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Role of Limnological Processes in Fate and Transport of Nitrogen and Phosphorus Loads Delivered Into Coeur d'Alene Lake and Lake Pend Oreille, Idaho, and Flathead Lake, Montana

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National Water-Quality Assessment Program

U.S. Department of the Interior
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Cover photo: Rainy day at Lake Pend Oreille, Idaho, 1989. Turbid snowmelt plume from Clark Fork overflowing clear, dark lake water in vicinity of Warren Island/Hope Point just downstream from Clark Fork delta. View is to the northwest. Photo reproduced with permission from Michael A. Beckwith, May 1989.

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By Paul F. Woods

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FOREWORD

The U.S. Geological Survey (USGS) is committed to serve the Nation with accurate and timely scientific information that helps enhance and protect the overall quality of life, and facilitates effective management of water, biological, energy, and mineral resources (**http://www.usgs.gov/**). Information on the quality of the Nation's water resources is of critical interest to the USGS because it is so integrally linked to the long-term availability of water that is clean and safe for drinking and recreation and that is suitable for industry, irrigation, and habitat for fish and wildlife. Escalating population growth and increasing demands for the multiple water uses make water availability, now measured in terms of quantity and quality, even more critical to the long-term sustainability of our communities and ecosystems.

The USGS implemented the National Water-Quality Assessment (NAWQA) Program to support national, regional, and local information needs and decisions related to water-quality management and policy (**http://water.usgs.gov/nawqa/**). Shaped by and coordinated with ongoing efforts of other Federal, State, and local agencies, the NAWQA Program is designed to answer: What is the condition of our Nation's streams and ground water? How are the conditions changing over time? How do natural features and human activities affect the quality of streams and ground water, and where are those effects most pronounced? By combining information on water chemistry, physical characteristics, stream habitat, and aquatic life, the NAWQA Program aims to provide science-based insights for current and emerging water issues and priorities. NAWQA results can contribute to informed decisions that result in practical and effective water-resource management and strategies that protect and restore water quality.

Since 1991, the NAWQA Program has implemented interdisciplinary assessments in more than 50 of the Nation's most important river basins and aquifers, referred to as Study Units (**http://water.usgs.gov/nawqa/nawqamap.html**). Collectively, these Study Units account for more than 60 percent of the overall water use and population served by public water supply, and are representative of the Nation's major hydrologic landscapes, priority ecological resources, and agricultural, urban, and natural sources of contamination.

Each assessment is guided by a nationally consistent study design and methods of sampling and analysis. The assessments thereby build local knowledge about water-quality issues and trends in a particular stream or aquifer while providing an understanding of how and why water quality varies regionally and nationally. The consistent, multi-scale approach helps to determine if certain types of water-quality issues are isolated or pervasive, and allows direct comparisons of how human activities and natural processes affect water quality and ecological health in the Nation's diverse geographic and environmental settings. Comprehensive assessments on pesticides, nutrients, volatile organic compounds, trace metals, and aquatic ecology are developed at the national scale through comparative analysis of the Study-Unit findings (**http://water.usgs.gov/nawqa/natsyn.html**).

The USGS places high value on the communication and dissemination of credible, timely, and relevant science so that the most recent and available knowledge about water resources can be applied in management and policy decisions. We hope this NAWQA publication will provide you the needed insights and information to meet your needs, and thereby foster increased awareness and involvement in the protection and restoration of our Nation's waters.

The NAWQA Program recognizes that a national assessment by a single program cannot address all water-resource issues of interest. External coordination at all levels is critical for a fully integrated understanding of watersheds and for cost-effective management, regulation, and conservation of our Nation's water resources. The Program, therefore, depends extensively on the advice, cooperation, and information from other Federal, State, interstate, Tribal, and local agencies, non-government organizations, industry, academia, and other stakeholder groups. The assistance and suggestions of all are greatly appreciated.

Robert M. Hirsch
Associate Director for Water

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

Multiply	By	To obtain
centimeter (cm)	0.3937	inch (in.)
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
kilogram (kg)	2.205	pound (lb)
kilometer (km)	0.6214	mile (mi)
meter (m)	3.281	foot (ft)
meter per year (m/yr)	3.281	foot per year (ft/yr)
square kilometer (km^2)	0.3861	square mile (mi^2)

To convert °C (degrees Celsius) to °F (degrees Farenheit), 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 (NGVD 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

µg/L microgram per liter
µm micrometer
mg/L milligram per liter
mg/kg milligram per kilogram

Role of Limnological Processes in Fate and Transport of Nitrogen and Phosphorus Loads Delivered Into Coeur d'Alene Lake and Lake Pend Oreille, Idaho, and Flathead Lake, Montana

By Paul F. Woods

Abstract

The fate and transport of nutrient loads, following their delivery into a lake, result from the integration of all hydrologic, physical, chemical, and biological processes that operate within that lake. If only empirical relations such as areal water load, hydraulic residence time, trap efficiency, and mean depth are used to estimate nutrient fate and transport without consideration of the other complex limnological processes involved, the magnitude of nutrient retention by the lake may be incorrectly predicted. The nutrient retentions empirically predicted for northern Idaho's Coeur d'Alene Lake and Lake Pend Oreille and northwestern Montana's Flathead Lake did not agree with the nutrient retentions measured for the three lakes on the basis of quantitative differences between input and output loads.

The three lakes are within the 81,600-square-kilometer Northern Rockies Intermontane Basins study area, which was added in 1996 to the U.S. Geological Survey's National Water-Quality Assessment Program. The lakes were selected for evaluation of nutrient fate and transport because they are affected by nutrient enrichment, their input and output nutrient loads had been quantified, and their limnological characteristics had been extensively studied.

The three lakes represent a broad range in physical limnological characteristics, which can be expected to influence the fate and transport of nutrients within the lakes. Lake volumes range from 2.8 (Coeur d'Alene Lake) to 53.9 (Lake Pend Oreille) cubic kilometers. Lake Pend Oreille is the deepest (357 meters), and Coeur d'Alene Lake is the shallowest (63.7 meters). Coeur d'Alene Lake has the shortest hydraulic residence time (lake volume divided by mean annual outflow volume), 0.50 year; the other two lakes have longer hydraulic residence times—2.2 years for Flathead Lake and 2.4 years for Lake Pend Oreille.

The annual loads of nutrients delivered into the three lakes from drainage basin and atmospheric sources varied widely; total nitrogen loads ranged from 945,000 to 5,670,000 kilograms, and total phosphorus loads ranged from 43,600 to 408,000 kilograms. Lake Pend Oreille received and discharged the largest loads of both nutrients; Coeur d'Alene Lake received and discharged the smallest loads. Coeur d'Alene Lake and Lake Pend Oreille retained about 15 percent of the total nitrogen loads they received; Flathead Lake retained about one-third of the nitrogen load it received. The retention of total phosphorus was much different for Coeur d'Alene and Flathead Lakes; respectively, they retained about one-half and three-fourths of the phosphorus loads they received. Lake Pend Oreille retained less than about 17 percent of the total phosphorus load it received.

If only morphometric values such as mean depth and maximum depth were considered, the lake with the largest values, Lake Pend Oreille, would be expected to retain the largest percentage of total nitrogen and phosphorus loads received. The unexpected small retention of both nutrients, particularly phosphorus, by Lake Pend Oreille indicated that limnological processes other than just physical sedimentation were affecting the fate

and transport of nutrient loads delivered to that lake.

Nutrient retention, or the lack thereof, was strongly related to circulation processes, in a spatial and temporal context, in the three lakes. The inflow plumes from their primary tributaries were routed primarily as overflow, especially during snowmelt runoff, when each lake received most of its annual loads of total nitrogen and phosphorus. The long, narrow shape of Coeur d'Alene Lake, along with its short hydraulic residence time, was not empirically predictive of nutrient retention. In contrast, the other two lakes were much deeper, had much larger and wider basins, and had hydraulic residence times longer than 2 years; all of which would predict substantial retention of nutrients. Inflow-plume routing in Flathead Lake during snowmelt runoff tended to follow a lengthy and somewhat circular path, both favorable to retention. Inflow-plume routing of snowmelt runoff in Lake Pend Oreille was directed primarily into the shallow northern basin that leads to the lake's outlet, not into the deep southern basin with its large retentive capacity for nutrients. The formation of a thermal bar along the approximate boundary between the shallow and deep basins of Lake Pend Oreille was postulated as a major cause of its small retention of nutrients.

The influence of chemical and biological processes, in addition to physical processes, was evident in each of the lakes on the basis of differences in partitioning of nutrients between the bioavailable (dissolved) and particulate fractions in input and output loads. Input and output loads of total nitrogen in Coeur d'Alene Lake differed little in their proportions of bioavailable and particulate nitrogen. Of the total nitrogen input to Flathead Lake, 42 percent was bioavailable; that proportion had declined to 23 percent at the lake's outlet. The proportion of bioavailable nitrogen in Lake Pend Oreille was comparable to that in Flathead Lake, but the average proportion declined from 36 percent at the lake's inlet to 24 percent at the outlet. The shifts in partitioning of nitrogen were attributable in part to phytoplankton assimilation of bioavailable nitrogen in each of the lakes. In Coeur d'Alene Lake, the addition of bioavailable nitrogen from a substantial benthic flux was an important internal source.

Input and output proportions of bioavailable and particulate phosphorus differed little in Coeur d'Alene Lake, even though the lake retained about 50 percent of its total phosphorus input load. Nutrient partitioning and retention in Flathead Lake were comparable to those in Coeur d'Alene Lake, except that Flathead Lake retained about 75 percent of its input load of phosphorus. The output proportion of bioavailable phosphorus in Lake Pend Oreille was slightly smaller than the input proportion. The lack of substantial shifts in partitioning of phosphorus between input and output loads, despite substantial sedimentation of input loads, was attributable both to the propensity of bioavailable phosphorus to sorb to inorganic and organic particulates and to the production of particulate phosphorus as a result of phytoplankton assimilation of bioavailable phosphorus.

The primary determinants of the fate and transport of nutrients in these three lakes were physical limnological processes such as inflow-plume routing and sedimentation. However, the evaluation of chemical and biological processes was essential to decipher how the fate and transport of nutrients were altered within each lake.

INTRODUCTION

Overview of National Water-Quality Assessment Program

Industry and government have made substantial financial investments over the past several decades with the intent to improve water quality across the Nation; despite these efforts, numerous water-quality issues remain. To provide consistent and scientifically sound information for managing the Nation's water resources, the U.S. Geological Survey (USGS) began full-scale implementation of a National Water-Quality Assessment (NAWQA) Program in 1991. The long-term goals of the NAWQA Program are to (1) provide a nationally consistent description of current water-quality conditions for a large part of the Nation's water resources, (2) detect long-term trends (or lack of trends) in water quality, and (3) identify and describe major factors that affect observed water-quality conditions and trends (Hirsch and others, 1988). The design of the program enables integration of information into a nationally consistent data base for comparisons of water-quality data over a large range of geographic and hydrologic conditions. Fifty-two NAWQA study areas, comprising many of the Nation's most important river basins and aquifer systems, have been investigated since the program started in 1991.

Overview of Northern Rockies Intermontane Basins Study Area

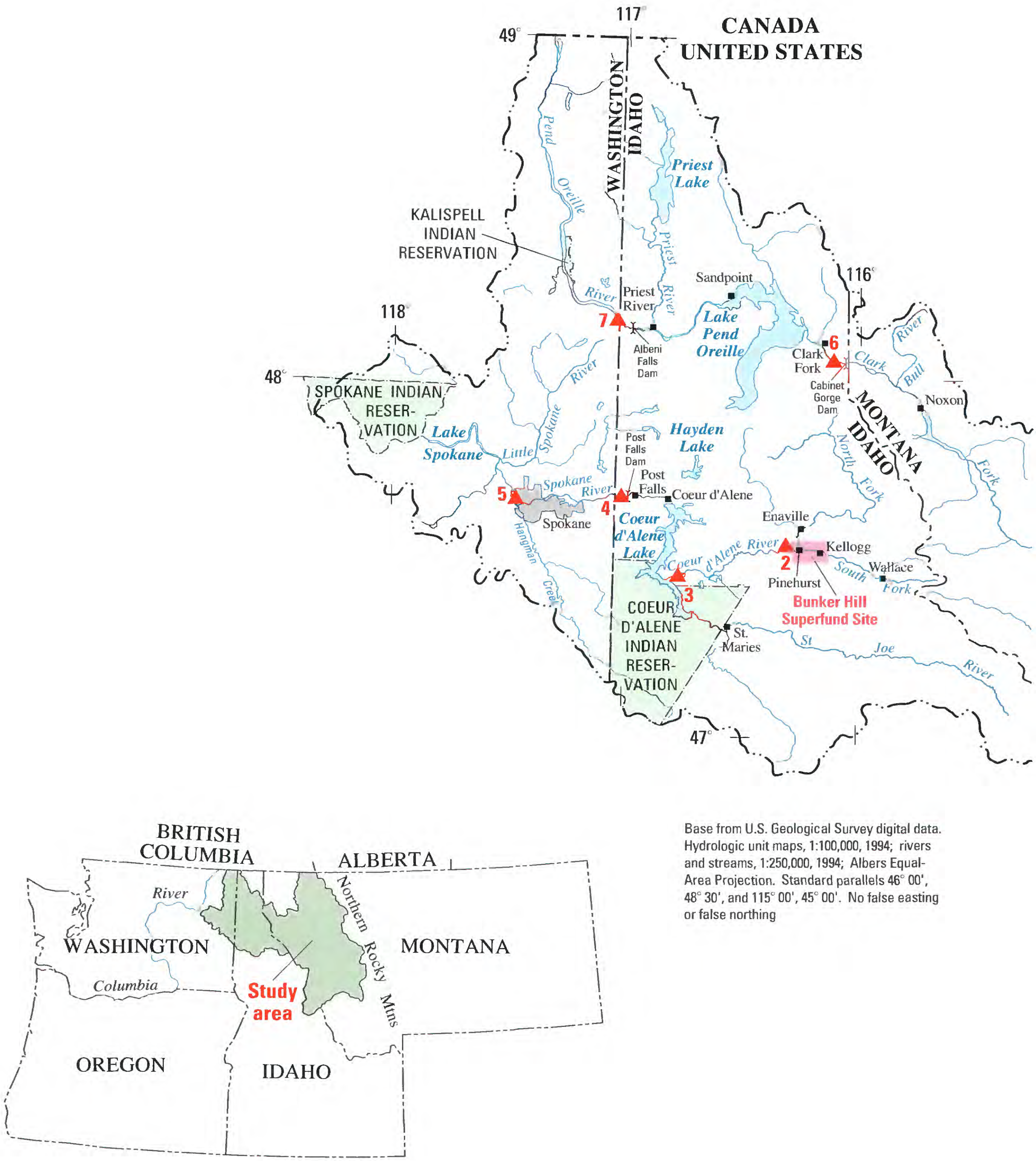
The Northern Rockies Intermontane Basins (NROK) study area was selected by the USGS for inclusion in the NAWQA Program for the following four reasons: (1) the area includes several important river systems; (2) land use/land cover in the area is a mixture of forested, agricultural, urban, and developing areas; (3) the area contains major sole-source aquifers such as the Spokane Valley/Rathdrum Prairie and Missoula Valley aquifers; and (4) mining practices have affected the quality of streams and aquifers (Tornes, 1997). Extensive consultation with water-resource managers, planners, State and local governments, and citizen groups identified five high-priority, regional-scale, water-quality issues within the NROK study area: (1) toxic trace elements in surface water and ground water; (2) nutrients in surface water and ground water from point and nonpoint sources; (3) degradation of surface water and ground water from urban areas and suburban development; (4) sedimentation from timber harvesting and agriculture; and (5) effects of these inputs on aquatic biological communities (Tornes, 1997). The USGS began study activities in the NROK study area in late 1996.

