beneath a landfill to attenuate leached materials from the landfill. According to Hartz and others (1984, p. I-3) leachate attenuation is the process by which a soil can reduce the amount of any water-quality constituent passing down through a column of soil.

By using lysimeters, Hartz and others (1984, p. I-28) experimentally tested the potential for groundwater contamination by applying ash leachate to various native soils. A lysimeter is a device used to measure the rate of percolation of water through soils and to determine the concentrations of soluble constituents in the drainage water. Although these methods are simulations, information can be generated about hypothetical situations occurring in full-scale landfill operations (Flaherty, 1983, p. 37). Hartz and others (1984) collected a variety of ash samples from six geographic sites in the ashfall plume, and soil samples were collected from the same areas of ash sampling. Both soil and ash were analyzed for a variety of physical and chemical characteristics; parameters such as particle size, cation-exchange capacity, and extractable metals were analyzed. Ash was sampled from representative sites such as Pullman, Spokane, Yakima, and Moses Lake, Washington. Similar to the findings of other researchers, the authors found significant variation in the heavy metal content of ash samples, depending on the sampling site's location in the plume. Ash samples were collected from six different locations lying within the volcanic ash plume. Soil samples were collected from the B horizon of six different soil series in the same geographic vicinity. Shredded solid waste was mixed with the ash samples in sealed lysimeters to simulate ash and refuse conditions in a landfill. Each sample lysimeter had water added on a weekly basis, and the leachate from the lysimeters was collected and analyzed. Samples of the leachate were added at intervals to a set of columns that contained the six soil types representing the different study areas. After a 9-month period, which simulated a 3-year-rainfall period, soils from the columns was analyzed. The migration of contaminants, such as metals, down through the soil column was investigated. For experimental methods, details, and data, the reader is referred to the report by Hartz and others (1984, p. I-60), who summarized their experimental findings as follows:

(1) The presence of volcanic ash aids in the reduction of leachate chemical oxygen demand.

(2) The presence of volcanic ash aids in the reduction of leachate boron, iron, chloride, and zinc concentration.

(3) Volcanic ash has the potential to contaminate leachate water with selenium, lead, chromium, and arsenic.

(4) Leach water contamination from volcanic ash will be significantly lower than the contamination produced by typical refuse.

(5) Leach water contamination by chrome appears to increase as water volume increases, based upon these test conditions.

(6) Landfills located on the north side of the fallout plume appear to have greater potential for producing leachate streams of health concern.

(7) The investigated soils appear to impede the travel progress of the leachate metals. Rates of travel for any of the contaminants does not appear to exceed more than a few inches per year.

The influences of weathering on ash in the Iron Creek drainage system and the possible changes in surface and ground waters were studied by White and others (1981, p. 579). The Iron Creek drainage is approximately 6.2 miles northeast of the volcano. Samples were taken from the creek and tributaries, and from lysimeters that had been installed through layers of ash upon the ground. In this study area, ashfall from

the May 18, 1980, eruption ranged from 1.2 to 3.9 inches in depth. The study provided information on transport of major chemical constituents in surface and ground waters, after ash had been leached or weathered in a natural environment. The authors reported increases of sodium, potassium, and silicon in water samples. The increases in these constituents corresponded to areas receiving the most ash; maximum weathering was observed during the winter season, when surface runoff was at a maximum. According to White and others (1981, p. 579):

> A considerable portion of potassium is being fixed within the soil zone.*** X-ray photoelectron spectroscopy (XPS) indicates that sodium had been completely leached from the surface of ash particles within a month after the eruption, which correlates with increases observed in the aqueous phase.

Gradually, the concentrations of surface potassium decreased and the concentrations of iron and calcium increased. It appeared that as weathering proceeded, secondary surface phases formed that were related to the changes in concentration of iron and calcium.

Summary of Eruption Effects on Ground Water

Changes in ground-water levels were considered a contributing factor in problems associated with sanitary-sewer systems of Kelso, Lexington, and Castle Rock, Washington. During parts of the year, some sewer lines were found to lie beneath the water table that became elevated after the eruption; subsequently, collapse holes were formed. The settling of the ground, due to the increased amount of water in the soil at the shallow depths, caused sewer lines to settle and become stressed. These damaged sewer lines, in turn, caused surface-ground-collapse holes to form. The ground-collapse events seemed correlated with a rise in ground-water levels. A hypothesis to logically explain these phenomena is that the sustained ground-water change resulted in large part from rises in the Cowlitz River bed and from surface-water elevation caused by the accumulation of sediment from the eruption. A short-term rise in the river level, due to heavy rainfall, likely contributed to the collapse-hole problems.

A number of wells existing at the time of the eruption were affected by the volcanic events—particularly wells in the vicinity of Toutle, Washington, within the mud-covered flood plains caused by the eruption. Several new wells, installed to replace water supplies directly disrupted by the volcanic effects, yielded water with large concentrations of iron and manganese; some new wells yielded water with moderate levels of dissolved organic carbon. Phenol compounds also were reported. It was suggested that hot or warm mud, mixed with vegetative debris, accelerated decomposition processes by the addition of heat and that the phenol compounds that were formed found their way into Recent alluvial aquifers connected to the Toutle River. A variety of organic compounds was reported in various wells in and around Toutle, and haloforms, like chloroform, were reported in addition to phenol and pentachlorophenol. It was suggested that chlorinated phenols may have been formed from phenol and chlorine, when combined through the action of gas blasts. Many other compounds were detected, in varying concentrations, in wells distributed over a wide area near Toutle, Washington.

Experiments evaluating the possibility that ash dumped in landfills might contaminate ground water were performed. The results of these experiments were previously presented in this report and are not repeated here.

EFFECTS OF THE ERUPTION ON PRECIPITATION

The most direct means of describing volcanic effects on precipitation involves examination of historical records of precipitation before, during, and after the eruptive events.

Events associated with the major May 18, 1980, eruption have been emphasized in this report; however, prior to and after the major explosion, several minor eruptive events dispersed varying quantities of ashfall. Precipitation recorded at a particular sampling site depended on the site's location in the ash plume and was affected by climatic factors such as direction and altitude of prevailing winds. To analyze volcanic effects on precipitation, historical information on many variables should be available.

The hydrologic effects, including analyses of precipitation effects, of the Mount St. Helens eruptions on the Bull Run Watershed, Oregon, were studied by Shulters and Clifton (1980). The Bull Run Watershed is about 50 miles south of the volcano, south of the Columbia River in the State of Oregon.

