NUTRIENT AND TRACE-ELEMENT ENRICHMENT OF COEUR D'ALENE LAKE, IDAHO

U.S. GEOLOGICAL SURVEY
OPEN-FILE REPORT 95-740

Prepared in cooperation with the

IDAHO DEPARTMENT OF HEALTH AND WELFARE, DIVISION OF ENVIRONMENTAL QUALITY, and COEUR D'ALENE TRIBE

U.S. DEPARTMENT OF THE INTERIOR
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By PAUL F. WOODS *and* MICHAEL A. BECKWITH

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Boise, Idaho
1996

U.S. DEPARTMENT OF THE INTERIOR

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CONTENTS

FIGURES

TABLES

CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
centimeter (cm)	0.3937	inch
cubic hectometer (hm^3)	810.7	acre-foot
cubic hectometer per square kilometer (hm^3/km^2)	3.281	acre-foot per acre
cubic kilometer (km^3)	0.2399	cubic mile
cubic meter (m^3)	35.31	cubic foot
cubic meter per second (m^3/s)	35.31	cubic foot per second
kilogram (kg)	2.205	pound
kilogram per hectare (kg/ha)	0.8922	pound per acre
kilogram per square kilometer (kg/km^2)	2,000	ton per acre
kilometer (km)	0.6214	mile
liter (L)	0.2642	gallon
meter (m)	3.281	foot
metric ton	1.102	ton (short)
millimeter (mm)	0.03937	inch
square kilometer (km^2)	0.3861	square mile
square meter (m^2)	10.76	square foot

To convert °C (degrees Celsius) to °F (degrees Fahrenheit), use the following equation:

$$°F = (1.8°C) + (32)$$

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.

Abbreviated water-quality units:

cells/mL	cells per milliliter
cells/cm^2	cells per square centimeter
cm^3/L	cubic centimeters per liter
μm^3/mL	cubic micrometers per milliliter
E	Einstein
E/m^2	Einsteins per square meter
(μE/m^2)/s	microEinsteins per square meter per second
µg/L	micrograms per liter
µm	micrometer
µS/cm	microsiemens per centimeter at 25°C
mg	milligram
(mg/m^3)/d	milligrams per cubic meter per day
mg/kg	milligrams per kilogram
mg/m^2	milligrams per square meter
(mg/m^2)/E	milligrams per square meter per Einstein
mL	milliliter

NUTRIENT AND TRACE-ELEMENT ENRICHMENT OF COEUR D'ALENE LAKE, IDAHO

By Paul F. Woods *and* Michael A. Beckwith

Abstract

This study of Coeur d'Alene Lake was undertaken because of concerns over the potential for release of previously deposited nutrients and trace elements from the lakebed if an anoxic hypolimnion were to develop as a consequence of eutrophication. The primary purpose of the study was to determine the lake's assimilative capacity for nutrients. The scope included characterization of water quality in the limnetic and littoral zones of the lake, quantification of hydrologic and nutrient budgets, development of a nutrient load/lake response model, and characterization of trace-element enrichment in surficial and subsurface lakebed sediments.

Coeur d'Alene Lake was classified as oligotrophic during 1991–92, on the basis of annual geometric mean concentrations, in micrograms per liter, of total phosphorus (4.1), total nitrogen (247), and chlorophyll-*a* (0.54). On the basis of nitrogen-to-phosphorus ratios, phosphorus was the nutrient most likely to limit phytoplankton growth. Despite its oligotrophy, Coeur d'Alene Lake developed a substantial hypolimnetic dissolved-oxygen deficit in both years during the late summer. In the deep, northern half of the lake, hypolimnetic dissolved oxygen was reduced to 6.4 milligrams per liter (58 percent saturation). In the lake's shallow, southern end, anoxic conditions developed in the lower water column. A review of historical studies of the lake revealed that substantial hypolimnetic dissolved-oxygen deficits were measured in 1911 and 1975. Historical loads of nutrients and oxygen-demanding substances were estimated to have been much larger than those measured during this study and, thus, capable of producing the earlier deficits.

The lake's current (1992) oligotrophic classification differs from the mesotrophic classification it received in 1975 during the National Eutrophication Survey. The shift in trophic state is consistent with nutrient load reductions in the lake's 9,690-square-kilometer drainage basin since the early 1970's. During 1991, loads of nitrogen and phosphorus to Coeur d'Alene Lake were about half those in 1975. Most of the nutrient load reduction has occurred in the Coeur d'Alene River drainage basin where phosphorus-export coefficients, in kilograms per square kilometer, have declined from 26 in 1975 to 4.5 in 1991.

Approximately 85 percent of the lakebed's surface area was highly enriched in antimony, arsenic, cadmium, copper, lead, mercury, silver, and zinc. Median concentrations of total cadmium, lead, and zinc in the enriched lakebed sediments were 56, 1,800, and 3,500 milligrams per kilogram, respectively. In contrast, median concentrations of cadmium, lead, and zinc in unenriched lakebed sediments in the lake's southern end were 2.8, 24, and 110 milligrams per kilogram, respectively. Most of the trace elements in the surficial and subsurface sediments were associated with ferric oxides, not sulfides, as previously postulated. Under reducing conditions, such as within an anoxic hypolimnion, the ferric oxides would be readily soluble and the trace elements would be released into the overlying water column. The trace-element enrichment of the lake was largely restricted to the lakebed sediments; however, the median concentration of total recoverable zinc in the water column was 98.6 micrograms per liter. This

concentration exceeded the criterion of 32.4 micrograms per liter for protection of freshwater biota in Coeur d'Alene Lake. Phytoplankton bioassays conducted in chemically defined media showed that dissolved, uncomplexed concentrations of zinc typical for much of Coeur d'Alene Lake were strongly inhibitive to growth of three phytoplankton isolates from the lake.

The combined inflows of the Coeur d'Alene and St. Joe Rivers during 1991–92 provided more than 92 percent of the lake's inflow. Streamflow during 1991 in the two rivers was about 130 percent of the long-term mean, whereas in 1992, it was about 60 percent. The residence time of water in the lake was 0.45 year in 1991 and 0.89 year in 1992. During 1991, the lake received 71 and 81 percent, respectively, of its loads of total phosphorus and nitrogen from the combined inflows of the Coeur d'Alene and St. Joe Rivers. The lake retained most of its phosphorus load but very little of its nitrogen load. The Coeur d'Alene River contributed most of the loads of arsenic, cadmium, lead, and zinc. In 1991, the lake retained 85 percent of the 300,000 kilograms of lead it received and 31 percent of the 929,000 kilograms of zinc it received.

The empirical nutrient load/lake response model was used to determine the effect of increased nutrient loads on the hypolimnetic dissolved-oxygen deficit. Modeling results indicated Coeur d'Alene Lake has a large assimilative capacity for nutrients before anoxic conditions could develop in its hypolimnion. The large assimilative capacity and the shift from mesotrophic to oligotrophic have reduced the potential for development of an anoxic hypolimnion and the consequent release of nutrients and trace elements back into the overlying water column.

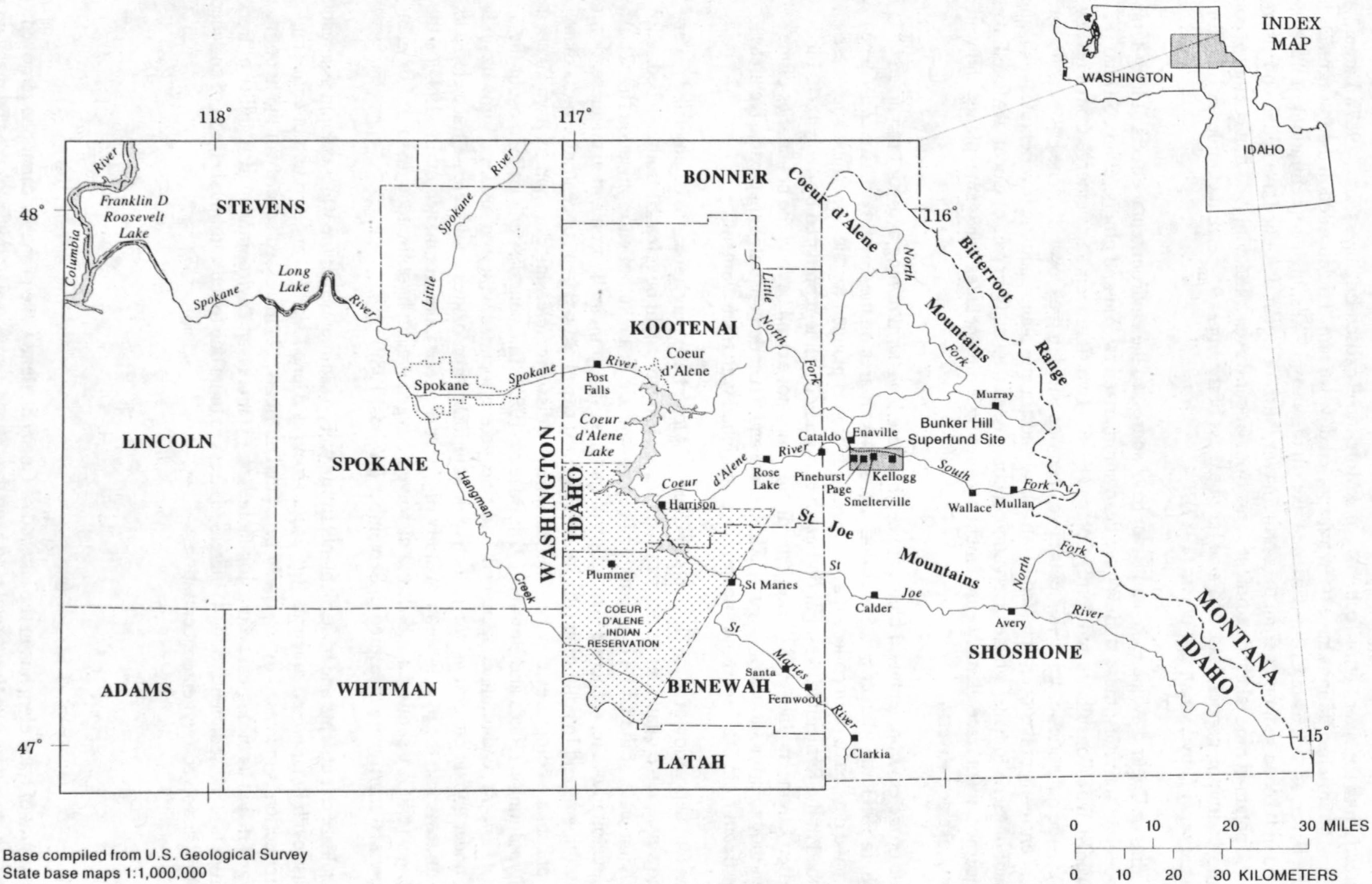
INTRODUCTION

Water-Quality Issues

Coeur d'Alene Lake, Idaho's second largest, is located in northern Idaho within the 17,300-km^2 Spokane River drainage basin (fig. 1). The lake has become a prime recreational site for residents of northern Idaho and eastern Washington because of its beautiful setting and proximity to the cities of Spokane and Coeur d'Alene. Population growth within 80 km of the lake was 24 percent between 1970 and 1980; by 1980, 80 percent of the lake's shoreline had been developed (Milligan and others, 1983). Post-1980 shoreline development includes a $60 million resort complex in the city of Coeur d'Alene that attracts international travelers.

Extensive residential and commercial development of the drainage basin and shoreline, plus intensive recreational use of Coeur d'Alene Lake, have created considerable concern over the potential for nutrient enrichment and subsequent eutrophication of the lake. Although numerous point and nonpoint sources of nutrients exist within the drainage basin, the only nutrient load study of the lake was done in 1975 as part of the National Eutrophication Survey (U.S. Environmental Protection Agency, 1977). As a result of that study, the U.S. Environmental Protection Agency (EPA) classified the lake as mesotrophic, or moderately productive, and recommended that additional studies of the sources and magnitudes of nutrient loads to the lake be done prior to development of management decisions for controlling eutrophication.

Another major water-quality problem for Coeur d'Alene Lake is the massive amount of trace elements that have been introduced into the lake as a consequence of more than 100 years of mining and ore-processing activities in the Coeur d'Alene River drainage basin. Approximately 104 million metric tons of trace-element-enriched tailings have been produced in the drainage basin of the South Fork Coeur d'Alene River; 65.3 million metric tons



Base compiled from U.S. Geological Survey
State base maps 1:1,000,000

Figure 1. Location of study area.

were discharged directly into the river (Tetra Tech, Inc., and Morrison-Knudsen Engineers, Inc., 1987). Large amounts of trace-element-enriched tailings have been transported downstream and deposited in the lower reaches of the Coeur d'Alene River, as well as in Coeur d'Alene Lake. In the early 1970's, high concentrations of trace elements were measured in lakebed sediments from the northern two-thirds of Coeur d'Alene Lake (Funk and others, 1973, 1975). The EPA obtained nine lakebed sediment cores from Coeur d'Alene Lake in 1986 that contained concentrations of arsenic, cadmium, copper, lead, and zinc far in excess of the upper 95-percent confidence limit for sediments reported nationwide by Lyman and others (1987).

Numerous studies of Coeur d'Alene Lake and River have addressed the environmental effects of long-term mining and ore-processing activities; these studies have been summarized by Wai and others (1985), Savage (1986), and Woodward-Clyde Consultants and Terragraphics (1986). Two significant facts emerge from a review of these studies: (1) Large quantities of trace elements have been deposited in the Coeur d'Alene Lake and River; and (2) trace-element enrichment has been detected in terrestrial and aquatic plants, aquatic invertebrates, fish, and waterfowl. The Coeur d'Alene Indians, whose reservation encompasses the southern part of Coeur d'Alene Lake, are particularly concerned about trace-element enrichment because their diet includes fish, game, plants, and water from Coeur d'Alene Lake and River.

The magnitude of the environmental problems created by these long-term mining activities prompted the EPA to establish, in 1983, the Bunker Hill Superfund site, a 54-km^2 area on the South Fork Coeur d'Alene River (fig. 1). Extensive data have been collected and site remediation is planned for the Superfund site; these activities are described in the Remedial Investigation/Feasibility Study document prepared by Tetra Tech, Inc., and Morrison-Knudsen Engineers, Inc. (1987). Site remediation does not extend beyond the boundaries of the Superfund site, even though prior studies of Coeur d'Alene Lake and River demonstrated that extensive areas upstream and downstream from the Superfund site have been enriched with trace elements.

Eutrophication and deposition of trace elements in Coeur d'Alene Lake may appear to be unrelated water-quality problems; however, large quantities of nutrients and trace elements might be released from lakebed sediments into the overlying water if the lake's hypolimnion becomes anoxic as a result of eutrophication (fig. 2). As anoxic conditions develop in a lake, reductive dissolution of metal oxides, principally iron and manganese, occurs within the lakebed sediments and hypolimnion (Brezonik, 1994). At dissolved-oxygen concentrations less than 1 mg/L, iron oxide-phosphate complexes may become unstable and dissolve, releasing phosphorus from lakebed sediments into the hypolimnion (Jones and Bowser, 1978; Baccini, 1985). In Coeur d'Alene Lake, most of the trace elements such as arsenic, cadmium, copper, lead, and zinc were associated with iron oxides (Horowitz and others, 1993); thus, under anoxic conditions, the reductive dissolution of iron oxides could release trace elements from the lakebed sediments into the hypolimnion. A study of Coeur d'Alene Lake, conducted during 1987 by the U.S. Geological Survey (USGS), showed a substantial dissolved-oxygen deficit; hypolimnetic dissolved-oxygen concentrations as low as 4 mg/L were measured in September (Woods, 1989).

The potential release of nutrients and trace elements from lakebed sediments into the water column as a result of eutrophication has several major consequences (fig. 2) for Coeur d'Alene Lake: (1) acceleration of eutrophication as biological production is increased by internally generated nutrients; (2) increased severity of the hypolimnetic dissolved-oxygen deficit as biological production increases; (3) increased environmental availability of trace elements released from lakebed sediments; and (4) increased stress to biota due to the combined effects of enriched trace elements and low dissolved-oxygen concentrations.

Need for Study

The massive amount of trace elements in the lakebed of Coeur d'Alene Lake probably cannot be removed economically. Therefore, an alternative to removal is to keep those trace elements within the lakebed by managing

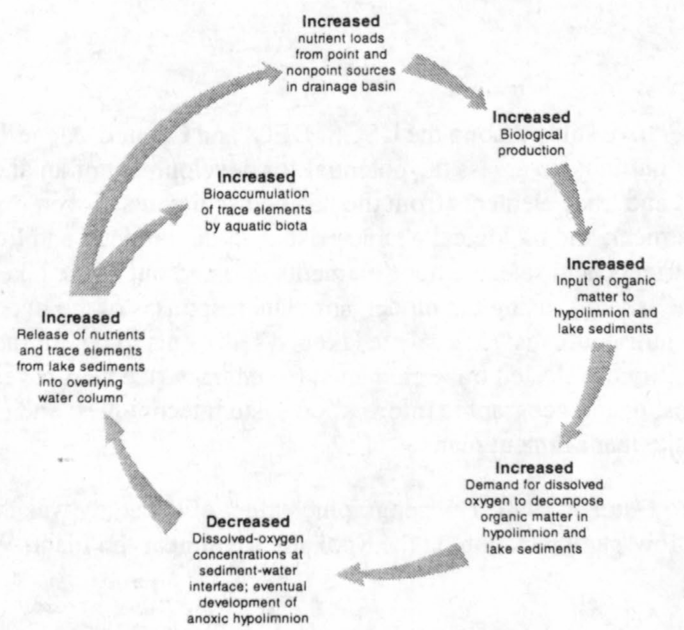


Figure 2. Cyclic relation of the eutrophication process and trace-element enrichment.

the lake's nutrient income to curtail development of anoxic conditions in the hypolimnion. Lake water-quality models are available for predicting the limnological response of a lake to incremental changes in nutrient loads; however, such models require a data base much more comprehensive than that available for Coeur d'Alene Lake prior to this study.

Idaho's recently enacted Nutrient Management Act mandates that a nutrient management plan be developed for Coeur d'Alene Lake. The Act requires the plan to (1) identify nutrient sources; (2) identify the dynamics of nutrient removal, use, and dispersal; and (3) identify preventive or remedial actions where feasible and necessary to protect surface water. The Idaho Department of Health and Welfare, Division of Environmental Quality (DEQ) has been given responsibility for developing the nutrient management plan for Coeur d'Alene Lake and has requested assistance from the USGS in developing the necessary data base. The Coeur d'Alene Tribe also has requested that the USGS provide information on the status of eutrophication in the southern end of Coeur d'Alene Lake.

Purpose and Scope

The purpose of this cooperative study among the USGS, DEQ, and Coeur d'Alene Tribe was to determine the lake's assimilative capacity for nutrients to assess the potential for development of an anoxic hypolimnion and the consequent release of nutrients and trace elements from the lakebed sediments. Seven major tasks were undertaken: (1) Assess physical, chemical, and biological characteristics in the limnetic and littoral zones of the lake; (2) quantify loads of water, nutrients, and selected trace elements into and out of the lake; (3) develop a nutrient load/lake response model of the lake; (4) using the model, simulate responses of the hypolimnetic dissolved-oxygen deficit to alterations in nutrient loads; (5) analyze lakebed sediments to determine concentration, partitioning, and environmental availability of selected trace elements; (6) characterize land cover/land use throughout the study area by using remote-sensing and geographic information system techniques; and (7) assemble the data base needed for development of a lake management plan.

The 4-year study began in October 1990. The geographic extent of the study was the drainage basin upstream from the USGS streamflow-gaging station on the Spokane River near the Idaho-Washington border (station 12419000).

The DEQ and Coeur d'Alene Tribe intend to use the results of this study in applications to the EPA for grants to implement lake management plan(s) for Coeur d'Alene Lake. The grants are administered under the Clean Lakes Program and consist of Phase I (diagnostic/feasibility) and Phase II (implementation) grants. Applications for Phase II grants require a broad array of limnological and drainage basin data, as well as extensive socioeconomic data (U.S. Environmental Protection Agency, 1980). This report presents most of the information needed for an application for a Phase II grant.

HUMAN EFFECTS ON WATER QUALITY

Early History

By the early 1800's, perhaps 2,000 Native Americans inhabited the Coeur d'Alene Lake watershed (Rabe and Flaherty, 1974). They lived primarily on lakeshores, edges of forests near the marsh areas of the lower Coeur d'Alene and St. Joe Rivers, and the camas grounds around what is now Tensed, Idaho. Fish, game, and edible plants were abundant and easily obtained. The Native Americans were known to have practiced communal hunting drives, occasionally burned areas to improve tribal hunting grounds, built fish weirs, and gathered edible plants from the wetlands.

Among the first settlers to live in the area, Father Nicolas Point noted the abundance of natural resources in the Coeur d'Alene country. Army Captain John Mullan, while surveying a land route between the Missouri and Columbia Rivers in 1858, described Coeur d'Alene Lake as a "noble sheet of water filled with an abundance of delicious salmon trout." Ruby El Hult, an early settler, recalled the Coeur d'Alene River as "one of the most beautiful streams imaginable . . . clear as crystal, deep . . . alive with trout and other fish . . . they could be seen by the thousands in the clear water" (Rabe and Flaherty, 1974). Stands of cottonwood and giant cedar, interspersed with fertile grassy meadows grew along the Coeur d'Alene and St. Joe Rivers. Both drainages also contained some of the largest stands of old-growth white pine on the continent (U.S. Department of Agriculture, 1994a).

Settlement and Development

The original inhabitants were called "Shee-Chu-Umsh" in their native Salish language (Greater Coeur d'Alene Convention and Visitors Bureau, 1993). French-Canadian fur traders in the early 1800's referred to them as having "hearts like the point of an awl," probably in reference to their business manners. Rather than trinkets and beads in exchange for their furs, the Shee-Chu-Umsh demanded practical goods such as iron tools and insisted on conducting trade some distance from their lands and villages (Rabe and Flaherty, 1974). The French name Coeur d'Alene (Coeur - heart; Alene - awl) was applied to the Shee-Chu-Umsh and eventually applied to the area and its features (Greater Coeur d'Alene Convention and Visitors Bureau, 1993).

Early westward exploration and expansion by settlers bypassed the land of the Coeur d'Alene Indians, largely because of its ruggedness and isolation. Lewis and Clark and other early travelers to the Northwest passed to the south, generally following the Snake and Columbia Rivers to the Oregon Territory (Rabe and Flaherty, 1974; Schwantes, 1990). Roman Catholic missionaries were the first nonnatives to live permanently among the Coeur d'Alene Indians. Unlike the earlier fur traders, the Jesuit "Black Robes" were welcomed as a fulfillment of tribal prophesy (Rabe and Flaherty, 1974; Peltier, 1982). Father Nicolas Point founded the Mission of the Sacred Heart among the Coeur d'Alene Indians in late 1842 (Schwantes, 1990). The church, built in 1853 and overlooking the Coeur d'Alene River at Cataldo, is believed to be the oldest standing building in Idaho (Rabe and Flaherty, 1974).

The first serious exploration of the Coeur d'Alene country came with the 1853 search for a railroad route to the Pacific (Schwantes, 1990). Isaac Stevens, first Governor of the Washington Territory, led a reconnaissance party over the Bitterroot Range, down the South Fork Coeur d'Alene River, past the now-thriving Cataldo Mission, and on to Puget Sound (Rabe and Flaherty, 1974; Schwantes, 1990).

Although they were relatively few in number during the early and mid-1800's, settlers quickly brought great changes to the area, such as smallpox and other diseases that decimated the Coeur d'Alene Tribe, reducing them, at one time, to as few as 320 (Rabe and Flaherty, 1974). Their ancestral lands were forcibly opened to settlement (by Governor Stevens and the U.S. Army under Col. George Wright) after a short uprising by regional tribes in 1853 known as the Steptoe War (Peltier, 1982). In 1871, Frederick Post acquired land from Coeur d'Alene Indian Chief Seltice for grist and lumber mills at the falls on the Spokane River to serve growing settlements to the west (Rabe and Flaherty, 1974). In 1873, the Coeur d'Alene Indians were officially restricted to a fraction of their ancestral lands; the reservation did not even include the mission at Cataldo (Coeur d'Alene Tribe, written commun., 1974; Peltier, 1982). In 1877, Gen. William Tecumseh Sherman chose a site for a military outpost that would become the city of Coeur d'Alene (Schwantes, 1990).

Mining

The discovery of precious metals had by far the most profound effect on the Coeur d'Alene country. In the winter of 1883–84, as many as "5,000 men and scores of women stampeded" up the North Fork Coeur d'Alene River in search of gold (Rabe and Flaherty, 1974). In the fall of 1885, Noah Kellogg discovered outcrops of silver ore on the South Fork Coeur d'Alene River. Miners rushed to this new mining district and, by late 1885, all major claims had been staked (Rabe and Flaherty, 1974).

The "boom" was underway in what was to become known as the Fabulous Silver Valley. Steamboats soon plied the waters of Coeur d'Alene Lake and the lower Coeur d'Alene and St. Joe Rivers, transporting passengers and freight (Rabe and Flaherty, 1974). Railroads were built linking the Coeur d'Alene mining district with other population and commerce centers of the rapidly developing West (Schwantes, 1990). Perhaps nowhere in the history of Euro-American settlement of western North America was an area so rapidly and drastically transformed. In an 1888 letter to a friend, General Sherman debated retiring in the vicinity of the fort he founded: "Gold was discovered there, a railroad built, and the beautiful forests are being swept away and the virgin lakes and streams robbed of their trout" (Royster, 1991).

By the early 1900's, all major mines in the Silver Valley were producing thousands of tons of silver ore concentrate and, later, lead and zinc. Many more thousands of tons of mine wastes (containing arsenic, cadmium, copper, mercury, zinc, and many other substances) were deposited in or on the banks of the river to be washed downstream toward Coeur d'Alene Lake. Although the hard-rock mining and processing techniques required advanced technologies of the day (as well as a large labor force), little attention was paid to mine waste disposal (Rabe and Flaherty, 1974). The lake's outlet was dammed and its level raised approximately 3.6 m in 1906 to produce hydroelectric power for the booming mines and cities; fertile bottomlands and wetlands were flooded and Benewah, Chatcolet, Hidden, and Round Lakes were created or enlarged near the mouth of the St. Joe River (Rabe and Flaherty, 1974; Coeur d'Alene Tribe, written commun., 1974).

Cities and towns in the Coeur d'Alene mining district and the surrounding area soon resembled those of the industrialized East. The forests around the lake and in the St. Joe and Coeur d'Alene River drainages supplied the growing region with building materials. Farms and ranches in the fertile valleys supplied the growing population with food. The Coeur d'Alene mines soon became the largest producers of silver, lead, and zinc in the Nation. They played a major role in the settlement and economic development of the entire Coeur d'Alene Lake watershed, as well as the Spokane, Wash., area to the west, which served as a major supply point (Schwantes, 1990). As the Silver Valley mines drove the economic, social, and political development of the region, they also profoundly affected its natural environment.

By the early 1900's, the Coeur d'Alene River ran murky with mining wastes and Coeur d'Alene Lake became clouded (Rabe and Flaherty, 1974). The river channel became clogged with sediment. The once-abundant fish disappeared. Riverbank trees and vegetation died. Migratory waterfowl died in the marshes and adjoining lakes. Livestock feeding near the riverbanks sickened and died. Fertile croplands adjacent to the river were contaminated by mine wastes carried by the spring floods (Casner, 1989, 1991). Thousands of acres of forest were killed by toxic smelter fumes (U.S. Department of Agriculture, 1994a).

Bitter social, economic, political, and legal struggles erupted, pitting the mining interests of the Silver Valley against agricultural and other interests downstream. The mining interests generally prevailed (Casner, 1989, 1991). In the early 1930's, the issues entered the political realm when the Idaho Legislature formed a commission to "make a series of investigations of the pollution problems in the Coeur d'Alene District, not only from the standpoint of property damage and alleged injuries to stock and land, but from all angles affecting the State or its assets" (Rabe and Flaherty, 1974).

Dr. M.M. Ellis of the U.S. Bureau of Fisheries conducted the first comprehensive investigations of the Coeur d'Alene Lake and River system in the summer of 1932 (Ellis, 1940). Ellis found "that as far as fisheries are concerned, the mine wastes poured in the South Fork in the Wallace-Kellogg area have reduced the 50 miles [80 km] of the South Fork and Main Coeur d'Alene River from above Wallace to the mouth of the river at Harrison, to a barren stream practically without fish fauna, fish food, or plankton, and with enormous lateral supplies of potentially toxic materials which as they now stand will continue to poison the waters of the Coeur d'Alene River for a considerable period of time."

Other sources of contamination such as raw sewage from the mining settlements and from extensive timber harvest and other land disturbances, as well as human-caused and natural wildfires, undoubtedly contributed significantly to environmental degradation during this period. However, Ellis (1940) concluded, "There is only one complete solution to this [water pollution] problem and that is the exclusion of all mine wastes from the Coeur d'Alene River."

Ellis also investigated a similar mining operation near Kimberly, British Columbia, which employed a system of settling ponds. He found that the water was "so reduced in volume and so purified that within a few yards of the mouth of the outlet ditch . . . plankton, algae, aquatic insects and fish were found . . ." (Ellis, 1940). He recommended that a similar system be employed in the Coeur d'Alene district. However, such treatment facilities were not installed by the Silver Valley mines until 1968 after much pressure from Federal and State authorities (Rabe and Flaherty, 1974).

Logging

Logging also became a major industry in the region. Initially, timber was harvested near the mines and towns or from the lakeshore and riverbanks for easy water transport. As the easily accessible timber was cut, logging crews pushed farther up the Coeur d'Alene and St. Joe River drainages.

Early logging operations often employed extremely damaging methods; frequently, every tree in an entire drainage was cut. Uncontrolled slash burning often resulted in destruction of even more forest. Stream channels were straightened or converted to wooden chutes or flumes down which logs were floated. These flumes often led to temporary lakes formed by earth and log "splash dams." The dams were then periodically opened or blown up, releasing a torrent that carried not only the cut logs, but also sediment and logging slash downstream. The process sometimes was repeated several times (with devastating results to the stream channel) until the logs reached a sawmill, railhead, or steamship landing. Narrow-gage railroads were built to haul logs, usually at the bottoms of fragile drainages, resulting in further erosion and channel destabilization (Rabe and Flaherty, 1974).

Logging practices common to the late 1800's and early 1900's often resulted in depleted forests, massive soil erosion, and severely destabilized streambanks and channels. Combined with man-caused and natural wildfires and floods, many drainages have yet to recover fully. An example is the Little North Fork Coeur d'Alene River, where flumes were built in almost all side streams and the main channel was repeatedly dammed; splash dams also flushed logs out of Shoshone Creek on the North Fork Coeur d'Alene River (Rabe and Flaherty, 1974). This type of logging peaked in the late 1920's (U.S. Department of Agriculture, 1994a). Similar practices were employed throughout the St. Joe River drainage with similar effects.

Modern logging practices, utilizing extensive road systems and clearcutting, began in the late 1930's and reached peak application in the 1970's. Roads often were built along fragile stream channels and (or) on steep, erodible hillsides (Rabe and Flaherty, 1974). Extensive clearcutting changed the timing and amount of water flowing from heavily logged drainages, further damaging stream and river channels and altering flood patterns (Rabe and Flaherty, 1974).

Agriculture

Agriculture has played a significant role in altering water quality, aquatic ecosystems, and hydrologic conditions in the Coeur d'Alene Lake basin. Extensive dryland agriculture began in the Palouse country to the south around the beginning of the 20th century. Forested areas near the lake were cleared and converted to cropland. Erosion rates from these soils can be among the highest in the Nation, especially if the practice of summer fallowing is employed (Rabe and Flaherty, 1974). Much of the sediment entering the southern end of Coeur d'Alene Lake and the bays on the western lakeshore comes from surrounding farms (Rabe and Flaherty, 1974). Livestock grazing also has contributed to disturbance of tributary riparian areas, resulting in further nutrient and sediment transport.

Human and Animal Waste

Population in the Coeur d'Alene River Basin was probably about 5,000 in the late 1800's (Rabe and Flaherty, 1974; U.S. Department of Agriculture, 1994a). However, because of the transient nature of the logging and mining "boomtowns," the population at times may have been much larger. Old photographs show numerous outhouses and latrines built directly over watercourses. Early sewer systems serving the growing towns and industrial sites also discharged waste directly without treatment (Cornell, Howland, Hayes, and Merryfield, Engineers and Planners, 1964). Wastes from the horses and mules used for transportation at the time undoubtedly entered rivers and streams as well. The Coeur d'Alene River (especially the narrow canyons of the South Fork drainage that confined the Silver Valley mining district) probably carried a substantial load of industrial, human, and animal waste and wastewater, significantly affecting lake and river water quality in the early 1900's.

Wildfire and Floods

Man-caused and natural wildfire burned large parts of the Coeur d'Alene Lake basin on several occasions. The effects of these fires, combined with floods and other land disturbances, contributed significantly to sediment and nutrient loads entering the lake.

Early miners sometimes set fires to expose mineral-bearing rock formations. By the late 1800's, much of the timber along the South Fork Coeur d'Alene River had been burned. Thousands of acres of forest in the upper North Fork basin burned when slash fires from railroad construction spread from the Clark Fork River Valley (U.S. Department of Agriculture, 1994a). Construction of railroads across the Bitterroot Mountains and down the St. Joe River caused similar disturbances. Massive fires in 1910, 1919, 1926, and 1931 burned much of the northern part of the basin, along the Bitterroot divide, the upper St. Joe River drainage, and the divide between the South Fork Coeur d'Alene and St. Joe Rivers.

Flooding has occurred frequently in the basin. Major destructive floods were recorded in 1933, 1948, 1956, 1964, and 1974; less severe floods were recorded in 1893, 1904, 1909, 1910, 1913, 1917, 1925, and 1963 (U.S. Department of Agriculture, 1994a).

SOCIOECONOMIC CONDITIONS

Socioeconomic Transition

Until quite recently, the Coeur d'Alene region's economy depended on its abundant natural resources. However, in the early 1980's, the mining industry all but collapsed; the Silver Valley mines were no longer competitive in an increasingly global market due to falling metals prices and rising costs of production. Trouble in the timber industry soon followed; a national economic slowdown, environmental concerns, dwindling timber supply, and outdated equipment led to the closure of several large mills in the late 1980's (Panhandle Area Council, 1993).

Tourism became a growing component of the region's economy in the 1950's as the scenic beauty, high-quality water resources, and abundant outdoor recreation opportunities drew increasing numbers of visitors (Kootenai County Planning Commission, 1993). As the natural resource industrial base declined, tourism, recreation, and associated services became the region's new growth industries. Tourism could be the region's largest industry by the year 2000 (Panhandle Area Council, 1993).

The population dynamics of north Idaho during 1970 to 1980 were evaluated (Panhandle Area Council, 1993). During that period, north Idaho's population grew 54 percent (82,300 to 126,600); the largest increase was during the 1970's. Bonner and Kootenai Counties gained the most population, whereas Shoshone County lost population, particularly during the 1980's. Projections call for as much as 10-percent growth during the 1990's (Panhandle Area Council, 1993).

Benewah County

Benewah County is the smallest in both area and population of the three counties that compose the Coeur d'Alene Lake basin (table 1). It was part of Kootenai County until 1915. Population increased 27.4 percent from 1970 to 1990 but declined 4.3 percent during the 1980's, possibly as a result of declines in the timber industry (Panhandle Area Council, 1993).

Benewah County contains much of the productive agricultural land in the watershed. Forested areas in the lower St. Joe and St. Maries River Basins support extensive timber harvest and large forest-products processing mills. St. Maries serves as the county seat and as a major transshipment point for logs, many of which are towed down the St. Joe River and onto Coeur d'Alene Lake to mills in Coeur d'Alene. Benewah County contains one of the largest sources of placer-mined industrial and gem-grade garnets in the United States. The county also is becoming a major producer of wild rice grown in wetlands and flooded fields along the lower St. Joe and St. Maries Rivers.

Benewah County contains Heyburn State Park, one of the largest and most heavily used in the State. The county also serves as a gateway for travelers to the St. Joe River and surrounding public lands. However, the recreation/tourism potential of the county remains largely undeveloped (Harris and others, 1989).

Kootenai County

About 76 percent of the population of the Coeur d'Alene watershed resides in Kootenai County, primarily in the cities of Coeur d'Alene, Post Falls, and their immediate vicinities. Kootenai County contains large parts of the forested and agricultural lands in the watershed. The county contains a significant part of the watershed's wetlands,

Table 1. Population of Benewah, Kootenai, and Shoshone Counties, 1890–1990

Population assessment year	Benewah County	Kootenai County	Shoshone County
1890	([1])	4,108	5,382
1900	([1])	10,216	11,950
1910	([1])	22,247	13,936
1920	6,977	17,878	14,250
1930	6,371	19,469	19,060
1940	7,332	22,283	21,230
1950	6,173	24,947	22,806
1960	6,036	29,556	20,876
1970	6,230	35,332	19,718
1980	8,292	59,770	19,226
1990	7,937	69,795	13,931

[1]Benewah County was combined with Kootenai County until 1915.

especially at the heads of lake bays, along the Coeur d'Alene River, and around the 10 shallow lakes adjacent to the river's lower reach.

The county's population increased by 136 percent over the last 30 years to 69,795 in 1990. The increase was greatest (69 percent) during the 1970's (table 1). Some current forecasts predict as much as a 20-percent growth in Kootenai County during the 1990's (Kootenai County Planning Commission, 1993; Panhandle Area Council, 1993). Considering tourists in hotels/motels and part-time residents of second homes, the population of Kootenai County may exceed 100,000 in the summer (Kootenai County Planning Commission, 1993).

Much of the direct recreational use of Coeur d'Alene Lake and associated tourist-related business is in Kootenai County. In 1993, total hotel/motel and lodging sales in Kootenai County amounted to more than $27 million, based on stated travel and convention room tax receipts. This figure represents at least a fourfold increase over the last decade (Idaho Department of Commerce, 1992; Idaho Department of Employment, 1993).

The county also contains most of the lakeshore homesites, which are increasingly becoming year-round residences. The total 1991 market value of all property in Kootenai County was estimated to be more than $2.3 billion (Idaho Department of Commerce, 1992), and property on or immediately nearby Coeur d'Alene Lake accounted for more than half that figure (Kootenai County Assessor, written commun., 1993).

Shoshone County

Shoshone County is the largest of the three counties that compose the Coeur d'Alene Lake basin. It contains both rural and mountainous areas, the headwater areas of the Coeur d'Alene and St. Joe Rivers, and the Coeur d'Alene mining district (the Silver Valley). The county's population (about 15.2 percent of the watershed's total) has declined by about 29 percent from 1970 to 1990 (table 1). Shoshone County supports significant timber harvest and some mining activities.

Although Shoshone County's economy has not fully recovered from the collapse of the Silver Valley mining industry, diversification efforts are underway (Panhandle Area Council, 1993). The city of Kellogg is developing a major mountain resort served by the world's longest gondola, which draws increasing numbers of skiers in the winter and sightseers and mountain bikers in the summer. An analytical laboratory, once serving the mining industry almost exclusively, is expanding into the environmental analytical services field. The entire town of Wallace, the county seat, is listed on the National Register of Historic Places, largely because of its unique period architecture and colorful mining past. The town also draws visitors because of its location as a gateway to national forest and other public lands.

Hotel/motel and lodging sales in Shoshone County amounted to $1.8 million in 1991, or about three times those of 1983 (Idaho Department of Commerce, 1992). This trend is expected to continue as plans to develop tourism based on the Silver Valley's mining history and even its environmental damage and cleanup efforts are pursued (Hudson, Jelaco, Welch, and Comer, 1993). Environmental cleanup and mine restoration technology and services also may emerge as viable industries in the future.

The forests of the Coeur d'Alene and St. Joe River drainages are home to large big-game herds, attracting hunters from the region and throughout the Nation. The upper St. Joe River drainage, parts of which are designated as a Wild and Scenic River, contains challenging whitewater runs, a nationally famous wild trout fishery, and some of the most rugged and scenic wildlands in the continental United States. Consequently, outdoor recreation contributes significantly to the county's economy.

Coeur d'Alene Tribe

The 1,400-km^2 Coeur d'Alene Indian Reservation encompasses parts of Benewah and Kootenai Counties. Of the 3,600 km^2 originally included in the reservation at the time of its establishment in 1891, approximately 235 km^2 remains in Indian ownership. The traditional homeland of the Tribe was originally about 16,200 km^2.

The communities within the reservation boundary include St. Maries, Plummer, Worley, Tensed, and De Smet. Tribal headquarters are in Plummer. Of about 6,000 residents on the reservation, about 750 are members of the Coeur d'Alene Tribe. Another 550 tribal members reside outside the reservation. The Tribe operates farming, logging, construction, and retail businesses, a school system, and a health-care facility (Coeur d'Alene Tribe, written commun., 1974). Recently, the Tribe opened a bingo hall and is exploring other tourism, recreation, and service enterprises.

About 800 km^2 of the reservation drain into Coeur d'Alene Lake and about a third of the lake lies within the reservation. West and southwest of the lake, the reservation's land use is dominated by agriculture on fertile but highly erodible soils. Land use on the east side of the reservation is devoted largely to timber production.

Lake Uses

Coeur d'Alene Lake is heavily used for recreational boating and fishing. Although Kootenai County contains only 6.9 percent of Idaho's boatable water, 18.5 percent of the State's boats are registered in the county. Boat registration increased by almost 62 percent in the last 5 years, from 12,800 in 1988 to 20,800 in 1992 (Bureau of Land Management, 1993). A large number of Coeur d'Alene Lake boaters are from outside the State. Of the 10,000 out-of-State boats registered in Idaho, a little more than half of the owners declare Benewah and Kootenai Counties as their primary area of use; out-of-State boaters account for about one-fourth of the boats registered in Kootenai County (Idaho Department of Parks, written commun., 1993).

Coeur d'Alene Lake is probably the region's major attraction as a recreation and tourist area. A large lakeshore resort in Coeur d'Alene continues to expand, especially after the addition of a golf course on the site of a former sawmill on the city's eastern edge. Many public and private recreation areas are located on the lake (table 2). A recent Bureau of Land Management recreation management plan describes in greater detail the characteristics and services offered at each site (Bureau of Land Management, 1993). Other large-scale resort/recreation and lodging facilities are planned or are under development.

The cities of Coeur d'Alene, Harrison, Post Falls, and St. Maries operate popular parks offering picnic and (or) camping facilities and water access for boating and (or) swimming. Public beach and picnic areas also are provided along the shoreline property of North Idaho College at the lake's outlet. Many other public outdoor recreation sites are located on the lower Coeur d'Alene River and its lateral lakes, the lower St. Joe River, and throughout the watershed. The historic Cataldo Mission along the Coeur d'Alene River also attracts many visitors.

Within an 80-km radius of the city of Coeur d'Alene are numerous lakes that offer recreation opportunities similar to those at Coeur d'Alene Lake (table 3). By far the largest is Lake Pend Oreille, the southern end of which is within the 80-km radius. Most of these lakes are accessible by car; only a few of the lateral lakes adjacent to the Coeur d'Alene River are not.

In 1991, the Idaho Department of Fish and Game conservatively estimated the gross economic value of the Coeur d'Alene Lake fishery at $6 million. The kokanee fishery contributed almost half, and chinook salmon and

Table 2. Public and private recreation facilities at Coeur d'Alene Lake

[D, docks; T, toilets; DW, drinking water; BR, boat ramp; C, camping; RS, rental boat slips; data from Bureau of Land Management, 1993]

Facility name	Services available
Public	
North Idaho College beach	D, T, DW
Third Street beach	BR, D, T, DW
Boothes Park	BR, D, T
I-90 boat launch	BR, D
Higgins Point	D
Wolf Lodge Bay	BR, D, T
Squaw Bay	BR, D, T
Turner Point	D, T
Turner Bay	D, T
Carlin Bay	BR, D
Bell Bay	D, T, DW, C
Harlow Point	D
Mowry State Park	D, T, C
Windy Bay	D, T, C
Sun Up Bay	BR, D, T
Rockford Bay	BR, D, T
Loffs Bay	BR, D, T
Mica Bay boat park	D, T, C
Mica Bay	BR, D, T
Goulds Landing	BR, D, T
Rocky Point Marina	D, T, DW, BR, RS
Chatcolet, day use	D, T, BR
Plummer Point	D, T, DW
Hawleys Landing	D, T, DW, C
Private	
Boardwalk Marina	D, RS
Yacht Club Sales	BR, T, DW, RS
Northwest Resort	BR, T, DW, RS
Silver Beach Resort	D, RS
Delevans Marine	RS
Wolf Lodge campground	T, DW, C
Coeur d'Alene Lake Resort	D, T, DW, C
Beauty Bay Resort	D, RS
Squaw Bay Resort	BR, D, T, DW, C, RS
Panhandle Yacht Club	RS
Arrow Point RV Park	T
Arrow Point Resort	D, T, DW
Carlin Bay Resort	D, T, DW, C
Conklin Park Marina	D, T, DW, BR, RS

spiny rays (which included the "trophy" pike fishery) contributed approximately $225,000 and $330,000, respectively (Coeur d'Alene Tribe, written commun., 1994).

The Coeur d'Alene area's extensive and varied aquatic and terrestrial habitats offer excellent wildlife-viewing and birdwatching opportunities. Migrating bald eagles feed on spawning kokanee salmon during winter months and can be seen easily from vehicles on main roads. Birdwatching is popular in or near the area's extensive wetlands.

Coeur d'Alene Lake is a source of water for agricultural, domestic, and industrial use. At least six public water-supply systems use the lake water; however, the city of Coeur d'Alene recently changed to a ground-water supply. The Idaho Department of Water Resources has recorded 220 water rights filed to withdraw water from Coeur d'Alene Lake (Idaho Department of Water Resources, written commun., 1993). Although environmental and public health agencies advise against using surface water for domestic purposes without extensive treatment, many of these permitted withdrawals serve as a drinking-water source. There are many more unpermitted withdrawals, some of which probably are also used for domestic purposes (Ken Lustig, Panhandle Health District, oral commun., 1993).

Current trends of population growth and transition in an economy based on tourism and associated services (with a significant small manufacturing component) are expected to continue through the 1990's (Kootenai County Planning Commission, 1993; Panhandle Area Council, 1993). The demand for high-quality water also can be expected to increase. Therefore, protection and responsible management of water quality are important economic and environmental issues.

DESCRIPTION OF STUDY AREA

Physical Attributes

The 10,310-km^2 study area is located within Benewah, Kootenai, and Shoshone Counties in northern Idaho and Spokane County in eastern Washington (fig. 1). The Bitterroot Range composes most of the study area and is characterized by high, massive mountains mantled with coniferous forests and deep, intermontane valleys. Elevations range from approximately 610 m above sea level at the Idaho-Washington border to 2,086 m at the Idaho-Montana border. Coeur d'Alene Lake has a surface elevation of 648.7 m at full pool. The lake's two principal tributaries are the Coeur d'Alene and St. Joe Rivers, which drain the Coeur d'Alene and St. Joe Mountains, subsets of the Bitterroot Range. The lake is drained by the Spokane River, a tributary to the Columbia River.

The Coeur d'Alene and St. Joe Mountains are primarily metasedimentary rocks of the Proterozoic Belt Supergroup that have been intruded locally by granitic rocks of Cretaceous age. The lower elevations west of the Coeur d'Alene and St. Joe Mountains are underlain by glaciofluvial deposits and remnants of multiple basaltic lava flows. An important feature in the northwestern part of the study area is the Rathdrum Prairie, a 1,060-km^2 valley-fill aquifer created during the Pleistocene by repeated outburst floods from glacial Lake Missoula.