The NROK study area is situated in western Montana, northern Idaho, and eastern Washington and encompasses 81,600 km^2 (fig. 1). The Clark Fork-Pend Oreille River Basin constitutes about 79 percent of the area; the Spokane River Basin constitutes the remainder. The study area lies entirely within the Columbia River Basin and Northern Rocky Mountains physiographic provinces. Topography ranges from high, mountainous areas to large, flat-lying valleys. Elevations range from about 3,000 m in the mountains and about 1,700 m in the mountain valleys of western Montana to about 460 m along the Spokane River in eastern Washington. The intermontane basins of western Montana receive as little as 38 cm of precipitation annually, whereas the area near the Continental Divide in northwestern Montana receives more than 250 cm of precipitation (Maret and Dutton, 1999). Snowmelt from April to July generates most of the annual runoff in the study area (Kendy and Tresch, 1996).

The Clark Fork originates in southwestern Montana near Butte and flows northwestward about 560 km to Lake Pend Oreille in northern Idaho. The Pend Oreille River exits the lake and flows northward to join the Columbia River in Canada. The mean annual streamflow of the Pend Oreille River near the United States-Canadian border is about 790 m^3/s (Tornes, 1997). The Clark Fork's major tributaries, in downstream order, are the Blackfoot, Bitterroot, and Flathead Rivers. Within northern Idaho, the Coeur d'Alene and St. Joe Rivers are the two principal tributaries to Coeur d'Alene Lake, which is drained by the Spokane River. The Spokane River flows westward and enters the Columbia River in eastern Washington. The mean annual streamflow at the USGS gaging station Spokane River at Spokane, Washington (station 5, fig. 1), is about 200 m^3/s (Tornes, 1997).

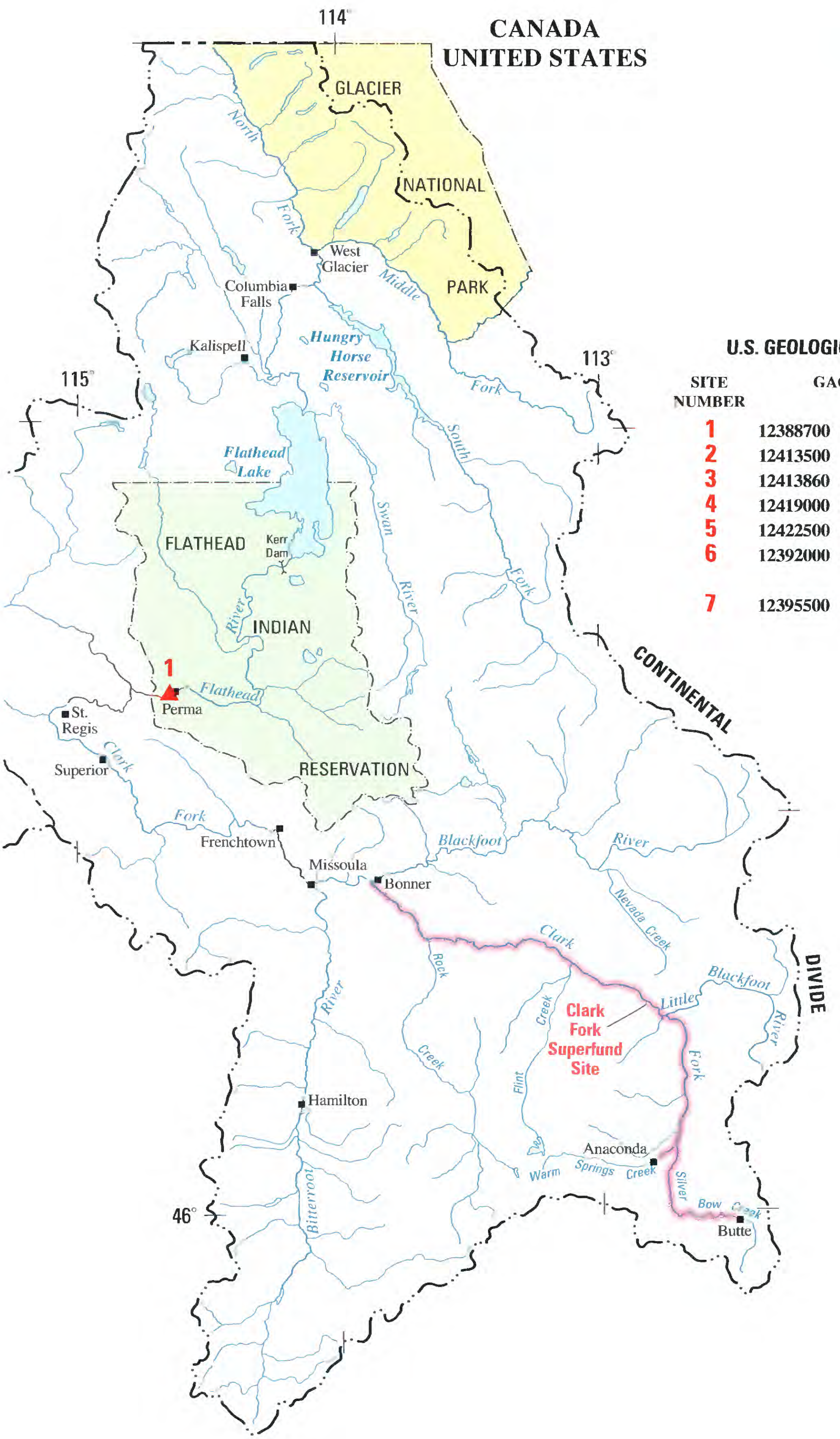
The NROK study area contains numerous large, natural lakes and reservoirs. The Clark Fork-Pend Oreille River Basin contains Hungry Horse Reservoir, Flathead Lake, Lake Pend Oreille, and Priest Lake; the Spokane River Basin contains Coeur d'Alene Lake (fig. 1). Flathead Lake is the largest natural freshwater lake in the Western United States; Lake Pend Oreille is the 21st-largest and fifth-deepest freshwater lake in the United States (Bue, 1963). These five water bodies significantly influence the hydrology and water quality of the NROK study area; their combined volume, about 87 km^3, represents more than 3 times the combined annual discharge, about 28 km^3, delivered to the Columbia River by the Pend Oreille and Spokane Rivers.

Several of the high-priority, regional-scale, water-quality issues listed by Tornes (1997) for the NROK study area have affected Coeur d'Alene and Flathead Lakes and Lake Pend Oreille. Nutrients from point and nonpoint sources have led to concerns about nutrient enrichment and potential eutrophication of all three lakes. Historical mining, ore-processing, and tailings-disposal activities in the study area have led to substan-



Base from U.S. Geological Survey digital data. Hydrologic unit maps, 1:100,000, 1994; rivers and streams, 1:250,000, 1994; Albers Equal-Area Projection. Standard parallels 46° 00', 48° 30', and 115° 00', 45° 00'. No false easting or false northing

Figure 1. Location of the Northern Rockies Intermontane Basins study area, selected dams, selected U.S. Geological Survey gaging stations, Indian Reservations, and Glacier National Park, Montana, Idaho, and Washington.



EXPLANATION

- Superfund study area
- Basin boundary
- ▲ 4 — U.S. Geological Survey gaging station and site number
- Kerr Dam — Dam and name

U.S. GEOLOGICAL SURVEY GAGING STATIONS

SITE NUMBER	GAGING STATION IDENTIFICATION NUMBER AND NAME	
1	12388700	Flathead River at Perma, Montana
2	12413500	Coeur d'Alene River near Cataldo, Idaho
3	12413860	Coeur d'Alene River near Harrison, Idaho
4	12419000	Spokane River near Post Falls, Idaho
5	12422500	Spokane River at Spokane, Washington
6	12392000	Clark Fork at Whitehorse Rapids, near Cabinet, Idaho
7	12395500	Pend Oreille River at Newport, Washington

0 10 20 30 40 50 KILOMETERS
0 10 20 30 MILES

tial trace-element contamination of terrestrial, riparian, and riverine habitats (Idaho Department of Environmental Quality, 2001; URS Greiner Inc., and CH2M-Hill Inc., 2001a) upstream from Coeur d'Alene Lake and Lake Pend Oreille. The NROK study area contains two of the Nation's largest Superfund sites, the Clark Fork Superfund site in the Clark Fork-Pend Oreille River Basin and the Bunker Hill Superfund site in the Spokane River Basin (fig. 1).

Despite these water-quality issues and the importance of these lakes to the hydrology of the NROK study area, no limnological sampling was conducted by the NAWQA Program within the NROK study area. That lack of limnological sampling reflected the NAWQA Program's decision not to study water quality in lakes and reservoirs for any of the 52 study areas; that decision was based primarily on budgetary constraints. The planning phase of the NAWQA Program, begun in 1986, resulted in a national program that was an aggregation of individual study areas in key river basins and aquifer systems. The program design emphasized a multitude of physical, chemical, and biological measurements over multiyear and decadal time-scales. The high cost of conducting limnological sampling according to the NAWQA Program design resulted in the decision to target only freshwater streams and aquifers.

The desirability for limnological evaluation of lakes in the NROK study area became evident for several reasons as the study team reviewed historical data and published reports for the study area. First, several of the lakes were likely to significantly affect downstream water quality because of their very large volume in relation to annual discharge. Second, several of the lakes have been studied extensively over the past two decades. Substantial riverine loading data for nutrients are available for Coeur d'Alene and Flathead Lakes and Lake Pend Oreille; evaluation of these data revealed a distinct lake effect on the relation between inflow and outflow loads. Besides riverine loading data, these three lakes also have been sampled extensively for physical, chemical, and biological characteristics that would be useful for evaluating limnological effects on constituent transport. Third, each of the three lakes receives more than 85 percent of its annual inflow of water from a single tributary (Flathead Lake and Lake Pend Oreille) or two tributaries (Coeur d'Alene Lake). In lieu of NAWQA-funded limnological sampling of lakes in its study area, the NROK study team devised this analysis as an alternative approach for their evaluation of the effects of lakes on constituent transport.

Purpose and Scope

The purpose of this report is to describe the role of limnological processes in determining the fate and transport of nutrients delivered into and discharged from three large, natural lakes within the NROK study area. Coeur d'Alene and Flathead Lakes and Lake Pend Oreille represent a broad range in physical limnological characteristics, which can be expected to significantly influence the fate and transport of nutrients delivered into the lakes. The study approach was to evaluate the substantial amount of historical limnological and riverine loading data for these three lakes. The initial phase of the evaluation was quantification of inflow and outflow loads of nutrients; subsequent phases of the evaluation focused on the influence of physical, chemical, and biological processes on in-lake distribution and partioning of nutrients. Information gained from this study of the cumulative limnological processes influencing nutrients in the NROK lakes will benefit future lake-assessment studies and activities designed to manage and protect lake and reservoir quality.

DESCRIPTION OF DRAINAGE BASINS

Coeur d'Alene Lake

Coeur d'Alene Lake, Idaho's second largest, is located in northern Idaho within the 17,300-km^2 Spokane River Basin. The lake occupies the drowned river valley of the Pleistocene Spokane River and its two principal tributaries, the Coeur d'Alene and St. Joe Rivers. The valley was dammed by infilling of the present Rathdrum Prairie-Spokane River Valley with about 100 m of coarse gravel deposits during a series of glacial outburst floods from Lake Missoula between about 18,000 and 13,000 years ago (URS Greiner Inc., and CH2M-Hill Inc., 2001b). Present-day Coeur d'Alene Lake is about 35 km long in a north-south orientation and has a maximum width of about 3.7 km and a maximum depth of about 64 m. The lake covers 129 km^2 and has a volume of 2.8 km^3 at its full-pool elevation of 648.7 m. The southern end of the lake is contiguous with four shallow lakes that were flooded in 1906 by impoundment of the Spokane River by Post Falls Dam at Post Falls. The dam provides hydroelectric power, flood control, and irrigation supply.