The 102-square-mile watershed provides the main water supply for the City of Portland, Oregon; there were concerns that it might be affected by ashfall if wind carried ash south from the volcano to the watershed. Prior to the major eruption on May 18, 1980, there had been a minor eruption and ashfall on March 30, 1980. The ash from this eruption had been wind-borne to the Bull Run Watershed. Similarly, on other occasions, ash was ejected to high altitudes and carried to the watershed by north-northwesterly winds. Although the prevailing winds carried ash away from the watershed during the explosion of May 18, 1980, another eruption transported ash via high-altitude northerly winds to the watershed and nearby Portland metropolitan region on May 25, 1980. Ash also fell on the watershed on June 3, 1980, and on June 12–13, 1980. In anticipation of a major eruption, presaged by the minor eruptive events, precipitation and ash collectors were placed at five locations in the Bull Run Watershed by the U.S. Geological Survey.

Samples of snow that had been covered by ash from the earlier eruption of March 30, 1980, were collected and analyzed. The bulk of the precipitation samples were taken June 13, 1980, to analyze the effects of the June 12–13, 1980, ashfall. Precipitation data were collected in conjunction with stream water-quality data in the watershed. Pre-eruption information dating to 1973 was available from records kept by the City of Portland Water Bureau. However, no baseline precipitation data for the Bull Run Watershed were available.

The authors reported on various properties and constituents of precipitation samples. Characteristics measured included pH, specific conductance, sulfate, chloride, fluoride, calcium, magnesium, potassium, silica, and alkalinity and hardness as calcium carbonate. Data relating the following three variables were presented graphically:

(1) precipitation at the Bull Run headworks,

(2) maximum northerly wind speed, and

(3) maximum ash-plume elevation.

The data and graphs that correlate these variables indicate that on June 12, 1980, when a high elevation ash plume was carried for many miles by northerly winds, precipitation at the Bull Run headworks on June 12, 1980, was the highest recorded in the 2-1/2-month period examined. On May 18–20, 1980, there was no recorded daily precipitation at the Bull Run headworks. There were no northerly winds to carry the ash plume to the sample sites during this period, although the plume attained maximum heights during the 3-day timespan. The statistical significance of these observations cannot be evaluated without more historical data, but they point to a possible field of further inquiry. For example, might ash particles serve as condensation nuclei for water vapor or steam that was generated by eruption processes?

Data from seven precipitation sampling stations indicate that after the June 12, 1980, ashfall on the watershed, the specific conductance of the samples at 5 of 7 stations was a maximum for the sampling period April 2 to June 13, 1980. For example, at sampling site 1, the specific conductance ranged from 8 to 16 µS/cm at 25°C before the June 12, 1980, ashfall; whereas on June 10–13, 1980, the specific conductance was 41 µS/cm. Data on pH were available for seven sites during the period May 19, 1980, to June 13, 1980. Acidic pH values ranging from 4.0 to 4.3 were recorded at all sites during the period June 10–13, 1980. This is a substantial change from a range of pH values (5.2 to 5.4) recorded during May 19–28, 1980, when the ashfall was primarily carried eastward from Mount St. Helens and away from the Bull Run Watershed. Shulters and Clifton (1980, p. A7) summarized their conclusions:

> In most precipitation samples collected on June 13 [1980], the specific-conductance values are higher than in any of the previous samples and are about equal to or greater than stream conductivities on the same day. Nearly all the precipitation collected on this date fell during and immediately following the June 12 ashfall. Precipitation data ***seem to show that pH decreases as specific conductance increases.

Lewis and Grant (1981, p. 1539) analyzed precipitation chemistry records for the Como Creek Watershed, located in the Rocky Mountains of Colorado. (Not shown on plate 1; see Lewis and Grant, 1981, for details.) In operation since June 1975, the Como Creek Watershed is the oldest precipitation-chemistry-collection site in the Western United States and is located at 40°2′ N., 105°32′ W., in the central Rocky Mountains. Sample collectors are mounted 13 feet above the ground at a cleared forest site. The precipitation study site is relatively unaffected by human activities, because few people live within a 12-to 19-mile radius of the station. The apparatus is used to collect wet and dry fractions, and precipitation chemistry data represents a composite of wet and dry deposition. The authors averaged the data for two

stations that are located 0.6 miles apart, because there were no significant differences in the amounts of the components examined.

According to Lewis and Grant (1981, p. 1540), May 17 to June 21, 1980, was selected as the observation window and the collected data incorporated information related to major ashfall events that occurred on May 18, 1980, May 25, 1980, and June 12, 1980. The authors compared data for the observation window to historical information corresponding to equivalent time periods of the previous 4 years and also examined comparison windows that were 5-week periods preceding the observation window. This second window was a control, which was used to detect other possible changes related to annual differences not associated with volcanic phenomena. Data from the background windows were tabulated for the years 1975 to 1979 and compared to the 1980 volcano year data. Constituents examined included major cations; bicarbonate; sulfate; chloride; phosphate phosphorus; nitrate, nitrite, and ammonia-nitrogen; dissolved organic carbon, nitrogen, and phosphorus; insoluble compounds; and pH.

Lewis and Grant (1981, p. 1541) stated that observed precipitation loading rates do not differ substantially for any variables at a significant statistical level. According to the authors (Lewis and Grant, 1981, p. 1541):

> [The] data are suggestive of increased phosphorous and chloride loading, but the probability levels are well above 0.05. [Similarly, the level of particulate loading seemed to be slightly higher than observed during background years. During the peak-week-ashfall period, the particulate loading was at the] highest level we have recorded for the observation window over a 5-year span, which is almost certainly due to ash.

The authors, however, stated that comparisons of data from the entire observation window with corresponding background windows reveal no substantial differences in aggregate particulate loading.

According to Lewis and Grant (1981, p. 1541), observed sulfate and major cation-loading rates were lower than normal but were attributed to decreased wet precipitation during the observation window period. The correction of loading rates to average background precipitation levels by regression statistical methods show few changes of statistical significance. The pH values reported during the observation period (4.49) were lower than values (4.99) for the corresponding background windows, but the authors did not consider this change to be statistically significant. The same lack of statistical significance existed for bicarbonate loading, which seemed to be lower during the observation time. In summary, Lewis and Grant (1981, p. 1541) concluded:

> [The] chemical deposition effects of the volcanic releases*** were easily within the normal background of variation between weeks and between years by the time the materials had been dispersed as far as the central Rockies.