A generalized description of the major soil types in the study area was derived from the U.S. Department of Agriculture (1984). Most of the mountainous area east of Coeur d'Alene Lake contains soils formed in volcanic ash and loess over metasedimentary rocks. The mountainous area west of the lake contains soil formed in volcanic ash and loess over granite, gneiss, and schist. Much of the hilly margin of the lake contains two major soil types. The first type is soils on undulating to steep hills, formed in deep loess with some volcanic ash influence. The second type is soils on mountainous slopes and canyon walls associated with hills and plateaus, formed mainly in basalt with a thin loess cover. In the Rathdrum Prairie, soils on glaciated mountainsides, glacial moraines, and associated terraces have formed in volcanic ash overlying glacial drift and in sandy, glacial, lacustrine sediments.

Table 3. Lakes within an 80-kilometer radius of the city of Coeur d'Alene

[km^2, square kilometer; —, no data available]

Lake name	Surface area (km^2)	Lake name	Surface area (km^2)
Idaho lakes		**Idaho lakes—Continued**	
Anderson[1]	1.2	Pend Oreille	330
Black[1]	1.4	Porter	.1
Blue[1]	.8	Rose[1]	1.4
Bull Run[1]	.3	Round	.2
Cave[1]	2.4	Spirit	5.2
Chilco	—	Swan[1]	1.5
Fernan	1.4	Thompson[1]	.8
Granite	.1	Twin	7.8
Hauser	2.4		
Hayden	17	**Washington lakes**	
Kelso	.2	Liberty	2.8
Killarney[1]	1.9	Long Lake	21
Medicine[1]	.7	Newman	4.9

[1]Lateral lakes adjacent to Coeur d'Alene River.

The lower valleys of the St. Joe and Coeur d'Alene Rivers contain soils on flood plains and low terraces, formed in silty alluvium.

The study area receives some of the largest amounts of precipitation in Idaho. About 70 percent of the annual precipitation occurs as snow during October to April. The areal distribution of precipitation is influenced by the basin's topography. For example, the climatological station at Coeur d'Alene (elevation 658 m) records a mean annual precipitation of 644 mm, whereas the station at Wallace (elevation 896 m) records 971 mm. Ambient temperature varies throughout the study area, depending on elevation; at Coeur d'Alene, the mean annual temperature is 9.1°C, whereas it is 6.8°C at Wallace. Although winter temperatures at Coeur d'Alene Lake are often below freezing, the lake normally does not freeze except in its shallow southern end.

Coeur d'Alene Lake lies in a naturally dammed river valley, covers 129 km^2, and has a volume of 2.84 km^3. The southern end of the lake contains four shallow lakes, Benewah, Chatcolet, Hidden, and Round, that were flooded in 1906 by impoundment of the Spokane River by Post Falls Dam at Post Falls. The four shallow lakes are contiguous with Coeur d'Alene Lake. The lake's outflow volume is controlled by Post Falls Dam, which provides hydroelectric power, flood control, and irrigation supply. At its outlet, the mouth of the Spokane River, the lake receives surface-water inflow from a 9,690-km^2 drainage area. About 90 percent of the surface-water inflow to the lake is delivered by two rivers, the Coeur d'Alene and the St. Joe.

The Coeur d'Alene River (drainage area, 3,812 km^2) discharges into the lake near Harrison (fig. 1). The river has three major reaches, the North Fork, the South Fork, and the reach downstream from the confluence of the North and South Forks. Land-use activities in the Coeur d'Alene River Basin include recreation, logging, agriculture, and mining and ore processing. Most of the mining and ore-processing activities are in the basin of the South Fork, which contains the Bunker Hill Superfund site.

The St. Joe River (drainage area, 4,520 km^2) discharges into the southern end of the lake (fig. 1). The St. Joe River is joined by the St. Maries River at the town of St. Maries. Recreation and logging are the dominant land uses; little mining activity has occurred in the St. Joe River Basin.

Biological Attributes

Historically, the native fish species abundant in Coeur d'Alene Lake and its tributaries included westslope cutthroat trout, bull trout, mountain whitefish, peamouth, northern squawfish, suckers, and sculpins (Coeur d'Alene Tribe, written commun., 1994). Despite unsubstantiated reports to the contrary, anadromous fish probably did not enter Coeur d'Alene Lake (Coeur d'Alene Tribe, written commun., 1994). Nevertheless, native species provided an abundant subsistence fishery for the area's indigenous people (Rabe and Flaherty, 1974; Peltier, 1982).

In 1937, kokanee salmon were introduced, beginning the lake's transformation into a sportfishery dominated by introduced species. Other introduced species now include chinook salmon, rainbow trout, brook trout, northern pike, tiger muskie, yellow perch, tench, black bullhead, pumpkinseed, largemouth bass, smallmouth bass, and black crappie (Coeur d'Alene Tribe, written commun., 1994).

The extensive forests of the watershed support deer, elk, moose, black bears, coyotes, bobcats, cougars, porcupines, squirrels, martens, badgers, wolverines, beavers, mice, and other small rodents; several species of songbirds, forest grouse, owls, hawks, and other raptors; and many species of amphibians, reptiles, insects, and other invertebrates. The mainly coniferous forests are composed of fir, pine, hemlock, cedar, and larch. Deciduous trees such as cottonwood and willow grow along lakeshores and streambanks or are interspersed among the conifers, as are isolated stands of aspen and birch. Many species of grasses, mosses, fungi, and deciduous shrubs blanket the forest floor or grow in open areas.

The region's numerous wetlands and nearshore areas also support an abundance of plant, animal, and bird life. Waterfowl are abundant year around, and large numbers pass through the area seasonally during migration. Many species of songbirds, waterbirds, and raptors are plentiful. These areas also support otters, beavers, musk-rats, weasels, and other furbearers, as well as numerous species of rodents, amphibians, and reptiles.

CLASSIFICATION OF LAND USE AND LAND COVER

Land use and land cover in the study area were classified using remote-sensing and geographic information system technology. The classification was performed by the Idaho Department of Water Resources under contract with the USGS; their report (Idaho Department of Water Resources, 1993) describes the methods and results and, therefore, will only be summarized here.

Two Landsat scenes were classified; they represented the most current summer scenes with less than 10-percent cloud cover. Scene 42/27 was a full scene acquired on July 21, 1989. Scene 43/27 was a subscene acquired on July 27, 1989. The scenes were geocoded to a UTM projection and mosaicked to produce a single scene. The total root mean square error of the final scene was 16.5 m. An unsupervised classification approach was selected because of the complexity of the study area. Image processing and image interpretation procedures were used to produce the following list of 15 land use and land cover classes:

- dense urban or built-up land
- sparse urban or built-up land
- irrigated agriculture and pasture
- dryland agriculture and pasture
- rangeland
- deciduous forest
- coniferous forest
- sparse forest
- recent clearcuts
- recovering clearcuts
- water
- wetlands
- barren land
- mined land
- clouds and cloud shadows

An accuracy assessment was conducted to determine individual class accuracies and overall accuracy. The overall accuracy for the classifications was 96 percent.

The study area was divided into 40 subbasins (fig. 3 and table 4) to provide detailed information on land use and land cover. Twenty-seven of the subbasins are of small to moderate size and are contiguous to Coeur d'Alene Lake. The Coeur d'Alene River Basin was divided into seven subbasins, whereas the St. Joe River Basin was divided into five subbasins. The remaining subbasin represented the area between the lake outlet and the USGS gaging station near the Idaho-Washington border. The detailed breakdown of land use and land cover for the 40 subbasins is listed in the report by the Idaho Department of Water Resources (1993).

The land use and land cover within the study area (table 5) are dominated by coniferous forest (51.6 percent) and sparse forest (23 percent). The two agriculture classes together represent 5.4 percent of the land use and land cover; recent and recovering clearcuts together represent 6 percent. Mined land represents the smallest amount of land use and land cover, 0.05 percent. Wetlands represent only 0.23 percent of the land use and land cover, but they are significant resources. Within the border of Coeur d'Alene Lake are 11 priority wetland areas (Idaho Department of Parks and Recreation, 1993). Priority wetlands are those that (1) provide a high degree of public benefits, (2) are representative of rare or declining wetland types within an ecoregion, and (3) are subject to an identified threat of loss or degradation.

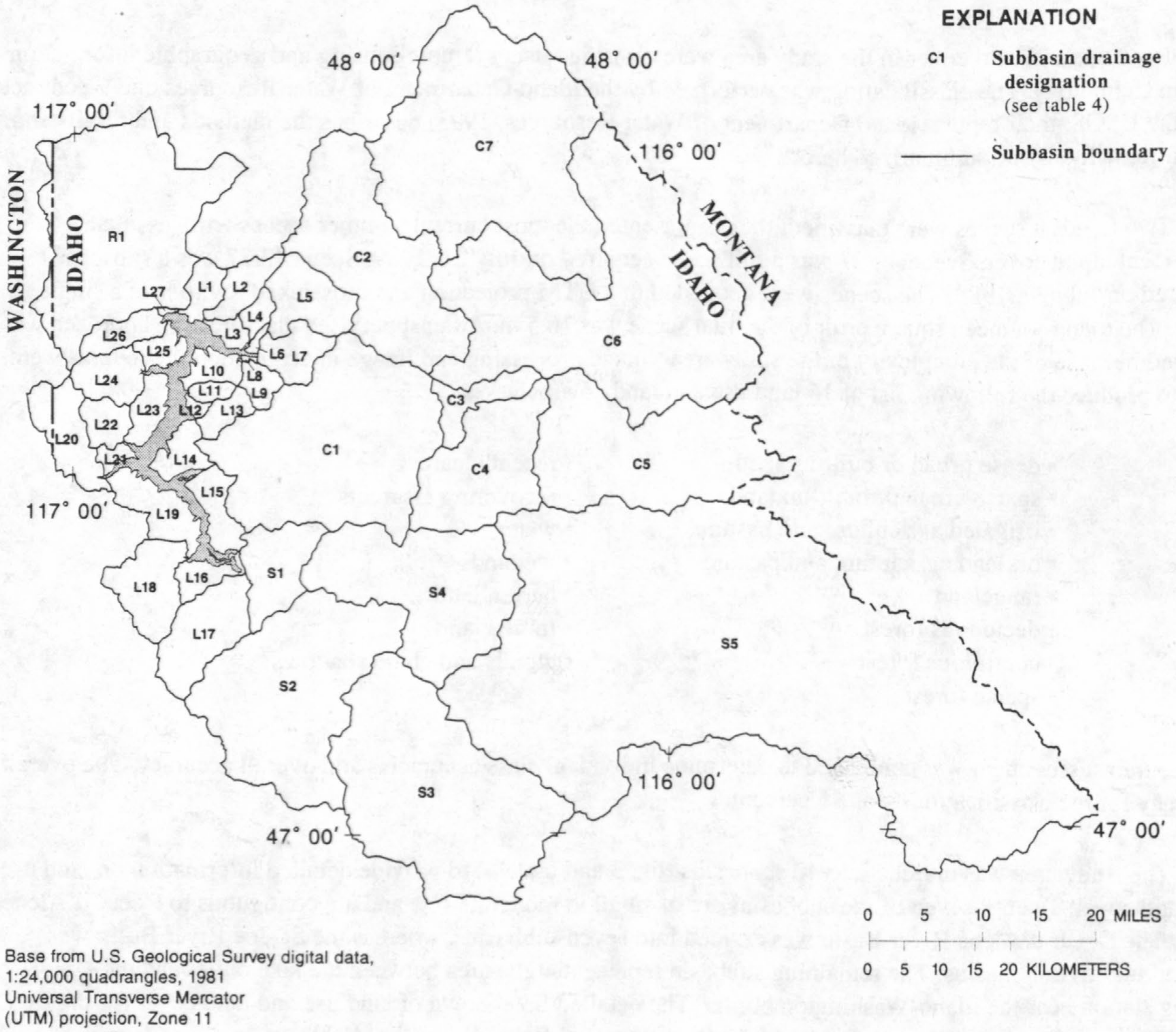


Figure 3. Locations of 40 subbasins within study area.

Table 4. Subbasins and associated drainage areas in the study area

[km^2, square kilometer; L, Lake; C, Coeur d'Alene River; S, St. Joe River; R, Spokane River; USGS, U.S. Geological Survey]

Subbasin No. (fig. 3)	Subbasin name	Drainage area (km^2)	Subbasin No. (fig. 3)	Subbasin name	Drainage area (km^2)
L1	City of Coeur d'Alene	37.1	L27	Cougar Bay, nearshore, northwest	2
L2	Fernan Creek	49.5	C1	Coeur d'Alene River, Harrison to Cataldo gaging stations	652
L3	Bennett Bay, nearshore	18.9	C2	Coeur d'Alene River, Little North Fork	445
L4	Blue Creek	20.5	C3	Coeur d'Alene River, Enaville gaging station	67.1
L5	Wolf Lodge Creek	104	C4	Coeur d'Alene River, South Fork, Pinehurst to Elizabeth Park gaging stations	270
L6	Wolf Lodge Bay, nearshore, northeast	5.4	C5	Coeur d'Alene River, South Fork, Elizabeth Park gaging station	482
L7	Cedar Creek	62.5	C6	Coeur d'Alene River, South Fork, Pinehurst to North Fork, Enaville to Prichard gaging stations	1,020
L8	Wolf Lodge Bay, nearshore, southeast	1.7	C7	Coeur d'Alene River, North Fork, upstream from Prichard gaging station	876
L9	Beauty Creek	28.9	S1	St. Joe River, lake to St. Maries gaging station	117
L10	Squaw Bay to Echo Bay, nearshore	34.2	S2	St. Maries River, St. Maries to Santa gaging station	565
L11	Turner Creek	16.5	S3	St. Maries River, upstream from Santa gaging station	713
L12	Carlin Bay, nearshore	7.2	S4	St. Joe River, St. Maries to Calder gaging stations	438
L13	Carlin Creek	31.7	S5	St. Joe River, upstream from Calder gaging station	2,687
L14	Powderhorn Bay, nearshore	44.3	R1	Spokane River, lake outlet to USGS gaging station near State line	624
L15	Harrison to St. Maries, nearshore	54.9			
L16	Chatcolet Lake, nearshore, south	34.3			
L17	Benewah Creek	138			
L18	Plummer Creek	114			
L19	Windy Bay to Chatcolet Lake, nearshore	79.9			
L20	Lake Creek	99.5			
L21	Windy Bay, nearshore, north	14.1			
L22	Fighting Creek	41.6			
L23	Rockford Bay to Mica Bay, nearshore	41.9			
L24	Mica Creek	67.7			
L25	Mica Bay to Cougar Bay, nearshore	29.6			
L26	Cougar Creek	48.5			

Table 5. Land use and land cover in the study area

[km^2, square kilometers]

Land use and land cover classification	Area (km^2)	Percent of total
Coniferous forest	5,260	51.6
Sparse forest	2,350	23.0
Rangeland	688	6.8
Clouds	402	3.9
Recovering clearcut forest	385	3.8
Dryland agriculture and pasture	357	3.5
Recent clearcut forest	227	2.2
Irrigated agriculture and pasture	196	1.9
Water	166	1.6
Dense urban or built-up land	48.9	.48
Cloud shadows	34.6	.34
Sparse urban or built-up land	29.1	.29
Wetland	23.9	.23
Barren land	15.2	.15
Deciduous forest	7	.07
Mined land	4.1	.05
TOTAL (rounded)	10,200	100

LIMNOLOGY

Limnological characteristics of Coeur d'Alene Lake were studied to (1) assess spatial and temporal trends in physical, chemical, and biological conditions; (2) characterize the lake's trophic state; and (3) provide limnological data for a nutrient load/lake response model. Numerous limnological variables were monitored to gain an understanding of lake-mixing processes, water-column transparency, nutrient dynamics, dissolved-oxygen deficits, and overall water-quality conditions. The monitoring results also were used to determine whether observed water-quality conditions differed from those reported in earlier studies of Coeur d'Alene Lake.

Data Collection and Analysis

BATHYMETRY

The bathymetry of the lake was mapped to allow computation of volume, surface area, and a hypsometric curve, three variables required in the nutrient load/lake response model. A calibrated video depth sounder and a global positioning system receiver were used to determine depths at 580 locations throughout the lake. The depths were digitized onto a digital base map; depth contours were drawn manually and digitized to determine the surface area of each depth plane. The volume of the lake was computed with the following equation from Håkanson (1981):

$$V_p = \sum_{i=0}^{n} \frac{l_c}{3} \left(a_i + a_{i+1} + \sqrt{a_i + a_{i+1}} \right), \qquad (1)$$

where

V_p is the parabolic approximation of the lake volume, in cubic kilometers;

l_c is the contour line interval, in meters; and

a_i is the total surface area within the limits of the contour line l, in square kilometers.

LIMNETIC ZONE

Monitoring of the limnetic zone (open waters, away from shore) began in mid-January 1991 and ended in mid-December 1992. Seven stations were monitored in 1991 and six in 1992 (fig. 4). Each station's latitude, longitude, depth, and official USGS name are listed in table 6. Station selection was based largely upon the results of reconnaissance sampling conducted by the USGS from May through November 1987 (Woods, 1989). Each of the seven limnetic stations represented an important limnological zone. Station 1, south-southeast of Tubbs Hill, monitored the large, deep mass of water in the lake's northern arm. Station 2, in Wolf Lodge Bay, was selected because it was hydrologically isolated from the major northward flow in the lake. Station 3, near Driftwood Point, was in the lake's deepest region. Station 4, near University Point, monitored the water quality of the combined flows of the Coeur d'Alene and St. Joe Rivers after they mixed with lake water. Station 5, near Blue Point, monitored the relatively shallow southern part of the lake that is minimally influenced by the Coeur d'Alene River. Station 6, in Chatcolet Lake, monitored the shallow, macrophyte-dominated southernmost part of the lake. Station 7, near Donavons Point, was selected for special monitoring of near-bottom water quality in log-storage areas within Cougar Bay. This station was discontinued in 1992. Data from several of the stations have been collected by other investigators and can be used for comparative purposes.

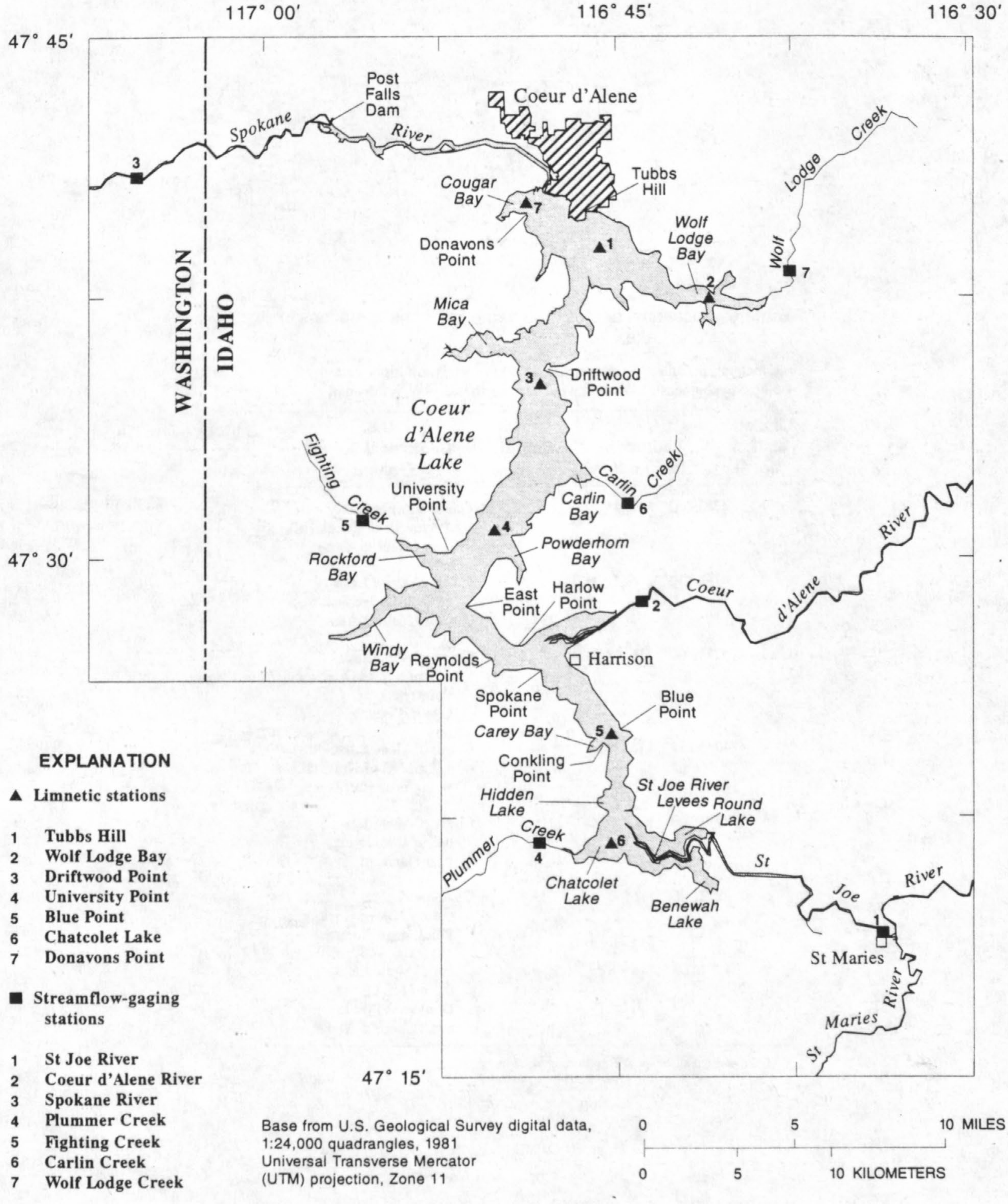


Figure 4. Locations of limnetic sampling and streamflow-gaging stations.

Table 6. Locations, depths, and names of limnetic stations in Coeur d'Alene Lake

[m, meters; mi, miles. To convert miles to kilometers, multiply miles by 1.609. SE, southeast; SW, southwest; NE, northeast; NW, northwest]

Limnetic station (fig. 4)	Latitude, longitude	Depth[1] (m)	U.S. Geological Survey name
1	47°39'00", 116°45'30"	42.5	Coeur d'Alene Lake, 1.3 mi SE of Tubbs Hill, near Coeur d'Alene
2	47°37'30", 116°41'00"	29.5	Coeur d'Alene Lake, at Wolf Lodge Bay, near Coeur d'Alene
3	47°35'00", 116°48'20"	52.0	Coeur d'Alene Lake, 0.8 mi SW of Driftwood Point, near Coeur d'Alene
4	47°30'54", 116°50'06"	40.0	Coeur d'Alene Lake, 1.7 mi NE of University Point, near Harrison
5	47°25'00", 116°45'00"	16.5	Coeur d'Alene Lake, NE of Blue Point, near Harrison
6	47°21'20", 116°45'10"	11.0	Chatcolet Lake, 0.4 mi NW of Rocky Point, near Plummer
7	47°40'03", 116°48'27"	4.8	Coeur d'Alene Lake, 0.2 mi NE of Donavons Point, near Coeur d'Alene

[1] Lake surface at full-pool elevation of 648.7 m.

The stations were visited every 3 weeks from May through October and every 4 to 6 weeks during the remaining months. During each monitoring visit, a Hydrolab multiparameter water-quality instrument (model Surveyor II) was used to profile the water column for temperature, specific conductance, pH, dissolved-oxygen concentration, and percent saturation as a means to assess water-column stratification and general water-quality conditions. Vertical profiles of photosynthetically active radiation (PAR) were made with a LiCor integrating quantum radiometer/photometer (model LI–188B) equipped with a LiCor spherical quantum sensor (model LI–193SA) to determine euphotic zone depths and to compute extinction coefficients. The euphotic zone is defined as that part of the water column in which *in situ* PAR is equal to or greater than 1 percent of the PAR incident upon the lake's surface. The equation for computation of an extinction coefficient is as follows:

$$n = \frac{lnI_z - lnI_0}{z}, \tag{2}$$

where

n is extinction coefficient, per meter;
ln is natural logarithm, unitless;
I_z is PAR at depth z, in microEinsteins per square meter per second;
I_0 is PAR immediately above lake surface, in microEinsteins per square meter per second; and
z is depth below lake surface, in meters.

Water-column transparency was measured with a 20-cm-diameter secchi disc. Observations also were recorded for PAR incident upon the lake surface, weather and lake-surface conditions, and any unusual conditions. Water samples were obtained with a nonmetallic Van Dorn bottle. Within the euphotic zone, a depth-weighted composite sample was derived from three point samples. Two additional point samples were taken at mid-depth and 1 m above the lakebed. Because of the shallow depths at stations 5 and 6, mid-depth samples were not taken. At station 7, water samples were obtained only from 0.5 m above the lakebed. At stations 1 through 6, each water sample was analyzed for concentrations of total phosphorus, dissolved orthophosphorus, total organic plus ammonia nitrogen, dissolved ammonia, and dissolved nitrite plus nitrate. The ratio of nitrogen to phosphorus, N:P, was calculated with the following equation:

$$N:P = \frac{DIN}{DOP}, \tag{3}$$

where

$N:P$ is the nitrogen-to-phosphorus ratio, unitless;
DIN is the combined concentration of dissolved ammonia, nitrite, and nitrate (as nitrogen), in micrograms per liter; and
DOP is the concentration of dissolved orthophosphorus (as phosphorus), in micrograms per liter.

The euphotic-zone composites from stations 1 through 6 were also analyzed for chlorophyll-*a* and phytoplankton taxonomy. Chlorophyll-*a* samples were field filtered onto glass-fiber filters (Whatman GF/F) and the filters were kept frozen until analyzed. On alternate monitoring visits, the euphotic zone composites and the lower hypolimnion samples from stations 1 through 6 were analyzed for total recoverable concentrations of arsenic, cadmium, copper, lead, mercury, and zinc. The euphotic zone and lower hypolimnion waters of these six stations were also sampled for major and minor cations and anions on a semiannual basis. At station 7, near-bottom water samples were analyzed for dissolved concentrations of orthophosphorus, ammonia, and nitrite plus nitrate. Except for the phytoplankton samples, analyses of the water samples were performed at the USGS's National Water-Quality Laboratory using methods described by Fishman and Friedman (1985) and Britton and Greeson (1987). The phytoplankton analyses were performed under contract by Aquatic Analysts of Portland, Oregon.

Phytoplankton bioassays were conducted to determine whether trace elements in Coeur d'Alene Lake could significantly suppress phytoplankton growth. Dissolved (0.2-micron filter) concentrations of cadmium, copper, iron, zinc, and organic carbon were sampled from 0.5 m beneath the water surface during June and September 1993 and June and August 1994 at the following six locations: St. Joe River about 6.6 km upstream from Chatcolet Lake, Coeur d'Alene River about 4 km upstream from Coeur d'Alene Lake, Mica Bay, and limnetic stations 1, 4, and 6 (fig. 4). Additionally, phytoplankton samples were collected at the six locations to identify and isolate species for culturing and use in the bioassays.

Trace-element concentrations were determined by Zeeman-corrected atomic absorption spectroscopy in conjunction with ultraclean methods. Dissolved organic carbon concentrations were determined by oxygen/ultraviolet/persulfate oxidation as described by Hunter and Kuwabara (1994). The trace-element and dissolved organic carbon data were combined with data on major and minor cations and anions measured in the lake during this study to compute chemical speciation with the geochemical modeling program HYDRAQL (Papelis and others, 1988).

The chemically defined phytoplankton bioassays were conducted using the methods reported by Kuwabara (1985). Three treatments were devised on the basis of the geochemical modeling. Each treatment was conducted in triplicate using three phytoplankton genera isolated from Coeur d'Alene Lake. The number of cells and biomass were monitored with a particle-size analyzer (model Multisizer 2E, Coulter Instruments) until the stationary growth phase was attained.

LITTORAL ZONE

A comparison of water-quality conditions among limnetic and littoral stations (shoreline waters) was made by analyzing data collected concurrently at those stations during September 1991 and August 1992. In 1991, water-quality samples were collected at limnetic stations 1 through 6 and 20 littoral stations (table 7) during September 16 to 18. The sampling protocol for the limnetic stations was employed at the 20 littoral stations, except that phytoplankton and trace elements were not sampled. In 1992, water-quality samples were collected at limnetic stations 1 through 6 and 15 shallow littoral stations (table 8) during August 10 to 13. At the littoral stations, a 1-m-deep discrete sample was retrieved for analysis of the same constituents sampled at the limnetic stations, except for extinction coefficient and phytoplankton.

Periphyton samples collected from artificial substrates at the 15 shallow littoral stations listed in table 8 were used to assess periphyton production in relation to various levels of nearshore development. Artificial substrates were chosen, instead of natural substrates, to reduce the number of environmental variables used for the statistical assessment. Artificial substrates were placed at the 15 littoral stations during July 21 to 22, 1992, and were incubated *in situ* for about 30 days. The substrates were retrieved during August 17 to 19 for analysis of biomass accrual, quantified as chlorophyll-*a*. The substrates at stations C, D, L, M, and O were vandalized so were unusable for analysis.

Each artificial substrate consisted of a 5-cm-diameter unglazed ceramic ball affixed with silicone adhesive to a 1-m-long rigid plastic shaft. At each station, five substrates were held vertically by a concrete-filled, plastic bucket. The bucket was placed on the lakebed such that the ceramic balls were about 1 m beneath the lake surface and about 1 m above the lakebed. The design and placement of the artificial substrates reduced the potential losses of periphyton due to benthic-invertebrate grazing and wave-induced sloughing. The amount of PAR received by each station's artificial substrates during the incubation was computed so periphyton growth rates could be normalized to PAR. A LiCor solar monitor (model LI–1776) located on the northern shore of Coeur d'Alene Lake recorded the hourly input of PAR during the incubation period. At each station, an extinction coefficient was computed from depth profiles of PAR. The amount of shading by the horizon and nearby structures and vegetation was quantified at each site using a solar pathfinder. This allowed adjustment of incubation PAR data to account for

Table 7. Locations, depths, and names of littoral stations in Coeur d'Alene Lake sampled during September 1991

[m, meters]

Littoral station (fig. 20)	Latitude, longitude	Depth[1] (m)	U.S. Geological Survey name
1	47°38'43", 116°47'52"	9.8	Kid Island Bay
2	47°40'00", 116°46'03"	14.0	Sanders Beach
3	47°38'43", 116°43'06"	12.8	Bennett Bay
4	47°37'51", 116°40'26"	16.2	Blue Creek Bay
5	47°36'59", 116°41'04"	22.2	Beauty Bay
6	47°37'30", 116°44'49"	9.8	Squaw Bay
7	47°36'40", 116°48'08"	11.9	Echo Bay
8	47°36'15", 116°51'00"	11.6	Mica Bay
9	47°35'33", 116°47'22"	15.2	Driftwood Bay
10	47°34'24", 116°46'59"	13.4	Turner Bay
11	47°33'23", 116°49'18"	12.2	Loffs Bay
12	47°32'20", 116°46'26"	12.5	Carlin Bay
13	47°29'41", 116°48'57"	16.5	Powderhorn Bay
14	47°30'18", 116°53'18"	15.5	Rockford Bay
15	47°28'46", 116°54'55"	14.9	Windy Bay
16	47°28'16", 116°53'12"	12.5	16 to 1 Bay
17	47°27'56", 116°52'36"	14.0	Aberdeen Lodge Bay
18	47°26'49", 116°50'04"	12.8	Cottonwood Bay
19	47°26'02", 116°47'22"	12.8	Fullers Bay
20	47°24'35", 116°45'44"	11.8	Carey Bay

[1] Lake surface at full-pool elevation of 648.7 m.

Table 8. Locations, depths, and names of littoral stations in Coeur d'Alene Lake sampled during August 1992

[m, meters]

Littoral station (fig. 20)	Latitude, longitude	Depth[1] (m)	U.S. Geological Survey name
A	47°38'26", 116°47'57"	1.8	Kid Island Bay
B	47°38'49", 116°43'08"	1.8	Bennett Bay
C	47°37'35", 116°40'54"	1.8	Wolf Lodge Bay
D	47°36'42", 116°46'00"	1.8	Echo Bay
E	47°36'28", 116°50'42"	2.4	Mica Bay
F	47°34'15", 116°46'23"	1.8	Turner Bay
G	47°33'30", 116°49'17"	1.8	Loffs Bay
H	47°32'35", 116°46'25"	1.8	Carlin Bay
I	47°29'50", 116°48'55"	1.8	Powderhorn Bay
J	47°30'25", 116°53'27"	1.8	Rockford Bay
K	47°28'40", 116°55'11"	1.8	Windy Bay
L	47°28'19", 116°53'18"	1.8	16 to 1 Bay
M	47°28'02", 116°52'41"	1.8	Cave Bay
N	47°26'06", 116°47'28"	1.8	Fullers Bay
O	47°24'37", 116°46'08"	1.8	Carey Bay

[1] Lake surface at full-pool elevation of 648.7 m.

differences in incident PAR at each station. Finally, the PAR received during incubation at each station's substrates was computed with the following equation:

$$PAR_z = PAR_i \ (e^{-nz}) \ PS , \tag{4}$$

where

PAR_z is PAR input to artificial substrate during incubation, in Einsteins per square meter;
PAR_i is PAR input to lake surface during incubation, in Einsteins per square meter;
e is base of natural logarithms, unitless;
n is extinction coefficient, per meter;
z is depth of artificial substrate, in meters; and
PS is decimal percent of station unshaded.

When each artificial substrate was retrieved, the periphyton attached to the ceramic ball were brushed gently into a 500-mL plastic jar containing 250 mL of filtered lake water. The 250-mL sample was homogenized for 1 minute, then three subsamples were withdrawn and each was filtered through a Whatman GF/F glass-fiber filter. The filters were frozen until subsequent analysis for chlorophyll-*a*. The chlorophyll-*a* analyses were performed by the authors using a Turner Designs fluorometer (model 10-005R) and the methods described by Koenings and others (1987). Two replicate analyses were run on the supernatant derived from the acetone extraction of each chlorophyll-bearing filter. The amount of chlorophyll-*a* associated with the periphyton on each ceramic ball was computed with the following equation:

$$B_{chl} = \frac{(C)\ (V_e)\left(\frac{V_t}{V_f}\right)(CF)}{A} , \tag{5}$$

where

B_{chl} is periphyton biomass, as chlorophyll-*a*, on artificial substrate, in milligrams per square meter;
C is concentration of chlorophyll-*a* in extract, in micrograms per liter;
V_e is volume of extract, in liters;
V_t is volume of periphyton sample, in liters;
V_f is volume of periphyton sample filtered, in liters;
CF is factor to convert micrograms to milligrams; and
A is area of artificial substrate, in square meters.

The distribution, relative abundance, and taxonomic composition of aquatic macrophytes were determined in August 1993. Sixty-three sites throughout the lake, mostly in bays, were sampled (fig. 5). Divers sampled macrophytes along transects from the shoreline to the maximum depth of macrophyte occurrence. Representative specimens were taxonomically identified onsite by a Bureau of Land Management botanist.

Bathymetry

At its normal full-pool elevation of 648.7 m above NGVD, Coeur d'Alene Lake covers 129 km^2 and contains 2.84 km^3 of water (table 9). At full pool, the lake's mean depth is 22.0 m and its maximum depth is 63.7 m. When the lake level is reduced to an elevation of 646.2 m, the limit of available drawdown, the surface area is reduced to 122 km^2 and the volume to 2.60 km^3. The relation of depth to lake surface area and volume is illustrated in figure 6. The variation in lake surface elevation during 1991–92 is shown in figure 7. A bathymetric map of Coeur d'Alene Lake (Woods and Berenbrock, 1994) is shown in figure 8.

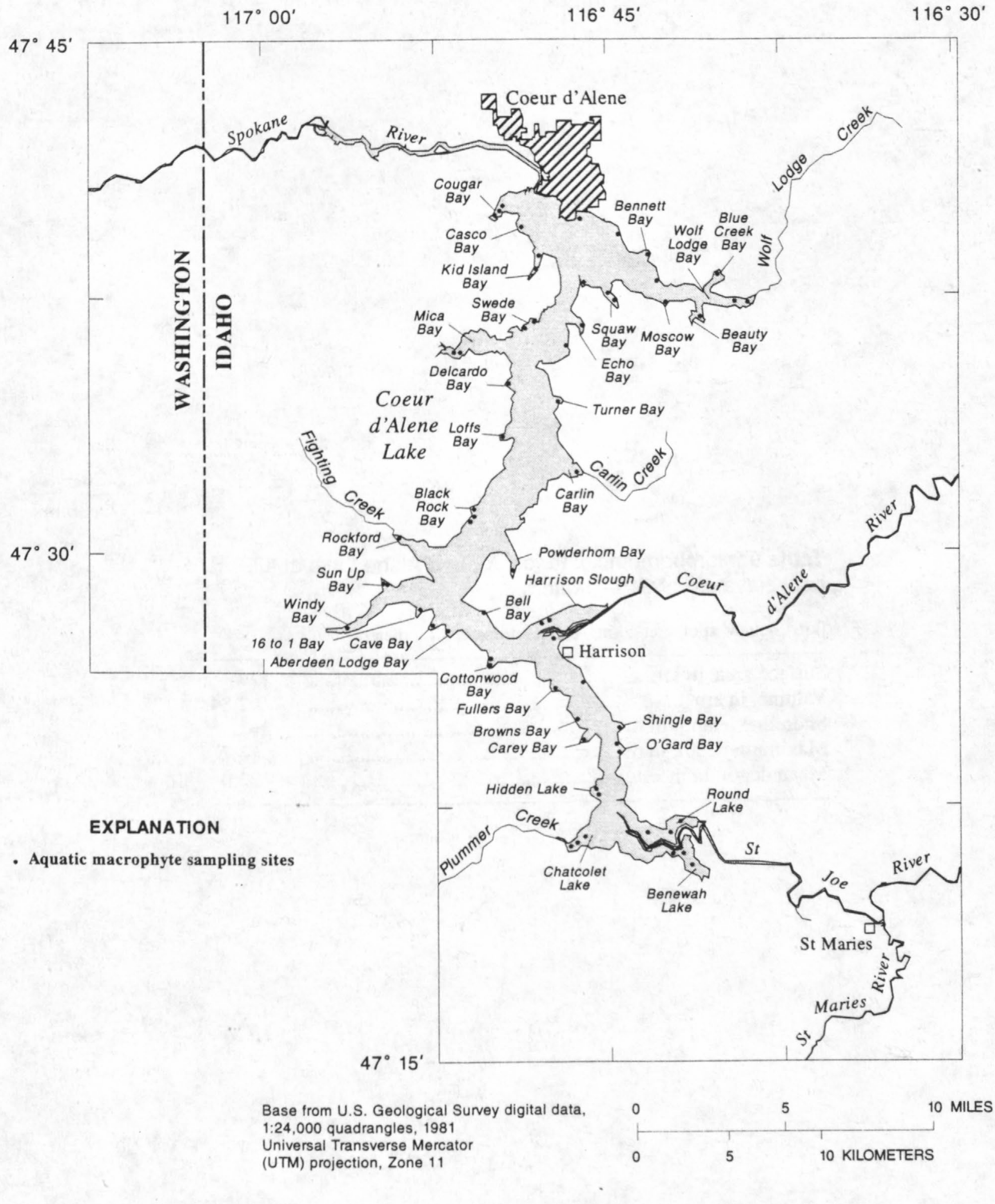


Figure 5. Locations of aquatic macrophyte sampling sites.

Table 9. Morphometric data for Coeur d'Alene Lake at full-pool elevation of 648.7 meters

[km^2, square kilometers; km^3, cubic kilometers; m, meters]

Surface area, in km^2	129
Volume, in km^3	2.84
Shoreline length, in m	243
Maximum depth, in m	63.7
Mean depth, in m	22.0

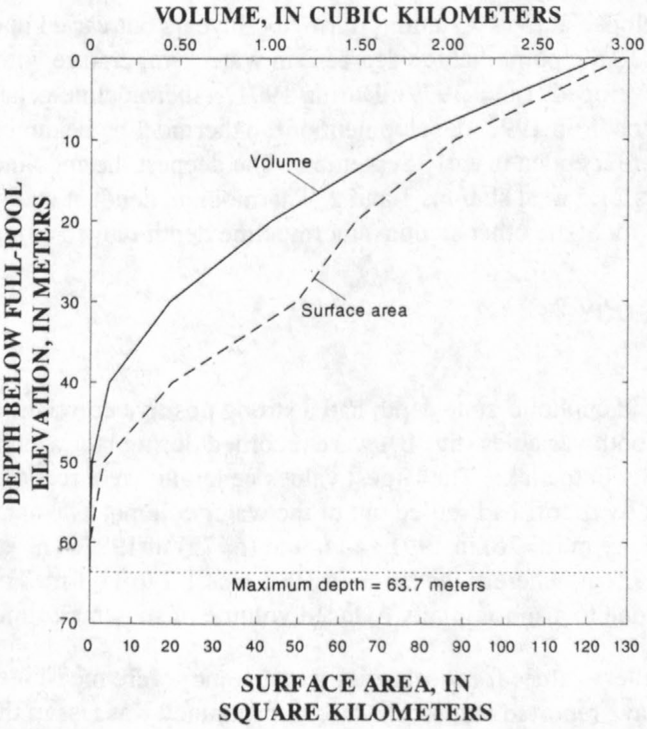


Figure 6. Relation of depth to lake surface area and volume for Coeur d'Alene Lake.

Limnetic Zone

WATER TEMPERATURE

The maximum water temperature measured at the six limnetic stations during 1991 was 23.4°C at station 6 and, during 1992, 23.1°C at station 4 (fig. 9). During 1991, water temperature at the six stations reached a maximum in early August. The date of the maximum was more variable in 1992, occurring between mid-July and mid-August. Minimum water temperatures reached 0°C at station 6 in January 1991 and December 1992 when ice covered the lake at that station. Minimum water temperatures at the other five stations were about 2°C during January 1991, whereas the minimums were slightly warmer, 4 to 5°C, during January and February 1992.

Thermal stratification developed at the six stations during both years but varied in duration and depth (fig. 9). If thermal stratification develops to the point that the decrease in water temperature with depth exceeds 1°C per meter, then a thermocline has developed (Lind, 1979). During 1991, a thermocline generally developed by mid-July and ended by early October. In 1992, development of the thermocline began in June and ended in mid-October, except at station 6, where it ended in early September. The deepest thermocline in 1991 was 16.5 m at station 1, whereas in 1992, it was 21.5 m at stations 1 and 2. Thermocline depth at station 6, the shallowest, was atypical, ranging from 4.5 to 8.5 m; at the other stations, thermocline depth ranged from 7.5 to 21.5 m.

WATER-COLUMN TRANSPARENCY

Secchi-disc transparency and euphotic-zone depth had a strong positive correlation ($r=0.92$, $p<0.00001$, $n=130$). The smallest values for both variables (fig. 10) were recorded during late winter and spring when snowmelt runoff had increased turbidity in the lake. The largest values generally were recorded during late summer and autumn after the sediments input by runoff had settled out of the water column. The area-weighted lakewide mean for secchi-disc transparency was 4.9 m (n=76) in 1991 and 6.9 m (n=75) in 1992. The overall range in secchi-disc transparency in 1991 was 0.7 to 9.5 m, whereas the range in 1992 was 1.7 to 11.1 m. The larger mean secchi-disc transparency in 1992 was likely due to a substantially reduced volume of snowmelt runoff into the lake in 1992.

During both years, the smallest values for secchi-disc transparency were measured at stations 5 and 6. Other studies of Coeur d'Alene Lake have reported that secchi-disc transparency was less in the shallow, southern end of the lake than in the deeper, northern end (Kemmerer and others, 1923; Rieman, 1980; Woods, 1989). The consistently smaller values for secchi-disc transparency in the lake's southern end are due largely to its proximity to the mouths of the two major inflows, the St. Joe and Coeur d'Alene Rivers; the shallow depths, which permit resuspension of bottom sediments by wind-induced turbulence; and increased biological production.

Typically, the euphotic zone was deeper than the thermocline at stations 1 through 4 (fig. 10) . Under that condition, the phytoplankton circulating within the epilimnion (mixing zone), above the thermocline, remain exposed to amounts of PAR sufficient for photosynthetic production of carbon in excess of respiratory demands.

SPECIFIC CONDUCTANCE

Specific conductance is a measure of the ability of water to conduct electricity and is typically proportional to the water's dissolved-solids concentration. The mean ratio of dissolved-solids concentration (in milligrams per liter) to specific conductance (in microsiemens per centimeter) in Coeur d'Alene Lake during 1991–92 was 0.70, which is within the range of most natural waters (Hem, 1985).

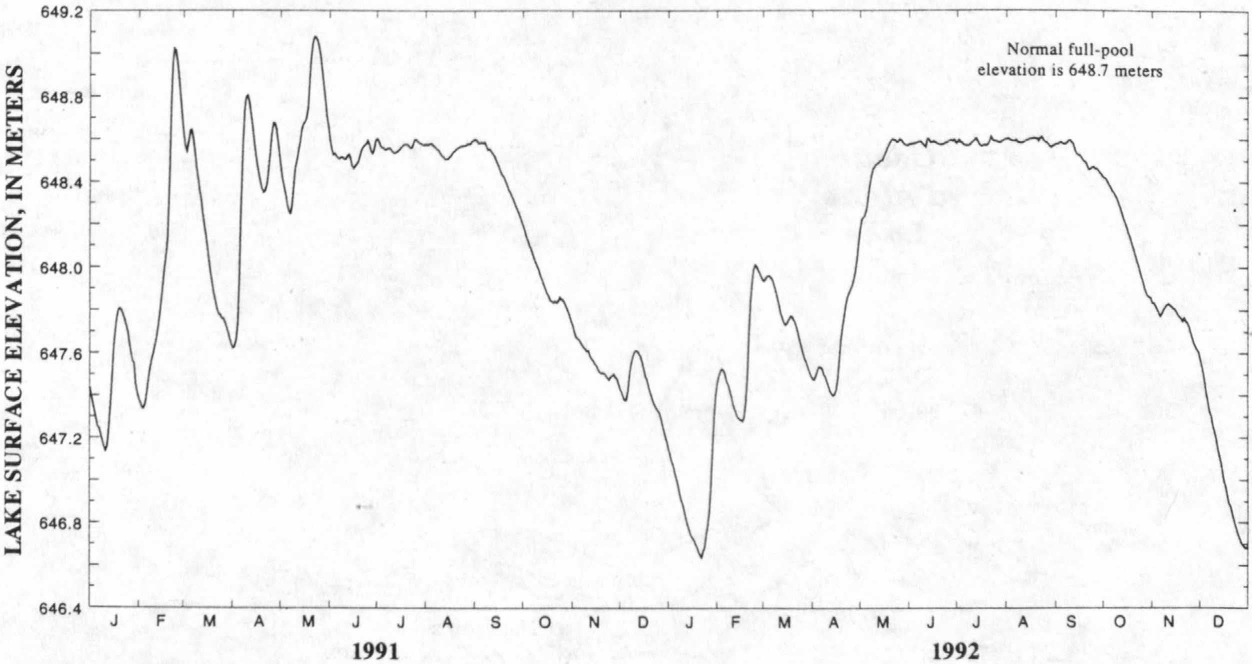


Figure 7. Variation in lake surface elevation of Coeur d'Alene Lake during 1991–92.