Coeur d'Alene Lake receives surface-water inflow from a 9,690-km^2 drainage area. About 90 percent of that inflow is delivered by the Coeur d'Alene and St. Joe Rivers (Woods and Beckwith, 1997); the lake is drained by the Spokane River, a tributary to the Columbia River. The Coeur d'Alene and St. Joe Rivers arise within the Coeur d'Alene and St. Joe Mountains, respectively. Much of the lake's drainage area is characterized by high, massive mountains and deep, intermontane valleys. Elevations range from about 650 m above sea level at the lake outlet to about 2,090 m at the Idaho-Montana border. About 75 percent of the drainage's land cover is forest (coniferous, sparse, or recovering harvest); rangeland and agriculture account for about 7 and 5 percent, respectively (Woods and Beckwith, 1997).

The lake's drainage basin receives some of the largest amounts of precipitation in Idaho. Basin topography affects the areal distribution of precipitation. Mean annual precipitation is about 64 cm at the lake, whereas mean annual precipitation is about 97 cm at Wallace, about 75 km east and 250 m higher in elevation than the lake. About 70 percent of the annual precipitation is snow during October to April. The influence of Pacific Maritime conditions can produce large rain-on-snow events during the winter. Although winter temperatures at Coeur d'Alene Lake are often below freezing, the lake normally does not freeze except at the shallow southern end.

The Coeur d'Alene River (drainage area 3,810 km^2) discharges into the southern third of the lake. Land-use activities in the drainage basin include recreation, logging, agriculture, and mining and ore processing. Most of the mining and ore-processing activities are in the drainage basin of the South Fork Coeur d'Alene River, which contains the Bunker Hill Superfund site (fig. 1). The St. Joe River (drainage area 4,520 km^2) discharges into the extreme southern end of the lake. Recreation and logging are the dominant land uses; little mining activity has occurred in this basin. Urban land use in the two basins is less than 1 percent (Woods and Beckwith, 1997).

Considerable concern exists about the potential for nutrient enrichment and subsequent eutrophication of Coeur d'Alene Lake because of land-use activities within its drainage basin and near its shoreline, in addition to intensive recreational use of the lake (Woods and Beckwith, 1997). A 1975 nutrient load study, done as part of the National Eutrophication Survey, led to the conclusion that Coeur d'Alene Lake was mesotrophic, or moderately productive (U.S. Environmental Protection Agency, 1977). A second concern is the large amount of trace elements that have been introduced into Coeur d'Alene Lake as a consequence of more than 100 years of mining and ore-processing activities in the Coeur d'Alene River Basin (Woods and Beckwith, 1997). About 85 percent of the bottom of Coeur d'Alene Lake is substantially enriched in antimony, arsenic, cadmium, copper, lead, mercury, silver, and zinc (Horowitz and others, 1993, 1995).

Flathead Lake

The Flathead Lake and River Basin, at the confluence with the Clark Fork, cover about 18,400 km^2 of northwestern Montana and southeastern British Columbia, Canada. Flathead Lake lies in a tectonic graben basin that underwent extensive glaciation during the Pleistocene; the lake was formed by moraines at the western and southern boundaries of the last ice advance and is probably a remnant of a larger glacial lake system (Moore and others, 1982). The present-day lake is about 56 km long and has a maximum width of about 26 km and a maximum depth of about 113 m. The lake's 300-km shoreline is often steep and rocky, especially along the eastern shore. The lake covers 496 km^2 and has a volume of 23.2 km^3 at its full-pool elevation of 879 m. The lake's surface elevation was raised about 3.4 m by completion of Kerr Dam in the 1930's. The dam, about 7 km downstream from the lake's natural outlet, is operated for flood control and hydropower purposes.

The Flathead River is the lake's major tributary; it enters the lake at the shallow northern end. At its inflow to the lake, the Flathead River drains about one-half of the Flathead Lake and River Basin. Inflow from other tributaries increases the drainage area of Flathead Lake to about 11,400 km^2 at its outlet. The lake is drained at the shallow southern end by the Flathead River, which is the largest tributary to the Clark Fork.

Most of the basin's northern, northwestern, and eastern regions are characterized by high, rugged mountains interspersed with deep, intermontane valleys. The southern and southwestern regions are dominated by the Flathead Valley, which contains Flathead Lake. Elevations range from about 880 m at the lake outlet to more than 3,000 m in Glacier National Park along the basin's eastern boundary. The dominant land cover in the basin's high mountain region is coniferous forest, whereas the dominant land cover in the Flathead Valley and adjacent foothills is grasses and, in drier areas, sagebrush. Logging is the dominant land use in the mountainous areas of the basin. Within the Flathead Valley, agriculture is an important land use, along with urban and rural development. Recreation is also an important land use in the basin because about 60 percent of the basin's area is contained within Glacier National Park and National Forest wilderness and roadless areas.

Climatic conditions in the basin are dominated by Pacific Maritime influences; however, cold airmasses of continental origin occasionally affect the area in the winter. At the lake, mean annual precipitation is about 50 cm; along the Continental Divide, it is about 250 cm. Most of the annual precipitation is snow during the winter. Flathead Lake's substantial heat-storage capacity influences local weather conditions by moderating air temperatures and increasing precipitation to the east of the lake. Although winter air temperatures are often below freezing, the lake normally does not freeze over for any appreciable period, primarily because of its very large volume and wind-induced turbulence.

Eutrophication is the primary water-quality issue for Flathead Lake (Stanford and others, 1997). Nutrient loadings to the lake originate from a combination of drainage basin and nearshore sources. The extensive road network developed for logging has contributed sediment and associated nutrients to the lake. Farming and grazing in the Flathead Valley are also sources of sediment and nutrients to the lake. Residential development around the lake's shoreline and its adjacent drainages has increased nutrient loadings from nonpoint sources, as well as from municipal wastewater-treatment facilities.

Lake Pend Oreille

Lake Pend Oreille is Idaho's largest lake. The lake is located in northern Idaho and is an important feature of the 64,300-km^2 Clark Fork-Pend Oreille River Basin. The lake lies in a glacially scoured graben, the southern end of which was plugged by massive deposition of sediments transported by catastrophic glacial outburst floods from Lake Missoula during the late Pleistocene (Molenaar, 1988). The deep, U-shaped basin of the lake separates three mountain ranges: the Cabinet, the Selkirk, and the Coeur d'Alene. Albeni Falls Dam, on the Pend Oreille River (fig. 1), was completed in 1952 and increased the lake's normal surface elevation by 4.3 m. The dam is operated to provide hydroelectric power, flood control, navigation, recreation, and fish and wildlife conservation. Present-day Lake Pend Oreille, including its outlet arm behind Albeni Falls Dam, is about 110 km long and has a maximum width of about 10.8 km and a maximum depth of about 357 m. The lake and its outlet arm cover 369 km^2 and have a volume of 54.2 km^3 at a normal full-pool elevation of 628.6 m. Excluding its outlet arm, the lake covers 329 km^2, contains 53.9 km^3, and is about 50 km in length.

Lake Pend Oreille, including its outlet arm, receives surface-water inflow from a 62,700-km^2 drainage area, the vast majority of which is in northwestern Montana. About 85 percent of the lake's surface-water inflow is delivered by the Clark Fork (Frenzel, 1993a), which enters the lake from the east. The Clark Fork begins near Butte, Montana, and drains an extensive area west of the Continental Divide, including the Flathead River and Flathead Lake. The Clark Fork is impounded by Cabinet Gorge Dam about 11 km upstream from Lake Pend Oreille; the drainage area upstream from Cabinet Gorge Dam is 57,150 km^2. The dam was completed in 1951 and is operated primarily for hydroelectric power generation. Lake Pend Oreille is drained by the Pend Oreille River, a tributary to the Columbia River.

Much of Lake Pend Oreille's drainage basin is characterized by mountainous terrain interspersed with broad valleys. Elevations range from about 3,000 m in northwestern Montana and Glacier National Park to about 600 m near the Idaho-Washington border. In the lake's southern basin, much of the shoreline rises precipitously to elevations between 1,500 and 2,000 m. Most land cover in the basin is coniferous forest; rangeland and agriculture together account for about 20 percent. Land-use activities include recreation, logging, agriculture, mining, and grazing; urban land use applies to only about 1 percent of the drainage area.

Lake Pend Oreille responds to a wide range of climatological conditions because the drainage area of the Clark Fork is so large relative to the lake's local drainage area. Most of the annual precipitation is snow during the winter months. The influence of Pacific Maritime conditions can produce large rain-on-snow events during the winter. Mean annual precipitation at the northern end of the lake is 84 cm, whereas it is 125 cm in the adjacent mountains. Near the Continental Divide in northwestern Montana, mean annual precipitation is about 250 cm. Because of its considerable volume and heat-storage capacity, the lake does not freeze except at the shallow northern end.

Similar to Coeur d'Alene and Flathead Lakes, the potential for eutrophication by excessive nutrient loads is a water-quality concern for Lake Pend Oreille. Studies in the early 1990s documented that increased lake productivity was manifested largely in the littoral zone; the lake's limnetic zone remained oligotrophic (Hoelscher and others, 1993). The lake's primary inflow, the Clark Fork, contributed about 80 percent of the nitrogen and phosphorus loads annually delivered to the lake (Frenzel, 1993b). Trace-element contamination is another water-quality issue for Lake Pend Oreille. More than a century of mining, ore-processing, and tailings disposal has left the upper Clark Fork severely contaminated with trace elements (Andrews, 1987; Moore and Luoma, 1990); as a result, four Superfund sites have been listed in the upper Clark Fork. Several impoundments downstream from the Superfund sites and upstream from Lake Pend Oreille have trapped part of the trace-element-contaminated sediments introduced into the Clark Fork (Moore, 1997). However, bed-sediment samples collected from Lake Pend Oreille by the U.S. Army Corps of Engineers (P.L. Hall, U.S. Army Corps of Engineers, written commun., 1989) and collected in the Pend Oreille River near its confluence with the Priest River by the U.S. Geological Survey (Beckwith, 2002) indicated substantially elevated concentrations of cadmium, copper, lead, and zinc. These results suggest that trace-element-contaminated sediments are being transported into and through the lake.

EVALUATION APPROACH

The fate and transport of water and associated constituents following their delivery into a lake are determined by the interactions of a myriad of physical, chemical, and biological processes operating within the lake over a wide range of spatial and temporal scales. The outcome of those interactions determines the quantity and nature of constituents discharged from the lake at its surface-water outlet. Nitrogen and phosphorus compounds, the principal constituents of concern in this report, occur in dissolved, colloidal, and particulate fractions. These fractions of nitrogen and phosphorus vary in their degree of participation in chemical and biological processes within the lake's water column, as well as within the lakebed sediments. The lake's effect on fate and transport is likely to be quite different for particulate-fraction constituents, which have high densities relative to that of water, than for dissolved-fraction and colloidal-fraction constituents, which have low densities. In general, lakes are efficient traps for sediment because the significant decrease in flow velocity and turbulence within a lake inhibits advective transport of sediments and particulate-fraction constituents. In contrast, dissolved and colloidal constituents are transported by convection and diffusion, as well as by advection, after their delivery into a lake.

The initial phase of the evaluation was to quantify the differences in nutrient loadings upstream and downstream from each lake. The second phase was to define the combined influence of the hydrologic characteristics of each drainage basin and physical limnological characteristics of each lake on the fate and transport of nutrients. The third phase was to determine the spatial and temporal variability of chemical and biological constituents and partitioning of nutrients within each lake. The final phase was to combine the insight gained from the first three phases of evaluation to distinguish the effects of hydrological and physical limnological processes from the effects of chemical and biological processes in determining nutrient fate and transport through each lake's water mass.

NUTRIENT LOADS

Overview

The primary objective of quantifying nutrient loads in this evaluation was to demonstrate the importance of understanding how limnological processes influence the quantitative differences between loads of nutrients input to and output from a lake. The initial step in gaining this understanding is to quantify those nutrient loads over equivalent timescales. Load is defined as the quantity of a constituent passing a riverine cross section per unit of time and is calculated as the product of constituent concentration, discharge, and appropriate conversion factors for measurement units.

Although the calculation of load is simple mathematically, the method of deriving concentration and discharge can produce substantial differences in load calculations, especially for periods longer than 1 day. Both constituent concentration and discharge vary substantially over the course of a year. Perhaps more importantly, the two quantities are nonsynchronous in their temporal variation; also, concentrations of dissolved constituents respond differently to discharge changes than do concentrations of particulate constituents. Thus, constituent loads may vary on a daily, monthly, and (or) annual basis. A variety of methods, from basic to complex, have been used to process multiple-date data sets of concentration and discharge into estimates of seasonal and annual loads. A basic method is to multiply the mean values of concentration and discharge over the period of interest to derive the load. Additional temporal resolution can be gained by linear interpolation of measured values of concentration and discharge to examine daily load variability over the period of interest. More complex methods use linear regression, either simple or multiple, to relate load or concentration to discharge and other explanatory variables such as seasonality and time trend.

Constituent loads typically are quite variable, both within and among years, because changes in discharge are often the dominant influence on loads. This is especially true for sediment-associated constituents where the sediment supply is not limited. In this situation, the smallest loads of sediment-associated constituents within a year typically are associated with minimum discharges, owing to reduced water velocities that produce less erosion and transport. Alternatively, elevated water velocities during maximum discharge within a year result in erosion and transport of the largest loads of sediment-associated constituents. The pattern is generally similar for dissolved constituents, but differences in loads between high and low discharge are reduced because the transport of dissolved constituents is less dependent on stream velocity. These within-year patterns of variability in loads for sediment-associated and dissolved constituents are important considerations in assessing a lake's effects on the fate and transport of nutrient loads. The foregoing logic for seasonal loads also applies to annual loads; in general, larger constituent loads are transported during high-discharge years than during low-discharge years.