Bulk precipitation chemistry in the Como Creek Watershed, Colorado, was analyzed by Lewis and Grant (1981). The authors concluded that observed precipitation loading rates for various chemical constituents did not differ substantially at significant statistical levels. Some changes in sulfate and cation loading rates were observed, in addition to slightly lower pH values and concentrations of bicarbonate. Nonetheless, the authors considered observed changes to be within the historical range of variation.

The distance between the sampling sites of Lewis and Grant (1981) and the volcano should be considered when evaluating the analyses and conclusions. Investigations by various authors (cited in this report) point to significant differences in the physical and chemical characteristics of ash falling at various locations. In general, the magnitude of change in chemical characteristics in surface waters was inversely related to the distance away from the volcano. The extent to which a distance factor applies to precipitation effects is not clearly documented; however, the work of Shulters and Clifton (1980), who studied the effects of ashfall much closer to the volcano, at least suggest that distance may be a factor.

Shulters and Clifton (1980) reported changes in the specific conductance, and possibly pH, that likely were related to ashfall events. It appears possible that volcanic ash has some effect on precipitation. In terms of research, it was and still is extremely difficult to design sampling programs to test various hypotheses concerning volcanic effects because of the inability to predict when and where an ashfall plume will occur. The availability of preestablished, well-distributed, precipitation-sampling sites, with adequate baseline data for comparative purposes, is a matter of chance—and will likely be a continuing problem for future investigators.

SELECTED REFERENCES

The references listed here are by no means a completely exhaustive bibliography of all the papers dealing with the effects of the eruptions of Mount St. Helens on various aspects of water quality and precipitation. However, the list adequately represents the literature published within a 2- to 3-year period following the 1980 eruptions and in some cases draws upon papers published somewhat later. The emphasis on the early papers is deliberate; if all papers dealing with followup studies were included, some of which were begun long after 1980, this review would be virtually open-ended. This literature review deals mainly with projects that were initiated early during the volcanic activity, to provide a retrospective appraisal of which topics were or were not covered during the initial stage of change. Due to rapidly changing events and phenomena associated with volcanic eruptions, this review should provide clues regarding what was previously researched and what might need to be accomplished in the future. The references were selected to examine these questions.

Anderson, R.Y., Nuhfer, E.B., Dean, W.E., and Delmastro, G.A., 1984, Sedimentology of Mount St. Helens tephra at Merrill, Soap, and Williams Lakes, Washington, USA [abs.]: Geological Society of America Abstracts with Programs, v. 16, no. 6, p. 430.

Baker, E.T., and Curl, H.C., Jr., 1981, Observations of the Columbia River plume after the eruption of Mount St. Helens: Coastal Ocean Pollution, Assessment News, 1, p. 1–2.

Baross, J.A., Dahm, C.N., Ward, A.K., Lilley, M.D., and Sedell, J.R., 1982, Initial microbiological response in lakes to the Mount St. Helens eruption: Nature, 296, no. 5852, p. 49–52.

Bartlett, Larry, Rabe, F.W., and Funk, W.H., 1974, Effects of copper, zinc, and cadmium on *Selanastrum capricornutum*: Water Research, v. 8, p. 179–185.

Bisson, P.A., Nielsen, J.L., and Ward, J.W., 1988, Summer production of coho salmon stocked in Mount St. Helens streams 3–6 years after the 1980 eruption: Transactions of the American Fisheries Society, 1988, v. 117, no. 4, p. 322–335.

Boehlert, G.W., 1984, Abrasive effects of Mount Saint Helens ash upon epidermis of yolk-sac larvae of Pacific herring, *Clupea harengus pallasi:* Marine Environmental Research, 12, no. 2, p. 113–126.

Boehlert, G.W., Morgan, J.B., and Yoklavich, M.M., 1983, Effects of volcanic ash and estuarine sediment on the early life history stages of the Pacific Herring, *Clupea harengus pallasi*: Washington, D.C., U.S. Department of the Interior, Bureau of Reclamation, Final Technical Completion Report, WWRI-87, Grant No. 14-34-0001-1461, 73 p. [Available from State of Washington Water Research Center, Washington State University, Pullman, Washington 99164-3002.]

Bonelli, J.E., and Taylor, H.E., 1981, Impact of Mount St. Helens eruption on hydrology and water quality, *in* Hemphill, D.D., ed., Conference on trace substances in environmental health, 15th, Columbia, Missouri, 1981, Proceedings: University of Missouri Environmental Trace Substances Research Center and Extension Division, p. 261–264.

Bonelli, J.E., Taylor, H.E., and Klein, J.M., 1980, Impact of Mount St. Helens eruption on hydrology and water quality, *in* Deepak, Adarsh, ed., Symposium on atmospheric effects and potential climatic impact of the 1980 Eruptions of Mount St. Helens, Washington, D.C., November 18–19, 1980, Proceedings: National Aeronautics and Space Administration, NASA Conference Publication 2240, p. 43–46.

Bortleson, G.C., Dion, N.P., McConnell, J.B., and Nelson, L.M., 1976, Reconnaissance data on lakes in Washington, v. 4: Washington Department of Ecology, Water-Supply Bulletin 43, 197 p.

Boyd, R.F., and Marr, J.J., 1980, Medical microbiology: Little, Brown and Co., 1st ed., Boston, Massachusetts, 753 p.

Brannon, E.L., Whitman, R.P., and Quinn, T.P., 1981, Report on the influence of suspended volcanic ash on the homing behavior of adult chinook salmon *(Oncorhynchus tshawytsha)*: Final report to the Office of Water Research and Technology Reports and Proposals Control Center, Grant Agreement No. 14-34-0001-1422, 30 p. [Available from State of Washington Water Research Center, Washington State University, Pullman, Washington 99164-3002.]

Brown, Carol, and Seidler, R.J., 1973, Potential pathogens in the environment—*Klebsiella pneumoniae*, a taxonomic and ecological enigma: Applied Microbiology, 25, no. 6, p. 900–904.

Brzezinski, M.A., and Holton, R.L., 1983, A report on the macroinvertebrates of the Columbia River Estuary found in deposits of volcanic ash from the May 18, 1980 eruption of Mount St. Helens: Estuaries 6, p. 172–174.