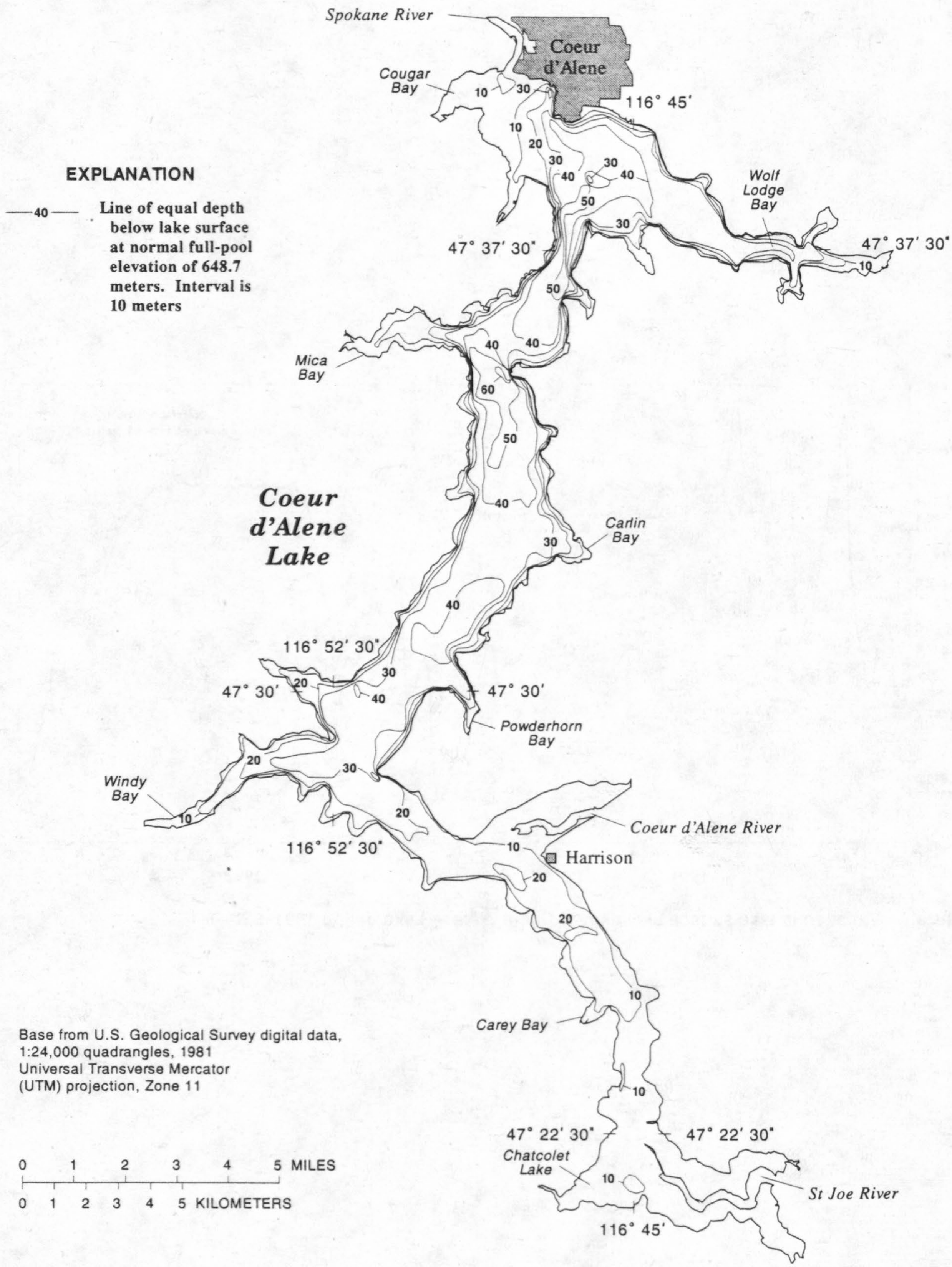


Figure 8. Bathymetric map of Coeur d'Alene Lake.

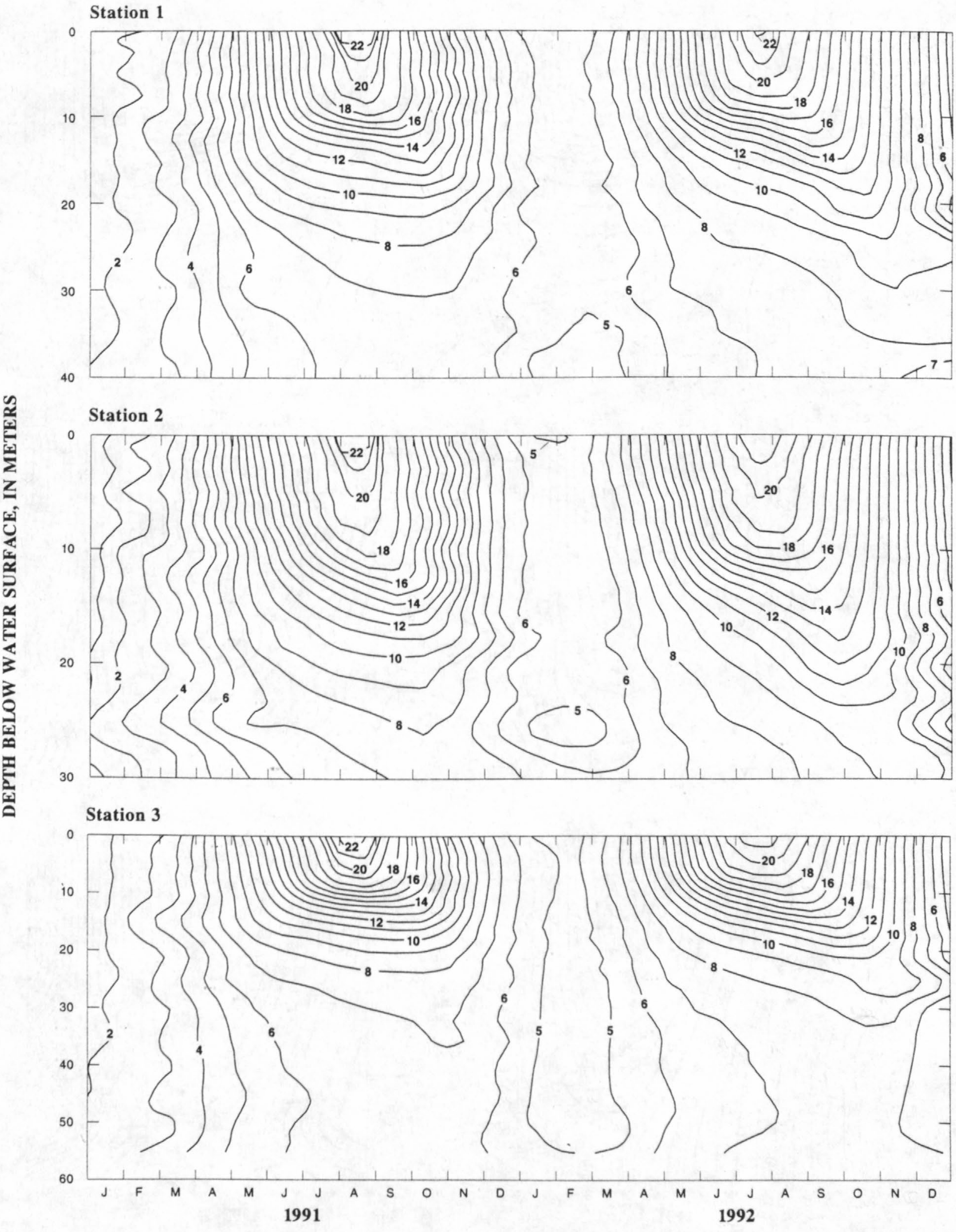


Figure 9. Lines of equal water temperature, in degrees Celsius, at stations 1–6 during 1991–92.

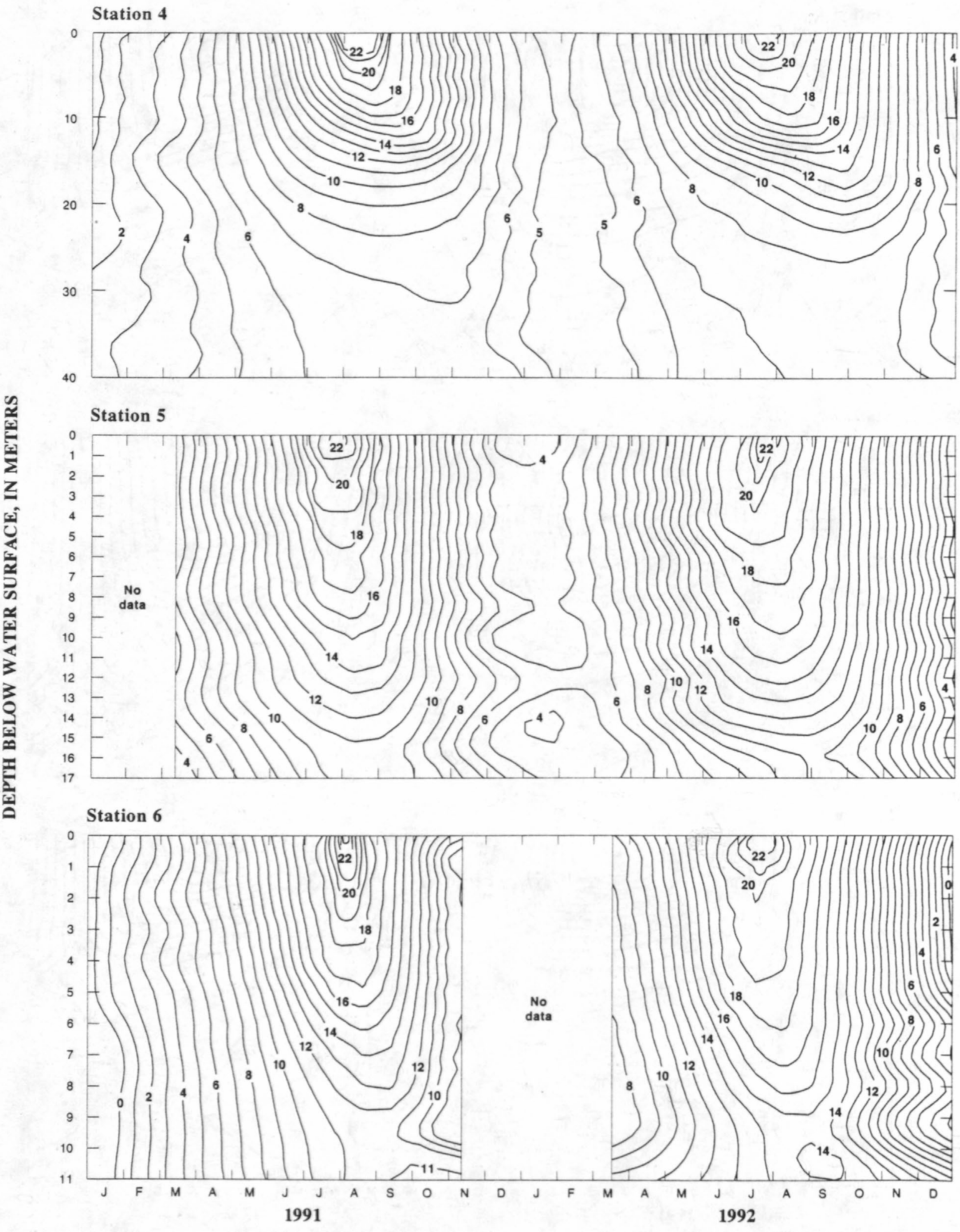


Figure 9. Lines of equal water temperature, in degrees Celsius, at stations 1–6 during 1991–92—Continued.

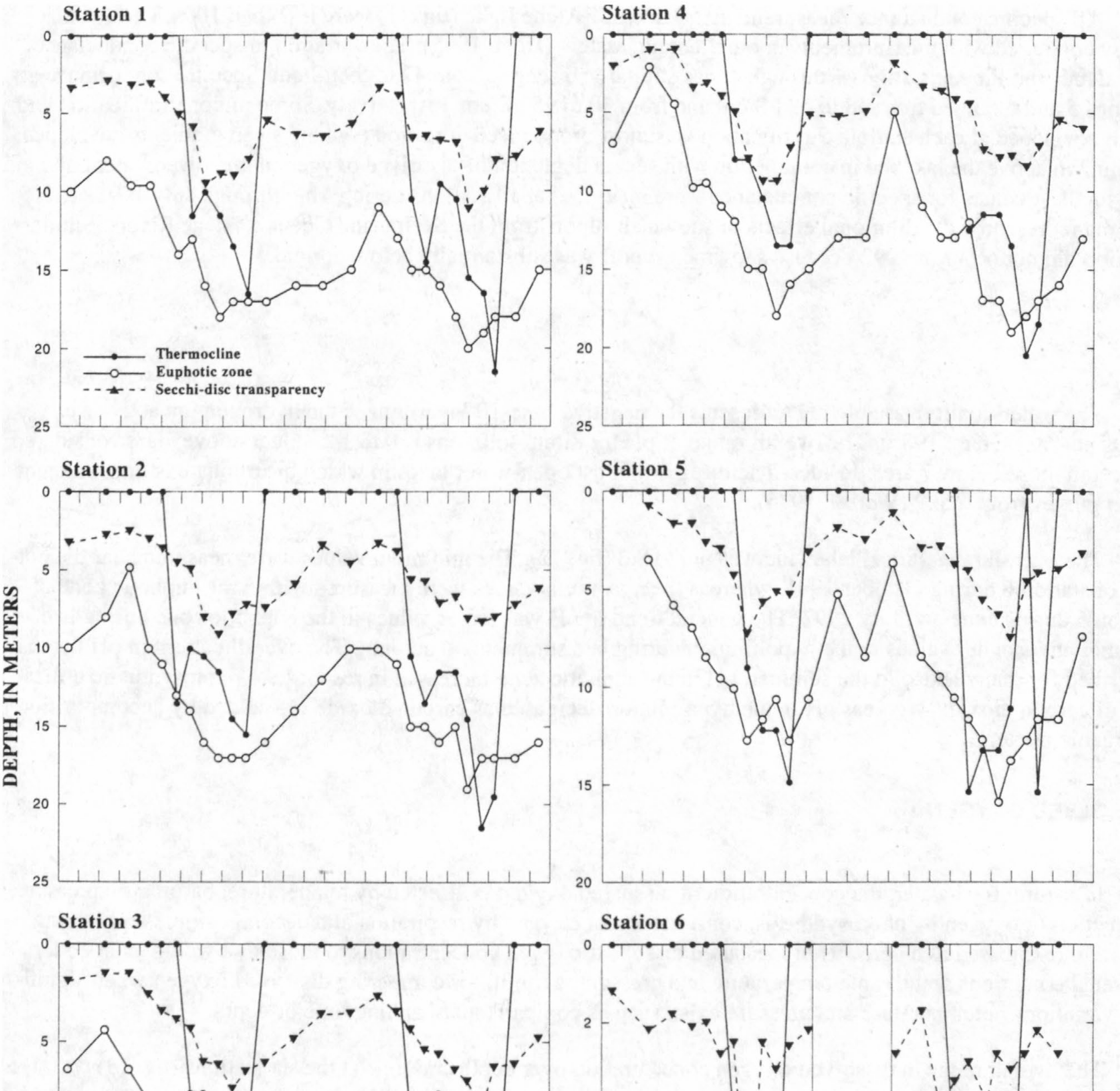


Figure 10. Depths of thermocline, euphotic zone, and secchi-disc transparency at stations 1–6 during 1991–92.

All specific conductance measurements in Coeur d'Alene Lake (fig. 11) were less than 100 μS/cm, which is low compared with measurements in other natural waters (Hem, 1985). The variation in specific conductance over depth and time at stations 1 through 4 was similar and ranged from 42 to 59 μS/cm. Specific conductance at stations 5 and 6 ranged from 38 to 63 μS/cm and from 30 to 95 μS/cm, respectively. Some minor stratification with depth developed at each station. Stratification was most pronounced at station 6 where steep gradients developed within 2 m above the lakebed in conjunction with severe depletion of dissolved oxygen in the lower water column. The smallest values for specific conductance were measured at all stations during May through July 1991. These minima represented the dilutional effects of snowmelt runoff from the St. Joe and Coeur d'Alene Rivers. Similar dilution did not occur in 1992 because snowmelt runoff was substantially below normal.

pH

The water-quality variable pH represents the negative base-10 logarithm of the hydrogen ion activity in moles per liter (Hem, 1985). The overall range of pH for dilute solutions is 0 to 14; values above 7 are considered basic and those below 7 are considered acidic. pH in most open-water lakes in which bicarbonate is the dominant anion ranges from 6 to 9 (Wetzel, 1975).

The overall range in pH lakewide was 6.6 to 8.2 (fig. 12). The minimum values were measured near the bottom of station 6 during October 1991, whereas the maximum values were measured within the euphotic zone of station 5 during June and July 1992. The general trend in pH was larger values in the euphotic zone during late summer and smaller values in the hypolimnion during late summer and autumn. The overall pattern in pH fits that described for many lakes. In the summer, pH in the euphotic zone increased in response to photosynthetic utilization of carbon dioxide, whereas pH in the hypolimnion decreased as carbon dioxide was added by decomposition of organic matter.

DISSOLVED OXYGEN

In natural freshwater, the concentration of dissolved oxygen is affected by temperature, barometric pressure, production of oxygen by photosynthesis, consumption of oxygen by respiration and decomposition, and mixing. The ratio (expressed as a percent) of measured dissolved-oxygen concentrations to those that would exist under saturated conditions at the same temperature and pressure is useful for comparing dissolved oxygen when significant variations in temperature and pressure exist, such as comparisons spanning time or depth.

The overall range in dissolved-oxygen concentration over depth and time at the six stations (fig. 13) was 0 to 13.6 mg/L; both extremes were measured at station 6. At each station, the highest concentrations were measured in the winter in association with minimum water temperatures; this conforms to the inverse relation between dissolved oxygen and temperature. The minimum dissolved-oxygen concentrations at each station were measured in the hypolimnion during late summer or autumn. The dissolved-oxygen minima resulted when thermal stratification reduced mixing of the oxygenated epilimnion with the hypolimnion. The minimum concentration ranged from 6.4 to 6.5 mg/L at stations 1 through 4, was 2.8 mg/L at station 5, and declined to anoxia at station 6.

The variation in percent saturation of dissolved oxygen over depth and time (fig. 14) was similar in both years at each of the stations, but the overall maximum values were measured in 1992. Saturation greater than 100 percent was measured in the euphotic zone of each station during the summer months when photosynthetic production of oxygen exceeded oxygen consumption by respiration and decomposition. The maximum saturation at stations 1 through 4 ranged from 113 to 117 percent and was 120 percent at station 5. At station 6, dense beds of aquatic macrophytes and associated periphyton augmented phytoplanktonic oxygen production and yielded saturation as high as 133 percent during August 1992. The minimum percent saturations were measured in the hypolim-

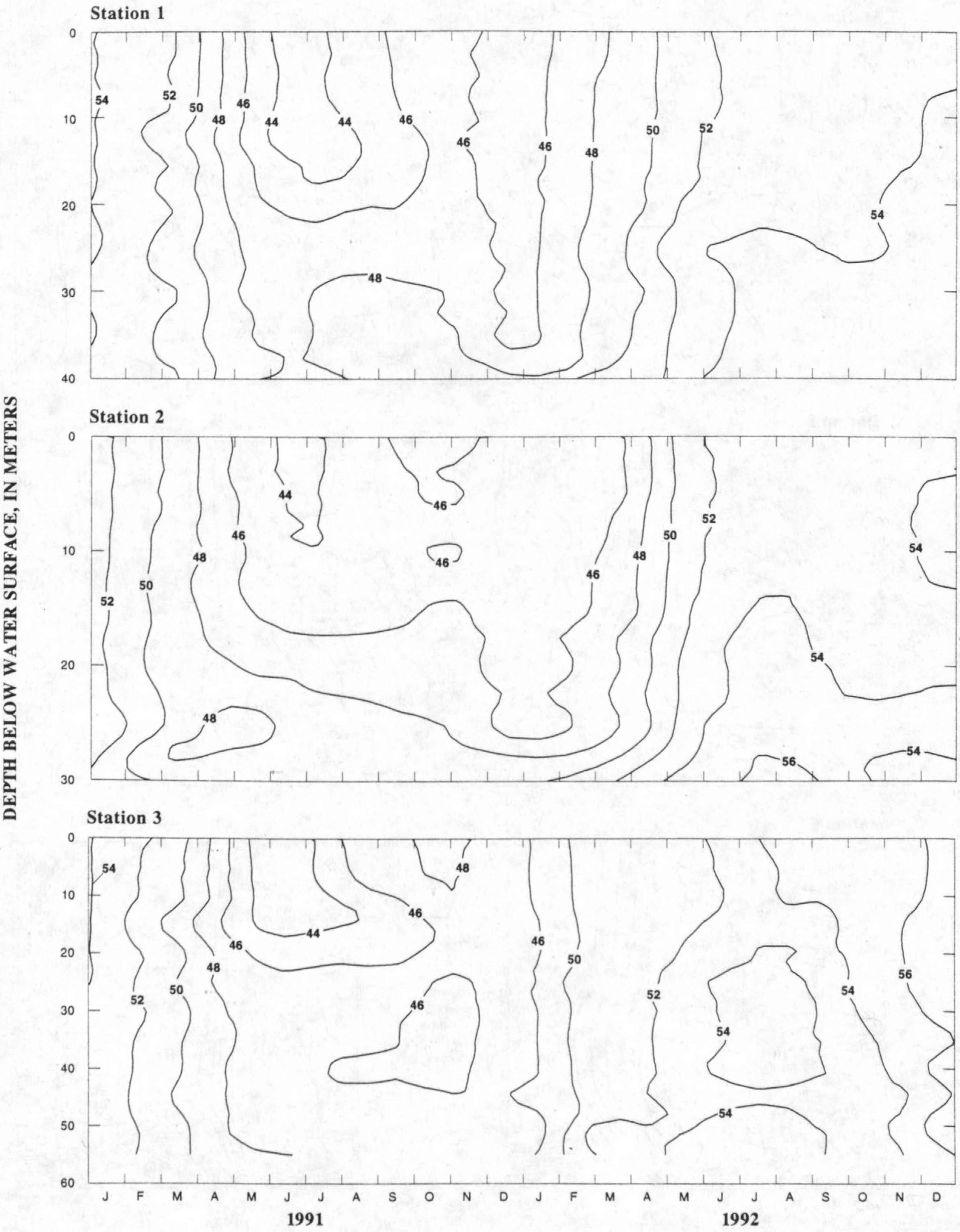


Figure 11. Lines of equal specific conductance, in microsiemens per centimeter, at stations 1–6 during 1991–92.

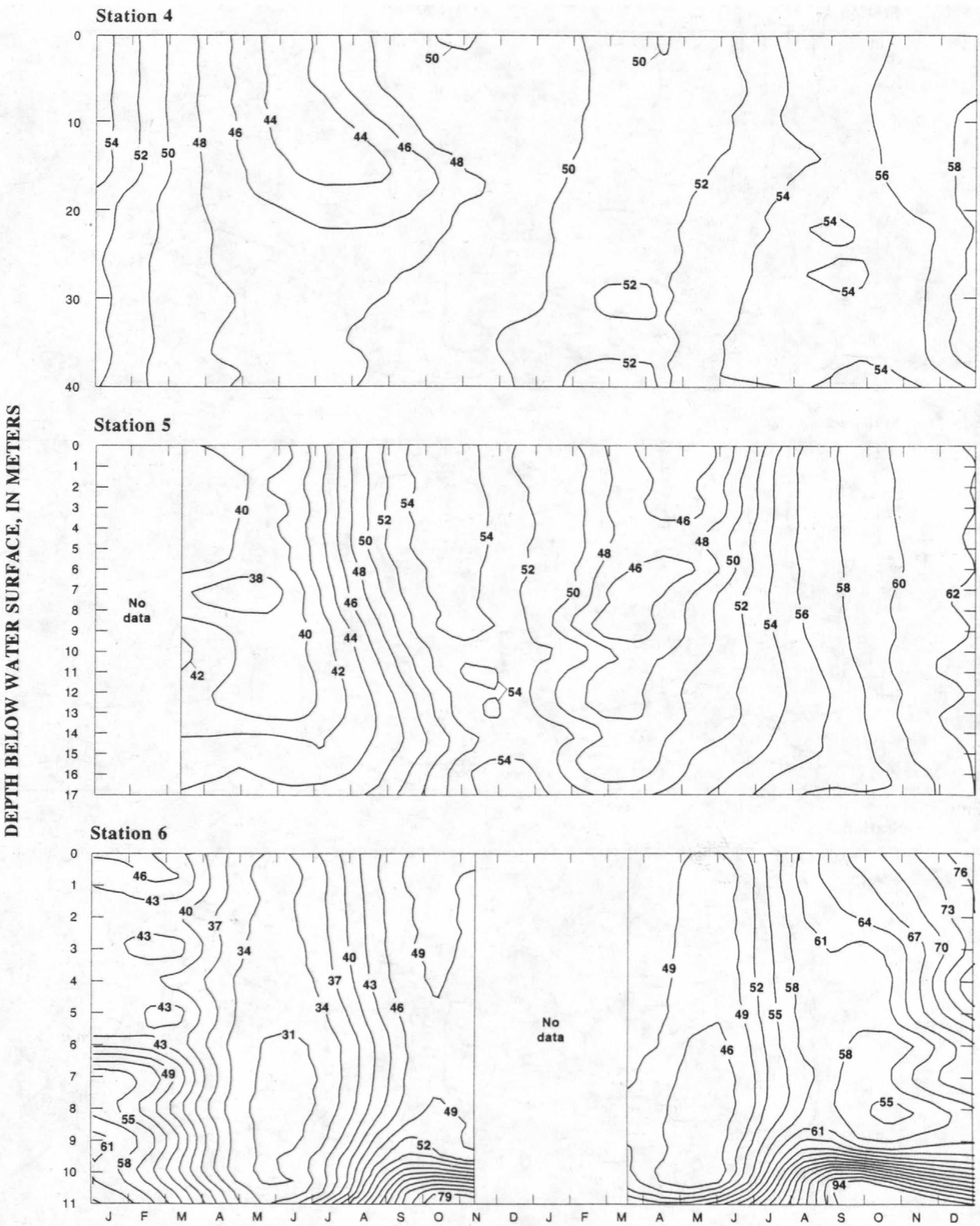


Figure 11. Lines of equal specific conductance, in microsiemens per centimeter, at stations 1–6 during 1991–92—Continued.

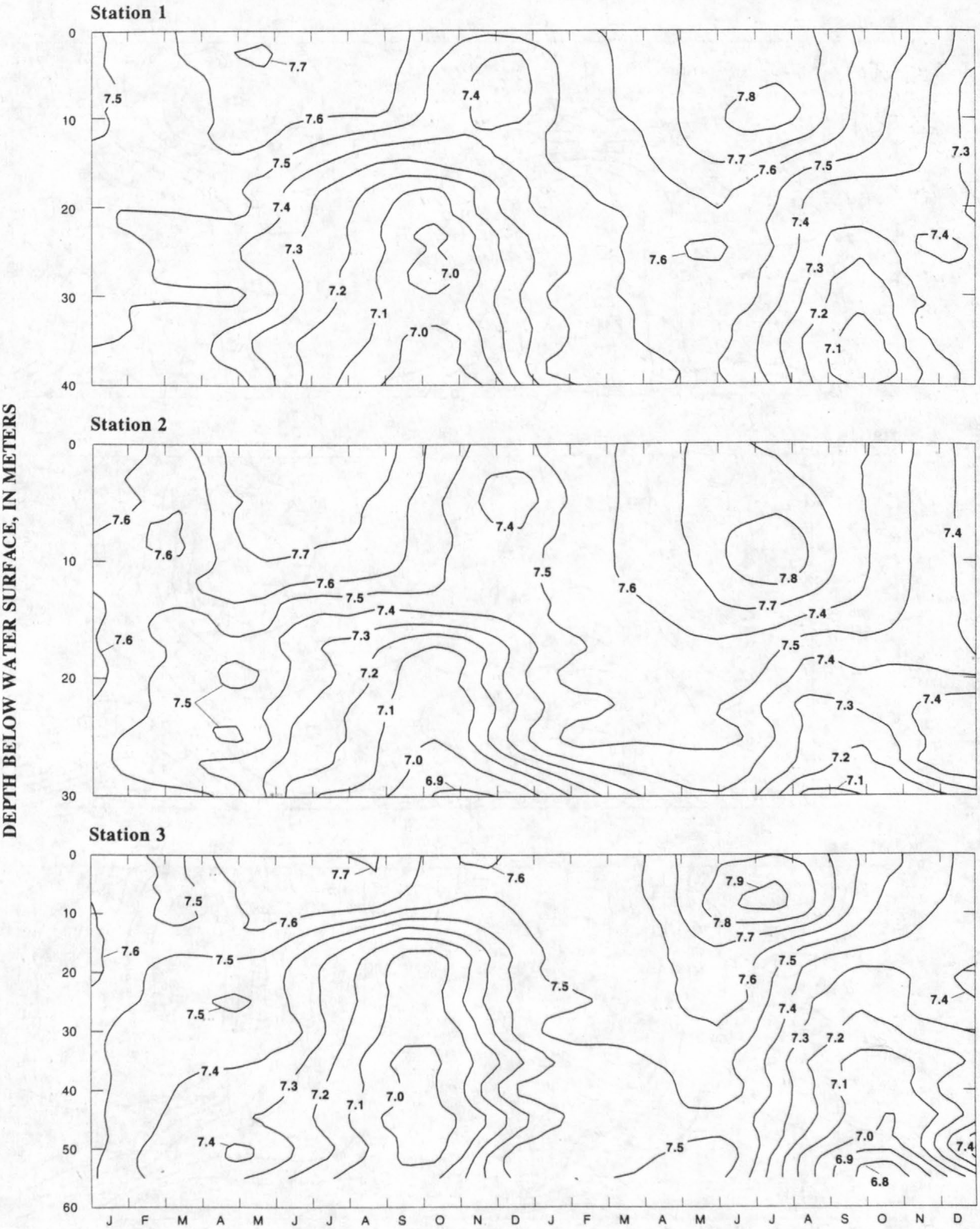


Figure 12. Lines of equal pH, in standard units, at stations 1–6 during 1991–92.

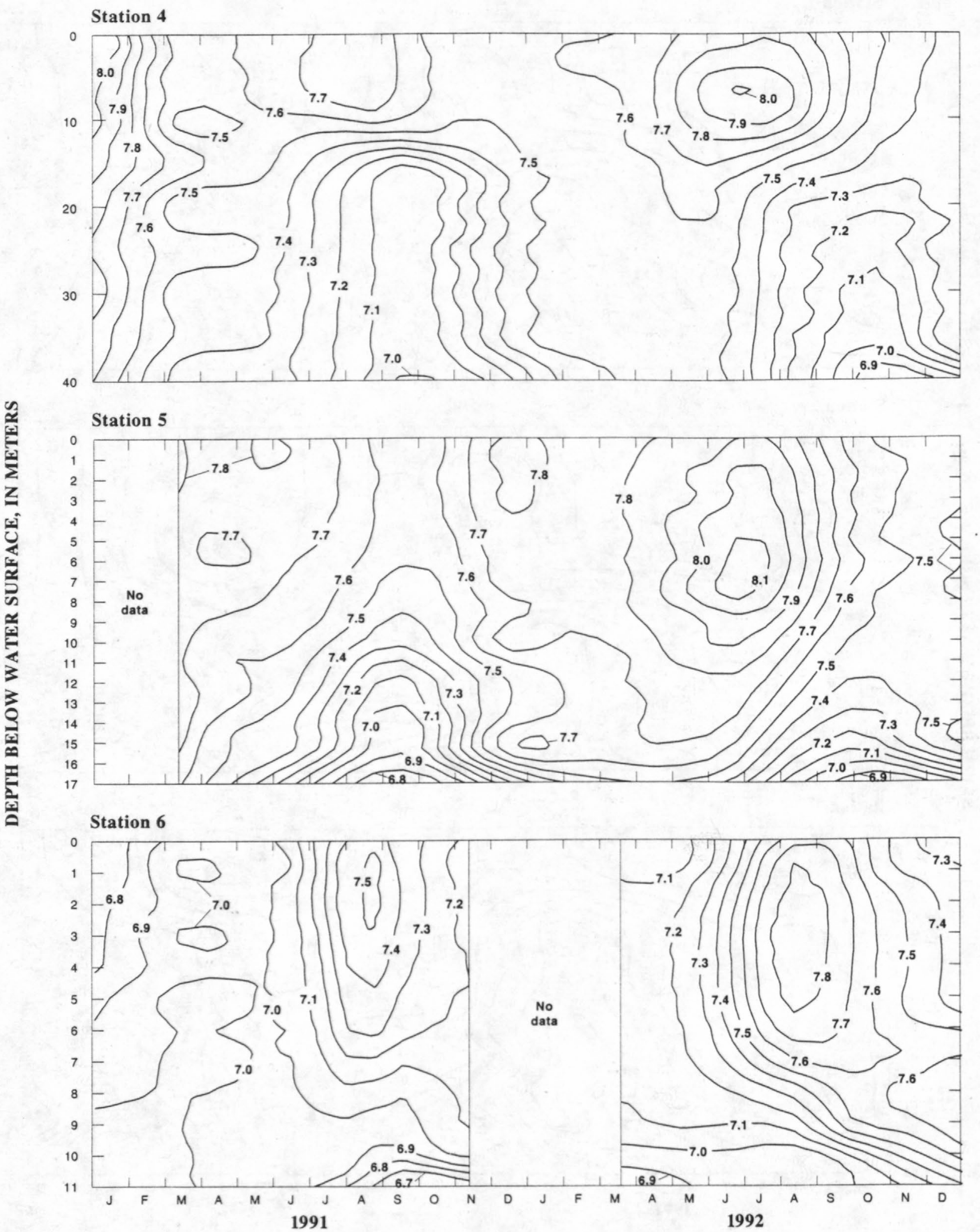


Figure 12. Lines of equal pH, in standard units, at stations 1–6 during 1991–92—Continued.

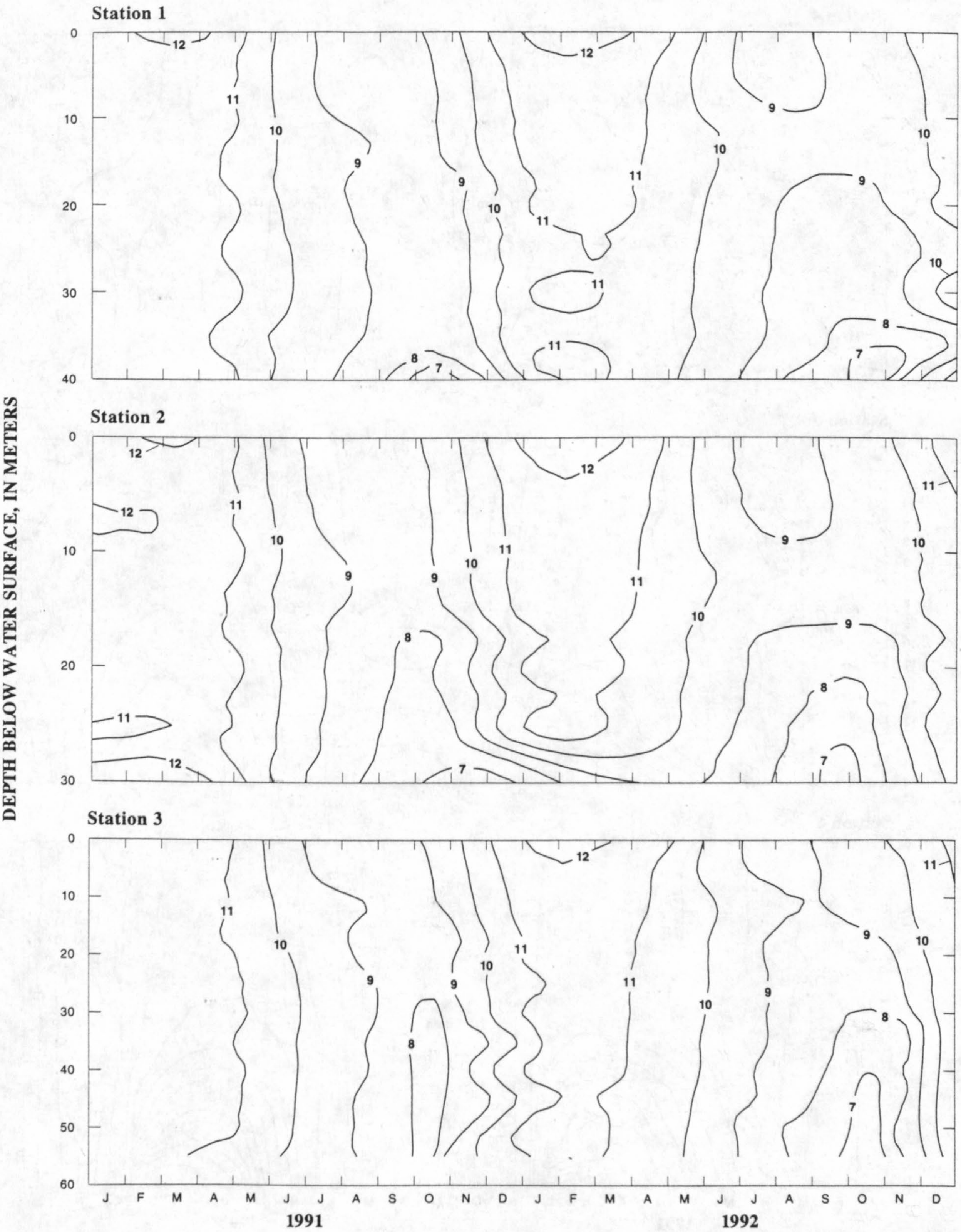


Figure 13. Lines of equal dissolved-oxygen concentration, in milligrams per liter, at stations 1–6 during 1991–92.

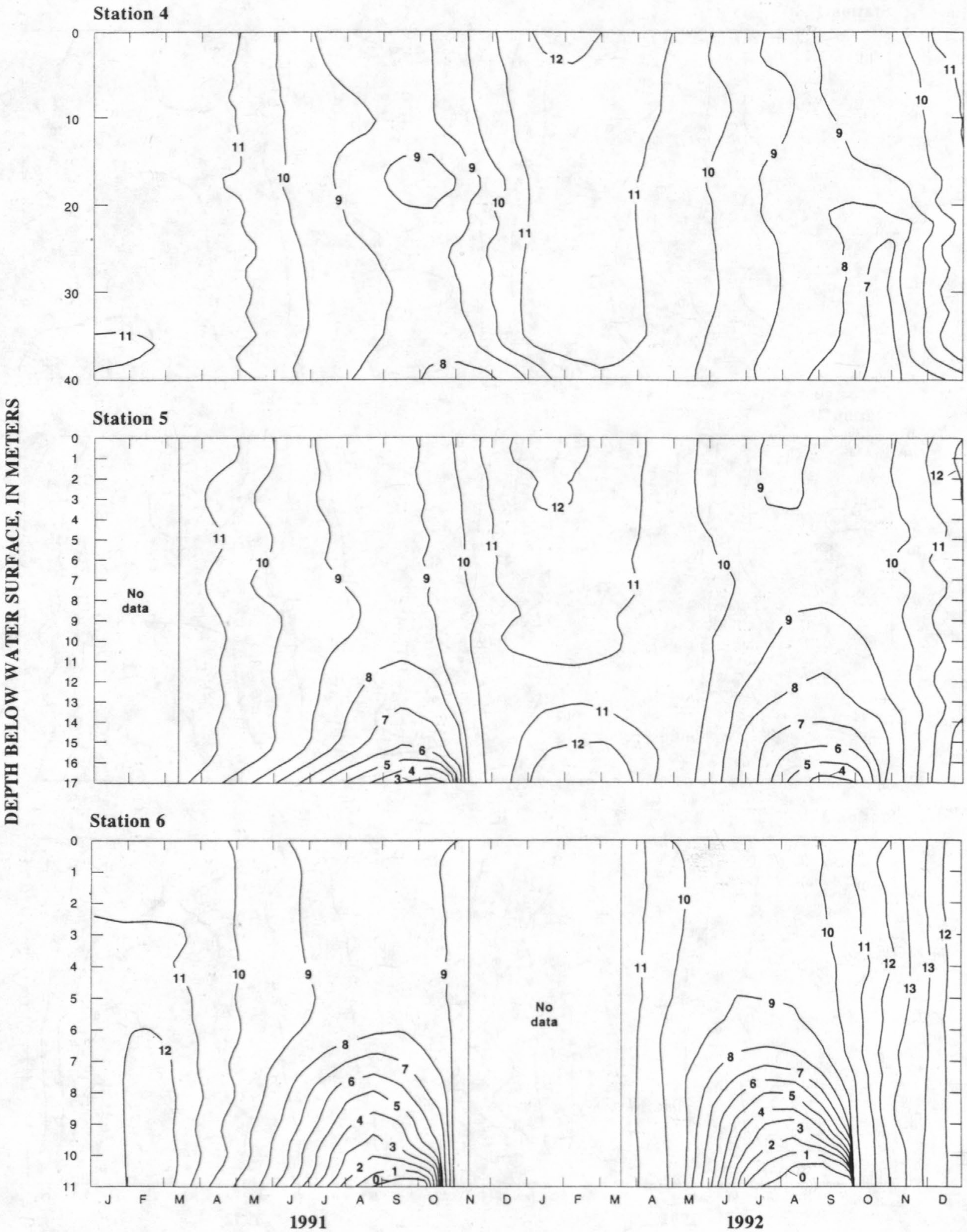


Figure 13. Lines of equal dissolved-oxygen concentration, in milligrams per liter, at stations 1–6 during 1991–92—Continued.

nion during late summer or autumn and corresponded with minimum dissolved-oxygen concentrations. The minimum saturation at stations 1 through 4 ranged from 58 to 60 percent, was 28 percent at station 5, and was 0 at station 6.

Several previous studies, one done as early as 1911, reported dissolved-oxygen data for Coeur d'Alene Lake. Among these earlier studies is a comparable time period, July through September, and a comparable location, near limnetic station 3 of the current study. Most of these earlier studies did not report percent saturation; using reported water temperatures and an assumed barometric pressure of 700 mm of mercury, saturation was calculated for the dissolved-oxygen concentrations. Kemmerer and others (1923) conducted biological and chemical studies of numerous northwestern lakes to assess their potential for fish production. For Coeur d'Alene Lake, they measured a dissolved-oxygen concentration on July 15, 1911, as low as 7.8 mg/L (5.4 cm^3/L) at the 50-m depth. The water temperature at that depth was 6.9°C; therefore, the saturation was 63 percent. Ellis (1940) studied Coeur d'Alene Lake in 1932 to assess pollution from mine wastes. He reported that at the 60-m depth (near-bottom) on July 15, 1932, the dissolved-oxygen concentration was 8.4 mg/L and saturation was 80.3 percent. During July 1971, Winner (1972) reported that the lower 35 m of a 50-m-deep water column contained a dissolved-oxygen concentration of about 4 mg/L. The water temperature in the lowermost 10 m was 5°C, which yielded a saturation of 30 percent. The EPA (1977) studied Coeur d'Alene Lake during 1975 as part of its National Eutrophication Survey. On September 9, the EPA measured a dissolved-oxygen concentration of 7.0 mg/L at a depth of 43 m (station depth of 56 m). The associated water temperature was 7.2°C, which yielded a saturation of 57 percent. The USGS studied the lake during 1987 (Woods, 1989). On September 22, 1987, the dissolved-oxygen concentration and saturation in the metalimnion were 5.6 mg/L and 54 percent, respectively.

Dissolved-oxygen concentrations in the southern end of Coeur d'Alene Lake, represented by limnetic station 6, also have been studied previously. Data for July 10, 1932, showed dissolved-oxygen concentration and saturation down to 2.7 mg/L and 28.2 percent, respectively, near the lake bottom (Ellis, 1940). Winner (1972) measured a dissolved-oxygen concentration of 1 mg/L in a near-bottom water sample in July 1971. That value represented a saturation of 7 percent at a water temperature of 6°C. The EPA (1977) reported a dissolved-oxygen concentration of 2.8 mg/L near the lake bottom on September 9, 1975. That value equated to a saturation of 28.2 percent, given a water temperature of 13.3°C.

MAJOR CATIONS AND ANIONS

Concentrations of major cations (Ca^{2+}, K^+, Mg^{2+}, Na^+) and anions (Cl^-, HCO_3^-, SO_4^{2-}) at the six stations were determined from near-surface and near-bottom samples obtained in January and July 1991 and March and September 1992. The ranges in concentrations, in milligrams per liter, were as follows: Ca^{2+}, 5.2 to 6.4; K^+, 0.5 to 1.1; Mg^{2+}, 1.2 to 1.9; Na^+, 1.2 to 2.1; Cl^-, 0.1 to 0.8; HCO_3^-, 22 to 40; and SO_4^{2-}, 1 to 6.6. Alkalinity ranged from 19 to 33 mg/L as $CaCO_3$, whereas hardness ranged from 16 to 28 mg/L as $CaCO_3$. Differences in concentrations in near-surface and near-bottom samples were minor. The concentrations of the cations and anions were converted to milliequivalents to determine the percentage contribution of each constituent. On the average, calcium represented 67 percent of the major cations and bicarbonate represented 82 percent of the major anions. Therefore, water in Coeur d'Alene Lake is a calcium bicarbonate type.

TRACE ELEMENTS

Six trace elements were analyzed in samples from the euphotic zone and lower hypolimnion of the six stations. Concentrations of arsenic, cadmium, and mercury were below their detection limits in at least 75 percent of the samples (table 10). Copper was above the detection limit (1 μg/L) in 80 percent of the samples and the median concentration was 1.6 μg/L. Lead was above the detection limit (1 μg/L) in about three-fourths of the samples and

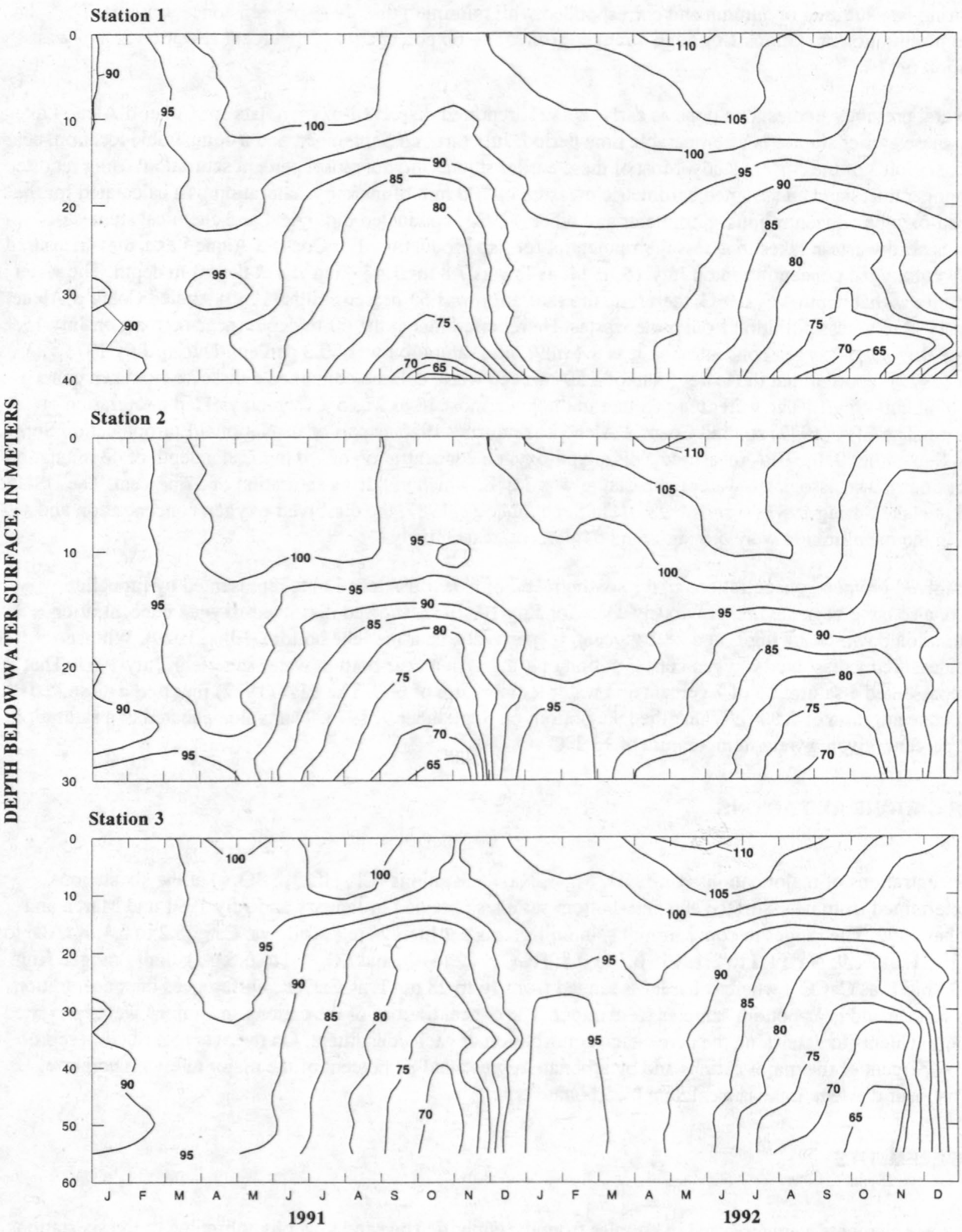


Figure 14. Lines of equal percent saturation of dissolved oxygen at stations 1–6 during 1991–92.