A lake's hydrologic budget, an accounting of the amount of water entering and exiting the lake, is an important determinant of constituent loads delivered into and discharged from the lake. The hydrologic budget provides an accounting of gains and losses of water associated with surface-water inflow and outflow, precipitation and evaporation, ground-water inflow and outflow, wastewater-treatment facility inflows, industrial and municipal withdrawals, and changes in lake storage. If each water source for the lake can be quantified and assigned an associated concentration, then a constituent budget can be calculated for the lake. Hydrologic and constituent budgets are important tools for evaluating the in-lake fate and transport of particulate, colloidal, and dissolved constituents that affect lake water-quality characteristics.

Coeur d'Alene Lake

A nutrient load/lake response study of Coeur d'Alene Lake conducted cooperatively by the USGS and Idaho Department (formerly, Division) of Environmental Quality (IDEQ) quantified hydrologic, nutrient, and trace-element budgets for calendar years 1991 and 1992 (Woods and Beckwith, 1997). Numerous budget components were quantified, either by measurement or estimation; details about data sources and computations were presented by Woods and Beckwith (1997). Riverine-derived constituent loads were computed using the computer program FLUX (Walker, 1996), a regression-based approach for estimating loads that stratifies streamflow and constituent concentration data to reduce prediction error. The stratified data sets then are used to compute a series of loads on the basis of five different regression equations. The regression equation and stratification method that yields the smallest coefficient of variation is considered the best estimate of load. FLUX provides several additional diagnostic tools for assessing results; these include plots of residuals and hypothesis tests for various model parameters.

The hydrologic budgets reported by Woods and Beckwith (1997) indicated that the combined inflows from the lake's two primary tributaries, the Coeur d'Alene and St. Joe Rivers, accounted for about 92 percent of all inflows to the lake. The St. Joe River was the larger inflow source, delivering about one-half of the inflow to the lake. Precipitation on the lake surface accounted for less than 2.5 percent of the hydrologic budget in each year. At least 90 percent of the water exiting the lake was by way of the Spokane River, the remainder was evaporation loss from the lake surface and ground-water outflow from the lake's northern margin.

Annual loads of total nitrogen and phosphorus delivered to and discharged from Coeur d'Alene Lake during 1991 and 1992 (table 1) were calculated on the basis of constituent budgets reported by Woods and Beckwith (1997). These 2 years represented different hydrologic conditions for the lake. In 1991, the annual mean lake outflow as measured in the Spokane River was 199 m^3/s, or 112 percent of the long-term mean annual outflow of 177 m^3/s (Brennan and others, 2001); in contrast, annual mean lake outflow for the 1992 water year was 99 m^3/s, only 56 percent of the long-term value. As expected, nitrogen and phosphorus loads for 1992 were also substantially less than those for 1991. On the basis of magnitude, the St. Joe River, and then the Coeur d'Alene River, delivered the most nitrogen and phosphorus to the lake. Combined, these two rivers delivered 83 and 82 percent, respectively, of the total nitrogen and phosphorus loads during 1991–92. Atmospheric deposition of nutrients on the lake surface by precipitation and dryfall was minor, delivering less than 8 percent of the nitrogen and less than 15 percent of the phosphorus.

Table 1. Annual input, output, and retained loads of total nitrogen and phosphorus, Coeur d'Alene Lake, Idaho, calendar years 1991 and 1992

[kg, kilograms; km^3, cubic kilometers; retained load values are rounded]

Variable, unit	[1]1991	[1]1992
Mean annual lake outflow[2], km^3	6.37	3.17
Total nitrogen		
Input load, kg	2,150,000	945,000
Output load, kg	2,030,000	860,000
Retained load[3], kg	120,000	85,000
Retained load/input load, percent	6	9
Total phosphorus		
Input load, kg	115,000	43,600
Output load, kg	36,100	27,600
Retained load[3], kg	78,900	16,000
Retained load/input load, percent	69	37

[1] From Woods and Beckwith (1997).
[2] Measured at Spokane River near Post Falls, Idaho (station 4, fig. 1).
[3] Input load - output load.

The magnitude and percentage of the total nitrogen and phosphorus loads retained by the lake also were calculated on the basis of Woods' and Beckwith's 1997 constituent budgets (table 1). The retained load of nitrogen was 85,000 kg in 1992, 35,000 kg less than in 1991. However, the retained loads for each year were a similar percentage of their respective input loads, 5.6 percent in 1991 and 9.0 percent in 1992. The retained load of phosphorus in 1991 was 78,900 kg, about 5 times that retained in 1992. Unlike nitrogen, the retained loads for phosphorus were not similar between the 2 years; the percentage in 1991 was 69 but, in 1992, the percentage was only 37. On this basis, the large differences in inflow and outflow volumes for 1991 and 1992 had little effect on the lake's ability to retain nitrogen but a large effect on its ability to retain phosphorus.

Flathead Lake

The primary sources of hydrologic and nutrient budget information for Flathead Lake were twofold: a doctoral dissertation examining the effects of turbidity on the lake's biogeochemistry and trophic state (Stuart, 1983), and a 1978–82 limnological assessment (Stanford and others, 1983) prepared for the U.S. Environmental Protection Agency (EPA). Numerous additional years of nutrient budget information for Flathead Lake also were presented by Stanford and others (1995, 1997); however, much of their phosphorus load data could not be used for the purposes of this report because of an introduced bias. These authors adjusted their nutrient load calculations for phosphorus to focus on bioavailable (dissolved) phosphorus; when the total suspended-solids concentration in a sample exceeded 10 mg/L, they reduced the associated total phosphorus concentration in that sample by 90 percent. The effect was to mathematically discount most of the sediment-associated phosphorus load from the lake's primary inflow source, the Flathead River, and, thereby, bias the calculation of phosphorus retention in Flathead Lake.

The limnological assessment (Stanford and others, 1983) presented hydrologic and nutrient budgets for 1978–82, as well as details about data sources and computations for loads delivered from riverine, atmospheric, wastewater, and nearshore sources. Riverine-derived constituent loads were computed using monthly mean values of streamflow and nutrient concentration. The total phosphorus loads reported in the limnological assessment included the introduced bias described earlier, but the bias affected only the influent Flathead River because suspended-sediment concentrations at the lake's outlet did not exceed 10 mg/L. Fortunately, the authors reported both unbiased and biased total phosphorus loads for the Flathead River for 1978–82, thereby providing the data needed to calculate an unbiased total phosphorus budget for the lake over that period. The additional years of nutrient budgets reported by Stanford and others (1995, 1997) covered a wide range of hydrologic conditions; however, only biased phosphorus loads were reported.

Hydrologic and nutrient budgets calculated by Stanford and others (1983) for 1978–82 were reported as a mean for that period; these are summarized in table 2. Inflow from the Flathead River accounted for 87 percent of the lake's hydrologic budget during 1978–82; the Swan River (fig. 1) and direct precipitation on the lake surface accounted for most of the remaining inflow (Stuart, 1983). About one-half of the annual inflow to the lake was delivered during April to July, the period of snowmelt runoff (Stuart, 1983). Regarding outflow from the lake, 97 percent was by way of the Flathead River, and 3 percent was evaporation loss from the lake surface (Stuart, 1983). Hydrologic conditions were slightly less than average; the mean annual lake outflow of 294 m^3/s, as measured at Perma, during 1978–82 (table 2) was about 88 percent of the long-term mean of 336 m^3/s (Shields and others, 2001). Similar to Coeur d'Alene Lake, the input and output loads of total nitrogen were much larger than those of total phosphorus (table 2). Details on the nitrogen budget reported by Stanford and others (1983) indicated that the Flathead River delivered 80 percent of the nitrogen load to the lake, and precipitation on the lake surface delivered 11 percent. For the biased total phosphorus loads to the lake (Stanford and others, 1983), the Flathead River delivered 64 percent, whereas precipitation on the lake surface delivered 25 percent. If unbiased total phosphorus inputs are used, the Flathead River delivered 82 percent of the lake's total phosphorus load; precipitation delivered 12 percent.

Table 2. Mean annual input, output, and retained loads of total nitrogen and phosphorus, Flathead Lake, Montana, 1978–82

[kg, kilograms; km^3, cubic kilometers; mg/L, milligrams per liter]

Variable, unit	[1]1978 – 82
Mean annual lake outflow, km^3	9.41
Total nitrogen	
Input load, kg	1,590,000
Output load, kg	1,020,000
Retained load[2], kg	570,000
Retained load/input load, percent	36
Total phosphorus, biased[3]	
Input load, kg	118,000
Output load, kg	59,300
Retained load[2], kg	58,700
Retained load/input load, percent	50
Total phosphorus, unbiased[4]	
Input	242,000
Output	59,300
Retained load[2], kg	183,000
Retained load/input load, percent	76

[1] From Stanford and others (1983); loads converted from metric tons to kilograms.
[2] Input load - output load.
[3] Concentrations reduced 90 percent if suspended-solids concentrations larger than 10 mg/L for Flathead River inflow.
[4] Concentrations not reduced to account for suspended-solids concentrations larger than 10 mg/L for Flathead River inflow.

During 1978–82, the retained load of nitrogen in Flathead Lake was 570,000 kg, or 36 percent of the input load (table 2). The biased retained load of phosphorus was 58,700 kg, or 50 percent of the input load; the unbiased retained load of phosphorus was 183,000 kg, or 76 percent of the input load. Unlike the multiple-year data set available for Coeur d'Alene Lake, Flathead Lake lacks unbiased nutrient data for estimating the effects of streamflow on the magnitude of nutrient loads retained by the lake.

Lake Pend Oreille

As part of a nutrient load/lake response study of Lake Pend Oreille conducted cooperatively by the USGS and IDEQ, hydrologic and nutrient budgets for numerous sources were quantified for water years 1989 and 1990 (Frenzel, 1993a,b). Riverine-derived nutrient loads were computed using the same computer program, FLUX (Walker, 1996), that was used for the nutrient load/lake response study of Coeur d'Alene Lake (Woods and Beckwith, 1997). Hydrologic budgets reported by Frenzel (1993a) indicated that the inflow from the lake's primary tributary, the Clark Fork, accounted for about 85 percent of all inflows to the lake and its outlet arm. The Priest River (fig. 1), located near the downstream end of the lake's outlet arm, accounted for 6.4 percent of inflow to the lake and its outlet arm. Precipitation on the lake and outlet arm surface accounted for about 1.3 percent of the hydrologic budget in both years. At least 98 percent of the water discharged from the lake was by way of the Pend Oreille River; much of the remainder was evaporation loss from the lake surface.

Annual loads of total nitrogen and phosphorus delivered to and discharged from Lake Pend Oreille, including its outlet arm, during 1989 and 1990 (table 3) were calculated on the basis of the constituent budgets reported by Frenzel (1993b). In 1989, the annual mean lake outflow of 627 m^3/s was 88 percent of the long-term mean annual outflow of 716 m^3/s (Brennan and others, 2001); the annual mean lake outflow of 799 m^3/s in 1990 was 112 percent of the long-term value. Nitrogen and phosphorus loads for the above-average outflow year, 1990, were larger than those for 1989, thereby illustrating the strong positive correlation between load and streamflow. In both years, the Clark Fork delivered about 80 percent of the lake's nitrogen load and about 70 percent of its phosphorus load (Frenzel, 1993b). The Priest River delivered about 6 percent of the nitrogen load and about 9 percent of the phosphorus load. Atmospheric deposition delivered about 4.3 percent of the nitrogen load and about 5.8 percent of the phosphorus load in both years.

The retained load of nitrogen in Lake Pend Oreille was 670,000 kg in 1989 and 840,000 kg in 1990 (table 3). Despite a substantial difference in outflow volumes, the retained loads were similar percentages of the input load, 15.2 in 1989 and 14.8 percent in 1990. Retained loads of phosphorus also were similar percentages of the input load, 16.9 in 1989 and 13.5 in 1990. On this basis, the large difference in the lake's hydrologic budgets for 1989 and 1990 had little effect on the percentages of nitrogen and phosphorus loads retained by the lake.

Table 3. Annual input, output, and retained loads of total nitrogen and phosphorus, Lake Pend Oreille, Idaho, water years 1989 and 1990

[kg, kilograms; km^3, cubic kilometers]

Variable, unit	[1]1989	[1]1990
Mean annual lake outflow[2], km^3	20.0	25.6
Total nitrogen		
Input load, kg	4,410,000	5,670,000
Output load, kg	3,740,000	4,830,000
Retained load[3], kg	670,000	840,000
Retained load/input load, percent	15	15
Total phosphorus		
Input load, kg	326,000	408,000
Output load, kg	271,000	353,000
Retained load[3], kg	55,000	55,000
Retained load/input load, percent	17	14

[1] From Frenzel (1993b).
[2] Measured at Pend Oreille River at Newport, Wash. (station 7, fig. 1).
[3] Input load - output load.

Among-Lake Comparisons

The annual loads of nutrients delivered to the three lakes varied widely; total nitrogen loads ranged from 945,000 to 5,670,000 kg, whereas total phosphorus loads ranged from 43,600 to 408,000 kg (tables 1–3). Lake Pend Oreille received the largest loads of both nutrients; Coeur d'Alene Lake received the smallest. Nutrient loads discharged from the lakes ranged from 860,000 to 4,830,000 kg of total nitrogen and from 27,600 to 353,000 kg of total phosphorus (tables 1–3). Similar to input loads, Lake Pend Oreille discharged the largest loads of both nutrients and Coeur d'Alene Lake discharged the smallest.

The variable, retained load/input load (tables 1–3), was averaged for total nitrogen and phosphorus (table 4). Coeur d'Alene Lake retained the smallest percentage (7.3) of nitrogen and Flathead Lake retained the largest percentage (36). On the basis of unbiased loads, Lake Pend Oreille retained the smallest percentage (15) of phosphorus, Coeur d'Alene Lake retained 53 percent, and Flathead Lake retained the largest percentage (76).