Burgis, Mary, 1987, The natural history of lakes: Cambridge, Great Britain, Cambridge University Press, 218 p.

Campbell, K.P., Johnson, S.R., Wolniakowski, K.U., 1982, A pilot study of potential phenolic contamination of fishes in the Columbia River and tributaries in the vicinity of Mount St. Helens, Final Report: Portland, Oregon, Beak Consultants, Inc., 32 p. [Available from National Technical Information Service, Springfield, Virginia 22161 as NTIS Report PB–83 146–357.]

Collins, B.D., Dunne, Thomas, and Lehre, A.K., 1982, Sediment influx to the Toutle River from erosion of tephra, May 1980–May 1981, *in* Conference on Mount St. Helens—Effects on water resources, Jantzen Beach, Oregon, 1981, Proceedings: Pullman, Washington, State of Washington Water Research Center, Washington State University, and the University of Washington, Report No. 41, p. 82–97.

Crandell, D.R., and Mullineaux, D.R., 1978, Potential hazards from future eruptions of Mount St. Helens volcano, Washington: U.S. Geological Survey Bulletin 1383–c, 26 p.

Crawford, B.A., 1986, The recovery of surviving fish populations within the Mount St. Helens National Volcanic Monument and adjacent area, *in* Keller, S.A.C., ed., Mount St. Helens—Five years later: Cheney, Washington, Eastern Washington University Press, p. 293–296.

Cummans, John, 1981, Mudflows resulting from the May 18, 1980 eruption of Mount St. Helens, Washington: U.S. Geological Survey Circular 850-B, 16 p.

Cushing, C.E., and Smith, S.D., 1982, Effects of Mount St. Helens ashfall on lotic algae and caddisflies: Journal of Freshwater Ecology: v. 1, no. 5, p. 527–538.

Dahm, C.N., Baross, J.A., Lilley, M.D., Ward, A.K., and Sedell, J.R., 1981, Microbial and chemical responses of lakes in the blast zone, Mount St. Helens, 1980 and 1981 [abs.]: Eos (American Geophysical Union Transactions), v. 62, no. 45, p. 868.

———1982, Lakes in the blast zone of Mount St. Helens—Chemical and microbial responses following the May 18, 1980 eruption, *in* Conference on Mount St. Helens—Effects on water resources, Jantzen Beach, Oregon, 1981, Proceedings: Pullman, Washington, State of Washington Water Research Center, Washington State University, and the University of Washington, Report No. 41, p. 98–137.

———1983, Initial effects of the Mount St. Helens eruption on nitrogen cycle and related chemical processes in Ryan Lake: Applied and Environmental Microbiology, v. 45, no. 5, p. 1633–1645.

Datta, Bithin, Lettenmaier, D.P., and Burges, S.J., 1983, Assessment of changes in storm and seasonal runoff response of watersheds impacted by Mount St. Helens ash deposition: U.S. Department of the Interior, OWRT Agreement No. 14–34–111–1429, Bureau of Reclamation, Water Resources Series Technical Report No. 82, 96 p. [Available from State of Washington Water Research Center, Washington State University, Pullman, Washington 99164-3002.]

Davis, P.T., 1982, Tephrochronology, Davis Lake, southwest Washington *in* Keller, S.A.C., ed., Mount St. Helens—One year later [abs.]: Cheney, Washington, Eastern Washington University Press, p. 235–236.

Dethier, D.P., Frank, David, and Pevear, D.R., 1980, Chemistry of thermal waters and mineralogy of the new deposits at Mount St. Helens—A preliminary report: U.S. Geological Survey Open-File Report 81–80, 23 p.

Dinehart, R.L., 1986, Sediment data for streams near Mount St. Helens, Washington, v. 2, Water Years 1981–83: U.S. Geological Survey, Open-File Report 85–632, 438 p.

Dinehart, R.L., and Culbertson, J.K., 1982, Sediment-discharge characteristics of the Toutle River following the Mount St. Helens eruption, *in* Conference on Mount St. Helens—Effects on water resources, Jantzen Beach, Oregon, 1981, Proceedings: Pullman, Washington, State of Washington Water Research Center, Washington State University, and the University of Washington, Report No. 41, p. 149.

Dion, N.P., and Embrey, S.S., 1981, Effects of Mount St. Helens eruption on selected lakes in Washington: U.S Geological Survey Circular 850–G, 25 p.

Edmondson, W.T., 1984, Volcanic ash in lakes: Northwest Environmental Journal, v. 1, no. 1, p. 139–150.

Edmondson, W.T., and Litt, A.H., 1983, Mount St. Helens ash in lakes in the Lower Grand Coulee, Washington State: National Technical Information Service, Springfield, Virginia 22161, CONF–8308226–1, DE86 010297, 12 p.

———1984, Mount St. Helens ash in lakes in the lower Grand Coulee, Washington State, *in* International Association of Theoretical and Applied Limnology: Proceedings v. 22, part 1, p. 510–512.

Embrey, S.S., and Dion, N.P., 1982, Effects of Mount St. Helens eruption on nearby lakes in Washington, *in* Conference on Mount St. Helens—Effects on water resources, Jantzen Beach, Oregon, 1981, Proceedings: Pullman, Washington, State of Washington Water Research Center, Washington State University, and the University of Washington, Report No. 41, p. 150.

———1988, Effects of the 1980 eruption of Mount St. Helens on the limnological characteristics of selected lakes in western Washington: U.S. Geological Survey Water-Resources Investigations Report 87–4263, 60 p.

Faulconer, Lee, and Mongillo, Paul, 1981, Effects of Mount St. Helens ashfall on three trout streams and Bumping Lake in the Yakima Basin: Washington State Game Department Bulletin 16, 34 p.

Flaherty, D.C., 1983, Mount St. Helens—The aftermath: Office of Water Research and Technology, Bureau of Reclamation, U.S. Department of the Interior, 65 p. [Available from State of Washington Water Research Center, Washington State University, Pullman, Washington 99164-3002.]

Foxworthy, B.L., and Hill, Mary, 1982, Volcanic eruptions of 1980 at Mount St. Helens—The first 100 days: U.S. Geological Survey Professional Paper 1249, 125 p.

Franklin, J.F., Frenzen, P.M., and Swanson, F.J., 1988, Re-creation of ecosystems at Mount St. Helens—Contrasts in artificial and natural approaches, *in* v. II, chap. 11, Cairns, John, ed., Rehabilitating Damaged Ecosystems: Boca Raton, Florida, CRC Press, Inc., 222 p.