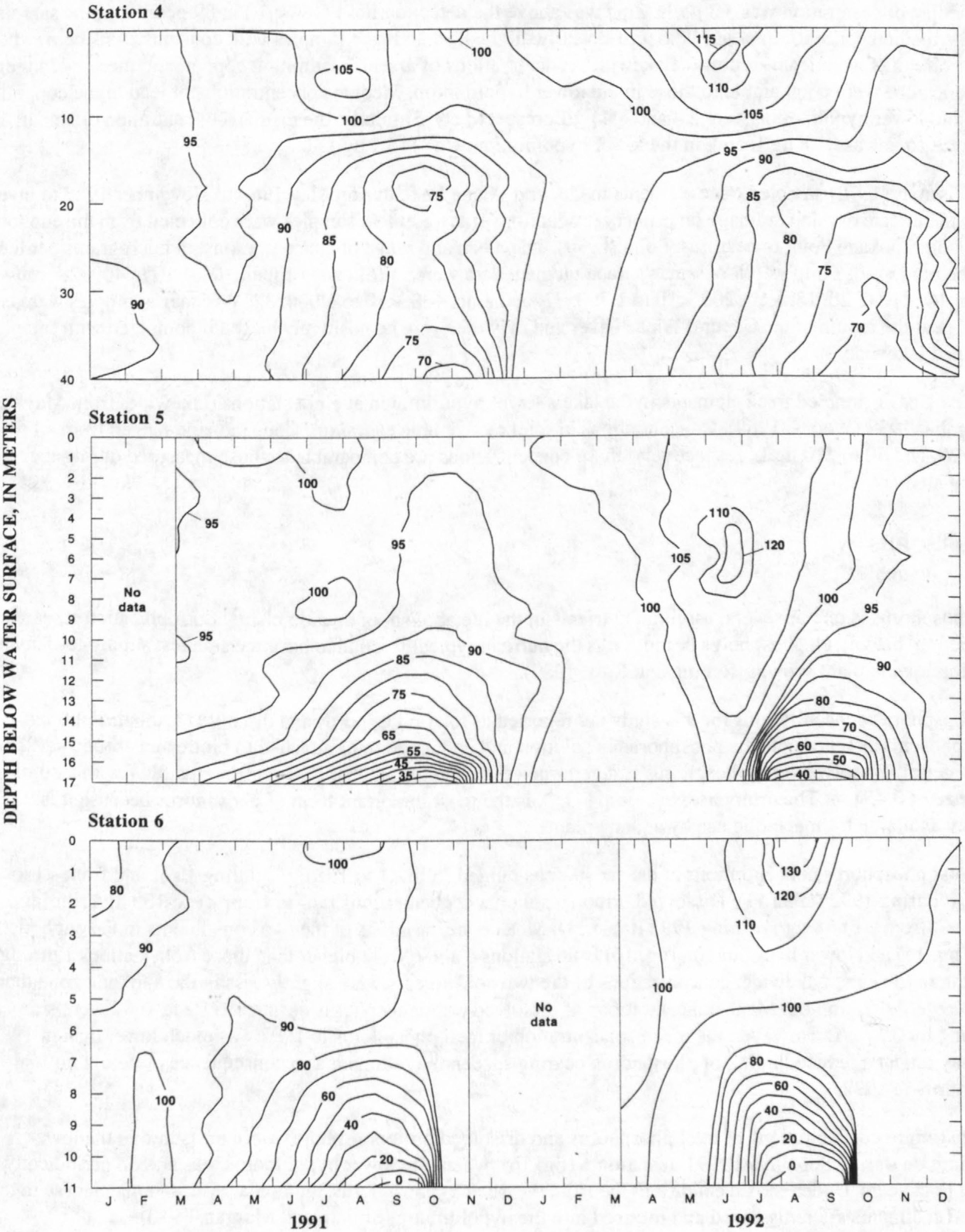


Figure 14. Lines of equal percent saturation of dissolved oxygen at stations 1–6 during 1991–92—Continued.

the median concentration was 3.3 µg/L. Zinc was above the detection limit (10 µg/L) in 89 percent of the samples and the median concentration was 98.6 µg/L. Nearly all the lead and zinc samples with concentrations below their detection limits were from station 6. Lakewide, concentrations of arsenic, cadmium, copper, and mercury in the euphotic zone were comparable to those in the lower hypolimnion. Median concentrations of lead in the euphotic zone and lower hypolimnion were 2.4 and 4.4 µg/L, respectively. Similarly, the median concentration of zinc in the euphotic zone was 81.8 µg/L and, in the lower hypolimnion, was 115.3 µg/L.

Wissmar (1972) sampled trace elements in Coeur d'Alene Lake during May 1969 to November 1970 to investigate the effects of mine drainage on primary production. Trace-element samples were collected from the euphotic zone from Spokane Point to near East Point (fig. 4). The mean and range of concentrations, in micrograms per liter, and the number of samples for Wissmar's trace-element data were as follows: copper, 100, <10 to 400, 28; cadmium, 10, <10 to 20, 18; lead, 200, <10 to 1,700, 32; and zinc, 400, <10 to 1,000, 32. Wissmar's samples were collected near the mouth of the Coeur d'Alene River and may therefore be positively biased if compared with samples collected lakewide.

The USGS sampled trace elements in the lake's lower hypolimnion at eight stations (lakewide) from May to November 1987 (Woods, 1989). Concentrations of total recoverable cadmium, lead, and zinc ranged from <1 to 1, <5 to 29, and 50 to 210 µg/L, respectively; these concentrations are comparable to those measured during the present study.

PHOSPHORUS

Phosphorus is one of several essential nutrients in the metabolism of aquatic plants. Eutrophication research has focused heavily on phosphorus because it is the nutrient typically found to have the smallest supply-to-demand ratio for aquatic plant growth (Ryding and Rast, 1989).

Phosphorus concentrations for this study are reported as total phosphorus and dissolved orthophosphorus. Total phosphorus represents the phosphorus in solution and contained in or attached to biotic and abiotic particulate material. Dissolved orthophosphorus is determined from the filtrate that passes through a filter with a nominal pore size of 0.45 µm. The orthophosphate ion, PO_4^{3-}, is the most important form of phosphorus because it is directly available for metabolic use by aquatic plants.

Total phosphorus concentrations at the six stations ranged from <1 to 192 µg/L during 1991 and from <1 to 25 µg/L during 1992 (table 11). Dissolved orthophosphorus concentrations ranged from <1 to 100 µg/L during 1991 and from <1 to 8 µg/L during 1992 (table 11). Mean concentrations of the two constituents in the euphotic zone (fig. 15) and lower hypolimnion (fig. 16) from stations 5 and 6 were higher than those from stations 1 through 4 during both years. Lakewide, concentrations of the two constituents were slightly less in the euphotic zone than in the lower hypolimnion. Mean concentrations of dissolved orthophosphorus during 1991 and 1992 were similar, differing by 0.2 µg/L. However, the mean concentration of total phosphorus in 1992 was much lower than in 1991 and may reflect a reduced influx of phosphorus-bearing suspended sediment as a consequence of below-normal streamflow in 1992.

Maximum concentrations of total phosphorus and dissolved orthophosphorus were measured in the lower hypolimnion during September 1991 at station 6 (fig. 16), where the lower hypolimnion was anoxic periodically during both years. Under anoxic conditions, constituents such as phosphorus, ammonia, iron, and manganese in the lakebed sediments are redissolved and released into the hypolimnion (Stumm and Morgan, 1970).

Uptake of orthophosphorus by phytoplankton during the summer growing season often is revealed by distinct declines in dissolved orthophosphorus and concomitant increases in total phosphorus as dissolved phosphorus is converted to particulate phosphorus within the phytoplankton population. On the basis of temporal patterns illus-

Table 10. Lakewide concentrations of six trace elements in samples from the euphotic zone and lower hypolimnion, Coeur d'Alene Lake, 1991–92

[µg/L, micrograms per liter; <, less than]

Trace element	Concentration (µg/L) Range	Concentration (µg/L) Median	Percent of samples below detection limit	No. of samples
Arsenic, total	<1–1	<1	94.5	145
Cadmium, total recoverable	<1–2	<1	97.3	146
Copper, total recoverable	<1–15	1.6	40.0	136
Lead, total recoverable	<1–41	3.3	26.7	146
Mercury, total recoverable	<0.1–1.8	<.1	79.3	145
Zinc, total recoverable	<10–390	98.6	11.0	146

Table 11. Means and ranges of concentrations of total phosphorus and dissolved orthophosphorus in samples from the euphotic zone and lower hypolimnion at six limnetic stations and lakewide, Coeur d'Alene Lake, 1991–92

[µg/L, micrograms per liter; n, number of samples; <, less than]

Limnetic station (fig. 4)	Total phosphorus (µg/L) Euphotic zone Mean[1]	Range	n	Lower hypolimnion Mean[1]	Range	n	Dissolved orthophosphorus (µg/L) Euphotic zone Mean[1]	Range	n	Lower hypolimnion Mean[1]	Range	n
						1991						
1	5.2	1–16	13	4.9	<1–12	13	1	<1–1	13	2	<1–5	12
2	4.4	2–10	13	4.9	<1–8	12	1.2	<1–3	13	1.6	<1–4	12
3	4.6	1–6	13	4.8	2–6	13	1	<1–2	12	1.3	<1–3	13
4	5.6	<1–9	13	6.2	3–10	13	1.2	<1–2	13	1.5	<1–3	13
5	8.8	4–17	12	10.1	<1–21	12	2.3	<1–7	11	2.3	<1–7	12
6	14.2	7–41	12	42.1	12–192	8	2.7	<1–11	12	13.6	<1–100	9
Lakewide	6.5	1–41	76	8.1	<1–192	71	1.4	<1–11	74	2.4	<1–100	71
						1992						
1	2.4	<1–6	13	2.5	<1–4	13	1	<1–1	13	1.1	<1–2	12
2	3.8	<1–10	12	4.8	<1–25	13	1.1	<1–2	12	1.6	<1–8	13
3	2.9	<1–13	13	2.8	<1–8	13	1.4	<1–6	13	1.1	<1–2	13
4	4.2	<1–8	13	3.7	<1–8	13	1	<1–1	12	1.4	<1–4	13
5	5.0	<1–13	12	5.8	<1–15	12	1.4	<1–5	12	1.9	<1–7	12
6	5.2	<1–8	9	10.0	7–17	8	1	<1–3	9	2.1	<1–4	8
Lakewide	3.7	<1–13	72	3.8	<1–25	72	1.2	<1–6	71	1.3	<1–8	71

[1] Mean computed by assigning detection limit value to less-than values.

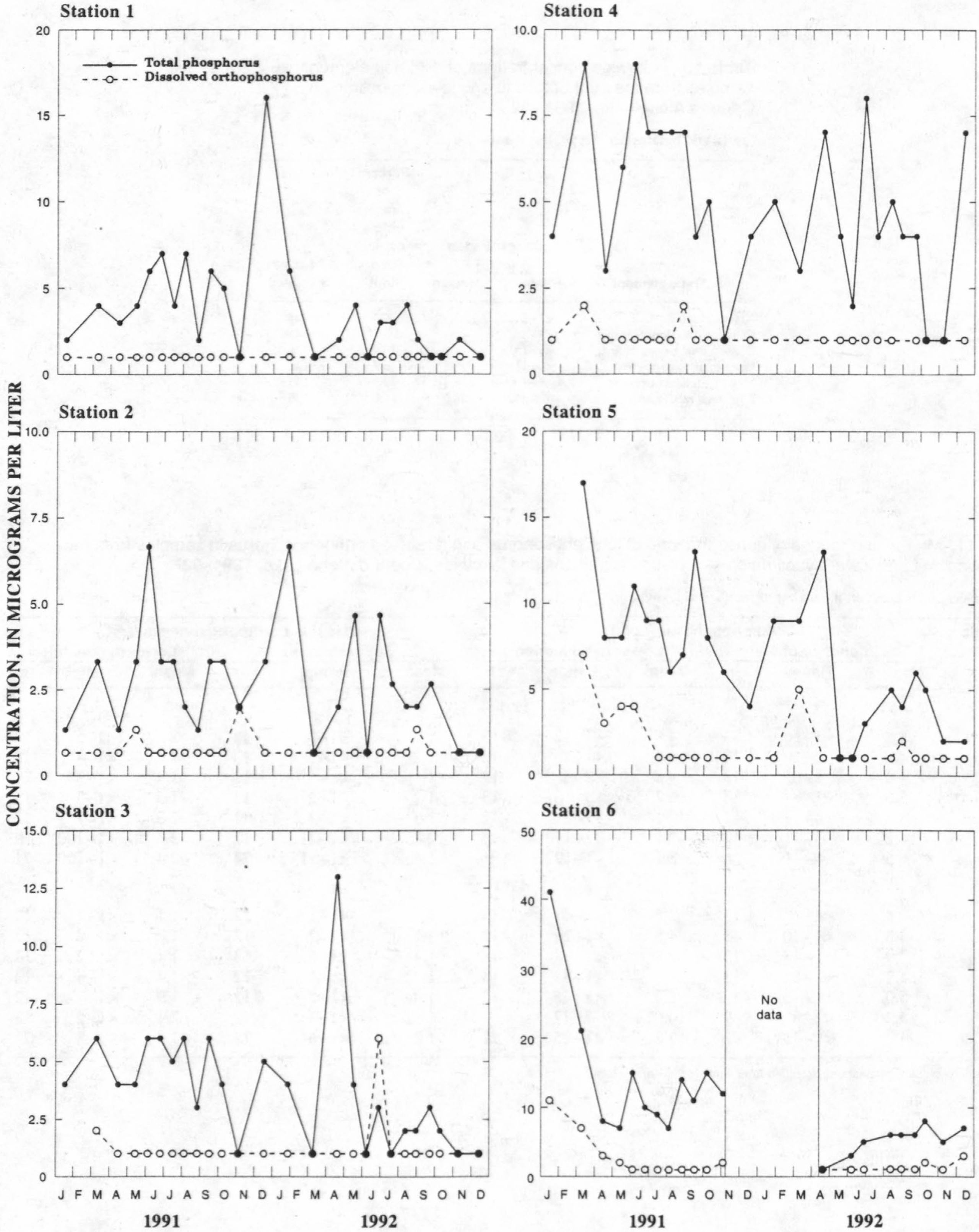


Figure 15. Concentrations of total phosphorus and dissolved orthophosphorus within the euphotic zone of stations 1–6 during 1991–92. (Values less than detection limit represented at detection limit value)

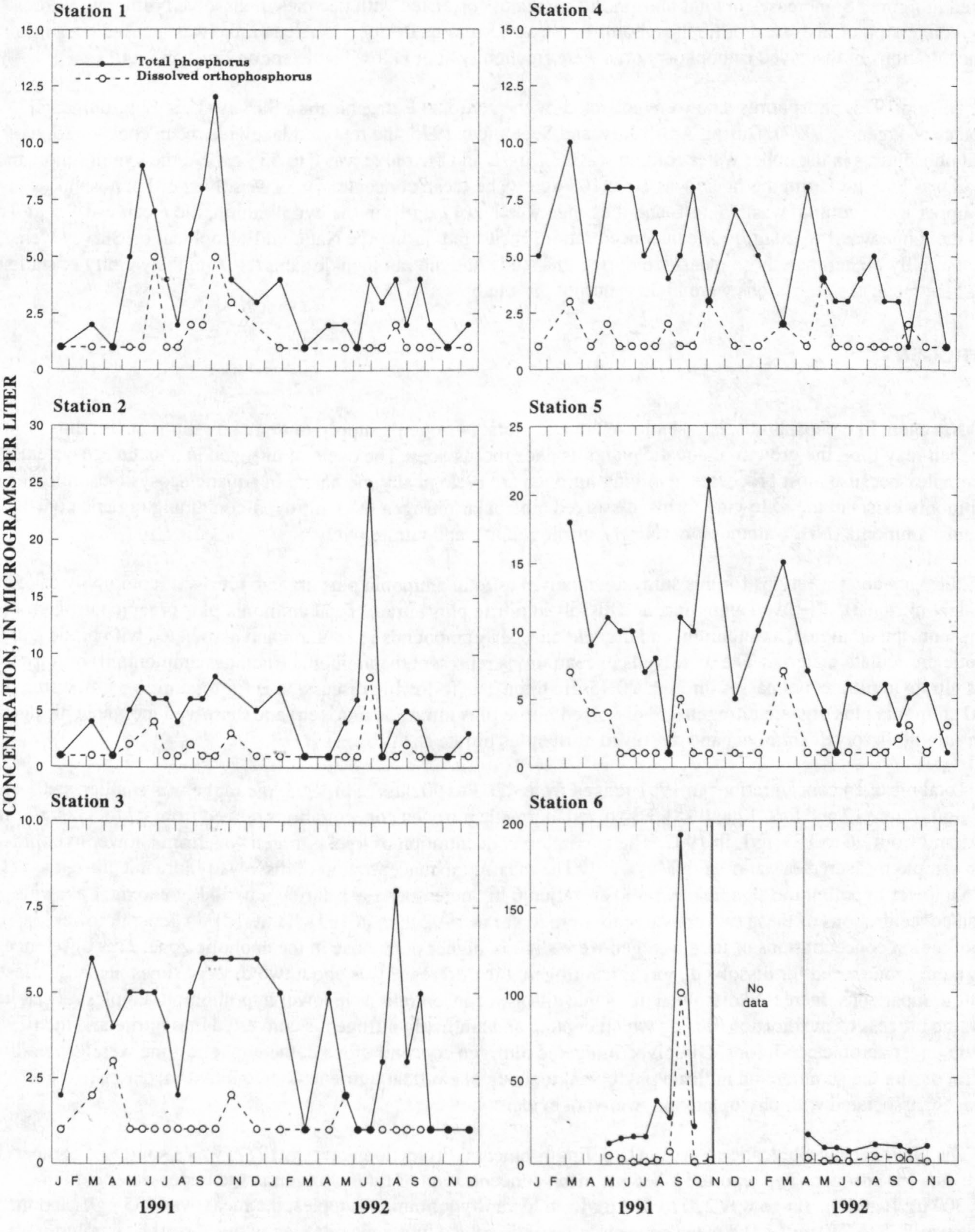


Figure 16. Concentrations of total phosphorus and dissolved orthophosphorus in the lower hypolimnion at stations 1–6 during 1991–92. (Values less than detection limit represented at detection limit value)

trated in figure 15, increases in total phosphorus were not correlated with declines in dissolved orthophosphorus. The conversion of dissolved orthophosphorus to total phosphorus in Coeur d'Alene Lake was masked because concentrations of dissolved orthophosphorus were frequently at or below the detection limit of 1 μg/L.

During 1975, phosphorus data were collected by the National Eutrophication Survey (U.S. Environmental Protection Agency, 1977). During April, July, and September 1975, the reported lakewide mean concentration of total phosphorus in the upper water column was 22.1 μg/L and the range was 8 to 53 μg/L; in the hypolimnion, the mean was 29.8 μg/L and the range was 10 to 108 μg/L. The mean concentration of dissolved orthophosphorus in the upper water column was 5.5 μg/L and the range was 1 to 12 μg/L; in the hypolimnion, the mean was 7.5 μg/L and the range was 1 to 20 μg/L. Mean concentrations measured during the National Eutrophication Survey were substantially higher than those measured during this study and did not include samples from the vicinity of station 6, where mean concentrations were highest during this study.

NITROGEN

Nitrogen, like phosphorus, is essential to aquatic biota. Nitrogen's supply-to-demand ratio is small; thus, nitrogen may limit the growth of aquatic plants as phosphorus does. The cycle of nitrogen in aquatic ecosystems is complex because most processes involving nitrogen are biologically mediated. In aquatic ecosystems, nitrogen commonly exists in the following forms: dissolved molecular nitrogen (N_2), nitrogen-containing organic compounds, ammonia (NH_3), ammonium (NH_4^+), nitrite (NO_2^-), and nitrate (NO_3^-).

Nitrogen concentrations for this study are reported as total ammonia plus organic nitrogen (commonly called kjeldahl nitrogen), dissolved ammonia, and dissolved nitrite plus nitrate. Total ammonia plus organic nitrogen represents the ammonia, ammonium, and organic nitrogen compounds in solution and associated with biotic and abiotic particulate material. The dissolved concentrations represent the ammonia (includes ammonium) or nitrite plus nitrate in filtrate that passes through a 0.45-μm filter. The following discussion is for total nitrogen (the sum of total ammonia plus organic nitrogen and dissolved nitrite plus nitrate as nitrogen) and dissolved inorganic nitrogen (the sum of dissolved ammonia and dissolved nitrite plus nitrate as nitrogen).

Total nitrogen concentrations in 1991 ranged from <205 to 902 μg/L; in 1992, the range was smaller, <205 to 607 μg/L (table 12 and figs. 17 and 18). Dissolved inorganic nitrogen concentrations ranged from <7 to 332 μg/L in 1991 and from <6 to 153 μg/L in 1992. The maximum concentration of total nitrogen was from a lower hypolimnion sample measured at station 3 in May 1991. The maximum concentration of dissolved inorganic nitrogen was from a lower hypolimnion sample measured at station 6 in September 1991 during a period of anoxia. Lakewide mean concentrations of these two constituents were lower in 1992 than in 1991 (table 12). In general, lower hypolimnion concentrations of total nitrogen were slightly higher than those in the euphotic zone. This difference was more pronounced for dissolved inorganic nitrogen; the difference was about two to three times higher in most of the comparisons. Increased dissolved inorganic nitrogen concentrations in lower hypolimnion samples reflect, in part, the process of nitrification, during which organic and ammonia nitrogen is converted into nitrite and then nitrate under aerobic conditions. Dissolved inorganic nitrogen concentrations in the euphotic zone were generally lowest during the summer and indicate phytoplanktonic uptake of that nutrient. Concomitant increases in total nitrogen, associated with phytoplankton, were not evident, however.

The National Eutrophication Survey (U.S. Environmental Protection Agency, 1977) was a source of comparative data for nitrogen. The reported lakewide mean concentration of total nitrogen in the upper water column was 309 μg/L and the range was 220 to 660 μg/L; in lower hypolimnion samples, the mean was 335 μg/L and the range was 225 to 730 μg/L. The mean concentration of dissolved inorganic nitrogen in the upper water column was 72 μg/L and the range was 20 to 360 μg/L; in lower hypolimnion samples, the mean was 105 μg/L and the range was 25 to 430 μg/L. Total nitrogen concentrations measured during the 1975 National Eutrophication Survey were

Table 12. Means and ranges of concentrations of total nitrogen and dissolved inorganic nitrogen in samples from the euphotic zone and lower hypolimnion at six limnetic stations and lakewide, Coeur d'Alene Lake, 1991–92

[µg/L, micrograms per liter; n, number of samples; <, less than; LW, lakewide]

Limnetic station (fig. 4)	Total nitrogen (µg/L)						Dissolved inorganic nitrogen (µg/L)					
	Euphotic zone			Lower hypolimnion			Euphotic zone			Lower hypolimnion		
	Mean[1]	Range	n	Mean[1]	Range	n	Mean[1]	Range	n	Mean[1]	Range	n
							1991					
1	289	<205–427	13	349	244–631	11	38.3	<7–161	13	102	43–141	13
2	267	<205–409	13	309	229–481	13	32.8	<7–101	13	87.2	35–229	13
3	292	<205–616	13	375	249–902	13	42.2	9–117	13	94.4	30–137	13
4	309	<205–805	13	337	241–887	13	43.3	<7–104	13	102	43–131	13
5	329	<205–808	12	279	<205–459	12	36.6	11–117	12	54.8	14–137	12
6	365	<205–821	12	402	<205–833	8	45.8	8–234	12	84.6	<7–332	9
LW	307	<205–821	76	290	<205–902	70	41.9	<7–234	76	70.8	<7–332	73
							1992					
1	211	<205–221	13	265	222–340	13	19.7	<7–58	13	74.6	28–144	13
2	212	<205–239	12	240	<205–281	13	20.4	<7–47	12	48.7	<6–86	13
3	216	<205–257	13	274	224–316	13	23.2	<7–66	13	84.9	27–123	13
4	220	<205–270	13	273	<205–333	13	27.9	9–76	13	81.7	19–141	13
5	219	<205–287	12	238	<205–334	12	28.0	<7–98	12	50.2	16–153	12
6	206	<205–216	9	258	<205–607	8	15.0	<7–31	9	21.8	<7–48	8
LW	216	<205–287	72	256	<205–607	72	23.8	<7–98	72	56.7	<6–153	72

[1]Mean computed by assigning detection limit value to less-than values.

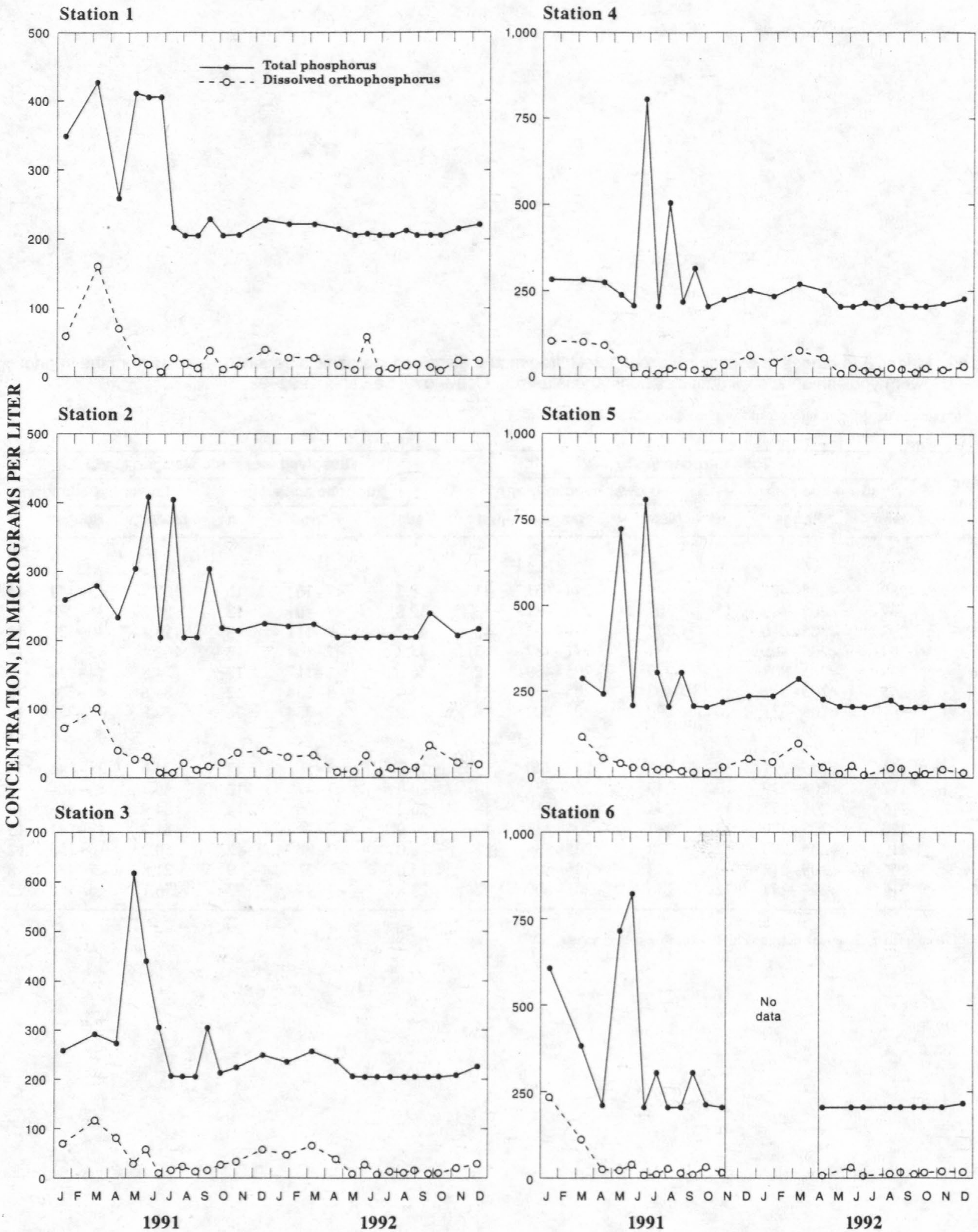


Figure 17. Concentrations of total nitrogen and dissolved inorganic nitrogen within the euphotic zone of stations 1–6 during 1991–92. (Values less than detection limit represented at detection limit value)

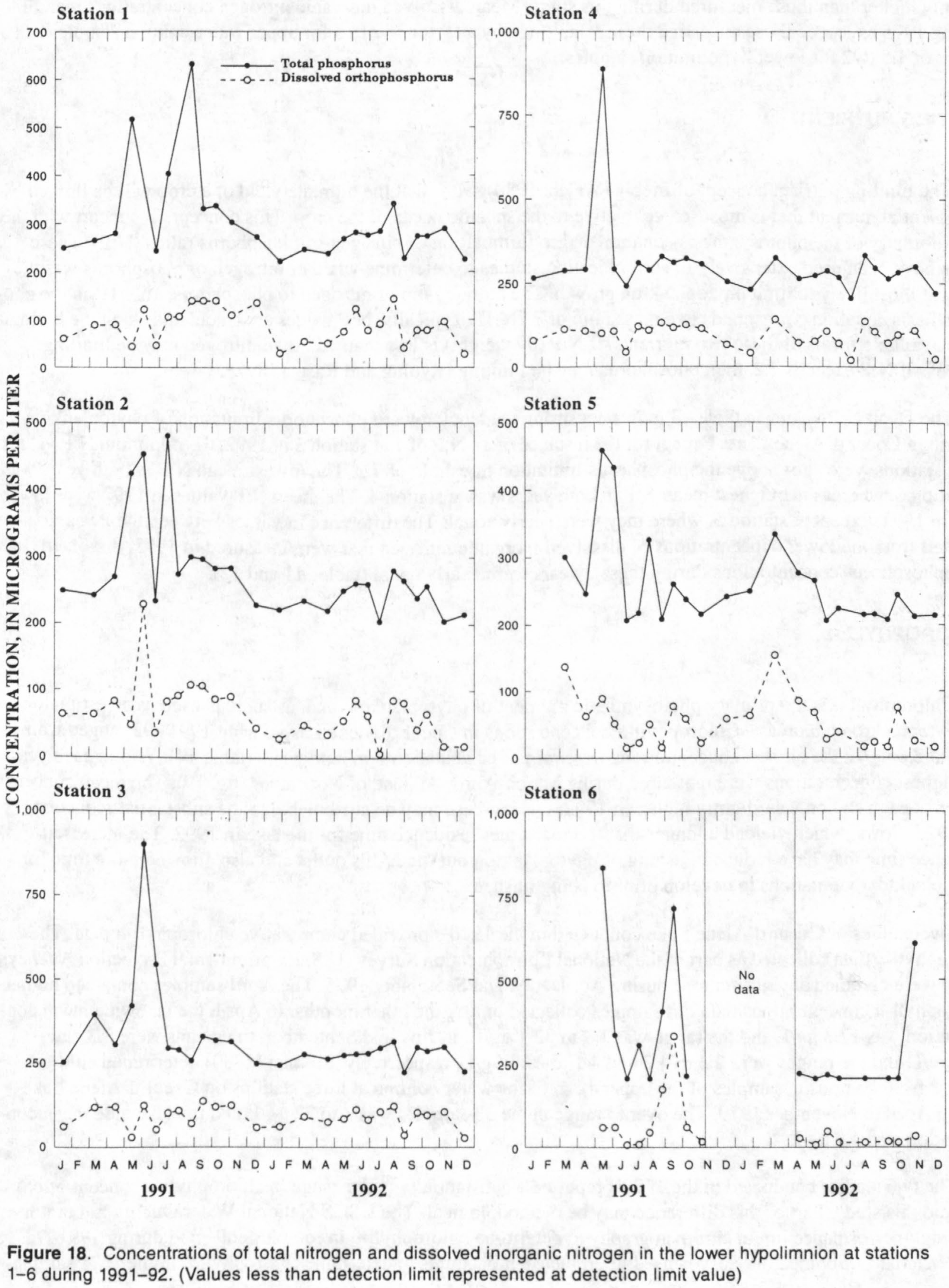


Figure 18. Concentrations of total nitrogen and dissolved inorganic nitrogen in the lower hypolimnion at stations 1–6 during 1991–92. (Values less than detection limit represented at detection limit value)

slightly higher than those measured during this study. Mean dissolved inorganic nitrogen concentrations measured during 1975 exceeded those measured during this study by a factor of 2 to 3 for upper water-column samples and a factor of 1.5 to 2 for lower hypolimnion samples.

LIMITING NUTRIENT

The limiting nutrient concept of Liebig (Welch, 1980) states that the ultimate yield of a crop will be limited by the essential nutrient that is most scarce relative to the specific needs of the crop. This concept, in concert with the stoichiometry of the photosynthesis equation, led to formulation of nitrogen-to-phosphorus ratios (N:P). These ratios have been used extensively in eutrophication studies to determine whether nitrogen or phosphorus was the nutrient most likely to limit phytoplankton growth. The atomic ratio of nitrogen to phosphorus, 16N:1P, in the photosynthesis equation corresponds to a mass ratio of 7.2N:1P. Typically, N:P values are calculated using the biologically available forms of these two nutrients. If N:P (by weight) is less than 7.2, then nitrogen may be limiting, whereas if N:P exceeds 7.2, then phosphorus may be limiting (Ryding and Rast, 1989).

The mean N:P values in table 13 indicate a strong tendency toward phosphorus limitation of phytoplankton growth in Coeur d'Alene Lake. Except for the instance of an N:P of 1 at station 3 in 1992, the minimum N:P values at all stations were at or above the phosphorus-limitation threshold of 7.2. The lowest mean N:P in both years was at station 6, whereas the highest mean N:P in both years was at station 4. The mean N:P values in 1992 were lower than in 1991, except at station 5, where they were nearly equal. The difference in values between the 2 years resulted from the lower concentrations of dissolved inorganic nitrogen that were measured in 1992; dissolved orthophosphorus concentrations during these 2 years were nearly equal (tables 11 and 12).

CHLOROPHYLL-*a*

Chlorophyll-*a* is the primary photosynthetic pigment of phytoplankton and, as such, is used as an estimator of phytoplanktonic biomass. Chlorophyll-*a* concentrations in Coeur d'Alene Lake during 1991–92 ranged from <0.1 to 2.6 µg/L; the highest concentrations were measured at station 6 in both years (table 14). Within each year, the highest concentrations were measured during March-April, August, or November (fig. 19). The mean concentration at each station was slightly higher in 1992; this increase may be attributable to the substantial reduction in 1992 inflows, which yielded a longer-than-normal water residence time for the lake in 1992. The increased residence time may have reduced flushing of phytoplankton out the lake's outlet and also allowed more time for phytoplankton populations to develop prior to being flushed.

Two studies of Coeur d'Alene Lake conducted in the 1970's provided comparative chlorophyll-*a* data. The chlorophyll-*a* data collected as part of the National Eutrophication Survey (U.S. Environmental Protection Agency, 1977) were obtained at eight stations during April, July, and September 1975. The April samples contained higher chlorophyll-*a* concentrations than did samples collected during the other months. In April, the lakewide mean concentration was 17.3 µg/L and the range was 1.9 to 32.1 µg/L; in July and September, the means were 3.3 and 11.4 µg/L and the ranges were 2.3 to 4.2 and 4.1 to 29.3 µg/L, respectively. Rieman (1980) determined chlorophyll-*a* from composite samples of the upper 12 m of the water column at three stations on Coeur d'Alene Lake during April to November 1979. The overall range in the 33 samples was 1 to 22 µg/L and the lakewide mean concentration was 4.0 µg/L.

The two studies conducted in the 1970's reported a substantially wider range in chlorophyll-*a* concentrations than did this study. Part of this difference may be methodological. The USGS National Water Quality Laboratory used high-performance liquid chromatography to determine chlorophyll-*a* in samples collected during 1991–92. The National Eutrophication Survey used fluorometric procedures to determine chlorophyll-*a* in the 1975 samples

Table 13. Means and ranges of ratios of dissolved inorganic nitrogen to dissolved orthophosphorus in samples from the euphotic zone at six limnetic stations and lakewide, Coeur d'Alene Lake, 1991–92

[LW, area-weighted lakewide value]

Limnetic station (fig. 4)	Ratio		No. of samples
	Mean	Range	
	1991		
1	38.3	7–161	13
2	30	7–101	13
3	35	9–81	12
4	38.3	7–104	13
5	20.3	7–54	11
6	17.1	8–39	12
LW	34.4	7–161	74
	1992		
1	19.7	7–58	13
2	19.8	7–47	12
3	22.8	1–66	13
4	28.5	9–76	12
5	20.4	7–45	12
6	12.8	6–31	9
LW	22.7	1–76	71

Table 14. Means and ranges of chlorophyll-*a* concentrations in samples from the euphotic zone at six limnetic stations and lakewide, Coeur d'Alene Lake, 1991–92

[µg/L, micrograms per liter; <, less than; LW, area-weighted lakewide value]

Limnetic station (fig. 4)	Chlorophyll-*a* (µg/L)		No. of samples
	Mean[1]	Range	
	1991		
1	0.5	0.1–1	13
2	.5	.2–1.1	13
3	.4	.3–1	13
4	.5	<.1–1	13
5	.6	.3–1.4	12
6	.8	.1–2	11
LW	.5	<.1–2	75
	1992		
1	.6	<.1–1.3	12
2	.8	.4–1.4	11
3	.7	.2–1.2	13
4	.7	.2–1.5	13
5	.9	.2–1.7	13
6	1.1	.1–2.6	11
LW	.8	<.1–2.6	73

[1]Mean computed by assigning detection limit to less-than values.

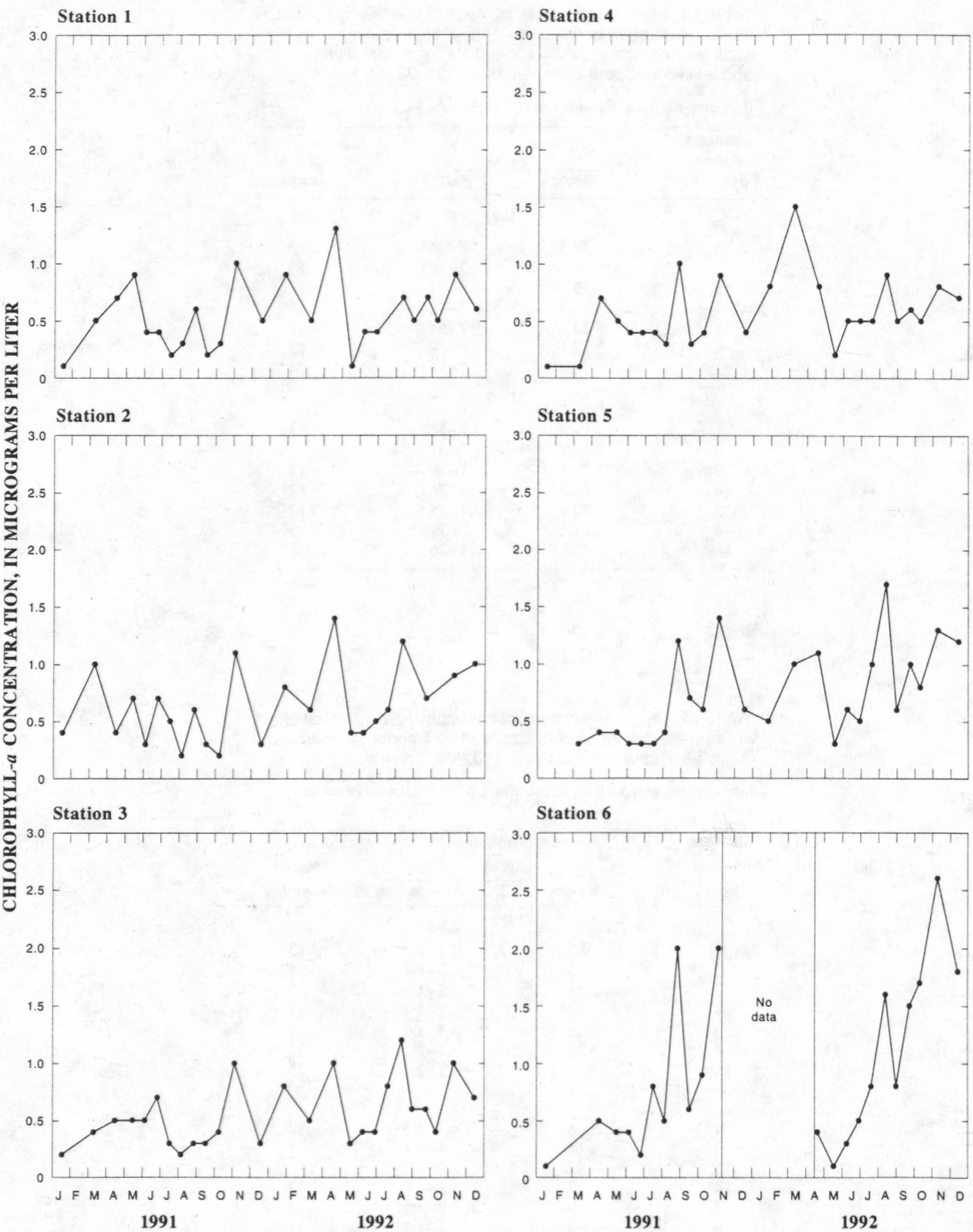


Figure 19. Chlorophyll-*a* concentrations at stations 1–6 during 1991–92. (Values less than detection limit represented at detection limit value)

(U.S. Environmental Protection Agency, 1975). Rieman's samples were analyzed using the spectrophotometric method (U.S. Environmental Protection Agency, 1973).

Regardless of methodological differences among the three studies, chlorophyll-*a* concentrations in Coeur d'Alene Lake declined substantially from the 1970's to the early 1990's. The substantially lower concentrations measured during this study were corroborated recently by chlorophyll-*a* analyses conducted by personnel at the Coeur d'Alene wastewater-treatment plant (H. Sid Fredrickson, City of Coeur d'Alene, written commun., 1993). Fredrickson's samples were collected approximately 0.2 km downstream from the outlet of Coeur d'Alene Lake. Chlorophyll-*a* concentrations in the five samples collected in May, June, August, and September 1993 were <1 μg/L, on the basis of spectrophotometric methods.

PHYTOPLANKTON

The taxonomic composition of phytoplankton at the six limnetic stations in Coeur d'Alene Lake comprised 65 genera during 1991–92 (table 15). The following six phyla were represented: Chlorophyta, or green algae; Chrysophyta, or yellow-brown algae; Cryptophyta, or cryptomonads; Cyanophyta, or blue-green algae; Euglenophyta, or euglenoids; and Pyrrhophyta, or dinoflagellates.

The lakewide median density and biovolume of phytoplankton was 400 cells/mL and 174,000 μm^3/mL, respectively (table 16). The lakewide range in density and biovolume for the 151 samples was 28 to 7,100 cells/mL and 6,100 to 1,500,000 μm^3/mL, respectively. The maximum density was at station 6 in November 1992, whereas the maximum biovolume was at station 2 in May 1991. The dominant algal genera, based on density, were *Asterionella* and *Synedra* at stations 1 through 5 and *Cyclotella* at station 6. These three genera are members of subphylum Bacillariophyceae, or diatoms, of the phylum Chrysophyta. The Cyanophyta were incidental or absent at stations 1 through 5. At station 6, the Cyanophyta constituted at least 10 percent of the phytoplankton density during the summer months of 1991 and 1992. The blue-green alga, *Anabaena flos-aquae*, numerically dominated the phytoplankton at station 6 during June and July 1992.

Two studies conducted in the 1970's provided comparative data on the presence of Cyanophyta in Coeur d'Alene Lake. Parker (1972) sampled phytoplankton from 12 stations (lakewide) during July to November 1971. He determined that, on the basis of density, the Cyanophyta composed 10 percent of the phytoplankton population and were dominant in August at one-half of the stations. *Aphanizomenon* was most frequently observed; *Nostoc* and *Anabaena* were rarely observed. The National Eutrophication Survey of Coeur d'Alene Lake (U.S. Environmental Protection Agency, 1977) reported a range of phytoplankton density of 1,250 cells/mL in September to 10,651 cells/mL in April 1975 but provided no information on the spatial distribution of the phytoplankton genera. During July, *Aphanizomenon* and *Anabaena* composed 18 and 15 percent, respectively, of the phytoplankton population. During September, *Aphanizomenon* codominated with the diatom *Tabellaria* at 37.7 percent each. On the basis of this study and the two conducted in the 1970's, the presence of Cyanophyta in Coeur d'Alene Lake has declined substantially since the 1970's.

TROPHIC STATE

The term "trophic state" refers to the biological productivity of a water body. For ease of categorization, three trophic states commonly are defined: oligotrophic, or low productivity; eutrophic, or high productivity; and mesotrophic, a middle ground between oligotrophic and eutrophic. Numerous variables have been employed as the basis for trophic-state classification. Although no classification system is universally accepted, variables such as total phosphorus, total nitrogen, chlorophyll-*a,* and secchi-disc transparency frequently have been used to classify trophic state.