Table 4. Average of retained load/input load for total nitrogen and phosphorus, Coeur d'Alene Lake and Lake Pend Oreille, Idaho, and Flathead Lake, Montana

Lake	Average retained load [1] / input load, in percent	
	Total nitrogen	Total phosphorus
Coeur d'Alene[2]	7.3	53
Flathead[3]	36	[4]76
Pend Oreille[5]	15	15

[1] Input load - output load.
[2] Based on calendar years 1991–92, see table 1.
[3] Based on calendar years 1978–82, see table 2.
[4] Unbiased loads from Flathead River.
[5] Based on water years 1989–90, see table 3.

PHYSICAL LIMNOLOGY

Overview

The initial phase of evaluation demonstrated substantial quantitative differences in the relative amounts of nutrient loads delivered to and discharged from the three lakes. The next phase, discussed in this section, defines the quantitative differences in light of the combined influence of the hydrologic characteristics of each drainage basin and physical limnological characteristics of each lake.

One measure of the potential influence of a drainage basin on a lake is the ratio of drainage basin area to lake surface area. As that ratio increases, a concomitant increase in the hydrologic influence of the drainage basin upon the lake receiving the basin's runoff might be expected. However, two problems arise in this comparison of surface areas: (1) runoff from a drainage basin is highly dependent upon the amount of precipitation it receives, and (2) lake surface area is a poor indicator of lake volume. Calculation of areal water load deals more effectively with the issue of drainage basin area because the volume of runoff delivered into the lake is divided by lake surface area. As areal water load increases, the drainage basin's hydrologic influence on the lake also increases. The second problem, lake surface area, can be dealt with by considering the ratio of inflow volume to lake volume, commonly termed flushing rate (Ryding and Rast, 1989). As flushing rate increases, the drainage basin's hydrologic influence on the lake also increases because the lake's volume is replaced more frequently. The inverse of flushing rate is termed retention time and represents the time theoretically needed to fill a lake if it were empty. If lake volume is divided by lake outflow volume instead of inflow volume, then the time needed to empty the lake, the hydraulic residence time, is obtained. On an annual basis, retention time and hydraulic residence time often are comparable. Hydraulic residence time was chosen for analysis in this report because outflow volumes for the three lakes have been measured for many years.

Although retention time and hydraulic residence time are theoretical concepts, the processes that they incorporate are important for understanding fate and transport of constituents in lakes. The rate at which water enters and leaves a lake affects the amount of turbulence within the lake's water column, both in the horizontal and vertical dimensions. Years of above-normal inflow and outflow produce more water-column turbulence and increase advective transport of particulate materials. Conversely, years of below-normal inflow and outflow produce less water-column mixing and, hence, increase the trapping of sediment and associated constituents.

The potential for trapping of sediment by water bodies such as lakes and reservoirs can be estimated empirically on the basis of a nomograph that relates the ratio of storage capacity (lake volume) to inflow volume (Gray, 1973). That ratio is analogous to retention time. In the case of these three lakes, outflow volume was substituted for inflow volume; as such, hydraulic residence time was used in the nomograph to estimate trap efficiency. Given a hydraulic residence time of 0.01 year (for example, a 25-km^3 volume with a 2,500-km^3-per-year outflow volume), the estimated trap efficiency for sediment from the nomograph would be about 45 percent. If the hydraulic residence time were increased to 0.1 year (for example, a 25-km^3 lake volume with a 250-km^3-per-year outflow volume), the estimated trap efficiency would be about 86 percent. The estimated trap efficiency would increase to 95 percent or greater for hydraulic residence times equal to or longer than 1.0 year (for example, a 25-km^3 lake volume with a 25-km^3-per-year outflow volume).

The foregoing discussion provides insight into the relation of inflow or outflow magnitude on the generation of turbulence and advective transport within lakes. However, the concepts of retention and hydraulic residence times remain theoretical because lakes rarely are filled or emptied; the two descriptors are best suited for general comparisons among lakes representing wide ranges of retention and hydraulic residence times. In actuality, the movement of riverine inflows within a lake can be quite complex because of characteristics such as lake shape, lake depth, and temporal and spatial differences in density between riverine and lake water. Three generalized cases of inflow-plume routing were discussed by Fischer and others (1979): overflow, interflow, and underflow. Overflow occurs if the inflow plume is warmer (less dense) than the lake; river water floats on the lake's surface. Interflow occurs when the inflow plume is colder than the lake's upper water column but warmer than the lower water column; thus, interflow is routed to the lake depth where the temperature, or density, of the inflow plume and lake is equal. Underflow occurs when the inflow plume is colder than, or about the temperature of, the lake's lower water column. Turbulence at the interface of the inflow plume and the lake mixes the two water masses until thermal equilibrium is reached. The spatial extent of inflow-plume routing is highly dependent on the magnitude of riverine discharge. Riverine inflows generated by snowmelt runoff and floods can penetrate farther into the receiving lake because the large inflow volumes produced by such events increase turbulence and advective transport.

The physical, chemical, and biological responses of a lake to the delivery of water and associated constituents from its drainage basin are closely tied to morphometric characteristics of the lake. Calculation of such characteristics requires a bathymetric map of the lake; such maps are available for Coeur d'Alene Lake (Woods and Berenbrock, 1994), Flathead Lake (Stanford and others, 1997), and Lake Pend Oreille (Fields and others, 1996). Lake shape can vary from circular to elongate to dendritic. A long, narrow lake such as Coeur d'Alene Lake is more prone to channel inflow along its major axis. Flathead Lake and Lake Pend Oreille are also long but are much wider than Coeur d'Alene Lake; hence, their inflows are less prone to channeling along their major axis. Surface area affects the amount of atmospheric materials that may be directly deposited onto the lake's surface versus those deposited onto the lake's drainage basin. Surface area and lake shape are determinants of the lake's exposure to wind. A large surface area in combination with long or wide reaches increases the wind's ability to generate turbulence and mix the lake's water column. The maximum length and maximum width of a lake are useful descriptors of this effect but fail to convey the sheltering effects of islands or the shoreline. Maximum effective length and maximum effective width (Häkanson, 1981) are better indicators of wind exposure because they represent linear reaches absent from wind sheltering. Increased wind exposure favors the development of large-scale turbulent processes such as surface and internal seiches, which can displace large masses of water in the horizontal and vertical dimensions and, thus, are important mechanisms for water-column mixing.

Depth is also a critical lake dimension for several reasons. Deep lakes are more resistant to turbulent, full-depth mixing by wind energy, so lakebed sediments are less likely to be periodically resuspended. Because of longer settling time, organic detritus in a deep lake is more likely to have undergone remineralization by the time it reaches the lakebed. The low frequency of turbulent, full-depth mixing in deep lakes also restricts the exchange of dissolved, colloidal, and particulate constituents between the upper and lower water columns. Maximum depth only conveys information about the deepest part of a lake. The mean depth, defined as lake volume divided by lake surface area, provides more information about the distribution of depth throughout a lake. A lake with a large surface area and extensive shallow areas has a relatively small mean depth because of its small volume. A similar-sized lake with extensive deep areas has a larger mean depth because of its large volume. For large lakes, mean depth is considered the primary morphometric variable because of its general inverse correlation with lake productivity (Wetzel, 1975). Mean depth also has been an important variable in the development of empirical models relating lake productivity to nutrient loadings (Reckhow and Chapra, 1983).

The vertical distribution of water-quality properties and constituents are closely linked to the physical limnological processes of thermal stratification and convective circulation. Thermal structure in some lakes may be established, in part, by riverine inflows routed as overflow. However, the major source of heat for most lakes is the solar radiation that impinges upon the lake's surface (Wetzel, 1975). Wind energy distributes the surface heat into the water column until density differences impede deeper mixing. In lakes deep enough to resist full-depth convective circulation, solar heating and wind mixing during the summer vertically segregate the water column into three zones: epilimnion, metalimnion, and hypolimnion. The upper zone, the epilimnion, is the stratum in which most of the lake's biological production occurs because light is generally sufficient to drive photosynthetic production by phytoplankton. The metalimnion is the stratum of maximum temperature change; density differences may be sufficient to impede settling of detrital material into the lower stratum, the hypolimnion. A thermocline is present within the metalimnion if the rate of temperature change exceeds 1°C/m. The hypolimnion overlies the lakebed sediments and typically has more thermal stability than the epilimnion and metalimnion do. During thermal stratification, the hypolimnion is isolated from atmospheric exchange and may develop a dissolved oxygen deficit if biological and chemical oxygen demands exceed the oxygen mass available within the hypolimnion at the onset of thermal stratification. During the spring and autumn, solar radiation is less than during the summer, and windy conditions also are more prevalent. This combination facilitates convective circulation, the process whereby a weakly stratified water column undergoes vertical mixing when wind energy is sufficient to overcome the thermal gradient. A lake is termed dimictic if it undergoes convective circulation in the spring and autumn. Such mixing is an important mechanism for the vertical movement of water-quality constituents such as dissolved oxygen, nutrients, and trace elements.

Among-Lake Comparisons

The three lakes differ widely in many of their physical limnological characteristics, as shown in table 5. The drainage areas of Coeur d'Alene and Flathead Lakes are comparable; that of Lake Pend Oreille is about 6 times larger. Coeur d'Alene Lake has a surface area about 4 times smaller than Flathead Lake's; the surface area of Lake Pend Oreille is about midway between that of the other two lakes. These areal differences yield ratios of drainage area to lake surface area of 23 for Flathead Lake, 75 for Coeur d'Alene Lake, and 190 for Lake Pend Oreille. On the basis of this ratio alone, Flathead Lake is expected to be the least affected by its drainage basin and Lake Pend Oreille to be the most affected. A similar conclusion results from comparison of areal water loads for the three lakes. Owing to the large surface area of Flathead Lake, the lake's mean annual outflow volume yields the smallest areal water load of the three lakes. The large mean annual outflow volume for Lake Pend Oreille, coupled with its intermediate surface area, yields the largest areal water load.

When mean annual outflow volume and lake volume are considered together and expressed as hydraulic residence time, a more realistic appraisal of the hydrologic effects of the drainage basins on physical mixing processes within the three lakes is obtained. Lake volumes range from 2.8 (Coeur d'Alene Lake) to 53.9 km^3 (Lake Pend Oreille), as shown in table 5. Coeur d'Alene Lake also has the shortest hydraulic residence time, 0.50 year, and so by this measure is expected to be the most rapidly affected by runoff from its drainage basin. The other two lakes have longer and comparable hydraulic residence times; 2.2 years for Flathead Lake and 2.4 years for Lake Pend Oreille. Although Lake Pend Oreille has about twice the volume of Flathead Lake, it also has about twice the mean annual outflow volume. To put these values in perspec-

Table 5. Physical limnological characteristics, Coeur d'Alene Lake and Lake Pend Oreille, Idaho, and Flathead Lake, Montana

[km^2, square kilometers; m, meters; km, kilometers; km^3, cubic kilometers; m/yr, meters per year; yr, year]

Characteristic, unit	Coeur d'Alene	Flathead	Pend Oreille[1]
Drainage area at outlet, km^2	9,690	11,400	62,700
Lake surface elevation[2], m	648.7	879	628.6
Surface area[2], km^2	129	496	329
Maximum length, km	35	56	50
Maximum effective length, km	12.5	56	21
Maximum width, km	3.7	26	10.8
Maximum effective width, km	3.7	18.5	10.8
Volume[2], km^3	2.8	23.2	53.9
Maximum depth[2], m	63.7	113	357
Mean depth[2], m	21.7	50.2	164
Drainage area:surface area, unitless	75	23	190
Mean annual outflow volume, km^3	5.6	10.6	22.6
Areal water load[3], m/yr	43.2	21.4	68.6
Hydraulic residence time[3], yr	.50	2.2	2.4
Trap efficiency[3], percent	93	97	98

[1] Exclusive of Pend Oreille River outlet arm, which starts at Sandpoint, Idaho.
[2] At normal full pool.
[3] At mean annual outflow volume.

tive, note that hydraulic residence times (equivalently, retention times) may be on the order of days for rapidly flushed, run-of-the-river reservoirs to hundreds of years for large-volume lakes with relatively small drainage basins. Examples of the latter are Crater Lake, Oregon, with a retention time of about 150 years, and Lake Tahoe, California/Nevada, with a retention time of about 700 years.

The trap efficiency for sediment delivered to these three lakes was estimated empirically by applying their hydraulic residence times to the previously discussed nomograph presented by Gray (1973). As listed in table 5, trap efficiencies for the three lakes exceed 90 percent. Coeur d'Alene Lake has the smallest, 93 percent; the other two lakes can be expected to trap more than 97 percent of the sediment loads delivered to them.

Morphometric features for the three lakes are illustrated in bathymetric maps (figs. 2–4) and described in table 5. None of these lakes approaches a round shape, but Coeur d'Alene Lake is the smallest in width and length (3.7 and 35 km, respectively); Flathead Lake is the largest (26 and 56 km, respectively); and Lake Pend Oreille is intermediate (10.8 and 50 km, respectively). The degree of lake surface exposure to wind can be judged on the basis of maximum effective widths and lengths. Coeur d'Alene Lake has the smallest dimensions for these two variables, 3.7 and 12.5 km, respectively. Flathead Lake's maximum effective width is about 70 percent of its maximum width, but its maximum effective length and maximum length are equal (56 km). Lake Pend Oreille's maximum effective width and maximum width are also equal (10.8 km); however, its maximum effective length is less than half of its maximum length. Given equivalent wind conditions, Flathead Lake is most exposed to wind over both width and length; Coeur d'Alene Lake is least exposed in both dimensions.