Franklin, J.F., MacMahon, J.A., Swanson, F.J., and Sedell, J.R., 1985, Ecosystem responses to the eruption of Mount St. Helens: National Geographic Research, v. 1, p. 198–216.

Frenzel, S.A., 1983, Effects of volcanic ash on the benthic environment of a mountain stream, northern Idaho: U.S. Geological Survey Water-Resources Investigations Report 82–4106, 32 p.

———1984, Effects of volcanic ash on aquatic environments in northern Idaho [abs.]: U.S. Geological Survey Professional Paper 1375, p. 230.

Frey, B.E., Lara, J.R., and Small, L.F., 1983, Reduced rates of primary production in the Columbia River Estuary following the eruption of Mount St. Helens on 18 May 1980: Estuarine, Coastal and Shelf Science, v. 17, no. 2, p. 213–218.

Fruchter, J.S., Robertson, D.E., Evans, J.C., Olsen, K.B., Lepel, E.A., Laul, J.C., Abel, K.H., Sanders, R.W., Jackson, P.D., Wogman, N.W., Perkins, R.W., Van Tuyl, H.K., Beauchamp, R.H., Shade, J.W., Daniel, J.L., Erickson, R.L., Sehmel, G.A., Less, R.N., Robinson, A.V., Moss, O.R., Briant, J.K., and Cannon, W.C., 1980, Mount St. Helens ash from the 18 May 1980 eruptions: Chemical, physical, mineralogical and biological properties: Science, September 1980, v. 209, p. 1116–1125.

Fuhrer, G.J., and Rinella, F.A., 1983, Analyses of elutriates, native water, and bottom material in selected rivers and estuaries in western Oregon and Washington: U.S. Geological Survey Open-File Report 82–922, 147 p.

Funk, W.H., 1980, Effects of ash fallout on eastern Washington lakes and the upper Spokane River, *in* Cassidy, J.J., chairperson, Conference on the aftermath of Mount St. Helens, Pullman, Washington, 1980, Proceedings: Pullman, Washington, Washington State University, p. 18–19

Fuste', L.A., 1981, Effects of the Mount St. Helens eruption on the benthic fauna of the Toutle River, Muddy River, and Pine Creek drainage basins, Washington: U.S. Geological Survey Circular 850–H, 13 p.

Haeni, F.P., 1983, Sediment deposit in the Columbia and lower Cowlitz River, Washington-Oregon, due to the May 18, 1980, eruption of Mount St. Helens: U.S. Geological Survey Circular 850–K, 21 p.

Hartz, K.E., Bhagat, S.K., Starlin, L.A., Mott, H.V., and Krivanek, K.R., 1984, Attenuation of leachate generated from co-disposal of volcanic ash and solid waste, 97 p. [Available from the State of Washington, Water Research Center, Washington State University, Pullman, Washington 99164-3002.]

Hawkins, C.P., 1988, Effects of watershed vegetation and disturbance on invertebrate community structure in western Cascade streams—Implications for stream ecosystem theory: International Vereinigung fuer Theoretische and Angewandte Limnologie, Verhandlungen IV TLAP, v. 23, no. 2, p. 1167–1173.

Hawkins, C.P., and Anderson, N.H., 1982, Habitats and fauna—The aftermath of the Mount St. Helens eruption in stream systems, *in* Keller, S.A.C., ed., Mount St. Helens—One year later [abs.]: Cheney, Washington, Eastern Washington University Press, p. 237.

Hindin, Ervin, 1983, Occurrence of organic compounds in water and stream sediments due to the Mount St. Helens eruptions: Pullman, Washington, Washington Water Research Center Report 52, 91 p. [Available from State of Washington Water Research Center, Washington State University, Pullman, Washington 99164-3002.]

Hoblitt, R.P., Miller, C.D., and Vallance, J.W., 1981, Origin and stratigraphy of the deposit produced by the May directed blast, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 401–420.

Hooper, P.R., Herrick, I.W., and Laskowski, E.R., 1980, Composition of the Mount St. Helens ashfall in the Moscow-Pullman area on 18 May 1980: Science, v. 209, September 1980, p. 1125–1126.

Hopman, R.J., 1982, An update on dredging activities in the Pacific Northwest, *in* Willey, R.G., ed., Seminar on attaining water-quality goals through water-management procedures, Dallas, Texas, 17–18 February 1982, Proceedings: Washington D.C., U.S. Army Corps of Engineers Committee on Water Quality, p. 135–142.

Hubbell, D.W., Laenen, Julija M., McKenzie, S.W., 1983, Characteristics of Columbia River sediment following the eruption of Mount St. Helens on May 18, 1980: U.S. Geological Survey Circular 850–J, 21 p.

Hutchinson, B.E., 1957, A treatise on limnology, Volume I, Geography, Physics, and Chemistry: New York, John Wiley and Sons, 1014 p.

Janda, R.J., Scott, K.M., Nolan, K.M, and Martinson, Holly A., 1982, Lahars associated with the 1980 eruption of Mount St. Helens, *in* Conference on Mount St. Helens—Effects on water resources, Jantzen Beach, Oregon, 1981, Proceedings: Pullman, Washington, State of Washington Water Research Center, Washington State University, and the University of Washington, Report No. 41, p. 163.

Jones, R.P., and Salo, E.O., 1986, The status of anadromous fish habitat in the North and South Fork Toutle River watersheds, Mount St. Helens, Washington, 1984: FRI-UW-8601, Project Completion Report to The State of Washington Water Research Center and the U.S. Department of the Interior, U.S. Geological Survey, Grant No. 14–08–0001–G940, Project No. G940-07, Water Research Center Project No. A–131–WASH, 53 p. [Available from State of Washington Water Research Center, Washington State University, Pullman, Washington 99164-3002.]

Juday, R.E., and Keller, E.J., 1984, Effect of ash fallout on water quality in western Montana: Missoula, Montana, University of Montana Department of Chemistry, Office of Water Research and Technology, Washington D.C., OWRTC-10095-V (1), Final Report, 156 p. [Available from National Technical Information Service, Springfield, Virginia 22161 as NTIS Report PB–85 157–824.]

Karlstrom, E.L., 1986, Amphibian recovery in the North Fork Toutle River debris avalanche area of Mount St. Helens, *in* Keller, S.A.C., ed., Mount St. Helens—Five years later: Cheney, Washington, Eastern Washington University Press, p. 334–344.