Table 15. Phytoplankton taxa at six limnetic stations, Coeur d'Alene Lake, 1991–92

Phytoplankton taxa[1]

- Phylum Chlorophyta
  - Subphylum Chlorophyceae
    - Order Chlorococcales
      - Family Chlorococcaceae
        - *Tetraedron* sp. (6)
      - Family Coccomyxaceae
        - *Elakatothrix gelatinosa* (1,2,3,4,5,6)
      - Family Dictyosphaeriaceae
        - *Botryococcus braunii* (1,2,3,4)
      - Family Hydrodictyaceae
        - *Pediastrum boryanum* (5,6)
        - *P. duplex* (5,6)
      - Family Oocystaceae
        - *Ankistrodesmus falcatus* (1,2,3,4,5,6)
        - *Chodatella wratislawiensis* (3,4)
        - *Nephrocytium* sp. (1,2,3,4,6)
        - *Oocystis lacustris* (1,2,4,5,6)
        - *O. pusilla* (1,2,3,4,5,6)
        - *Quadrigula closterioides* (4,6)
        - *Selenastrum minutum* (1,3,4,5,6)
      - Family Palmellaceae
        - *Sphaerocystis schroeteri* (1,2,3,4,5)
      - Family Scenedesmaceae
        - *Crucigenia quadrata* (6)
        - *C. tetrapedia* (1)
        - *Scenedesmus denticulatus* (1,3,4,5)
        - *S. quadricauda* (1,3,4,5,6)
        - *Tetrastrum staurogeniaeforme* (6)
    - Order Tetrasporales
      - Family Gloeocystaceae
        - *Gloeocystis* sp. (1,2,3,4,5,6)
    - Order Ulotrichales
      - Family Ulotrichaceae
        - *Ulothrix* sp. (3,5)
    - Order Volvocales
      - Family Chlamydomonadaceae
        - *Chlamydomonas* (1,2,3,4,5,6)
    - Order Zygnematales
      - Family Desmidiaceae
        - *Cosmarium* sp. (6)
        - *Staurastrum* sp. (4)
        - *S. gracile* (4,5)
      - Family Zygnemataceae
        - *Mougeotia* sp. (2,3,4,5)
- Phylum Chrysophyta
  - Subphylum Bacillariophyceae
    - Order Centrales
      - Family Coscinodiscaceae
        - *Cyclotella* sp. (2)
        - *C. atomus* (1,4,5,6)
        - *C. kutzingiana* (3,5,6)
        - *C. meneghiniana* (4,5,6)
        - *C. stelligera* (1,2,3,4,5,6)
        - *Melosira* sp. (3,6)
        - *M. ambigua* (2,5,6)
        - *M. distans* (1,2,3,4,5,6)
        - *M. granulata* (4,5,6)
        - *M. granulata* var. *angustissima* (4,5,6)
        - *M. italica* (1,2,3,4,5,6)
        - *M. varians* (2)
      - Family Coscinodiscaceae (Continued)
        - *Stephanodiscus astraea* (5,6)
        - *S. astraea* var. *minutula* (1,2,3,4,5)
        - *S. hantzschii* (1,2,3,4,5)
        - *S. subsalsus* (6)
      - Family Rhizosoleniaceae
        - *Rhizosolenia eriensis* (1,2,3,4,5)
    - Order Pennales
      - Family Achnanthaceae
        - *Achnanthes* sp. (6)
        - *A. clevei* (5,6)
        - *A. exigua* (5,6)
        - *A. hauckiana* (5)
        - *A. lanceolata* (1,2,3,4,5,6)
        - *A. lewisiana* (2,3,5,6)
        - *A. linearis* (2,4,5,6)
        - *A. marginulata* (6)
        - *A. microcephala* (2)
        - *A. minutissima* (1,2,3,4,5,6)
        - *A. peragalli* (6)
        - *Cocconeis placentula* (2,4,5,6)
        - *Rhoicosphenia curvata* (5,6)
      - Family Cymbellaceae
        - *Amphora ovalis* (5,6)
        - *A. perpusilla* (5,6)
        - *Cymbella affinis* (6)
        - *C. lunata* (6)
        - *C. microcephala* (4)
        - *C. minuta* (1,2,3,4,5,6)
        - *C. sinuta* (4,5,6)
        - *C. tumida* (6)
      - Family Epithemiaceae
        - *Epithemia sorex* (5,6)
        - *E. turgida* (1,6)
        - *Rhopalodia gibba* (6)
      - Family Eunotiaceae
        - *Eunotia pectinalis* (2,4,6)
      - Family Fragilariaceae
        - *Asterionella formosa* (1,2,3,4,5,6)
        - *Diatoma hiemale* var. *mesodon* (5,6)
        - *Fragilaria* sp. (1,5)
        - *F. brevistriata* (1,2,5,6)
        - *F. capucina* (2,5)
        - *F. capucina* var. *mesolepta* (5,6)
        - *F. construens* (1,2,4,5,6)
        - *F. construens* var. *venter* (1,2,3,4,5,6)
        - *F. crotonensis* (1,2,3,4,5,6)
        - *F. leptostauron* (4,6)
        - *F. pinnata* (1,2,3,5,6)
        - *F. vaucheriae* (1,2,3,4,5,6)
        - *Hannaea arcus* (1,2,3,5,6)
        - *Meridion circulare* (2,3,5)
        - *Synedra* sp. (1,2,3,4)
        - *S. delicatissima* (3)
        - *S. mazamaensis* (5)
        - *S. parasitica* (5)
        - *S. radians* (1,2,3,4,5)
        - *S. rumpens* (1,2,3,4,5)
        - *S. socia* (1,2,3,4,5)
        - *S. ulna* (2,5)

Table 15. Phytoplankton taxa at six limnetic stations, Coeur d'Alene Lake, 1991-92-Continued

Phytoplankton taxa[1]	Phytoplankton taxa[1]
Family Fragilariacea (Continued)	Subphylum Chrysophyceae
Tabellaria fenestrata (1,2,3,4,5,6)	Order Chromulinales
T. flocculosa (1,2,3,4,5)	Family Chromulinaceae
Family Gomphonemaceae	*Chromulina* sp. (1,2,3,4,6)
Gomphonema sp. (3,5,6)	*Kephyrion* sp. (1,2,3,4,6)
G. acuminatum (6)	*K. obliquum* (1,2,3,4)
G. angustatum (1,2,3,4,5,6)	*K. spirale* (4)
G. clevei (5,6)	Family Chrysococcaceae
G. gracile (6)	*Chrysococcus rufescens* (1,2,3,4,5,6)
G. olivaceum (5,6)	Family Pedinellaceae
G. subclavatum (4,5,6)	*Pseudopedinella* sp. (1,2,4,5)
G. tenellum (3,5,6)	Order Ochromonadales
G. ventricosum (6)	Family Dinobryaceae
Family Naviculaceae	*Dinobryon* sp. (1,2,4,5,6)
Caloneis sp. (2,5,6)	*D. bavaricum* (1,2,3,4)
C. placentula (6)	*D. sertularia* (1,2,3,4,5,6)
C. ventricosa var. *minuta* (6)	Family Ochromonadaceae
Diploneis elliptica (4,5,6)	*Ochromonas* sp. (3,6)
D. puella (5)	Family Synuraceae
D. smithii (6)	*Mallomonas* sp. (1,2,3,4,5,6)
Navicula sp. (1,2,3,4,5,6)	Order Prymnesiales
N. anglica (6)	Family Prymnesiaceae
N. capitata (5,6)	*Chrysochromulina* sp. (1,2,3,4,6)
N. cascadensis (6)	Phylum Cryptophyta
N. contenta var. *biceps* (6)	Family Cryptochrysidaceae
N. cryptocephala (2,4,5,6)	*Rhodomonas minuta* (1,2,3,4,5,6)
N. cryptocephala var. *veneta* (5,6)	Family Cryptomonadaceae
N. decussis (3,5,6)	*Cryptomonas* sp. (1,2,3,4,6)
N. graciloides (6)	*C. erosa* (1,2,3,4,5,6)
N. gregaria (5)	Phylum Cyanophyta
N. minima (1,2,3,4,5,6)	Order Chroococcales
N. minuscula (5)	Family Chroococcaceae
N. mournei (3)	*Anacystis* sp. (6)
N. mutica (3,5)	*Chroococcus* sp. (3,4,5,6)
N. pelliculosa (2)	Order Nostocales
N. pseudoscutiformis (5,6)	Family Nostocaceae
N. pupula (1,2,3,4,5,6)	*Anabaena* sp. (5)
N. radiosa (6)	*A. circinalis* (5,6)
N. rhynchocephala (4,5,6)	*A. flos-aquae* (1,5,6)
N. scutiformis (6)	*A. planctonica* (5,6)
N. seminulum (6)	*Aphanizomenon flos-aquae* (6)
Neidium sp. (4,6)	Phylum Euglenophyta
Pinnularia sp. (1,2,3,5,6)	Order Euglenales
Stauroneis sp. (2)	Family Euglenaceae
Family Nitzschiaceae	*Trachelomonas* sp. (5,6)
Nitzschia sp. (1,2,4,5,6)	*T. hispida* (5,6)
N. acicularis (1,2,3,4,5,6)	*T. pulchella* (6)
N. amphibia (6)	*T. robusta* (5,6)
N. capitellata (2,6)	*T. volvocina* (4,5,6)
N. communis (5)	Phylum Pyrrhophyta
N. dissipata (4,5,6)	Class Dinophyceae
N. epiphytica (1)	Order Dinokontae
N. fonticola (1,2,3)	Family Ceratiaceae
N. frustulum (3,4,5,6)	*Ceratium hirundinella* (6)
N. linearis (3)	Family Glenodiniaceae
N. palea (3,5,6)	*Glenodinium* sp. (1)
N. paleacea (1,2,4,5,6)	

[1] Taxonomy based on Prescott (1970).

Table 16. Median density and biovolume of phytoplankton at six limnetic stations and lakewide, Coeur d'Alene Lake, 1991–92

[cells/mL, cells per milliliter; μm^3/mL, cubic micrometers per milliliter; LW, lakewide]

Limnetic station (fig. 4)	Density (cells/mL)	Biovolume (μm^3/mL)	No. of samples
1	490	172,000	26
2	450	220,000	25
3	370	172,000	26
4	450	221,000	26
5	440	238,000	25
6	210	150,000	23
LW	400	174,000	151

Table 17. Trophic-state classification based on open-boundary values for four limnological variables

[Modified from Ryding and Rast (1989); µg/L, micrograms per liter; m, meters]

Limnological variable[1]		Oligotrophic	Mesotrophic	Eutrophic
Total phos-	$\bar{x}$	8.0	26.7	84.4
phorus	$\bar{x} \pm 1$ SD	4.8–13.3	14.5–49.0	48.0–189.0
(µg/L)	$\bar{x} \pm 2$ SD	2.9–22.1	7.9–90.8	16.8–424.0
Total nitrogen	$\bar{x}$	661	753	1,875
(µg/L)	$\bar{x} \pm 1$ SD	371–1,180	485–1,170	861–4,081
	$\bar{x} \pm 2$ SD	208–2,103	313–1,816	395–8,913
Chlorophyll-*a*	$\bar{x}$	1.7	4.7	14.3
(µg/L)	$\bar{x} \pm 1$ SD	0.8–3.4	3.0–7.4	6.7–31.0
	$\bar{x} \pm 2$ SD	0.4–7.1	1.9–11.6	3.1–66.0
Secchi-disc	$\bar{x}$	9.9	4.2	2.4
transparency	$\bar{x} \pm 1$ SD	5.9–16.5	2.4–7.4	1.5–4.0
(m)	$\bar{x} \pm 2$ SD	3.6–27.5	1.4–13.0	0.9–6.7

[1]Annual geometric mean values and standard deviations.

A system developed by the United Nation's Organization for Economic Cooperation and Development (Ryding and Rast, 1989) was used to classify the trophic state of Coeur d'Alene Lake. Total phosphorus, total nitrogen, chlorophyll-*a,* and secchi-disc transparency (table 17) were analyzed statistically and an open-boundary trophic-state classification system was developed. This approach compensates for the overlap in classification that commonly occurs with fixed-boundary systems. Under the open-boundary system, a water body is considered to be classified correctly if three of the four variables are within two standard deviations of their geometric mean for the same trophic state.

Annual geometric mean values for total phosphorus, total nitrogen, chlorophyll-*a,* and secchi-disc transparency during 1991–92 were computed for limnetic stations 1 through 6 and lakewide (table 18). These values were compared with those shown in table 17 to determine the lake's trophic state. On the basis of concentrations of total phosphorus, total nitrogen, and chlorophyll-*a,* all stations were oligotrophic in both years. However, on the basis of secchi-disc transparency, five of the six stations were mesotrophic in both years. At station 6, secchi-disc transparencies fell into both the mesotrophic and eutrophic categories.

Several studies conducted during the 1970's classified the trophic state of Coeur d'Alene Lake. Parker (1972) used the results of carbon-14 primary productivity measurements to delineate three lake areas of different trophic state. Parker classified the lake area north of Rockford Bay as oligotrophic, the area south of Rockford Bay to Conkling Point as mesotrophic, and the Chatcolet Lake area as strongly mesotrophic. The National Eutrophication Survey classified the lake as mesotrophic on the basis of nutrient and chlorophyll-*a* concentrations (U.S. Environmental Protection Agency, 1977). The Idaho Department of Fish and Game classified the lake as mesotrophic on the basis of chlorophyll-*a* concentrations in samples collected from three stations during April to November 1979 (Rieman, 1980).

Of these three studies, the National Eutrophication Survey data base was most comparable to that of the present study. The open-boundary trophic-state classification listed in table 17 was compared with geometric mean values computed from the National Eutrophication Survey data. The comparison data were upper water-column samples obtained from eight stations during April, July, and September 1975. The geometric mean value for total nitrogen, 292 μg/L, resulted in an oligotrophic classification, whereas the geometric mean values for total phosphorus (19.1 μg/L), chlorophyll-*a* (7.2 μg/L), and secchi-disc transparency (2.7 m) resulted in a mesotrophic classification. Nutrient and biological productivity (chlorophyll-*a* and primary productivity) data from the three earlier studies resulted in a mesotrophic classification; however, the data from the present study, except for secchi-disc transparency, resulted in an oligotrophic classification.

WATER QUALITY AT LIMNETIC STATION 7

Water quality at limnetic station 7 was assessed during 1991 to determine whether log-storage wastes created sufficient biochemical oxygen demand to reduce dissolved-oxygen concentrations to anoxic levels. Dissolved-oxygen concentrations ranged from 6.6 to 12 mg/L (saturation ranged from 83 to 105 percent); the minimum concentrations were measured near the lake bottom, at a depth of 4 m, in early August.

Sampling results failed to show any significant adverse water-quality effects attributable to log wastes at limnetic station 7. However, the superintendent of the Coeur d'Alene wastewater-treatment plant supplied data indicative of substantial dissolved-oxygen depletion at their lake sampling station about 0.2 km north of limnetic station 7 and situated over a 20-m-deep depression near the lake's outlet (H. Sid Fredrickson, City of Coeur d'Alene, written commun., 1993). Fredrickson's data showed dissolved-oxygen concentrations as low as 1 mg/L and saturations as low as 10 percent in the lower half of the water column on August 19 and September 15, 1993. Apparently, the cumulative effects that were measured at Fredrickson's sampling station were not detected at limnetic station 7 because it was situated at the "upstream" side of the log-storage areas.

Table 18. Trophic state of Coeur d'Alene Lake at six limnetic stations and lakewide during 1991–92 based on annual mean values for four limnological variables

[μg/L, micrograms per liter; m, meters; TS, trophic state; O, oligotrophic; M, mesotrophic; E, eutrophic; LW, area-weighted lakewide value]

Limnetic station (fig. 4)	Total phosphorus (μg/L) [1] $\bar{\chi}$	TS	Total nitrogen (μg/L) [1] $\bar{\chi}$	TS	Chlorophyll-*a* (μg/L) [1] $\bar{\chi}$	TS	Secchi-disc transparency (m) [2] $\bar{\chi}$	TS
1991								
1	4.2	O	275	O	0.39	O	5.3	M
2	3.9	O	259	O	.45	O	4.9	M
3	4.3	O	276	O	.39	O	4.7	M
4	5.0	O	282	O	.38	O	4.0	M
5	8.3	O	290	O	.52	O	3.1	M
6	12.4	O	316	O	.55	O	2.4	M/E
LW	5.6	O	282	O	.43	O	4.0	M
1992								
1	2.0	O	211	O	.54	O	6.6	M
2	2.8	O	212	O	.71	O	5.6	M
3	2.1	O	215	O	.62	O	6.2	M
4	3.6	O	219	O	.62	O	5.2	M
5	3.7	O	218	O	.81	O	4.6	M
6	4.6	O	206	O	.79	O	2.9	M/E
LW	2.9	O	214	O	.67	O	5.1	M
1991–92								
LW	4.1	O	247	O	.54	O	4.5	M

[1] Annual geometric mean concentration within euphotic zone.

[2] Annual geometric mean value.

Table 19. Bioassays showing effects of dissolved, uncomplexed zinc on cell number, biomass, and doubling rate of three phytoplankton isolates from Coeur d'Alene Lake, 1994

[μg/L, micrograms per liter; Kcells/mL, thousand cells per milliliter; mg/L, milligrams per liter; 1/d, number per day; ND, no discernible growth detected]

Bioassay number, culturing period, and phytoplankton isolate	Treatment	Dissolved bioavailable zinc concentration (μg/L)	Phytoplankton conditions at end of bioassay: Mean cell concentration (Kcells/mL)	Biomass, dry weight (mg/L)	Doubling rate (1/d)
1					
5/24–6/7	Basal	0.5	4,481	45.7	0.87
Achnanthes	Mid	19.6	17.7	.16	ND
minutissima	Station 4	39.2	20.4	.18	ND
2					
6/14–21	Basal	.5	48.9	31.9	.55
Cyclotella	Mid	19.6	11.0	6.3	ND
stelligera[1]	Station 4	39.2	8.1	4.5	ND
3					
9/2–9	Basal	.5	48.6	29.8	.52
Cyclotella	Mid	19.6	15.0	9.8	.23
stelligera[2]	Station 4	39.2	12.1	8.1	.19

[1] From limnetic station 6.

[2] From limnetic station 4.

PHYTOPLANKTON BIOASSAYS

A topical review of environmental studies of the Coeur d'Alene area (Savage, 1986) concluded that most studies of the effects of trace elements on the lake's biota dealt with fish and invertebrates. Only two studies dealt with phytoplankton, even though photosynthetic production of organic matter by phytoplankton is the basis of the food web in most lakes. The two phytoplankton studies were done in the early 1970's and used a bioassay approach to test the inhibitory effects of cadmium, copper, and zinc (Wissmar, 1972; Bartlett and others, 1974).

The present study demonstrated that concentrations of total recoverable cadmium, copper, and zinc have declined since Wissmar (1972) measured them (see "Trace Elements" section). Of the three, only zinc remains well above its detection limit. Therefore, only zinc was used in the 1994 bioassays to assess inhibition of phytoplankton growth in Coeur d'Alene Lake.

The two earlier phytoplankton bioassay studies arrived at different conclusions regarding the inhibitory effects of zinc on phytoplankton. Wissmar (1972) did not observe significant inhibition; Bartlett and others (1974) did. The discrepancy in the results is due, in part, to interpretive limitations associated with the two different approaches. Wissmar measured the primary productivity of nanoplankton from Coeur d'Alene Lake in a series of short-term (hours) bioassays conducted in a laboratory incubation system. Bartlett and others measured biomass changes in the green alga *Selenastrum* in a series of long-term (days) bioassays using algal-assay bottle-test procedures (U.S. Environmental Protection Agency, 1971). Both studies reported total concentrations of zinc and, therefore, did not consider speciation and bioavailability of zinc.

The question of zinc inhibition of phytoplankton growth in Coeur d'Alene Lake remained important in the early 1990's; however, the methodological differences and inconclusive results of the two 1970's bioassays left the question unresolved. Therefore, current-technology bioassays were conducted in 1994 using phytoplankton isolated from the lake and chemically defined media. The media was formulated on the basis of geochemical data from Coeur d'Alene Lake. This approach accounted for speciation and bioavailability of zinc to phytoplankton that were adapted to the chemical conditions in Coeur d'Alene Lake.

The three bioassays conducted in 1994 (table 19) showed that phytoplankton growth was strongly inhibited by zinc concentrations greater than the basal media treatment (Kuwabara and others, 1994). In each bioassay, the mean cell concentrations, biomasses, and doubling rates of the mid and station 4 media treatments were much lower than those of the basal media treatment. Inhibition was particularly evident for *Achnanthes minutissima*, a pennate diatom known to be intolerant of elevated trace-element concentrations. Inhibition in the three bioassays occurred at dissolved zinc concentrations >0.5 μg/L, the basal treatment, and <19.6 μg/L, the mid treatment. This concentration range lies well below the median concentrations of dissolved zinc measured in Coeur d'Alene Lake during 1993–94, except for limnetic station 6 and the St. Joe River (table 20). Concentrations of dissolved organic carbon, concurrently measured with zinc, were consistently low in the lake (table 20). The low concentrations enhanced the bioavailability of zinc to phytoplankton because dissolved organic carbon compounds represent an important source of ligands for chemically binding (complexing) with trace elements such as zinc (J.S. Kuwabara, U.S. Geological Survey, written commun., 1994).

Littoral Zone

COMPARISONS TO LIMNETIC ZONE

Water quality at 20 littoral stations (fig. 20) was assessed during mid-September 1991 to compare littoral and limnetic water quality and to identify potential sites for a 1992 assessment of littoral periphyton production. No major differences were detected in water quality, based on concentrations of total phosphorus, dissolved ortho-

Table 20. Concentrations of dissolved zinc and organic carbon in samples of near-surface water from Coeur d'Alene Lake and the St. Joe and Coeur d'Alene Rivers, 1993–94

[Zn, dissolved zinc concentration, in micrograms per liter; DOC, dissolved organic carbon concentration, in milligrams per liter; NS, not sampled]

Sampling station (fig. 4)	Constituent	Sample month and year 6/93	9/93	6/94	8/94	Median concentration
Limnetic station 1	Zn	33.1	64.5	63.3	44.7	54.0
	DOC	1.39	1.36	1.48	1.17	1.38
Limnetic station 4	Zn	40.1	66.0	57.6	45.4	51.5
	DOC	1.23	1.25	1.32	1.33	1.29
Limnetic station 6	Zn	.55	.16	.73	.40	.48
	DOC	1.20	1.53	1.47	1.82	1.50
Mica Bay	Zn	40.1	NS	63.0	44.5	44.5
	DOC	1.34	NS	1.40	1.24	1.34
St. Joe River	Zn	NS	.26	1.18	.49	.49
	DOC	NS	1.14	1.29	1.28	1.28
Coeur d'Alene River	Zn	NS	400.0	69.6	202.5	202.5
	DOC	NS	.66	.86	.81	.81

Table 21. Water-quality data for 20 littoral and 6 limnetic stations, Coeur d'Alene Lake, mid-September 1991

[µg/L, micrograms per liter; mg/L, milligrams per liter; <, less than; —, missing value]

Station No.	Station name	Dissolved inorganic nitrogen (µg/L)	Total phosphorus (µg/L)	Dissolved ortho-phosphorus (µg/L)	Chlorophyll-*a* (µg/L)	Dissolved oxygen Concentration (mg/L)	Percent saturation
	Littoral stations[1] (fig. 20)						
1	Kid Island Bay	28	5	<1	0.2	8.1–8.4	94–99
2	Sanders Beach	65	—	9	.2	8.2–8.3	95–100
3	Bennett Bay	<12	5	<1	.1	8.3–8.6	96–101
4	Blue Creek Bay	19	6	<1	.2	8.0–8.4	91–97
5	Beauty Bay	<12	5	<1	.2	7.7–8.3	72–97
6	Squaw Bay	93	5	—	.2	8.2–8.4	95–100
7	Echo Bay	14	4	<1	.2	8.4–8.6	96–100
8	Mica Bay	13	4	<1	.2	8.4–8.5	96–98
9	Driftwood Bay	<11	13	<1	.2	8.4–8.6	87–99
10	Turner Bay	<11	4	<1	.2	8.2–8.6	89–99
11	Loffs Bay	<10	4	<1	.1	8.5–8.6	98–99
12	Carlin Bay	10	8	<1	.4	8.2–8.7	93–100
13	Powderhorn Bay	55	7	<1	.4	7.2–8.7	82–100
14	Rockford Bay	<12	4	<1	.2	7.6–8.6	83–99
15	Windy Bay	<9	6	<1	.3	7.9–8.6	88–99
16	16 to 1 Bay	13	5	<1	.2	8.3–8.6	94–99
17	Cave Bay	<8	6	2	.2	8.2–8.6	91–99
18	Cottonwood Bay	14	8	<1	.4	8.3–8.7	94–100
19	Fullers Bay	9	7	<1	.3	7.2–8.4	74–96
20	Carey Bay	15	10	<1	.5	7.7–8.1	86–92
	Limnetic stations[2] (fig. 4)						
1	St. Joe River	38	6	<1	.2	8.4–8.5	84–98
2	Coeur d'Alene Lake	16	5	<1	.3	8.2–8.4	88–97
3	Spokane River	<16	6	<1	.3	8.4–8.6	84–100
4	Plummer Creek	18	4	<1	.3	7.6–8.5	77–98
5	Fighting Creek	14	13	<1	.7	5.4–8.4	52–96
6	Carlin Creek	<10	11	<1	.6	0–7.8	0–88

[1] Dissolved inorganic nitrogen, total phosphorus, dissolved orthophosphorus, and chlorophyll-*a* data from 1-meter-depth samples.
[2] Data from euphotic zone samples.

phosphorus, and chlorophyll-*a*, between littoral and limnetic stations (table 21). Some differences were detected in dissolved-oxygen concentrations, percent saturations, and dissolved inorganic nitrogen (table 21). The differences in dissolved oxygen were largely attributable to the anoxic conditions at limnetic station 6 and the substantial oxygen depletion at limnetic station 5. None of the 26 stations exhibited supersaturated oxygen concentrations. Dissolved inorganic nitrogen at the littoral stations ranged from <8 to 93 μg/L and, at the limnetic stations, from <10 to 38 μg/L. The median and 75th-percentile concentrations of dissolved inorganic nitrogen at the littoral stations were 12 and 15 μg/L, respectively. Concentrations in excess of 15 μg/L were measured at littoral stations 1, 2, 4, 6, and 13. Of these five, four were in bays where beds of aquatic macrophytes were extensive. The fifth station, Sanders Beach, was adjacent to the mouth of Fernan Creek, the outlet for Fernan Lake, a mesotrophic lake 0.3 km north of Coeur d'Alene Lake. Mossier (1993) reported that summer concentrations of total inorganic nitrogen in Fernan Lake ranged from 50 to 60 μg/L; these concentrations were similar to the concentration of 65 μg/L measured at littoral station 2.

Water quality among 15 littoral and 6 limnetic stations also was compared during mid-August 1992 (table 22). Unlike the 1991 comparison of euphotic-zone composites, the 1992 comparison was based on 1-m-deep samples because the littoral stations were used for an assessment of periphyton production. Minor differences in concentrations of total phosphorus, dissolved orthophosphorus, chlorophyll-*a*, and percent saturation of dissolved oxygen were detected. Unlike the 1991 comparison, the range in dissolved inorganic nitrogen was larger at the limnetic stations; however, the median concentrations were comparable. Zinc concentrations at the limnetic stations had a wider range (10 to 90 μg/L) than at the littoral stations (40 to 70 μg/L). The median concentration of zinc at the limnetic stations was 90 μg/L, whereas at the littoral stations, it was 60 μg/L. The other five trace elements that were analyzed (arsenic, cadmium, copper, mercury, and lead) were at or below detection limits at the 21 stations.

AQUATIC MACROPHYTES

Coeur d'Alene Lake contained 22 genera of aquatic macrophytes on the basis of sampling at 63 stations (table 23). Four of the genera were observed rarely. *Nymphaea* was observed only in Hidden Lake, and the only specimens of *Brasenia*, *Spirodela*, and *Utricularia* were observed in Bell Bay. Seven genera—*Equisetum*, *Fontinalis*, *Myriophyllum*, *Nuphar*, *Sagittaria*, *Typha*, and *Zizania*—were observed infrequently. The remaining 11 genera were observed at most of the stations. The genus *Potamogeton* was the most common aquatic macrophyte at most of the stations. The aquatic macrophytes were observed only at water depths less than 6 m.

The southern end of the lake contained the most abundant beds of aquatic macrophytes, although Cougar Bay at the lake's northern end also was heavily populated. Most of the bays with extensive sedimentary deltas contained abundant beds of aquatic macrophytes. Those bays were Carey, Carlin, Kid Island, Loffs, Mica, Powderhorn, Rockford, 16 to 1, Windy, and the eastern end of Wolf Lodge (fig. 5). Beds of aquatic macrophytes were abundant in Harrison Slough, north of the mouth of the Coeur d'Alene River; were moderate in Bennett, Echo, Fullers, and Turner Bays; and were sparse to very sparse at the remaining stations.

PERIPHYTON PRODUCTION

Limnological studies of eutrophication traditionally have focused on the limnetic zone. However, recent studies of several large lakes have detected eutrophication much earlier in the littoral zone than in the limnetic zone (Loeb, 1986; Aloi and others, 1988; Kann and Falter, 1989; Jacoby and others, 1991). The additional influx of nutrients caused by disturbance of the lake's shoreline can stimulate periphyton production on natural substrates as well as constructed substrates such as docks and pilings.

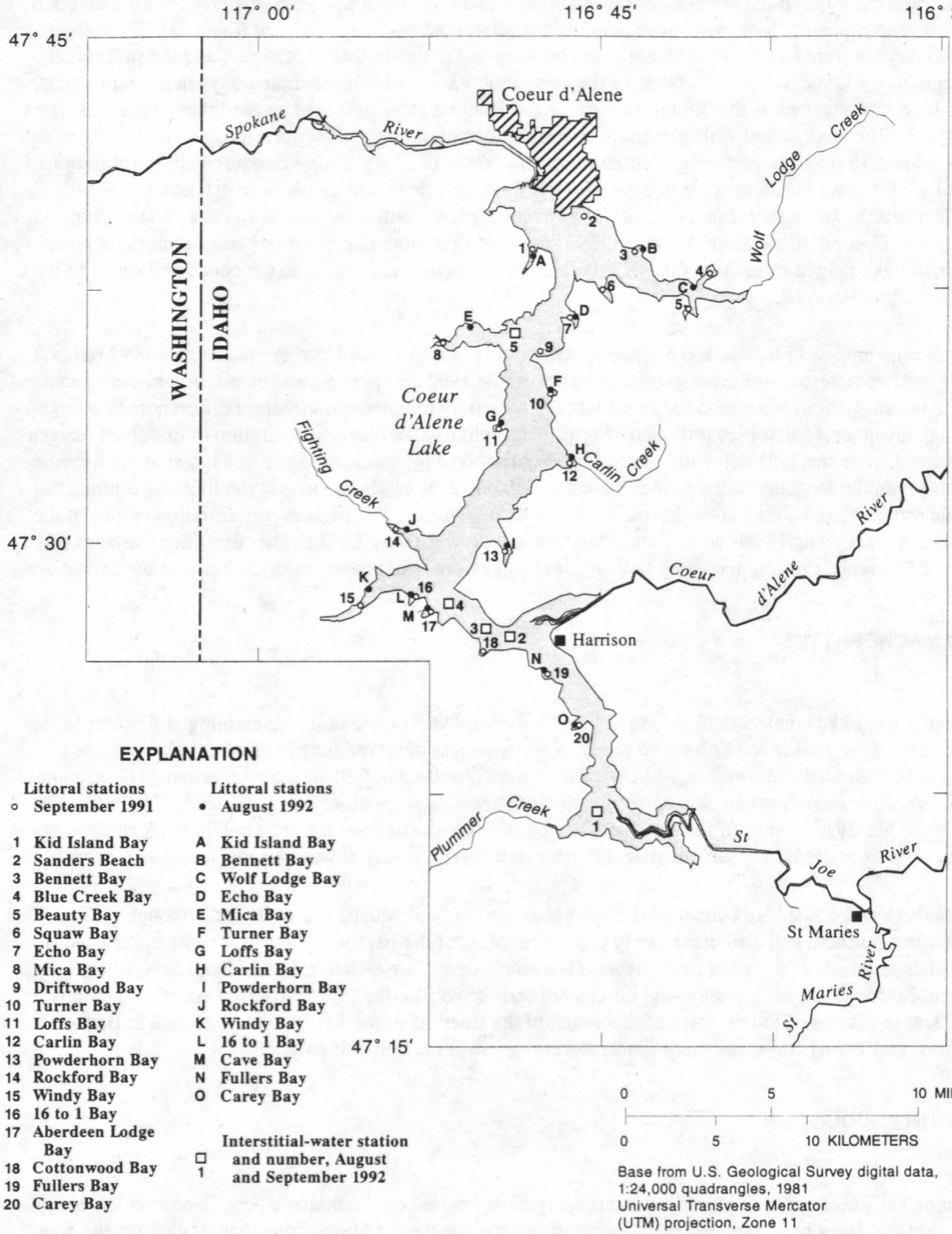


Figure 20. Locations of littoral sampling stations, September 1991 and August 1992, and interstitial-water sampling stations, August and September 1992.

Table 22. Water-quality data for 15 littoral and 6 limnetic stations, Coeur d'Alene Lake, mid-August 1992

[µg/L, micrograms per liter; mg/L, milligrams per liter; <, less than]

Station No.	Station name	Dissolved inorganic nitrogen (µg/L)	Total phosphorus (µg/L)	Dissolved ortho-phosphorus (µg/L)	Chloro-phyll-*a* (µg/L)	Dissolved oxygen Concentration (mg/L)	Dissolved oxygen Percent saturation	Zinc, total recoverable (µg/L)
			Littoral stations[1] (fig. 20)					
A	Kid Island Bay..........	21	16	1	1.7	9.0	105	40
B	Bennett Bay.............	44	4	<1	.8	8.8	111	50
C	Wolf Lodge Bay	18	4	<1	.7	8.4	105	60
D	Echo Bay	44	3	<1	.8	8.6	107	60
E	Mica Bay	19	3	<1	.8	8.8	107	50
F	Turner Bay...............	32	3	1	1.0	8.7	107	50
G	Loffs Bay.................	34	2	<1	1.0	8.9	109	60
H	Carlin Bay	42	4	<1	.9	8.7	106	60
I	Powderhorn Bay.......	44	4	<1	1.0	8.9	110	60
J	Rockford Bay	33	2	<1	1.1	8.8	107	60
K	Windy Bay...............	25	3	<1	1.0	9.1	111	60
L	16 to 1 Bay	15	4	<1	.9	9.0	111	60
M	Cave Bay	16	2	1	1.3	9.0	108	70
N	Fullers Bay	21	5	1	.9	8.7	105	60
O	Carey Bay................	23	6	<1	1.0	9.0	108	50
			Limnetic stations[1] (fig. 4)					
1	St. Joe River	16	4	1	.7	8.4	104	90
2	Coeur d'Alene Lake .	86	3	<1	1.2	8.4	104	90
3	Spokane River	11	2	1	1.2	8.8	108	90
4	Plummer Creek.........	25	5	1	.9	8.6	107	90
5	Fighting Creek..........	26	5	<1	1.7	8.5	106	70
6	Carlin Creek	<11	6	<1	1.6	7.9	98	10

[1]Data from 1-meter-depth samples.

Table 23. Aquatic macrophyte taxa, Coeur d'Alene Lake, 1993

Aquatic macrophyte taxa[1]	Aquatic macrophyte taxa[1]	Aquatic macrophyte taxa[1]
Phylum Bryophyta	Class Angiospermae (Continued)	Class Angiospermae (Continued)
Class Musci	Family Callitrichaceae	Family Naiadaceae
Family Fontinalaceae	*Callitriche hermaphroditica*	*Potamogeton amplifolius*
Fontinalis	*C. heterophylla*	*P. epihydrus*
Phylum Chlorophyta	Family Ceratophyllaceae	*P. foliosus*
Family Characeae	*Ceratophyllum demersum*	*P. praelongus*
Nitella	Family Elatinaceae	*P. richardsonii*
Phylum Pteridophyta	*Elatine triandra*	*P. robbinsii*
Family Equisetaceae	Family Gramineae	Family Nymphaeaceae
Equisetum fluviatile	*Zizania aquatica*	*Brasenia schreberi*
Family Isoetaceae	Family Haloragaceae	*Nuphar polysepalum*
Isoetes sp.	*Myriophyllum spicatum* var. *exalbescens*	*Nymphaea odorata*
Phylum Spermatophyta	Family Hydrocharitaceae	Family Ranunculaceae
Class Angiospermae	*Elodea canadensis*	*Ranunculus aquatilis*
Family Alismaceae	Family Lemnaceae	Family Sparganiaceae
Alisma gramineus	*Lemna minor*	*Sparganium eurycarpum*
A. plantago-aquatica	*Spirodela polyrhiza*	Family Typhaceae
Sagittaria cuneata	Family Lentibulariaceae	*Typha latifolia*
S. latifolia	*Utricularia vulgaris*	

[1]Taxonomy based on Prescott (1969) and Steward and others (1963).

Table 24. Periphyton production, as chlorophyll-*a*, at 10 littoral stations, Coeur d'Alene Lake, July and August 1992

[PAR, photosynthetically active radiation; E, Einstein; mg/m^2, milligrams per square meter; (mg/m^2)/E, milligrams per square meter per Einstein]

Littoral station (fig. 20)	Station name	PAR input (E)[1]	Periphyton production (mg/m^2)	Periphyton production normalized to PAR [(mg/m^2)/E]
A	Kid Island Bay	278	3.92	0.014
B	Bennett Bay	945	.66	.00070
E	Mica Bay	944	.44	.00047
F	Turner Bay	914	.59	.00064
G	Loffs Bay	892	.32	.00036
H	Carlin Bay	971	.61	.00063
I	Powderhorn Bay	856	.70	.00082
J	Rockford Bay	924	.56	.00061
K	Windy Bay	888	.72	.00081
N	Fullers Bay	896	.96	.00110

[1]Quantity of photon flux, as Einsteins (1 E = 1 mole of photons), input to periphyton during incubation period.

Periphyton production in the littoral zone of Coeur d'Alene Lake during July and August 1992 was assessed to determine whether a statistical relation existed between periphyton production and various indices of nearshore and watershed development. Comparison of periphyton production in Coeur d'Alene Lake with that of other lakes was not a goal because such studies are not standardized. After evaluating numerous studies of periphyton production, Morin and Cattaneo (1992) concluded that the ability to detect patterns in periphyton ecology was limited because numerous environmental factors affect sampling variability. Periphyton production also is known to exhibit large temporal and spatial variations, such as those observed at Lake Tahoe, Nev. (Aloi and others, 1988).

In Coeur d'Alene Lake, periphyton production, as chlorophyll-*a*, at 10 littoral stations ranged from 0.32 to 3.92 mg/m^2, a difference of 12.2 times (table 24). When normalized to PAR input, the production ranged from 0.00036 to 0.014 $(mg/m^2)/E$, a difference of 38.9 times. For both comparisons, production was lowest at station G and highest at station A.

The relation of PAR-normalized periphyton production to nearshore and watershed development was investigated with multiple linear regression using procedures described by Helsel and Hirsch (1992). The periphyton production rates were normalized to PAR input to remove the influence of that variable from the predictive equations. For each littoral station, the following variables were tested as predictors of periphyton production: concentration of total phosphorus in the littoral zone, percentage of agricultural land use in the contributing watershed, number of nearshore homes using septic tanks, and degree of nearshore development (low, moderate, and high). The relation of the individual predictor variables to the response variable was examined with scatter plots, whereas a correlation matrix was used to test for multicollinearity among the variables. Initial analyses indicated that station A (Kid Island Bay) unduly influenced the regression models; station A was deemed an outlier and was removed from the data set. For the remaining nine stations, PAR-normalized periphyton production was best predicted by the following equation:

$$PP = 0.000045 + 0.00015\,(TP) + 0.000006\,(PA)\,, \tag{6}$$

where

PP is periphyton production, as chlorophyll-*a*, in milligrams per square meter per Einstein;

TP is concentration of total phosphorus in the littoral zone, in micrograms per liter; and

PA is decimal percent of agricultural land in the contributing watershed.

This two-variable regression model explained 88.4 percent of the variation in PAR-normalized periphyton production and was highly significant with a probability of 0.0016. The regression coefficients for *TP* and *PA* were significantly different from 0 and probabilities were <0.01; the intercept coefficient was not significantly different from 0. The residuals were plotted and were deemed satisfactory. The positive sign for the regression coefficients indicates that as total phosphorus concentrations and percentage of agricultural land use increase, so does periphyton production.

The excluded variables, number of nearshore homes using septic tanks and degree of nearshore development, appeared to be reasonable for inclusion in the regression models; additional examination, however, revealed reasons why they were poor predictors. The efficiency of wastewater treatment by septic tanks may be quite variable and often is a function of age. Gilliom (1983) reported that older septic-tank systems contributed more phosphorus to Puget Sound region lakes than did newer systems. Gilliom also noted that long lag times are possible between installation of a septic-tank system and detection of its effects on phosphorus concentrations in a lake. Around Coeur d'Alene Lake, a wide disparity exists for the installation dates and adequacy of maintenance for septic-tank systems. The degree of nearshore development was a qualitative variable and did not adequately differentiate among the numerous factors that can affect periphyton production in the littoral zone.

The taxonomic composition of periphyton grown on the artificial substrates was assessed for seven of the littoral stations. The number of algal species at each station ranged from 19 to 32; the mean density was 50,400 cells/cm^2 and the range was 25,400 to 75,900. *Fragilaria construens* and *F. crotonensis* composed more than 50 percent of the density at stations B, I, J, K, and N (fig. 20). *F. crotonensis*, *F. vaucheriae*, *Cymbella microcephala*, *Achnanthes minutissima*, and *Mougeotia* sp. composed more than 50 percent of the density at stations F and H. One species, *Rhopalodia gibba*, composed between 32 and 76 percent of the biovolume at each littoral station. Of the algal genera just discussed, all are diatoms except *Mougeotia*, which is a filamentous green alga.

LAKEBED SEDIMENT GEOCHEMISTRY

Several studies of Coeur d'Alene Lake have reported concentrations of trace elements in the lakebed sediments (Funk and others, 1973, 1975; Maxfield and others, 1974a, 1974b; Hornig and others, 1988); however, these studies have not assessed potential environmental availability of trace elements. As part of this study, an intensive geochemical analysis of lakebed sediments was conducted to determine concentration, partitioning, and environmental availability of selected trace elements. The trace-element analysis was conducted in three phases: (1) surficial lakebed sediments, (2) lakebed sediment cores, and (3) interstitial water. Concentrations of total phosphorus and nitrogen in the surficial lakebed sediments also were determined.

Data Collection and Analysis

Surficial samples of the lakebed sediments were collected in August 1989 at 172 stations, at a density of one per square kilometer, in the lake and the lower reaches of the Coeur d'Alene and St. Joe Rivers. Samples were collected with a stainless-steel Ekman dredge. Subsamples of the upper 2 cm of sediment in the dredge were collected for trace-element analyses. A detailed description of the sampling locations and analytical methods is presented in a report by Horowitz and others (1993) and is only summarized here. Bulk sediment samples were analyzed for concentrations of total aluminum, antimony, arsenic, cadmium, chromium, cobalt, copper, iron, lead, manganese, mercury, nickel, selenium, titanium, zinc, and total organic carbon. Selected samples were separated according to grain size and the resulting size fractions were analyzed for the same chemical constituents as were the bulk samples. Selected samples were separated into heavy and light mineral fractions to help determine phase association. Selected heavy/light mineral separates were subjected to scanning-electron microscopy linked to an energy-dispersive X-ray system to help infer mineralogy.

During June 1992, 12 lakebed sediment cores were obtained using a 2.4-m, stainless-steel, Wildco gravity corer equipped with a clear polycarbonate liner and nonmetallic core catcher. Coring locations were based on results of the surficial lakebed sediment samples. The sampling locations and analytical procedures used for the cores are described in detail in a report by Horowitz and others (1995). The same chemical constituents were analyzed as for the surficial lakebed sediments. A core near the mouth of the Coeur d'Alene River was evaluated for cesium-137 activity to help estimate the ages of various layers in that core.

Interstitial water in lakebed sediments at five stations (fig. 20) was sampled using diffusion-controlled equilibrator samplers, or "peepers"; the samplers and their operation are described in a report by Simon and others (1985). The samplers were placed in the lakebed by scuba divers in late August 1992 and were retrieved after a 30-day incubation. The samplers obtained interstitial water at 1-cm intervals within the upper 20 cm of the lakebed sediments. All analytical work was performed in a nitrogen atmosphere to prevent redox changes by the introduction of oxygen. The interstitial water samples were analyzed for concentrations of dissolved copper, lead, and zinc, as well as calcium and magnesium, for calculation of hardness.

Twenty stations were sampled for lakebed sediment nutrients in late June 1992. Samples were collected with a stainless-steel Ponar dredge. A subsample, taken from the centroid of the dredged sample, was analyzed for total phosphorus and total nitrogen using methods described by Fishman and Friedman (1985).

Sediment Trace Elements

Results from the geochemical study of lakebed sediments in Coeur d'Alene Lake were reported in detail by Horowitz and others (1993, 1995); they are summarized briefly here. The surficial and subsurface sediments over about 85 percent of the lakebed's surface area were highly enriched in antimony, arsenic, cadmium, copper, lead, mercury, silver, and zinc. Concentrations of selected trace elements were highest in the subsurface sediments; however, median concentrations in the surficial sediments exceeded the median concentrations in the subsurface sediments (table 25). The higher medians in the surficial sediments may have resulted from post-depositional remobilization, upward diffusion, and reprecipitation caused by reducing conditions in the sediment column beneath the oxidized surficial zone. Remobilization is likely to have occurred because most of the trace elements are associated with an operationally defined ferric oxide phase. The ferric oxide can redissolve under reducing conditions present in the sediment column. Most of the trace elements in the lakebed were associated with ferric oxides; only near the mouth of the Coeur d'Alene River were the trace elements strongly associated with sulfide minerals.

The trace-element-enriched sediments extended northward from about Conkling Point (fig. 4) and varied in thickness from 17 to 119 cm; the thickest layer was near the mouth of the Coeur d'Alene River. The chemical distribution pattern indicates the Coeur d'Alene River as the source of the trace elements. Some of the highest concentrations were measured near the river mouth. Other high concentrations were measured in the lake's northern end and reflected the advective transport of extremely fine-grained sediments from the mouth of the Coeur d'Alene River toward the lake's outlet to the Spokane River.

The recent geochemical history of the lakebed sediments was determined from a core taken north of the mouth of the Coeur d'Alene River. This core was chosen because it had readily discernible varves, the Mt. St. Helens, Wash., ash layer was present, the trace-element-enriched section was about 119 cm in length, and the interface between background and highly enriched trace-element layers was definitive. The age of the interface was determined by three different methods, which yielded dates of 1895, 1910, and 1911. These dates roughly coincide with the onset of mining in the Coeur d'Alene River Basin, which began around 1885.

Interstitial-Water Trace Elements

The highly enriched trace-element concentrations in the lakebed sediments of Coeur d'Alene Lake (Horowitz and others, 1993, 1995) represented total concentrations determined from only the solid phase; dissolved trace-element concentrations in interstitial water in the lakebed sediments were not included. The amount of biologically available trace elements in lakebed sediments is more realistically evaluated using dissolved trace-element concentrations in interstitial water (Ankley and others, 1994).

The concentrations of dissolved copper, lead, and zinc in interstitial water (table 26) were substantially lower than the total concentrations in the surficial and subsurface lakebed sediments (table 25). Median concentrations of dissolved copper in interstitial water sampled at the five stations were similar, ranging from 2 to 3 µg/L. The spatial variation of interstitial-water concentrations of lead and zinc was different from that of copper. The lowest median concentrations of lead and zinc were measured at station 1, in Chatcolet Lake; the highest median concentrations were measured at station 2, within the delta of the Coeur d'Alene River.