Bathymetric contours of the three lakes (figs. 2–4, table 5) illustrate Lake Pend Oreille as the deepest; it is more than 3 times deeper than Flathead Lake and about 5.5 times deeper than Coeur d'Alene Lake. Lake Pend Oreille also has the largest mean depth (164 m), whereas Coeur d'Alene Lake has the smallest (21.7 m). Owing to its large mean depth and intermediate-sized surface area, Lake Pend Oreille has the largest volume (53.9 km^3) of the three lakes. Woods (1993b) calculated that about 95 percent of Lake Pend Oreille's volume is contained in the deep southern basin, south of the northernmost extent of depths greater than 200 m (fig. 4). Although not uniform, the variation of depth in the other two lakes is less dramatic than in Lake Pend Oreille (figs. 2 and 3).

The foregoing section presented morphometric characteristics that indicate the extent to which runoff from the drainage basin or wind-induced mixing can produce varying degrees of water-column turbulence among the three lakes. These morphometric characteristics are fairly general and easily derived from bathymetric maps and annual discharge data. The next three sections present additional data to evaluate in more detail how water-column turbulence in each lake is affected by interannual (among multiple years) and intraannual (within each year) variations in hydraulic residence time, inflow-plume routing, thermal stratification, and convective turnover.

Coeur d'Alene Lake

The hydraulic residence time of 0.50 year for Coeur d'Alene Lake (table 5) is based on a normal full-pool volume of 2.8 km^3 divided by the mean annual outflow volume of 5.6 km^3. The lake's outflow volume statistics were derived for an 87-year period of record (1913–2000) for the USGS gaging station Spokane River near Post Falls, Idaho (station 4, fig. 1) (Brennan and others, 2001). Over that period of record, however, annual mean outflow volume has varied widely. For the minimum outflow volume of 1.9 km^3, the hydraulic residence time increases to 1.5 years; conversely, for the maximum outflow volume of 10.5 km^3, hydraulic residence time decreases to 0.27 year. This range of hydraulic residence times indicates that, in the absence of any inflow, the lake theoretically could drain in as few as 98 days or as many as 548 days. This range also represents an index of the physical limnological process of water-column turbulence and its presumed relation with hydraulic residence time. Coeur d'Alene Lake's ability to retain constituents delivered from its drainage basin is expected to decline as hydraulic residence time declines.

In addition to interannual variability, outflow from the lake varies intraannually in response to climatological conditions within its drainage basin. Over the 1913–2000 period of record, the smallest monthly mean outflow of 0.07 km^3 occurs in August, whereas the largest monthly mean outflow of 1.3 km^3 occurs in May. On the basis of these outflow volumes, constitu-

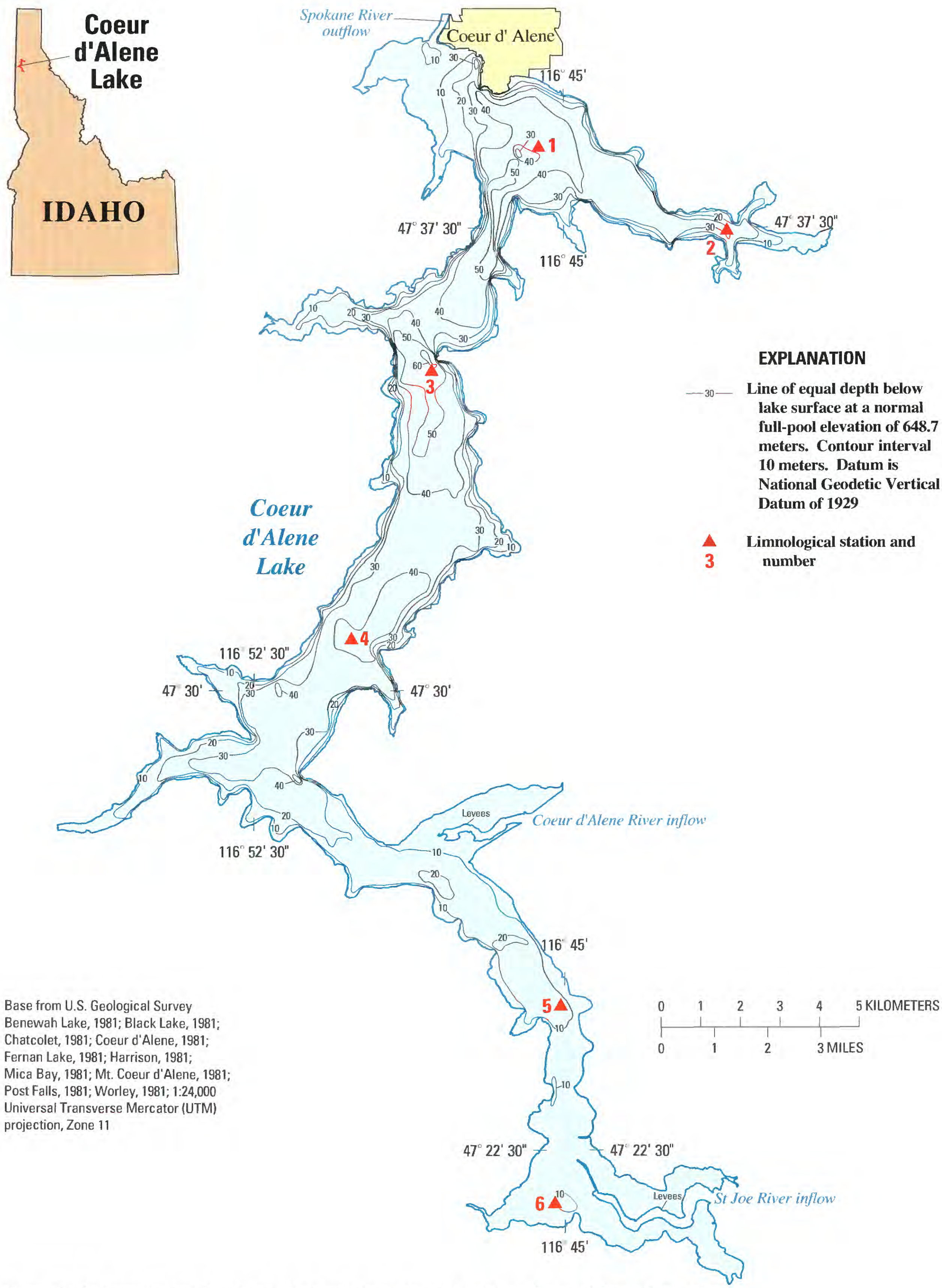


Figure 2. Bathymetry and locations of selected limnological stations, Coeur d'Alene Lake, Idaho.

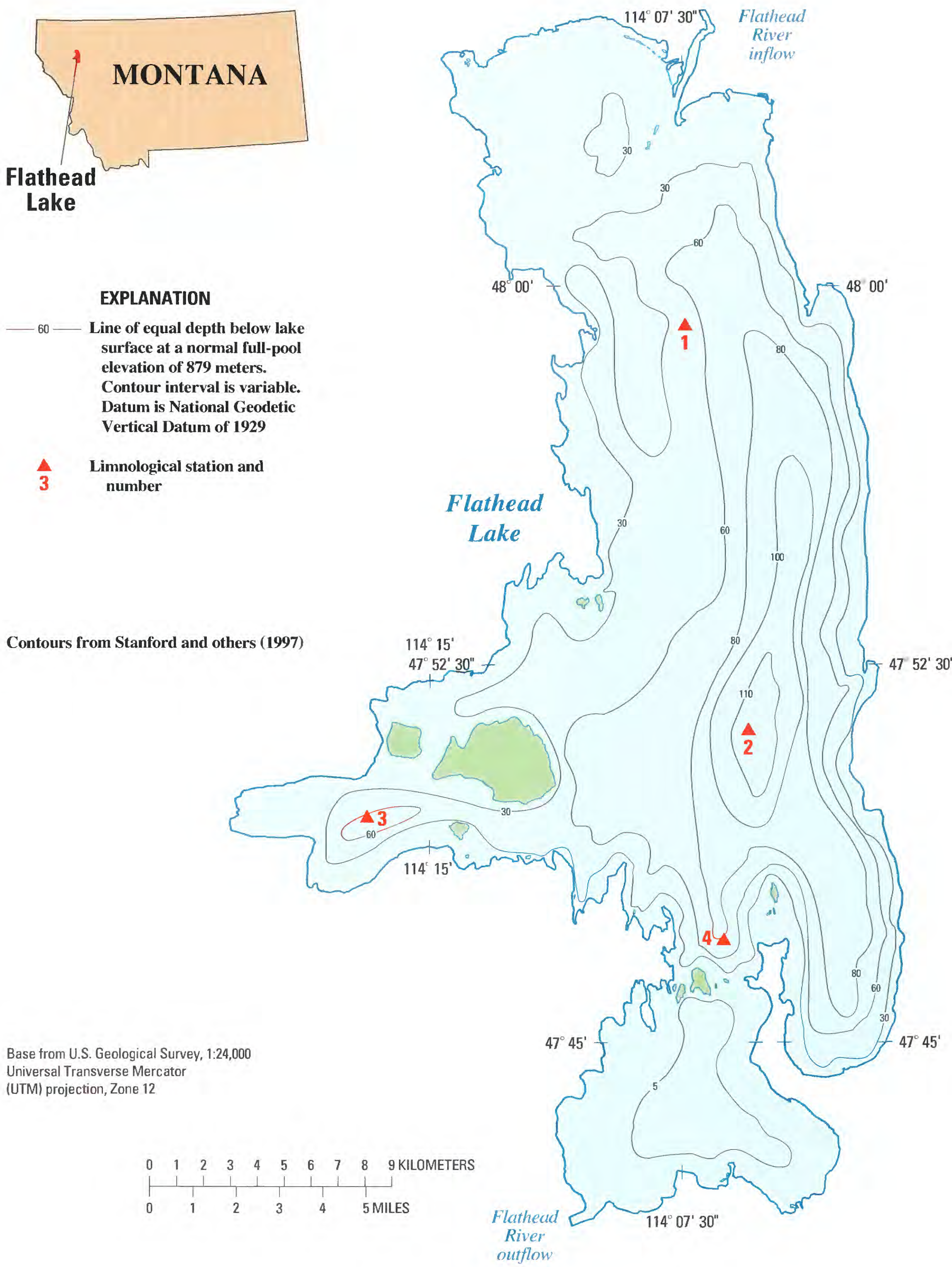


Figure 3. Bathymetry and locations of selected limnological stations, Flathead Lake, Montana.

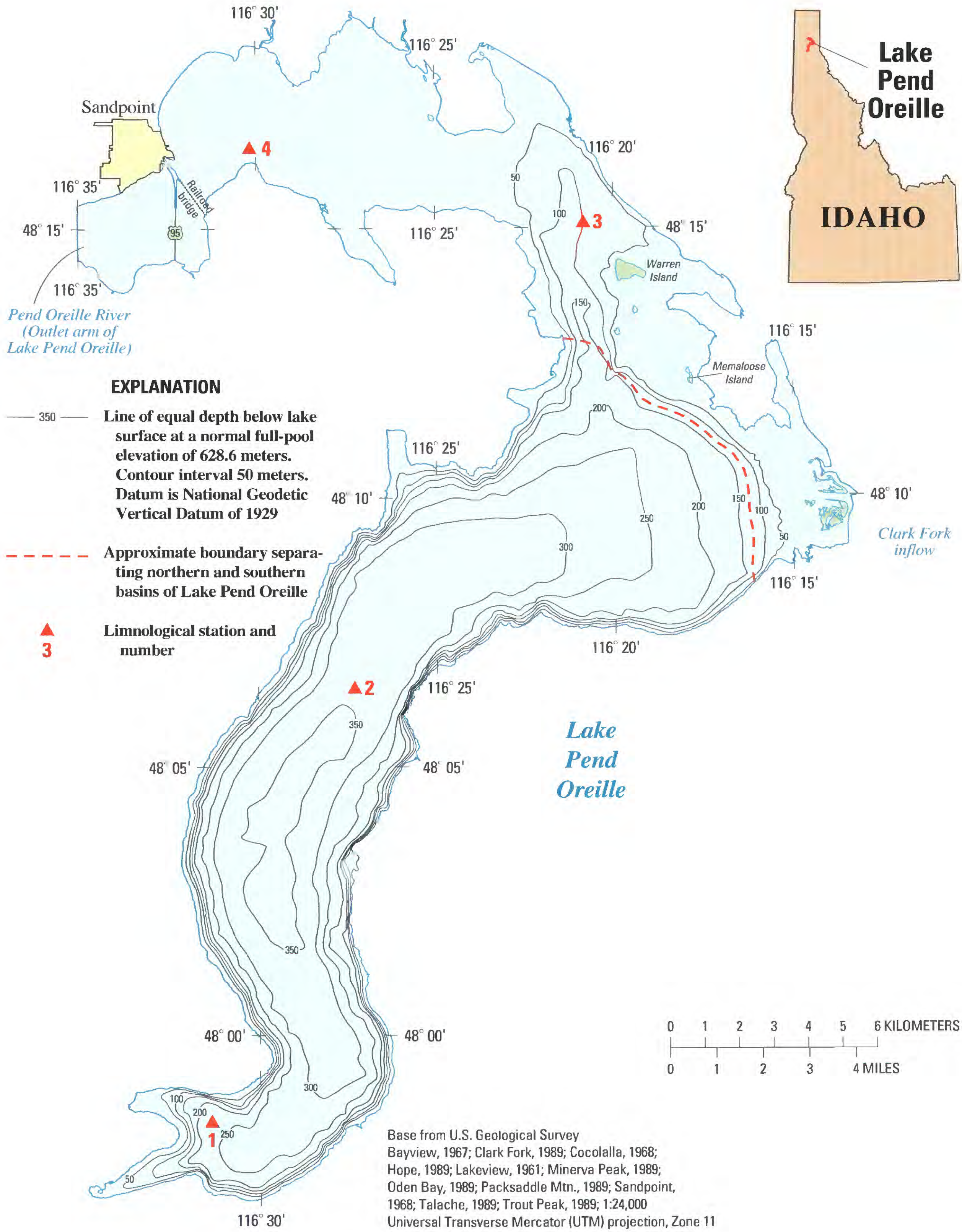


Figure 4. Bathymetry and locations of selected limnological stations, Lake Pend Oreille, Idaho.

ents delivered to the lake by way of inflow more likely would be retained in August when water-column turbulence is least.