Kerr, K.A., 1980, Mount St. Helens: An unpredictable foe: Science, v. 208, p. 1446–1448.

King, L.G., and Peterson, D.A., 1982, Surface irrigation as affected by ash from Mount St. Helens: Pullman, Washington, Office of Water Research and Technology, 109 p. [Available from National Technical Information Service, Springfield, Virginia 22121 as NTIS PB–83 219–998.]

Klein, J.M., 1981, Some effects of the Mount St. Helens eruption on river-water quality: Lipman, P.W., and Mullineaux, D.R., eds., U.S. Geological Survey Professional Paper 1250, p. 719–731.

———1984, Some chemical effects of the Mount St. Helens eruption on selected streams in the State of Washington: U.S. Geological Survey Circular 850–E, 31 p.

Klein, J.M., and Taylor, H.E., 1980, Mount St. Helens Washington, 1980 volcanic eruption, Part II, chemical variations in surface waters affected by volcanic activity [abs.]: Eos (American Geophysical Union Transactions), v. 61, no. 46, p. 956.

Larson, D.W., and Geiger, N.S., 1982, Existence of phytoplankton in Spirit Lake near active volcano Mount St. Helens, Washington—Post-eruption findings: Archiv fur Hydrobiologie, 93, no. 3, p. 375–380.

Larson, D.W., and Glass, M.W., 1987, Spirit Lake, Mount St. Helens, Washington—Limnological and bacteriological investigations: Portland, Oregon, U.S. Department of the Army, Army Engineer District, Final Report, v. 1, 322 p.

Larson, D.W., and U'ren, S.C., 1982, Effects of debris retaining structures on water quality of the Toutle River, Washington, *in* Conference on Mount St. Helens—Effects on water resources, Jantzen Beach, Oregon, 1981, Proceedings: Pullman, Washington, State of Washington Water Research Center, Washington State University, and the University of Washington, Report No. 41, p. 191–213.

Lewis, W.M., and Grant, M.C., 1981, Effect of the May–June Mount St. Helens eruptions on precipitation chemistry in central Colorado: Atmospheric Environment, 15, no. 9, p. 1539–1542.

Lipman, P.W., and Mullineaux, D.R., eds., 1981, The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, 844 p.

Lombard, R.E., Miles, M.B., Nelson, L.M., Kresh, D.L., and Carpenter, P.J., 1981, The impact of mudflows of May 18 on the lower Toutle and Cowlitz Rivers, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens: U.S. Geological Survey Professional Paper 1250, p. 693–699.

Lucas, R.E., 1986, Recovery of game fish populations impacted by the May 18, 1980 eruption of Mount St. Helens, *in* S.A.C. Keller, ed., Mount St. Helens—Five years later: Cheney, Washington, Eastern Washington University Press. p. 276–292

MacMahon, J.A., 1982, Mount St. Helens revisited: Natural History, v. 91, p. 14, 18–22, 24.

Martin, D.J., Wasserman, L.J., Jones, R.P., and Salo, E.O., 1982, Effects of the eruption of Mount St. Helens on salmon population and habitat of the Toutle River, *in* Conference on Mount St. Helens—Effects on water resources, Jantzen Beach, Oregon, 1981, Proceedings: Pullman, Washington, State of Washington Water Research Center, Washington State University, and the University of Washington, Report No. 41, p. 235–253.

McKnight, D.M., 1982, Fulvic acid-like substances from lakes near Mount St. Helens, Washington [abs.]: U.S. Geological Survey Professional Paper 1275, p. 149.

McKnight, D.M., Feder, G.L., and Stiles, E.A., 1981, Toxicity of Mount St. Helens ash leachate to a blue-green algae: U.S. Geological Survey Circular 850–F, 14 p.

McKnight, D.M., Klein, J.M., and Wissmar, R.C., 1984, Changes in the organic material in lakes in the blast zone of Mount St. Helens, Washington: U.S. Geological Survey Circular 850–L, 26 p.

McKnight, D.M., Pereira, W.E., and Ceazan, M.L., 1982, Characterization of dissolved organic materials in surface waters within the blast zone of Mount St. Helens, Washington: Organic Geochemistry, v. 4, no. 2, p. 85–92.

McKnight, D.M., Thorn, K.A., and Wershaw, R.L., 1987, Changes in dissolved organic material in Spirit Lake, Washington, USA: Science of the Total Environment 62, p. 189–192.

Meyer, D.F., and Janda, R.J., 1986, Sedimentation downstream from the 18 May 1980 North Fork Toutle River debris avalanche deposit, Mount St. Helens, Washington, *in* Keller, S.A.C., ed., Mount St. Helens—Five years later: Cheney, Washington, Eastern Washington University Press, p. 68–86.

Meyer, William, and Carpenter, P.T., 1983, Filling of Spirit Lake, Washington, May 18, 1980, to July 31, 1982: U.S. Geological Survey, Open-File Report 82–771, 19 p.

Milligan, J.M., Falter, C.M., Brusven, M.A., 1983, Instream distribution and hydraulic and ecological effects of volcanic ash from Mount St. Helens eruption: Moscow, Idaho, Idaho Water and Energy Resources Research Institute, University of Idaho, 131 p. [Available from State of Washington Water Research Center, Washington State University, Pullman, Washington 99164-3002.]

Moore, J.G., and Sisson, T.W., 1981, Deposits and effects of the May 18 pyroclastic surge, *in* Lipman, P.W., and Mullineaux, D.R. eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 421–438.

Moore, P.A., and Reese, J.R., 1982, Sediment physical and chemical analyses on the Cowlitz and Columbia River subsequent to the 18 May 1980 Mount St. Helens eruption, *in* Conference on Mount St. Helens—Effects on water resources, Jantzen Beach, Oregon, 1981, Proceedings: Pullman, Washington, State of Washington Water Research Center, Washington State University, and the University of Washington, Report No. 41, p. 254–271

Nammath, H.A., 1983, Effect of Mount St. Helens ash on soil erosion and water quality: Moscow, Idaho, University of Idaho M.S. thesis, 80 p.

Newcomb, T.W., and Flagg, T.A., 1983, Some effects of Mount St. Helens volcanic ash on juvenile salmon smolts: Marine Fisheries Review 45, (2), p. 8–12.