Table 25. Statistical summary of selected trace elements in surficial and subsurface lakebed sediments in enriched and unenriched areas, Coeur d'Alene Lake

[mg/kg, milligrams per kilogram; S, surficial sample; C, subsurface sample; <, less than; data from Horowitz and others (1993, 1995)]

Trace element	Sample type	Concentration for enriched area (mg/kg)				Median concentration for unenriched area[1] (mg/kg)
		Minimum	Maximum	Mean	Median	
Arsenic	S	2.4	660	151	120	4.7
	C	3.5	845	103	30	12
Cadmium	S	<.5	157	62	56	2.8
	C	<.1	137	25	26	.3
Copper	S	9	215	72	70	25
	C	20	650	91	60	30
Lead	S	14	7,700	1,900	1,800	24
	C	12	27,500	3,200	1,250	33
Mercury	S	.02	4.9	1.8	1.6	.05
	C	<.01	9.9	1.9	.95	.06
Zinc	S	63	9,100	3,600	3,500	110
	C	59	14,000	2,400	2,100	118

[1]Unenriched area median concentration for sample type S based on 17 samples from southern area of Coeur d'Alene Lake and lower reach of St. Joe River. Unenriched area median concentration for sample type C based on 189 sample aliquots from cores beneath enriched area.

Table 26. Statistical summary of concentrations of dissolved copper, lead, and zinc in interstitial water, August and September 1992

[µg/L, micrograms per liter; Min., minimum; Max., maximum; <, less than]

Interstitial water sampling station (fig. 20)	Latitude, longitude	Copper (µg/L)			Lead (µg/L)			Zinc (µg/L)		
		Median	Min.	Max.	Median	Min.	Max.	Median	Min.	Max.
[1]1	47°21'43" 116°45'03"	3	2	15	<6	<6	14	<20	<20	26
[2]2	47°27'15" 116°48'47"	2.5	2	4	205	85	562	287	212	451
[1]3	47°27'13" 116°49'27"	2	2	10	70	6	236	106	35	342
[1]4	47°28'06" 116°51'24"	3	2	8	26	6	134	133	68	319
[1]5	47°36'26" 116°48'38"	2	2	5	11	6	73	108	20	251

[1] Number of samples was 24.
[2] Number of samples was 12.

Sediment Nutrients

Total phosphorus concentrations in lakebed sediments at 20 stations on Coeur d'Alene Lake ranged from 500 to 1,600 mg/kg, whereas total nitrogen concentrations ranged from 860 to 3,900 mg/kg (table 27). The mean concentration of total phosphorus was 940 mg/kg and, of total nitrogen, was 2,100 mg/kg.

The smallest concentration of total phosphorus (500 mg/kg) was measured at limnetic station 5, where the lakebed is subject to erosion because it is 5.6 km from the mouth of the St. Joe River. The largest concentration of total phosphorus (1,600 mg/kg) was measured at limnetic station 1, in the deep northern end of the lake, where deposition predominates.

The smallest and largest concentrations of total nitrogen were measured in Rockford and Windy Bays, respectively. Analogous to concentrations of total phosphorus, the smallest concentration of total nitrogen among limnetic stations 1 through 6 was at limnetic station 5; the largest concentration was at limnetic station 1.

The sediment nutrient data for Coeur d'Alene Lake were compared with data for several northwestern United States lakes and reservoirs that drain to the Columbia River, as does Coeur d'Alene Lake. Lake Koocanusa in northwestern Montana is a large, oligotrophic reservoir created by Libby Dam in 1972. Iskander and Shukla (1981) analyzed 20 surficial lakebed sediment samples from Lake Koocanusa and reported a range in total phosphorus from 750 to 1,500 mg/kg. Lake Chelan in central Washington is a large, oligotrophic lake that was studied by Patmont and others (1989). On the basis of surficial lakebed sediment samples from four limnetic stations, they reported that total phosphorus and total nitrogen in Lake Chelan ranged from 300 to 1,100 mg/kg and from 470 to 1,830 mg/kg, respectively. Long Lake is a reservoir on the Spokane River downstream from Coeur d'Alene Lake. In 1974, when Long Lake was classified as eutrophic, Thomas and Soltero (1977) determined total phosphorus and nitrogen concentrations in a single core. For the surficial part of that core, total phosphorus ranged from 1,400 to 3,500 mg/kg, whereas total nitrogen ranged from 1,800 to 6,500 mg/kg. The range of total phosphorus concentrations in surficial sediments of the two oligotrophic water bodies was comparable to the range in Coeur d'Alene Lake, whereas the range of total phosphorus concentrations in Long Lake was much higher. The range of total nitrogen concentrations in surficial sediments of Coeur d'Alene Lake was higher than the range in Lake Chelan but was comparable to the low part of the range measured in Long Lake.

WATER-QUALITY STANDARDS AND CRITERIA AND SEDIMENT-QUALITY GUIDELINES

The Idaho water-quality standards (Idaho Department of Health and Welfare, 1985) designate the appropriate beneficial uses of Idaho's water and list general and specific criteria to determine whether beneficial uses are supported by the water-quality conditions of a particular water body. Idaho defines a beneficial use as the reasonable and appropriate use of water for a purpose consistent with Idaho State laws and the best interest of the people. The beneficial uses for Coeur d'Alene Lake are designated in the Idaho water-quality standards and include the following: domestic water supply, agricultural water supply, primary contact recreation, secondary contact recreation, cold water biota, and salmonid spawning. The 1992 Idaho Water Quality Status Report concluded that the designated beneficial uses for Coeur d'Alene Lake were fully supported but were threatened by nutrients, sediment, low dissolved oxygen, pathogens, metals, and "other" causes (Idaho Department of Health and Welfare, 1992).

The EPA (1986) has established water-quality criteria for assessing the potential toxicity of many water-quality constituents, including trace elements, to freshwater biota. The criteria are listed for continuous (chronic) and maximum (acute) concentrations. The toxicity criteria for the six trace elements sampled in Coeur d'Alene Lake are listed for total recoverable and dissolved concentrations (table 28). The original criteria were developed with total recoverable concentrations, but criteria for dissolved concentrations can be estimated as a percentage of the total recoverable concentration (M.G. Prothro, U.S. Environmental Protection Agency, written commun.,

Table 27. Concentrations of total phosphorus and total nitrogen in lakebed sediments at 20 stations, Coeur d'Alene Lake, June 1992

[m, meters; mg/kg, milligrams per kilogram]

Station name[1] (figs. 4, 5)	Water depth (m)	Concentration (mg/kg)	
		Total phosphorus	Total nitrogen
Limnetic station 1	42.7	1,600	2,900
Limnetic station 2	29.9	940	2,600
Limnetic station 3	53.0	1,500	2,600
Limnetic station 4	41.1	1,300	2,000
Limnetic station 5	17.7	500	1,100
Limnetic station 6	11.3	840	1,700
Between Harlow and Reynolds Points	18.0	730	1,300
Coeur d'Alene River delta	5.0	920	1,900
Cave Bay	19.8	830	1,400
16 to 1 Bay	18.6	590	1,100
Between East and Rockford Points	31.7	1,200	1,900
Windy Bay	29.6	1,000	3,900
Powderhorn Bay	29.3	900	1,600
Rockford Bay	19.2	920	860
Carlin Bay	15.8	920	1,900
Mica Bay	14.9	1,000	2,200
Squaw Bay	11.9	610	3,600
Bennett Bay	29.3	880	2,000
Casco Bay	11.3	580	3,200
Near Tubbs Hill	28.7	1,100	2,900

[1] Latitude and longitude reported by Harenberg and others (1993).

1993). The median concentrations for the six trace elements sampled in Coeur d'Alene Lake (table 10) were used to assess potential toxicity on the basis of toxicity criteria listed in table 28. The potential toxicity of cadmium and mercury could not be determined because their analytical detection limits exceeded the criteria. Arsenic concentrations did not exceed the criteria. Concentrations of total recoverable and dissolved (estimated) copper and lead exceeded the continuous concentration criteria. Concentrations of total recoverable and dissolved (estimated) zinc exceeded the continuous and maximum concentration criteria. On the basis of these comparisons, copper and lead were considered chronically toxic to freshwater biota in Coeur d'Alene Lake, whereas zinc was considered chronically and acutely toxic.

The concentrations of dissolved copper, lead, and zinc in interstitial water (table 26) were compared with the water-quality criteria for potential toxicity to freshwater biota (table 28). Criteria in table 28 are hardness-dependent and, thus, were computed with a hardness of 22 mg/L as $CaCO_3$. The hardness of the interstitial water was lower, about 5 mg/L as $CaCO_3$, on the basis of measured concentrations of calcium and magnesium. The decrease in hardness effectively lowered the concentrations at which copper, lead, and zinc would be considered chronically or acutely toxic. The adjusted acute (CMC) criteria for dissolved concentrations of the three trace elements are as follows: copper, 0.9 μg/L; lead, 0.9 μg/L; and zinc, 7.8 μg/L. The median concentrations of copper (3 μg/L), lead (26 μg/L), and zinc (108 μg/L) in interstitial water in Coeur d'Alene Lake are substantially higher than the criteria concentrations considered acutely toxic to freshwater biota.

The Ontario Ministry of Environment published guidelines for aquatic sediment quality for numerous elements and compounds, including trace elements and nutrients (Persaud and others, 1993). The guidelines include three levels: no effect, lowest effect, and severe effect. The lowest effect level signifies sediment contamination that can be tolerated by most benthic organisms. The severe effect level signifies severely polluted sediment that will significantly affect benthic organisms. The lowest effect and severe effect levels for arsenic, cadmium, copper, lead, mercury, and zinc are listed in table 29, as are the median concentrations of these six trace elements in unenriched and enriched surficial sediments in Coeur d'Alene Lake. Median concentrations of arsenic, lead, mercury, and zinc in unenriched sediments were less than the lowest effect level guidelines; median concentrations of cadmium and copper were slightly above those guidelines but were less than the severe effect level guidelines. Median concentrations of arsenic, cadmium, lead, and zinc in enriched sediments exceeded the severe effect level guidelines; median concentrations of copper and mercury did not. On the basis of these comparisons, the concentrations of arsenic, cadmium, lead, and zinc indicate severely polluted sediment that can significantly affect benthic organisms. The Ontario Ministry guidelines for nutrients are as follows: lowest effect level for total phosphorus, 600 mg/kg, and for total nitrogen, 550 mg/kg; severe effect level for total phosphorus, 2,000 mg/kg, and for total nitrogen, 4,800 mg/kg. The mean concentration of total phosphorus in the lakebed sediments of Coeur d'Alene Lake was 940 mg/kg, which is slightly higher than the lowest effect level guideline and much less than the severe effect level guideline. The mean concentration of total nitrogen was 2,100 mg/kg, which is about midway between the lowest effect level and severe effect level guidelines.

HYDROLOGIC BUDGETS

Hydrologic budgets for Coeur d'Alene Lake were determined for calendar years 1991 and 1992. The budgets accounted for the mass of water entering and leaving the lake via pathways such as streamflow, precipitation, and evaporation. Such data were important components of the nutrient load/lake response model and were used to compute budgets for nutrients and trace elements entering and leaving the lake.

Table 28. Concentrations of selected trace elements considered acutely or chronically toxic to freshwater biota based on hardness-dependent criteria

[µg/L, micrograms per liter; CMC, criterion maximum concentration; CCC, criterion continuous concentration; e, base of natural logarithms; ln, natural logarithm; H, hardness, in milligrams per liter as $CaCO_3$; —, data not available; mg/L, milligrams per liter]

Trace element	Criteria	Toxicity equation[1,2]	Concentration (µg/L) Total recoverable	Dissolved
Arsenic	CMC	None	360	342
	CCC	None	190	180
Cadmium....	CMC	$e^{[1.128(\ln H)-3.878]}$	.71	.60
	CCC	$e^{[0.7852(\ln H)-3.49]}$	.35	.30
Copper........	CMC	$e^{[0.9422(\ln H)-1.464]}$	4.3	3.7
	CCC	$e^{[0.8545(\ln H)-1.465]}$	.16	.14
Lead...........	CMC	$e^{[1.273(\ln H)-1.46]}$	11.9	6.0
	CCC	$e^{[1.273(\ln H)-4.705]}$	.5	.12
Mercury......	CMC	None	2.4	2.0
	CCC	None	.012	—
Zinc	CMC	$e^{[0.8473(\ln H)+0.8604]}$	32.4	27.5
	CCC	$e^{[0.8473(\ln H)+0.7614]}$	29.4	25.0

[1] From U.S. Environmental Protection Agency (1986).
[2] Hardness is median value for Coeur d'Alene Lake, 1991–92, 22 mg/L as $CaCO_3$.

Table 29. Median concentrations of selected trace elements in surficial lakebed sediments in Coeur d'Alene Lake related to aquatic sediment-quality guidelines

[mg/kg, milligrams per kilogram]

Trace element	Guideline concentration[1] (mg/kg) Lowest effect level	Severe effect level	Median concentration in surficial sediments (mg/kg) Unenriched	Enriched
Arsenic	6	33	4.7	120
Cadmium..	.6	10	2.8	56
Copper......	16	110	25	70
Lead..........	31	250	24	1,800
Mercury....	.2	2	.05	1.6
Zinc	120	820	110	3,500

[1] From Persaud and others (1993).

Data Collection and Analysis

The hydrologic budgets included a 28.6-km reach of the Spokane River from the outlet of Coeur d'Alene Lake to the USGS gaging station near the Idaho-Washington border. Inclusion of this station provided the most accurate method for measuring surface-water outflow from the lake and also permitted calculation of the residual between inflow and outflow quantities. Hydrologic budgets for 1991 and 1992 were computed using the following equation (quantities in cubic hectometers):

$$R = SWGI + SWUI + WWI + P - E - GWRP - SWGO - CS, \qquad (7)$$

where

R is the residual;
$SWGI$ is gaged surface-water inflow;
$SWUI$ is ungaged surface-water inflow;
WWI is wastewater inflow;
P is precipitation to the lake and river surface;
E is evaporation from the lake and river surface;
$GWRP$ is ground-water outflow to the Rathdrum Prairie aquifer;
$SWGO$ is gaged surface-water outflow; and
CS is change in lake storage.

Gaged surface-water inflow to the lake was determined at six USGS gaging stations; gaged surface-water outflow from the lake was determined at a USGS gaging station on the Spokane River 28.6 km downstream from the lake's outlet (fig. 4 and table 30). Discharge at the seven gaging stations was determined from continuous monitoring of stage (water-surface elevation) and periodic measurements of streamflow using standard USGS methods. Streamflow measurements were made weekly during March through May and biweekly otherwise at the St. Joe, Coeur d'Alene, and Spokane River gaging stations. The remaining four gaging stations were measured biweekly during March through May and monthly otherwise.

Daily discharges at the St. Joe River at St. Maries gaging station and the Coeur d'Alene River near Harrison gaging station were computed with a hydraulic model because backwater conditions created by Coeur d'Alene Lake negated the correlation between streamflow and stage that commonly is used to compute discharge. The hydraulic model is a USGS-developed branch-network flow model, referred to as BRANCH, and is based on one-dimensional, partial-differential equations of continuity and momentum that govern unsteady flow (Schaffranek and others, 1981). The model is applied by continuously measuring stage at two or more gaging stations in a low-gradient reach of stream. Multiple channel cross sections in the reach are input to the model to quantify channel capacity. For the St. Joe River application, the upstream and downstream stage-measurement stations were St. Joe River at St. Maries (gaging station 1) and St. Joe River near Chatcolet (USGS gaging station 12415140), respectively. For the Coeur d'Alene River application, the upstream and downstream stage-measurement stations were Coeur d'Alene River near Cataldo (USGS gaging station 12413500) and Coeur d'Alene River near Harrison (gaging station 2), respectively.

Ungaged surface-water inflows were estimated by multiplying drainage basin areas by unit-runoff coefficients. Unit-runoff coefficients for the gaged surface-water inflow at Carlin, Fighting, Plummer, and Wolf Lodge Creeks were determined using the following equation:

Table 30. Gaging stations used to calculate inflow to and outflow from Coeur d'Alene Lake

[km², square kilometer]

Gaging station name (fig. 4)	Gaging station No.	Drainage area (km^2)	Period of record
St. Joe River at St. Maries	12415075	4,400	1991–92
Plummer Creek near Plummer	12415250	114	1991–92
Coeur d'Alene River near Harrison	12413860	3,812	1991–92
Fighting Creek near Rockford Bay	12415285	41.6	1991–92
Carlin Creek near Harrison	12415290	31.7	1991–92
Wolf Lodge Creek near Coeur d'Alene	12415350	104	1985–Present
Spokane River near Post Falls	12419000	10,313	1912–Present

$$RO = \frac{Q}{A}, \qquad (8)$$

where

RO is a unit-runoff coefficient, in cubic hectometers per square kilometer per year;

Q is annual discharge, in cubic hectometers; and

A is drainage area, in square kilometers.

Each of 23 ungaged surface-water inflows was assigned a unit-runoff coefficient on the basis of factors such as similar land use/land cover characteristics and proximity to a particular gaged surface-water station.

Precipitation to the lake and river was determined by multiplying surface area by the precipitation recorded at the National Weather Service station in Coeur d'Alene. Precipitation during 1991 and 1992 at Coeur d'Alene was 0.50 and 0.58 m, respectively. Long-term average annual precipitation is 0.66 m (Woods, 1989). Precipitation was 76 percent of normal in 1991 and 89 percent of normal in 1992. Evaporation from the lake and river was estimated by multiplying the surface area by an evaporation rate of 0.76 m. The evaporation rate was derived from a map of annual free-water-surface evaporation in Idaho (Myron Molnau and K.C.S. Kpordze, University of Idaho, written commun., 1992).

The change in lake storage for 1991 and 1992 was reported in USGS annual reports of water resources data for Idaho (Harenberg and others, 1992, 1993, 1994). These reports contain tables of lake capacity and stage for numerous Idaho lakes and reservoirs. The change in lake storage represents the difference in contents between January 1 and December 31 in a given year.

An evaluation of ground-water flux to Coeur d'Alene Lake was beyond the scope of this study. However, Wyman (1993) reported that ground-water outflow from Coeur d'Alene Lake to the Rathdrum Prairie aquifer was 205 hm^3 per year; this value was assigned as an outflow quantity for the 1991 and 1992 hydrologic budgets. The remaining ground-water flux was assigned to the residual.

The volume of wastewater inflow to the lake was a summation of discharges from municipal wastewater-treatment plants and wastewater-disposal systems in the nearshore area of Coeur d'Alene Lake. The municipal wastewater-treatment plants serving Coeur d'Alene and Post Falls reported their annual discharge of effluent on the basis of frequent measurements during 1991 and 1992. During 1992, the small municipal wastewater-treatment plants serving Clarkia, Harrison, Mullan, Page, Plummer, Santa/Fernwood, Smelterville, and St. Maries measured their effluent discharge on an approximate biweekly basis to quantify their annual discharge. The 1992 discharge value was used as an estimate for the 1991 hydrologic budget. Several of the small municipal wastewater-treatment plants are upstream from gaged surface-water inflows; thus, their effluents are part of the gaged inflow. The Coeur d'Alene River at Harrison receives effluent from Mullan, Smelterville, and Page. The St. Joe River at St. Maries receives effluent from Santa/Fernwood and Clarkia. Plummer Creek receives effluent from Plummer. The effluent contribution from the nearshore area was determined differently because inflows could not be measured. In 1993, the Panhandle Health District, under contract to the USGS, conducted a survey of private and community wastewater-disposal systems and the associated user population within 150 m of Coeur d'Alene Lake (Hale, 1993). The population data were reported as full-time and part-time residency. The population data were converted to an equivalent full-time residency and then were multiplied by a yearly per capita effluent production rate of 55,000 L, which was based on a daily per capita rate of 150 L reported by Canter and Knox (1985). The 1993 survey also reported the volume of wastewater generated annually by nearshore commercial and camp facilities.

The residual for the hydrologic budget was computed as the difference between gaged surface-water outflow and the algebraic sum of inflow and outflow components upstream from the Spokane River gaging station near the

Idaho-Washington border. The residual includes the errors associated with all budget components and unmeasured components such as ground-water flux, bank-storage flux, and urban runoff.

The error associated with the hydrologic budgets was computed with methods described by Winter (1981) and Brown (1987). The error associated with each budget component was computed with the following equation (Brown, 1987):

$$E = \sqrt{(P)^2 (C)^2} , \qquad (9)$$

where

E is total standard error associated with budget component C,
P is percent error used to determine budget component C, and
C is value of the budget component.

Percent error for each budget component was adapted from Winter (1981). Assignment of percent error to each budget component was as follows: St. Joe River, Coeur d'Alene River, and precipitation, 15 percent; Carlin, Fighting, Plummer, and Wolf Lodge Creeks, lake storage change, and Spokane River, 7.5 percent; and ungaged surface-water inflow, wastewater, evaporation, and ground-water outflow, 25 percent. The propagation of error for the hydrologic budgets was computed with the following equation (Brown, 1987):

$$OE = \sqrt{(E_1)^2 + (E_2)^2 + \ldots + (E_n)^2} , \qquad (10)$$

where

OE is overall standard error associated with hydrologic budget, in cubic hectometers; and
E_n is total standard error associated with each budget component.

The residence time of water in Coeur d'Alene Lake was computed with the following equation:

$$RT = \frac{V}{Q} , \qquad (11)$$

where

RT is residence time, in years;
V is lake volume, in cubic hectometers; and
Q is total inflow, in cubic hectometers per year.

Streamflow, 1991 and 1992

Daily mean streamflows at the seven gaging stations varied widely (fig. 21). Maximum streamflows at the two primary inflow stations at the St. Joe and Coeur d'Alene Rivers were between February and May. Maximum streamflows at the four secondary inflow stations were earlier, from January to March, because these stations do not record drainage from upper-elevation areas as do the two primary inflow stations. The variability in the streamflow record at the outlet station, Spokane River, was somewhat muted because of regulation by Post Falls Dam.

Statistical summaries of streamflow at USGS gaging stations in Idaho were presented by Harenberg and others (1993); however, the summaries were computed for water years, not calendar years, as used in this study. The 1991 and 1992 streamflows, based on water years, at three stations in the study area were compared with long-term mean annual streamflows (table 31). Streamflow during the 1991 water year was about 130 percent of the long-term mean and, during the 1992 water year, was about 56 to 60 percent of the mean.

Unit-runoff coefficients for gaged and ungaged surface-water inflows for 1991 (0.10 to 0.74 hm^3/km^2) were about twice as large as those determined for 1992 (0.05 to 0.37 hm^3/km^2) (table 32). The largest coefficient in each year was for the St. Joe River at St. Maries; the coefficient for the Coeur d'Alene River near Harrison was slightly smaller. These two gaging stations record drainage from the highest elevation areas in the study area. Conversely, the smallest coefficients were for low-elevation, nearshore areas around Coeur d'Alene Lake.

Hydrologic Budgets, 1991 and 1992

Inflows from the St. Joe and Coeur d'Alene Rivers during 1991 accounted for 93.2 percent of the total inflow to Coeur d'Alene Lake (table 33). Gaged inflows from Plummer, Fighting, Carlin, and Wolf Lodge Creeks accounted for only 1.6 percent of the total, whereas the 23 ungaged surface-water inflows accounted for 4.1 percent. The smallest inflow contribution, 0.1 percent, was from wastewater. The outflows were dominated by the Spokane River at 94.8 percent. The residual of the total outflow of 6,610 hm^3 minus the total inflow of 6,390 hm^3 was 220 hm^3, which represented 3.4 percent of the total inflow. The overall error in the budget was 796 hm^3; thus, the residual was accounted for by the overall error.

During 1992, inflows from the St. Joe and Coeur d'Alene Rivers again dominated at 92.1 percent of the total (table 34). The relative magnitude of the other inflow sources was similar to that in the 1991 budget. The Spokane River accounted for 89.8 percent of the total outflow. The overall error in the 1992 budget was 436 hm^3 and encompassed the residual of 310 hm^3. The residual represented 9.7 percent of the total inflow for 1992.

The residence time of water in Coeur d'Alene Lake was different for each year because of the large differences in inflow. In 1991, the inflow of 6,390 hm^3 was delivered into a lake volume of 2,840 hm^3 and yielded a residence time of 0.45 year. In 1992, the smaller inflow of 3,190 hm^3 yielded a residence time of 0.89 year, nearly twice that of 1991.

NUTRIENT BUDGETS

Nutrient budgets for Coeur d'Alene Lake were determined for calendar years 1991 and 1992. The budgets accounted for the mass of total phosphorus and total nitrogen entering and leaving the lake via pathways such as gaged and ungaged streamflow, precipitation, and wastewater from point and nonpoint sources. The nutrient budgets were calculated from the hydrologic budgets and nutrient concentration data from several sources.

Data Collection and Analysis

Nutrient data for gaged inflows and the outflow at seven gaging stations (table 30) were collected using standard USGS cross-sectional and depth-integrating methods (Edwards and Glysson, 1988). The frequency of sampling is illustrated in figure 21. During 1991–92, each gaging station was sampled between 33 and 52 times; the gaging stations on the Coeur d'Alene, St. Joe, and Spokane Rivers were sampled the most frequently. Nutrient samples were analyzed for concentrations of total phosphorus, orthophosphorus, organic plus ammonia nitrogen, ammonia, and nitrite plus nitrate at the USGS National Water Quality Laboratory using methods described by Fishman and Friedman (1985).

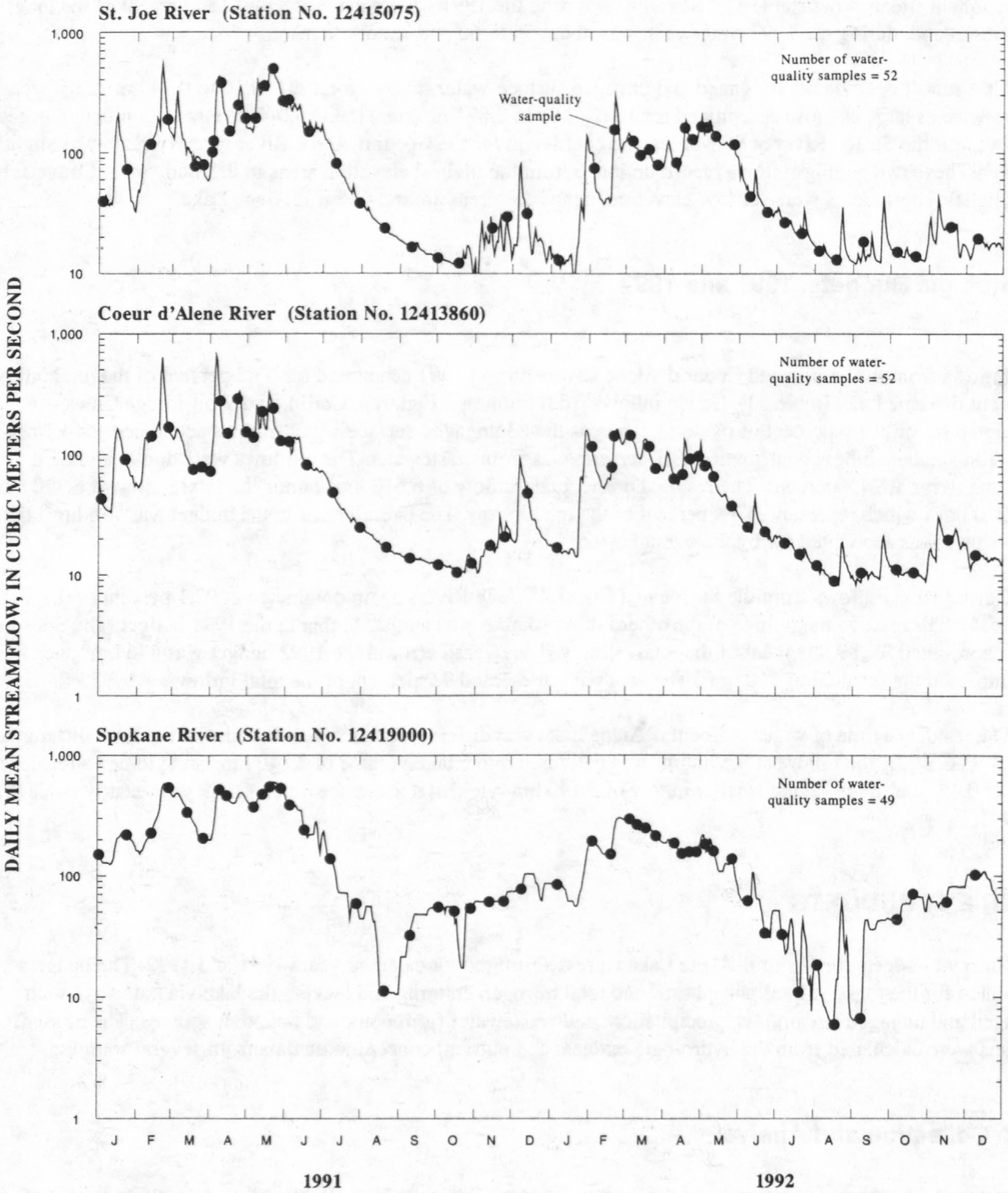


Figure 21. Daily mean streamflow and timing of water-quality samples at seven gaging stations during 1991–92.

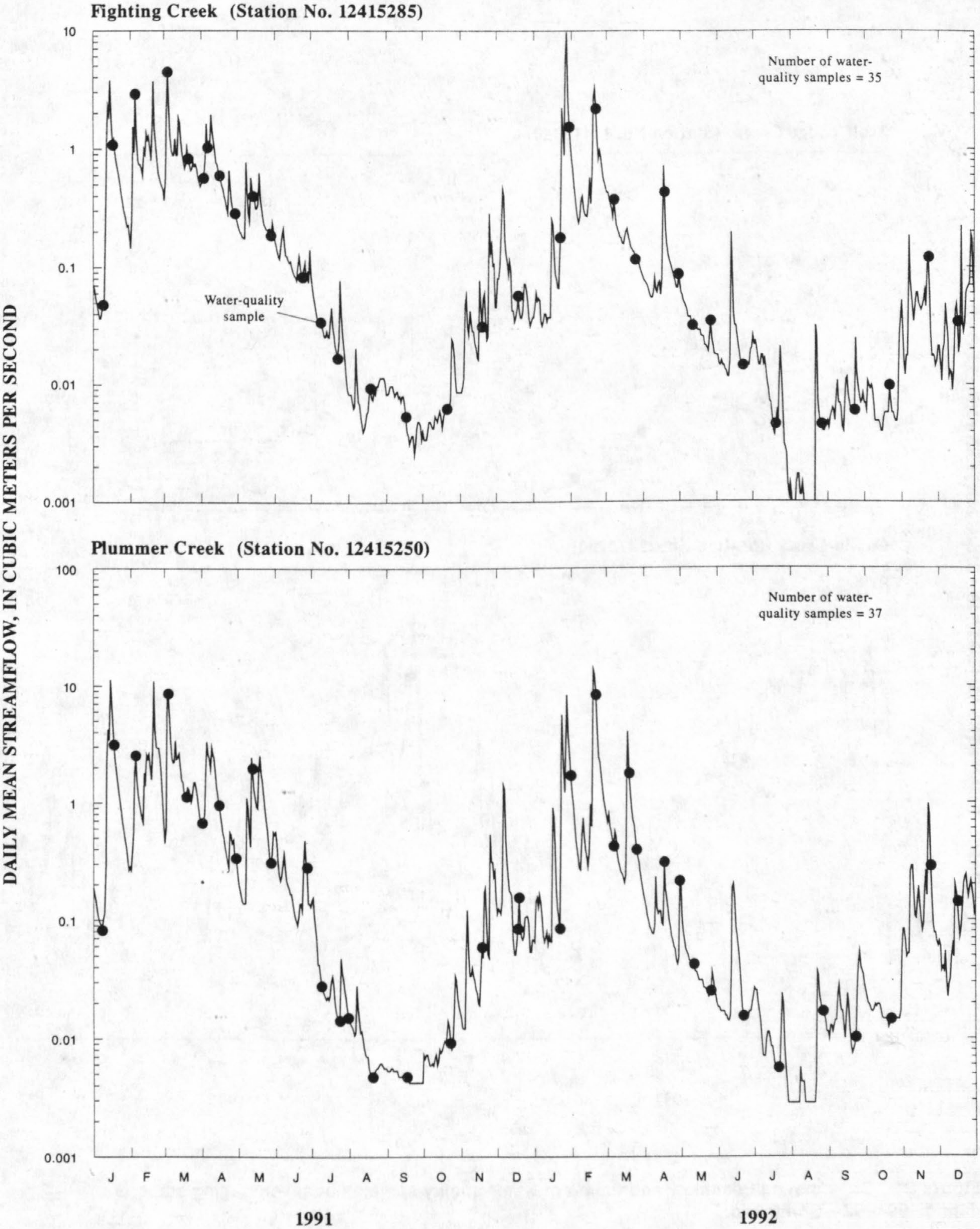


Figure 21. Daily mean streamflow and timing of water-quality samples at seven gaging stations during 1991–92—Continued.

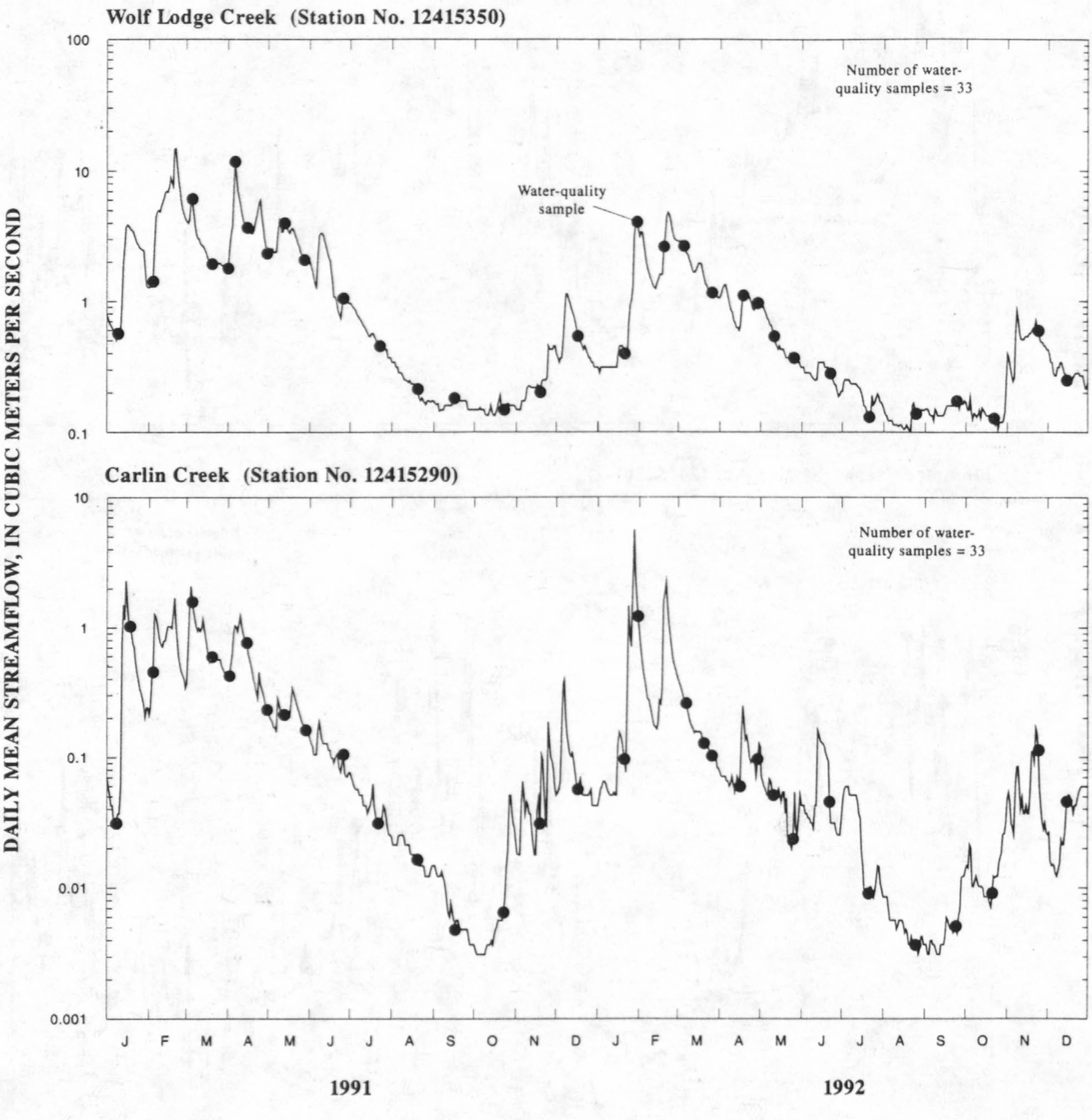


Figure 21. Daily mean streamflow and timing of water-quality samples at seven gaging stations during 1991–92—Continued.

Table 31. Long-term mean annual streamflow in relation to streamflow during 1991 and 1992 measured at three gaging stations near Coeur d'Alene Lake

[m^3/s, cubic meters per second; period of record in water years]

Gaging station name (fig. 4)	Gaging station No.	Mean annual streamflow (m^3/s)		Streamflow (m^3/s)		Percent of long-term mean	
		Long-term	Period of record	1991	1992	1991	1992
St. Joe River at Calder	12414500	66.4	1911–92	85.6	40.2	129	60.5
Coeur d'Alene River at Cataldo............	12413500	71.6	1911–92	92.9	40.1	130	56.0
Spokane River near Post Falls......	12419000	175	1912–92	227	97.8	130	55.9

Table 32. Unit runoff coefficients for surface-water inflow to Coeur d'Alene Lake, 1991–92

[km^2, square kilometer; hm^3/km^2, cubic hectometer per square kilometer; SA, study area; USGS, U.S. Geological Survey]

Subbasin No. (fig. 3)	Subbasin name (table 4)	Drainage area (km^2)	Unit runoff (hm^3/km^2) 1991	Unit runoff (hm^3/km^2) 1992
L1	City of Coeur d'Alene	[1]34.9	0.55	0.21
L2	Fernan Creek	49.5	.55	.21
L3	Bennett Bay, nearshore	18.9	.13	.07
L4	Blue Creek	20.5	.27	.14
L5	Wolf Lodge Creek	104	.55	.21
L6	Wolf Lodge Bay, nearshore, northeast	5.4	.13	.07
L7	Cedar Creek	62.5	.55	.21
L8	Wolf Lodge Bay, nearshore, southeast	1.7	.13	.07
L9	Beauty Creek	28.9	.27	.14
L10	Squaw Bay to Echo Bay, nearshore	34.2	.27	.14
L11	Turner Creek	16.5	.27	.14
L12	Carlin Bay, nearshore	7.2	.14	.07
L13	Carlin Creek	31.7	.27	.14
L14	Powderhorn Bay, nearshore	44.3	.27	.14
L15	Harrison to St. Maries, nearshore	54.9	.19	.10
L16	Chatcolet Lake, nearshore, south	34.3	.10	.05
L17	Benewah Creek	138	.17	.10
L18	Plummer Creek	114	.19	.10
L19	Windy Bay to Chatcolet Lake, nearshore	79.9	.19	.10
L20	Lake Creek	99.5	.25	.13
L21	Windy Bay, nearshore, north	14.1	.13	.06
L22	Fighting Creek	41.6	.25	.13
L23	Rockford Bay to Mica Bay, nearshore	41.9	.12	.06
L24	Mica Creek	67.7	.25	.13
L25	Mica Bay to Cougar Bay, nearshore	29.6	.25	.13
L26	Cougar Creek	48.5	.25	.13
L27	Cougar Bay, nearshore, northwest	2	.15	.06
R1	Spokane River, lake outlet to USGS gaging station near State line	624	.27	.14
C1–C7	Coeur d'Alene River upstream from Harrison	3,812	.68	.34
S1–S5	St. Joe River upstream from St. Maries	4,520	.74	.37
SA	Spokane River upstream from USGS gaging station	10,313	.61	.30

[1] Drainage area of 37.1 km^2 (table 4) reduced to 34.9 km^2 by subtraction of 2.2 km^2 area serviced by stormwater drainage system.

Table 33. Hydrologic budget and errors associated with each budget component, Coeur d'Alene Lake, 1991

[Volumes and errors are in cubic hectometers]

Budget component	Inflow or outflow		Error
	Volume	Percent of total	
Inflow			
St. Joe River	3,350	52.4	502
Coeur d'Alene River	2,610	40.8	391
Plummer Creek	22	.3	1.6
Fighting Creek	10.5	.2	.8
Carlin Creek	8.5	.2	.6
Wolf Lodge Creek	57	.9	4.3
Ungaged surface-water inflow	260	4.1	68
Wastewater	6.2	.1	1.5
Precipitation	64.6	1.0	9.7
Outflow			
Evaporation	98.3	1.5	24.6
Ground-water outflow to Rathdrum Prairie	205	3.1	51.2
Lake storage change	33.6	.06	2.5
Spokane River	6,270	94.8	470
Summary			
Total inflow	6,390		
Total outflow	6,610		
Residual (outflow - inflow)	220		
Overall error	796		

Table 34. Hydrologic budget and errors associated with each budget component, Coeur d'Alene Lake, 1992

[Volumes and errors are in cubic hectometers]

Budget component	Inflow or outflow: Volume	Inflow or outflow: Percent of total	Error
	Inflow		
St. Joe River	1,660	52.0	300
Coeur d'Alene River	1,280	40.1	200
Plummer Creek	11.4	.4	.9
Fighting Creek	5.5	.2	.4
Carlin Creek	4.5	.1	.3
Wolf Lodge Creek	21.9	.7	1.6
Ungaged surface-water inflow	125	3.9	34
Wastewater	5.5	.2	1.4
Precipitation	75	2.4	11
	Outflow		
Evaporation	98.3	2.8	24.6
Ground-water outflow to Rathdrum Prairie	205	5.8	51.2
Lake storage change	54.3	1.6	4.1
Spokane River	3,140	89.8	236
	Summary		
Total inflow	3,190		
Total outflow	3,500		
Residual (outflow - inflow)	310		
Overall error	436		

Annual loads of nutrients at the seven gaging stations were computed with methods presented by Walker (1987). Walker developed a computer program (FLUX) that stratifies streamflow and nutrient concentration data to reduce error. The stratified data sets then are used to compute load with five equations: direct load averaging, flow-weighted concentration, modified flow-weighted concentration, first-order regression, and second-order regression. The equation and stratification method that yields the smallest coefficient of variation is considered the best estimate of load. The program provides several diagnostic tools for assessing the results; these include plots of residuals and hypothesis tests for the various model parameters.

Annual loads of nutrients from ungaged surface-water inflows were computed with the following equation:

$$L = (A)\,(N)\,, \qquad (12)$$

where

L is annual nutrient load, in kilograms;
A is drainage basin area, in square kilometers; and
N is nutrient export coefficient, in kilograms per square kilometer.

The nutrient export coefficients were computed for the gaged inflows from Plummer, Fighting, Carlin, and Wolf Lodge Creeks. A coefficient is computed by dividing the annual nutrient load, in kilograms, by the drainage basin area, in square kilometers. The application of a specific nutrient export coefficient to an ungaged inflow was based on similarities in hydrology and land use/land cover characteristics.

Annual loads of nutrients from atmospheric sources were estimated with data presented by Stanford and others (1983), Hallock and Falter (1987), and National Atmospheric Deposition Program (1991). The annual areal deposition rates, in kilograms per square kilometer, were multiplied by lake surface area, in square kilometers, to determine the annual load to the lake.

Annual loads of nutrients from municipal wastewater-treatment plants were computed by multiplying their annual effluent volume, in cubic hectometers, by the mean nutrient concentration of their effluent, in micrograms per liter. Private and community wastewater-treatment systems in the nearshore area of the lake also contribute nutrient loads to the lake. Their annual effluent volumes, in cubic meters, computed for the hydrologic budgets, were multiplied by nutrient concentrations, in milligrams per liter, to compute annual loads. The nutrient concentrations in septic-tank effluents were estimated as 15 mg/L for total phosphorus and 38 mg/L for total nitrogen (Canter and Knox, 1985). Nutrients leached from septic tanks are partially retained by soil; therefore, the nutrient loads were adjusted by applying a soil retention coefficient: 0.9 for total phosphorus and 0.5 for total nitrogen (Soltero and others, 1993).

The annual loads of nutrients leaving Coeur d'Alene Lake in ground-water outflow to the Rathdrum Prairie aquifer were computed by multiplying the outflow volume, in cubic hectometers, by the mean nutrient concentration, in micrograms per liter, in the hypolimnion of the northern end of Coeur d'Alene Lake. Similarly, the mean annual concentration of nutrients, in micrograms per liter, in the epilimnion of the northern end of the lake was multiplied by the annual change in lake volume, in cubic hectometers, to compute the annual nutrient load associated with this budget component.

The residual for each nutrient budget was computed as the difference between the nutrient load discharged from the outflow station, Spokane River, and the algebraic sum of nutrient loads (inflow and outflow) upstream from the outflow station. The residual contains the errors associated with measured and unmeasured budget components. Residuals of these nutrient budgets cannot be used to assess the adequacy of the load computations because nutrients in Coeur d'Alene Lake are not conservative and are affected by physical, chemical, and biological processes.

Errors associated with each component of the nutrient budgets were computed using errors in the hydrologic budgets and errors in the collection and analysis of nutrient concentration data. Assignment of percent error to each concentration in the nutrient budget was as follows: gaged inflows and outflow, ground-water outflow, and lake storage change, 15 percent; and ungaged inflow, wastewater, and precipitation, 30 percent. Total error for each nutrient budget component was computed with the following equation (Brown, 1987):

$$E = \sqrt{[(E_c)^2 (Q)^2] + [(E_q)^2 (C)^2]}, \quad (13)$$

where

E is total standard error associated with a nutrient budget component, in kilograms;
E_c is standard error associated with a nutrient concentration, in micrograms per liter;
Q is quantity of water, in cubic hectometers;
E_q is standard error associated with quantity of water, in cubic hectometers; and
C is nutrient concentration, in micrograms per liter.

Overall error for each nutrient budget was computed with the following equation (Brown, 1987):

$$OE = \sqrt{(E_1)^2 + (E_2)^2 + \ldots + (E_n)^2}, \quad (14)$$

where

OE is overall standard error associated with nutrient budget, in kilograms; and
E_n is total standard error associated with each budget component.

Nutrient Budgets, 1991 and 1992

Total phosphorus contributed by the St. Joe River during 1991 accounted for 54.3 percent of the total phosphorus load to Coeur d'Alene Lake (table 35). The next largest loads, 16.6 and 15.0 percent, were contributed by the Coeur d'Alene River and wastewater, respectively. Of the 19,900 kg of total phosphorus contributed by wastewater, 17,910 kg, or 90 percent, was from the municipal wastewater-treatment plants at Coeur d'Alene and Post Falls, both of which are downstream from Coeur d'Alene Lake. Total phosphorus in outflow of the Spokane River, at 88.1 percent, dominated other outflow sources. The total inflow of total phosphorus was 133,000 kg, whereas the total outflow was 54,000 kg; thus, the lake acted as a trap for total phosphorus. The residual of 79,000 kg was larger than the overall error of 13,900 kg. The overall error was 10.4 percent of the total inflow.

During 1992, total phosphorus contributed by the St. Joe River again dominated, but to a lesser degree than during 1991 (table 36). Total phosphorus contributed by wastewater was the second-largest budget component at 24.4 percent. Total phosphorus from the Coeur d'Alene and Post Falls wastewater-treatment plants accounted for about 85 percent of the 13,400 kg from wastewater. The Coeur d'Alene River was the third-largest contributor of total phosphorus at 18.1 percent. The total inflow and outflow of total phosphorus in 1992 were substantially less than in 1991, reflecting the significant reduction in 1992 hydrologic loads. The lake again acted as a trap for total phosphorus because the total outflow was less than the total inflow by 16,000 kg. The overall error of 5,660 kg was contained within the residual and was 10.3 percent of the total inflow.