The fate and transport of nutrients in Coeur d'Alene Lake are highly dependent upon inflow-plume routing of the lake's two primary inflow sources, the Coeur d'Alene and St. Joe Rivers. Inflow-plume routing was evaluated using water-temperature data from two limnological studies of Coeur d'Alene Lake conducted in the 1990s. Water-temperature data for the two rivers and numerous full-depth profiles of water temperature collected for most months during 1991–92 at six limnological stations (fig. 2) were reported by Woods and Beckwith (1997). The 1999 water year also was evaluated using similar water-temperature data; however, lake water-column sampling was conducted only during June through October at limnological stations 1, 3, 4, and 5 (fig. 2) (URS Greiner Inc., and CH2M-Hill Inc., 2001b). The 44 comparisons of inflow and lake temperatures reported for 1991–92 and 1999 indicated that overflow was the most common mode of inflow-plume routing in about 60 percent of the comparisons (URS Greiner Inc., and CH2M-Hill Inc., 2001b). Interflow or underflow was identified in about 20 percent of the comparisons. Overflow occurred in all months except October, November, and December; during those 3 months, underflow was the most likely mode of inflow-plume routing. Interflow tended to occur during the spring or autumn when the lake was most likely to be transitioning into or out of thermal stratification. Inflow volume also was evaluated as part of the 44 comparisons because it affects the spatial extent of inflow-plume routing. At small inflows, the plume's influence on the lake is reduced by rapid mixing and equilibration of riverine and lake temperatures; the converse is true for large inflows. Underflows tended to be associated only with small inflows, typical for the period October through December. Underflows occurred during that 3-month period because the Coeur d'Alene and St. Joe Rivers cooled more rapidly than the lake, which has a much greater capacity to store heat. Overflows occurred over a wide range of inflows because both the Coeur d'Alene and St. Joe Rivers have lengthy backwater-affected reaches that produce heating of inflow water by solar radiation.

The extent of inflow-plume routing into Coeur d'Alene Lake during the 1990s also was evaluated using unpublished information and several data sets not used in the foregoing analysis. A powerful storm during February 1996 dropped several inches of rain on a substantial snowpack and created severe flooding in northern Idaho river basins, including the Coeur d'Alene and St. Joe River Basins. This storm delivered a large volume of sediment to Coeur d'Alene Lake and produced visible turbidity throughout the lake for several months (G.F. Harvey, Idaho Department of Environmental Quality, written commun., 2000). The magnitude of the February 1996 flood peaks at four long-term USGS gaging stations in the Coeur d'Alene and St. Joe River Basins was within about 10 percent of the 100-year flood peak, on the basis of data reported by Beckwith and others (1996). On February 10, 1996, the suspended-sediment concentration in the Coeur d'Alene River near its point of inflow to the lake (USGS gaging station Coeur d'Alene River near Harrison, Idaho, station 3, fig. 1) was 620 mg/L (Beckwith, 1996) and was associated with a mean daily discharge of 1,550 m^3/s. In comparison, the median and range of suspended-sediment concentrations in nine samples collected at the Harrison station during the 1999 water year were, respectively, 3.7 mg/L and 1.5 to 56 mg/L (A.J. Horowitz, U.S. Geological Survey, written commun., 1999); the latter concentration was associated with a mean daily discharge of 350 m^3/s.

Inflow-plume routing into the lake also was evaluated using data collected during snowmelt runoff in the 1997 water year. Changes in water-temperature profiles and water-column transparency (G.F. Harvey, Idaho Department of Environmental Quality, written commun., 2000) tracked the movement of the inflow plume into and through Coeur d'Alene Lake during May and June 1997. The temperature of the inflow plume on June 6, 1997, was 11°C, as measured at Coeur d'Alene River near Harrison (station 3, fig. 1) (Brennan and others, 1998). Water-column temperature profiles recorded on May 28 at four lake stations indicated the inflow plume was routed as a combination of overflow and interflow within the upper 10 m of the water column. Water-column transparencies, as measured by secchi disc on May 28, at the central and northern lake stations (stations 3 and 1, respectively, fig. 2) were 1.1 and 2.0 m, respectively. By comparison, annual mean water-column transparencies at all four stations during 1995 through 1999 ranged from 8 to 9 m (G.F. Harvey, Idaho Department of Environmental Quality, written commun., 2000).

Water-quality data from these large-volume discharge events of 1996 and 1997 revealed the routing of intact riverine inflows into and through Coeur d'Alene Lake; these inflows had been considered infrequent and exceptional hydrologic events in which the lake acted as a conduit for the transport of constituents from the Coeur d'Alene and St. Joe Rivers to the Spokane River. However, this conceptual model was invalidated by the results of a limnological study, described in the following paragraph, of inflow-plume routing conducted during snowmelt runoff in the 1999 water year.

Discharge and chemistry of the Coeur d'Alene and St. Joe River inflow plumes into and through Coeur d'Alene Lake were tracked by USGS scientists using specialized water-quality instrumentation and water-column sampling. The short-term study sought to answer two questions: (1) can the riverine inflows and their associated chemical nature be clearly identified within the lake? and (2) do sediment, nutrients, and trace elements carried by the riverine inflows travel far enough into the lake to be discharged out of the lake into the Spokane River? The field work was conducted during June 2 and 3, 1999, at limnological stations 1 through 5, in addition to three stations at the mouths of the Coeur d'Alene and St. Joe Rivers and at the lake's outlet into the Spokane River (fig. 2). The study results, reported in URS Greiner Inc., and CH2M-Hill Inc. (2001b), clearly identified the riverine inflows as a combination of overflow and interflow within the upper 5 to 13 m of the lake, from limnological station 4 and northward to the lake's outlet. Much of the lake south of limnological station 4 is shallow enough to allow full-depth mixing of the two riverine inflows. Only marginal influence from Coeur d'Alene and St. Joe River inflows was measured at limnological station 2, which is somewhat isolated from the northward flow of the two rivers. Light transmission, conductivity, and concentrations of lead, zinc, and nitrogen differed substantially between the riverine inflows and lake water. Lead concentrations delivered by the Coeur d'Alene River were larger than those in lake water. Zinc concentrations, also delivered almost exclusively by the Coeur d'Alene River, were smaller than those in lake water. Light transmission, conductivity, and nitrogen concentrations in riverine water also were smaller than those in lake water. The chemical nature of water exiting the lake to the Spokane River was more closely related to riverine inflows than to lake water. The January 1999 transport of sediment, nutrients, and trace elements through Coeur d'Alene Lake and into the Spokane River was measured during a snowmelt runoff event that occurs about every other year, on the basis of long-term streamflow records for the USGS gaging station Coeur d'Alene River at Cataldo (station 2, fig. 1) (Kjelstrom and others, 1996).

The extent of thermal stratification and convective circulation in Coeur d'Alene Lake was evaluated on the basis of isopleth diagrams of water temperature reported for 1991–92 at six limnological stations (fig. 2) by Woods and Beckwith (1997) and water-temperature profiles measured during 1995–99 at limnological stations 1, 3, and 4 (G.F. Harvey, Idaho Department of Environmental Quality, written commun., 2000). The lake was thermally stratified during 1991–92, commonly between early June and mid-November. Stratification developed in early June from a combination of solar heating of the lake's upper water column and riverine inflows from the Coeur d'Alene and St. Joe Rivers (URS Greiner Inc., and CH2M-Hill Inc., 2001b). Those riverine inflows were delivered into the lake as overflows because both rivers have lengthy, backwater-affected lower reaches that facilitate heating by solar radiation. During 1991, thermoclines had developed by mid-July and persisted until early October; thermoclines again developed in 1992 from mid-June until early October. Although thermoclines were lost in early October, the lake remained thermally stratified into mid-November. The maximum thermocline depth was 16.5 m in 1991 and 21.5 m in 1992. Similarly, maximum thermocline depths during 1995–99 ranged from 15 to 24 m; their duration could not be determined because water-column profiles typically were measured during July through October and, thus, did not encompass the temporal extent of thermal stratification. Over those 7 years (1991–92, 1995–99), and when thermoclines were present, the epilimnion depth averaged about 10 m during July through September; this represents about 38 percent of the lake's total volume, on the basis of the depth-to-volume curve presented by Woods and Berenbrock (1994). The upper depth limit of the hypolimnion over the same period averaged 15 m; thus, the hypolimnion constituted about 50 percent of the total lake volume. The remaining 12 percent of lake volume constituted the metalimnion during July through September. Coeur d'Alene Lake is dimictic in that it undergoes convective circulation twice a year. Spring circulation during 1991–92 was in April; the fall circulation was in late November of both years. The incidence of spring and fall circulation during 1995–99 could not be evaluated.

Flathead Lake

The hydraulic residence time for Flathead Lake is 2.2 years (table 5), or about 4 times longer than for Coeur d'Alene Lake. That value is based on a normal full-pool volume of 23.2 km^3 divided by the mean annual outflow volume of 10.6 km^3. The lake's outflow volume statistics were derived for a period of record from 1984 to 2000 for the USGS gaging station Flathead River at Perma, Montana (station 1, fig. 1) (Shields and others, 2001). The range in hydraulic residence time for this period was between 2.9 years, based on the minimum mean annual outflow of 7.9 km^3, and 1.4 years, based on the maximum mean annual outflow of 16.1 km^3. The variation in outflow volume within a year was evaluated on the basis of minimum and maximum values for monthly mean outflow volume. For the 1984–2000 period of record, the mean minimum outflow volume of 0.63 km^3 was in August, whereas the mean maximum outflow volume of 1.7 km^3 was in June. On the basis of these monthly mean outflow volumes, constituents delivered into the Flathead Lake by inflow would more likely be retained in August because of reduced water-column turbulence.

In-lake routing of the Flathead River's inflow within Flathead Lake was reported to occur as overflow during snowmelt runoff during 1978–80 (Stuart, 1983) and during 1983 (Stanford and others, 1983). The presence of overflow was determined from water-column profiles of percent light transmission (expressed as turbidity), spatial changes in transparency, and the lake's thermal structure in relation to the temperature of the influent Flathead River. The vertical extent of the plume ranged from the lake surface to between 10 and 50 m in 1979 (Stuart, 1983). The augmentation of limnological sampling with aerial photography permitted evaluation of the advective transport of the plume within the lake; two generalized patterns emerged from this evaluation. In 1979, the plume (10°C) entered the lake (4°C) in early May and traveled directly south; by late June, the plume had spread throughout the lake. The second pattern, observed in 1980 and 1983, was more complicated. After entering the lake, the plume was deflected along the western shore until it met the constriction formed by the lake's shallow southern basin (fig. 3). From there, the plume split; part traveled south toward the lake's outlet, and the rest traveled northward along the lake's eastern shore. Stanford and others (1983) also noted an instance in which strong, westerly winds pushed the plume away from the western shore and toward the middle of the lake. The dynamics of inflow-plume routing in Flathead Lake have been ascribed by Stanford and others (1983) to the following five principal factors: (1) natural flowpath of the Flathead River from north to south, (2) magnitude of snowmelt runoff, (3) density differences between influent Flathead River and the lake's thermal structure, (4) Coriolis effect owing to the Earth's rotation, and (5) co-occurrence of "thermal bars" adjacent to the littoral area of the lake during snowmelt runoff.

Patterns of thermal stratification and convective circulation in Flathead Lake were evaluated (Stanford and others, 1983) on the basis of isopleth diagrams of water temperature reported for 1978–79 at limnological station 2 (fig. 3). Additionally, the spatial similarity in thermal stratification among seven limnological stations was verified using selected temperature profiles from September 1991 through August 1993 (Stanford and others, 1994). Flathead Lake was thermally stratified between June and late October during 1978–79; thermocline depths ranged from about 8 to 15 m. Thermal stratification developed largely from solar heating of the lake's upper water column. Riverine input of snowmelt runoff as overflow was less of a factor in the development of thermal stratification because runoff preceded the onset of thermal stratification by about 1 month. When thermoclines were present during 1978–79, the epilimnion depth averaged about 12 m; this represents about 20 percent of the lake's total volume on the basis of the depth-to-volume curve for Flathead Lake (P.F. Woods, U.S. Geological Survey, written commun., 2002). The upper depth limit of the hypolimnion during 1978–79 averaged 25 m; thus, the hypolimnion constituted about 58 percent of the total lake volume. The remaining 22 percent of lake volume constituted the metalimnion during thermal stratification. Similar to Coeur d'Alene Lake, Flathead Lake is dimictic. During 1978–79, spring circulation was in April, about 1 month prior to snowmelt runoff; the fall circulation was in early November.

Lake Pend Oreille

Lake Pend Oreille has the longest hydraulic residence time, 2.4 years, of the three lakes (table 5). That value is based on a normal full-pool volume of 53.9 km^3 divided by the mean annual outflow volume of 22.6 km^3. The lake's outflow volume statistics were derived for a 97-year period of record (1903–2000) for the USGS gaging station Pend Oreille River at Newport, Washington (station 7, fig. 1) (Brennan and others, 2001). Annual mean outflow volume varied widely over that period of record, ranging from 11.5 to 34.7 km^3. The corresponding range in hydraulic residence time was 4.7 to 1.6 years. In addition to interannual variability, outflow from the lake also varied widely during each year. Monthly mean outflows for the 1903–2000 period of record indicated that the mean minimum outflow volume of 1.0 km^3 was in September, whereas the mean maximum outflow volume of 4.6 km^3 was in June.