Orwig, C.E., and Mathison, J.M., 1981, Forecasting considerations in Mount St. Helens affected rivers, *in* Mount St. Helens—Effects on water resources, Jantzen Beach, Oregon, October 7–8, 1981, Proceedings: Pullman, Washington, State of Washington Water Research Center, Washington State University, and the University of Washington, Report No. 41, p. 272–292.

Parker, R.A., and Gaddy, A.J., 1983, Some effects of volcanic ash on plankton productivity: Pullman, Washington, Washington State University, Mount St. Helens Research Program 14–34–0001–1441, Final Technical Completion Report for Project C-10049, 18 p. [Available from State of Washington Water Research Center, Washington State University, Pullman, Washington 99164-3002.]

Pereira, W.E., Rostad, C.E., Taylor, H.E., and Klein, J.M., 1982, Characterization of organic contaminants in environmental samples associated with Mount St. Helens 1980 volcanic eruption: Environmental Science and Technology, v. 16, no. 7, p. 387–396.

Phinney, D.E., 1982, General overview of the immediate and longer-term effects of Mount St. Helens on the salmon resources, *in* Conference on Mount St. Helens—Effects on water resources, Jantzen Beach, Oregon, 1981, Proceedings: Pullman, Washington, State of Washington Water Research Center, Washington State University, and the University of Washington, Report No. 41, p. 293–299.

Redding, J.M., and Schreck, C.B., 1982, Mount St. Helens ash causes sublethal stress responses in steelhead trout, *in* Conference on Mount St. Helens—Effects on water resources, Jantzen Beach, Oregon, 1981, Proceedings: Pullman, Washington, State of Washington Water Research Center, Washington State University, and the University of Washington, Report No. 41, p. 300–307.

Rees, William, 1981, Mount St. Helens and the fish, *in* Conference on salmon-spawning gravel—A renewable resource in the Pacific Northwest, October 6–7, 1980, Seattle, Washington, Proceedings: Pullman, Washington, State of Washington Water Research Center, Report No. 39, p. 168–175.

Reingold, A.L., Thomason, B.M., Brake, B.J., Thacker, L., Wilkinson, H.W., and Kuritsky, J.N., 1984, *Legionella pneumophila* in the United States—The distribution of serogroups and species causing human illness: Journal of Infectious Diseases, 149, p. 819.

Riedel, G.R., Wilson, S.L., and Holton, R.L., 1984, Trace metals in the Columbia River Estuary following the 18 May 1980 eruption of Mount St. Helens: Pacific Science, v. 38, no. 4, p. 340–349.

Rosenfeld, C.L., 1980, Observations on the Mount St. Helens eruption.: American Scientist, 68, p. 494–509.

Rosenfeld, C.L., and Beach, G.L., 1983, Evolution of a drainage network—Remote sensing analysis of the North Fork Toutle River, Mount St. Helens, Washington: Corvallis, Oregon, Water Resources Research Institute, Oregon State University, Final Technical Completion Report, Grant No. 14–34–0001–1452, WRR1–88, 89 p.

Rushforth, S.R., Squires, L.E., and Cushing, C.E., 1986, Algal communities of springs and streams in the Mount St. Helens region, Washington, USA, following the May 1980 eruption: Journal of Phycology, 22, p. 129–137.

Sarna-Wojcicki, A.M., Shipley, S.W., Dzurisin, Daniel, Hayes, W.H., Davis, J.O., Wood, S.H., and Bateridge, Thomas, 1980, Aerial distribution, thickness, and volume of downwind ash from the May 18, 1980, eruption of Mount St. Helens: U.S. Geological Survey Open-File Report 80–1078, 14 p.

Shulters, M.V., and Clifton, D.G., 1980, Mount St. Helens volcanic ashfall in the Bull Run watershed, Oregon, March–June 1980: U.S. Geological Survey Circular 850–A, 15 p.

Siebenmann, K.F., 1982, Potential for groundwater contamination by phenols and pH adsorbed onto Mount St. Helens ash/sediments: Pullman, Washington, Washington State University Master of Science Thesis, Washington State University Library, 36 p.

Skille, J.M., Falter, C.M., Kendra, W.R., and Schuchard, K.M., 1983, Fate, distribution and limnological effects of volcanic tephra in the St. Joe and Coeur d'Alene River Deltas of Lake Coeur d'Alene, Idaho: Moscow, Idaho, Idaho Water and Energy Resources Research Institute, 158 p. [Available from National Technical Information Service as NTIS Report PB–83 235–309.]

Smith, D.B., Zielinski, R.A., and Taylor, H.E., 1982, Leaching characteristics of ash from the May 18, 1980 eruption of Mount St. Helens volcano, Washington: U.S. Geological Survey Open-File Report 82–987, 22 p.

Smith, M.A., and White, M.J., 1985, Observations on lakes near Mount St. Helens—Phytoplankton: Archiv fuer Hydrobiologie, v. 104, no. 3, p. 345–362.

Staley, J.T., Lehmicke, L.G., Palmer, F.E., Peet, R.W., and Wissmar, R.C., 1982, Impact of Mount St. Helens eruption on bacteriology of lakes in the blast zone: Applied Environmental Microbiology, v. 43, no. 3, p. 664–670.

Steinman, A.D., and Lamberti, G.A., 1988, Lotic algal communities in the Mount St. Helens region six years following the eruption: Journal of Phycology, v. 24, no. 4, p. 482–489.

Stober, Q.J., Ross, B.D., Melby, C.L., Dinnel, P.A., Jagielo, T.H., and Salo, E.O., 1981, Effects of suspended volcanic sediment on coho and chinook salmon in the Toutle and Cowlitz Rivers: Seattle, Washington, Washington University, Fisheries Research Institute, 185 p. [Available from National Technical Information Service, Springfield, Virginia, 22161 as NTIS Report PB–82 256–801.]

Stradling, D.F., and Kiver, E.P., 1986, The significance of volcanic ash as a stratigraphic marker for the late Pleistocene in northeastern Washington, *in* Keller, S.A.C., ed., Mount St. Helens—Five years later: Cheney, Washington, Eastern Washington University Press, p. 120–125.

Svinth, Don, 1982, Effects on municipal and industrial water supplies in Cowlitz County, *in* Conference on Mount St. Helens—Effects on water resources, Jantzen Beach, Oregon, 1981, Proceedings: Pullman, Washington, State of Washington Water Research Center, Washington State University, and the University of Washington, Report No. 41, p. 365–377.