During 1991, 81.2 percent of the total nitrogen load was contributed by the St. Joe and Coeur d'Alene Rivers (table 35). Ungaged surface-water inflow was the next-largest contributor at 6.7 percent. Wastewater contributed 5.6 percent of the total nitrogen load; however, 117,000 kg, or 92 percent, of the total nitrogen from wastewater was input downstream from the lake. The total inflow of nitrogen in 1991 was 2,270,000 kg, whereas the total out-

Table 35. Nutrient budgets and errors for total phosphorus and total nitrogen, Coeur d'Alene Lake, 1991

[Loads and errors are in kilograms]

Budget component	Total phosphorus			Total nitrogen		
	Load	Percent of total	Error	Load	Percent of total	Error
Inflow						
St. Joe River	72,100	54.3	11,000	1,040,000	45.9	155,000
Coeur d'Alene River	22,000	16.6	3,120	801,000	35.3	121,000
Plummer Creek	2,060	1.6	180	38,000	1.7	3,460
Fighting Creek	610	.5	60	12,500	.6	1,190
Carlin Creek	205	.1	20	2,820	.1	330
Wolf Lodge Creek	590	.4	40	18,600	.8	1,320
Ungaged surface-water inflow	8,750	6.6	2,040	153,000	6.7	40,100
Wastewater	19,900	15.0	6,400	127,000	5.6	42,400
Precipitation	6,460	4.9	1,000	75,000	3.3	11,500
Outflow						
Ground-water outflow to Rathdrum Prairie	5,940	11.1	1,530	122,000	5.8	30,600
Lake storage change	410	.8	30	8,140	.4	720
Spokane River	47,600	88.1	3,760	2,020,000	93.8	150,000

Summary

Total phosphorus	Total nitrogen
Total inflow = 133,000	Total inflow = 2,270,000
Total outflow = 54,000	Total outflow = 2,150,000
Residual (outflow-inflow) = -79,000	Residual (outflow-inflow) = -120,000
Overall error = 13,900	Overall error = 256,000

Table 36. Nutrient budgets and errors for total phosphorus and total nitrogen, Coeur d'Alene Lake, 1992

[Loads and errors are in kilograms]

Budget component	Total phosphorus Load	Total phosphorus Percent of total	Total phosphorus Error	Total nitrogen Load	Total nitrogen Percent of total	Total nitrogen Error
Inflow						
St. Joe River	18,300	33.3	3,300	418,000	41.0	75,000
Coeur d'Alene River	9,980	18.1	1,600	314,000	30.8	49,000
Plummer Creek	1,130	2.1	100	21,900	2.1	1,920
Fighting Creek	410	.8	70	8,210	.8	1,490
Carlin Creek	106	.2	20	1,480	.2	330
Wolf Lodge Creek	217	.4	20	6,860	.7	620
Ungaged surface-water inflow	4,990	9.1	1,360	89,200	8.7	24,100
Wastewater	13,400	24.4	2,400	85,100	8.3	14,200
Precipitation	6,460	11.6	1,100	75,000	7.4	11,000
Outflow						
Ground-water outflow to Rathdrum Prairie	7,590	19.4	2,040	153,000	16.4	38,200
Lake storage change	200	.6	40	11,700	1.2	880
Spokane River	31,300	80.0	2,360	770,000	82.4	57,800

Summary

Total phosphorus

Total inflow = 55,000
Total outflow = 39,000
Residual (outflow-inflow) = -16,000
Overall error = 5,660

Total nitrogen

Total inflow = 1,020,000
Total outflow = 935,000
Residual (outflow-inflow) = -85,000
Overall error = 117,000

Table 37. Nutrient loads measured at three gaging stations near Coeur d'Alene Lake, 1991–92

[kg, kilograms; TP, total phosphorus; TOP, total orthophosphorus; TN, total nitrogen; TIN, total inorganic nitrogen]

Gaging station name and No. (fig. 4)	Year measured	Load (kg) TP	Load (kg) TOP	Percent TOP of TP	Load (kg) TN	Load (kg) TIN	Percent TIN of TN
St. Joe River at	1991	72,100	14,200	19.7	1,040,000	163,000	15.7
St. Maries (12415075)	1992	18,300	7,240	39.6	418,000	71,800	17.2
Coeur d'Alene River near	1991	22,000	10,100	45.9	801,000	170,000	21.2
Harrison (12413860)	1992	9,980	3,910	39.2	314,000	74,000	23.6
Spokane River near	1991	47,600	14,000	29.4	2,020,000	391,000	19.4
Post Falls (12419000)	1992	31,300	11,000	35.1	770,000	184,000	23.9

flow was 2,150,000 kg. The residual of 120,000 kg was about 50 percent of the overall error of 256,000 kg. The overall error was 11.3 percent of the total inflow of nitrogen.

During 1992, 71.8 percent of the total nitrogen load was contributed by the St. Joe and Coeur d'Alene Rivers (table 36). Wastewater contributed 85,100 kg of the total nitrogen load; 87.8 percent was input downstream from the lake. The total inflow of nitrogen in 1992 was 1,020,000 kg; total outflow was 935,000 kg. The residual of 85,000 kg was smaller than the overall error. The overall error was 11.5 percent of the total inflow of nitrogen. On the basis of residuals and overall errors for 1991 and 1992, the total inflow and outflow of nitrogen for each year were about equal.

The nutrient budgets in tables 35 and 36 account for inflow and outflow loads of total phosphorus and total nitrogen during 1991 and 1992. Nutrient loads also were computed for total orthophosphorus and total inorganic nitrogen (sum of ammonia and nitrite plus nitrate) measured at the three major surface-water gaging stations (table 37). The percentage contributions of total inorganic nitrogen to total nitrogen were similar between 1991 and 1992 and among the three stations; on the average, total inorganic nitrogen composed about 20 percent of total nitrogen. By subtraction, about 80 percent of the total nitrogen was composed of organic nitrogen. The relation of total orthophosphorus to total phosphorus was more variable but, on the average, total orthophosphorus was about 35 percent of total phosphorus.

The nutrient budgets quantify the absolute and relative magnitudes of load sources. For 1991 and 1992, loads of total phosphorus and total nitrogen were predominantly from the St. Joe and Coeur d'Alene Rivers because they drain the largest and highest elevation areas in the study area. The combined inflows from gaged and ungaged drainage basins, other than inflows measured at the St. Joe and Coeur d'Alene gaging stations, contributed less than 13 percent of the total phosphorus and total nitrogen loads. However, these smaller basins may be important determinants of nearshore water quality.

The nutrient load characteristics of these small basins may be assessed with nutrient export coefficients (table 38). During 1991, nutrient export coefficients for total phosphorus ranged from 2.4 to 18 kg/km^2. During 1992, the coefficients ranged from 0.7 to 9.9 kg/km^2. The coefficient for total nitrogen ranged from 33 to 333 kg/km^2 in 1991 and from 16.3 to 197 kg/km^2 in 1992. The smaller values for 1992 reflect the substantial reduction in the 1992 hydrologic budget. The largest coefficients were for Plummer, Lake, and Fighting Creeks and the drainage area from Mica Bay to Cougar Bay. Agriculture is the major land use in about 40 percent of the area drained by these four small basins (Idaho Department of Water Resources, 1993). Plummer Creek, with the highest nutrient export coefficients, also receives point source loads from the Plummer wastewater-treatment plant and a forest-products plant in the city of Plummer.

Nutrient loads from wastewater-treatment plants were evaluated in detail to determine whether particular plants were significant contributors to the overall load from wastewater. The evaluation did not include the municipal wastewater-treatment plants at Coeur d'Alene or Post Falls because neither discharges to Coeur d'Alene Lake. The municipal wastewater-treatment plant at Page, on the South Fork Coeur d'Alene River, was the primary contributor of total phosphorus and nitrogen (table 39). During 1991, the 5,400 kg of total phosphorus discharged by the Page plant represented 25 percent of the annual load of total phosphorus for the Coeur d'Alene River at its mouth; in 1992, a year of low streamflow, the contribution was 54 percent. The municipal wastewater-treatment plant for St. Maries, near the mouth of the St. Joe River, contributed 17.1 percent of the total phosphorus and 6.6 percent of the total nitrogen from wastewater sources. The next-largest contributor was wastewater-producing sources in the lake's nearshore area. The remaining wastewater sources each contributed less than 5 percent of the load for each nutrient.

The only other nutrient load study of Coeur d'Alene Lake was done in 1975 as part of the National Eutrophication Survey (U.S. Environmental Protection Agency, 1977). Nutrient loads for 1975 were calculated using average streamflow conditions and nutrient concentrations from periodically collected samples. For comparison, the

Table 38. Annual nutrient export coefficients for surface-water inflow to and outflow from Coeur d'Alene Lake, 1991–92

[kg/km², kilograms per square kilometer; TP, total phosphorus; TN, total nitrogen; L, lake; C, Coeur d'Alene River; S, St. Joe River; R, Spokane River; USGS, U.S. Geological Survey; SA, study area; E, estimated value; M, measured value]

Subbasin No. (fig. 3)	Subbasin name (table 4)	Status	Annual nutrient export coefficient (kg/km²) TP 1991	TP 1992	TN 1991	TN 1992
L1	City of Coeur d'Alene	E	5.7	2.1	180	65.8
L2	Fernan Creek	E	5.7	2.1	180	65.8
L3	Bennett Bay, nearshore	E	3.2	1.6	43.9	22.6
L4	Blue Creek	E	6.5	3.3	89.3	46.5
L5	Wolf Lodge Creek	M	5.7	2.1	180	65.8
L6	Wolf Lodge Bay, nearshore, northeast	E	3.1	.7	42.4	23.2
L7	Cedar Creek	E	5.7	2.1	180	65.8
L8	Wolf Lodge Bay, nearshore, southeast	E	2.9	1.2	38.8	19.4
L9	Beauty Creek	E	6.5	3.3	89.3	46.5
L10	Squaw Bay to Echo Bay, nearshore	E	6.5	3.3	89.3	46.5
L11	Turner Creek	E	6.5	3.3	89.3	46.5
L12	Carlin Bay, nearshore	E	3.2	1.6	46.1	22.6
L13	Carlin Creek	M	6.5	3.3	89.3	46.5
L14	Powderhorn Bay, nearshore	E	6.5	3.3	89.3	46.5
L15	Harrison to St. Maries, nearshore	E	9.0	5.0	164	96.5
L16	Chatcolet Lake, nearshore, south	E	2.4	1.2	33	16.3
L17	Benewah Creek	E	8.0	5.0	147	96.5
L18	Plummer Creek	M	18	9.9	333	192
L19	Windy Bay to Chatcolet Lake, nearshore	E	9.0	5.0	164	96.5
L20	Lake Creek	E	14	9.4	298	187
L21	Windy Bay, nearshore, north	E	7.4	5.0	152	96.5
L22	Fighting Creek	M	14	9.8	298	197
L23	Rockford Bay to Mica Bay, nearshore	E	3.5	2.4	71	47.6
L24	Mica Creek	E	6.0	3.0	83	41.3
L25	Mica Bay to Cougar Bay, nearshore	E	14	9.5	298	190
L26	Cougar Creek	E	7.4	4.7	152	94.3
L27	Cougar Bay, nearshore, northwest	E	4.5	2.4	89	48.5
C1–C7	Coeur d'Alene River, upstream from Harrison	M	5.8	2.6	210	82.4
S1–S5	St. Joe River, upstream from St. Maries	M	16	4.1	230	92.5
R1	Spokane River, lake outlet to USGS gaging station near State line	E	6.5	3.3	89	46.5
SA	Spokane River, upstream from USGS gaging station	M	4.6	3.0	196	74.7

Table 39. Annual loads of total phosphorus and total nitrogen to Coeur d'Alene Lake from nearshore and municipal wastewater-treatment systems, 1991–92

[kg, kilograms; TP, total phosphorus; TN, total nitrogen; WWTP, wastewater-treatment plants]

Load source (fig. 1)	Annual load for 1991 and 1992 (kg)		Percent contribution to annual load for 1991 and 1992 (kg)	
	TP	TN	TP	TN
Nearshore[1]	390	4,900	4.7	8.7
Municipal WWTP				
Clarkia	20	315	.3	.6
Santa/Fernwood	60	320	.7	.6
St. Maries	1,400	3,720	17.1	6.6
Plummer	290	1,560	3.5	2.8
Mullan	310	2,550	3.8	4.6
Smelterville	225	1,550	2.7	2.8
Page	5,400	40,500	65.7	72.5
Harrison	120	450	1.5	.8
TOTAL	8,220	55,900	100.0	100.0

[1]Sum of private, community, and commercial wastewater-treatment systems within 150 meters of lake shoreline.

Table 40. Loads of total phosphorus and total nitrogen to Coeur d'Alene Lake, 1975 and 1991

[kg, kilograms; TP, total phosphorus; TN, total nitrogen]

Load source	1975 loads[1] (kg)		1991 loads[2] (kg)	
	TP	TN	TP	TN
Coeur d'Alene River	98,100	1,490,000	11,000	572,000
St. Joe River	56,300	1,480,000	54,000	794,000
Other[3]	25,600	430,000	25,000	234,000
TOTAL	180,000	3,400,000	90,000	1,600,000

[1]From U.S. Environmental Protection Agency (1977); loads based on long-term annual mean discharge.

[2]Measured 1991 loads reduced by 30 percent to estimate loads at long-term annual mean discharge.

[3]Includes minor tributaries, nearshore septic tanks, direct precipitation to lake surface, and wastewater-treatment plants.

1991 loads were recomputed using average streamflow conditions; the results are listed in table 37. The 1975 input of total phosphorus to the lake was 180,000 kg; 98,100 kg, or 54.5 percent, was contributed by the Coeur d'Alene River, and 56,300 kg, or 31.3 percent, was contributed by the St. Joe River. For 1991, the input of total phosphorus was 90,000 kg; 11,000 kg, or 12.2 percent, was contributed by the Coeur d'Alene River, and 54,000 kg, or 60 percent, was contributed by the St. Joe River. In 1975, more than 87 percent of the 3,400,000 kg of total nitrogen input to the lake was contributed almost equally by the Coeur d'Alene and St. Joe Rivers. In 1991, 1,600,000 kg of total nitrogen was input to the lake; 572,000 kg, or 35.8 percent, was contributed by the Coeur d'Alene River, and 794,000 kg, or 49.6 percent, was contributed by the St. Joe River. The 1991 loads of total phosphorus and nitrogen to the lake were about one-half of the 1975 loads (table 40). Additionally, the Coeur d'Alene River was the predominant contributor of total phosphorus in 1975 but, in 1991, the St. Joe River was the predominant contributor. The St. Joe River was also the predominant contributor of total nitrogen in 1991, whereas the St. Joe and Coeur d'Alene Rivers contributed nearly equal amounts in 1975.

Nutrient load data for 1975 and 1991 permitted calculation of nutrient export coefficients for several tributaries sampled during both studies. Annual nutrient export coefficients for total phosphorus and nitrogen (table 41) indicate several significant changes between 1975 and 1991. Total phosphorus and nitrogen export coefficients for the Coeur d'Alene River declined substantially. The total nitrogen export coefficient for the St. Joe River also declined substantially, but the total phosphorus coefficient showed almost no change. The nutrient export coefficients for Wolf Lodge Creek were comparable for both years. The nutrient export coefficients for Plummer Creek increased substantially.

TRACE-ELEMENT BUDGETS

Data Collection and Analysis

Trace-element budgets for Coeur d'Alene Lake were determined for calendar years 1991 and 1992. The budgets accounted for the mass of selected trace elements entering the lake from the St. Joe and Coeur d'Alene Rivers and leaving the lake in the Spokane River.

Trace-element data for the two gaged inflows and the outflow were collected concurrently with nutrient data. The samples were analyzed for total arsenic and total recoverable cadmium, copper, lead, and zinc using methods described by Fishman and Friedman (1985). The annual loads at each station were computed with the same methods used for computation of nutrient loads.

Trace-Element Budgets, 1991 and 1992

Correspondent with annual loads of nutrients, the annual loads of trace elements were substantially larger in 1991 than in 1992 (table 42). The Coeur d'Alene River contributed larger loads of arsenic, cadmium, lead, and zinc than did the St. Joe River. Loads of copper were similar for the two rivers. The zinc loads were by far the largest; the Coeur d'Alene River contributed 847,000 kg in 1991. Lead loads were the next largest; the Coeur d'Alene River contributed 273,000 kg in 1991. The sum of loads for the St. Joe and Coeur d'Alene Rivers was compared to the outflow load from the Spokane River. Except for copper, the outflow loads were substantially less than the sum of inflow loads. The lake, therefore, acted as a trap for arsenic, cadmium, lead, and zinc during 1991 and 1992.

On the basis of annual loads, the Coeur d'Alene River was the major contributor of arsenic, cadmium, lead, and zinc to Coeur d'Alene Lake. The loads were normalized by dividing the load, in kilograms, by the drainage area, in square kilometers, to derive a trace-element export coefficient. The trace-element export coefficients for the St. Joe and Coeur d'Alene Rivers reveal large differences (table 43), especially for lead and zinc export. The

Table 41. Annual nutrient export coefficients for four tributaries to Coeur d'Alene Lake, 1975 and 1991

[kg/km², kilograms per square kilometer]

Load source (fig. 4)	Annual nutrient export coefficient (kg/km²)			
	Total phosphorus		Total nitrogen	
	1975[1]	1991[2]	1975[1]	1991[2]
Coeur d'Alene River......	26	4.5	389	162
St. Joe River..................	13	12.3	331	177
Wolf Lodge Creek..........	5	4.3	162	138
Plummer Creek.............	4	13.2	109	257

[1]From U.S. Environmental Protection Agency (1977); loads based on long-term annual mean discharge.

[2]Loads reduced by 30 percent to estimate loads at long-term annual mean discharge.

Table 42. Trace-element loads measured at three gaging stations near Coeur d'Alene Lake, 1991–92

[kg, kilograms; locations shown in fig. 4]

Trace element	Loads (kg)							
	St. Joe River at St. Maries		Coeur d'Alene River near Harrison		Sum of St. Joe and Coeur d'Alene Rivers		Spokane River near Post Falls	
	1991	1992	1991	1992	1991	1992	1991	1992
Arsenic........................	3,370	1,670	6,400	2,990	9,770	4,660	6,280	3,140
Cadmium.....................	4,850	1,870	8,100	3,900	12,950	5,770	6,280	3,140
Copper.........................	19,900	9,780	20,400	9,480	40,300	19,300	40,400	17,800
Lead	26,600	10,000	273,000	57,700	300,000	67,700	45,300	20,200
Zinc	82,400	43,500	847,000	409,000	929,000	452,000	639,000	305,000

Table 43. Annual trace-element export coefficients for two gaging stations near Coeur d'Alene Lake, 1991–92

[All values in kilograms per square kilometer; locations shown in fig. 4]

Trace element	St. Joe River at St. Maries		Coeur d'Alene River near Harrison	
	1991	1992	1991	1992
Arsenic	0.75	0.37	1.7	0.78
Cadmium.......................	1.1	.41	2.1	1.0
Copper...........................	4.4	2.2	5.4	2.5
Lead	5.9	2.2	72	15
Zinc	18	9.6	222	107

export of arsenic and cadmium for the Coeur d'Alene River was about twice as large as that for the St. Joe River; copper export was about equal for the two rivers.

NUTRIENT LOAD/LAKE RESPONSE MODEL

Model Description

A nutrient load/lake response model was used to provide a mathematical method for simulating Coeur d'Alene Lake's limnological responses to alterations in water and nutrient loads delivered to the lake from numerous sources. The empirical mathematical model simulated the following eutrophication-related variables: concentrations of total phosphorus, total nitrogen, and chlorophyll-*a*; secchi-disc transparency; and hypolimnetic dissolved-oxygen deficit.

The model was developed for the U.S. Army Corps of Engineers Waterways Experiment Station as part of its Environmental and Water Quality Operational Studies Program. The model was developed because most empirical lake-eutrophication models are inadequate to simulate eutrophication in reservoirs. Walker (1981, 1982, 1985, 1987) thoroughly described the model's conceptual basis, development history, and application procedures.

The model empirically relates eutrophication characteristics to tributary nutrient loads, tributary and lake hydrology, and lake morphometry. Three programs, FLUX, PROFILE, and BATHTUB, compose the model. The FLUX program quantifies tributary loads of water and nutrients using a variety of calculation methods. The PROFILE program generates statistical summaries of water-quality conditions in the water body within a temporal and spatial context. The BATHTUB program applies nutrient-balance models and eutrophication-response models within a spatially segmented hydraulic framework that accounts for advection, diffusion, and sedimentation.

The BATHTUB program is a highly evolved version of empirical lake-eutrophication models, and incorporates additional variables to account for the important differences between lakes and reservoirs. Some of BATHTUB's enhancements include nonlinear nutrient-sedimentation kinetics, inflow nutrient partitioning, seasonal and spatial variations, and algal growth limitation by factors such as phosphorus, nitrogen, light, and flushing rate. If error estimates are provided for input variables, BATHTUB can express output variables in probabilistic terms.

An important feature of the BATHTUB program is the provision for modeling linked segments of the lake to account for important spatial variations in water quality. Segment boundaries can be selected on the basis of factors such as lake morphometry, important sources of water and nutrients, observed spatial variations in water quality, and lake hydrodynamics.

Model Application

Coeur d'Alene Lake and the Spokane River outlet arm were divided into seven segments (fig. 22). Segment 1 includes the shallow, southern end of the lake south of Conkling Point. The four shallow lakes, Benewah, Chatcolet, Hidden, and Round, are within this segment. The St. Joe River is routed via levees through most of this segment. Breithaupt (1990) reported the St. Joe River had little influence on water quality in Chatcolet Lake. Therefore, the St. Joe River was routed into segment 2, which begins north of Conkling Point and extends to just south of the mouth of the Coeur d'Alene River. This segment is also relatively shallow. Segment 3 extends from the mouth of the Coeur d'Alene River to just south of Carlin Bay. This segment represents the mixing zone for the St. Joe and Coeur d'Alene Rivers because it contains a large volume and includes a turbulence-inducing right-angle turn to the north. Segment 4 contains the deepest area of the lake and extends from Carlin Bay to just south of the lake's large northern basin. Segment 5 includes the eastern end of Wolf Lodge Bay. This segment is somewhat

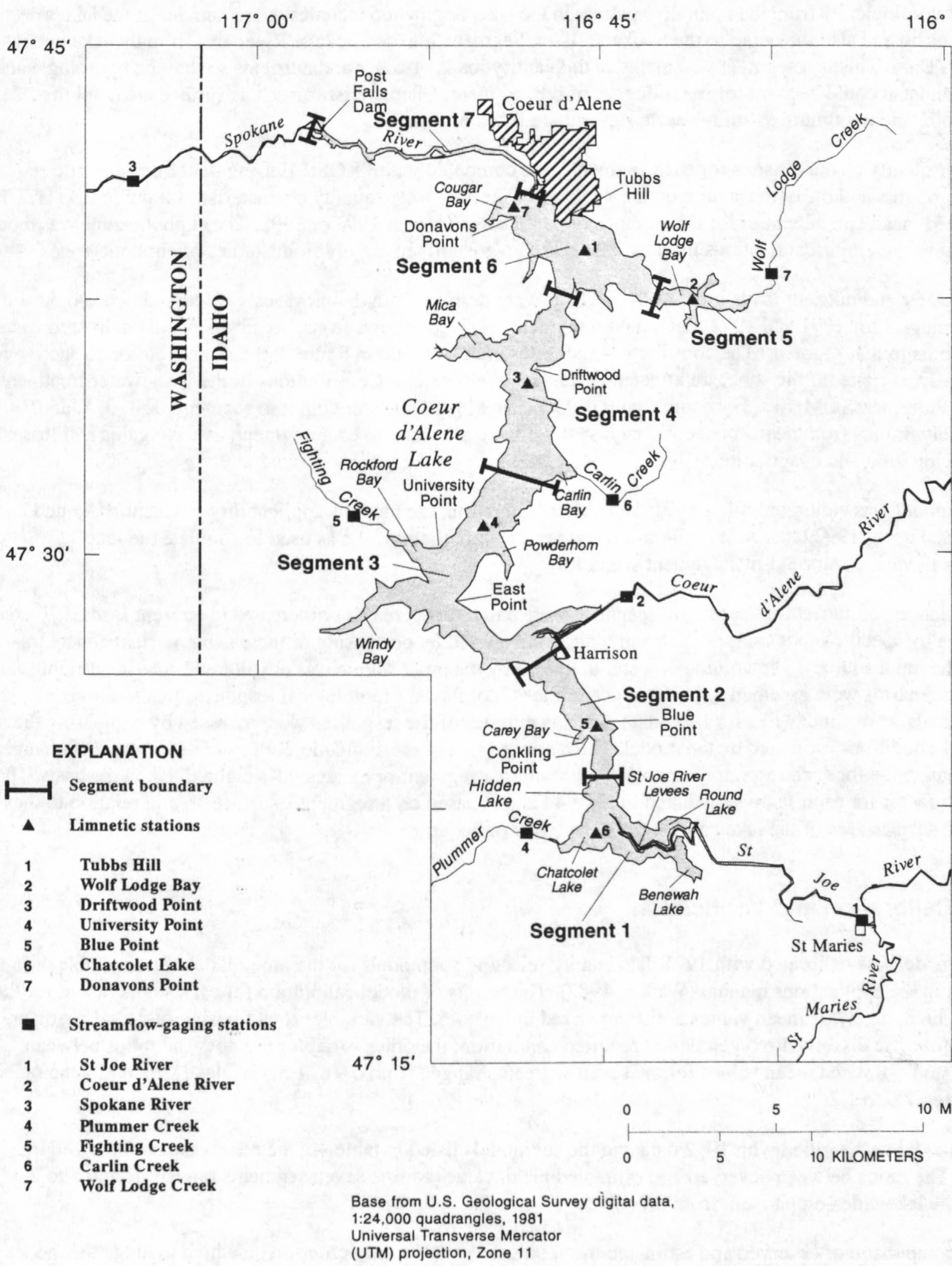


Figure 22. Segmentation of Coeur d'Alene Lake for nutrient load/lake response model.

isolated hydrologically from the main flow pattern in the lake. Segment 6 includes the remainder of the lake's deep, northern basin and also the outlet to the Spokane River. Segment 7 is the Spokane River arm from the lake outlet to Post Falls Dam. This last segment was included to quantify loads of water and nutrients so that the hydrologic and nutrient budgets could account for the influence of this segment. Characteristics such as surface area, volume, mean depth, and maximum depth for each segment are listed in table 44.

Water-quality characteristics for each segment were computed with PROFILE using data from limnetic stations 1 through 6 and the outlet station on the Spokane River. The water-quality characteristics input to BATHTUB represented mean annual values for the euphotic zone for calendar year 1991 or 1992. The euphotic zone was modeled because the empirical relations used by BATHTUB were derived largely from studies of euphotic zones.

The water and nutrient loads input to BATHTUB were derived from the previously discussed hydrologic and nutrient budgets for 1991 and 1992. Each model segment received inflows from the subbasins that delivered water and nutrients to that segment. The contributing subbasins are illustrated in figure 3; their contribution to each segment was apportioned if the subbasin affected more than one segment. Contributions of the wastewater-treatment plants at Plummer, St. Maries, Harrison, Coeur d'Alene, and Post Falls were input to segments 1, 1, 3, 7, and 7, respectively. Inputs from nearshore septic-tank systems were allocated to each segment, as were gains and losses from precipitation and evaporation.

The model was calibrated using 1991 data. After calibration, the model's applicability to Coeur d'Alene Lake was verified using 1992 data. After calibration and verification, the model was used to simulate the lake's responses to various nutrient-management scenarios.

Simulations of nutrient-management scenarios were based on decreases or increases in nutrient loads delivered to the lake by specific input sources. Nutrient loads were altered by decreasing or increasing nutrient concentrations of the input sources. The volume of water delivered by the input source was not altered because nutrient-management scenarios were assumed to affect concentrations, not flows. Limnological responses to alterations in nutrient loads were simulated with 1991 data. The magnitudes of the responses were assessed by comparing them with 1991 conditions estimated by the model. The output format of the simulations allowed assessment of changes in the mean value for each response variable, either within a segment or on an area-weighted, lakewide basis. The weighting factor for each segment is listed in table 44 and is based on a segment's surface area in relation to the combined surface area of the lake and the Spokane River outlet arm.

Model Calibration and Verification

The model was calibrated with 1991 data and by selecting submodels for the nine model options (table 45) discussed in the applications manual (Walker, 1987). The results of model calibration for each segment and for the area-weighted, lakewide mean values are summarized in table 46. The variables total phosphorus, total nitrogen, and hypolimnetic dissolved-oxygen deficit required calibration; the other variables did not. The ratios between observed and estimated mean values for the seven segments ranged from 0.9 to 1.5; on a lakewide basis, the ratios ranged from 1.0 to 1.2.

The model was verified with 1992 data and the submodels listed in table 42; the results are summarized in table 47. The ratios between observed and estimated mean values for the seven segments ranged from 0.5 to 2.4 and, for the lakewide comparison, from 0.7 to 1.5.

The comparison of observed and estimated mean values is not the only criterion on which to judge the model's performance. The model output displays the mean value, plus or minus one standard error, for each observed and estimated value. These statistical estimates are computed on the basis of errors associated with the model, as well as errors associated with each input variable. The presence or absence of overlap in the standard errors for each

Table 44. Characteristics of the seven segments of Coeur d'Alene Lake modeled by BATHTUB

[km^2, square kilometers; km^3, cubic kilometers; m, meters; L, Limnetic; T, Tributary]

Characteristics and units	Segment (fig. 22)						
	1	2	3	4	5	6	7
Surface area, km^2	15.6	11.7	41.5	29.5	4.45	26.2	3.0
Volume, km^3	.03	.12	.95	.97	.06	.71	.01
Mean depth, m	1.9	11.3	23.2	33.4	15.8	27.5	3.2
Maximum depth, m	12	23	45	63.7	30	55	8
Segment weight[1]	.12	.10	.31	.22	.03	.20	.02
Important tributary inflow source	Plummer Creek	St. Joe River	Coeur d'Alene River	None	Wolf Lodge Creek	None	None
Outflow routed to segment number	2	3	4	6	6	7	Outlet
Water-quality sampling station for segment	L 6	L 5	L 4	L 3	L 2	L 1	T 7

[1]Based on surface area of segment divided by surface area of lake and outlet arm.

Table 45. Submodel selection for calibration and verification of nutrient load/lake response model, Coeur d'Alene Lake

Model option	Submodel selected	Submodel description
Conservative substance	0	Do not compute.
Phosphorus sedimentation	1	Second order, available phosphorus.
Nitrogen sedimentation	1	Second order, available nitrogen.
Mean chlorophyll-*a*	4	Phosphorus, linear.
Secchi-disc transparency	1	Secchi-disc transparency versus chlorophyll-*a* and turbidity.
Dispersion	1	Fischer and others (1979); Walker (1985).
Phosphorus calibration	2	Multiply estimated concentrations by calibration factors.
Nitrogen calibration	1	Multiply estimated decay rates by calibration factors.
Error analysis	1	Compute using input data error and model error terms.

Table 46. Results of model calibration with 1991 data, Coeur d'Alene Lake

[TP, total phosphorus, in micrograms per liter; TN, total nitrogen, in micrograms per liter; CHL, chlorophyll-*a*, in micrograms per liter; SD, secchi-disc transparency, in meters; HOD, hypolimnetic dissolved-oxygen deficit, in milligrams per cubic meters per day]

Segment (fig. 22)	Variable	Mean value: Observed	Mean value: Estimated	Ratio of observed to estimated value
1	TP	14.2	9.4	1.5
	TN	365	301	1.2
	CHL	2.4	2.6	.9
	SD	2.7	2.4	1.1
2	TP	8.8	6.4	1.4
	TN	329	247	1.3
	CHL	1.8	1.8	1.0
	SD	3.6	3.3	1.1
3	TP	5.6	5.9	.9
	TN	309	242	1.3
	CHL	1.5	1.7	.9
	SD	4.9	4.3	1.1
4	TP	4.6	4.7	1.0
	TN	292	243	1.2
	CHL	1.2	1.3	.9
	SD	5.4	4.7	1.1
5	TP	4.4	4.3	1.0
	TN	267	240	1.1
	CHL	1.5	1.2	1.2
	SD	5.4	5.0	1.1
6	TP	5.2	5.0	1.0
	TN	289	248	1.2
	CHL	1.5	1.4	1.1
	SD	5.8	5.1	1.1
	HOD	17.7	17.6	1.0
7	TP	5.2	5.5	.9
	TN	289	253	1.1
	CHL	1.5	1.5	1.0
	SD	3.2	3.0	1.1
Lakewide	TP	6.5	5.9	1.1
	TN	308	251	1.2
	CHL	1.6	1.6	1.0
	SD	4.8	4.2	1.1

Table 47. Results of model verification with 1992 data, Coeur d'Alene Lake

[TP, total phosphorus, in micrograms per liter; TN, total nitrogen, in micrograms per liter; CHL, chlorophyll-*a*, in micrograms per liter; SD, secchi-disc transparency, in meters; HOD, hypolimnetic dissolved-oxygen deficit, in milligrams per cubic meters per day]

Segment (fig. 22)	Variable	Mean value Observed	Mean value Estimated	Ratio of observed to estimated value
1	TP	5.2	9.6	0.5
	TN	206	290	.7
	CHL	3.3	2.7	1.2
	SD	3.0	2.7	1.1
2	TP	5.0	5.5	.9
	TN	219	214	1.0
	CHL	2.7	1.5	1.8
	SD	4.9	4.6	1.1
3	TP	4.2	5.0	.8
	TN	220	213	1.0
	CHL	2.1	1.4	1.5
	SD	5.6	5.1	1.1
4	TP	2.9	4.0	.7
	TN	216	215	1.0
	CHL	2.1	1.1	1.9
	SD	6.5	6.0	1.1
5	TP	3.8	3.7	1.0
	TN	212	220	1.0
	CHL	2.4	1.0	2.4
	SD	5.8	5.7	1.0
6	TP	2.4	4.5	.5
	TN	211	222	1.0
	CHL	1.8	1.2	1.5
	SD	6.9	6.2	1.1
	HOD	18.7	16.6	1.1
7	TP	2.4	5.0	.5
	TN	211	228	.9
	CHL	1.8	1.4	1.3
	SD	3.2	3.0	1.1
Lakewide	TP	3.7	5.2	.7
	TN	215	225	1.0
	CHL	2.2	1.5	1.5
	SD	5.6	5.2	1.1

Table 48. Presence or absence of overlap in standard errors for observed and estimated values of five variables for calibration and verification model runs, Coeur d'Alene Lake

[LW, lakewide; Y, overlap present; N, overlap not present; —, not measured]

Variable	Calibration Segment No. (fig. 22) 1	2	3	4	5	6	7	LW	Verification Segment No. (fig. 22) 1	2	3	4	5	6	7	LW
Total phosphorus	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	N	N	Y
Total nitrogen	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y
Chlorophyll-*a*	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y
Secchi-disc transparency	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Hypolimnetic dissolved-oxygen deficit	—	—	—	—	—	Y	—	—	—	—	—	—	—	Y	—	—

Table 49. Simulation 1: Limnological response to doubling phosphorus and nitrogen loads contributed to Coeur d'Alene Lake by the Coeur d'Alene and St. Joe Rivers

[µg/L, micrograms per liter; m, meters; (mg/m³)/d, milligrams per cubic meters per day; —, not measured; LW, area weighted lakewide value]

Segment (fig. 22)	Total phosphorus (µg/L) 1991	Total phosphorus (µg/L) Response	Total nitrogen (µg/L) 1991	Total nitrogen (µg/L) Response	Chlorophyll-*a* (µg/L) 1991	Chlorophyll-*a* (µg/L) Response	Secchi-disc transparency (m) 1991	Secchi-disc transparency (m) Response	Hypolimnetic dissolved-oxygen deficit [(mg/m³)/d] 1991	Hypolimnetic dissolved-oxygen deficit [(mg/m³)/d] Response
1	9.4	12.5	301	467	2.6	3.5	2.4	2.3	—	—
2	6.4	10.1	247	420	1.8	2.8	3.3	3.0	—	—
3	5.9	8.7	242	411	1.7	2.4	4.3	4.0	—	—
4	4.7	6.5	243	403	1.3	1.8	4.7	4.4	—	—
5	4.3	4.9	240	320	1.2	1.4	5.0	4.9	—	—
6	5.0	6.6	248	402	1.4	1.9	5.1	4.8	17.6	20.8
7	5.5	7.0	253	406	1.5	2.0	3.0	2.9	—	—
LW	5.9	8.2	251	412	1.6	2.3	4.2	4.0	—	—

variable and segment is listed in table 48. For the calibration, the standard errors for all variables overlap in each segment and lakewide. For the verification, the standard error for total phosphorus does not overlap in segments 1, 6, and 7. The standard error for nitrogen does not overlap in segment 1 and, for chlorophyll-*a*, does not overlap in segment 5. The standard errors for all variables overlap lakewide.

Simulation Results

A wide variety of simulations was possible owing to the complexity of Coeur d'Alene Lake and its drainage basin, as well as to a diverse assortment of nutrient-reduction responses that could be tested and evaluated. The five simulations reported herein were designed to address two principal questions: (1) Would large increases in nutrient loads cause the lake's hypolimnion to become anoxic, and (2) would the lake's water quality be substantially improved by large reductions in nutrient loads.

The first question required an estimate of the hypolimnetic dissolved-oxygen deficit needed to produce an anoxic hypolimnion. A dissolved-oxygen data set was devised that represented a steady loss of hypolimnetic dissolved oxygen over the duration of summer thermal stratification. The data set was processed by the PROFILE program to yield the hypolimnetic dissolved-oxygen deficit necessary to produce an anoxic hypolimnion. This value, 73 (mg/m^3)/d, applies to the hypolimnion of segment 6 because the BATHTUB program specifies that the hypolimnetic dissolved-oxygen deficit be computed for the water body's deepest part that is nearest the outlet.

Simulations 1 (table 49) and 2 (table 50) assessed the effects of doubling and quadrupling nutrient loads to the lake. The doubled nutrient loads in simulation 1 increased lakewide concentrations of total phosphorus, total nitrogen, and chlorophyll-*a* by 2.3, 161, and 0.7 µg/L, respectively; secchi-disc transparency decreased by 0.2 m. The quadrupled nutrient loads in simulation 2 increased lakewide concentrations of total phosphorus, total nitrogen, and chlorophyll-*a* by 6, 437, and 1.7 µg/L, respectively; secchi-disc transparency decreased by 0.6 m. In simulation 1, the hypolimnetic dissolved-oxygen deficit increased from its simulated 1991 base value of 17.6 to 20.8 (mg/m^3)/d, whereas in simulation 2, the deficit increased to 25.1 (mg/m^3)/d. Both increases in the hypolimnetic dissolved-oxygen deficit produced values well below the 73 (mg/m^3)/d simulated with an anoxic hypolimnion in Coeur d'Alene Lake. On the basis of the results of these two simulations, Coeur d'Alene Lake has a large assimilative capacity for nutrients with respect to development of an anoxic hypolimnion.

Three nutrient-reduction simulations were selected by study cooperators. Simulation 3 assessed nutrient reductions from wastewater-treatment systems. Simulation 4 assessed nutrient reductions in the Coeur d'Alene and St. Joe River Basins because they contributed most of the nutrients to the lake. Simulation 5 assessed nutrient reductions contributed by nearshore subbasins where agricultural land use adjacent to the southern and western margins of the lake is significant.

Simulation 3 (table 51) assessed the complete removal of nutrient loads from nearshore, domestic, and commercial septic-tank systems and the municipal wastewater-treatment plants listed in table 39. A total of 8,220 kg of phosphorus and 55,900 kg of nitrogen was removed from the lake's 1991 nutrient load by this simulation. Nutrient inputs from the municipal wastewater-treatment plants at Coeur d'Alene and Post Falls also were removed but did not affect the lake, only its outlet arm (segment 7). Relative to simulated 1991 base values, simulated phosphorus, nitrogen, and chlorophyll-*a* concentrations in all seven segments declined between 0.5 and 1.9, 13 and 28, and 0.1 and 0.5 µg/L, respectively. Secchi-disc transparency in all segments increased between 0 and 0.3 m. The hypolimnetic dissolved-oxygen deficit in segment 6 declined from 17.6 to 15.8 (mg/m^3)/d. On a lakewide basis, phosphorus, nitrogen, and chlorophyll-*a* concentrations declined 1.2, 18, and 0.3 µg/L, respectively, whereas secchi-disc transparency increased 0.2 m.

Simulation 4 (table 52) assessed a 20-percent reduction in nutrient loads contributed to the lake by the Coeur d'Alene and St. Joe Rivers. The reductions were attributable to large-scale implementation of best-management

Table 50. Simulation 2: Limnological response to quadrupling phosphorus and nitrogen loads contributed to Coeur d'Alene Lake by the Coeur d'Alene and St. Joe Rivers

[µg/L, micrograms per liter; m, meters; (mg/m³)/d, milligrams per cubic meters per day; —, not measured; LW, area weighted lakewide value]

Segment (fig. 22)	Total phosphorus (µg/L)		Total nitrogen (µg/L)		Chlorophyll-*a* (µg/L)		Secchi-disc transparency (m)		Hypolimnetic dissolved-oxygen deficit [(mg/m³)/d]	
	1991	Response	1991	Response	1991	Response	1991	Response	1991	Response
1	9.4	17.5	301	760	2.6	4.9	2.4	2.1	—	—
2	6.4	16.4	247	740	1.8	4.6	3.3	2.7	—	—
3	5.9	13.2	242	706	1.7	3.7	4.3	3.5	—	—
4	4.7	9.3	243	673	1.3	2.6	4.7	4.1	—	—
5	4.3	5.7	240	446	1.2	1.6	5.0	4.8	—	—
6	5.0	8.9	248	657	1.4	2.5	5.1	4.5	17.6	25.1
7	5.5	9.3	253	661	1.5	2.6	3.0	2.7	—	—
LW	5.9	11.9	251	688	1.6	3.3	4.2	3.6	—	—

Table 51. Simulation 3: Limnological response to 100-percent removal of phosphorus and nitrogen loads contributed to Coeur d'Alene Lake by nearshore septic-tank systems and wastewater-treatment plants

[µg/L, micrograms per liter; m, meters; (mg/m³)/d, milligrams per cubic meters per day; —, not measured; LW, area weighted lakewide value]

Segment (fig. 22)	Total phosphorus (µg/L)		Total nitrogen (µg/L)		Chlorophyll-*a* (µg/L)		Secchi-disc transparency (m)		Hypolimnetic dissolved-oxygen deficit [(mg/m³)/d]	
	1991	Response	1991	Response	1991	Response	1991	Response	1991	Response
1	9.4	7.5	301	283	2.6	2.1	2.4	2.5	—	—
2	6.4	5.6	247	230	1.8	1.6	3.3	3.3	—	—
3	5.9	5.0	242	227	1.7	1.4	4.3	4.4	—	—
4	4.7	3.8	243	225	1.3	1.1	4.7	4.8	—	—
5	4.3	3.8	240	227	1.2	1.1	5.0	5.1	—	—
6	5.0	3.7	248	225	1.4	1.0	5.1	5.4	17.6	15.8
7	5.5	3.7	253	225	1.5	1.0	3.0	3.1	—	—
LW	5.9	4.7	251	233	1.6	1.3	4.2	4.4	—	—

Table 52. Simulation 4: Limnological response to 20-percent reduction in phosphorus and nitrogen loads contributed to Coeur d'Alene Lake by the Coeur d'Alene and St. Joe Rivers

[µg/L, micrograms per liter; m, meters; (mg/m³)/d, milligrams per cubic meters per day; —, not measured; LW, area weighted lakewide value]

Segment (fig. 22)	Total phosphorus (µg/L)		Total nitrogen (µg/L)		Chlorophyll-*a* (µg/L)		Secchi-disc transparency (m)		Hypolimnetic dissolved-oxygen deficit [(mg/m³)/d]	
	1991	Response	1991	Response	1991	Response	1991	Response	1991	Response
1	9.4	8.7	301	266	2.6	2.4	2.4	2.4	—	—
2	6.4	5.6	247	205	1.8	1.6	3.3	3.3	—	—
3	5.9	5.2	242	206	1.7	1.5	4.3	4.4	—	—
4	4.7	4.2	243	209	1.3	1.2	4.7	4.8	—	—
5	4.3	4.2	240	222	1.2	1.2	5.0	5.0	—	—
6	5.0	4.6	248	215	1.4	1.3	5.1	5.2	17.6	16.7
7	5.5	5.1	253	220	1.5	1.4	3.0	3.0	—	—
LW	5.9	5.3	251	216	1.6	1.5	4.2	4.3	—	—

Table 53. Simulation 5: Limnological response to 25-percent reduction in phosphorus and nitrogen loads contributed to Coeur d'Alene Lake by selected nearshore subbasins where agriculture constitutes more than 20 percent of land use

[µg/L, micrograms per liter; m, meters; (mg/m³)/d, milligrams per cubic meters per day; —, not measured; LW, area weighted lakewide value]

Segment (fig. 22)	Total phosphorus (µg/L)		Total nitrogen (µg/L)		Chlorophyll-*a* (µg/L)		Secchi-disc transparency (m)		Hypolimnetic dissolved-oxygen deficit [(mg/m³)/d]	
	1991	Response	1991	Response	1991	Response	1991	Response	1991	Response
1	9.4	9.0	301	287	2.6	2.5	2.4	2.4	—	—
2	6.4	6.3	247	238	1.8	1.8	3.3	3.3	—	—
3	5.9	5.8	242	238	1.7	1.6	4.3	4.3	—	—
4	4.7	4.6	243	239	1.3	1.3	4.7	4.7	—	—
5	4.3	4.3	240	238	1.2	1.2	5.0	5.0	—	—
6	5.0	5.0	248	244	1.4	1.4	5.1	5.1	17.6	17.4
7	5.5	5.4	253	249	1.5	1.5	3.0	3.0	—	—
LW	5.9	5.7	251	246	1.6	1.6	4.2	4.2	—	—

practices (BMP's) for forestry and agricultural industries in subbasins C1 to C7 and S1 to S5 (fig. 3 and table 4). Relative to simulated 1991 base values, phosphorus, nitrogen, and chlorophyll-*a* concentrations in all segments declined between 0.1 and 0.8, 18 and 38, and 0 and 0.2 µg/L, respectively. Secchi-disc transparency in all segments increased between 0 and 0.1 m. The hypolimnetic dissolved-oxygen deficit in segment 6 declined 0.9 $(mg/m^3)/d$. On a lakewide basis, concentrations of phosphorus, nitrogen, and chlorophyll-*a* declined 0.6, 35, and 0.1 µg/L, respectively; secchi-disc transparency increased 0.1 m.

Simulation 5 (table 53) assessed a 25-percent reduction in nutrient loads contributed to the lake from nearshore subbasins where agriculture constitutes more than 20 percent of land use. Those subbasins included L14, L15, L18–L23, L25, and R1 (fig. 3 and table 4). The reductions in nutrient loads were to be achieved through implementation of BMP's on agricultural lands. Relative to simulated 1991 base values, phosphorus, nitrogen, and chlorophyll-*a* concentrations in all segments declined between 0 and 0.4, 2 and 14, and 0 and 0.1 µg/L, respectively; secchi-disc transparency did not change. The hypolimnetic dissolved-oxygen deficit in segment 6 decreased 0.2 $(mg/m^3)/d$. On a lakewide basis, concentrations of phosphorus and nitrogen declined 0.2 and 5 µg/L, respectively; chlorophyll-*a* and secchi-disc transparency were unchanged.

Of the three nutrient-reduction simulations, nutrient reduction from wastewater-treatment systems (simulation 3) produced the largest changes in phosphorus, chlorophyll-*a*, and secchi-disc transparency. The reduction of nutrients gained by application of BMP's in the Coeur d'Alene and St. Joe River Basins (simulation 4) produced the largest decline in nitrogen. The implementation of BMP's in the nearshore subbasins (simulation 5) produced negligible changes in lake water quality.

HISTORICAL TRENDS IN WATER QUALITY

This study of Coeur d'Alene Lake was initiated largely in response to concerns over eutrophication and its potential to mobilize trace elements stored in the lakebed sediments. Eutrophication is a natural process but can be accelerated by increased nutrient inputs caused by human activities, a process commonly termed cultural eutrophication. The commonly held view is that a lake begins the cultural eutrophication process as human activity increases in its drainage basin. Cultural eutrophication may not be readily perceived by the public because nutrient loads may increase for years before a distinct increase in lake productivity is noticeable. However, the results of this lake study and a review of historical data raised doubts as to the applicability of this commonly held view to Coeur d'Alene Lake.

The review of historical data raised a perplexing issue: dissolved-oxygen deficits during 1911–12 were substantial (Kemmerer and others, 1923). On the basis of the common perception of cultural eutrophication, the dissolved-oxygen deficit would be expected to be of relatively recent origin. Instead, the deficits during 1911–12 were as pronounced as those measured during 1991–92. By 1991–92, more than 80 percent of the lakeshore had been developed (Milligan and others, 1983); the population in the contributing drainage basin was about 92,000; and land disturbances from agriculture, timber harvest, and mining had been taking place for a century. In contrast, during 1911–12, the lakeshore was sparsely developed, the population was about 36,000, and land disturbances had begun less than 25 years previously. An important question was whether the pre-1911 level of land disturbance could generate enough nutrients and oxygen-demanding substances to deplete dissolved oxygen in the lake during 1911–12. An early section of this report, "Human Effects on Water Quality," described how the population in the mid-1880's increased abruptly in response to the discovery of precious metals in the Coeur d'Alene River drainage. Timber harvest increased rapidly to supply material for mining and ore-processing activities, railroad construction, and construction of communities. These communities had no sewage treatment other than collection and disposal, often directly to the nearest waterway. A substantial dissolved-oxygen deficit again was measured in 1932 (Ellis, 1940) and, as late as 1975, the National Eutrophication Survey (U.S. Environmental Protection Agency, 1977) reported the same. These historical observations led to the hypothesis that nutrient and oxygen-demanding substances have been delivered to the lake over most of this century in amounts large enough to cause substantial declines in dissolved oxygen.

To test this hypothesis, estimates were made of the magnitude of nutrient loads delivered to Coeur d'Alene Lake in 1880, 1910, 1940, and 1970. Load estimates focused on phosphorus because it is the nutrient most likely to limit phytoplankton growth in Coeur d'Alene Lake. Estimates were made for two categories: natural background loads and incremental additions attributable to human activities. Data for four load sources—timber harvest, sewage, mining and ore processing, and phosphate fertilizer production—were sufficient to estimate phosphorus loads from human activities.

The initial task was to estimate natural background loads of phosphorus prior to the discovery of precious metals in the study area. Before the 1880's, most of the study area was forested. The forested area was estimated by subtracting the combined areas for water, wetlands, barren land, mined land, rangeland, Spokane River outlet area, and agricultural land from the total land area (table 5). This procedure yielded a forested area of 880,000 ha. Soil erosion from forested land in north Idaho averages 1,120 kg/ha (U.S. Department of Agriculture, 1994a, 1994b). The phosphorus content of soil and rock in the study area is about 500 mg/kg, on the basis of sample results from the National Uranium Resource Evaluation Program (Cole Smith, U.S. Geological Survey, written commun., 1994). Multiplication of the average soil erosion rate by the average phosphorus content yields a value of 0.56 kg/ha of phosphorus eroded per year. Only part of the eroded soil and associated phosphorus is delivered to major streams and rivers. The U.S. Department of Agriculture (1994a, 1994b) estimated a delivery rate of 5 percent for forest lands in the Coeur d'Alene Basin. Therefore, the 880,000 ha annually yielded about 24,600 kg of phosphorus to Coeur d'Alene Lake prior to 1880.

Phosphorus loads from forested lands where timber was harvested were estimated for two periods that represented different harvest methods and intensities. The two periods, 1890 to 1930 and 1930 to 1975, were chosen on the basis of historical information (Hult, 1968; Rabe and Flaherty, 1974; Fahey, 1978; Wood, 1984; and U.S. Department of Agriculture, 1994a).

The 1890 to 1930 period included the beginning of large-scale timber harvest in support of the new and rapidly expanding mining industry in the Coeur d'Alene River Basin. Harvesting of the extensive white pine forests of the St. Joe River Basin began around 1900. Railroad construction was extensive during this time, largely in support of the mining and timber harvest industries. Large amounts of timber were harvested for railroad rights-of-way. Railroad construction involved large amounts of slash burning, which contributed ash and associated nutrients to nearby watercourses. The timber harvest methods were highly disruptive to the soil and often were conducted close to watercourses to facilitate waterborne delivery of logs to downstream loading facilities. Several large-scale forest fires and floods during this period compounded the erosion problems created by the mining and timber harvest industries.

Timber harvest during the following period, 1930 to 1975, increased greatly as extensive networks of logging roads were built to accommodate more mechanized methods of timber harvest. These new methods increased erosion and sediment delivery rates because the roads disrupted natural drainage patterns and compacted soils. The use of clearcuts, many spanning headwater streams, increased peak runoff and erosion rates. The type and intensity of harvest practices during this period likely resulted in the largest inputs of phosphorus to Coeur d'Alene Lake.

Phosphorus loads from forested lands were estimated as the product of area harvested, soil erosion rate, sediment delivery rate, and a soil phosphorus content of 500 mg/kg. The phosphorus contribution from unharvested or regenerated areas was computed similarly and added to phosphorus contributed from harvested areas. The contributing harvested or unharvested/regenerated areas for 1890 to 1930 were 100,000 ha and 780,000 ha, respectively, and, for 1930 to 1975, were 200,000 ha and 680,000 ha, respectively. Soil erosion and sediment delivery rates for harvested areas during 1890 to 1930 were 3,360 kg/ha and 20 percent, respectively, and, during 1930 to 1975, were

3,360 kg/ha and 25 percent, respectively. For unharvested/regenerated areas, soil erosion and sediment delivery rates were 1,120 kg/ha and 5 percent, respectively.

The estimated annual load of phosphorus to Coeur d'Alene Lake from forested land during 1890 to 1930 was 55,400 kg—33,600 kg from harvested areas and 21,800 kg from unharvested/regenerated areas. The estimated annual load of phosphorus during 1930 to 1975 was 103,000 kg—84,000 kg from harvested areas and 19,000 kg from unharvested/regenerated areas.

Phosphorus loads attributable to sewage were estimated using population data and the annual per capita contribution of phosphorus in raw sewage, given as a median of 1.28 kg by Falter and Good (1987). Until the mid-1970's, sewage treatment in the study area was primarily collection and disposal of untreated sewage to the nearest water body. In 1910, the combined population of Kootenai and Shoshone Counties (Benewah County was established in 1915) was about 36,000; the population contributing sewage directly or indirectly to tributaries to Coeur d'Alene Lake was about 24,000. Thus, in 1910, about 30,700 kg of phosphorus was available for transport to the lake. In 1940, the combined population of the three counties was about 51,000 and the contributing population was about 34,000. The estimated phosphorus load in 1940 was about 43,500 kg. In 1970, the contributing population was about 45,000 and the estimated phosphorus load was about 57,600 kg. Not all of this phosphorus reached Coeur d'Alene Lake; a small amount was not discharged to water bodies, according to a study by Cornell, Howland, Hayes, and Merryfield, Engineers and Planners (1964). They noted that domestic sewage from all areas of the South Fork Coeur d'Alene River was discharged to the river without treatment. Some of the phosphorus load discharged to water bodies in a specific year was incorporated into riverbed sediments and biota. Most of this phosphorus eventually would make its way to the lake in later years by way of erosion and transport processes. Estimates of phosphorus load from sewage discharged to Coeur d'Alene Lake were reduced by 25 percent to be conservative. Thus, the estimates for 1910, 1940, and 1970 are 23,000, 33,000, and 43,000 kg, respectively.

Mining and ore-processing activities were additional sources of phosphorus to Coeur d'Alene Lake. As stated earlier, the average phosphorus content of soil and rock in the study area is about 500 mg/kg. Prior to about 1912, most ore processing was done by jigging, which was inefficient for removing zinc and left relatively coarse-grained waste for disposal to the river. Beginning about 1912, a more efficient flotation method was introduced for ore processing (Casner, 1989). As this new process became dominant, water pollution problems for the Coeur d'Alene River increased substantially because much larger quantities of low-grade ore were processed; wastes were much finer grained and, thus, traveled farther downstream; and additives increased the toxicity of the waste discharge (Woodward-Clyde Consultants and Terragraphics, 1986). An average of 454 million kg of tailings was directly or indirectly discharged annually to the South Fork Coeur d'Alene River from about 1920 to the late 1960's when large-scale settling ponds began to receive the tailings (Woodward-Clyde Consultants and Terragraphics, 1986). If all the tailings were transported to the lake, then about 227,000 kg of phosphorus would annually enter the lake. Much of this phosphorus would be associated with sediment particles and would be subject to alternating episodes of erosion and deposition in the Coeur d'Alene River. From 1920 to 1970, one-fourth of the annual load of phosphorus, or 57,000 kg, was estimated to reach Coeur d'Alene Lake. Prior to 1910, the annual phosphorus input to the lake was only about 10,000 kg because the less-efficient jigging process input larger sized particles and smaller amounts of tailings to the South Fork Coeur d'Alene River. After 1970, the annual phosphorus load declined to about 10,000 kg and was partly supplied by erosion of previously deposited tailings.

The fourth quantifiable source of phosphorus to the lake was from the phosphate fertilizer plant at Kellogg, which began operation in 1960. The plant annually discharged about 1.8 hm^3 of waste with a phosphorus concentration of 6,200 µg/L to Silver King Creek, a tributary to the South Fork Coeur d'Alene River (Cornell, Howland, Hayes, and Merryfield, Engineers and Planners, 1964). In 1970, the effluent was removed from the river and routed to a central impoundment area. The annual phosphorus load from 1960 to 1970 was 11,200 kg, all of which eventually reached the lake because phosphorus was released in the dissolved state.

Table 54. Estimated annual loads of phosphorus from five sources to Coeur d'Alene Lake in 1880, 1910, 1940, and 1970

[kg, kilograms]

Load source	Annual load (kg) 1880	1910	1940	1970
Background	24,600	21,800	19,000	19,000
Sewage	0	23,000	33,000	43,000
Timber harvest	0	33,600	84,000	84,000
Mining and ore processing	0	10,000	57,000	10,000
Phosphate fertilizer production	0	0	0	11,000
TOTAL	24,600	88,400	193,000	167,000

The foregoing estimates of historical loads of phosphorus to Coeur d'Alene Lake did not include several potentially large, but unquantifiable, sources such as soil erosion from extensive wildfires, severe floods, and agricultural development in the lake's southern drainages. The overall estimates were made on the conservative side in recognition of the uncertainties inherent in such estimations. On the basis of these estimates, annual loads of phosphorus were developed for 1880, 1910, 1940, and 1970 (table 54). The post-1880 phosphorus loads were about three to eight times larger than the 1880 natural background load of 24,600 kg. The load for 1970 was comparable to the 180,000 kg of phosphorus measured during the 1975 National Eutrophication Survey of the lake (U.S. Environmental Protection Agency, 1977).

On the basis of the magnitude of these historical phosphorus loads, the substantial dissolved-oxygen deficits measured during 1911–12 and 1932 might be assumed to be entirely a result of Coeur d'Alene Lake being mesotrophic or eutrophic as early as 1910. However, this is only part of the explanation because two other important processes also could have affected the dissolved-oxygen deficit. Post Falls Dam raised the level of Coeur d'Alene Lake in 1906 and inundated the shallow lakes and wetlands at the lake's southern end, the former lakeshore, and the lower reaches of the Coeur d'Alene and St. Joe Rivers. When these fertile wetland and terrestrial soils were inundated, they leached nutrients and oxygen-demanding substances into the lake. The timing of leaching coincided with the dissolved-oxygen deficit measured during 1911–12. The second, and more important, process was the addition of oxygen-demanding substances from sewage inflows. The biochemical oxygen demand (BOD) for raw sewage is about 77,000 mg of oxygen per day per capita, or 28 million mg per year per capita (Cornell, Howland, Hayes, and Merryfield, Engineers and Planners, 1964). BOD is satisfied by the addition of oxygen, which facilitates the aerobic decomposition process. The reaeration of water is highly dependent on water depth and velocity to produce turbulence for entrainment and distribution of oxygen throughout the water column (Velz, 1970). Following the 1906 impoundment of Coeur d'Alene Lake, the lower reaches of the Coeur d'Alene and St. Joe Rivers became deeper and slower because their streamflow was impeded by the lake. Reaeration was lessened and, as a consequence, BOD was satisfied more slowly. The lake's increased phosphorus loads also played a role in the depletion of dissolved oxygen because increased production of organic matter exerted oxygen demands by respiration and decomposition. The proportional effects of these three oxygen-demanding processes (nutrient and BOD leaching from inundation, sewage inputs, and increased phosphorus loads) were not readily quantifiable but were significant enough to produce mesotrophic conditions in the lake.

Prior to the late 1960's, the dissolved-oxygen demands attributable to biological production stimulated by phosphorus loads probably were muted by the extremely turbid conditions created in Coeur d'Alene Lake by the inflow of fine-grained sediments from mining, ore-processing, and timber harvest activities. In 1911, Kemmerer and others (1923) reported that the sediment plume from the Coeur d'Alene River extended far into Coeur d'Alene Lake and that railroad construction along the St. Joe River had muddied the southern end of the lake. In his 1932 study, Ellis (1940) reported that local residents and steamboat captains described the entire surface of Coeur d'Alene Lake as being discolored by mining sediments. Such turbid conditions would have severely reduced the depth of the euphotic zone and thereby reduced the lake's capacity to produce organic matter by photosynthesis. The mine wastes also contained high concentrations of trace elements potentially toxic to phytoplankton. Bioassays conducted by Bartlett and others (1974) and Wissmar (1972) at Coeur d'Alene Lake indicated that concentrations of cadmium, copper, and zinc were high enough to inhibit phytoplankton growth.

Coeur d'Alene Lake may not have responded fully to its phosphorus loads until after the late 1960's, when settling basins built by the mining companies began to reduce the influx of sediment and sediment-associated trace elements delivered by the Coeur d'Alene River. Following that, the inhibitory effects of trace elements were reduced and photosynthetic production of organic matter increased as the euphotic zone deepened. By the time of the 1975 National Eutrophication Survey, Coeur d'Alene Lake contained concentrations of phosphorus and chlorophyll-*a* in the mesotrophic range, blue-green algae were common, and the summer hypolimnion was severely depleted of dissolved oxygen (U.S. Environmental Protection Agency, 1977). The lake has responded favorably to nutrient reductions implemented in the 1970's by moving from mesotrophic to oligotrophic over the past two decades. The substantial dissolved-oxygen deficits measured during 1991 and 1992 indicated that the lake still had an excessive oxygen demand in the hypolimnion during summer stratification. However, two dissolved-oxygen profiles collected by the USGS during 1993 and 1994 near limnetic station 3 showed slightly reduced depletion of dissolved oxygen in the hypolimnion. In late September 1993, the minimum saturation in the hypolimnion was 74 percent. Similarly, the minimum saturation was 70 percent in mid-October 1994. Whether this is part of an improving trend or just an anomaly cannot be judged at this point, but future monitoring of dissolved oxygen in the late summer months could answer this important question.

The shift in trophic state from mesotrophic to oligotrophic from 1975 to 1992 was unexpected. In 1975, the National Eutrophication Survey (U.S. Environmental Protection Agency, 1977) reported concentrations of phosphorus and chlorophyll-*a* in the range of mesotrophic conditions. However, concentrations of phosphorus and chlorophyll-*a* measured during the present study were in the range of oligotrophic conditions. Phosphorus loads in 1991 were about half those measured in 1975. Therefore, Coeur d'Alene Lake's shift from mesotrophic to oligotrophic conditions can be attributed to reductions in nutrient loads between 1975 and 1992.

Reductions in nutrient loads resulted from the cumulative effects of numerous actions. Two of the more visible reductions resulted from decreases in direct discharge of mining and smelting wastes to the South Fork Coeur d'Alene River and diversion of untreated sewage to municipal wastewater-treatment plants. In 1968, most of the mining and smelting waste discharges to the South Fork Coeur d'Alene River were diverted to settling ponds. Beginning in 1974, effluents from the largest settling pond, the central impoundment area, were treated prior to discharge. Termination of smelting operations at the Bunker Hill complex in 1981 further reduced loads to the river. In the mid-1970's, many of the communities along the Coeur d'Alene and St. Joe Rivers began to divert their untreated sewage to municipal wastewater-treatment plants. The largest facility at Page began operation in late 1975. By the early 1980's, most communities along the Coeur d'Alene River had some form of municipal wastewater treatment. In the St. Joe River drainage, St. Maries began sewage treatment in the mid-1960's and upgraded the treatment process in 1978. The smaller communities of Avery, Calder, and Clarkia installed sewage-treatment plants between 1980 and 1985.

Although not as visible, additional reductions in nutrient loads were gained by implementation of BMP's for timber harvest and agricultural activities. Specific BMP's for timber harvest activities became mandatory in Idaho in 1974. Application of BMP's for agricultural activities is voluntary and is guided by Idaho's State Agricultural Water Quality Program and Federal agricultural policies and programs. These programs have been important factors in reducing water-quality degradation caused by agricultural practices.

SUMMARY

This study of Coeur d'Alene Lake was undertaken because of concerns over the potential for release of previously deposited nutrients and trace elements from the lakebed if an anoxic hypolimnion were to develop as a consequence of eutrophication. The primary purpose of the study was to determine the lake's assimilative capacity for nutrients. The scope included characterization of water quality in the limnetic and littoral zones of the lake, quantification of hydrologic and nutrient budgets, development of a nutrient load/lake response model, and characterization of trace-element enrichment in surficial and subsurface lakebed sediments. Additionally, previous studies of the lake were reviewed to assess historical trends in water quality.

The trophic state of the lake's limnetic zone was determined to be oligotrophic on the basis of concentrations of total phosphorus, total nitrogen, and chlorophyll-*a*. The phytoplankton community was highly diverse, dominated by diatoms, and contained a low percentage of blue-green algae. Nitrogen-to-phosphorus ratios showed phosphorus as the nutrient most likely to limit phytoplankton growth. Despite its oligotrophy, the deeper areas of the lake had a substantial hypolimnetic dissolved-oxygen deficit during the late summer. The shallow, southern end of the lake contained anoxic near-bottom water in the late summer. Median concentrations of copper, lead, and zinc in the water column exceeded water-quality criteria for the protection of freshwater biota. Phytoplankton bioassays demonstrated that the dissolved, uncomplexed zinc concentrations typical for the lake were highly inhibitive of phytoplankton growth.

Water quality in the littoral zone was similar to that in the limnetic zone. Aquatic macrophytes were abundant in the shallow, southern lake area and in the heads of many of the bays with sedimentary deltas. The growth rate of periphyton at selected nearshore sites was positively correlated with littoral-zone concentrations of total phosphorus and the percentage of agricultural land in the nearshore subbasins.

Surficial and subsurface samples of the lakebed sediments contained highly enriched concentrations of antimony, arsenic, cadmium, copper, lead, mercury, silver, and zinc. Approximately 85 percent of the lakebed surface area was highly enriched; only the southern lake area south of Conkling Point contained background concentrations. Most of the enriched trace elements were associated with ferric oxides and thus were subject to redissolution under the reducing conditions that can occur in an anoxic hypolimnion. Previously, the trace elements in the lakebed sediments were thought to be associated with sulfides and, under reducing conditions, would remain immobile and thus unlikely to migrate back into the water column. On the basis of sediment-quality guidelines, concentrations of arsenic, cadmium, lead, and zinc in the lakebed sediments of Coeur d'Alene Lake were indicative of severe pollution that can significantly affect benthic organisms.

The hydrologic and nutrient budgets for the lake were dominated by the St. Joe and Coeur d'Alene Rivers. The lake retained a large percentage of its influent load of phosphorus but only a small percentage of its nitrogen load. The Coeur d'Alene River contributed the largest loads of arsenic, cadmium, lead, and zinc to Coeur d'Alene Lake. The lake retained most of its lead load and smaller percentages of its arsenic, cadmium, and zinc loads.

A nutrient load/lake response model was used to determine the response of the hypolimnetic dissolved-oxygen deficit to increased and decreased nutrient loads. The results indicated the lake has a large assimilative capacity for nutrients before anoxic conditions develop in the hypolimnion. Several nutrient-reduction scenarios were modeled to assess their potential improvements in water quality. If nutrient loads from wastewater-treatment systems were eliminated, then the lakewide concentrations of total phosphorus and chlorophyll-*a* would decrease 1.2 and 0.3 μg/L, respectively. If BMP's for forestry and agricultural activities achieved a 20-percent nutrient-load reduction for the Coeur d'Alene and St. Joe River drainages, then lakewide concentrations of total phosphorus and chlorophyll-*a* would decrease 0.6 and 0.1 μg/L, respectively.

The review of historical studies of Coeur d'Alene Lake and its drainage basin yielded important insights into the lake's response to human development. The lake has received substantial loads of nutrients and oxygen-demanding substances since the late 1800's, as evidenced by the severe hypolimnetic dissolved-oxygen deficits recorded during 1911–12. In 1975, the lake was considered mesotrophic and received total phosphorus loads twice as large as those recorded in 1991. Construction of municipal wastewater-treatment plants began in the mid-1970's, concurrent with implementation of BMP's for forestry and agricultural industries. The net effect of reduced nutrient loads allowed the lake to shift from mesotrophy to oligotrophy between the mid-1970's and this study.

CONCLUSIONS

The primary research question addressed by this study of Coeur d'Alene Lake was, "Has Coeur d'Alene Lake advanced far enough in the eutrophication process to have a substantial risk to develop an anoxic hypolimnion, which would increase the potential for release of nutrients and trace elements from the lakebed sediments into the overlying water column?" The justification for originally posing the question was based on two key issues gleaned from previous studies of the lake. First, Coeur d'Alene Lake exhibited classic symptoms of eutrophication: elevated concentrations of nitrogen, phosphorus, and chlorophyll-*a*; extensive growths of blue-green algae; and a substantial hypolimnetic dissolved-oxygen deficit. Second, the lakebed sediments contained highly enriched concentrations of trace elements such as arsenic, cadmium, lead, and zinc.

With completion of this study, the research question can be answered. On the basis of results from the nutrient load/lake response model, Coeur d'Alene Lake has a large assimilative capacity for nutrients and, thus, is unlikely to develop an anoxic hypolimnion unless nutrient loads to the lake increase substantially. Lakebed geochemistry analyses revealed that most of the trace elements in surficial and subsurface sediments are associated with a ferric oxide phase and, thus, under reducing (anoxic) conditions, the trace elements would be readily solubilized and available for release to the overlying water column. Prior to this study, the trace elements were thought to be associated with sulfides and, thus, would not be solubilized under reducing conditions. The greater potential for release of trace elements from the lakebed sediments is mitigated by the lake's resistance to developing an anoxic hypolimnion.

The two cooperators intend to use the study results to develop a lake management plan for Coeur d'Alene Lake. Study results indicate distinct spatial differences in water quality that merit consideration in the lake management plan. Biological productivity of the lake's southern end, represented by limnetic station 6 and model segment 1, is greater than biological productivity in the rest of the lake, as demonstrated by several features: highest concentrations of total phosphorus, dissolved orthophosphorus, dissolved inorganic nitrogen, and chlorophyll-*a*; smallest secchi-disc transparencies; a range of dissolved-oxygen saturation from 0 to 133 percent; extensive growths of aquatic macrophytes; and the only limnetic station with blue-green algae. Although the southern end of the lake is the most biologically productive, it is relatively free of the trace-element enrichment observed in the lakebed sediments throughout the rest of the lake.

One area where water quality is affected by high biological productivity and trace-element enrichment of the lakebed sediments is the area south of the mouth of the Coeur d'Alene River and north of Conkling Point, represented by limnetic station 5 and model segment 2. Dissolved-oxygen concentrations at limnetic station 5 were as low as 2.8 mg/L during October 1991 and might eventually reach anoxia if biological productivity in the adjacent southern end of the lake were to increase substantially. The area of the lake represented by model segment 2 may be the most likely to release trace elements from the lakebed sediments after an anoxic hypolimnion developed.

Much of this study focused on defining the lake's response to nutrient loads. The two cooperators then could design a lake management plan to control biological production by controlling nutrient loads delivered to the lake from its drainage basin. The focus on nutrient management may need some modification because the phytoplankton bioassays demonstrated that phytoplankton growth is strongly inhibited by concentrations of dissolved, uncomplexed zinc typical in much of the lake. Total recoverable and dissolved zinc concentrations were well in excess of Federal water-quality criteria for protection of freshwater biota. If zinc concentrations were reduced, the inhibitory effects of zinc would be lessened and phytoplankton growth would increase unless nutrient load reductions were implemented to counteract the lessened inhibition.

A lingering question concerns the continued existence of the hypolimnetic dissolved-oxygen deficit in the lake's northern basin, even though the trophic state variables for limnetic stations 1 and 3 indicate oligotrophy. Results from the phytoplankton bioassays offer some insight into the question and have been used to develop the following research question (J.S. Kuwabara, U.S. Geological Survey, written commun., 1994): "Is the hypolimnetic dissolved-oxygen deficit a result of oxygen demands exerted by the advective transport of zinc-inhibited phytoplankton that settle through the water column into the lake's northern basin?" This study has shown that the distribution of dissolved, uncomplexed zinc has a strong longitudinal gradient in the lake; concentrations are noninhibitory only in the lake's southern end, the lake's most biologically productive area. As phytoplankton are advectively transported northward, they encounter the plume of the Coeur d'Alene River where concentrations of dissolved, uncomplexed zinc are highly inhibitory. The resultant inhibition of phytoplankton growth is hypothesized to produce a sestonic "rain" of dead and dying phytoplankton that settles into the hypolimnion of the lake's northern basin and produces the hypolimnetic dissolved-oxygen deficit when the lake is thermally stratified. Unfortunately, this research question cannot be adequately evaluated with the data base assembled by this study.

REFERENCES CITED

Aloi, J.E., Loeb, S.L., and Goldman, C.R., 1988, Temporal and spatial variability of the eulittoral epilithic periphyton, Lake Tahoe, Calif.-Nev.: Journal of Freshwater Ecology, v. 4, no. 3, p. 401–410.

Ankley, G.T., Thomas, N.A., Di Toro, D.M., Hansen, D.J., Mahony, J.D., Berry, W.J., Swartz, R.C., Hoke, R.A., Garrison, A.W., Allen, H.E., and Zarba, C.S., 1994, Assessing potential bioavailability of metals in sediments—a proposed approach: Duluth, Minn., U.S. Environmental Protection Agency, Environmental Management, v. 18, no. 3, p. 331–337.

Baccini, Peter, 1985, Phosphate interactions at the sediment-water interface, *in* Stumm, Werner, ed., Chemical processes in lakes: New York, John Wiley and Sons, p. 189–205.

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.

Brezonik, P.L., 1994, Chemical kinetics and process dynamics in aquatic systems: Boca Raton, Fla., Lewis Publishers, 754 p.

Briethaupt, S.A., 1990, Plummer Creek and Chatcolet Lake, Benewah and Kootenai Counties: Boise, Idaho Department of Health and Welfare, Division of Environmental Quality, Water Quality Status Report no. 94, 54 p.

Britton, L.J., and Greeson, P.E., eds., 1987, Methods for collection and analysis of aquatic biological and microbiological samples: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A4, 363 p.

Brown, R.G., 1987, Errors in estimating ground-water components of hydrologic and phosphorus budgets of lakes, *in* Selected Papers in the Hydrologic Sciences: U.S. Geological Survey Water-Supply Paper 2310–D, p. 53–64.

Bureau of Land Management, 1993, Recreation management plan for the Coeur d'Alene Lake recreation management area: Coeur d'Alene, Idaho, Bureau of Land Management, District Office, 39 p.

Canter, L.W., and Knox, R.C., 1985, Septic tank system effects on ground-water quality: Chelsea, Mich., Lewis Publishers, 336 p.

Casner, N.A., 1989, Leaded waters—a history of mining pollution on the Coeur d'Alene River in Idaho, 1900–1950: Boise, Idaho, Boise State University, M.S. thesis, 150 p.

———1991, Toxic river—politics and Coeur d'Alene mining pollution in the 1930's: Idaho Yesterdays, v. 35, no. 3, p. 3–19.

Cornell, Howland, Hayes, and Merryfield, Engineers and Planners, 1964, Mine, industrial, and domestic waste disposal study for the South Fork Coeur d'Alene River: Record no. B2763, 102 p., 5 apps.

Edwards, T.K., and Glysson, D.G., 1988, Field methods for measurement of fluvial sediment: U.S. Geological Survey Open-File Report 86–531, 118 p.

Ellis, M.M., 1940, Pollution of the Coeur d'Alene River and adjacent waters by mine wastes : Washington, D.C., U.S. Bureau of Fisheries Special Report no. 1 [Available from U.S. Fish and Wildlife Service, Washington, D.C.], 61 p.

Fahey, John, 1978, The Days of the Hercules: Moscow, University Press of Idaho, 324 p.

Falter, C.M., and Good, J.C., 1987, Cocolalla Lake phosphorus loading and trophic status assessment: Moscow, University of Idaho, College of Forestry, Wildlife, and Range Sciences, 124 p.

Fischer, H.B., List, E.J., Koh, R.C.Y., Imberger, Jörg, and Brooks, N.H., 1979, Mixing in inland and coastal waters: New York, Academic Press, 483 p.

Fishman, M.J., and Friedman, L.C., 1985, Methods for determination of inorganic substances in water and fluvial sediments: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A1, 709 p.

Funk, W.H., Rabe, F.W., and Filby, Royston, 1973, The biological impact of combined metallic and organic pollution in the Coeur d'Alene-Spokane River drainage system: Moscow, Idaho Water and Energy Resources Research Institute, 202 p.

Funk, W.H., Rabe, F.W., Filby, Royston, Bailey, Gary, Bennett, Paul, Shah, Kisher, Sheppard, J.C., Savage, N.L., Bauer, S.B., Bourg, A.C.M., Bannon, Gerald, Edwards, George, Anderson, Dale, Syms, Pat, Rothert, Jane, and Seamster, Alan, 1975, An integrated study on the impact of metallic trace element pollution in the Coeur d'Alene-Spokane Rivers-lake drainage system: Moscow, Idaho Water and Energy Resources Research Institute, 332 p.

Gilliom, R.J., 1983, Estimation of nonpoint source loads of phosphorus for lakes in the Puget Sound Region, Washington: U.S. Geological Survey Water-Supply Paper 2240, 24 p.

Greater Coeur d'Alene Convention and Visitors Bureau, 1993, The 1993 guide to the Coeur d'Alenes: Coeur d'Alene, Idaho, Greater Coeur d'Alene Convention and Visitors Bureau [not paged].

Håkanson, Lars, 1981, A manual of lake morphometry: New York, Springer-Verlag, 78 p.

Hale, Shireene, 1993, Inventory of near-shore septic tank systems, Coeur d'Alene Lake, Idaho: Coeur d'Alene, Panhandle Health District, 122 p.

Hallock, D.D., and Falter, C.M., 1987, Powerboat engine discharges as a nutrient source in high use lakes, *in* Lake and Reservoir Management: Washington, D.C., North American Lake Management Society, v. 3, p. 172–180.

Harenberg, W.A., Jones, M.L., O'Dell, Ivalou, Brennan, T.S., Lehmann, A.K., and Tungate, A.M., 1992, Water resources data, Idaho, water year 1991, v. 2, Upper Columbia River Basin and Snake River Basin below King Hill: U.S. Geological Survey Water-Data Report ID–91–2, 357 p.

———1993, Water resources data, Idaho, water year 1992, v. 2, Upper Columbia River Basin and Snake River Basin below King Hill: U.S. Geological Survey Water-Data Report ID–92–2, 431 p.

———1994, Water resources data, Idaho, water year 1993, v. 2, Upper Columbia River Basin and Snake River Basin below King Hill: U.S. Geological Survey Water-Data Report ID–93–2, 337 p.

Harris, C.C., Timko, S.E., and McLaughlin, W.J., 1989, An approach to assessing community tourism potential—results for four north Idaho communities—1990 to 1995: Moscow, University of Idaho, 31 p.

Helsel, D.R., and Hirsch, R.M., 1992, Statistical methods in water resources: Amsterdam, The Netherlands, Elsevier Science Publishers, 522 p.

Hem, J.P., 1985, Study and interpretation of the chemical characteristics of natural water (3d ed.): U.S. Geological Survey Water-Supply Paper 2254, 264 p.

Hornig, C.E., Terpening, D.A., and Bogue, M.W., 1988, Coeur d'Alene Basin EPA water-quality monitoring: Seattle, Wash., U.S. Environmental Protection Agency, EPA 910/9–88–216, 14 p., 2 apps.

Horowitz, Art, Elrick, Kent, and Cook, Robert, 1993, Effect of mining and related activities on the sediment trace element geochemistry of Lake Coeur d'Alene, Idaho, USA, Part I— surface sediments: Hydrological Processes, v. 7, p. 403–423.

Horowitz, A.J., Elrick, K.A., Robbins, J.A., and Cook, R.B, 1995, Effect of mining and related activities on the sediment trace element geochemistry of Lake Coeur d'Alene, Idaho, USA, Part II— Subsurface sediments: Hydrological Processes, v. 9, p. 35–54.

Hudson, Jelaco, Welch, and Comer, 1993, Peak and valley—10 steps to long-term economic stability: Coeur d'Alene, Idaho, Welch-Comer Engineers.

Hult, Ruby El, 1968, Steamboats in the timber: Portland, Oreg., Binfords and Mort, 209 p.

Hunter, Y.R., and Kuwabara, J.S., 1994, Ionic strength and DOC determinations from various freshwater sources to the San Francisco Bay: Bulletin of Environmental Contamination and Toxicology, v. 52, p. 311–318.

Idaho Department of Commerce, 1992, County profiles of Idaho: Boise, Idaho Department of Commerce [variously paged].

Idaho Department of Employment, 1993, Panhandle employment, July 1993: Coeur d'Alene, Idaho Department of Employment, 8 p.

Idaho Department of Health and Welfare, 1985, Idaho water-quality standards and wastewater treatment regulations: Boise, Idaho Department of Health and Welfare, Division of Environmental Quality, 72 p.

———1992, Idaho water-quality status report 1992: Boise, Idaho Department of Health and Welfare, Division of Environmental Quality, 69 p., 7 apps.

Idaho Department of Parks and Recreation, 1993, 1993 Idaho wetland conservation prioritization plan, summary: Boise, Idaho Department of Parks and Recreation, 20 p., 3 apps.

Idaho Department of Water Resources, 1993, Developing a land use and land cover database of the Coeur d'Alene Basin using LANDSAT thematic mapper data: Boise, Idaho Department of Water Resources, 29 p.

Iskander, I.K., and Shukla, S.S., 1981, Limnological investigations—Lake Koocanusa, Montana, part 5—phosphorus chemistry of sediments: Hanover, N.H., U.S. Army Cold Regions Research and Engineering Laboratory, Special Report 81–15, 9 p.

Jacoby, J.M., Bouchard, D.D., and Patmont, C.R., 1991, Response of periphyton to nutrient enrichment in Lake Chelan, Washington, *in* Lake and Reservoir Management: Washington, D.C., North American Lake Management Society, v. 7, no. 1, p. 33–43.

Jones, B.F., and Bowser, C.J., 1978, The mineralogy and related chemistry of lake sediments, *in* Lerman, Abraham, ed., Lakes—chemistry, geology, physics: New York, Springer-Verlag, p. 179–235.

Kann, Jacob, and Falter, C.M., 1989, Periphyton as indicators of enrichment in Pend Oreille Lake, Idaho, *in* Lake and Reservoir Management: Washington, D.C., North American Lake Management Society, v. 5, no. 2, p. 39–48.

Kemmerer, George, Bovard, J.F., and Boorman, W.R., 1923, Northwestern lakes of the United States—biological and chemical studies with reference to possibilities in production of fish: Bulletin of the Bureau of Fisheries, v. XXXIX, p. 51–140.

Koenings, J.P., Kyle, G.B., Edmundson, J.A., and Edmundson, J.M., 1987, Limnology field and laboratory manual—methods for assessing aquatic production: Juneau, Alaska Department of Fish and Game, Division of Fisheries Rehabilitation, Enhancement, and Development, Report no. 71, 212 p.

Kootenai County Planning Commission, 1993, Kootenai County comprehensive plan, Coeur d'Alene, Idaho: Coeur d'Alene, Kootenai County Planning Commission, 229 p.

Kuwabara, J.S., 1985, Phosphorus-zinc interactive effects on growth by *Selenastrum capricornutum* (chlorophyta): Environmental Science and Technology, v. 19, p. 417–421.

Kuwabara, J.S., Woods, P.F., Beckwith, M.A., Backsen, R.L., and Ashenmacher, D.M., 1994, The effects of elevated zinc concentrations on phytoplankton growth in Lake Coeur d'Alene, Idaho [abs.]: EOS, American Geophysical Union Transactions, v. 75 (44), p. 237.

Lind, O.T., 1979, Handbook of common methods in limnology: St. Louis, Mo., The C.V. Mosby Company, 199 p.

Loeb, S.L., 1986, Algal biofouling of oligotrophic Lake Tahoe—causal factors affecting production, *in* Evans, L.V., and Hoagland, K.D., eds., Algal biofouling: Amsterdam, The Netherlands, Elsevier Science Publishers, p. 159–173.

Lyman, W.J., Glazer, A.E., Ong, J.H., and Coons, S.F., 1987, An overview of sediment quality in the United States: Washington, D.C., U.S. Environmental Protection Agency, EPA–900/9–88–002, 112 p., 3 apps.

Maxfield, D., Rodriguez, J., Buettner, M., Davis, J., and Forbes, L., 1974a, Heavy metal content in the sediments of the southern part of the Coeur d'Alene Lake: Environmental Pollution, v. 6, p. 263–266.

——— 1974b, Heavy metal pollution in the sediments of the Coeur d'Alene River delta: Environmental Pollution, v. 7, p. 1–6.

Milligan, J.H., Lyman, R.A., Falter, C.M., Krumpe, E.E., and Carlson, J.E., 1983, Classification of Idaho's freshwater lakes: Moscow, Idaho Water and Energy Resources Research Institute, 67 p., 6 apps.

Morin, Antoine, and Cattaneo, Antonella, 1992, Factors affecting sampling variability of freshwater periphyton and the power of periphyton studies: Canadian Journal of Fisheries and Aquatic Sciences, v. 49, p. 1695–1703.

Mossier, Jere, 1993, Idaho lake water quality assessment report: Boise, Idaho Division of Environmental Quality, Water Quality Status Report no. 105, 232 p.

National Atmospheric Deposition Program, 1991, NADP/NTN Annual data summary—precipitation chemistry in the United States, 1990: Fort Collins, Colorado State University, Natural Resource Ecology Laboratory, 475 p.

Panhandle Area Council, 1993, Overall economic development program for north Idaho: Coeur d'Alene, Panhandle Area Council, 66 p.

Papelis, C., Hayes, K.F., and Leckie, J.O., 1988, HYDRAQL—a program for the computation of chemical equilibrium composition of aqueous batch systems including surface-complexation modeling of adsorption at the oxide/solution interface: Stanford, Calif., Stanford University, Department of Civil Engineering, Technical Report no. 306.

Parker, J.I., 1972, Algae production and nutrient enrichment in Lake Coeur d'Alene, Idaho: Moscow, University of Idaho, M.S. thesis, 39 p.

Patmont, C.R., Pelletier, G.J., Welch, E.B., Banton, D., and Ebbesmeyer, C.C., 1989, Lake Chelan water-quality assessment: Seattle, Wash., Harper-Owes Consulting Engineers [variously paged].

Peltier, J., 1982, A brief history of the Coeur d'Alene Indians—1806–1909: Fairfield, Wash., Ye Galleon Press, 93 p.

Persaud, D., Jaagumagi, R., and Hayton, A., 1993, Guidelines for the protection and management of aquatic sediment quality in Ontario: Ontario Ministry of Environment and Energy, 24 p.

Prescott, G.W., 1969, How to know the aquatic plants: Dubuque, Iowa, Wm. C. Brown Company Publishers, 171 p.

———1970, How to know the freshwater algae: Dubuque, Iowa, Wm. C. Brown Company Publishers, 348 p.

Rabe, F.W., and Flaherty, D.C., 1974, The river of green and gold: Moscow, Idaho Research Foundation, 98 p.

Rieman, B.E., 1980, Coeur d'Alene Lake limnology: Idaho Department of Fish and Game, Lake and Reservoir Investigations, Job Performance Report F–72–R–2, p. 27–68.

Royster, C., 1991, The destructive war: New York, A.A. Knopf, 523 p.

Ryding, S.O., and Rast, Walter, 1989, Control of eutrophication at lakes and reservoirs, v. 1 *of* Programme on man and the biosphere: Cambridge University Press, 295 p.

Savage, N.L., 1986, A topical review of environmental studies in the Coeur d'Alene River-Lake system: Moscow, Idaho Water Resources Research Institute, 81 p.

Schaffranek, R.W., Baltzer, R.A., and Goldberg, D.E., 1981, A model for simulation of flow in singular and interconnected channels: U.S. Geological Survey Techniques of Water-Resources Investigations, book 7, chap. C3, 110 p.

Schwantes, C.A., 1990, In mountain shadows—a history of Idaho: Lincoln, University of Nebraska Press, 292 p.

Simon, N.S., Kennedy, M.M., and Massoni, C.S., 1985, Evaluation and use of a diffusion-controlled sampler for determining chemical and dissolved oxygen gradients at the sediment-water interface: Hydrobiologia, v. 126, p. 135–141.

Soltero, R.A., Appel, R.J., Sexton, L.M., and Buchanan, J.P., 1993, Comparison of non-point source phosphorus loading to the Spokane River from its headwaters to Long Lake, Washington, with that used in the Spokane River from phosphorus attenuation model: Spokane, Wash., Idaho Public Works File no. 14099, 186 p.

Stanford, J.A., Stuart, T.J., and Ellis, B.K., 1983, Limnology of Flathead Lake: U.S. Environmental Protection Agency, Final Report, Flathead River Basin Environmental Impact Study [not paged].

Steward, A.N., Dennis, L.J., and Gilkey, H.M., 1963, Aquatic plants of the Pacific Northwest: Corvallis, Oregon State University Press, 261 p.

Stumm, Werner, and Morgan, J.J., 1970, Aquatic chemistry; an introduction emphasizing chemical equilibria in natural waters: New York, John Wiley and Sons, Inc., 583 p.

Tetra Tech, Inc., and Morrison-Knudsen Engineers, Inc., 1987, Bunker Hill site remedial investigation/feasibility study work plan for unpopulated areas: Boise, Idaho, Tetra Tech, Inc., and Morrison-Knudsen Engineers, Inc., 421 p.

Thomas, S.R., and Soltero, R.A., 1977, Recent sedimentary history of a eutrophic reservoir—Long Lake, Washington: Canada Journal Fisheries Research Board, v. 34, p. 669–676.

U.S. Department of Agriculture, 1984, General soil map and landform provinces of Idaho: Boise, Idaho, Soil Conservation Service, 1 sheet.

———1994a, Coeur d'Alene River cooperative river basin study: Boise, Idaho, Soil Conservation Service, 69 p.

———1994b, Coeur d'Alene River cooperative river basin study, geology report: Boise, Idaho, Soil Conservation Service, 27 p., 4 apps., 9 pls.

U.S. Environmental Protection Agency, 1971, Algal assay procedure—bottle test: Corvallis, Oreg., U.S. Environmental Protection Agency, 82 p.

———1973, Biological field and laboratory methods for measuring the quality of surface waters and effluents: Cincinnati, Ohio, U.S. Environmental Protection Agency, EPA–600/4–73–001.

———1975, National eutrophication survey methods 1973–1976: Las Vegas, Nev., Office of Research and Development, Working Paper no. 175, 91 p.

———1977, Report on Coeur d'Alene Lake, Benewah and Kootenai Counties, Idaho: Washington, D.C., U.S. Environmental Protection Agency, National Eutrophication Survey Working Paper no. 778, 20 p., 5 apps.

———1980, Clean lakes program guidance manual: Washington, D.C., U.S. Environmental Protection Agency, EPA–440/5–81–003, 103 p., 10 apps.

———1986, Quality criteria for water, 1986: Washington, D.C., U.S. Government Printing Office [not paged].

Velz, C.J., 1970, Applied stream sanitation: New York, J. Wiley and Sons, 619 p.

Wai, C.M., Hutchison, S.G., Kauffman, J.D., and Hutchison, F.I., 1985, A bibliography of environmental studies of the Coeur d'Alene mining area, Idaho: Moscow, University of Idaho Completion Report to the Idaho Department of Health and Welfare and the U.S. Environmental Protection Agency, 80 p.

Walker, W.W., Jr., 1981, Empirical methods for predicting eutrophication in impoundments, report 1, phase I, data base development: U.S. Army Corps of Engineers Technical Report E–81–9, 153 p., 1 app.

———1982, Empirical methods for predicting eutrophication in impoundments, report 2, phase II, model testing: U.S. Army Corps of Engineers Technical Report E–81–9, 229 p., 7 apps.

———1985, Empirical methods for predicting eutrophication in impoundments, report 3, phase II, model refinements: U.S. Army Corps of Engineers Technical Report E–81–9, 297 p., 2 apps.

———1987, Empirical methods for predicting eutrophication in impoundments, report 4, phase III, applications manual: U.S. Army Corps of Engineers Technical Report E–81–9 [variously paged].

Welch, E.B., 1980, Ecological effects of waste water, *with a section on* Hydrographic characteristics, by T. Lindell: Cambridge, U.K., Cambridge University Press, 337 p.

Wetzel, R.G., 1975, Limnology: Philadelphia, W.B. Saunders Co., 743 p.

Winner, J.E., 1972, Macrobenthic communities in the Coeur d'Alene Lake system: Moscow, University of Idaho, M.S. thesis, 41 p.

Winter, T.C., 1981, Uncertainties in estimating the water balance of lakes: Water Resources Bulletin, v. 17, no. 1, p. 82–115.

Wissmar, R.C., 1972, Some effects of mine drainage on primary production in Coeur d'Alene River and Lake, Idaho: Moscow, University of Idaho, Ph.D. dissertation, 61 p.

Wood, J.V., 1984, Railroads through the Coeur d'Alenes: Caldwell, Idaho, Caxton Printers, Ltd., 195 p.

Woods, P.F., 1989, Hypolimnetic concentrations of dissolved oxygen, nutrients, and trace elements in Coeur d'Alene Lake, Idaho: Boise, U.S. Geological Survey Water-Resources Investigations Report 89–4032, 56 p.

Woods, P.F., and Berenbrock, Charles, 1994, Bathymetric map of Coeur d'Alene Lake, Idaho: U.S. Geological Survey Water-Resources Investigations Report 94–4119, 1 sheet.

Woodward-Clyde Consultants and Terragraphics, 1986, Interim site characterization report for the Bunker Hill site: Woodward-Clyde Consultants and Terragraphics [not paged].

Wyman, S.A., 1993, The potential for heavy metal migration from sediments of Lake Coeur d'Alene into the Rathdrum Prairie aquifer, Kootenai County, Idaho: Moscow, Idaho Water Resources Research Institute, Research Technical Completion Report, 141 p.

Woods, P.F., and Beckwith, M.A.—Nutrient and Trace-Element Enrichment of Coeur d'Alene Lake, Idaho—Open-File Report 95–740