Sweet, H.R., and Edwards, J.E., 1983, Mount St. Helens eruptive impacts to the Toutle community groundwater supply: Bulletin of the Association of Engineering Geologists, v. 20, no. 2, p. 145–150.

Tangborn, W.V., and Lettenmaier, D.P., 1981, The impact of Mount St. Helens ash deposition on snowmelt, *in* Shafer, B.A., ed., Western Snow Conference, 49th, St. George, Utah, April 14-16, 1981, Proceedings: Fort Collins, Colorado, Colorado State University, p. 85–94.

Taylor, H.E., and Lichte, F.E., 1980, Chemical composition of Mount St. Helens ash: Geophysical Research Letters, v. 7, no. 11, p. 949–953.

Thurman, E.M., 1986, Organic geochemistry of natural waters: Boston, Massachusetts, M. Nijhoff & W. Junk Publishers, 497 p.

Tison, D.L., Baross, J.A., and Seidler, R.J., 1983, *Legionella* in aquatic habitats in the Mount St. Helens blast zone: Current Microbiology, v. 9, p. 345–348.

Tison, D.L., and Seidler, R.J., 1983, Ecology and virulence of Legionnaire's disease bacteria in aquatic habitats near Mount St. Helens: Corvallis, Oregon, Water Resources Research Institute, Oregon State University, Final Technical Completion Report for Project No. A–960–ORE, 11 p.

Turney, G.L., and Klein, J.M., 1982, Surface-water-quality data from selected sites in Washington affected by Mount St. Helens eruptions—March 27–September 30, 1980: U.S. Geological Survey Open-File Report 81–100, 158 p.

U.S. Army Corps of Engineers, 1981, Mount St. Helens eruption—Impacts on the Toutle, Cowlitz, and Columbia River system: Portland, Oregon, Portland District, Corps of Engineers, 150 p.

———1984, Mount St. Helens, Cowlitz and Toutle Rivers, Sedimentation study: Portland, Oregon, Portland District, Corps of Engineers.

U.S. Environmental Protection Agency, 1976, Quality criteria for water: Washington, D.C., U.S.E.P.A. 440/9–76–923, 256 p.

———1980, Water quality criteria documents: [Availability: Federal Register 45 (2317) 79318-79355, Washington, D.C.]

Vanoni, V.A., 1986, Comments on sedimentation problems resulting from the eruption of Mount St. Helens, *in* Conference on Mount St. Helens—Effects on water resources, Jantzen Beach, Oregon, 1981,

Proceedings: Pullman, Washington, State of Washington Water Research Center, Washington State University, and the University of Washington, Report No. 41, p. 395–403.

Voight, Barry, Glicken, Harry, Janda, R.J., and Douglass, P.M., 1981, Catastrophic rockslide avalanche of May 18, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 401–420.

Wagner, Richard, and Walker, R.B., 1986, Mineral nutrient availability in some Mount St. Helens surface samples, *in* Keller, S.A.C., ed., Mount St. Helens—Five years later: Cheney, Washington, Eastern Washington University Press, p. 153–162.

Waitt, R.B., Jr., 1981, Devastating pyroclastic density flow and attendant air fall of May 18—Stratigraphy and sedimentology of deposits, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 439–458.

Ward, A.K., Baross, J.A., Dahm, C.N., Lilley, M.D., and Sedell, J.R., 1983, Qualitative and quantitative observations on aquatic algal communities and recolonization within the blast zone of Mount St. Helens, 1980 and 1981: Journal of Phycology, 19, p. 238–247.

Warren, G.H., Kaufman, D.E., and Hammond, K.A., 1982, Come hell and high water—Mount St. Helens and the Federal response on the lower Cowlitz River: Washington, D.C., Office of Water Research and Technology, W8302724 OWRTC–10130–V(1), Technical Completion Report, 249 p. [Available from National Technical Information Service, Springfield, Virginia 22161 as NTIS Report PB–83 191–791.]

White, A.F., Benson, L.V., and Perry, D.L., 1981, The influence of weathering of Mount St. Helens ash on the chemistry of a small watershed, Iron Creek, Washington [abs.]: Geological Society of America Abstracts with Programs, v. 13, no. 7, p. 579.

Willey, R.G., ed., 1982, Seminar on attaining water-quality goals through water-management procedures, Dallas, Texas, February 17–18, 1982, Proceedings: Davis, California, Hydrologic Engineering Center, 278 p.

Williams, Chuck, 1980, Mount St. Helens—A changing landscape: Graphic Arts Center Publishing Co., Portland, Oregon, 128 p.

Willis, R.E., 1982, Mount St. Helens recovery operations, *in* Seminar on attaining water-quality goals through water-management procedures, Dallas, Texas, February 17–18, 1982, Proceedings: Washington, D.C., U.S. Army Corps of Engineers Committee on Water Quality, p. 208–217.

Wissmar, R.C., 1981, Dissolved organics and pH in lakes within Mt. St. Helens blast zone [abs.]: Eos (American Geophysical Union Transactions), v. 62, no. 45, p. 868.

———1982, Limnological features of lakes within the 18 May 1980 Mount St. Helens blast zone, *in* Keller, S.A.C., ed., Mount St. Helens—One year later: Cheney, Washington, Eastern Washington University Press, p. 119–123.

Wissmar, R.C., Baross, J.A., Lilley, M.D., and Dahm, C.N., 1988, Nitrogen cycling in altered and newly created lakes near the Mount St. Helens volcano: Journal of Freshwater Ecology, v. 4, no. 4, December 1988, p. 551–568.

Wissmar, R.C., Devol, A.H., Nevissi, A.E., and Sedell, J.R., 1982b, Chemical changes of lakes within the Mount St. Helens blast zone: Science, 216, no. 4542, p. 175–178.

Wissmar, R.C., Devol, A.H., Staley, J.T., and Sedell, J.R., 1982a, Biological responses of lakes in the Mount St. Helens blast zone: Science, 216, no. 4542, p. 178–181.

Wissmar, R.C., McKnight, D.M., and Dahm, C.N., 1990, Contribution of organic acids to alkalinity in lakes within the Mount St. Helens blast zone: Limnology and Oceanography, 35 (2), 1990, p. 535–542.

Youd, T.L., and Wilson, R.C., 1980, Stability of Toutle River blockage—Mount St. Helens hazards investigations: U.S. Geological Survey Open-File Report 80–898, 14 p.