In-lake routing of the Clark Fork's inflow plume within Lake Pend Oreille during snowmelt runoff was evaluated using data and observations from several sources. The nutrient load/lake response study conducted during 1989–90 by the USGS and IDEQ included a limnological assessment of the lake's pelagic, or open-water, zone (Woods, 1993a). As part of that assessment, the vertical and horizontal distribution of the inflow plume was tracked on May 18, 1989, using aerial photography and in-lake profiles of specific conductance, water temperature, and percent light transmission (measured with an *in-situ* transmissometer). Inflow-plume tracking was performed a few days after a week of elevated Clark Fork inflow discharges, ranging from 1,440 to 1,850 m^3/s (Harenberg and others, 1990), that were measured at the USGS gaging station Clark Fork at Whitehorse Rapids near Cabinet, Idaho (station 6, fig. 1). Results from the in-lake profiles showed that the more turbid river water overflowed the lake water to a depth of about 30 m. Aerial photographs (M.A. Beckwith, U.S. Geological Survey, written commun., 1989) revealed that most of the turbid riverine plume was routed into the lake's northern basin. However, part of the inflow plume was routed into the lake's southern basin, as evidenced by a decrease in transparency measured by secchi-disc readings at limnological station 2 (fig. 4); transparency decreased from 10 m in late April to less than 5 m during mid-May through mid-June. Runoff from snowmelt in 1990 began in late May and was of a longer duration and larger magnitude than in 1989; unfortunately, inclement weather and hazardous lake conditions prevented a repeat of the aerial photography and transmissometer profiles. However, decreased transparency throughout the lake's pelagic zone during June 1990 clearly demonstrated that the turbid inflow plume was distributed lakewide. The shallowest transparencies during the 1990 snowmelt runoff were in the lake's northern basin, indicating that the inflow plume's effects were more pronounced there.

The aerial photographs taken in mid-May 1989 raised the question of why the turbid inflow plume of the Clark Fork was routed so distinctly into Lake Pend Oreille's northern basin. As shown in figure 4, the Clark Fork enters the lake near the approximate boundary between its northern and southern basins. Four physical limnological processes can be suggested as explanations for the plume's northward, not southward, destination. Two processes, wind-driven surface currents and outflow-induced currents, are unlikely because of the transitory nature of the surface currents and the 65-km distance from the Clark Fork inlet to the lake's outlet at Albeni Falls Dam. The third process, counterclockwise circulation induced by the Coriolis effect, is also unlikely because it would be expected to have the opposite effect: routing of the inflow plume southward along the lake's western margin. The fourth process, development of a thermal bar near the approximate boundary between the northern and southern basins, is the most plausible explanation. A thermal bar, or vertical transition zone of 4°C water separating littoral and pelagic water masses, results from density gradients produced when shallow littoral water heats more rapidly than pelagic water does (Wetzel, 1975). Although water-temperature profiles for suitably located positions in Lake Pend Oreille were not available with which to quantitatively evaluate this process, the bathymetry of the lake (fig. 4) can be used to postulate the likelihood of thermal bar development. The southern basin has a mean depth of 220 m, whereas the northern basin has a mean depth of 29 m (Woods, 1993b), resulting in a very large difference in heat-storage capacity between these two basins. The more rapid warming of the northern basin could facilitate development of a thermal bar near the approximate boundary separating the two basins. This explanation is supported by the aerial photographs of May 18, 1989 (shown on front cover of this report), which clearly show the turbid inflow plume flowing northwesterly along the approximate boundary between the northern and southern basins.

In addition to inflow-plume routing during snowmelt runoff, the limnological assessment of 1989–90 (Woods, 1993a) produced data with which to assess the inflow-plume routing of the Clark Fork within Lake Pend Oreille during the 1989–90 non-snowmelt runoff periods. Frequent water-temperature measurements of the Clark Fork's inflow (Harenberg and others, 1990, 1991) and numerous full-depth profiles of water temperature at limnological station 3 (fig. 4) allowed evaluation of inflow-plume routing for December through September of 1989 and 1990. Fifty-seven comparisons of river and lake temperatures indicated that overflow was the most common mode of inflow-plume routing, identified in about 75 percent of the comparisons.

Characteristics of thermal stratification and convective circulation in Lake Pend Oreille were evaluated (Woods, 1993a) on the basis of isopleth diagrams of water temperature reported for 1989–90 at limnological stations 1 through 4 (fig. 4). During 1989–90, the lake was thermally stratified at the three deepest (depth greater than 70 m) stations (1 through 3), commonly between June and mid-October. Thermocline depths ranged from 8 to 20 m in 1989 and from 8 to 16 m in 1990. In contrast, the lake at limnological station 4 was shallow (depth less than 20 m) and did not thermally stratify for any appreciable period. The development of thermal stratification by early to mid-June at the two deepest stations in the lake's southern basin was largely the result of solar heating of the lake's upper water column and not the Clark Fork's input of snowmelt runoff, which was routed as overflow, primarily through the lake's shallow northern basin, during May and June. Water-column turbulence generated by such inflow-plume routing likely inhibited the development of thermal stratification at limnological station 4, owing to shallow depth. In contrast, the lake at limnological station 3 in the northern basin was thermally stratified, through a combination of inflow-plume routing as overflow and solar heating of the lake's upper water column. During 1989–90 and when thermoclines were present, the epilimnion depth averaged about 15 m; this represents about 7 percent of the lake's total volume, on the basis of the depth-to-volume curve for Lake Pend Oreille developed by Fields and others (1996). The upper depth limit of the hypolimnion over the same period averaged 30 m; thus, the hypolimnion constituted about 85 percent of the total lake volume. The remaining 8 percent of lake volume constituted the metalimnion. Similar to the other lakes, Lake Pend Oreille is dimictic; however, such circulation may not extend full depth during each occurrence. Spring circulation during 1989–90 was in April; the fall circulation was in mid-October of both years.

CHEMICAL AND BIOLOGICAL LIMNOLOGY

Overview

Hydrologic and constituent budgets, in conjunction with drainage basin and physical limnological characteristics, are important tools for evaluating fate and transport of constituents within a lake. However, the quantitative differences between input and output loads represent the net influence of limnological processes because constituent loads output from a lake result from the integration of all hydrologic, physical, chemical, and biological processes that operate within the lake. To distinguish the hydrologic and physical limnological effects on constituent fate and transport from those associated with chemical and biological processes, the third phase in the evaluation, discussed in this section, focuses on spatial and temporal variations in chemical and biological characteristics within each lake's water mass.

Subsequent to their delivery into a lake as dissolved, colloidal, and particulate fractions, nonconservative nutrients such as nitrogen and phosphorus can be involved in a variety of chemical and biological processes. Both nitrogen and phosphorus are involved in biological processes because they are essential for phytoplankton production. Phytoplankton assimilation of dissolved inorganic nitrogen (nitrite, nitrate, and ammonia) and orthophosphorus converts some of the dissolved fraction to a particulate, organically bound fraction that has several possible fates. Advective transport physically redistributes the particles within the lake, a part of which may exit the lake as an outflow load. The particles also can be retained within the water column by turbulence and be subjected to remineralization or uptake by zooplankton grazing. Dissolved and colloidally bound fractions are subject to in-lake sedimentation when converted to particles by processes such as assimilation, precipitation, complexation, and adsorption. Sedimentation delivers the particles to the lakebed, where they may be subjected to remineralization and possible recycling back into the water column; alternatively, subsequent sedimentation may permanently bury the particles within the lakebed.

Many of these chemical and biological processes are dynamic and transient; they occur over short timeframes (seconds to days) and, thus, are difficult to quantify and evaluate accurately when limnological samples are collected over weekly or longer timeframes. Limnological sampling at these three lakes was conducted over timeframes of 2 to 8 weeks. Consequently, much of the following evaluation of chemical and biological limnology focuses on spatial and temporal comparisons of mean conditions among the three lakes.

Trophic State

One of the primary reasons that nutrient loading has been assessed for many lakes was to evaluate biological productivity in relation to nutrient enrichment, or eutrophication; such is the case for Coeur d'Alene and Flathead Lakes and Lake Pend Oreille. Trophic state provides the initial comparison of chemical and biological limnology among the three lakes.

Trophic state refers to the biological productivity of a water body and integrates the physical, chemical, and biological processes within that water body. For ease of categorization, three trophic states commonly are defined: oligotrophic (low productivity), mesotrophic (intermediate productivity), and eutrophic (high productivity). Numerous variables have been employed as a 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. The United Nation's Organization for Economic Cooperation and Development used these four variables to develop a statistically based, open-boundary, trophic-state classification system (Ryding and Rast, 1989), which is shown in table 6. An open-boundary system compensates for the overlap in classification that commonly occurs with fixed-boundary, or single-value, systems. Under the open-boundary system, a water body is considered to be classified correctly if three of the four upper water-column variables are within two standard deviations of their geometric mean for the same trophic state.

On the basis of annual geometric mean values for upper water-column concentrations of total phosphorus, total nitrogen, chlorophyll-*a*, and transparency (table 7), all three lakes can be classified as oligotrophic. Even though the three lakes received very different quantities of nitrogen and phosphorus from their drainage basins (tables 1–3), their biological responses, expressed as trophic state, were quite similar.

Another important water-quality characteristic used to delineate trophic state is hypolimnetic dissolved oxygen. As lake productivity increases, decreases in hypolimnetic dissolved oxygen often result when biological and chemical oxygen demands

Table 6. Trophic-state classification based on open-boundary values for four limnological variables

[µg/L, micrograms per liter; m, meters; $\bar{x}$, annual geometric mean; SD, standard deviation]

Variable, unit[1]		Oligotrophic	Mesotrophic	Eutrophic
Total phosphorus (µg/L)	$\bar{x}$	8.0	26.7	84.4
	$\bar{x}$ ±1SD	4.8–13.3	14.5–49.0	48.0–189
	$\bar{x}$ ± 2SD	2.9–22.1	7.9–90.8	16.8–424
Total nitrogen (µg/L)	$\bar{x}$	661	753	1,875
	$\bar{x}$ ±1SD	371–1,180	485–1,170	861–4,081
	$\bar{x}$ ± 2SD	208–2,103	313–1,816	395–8,913
Chlorophyll-*a* (µg/L)	$\bar{x}$	1.7	4.7	14.3
	$\bar{x}$ ±1SD	.8–3.4	3.0–7.4	6.7–31.0
	$\bar{x}$ ± 2SD	.4–7.1	1.9–11.6	3.1–66.0
Secchi-disc transparency (m)	$\bar{x}$	9.9	4.2	2.4
	$\bar{x}$ ±1SD	5.9–16.5	2.4–7.4	1.5–4.0
	$\bar{x}$ ± 2SD	3.6–27.5	1.4–13.0	.9–6.7

[1] Modified from Ryding and Rast (1989).

Table 7. Trophic state of Coeur d'Alene Lake and Lake Pend Oreille, Idaho, and Flathead Lake, Montana, based on annual mean values for four limnological variables

[μg/L, micrograms per liter; m, meters; TS, trophic state; O, oligotrophic; M, mesotrophic]

Year	Total phosphorus (μg/L)		Total nitrogen (μg/L)		Chlorophyll-*a* (μg/L)		Secchi-disc transparency (m)	
	$\bar{x}$[1]	TS	$\bar{x}$[1]	TS	$\bar{x}$[1]	TS	$\bar{x}$[2]	TS
				Coeur d'Alene[3]				
1991	5.6	O	282	O	0.43	O	4.0	M
1992	4.6	O	206	O	.79	O	2.9	M
				Flathead[4]				
1978–82	7.4	O	120	O	1.2	O	8.8	O
				Pend Oreille[5]				
1989	9.0	O	142	O	.8	O	7.0	O
1990	6.5	O	116	O	.8	O	6.3	O

[1] Lakewide, annual geometric mean concentration within upper water column for Coeur d'Alene Lake and Lake Pend Oreille. Annual mean concentration at mid-lake station for Flathead Lake.

[2] Lakewide, annual geometric mean for Coeur d'Alene Lake and Lake Pend Oreille. Annual mean at mid-lake station for Flathead Lake.

[3] Data from Woods and Beckwith (1997).

[4] Data from Stanford and others (1983) and Stuart (1983).

[5] Data from Woods (1993a).

exceed the oxygen mass within the hypolimnion. The oligotrophic nature of these three lakes (table 7) indicates a small potential for development of a hypolimnetic dissolved oxygen deficit. On the basis of water-column profiles of dissolved oxygen concentrations for Coeur d'Alene Lake (Woods and Beckwith, 1997), Flathead Lake (Stuart, 1983), and Lake Pend Oreille (Woods, 1993a), the three lakes have well-oxygenated hypolimnia.

Hypolimnetic Nutrient Storage

Most biological production in lakes is within the well-mixed upper water column (epilimnion), where solar radiation is sufficient to drive phytoplankton photosynthesis. A notable difference among these three lakes is the percentage of epilimnion volume in relation to total lake volume: Lake Pend Oreille is 7 percent epilimnion, Flathead Lake is 20 percent epilimnion, and Coeur d'Alene Lake is 38 percent epilimnion. Relative to the total volume, Lake Pend Oreille has the smallest epilimnetic volume in which to convert nutrients into phytoplankton biomass. Conversely, and in relation to total volume, Lake Pend Oreille has the largest hypolimnetic volume; Coeur d'Alene Lake has the smallest. In contrast to phytoplankton photosynthesis, remineralization throughout the water column converts particulate constituents into dissolved constituents throughout the year; however, the hypolimnion is the primary strata for remineralization. During thermal stratification, which often coincides with the period of elevated biological production, the hypolimnion receives the downward "rain" of organic and inorganic constituents delivered into the lake or produced in the epilimnion and metalimnion. If convective circulation is strong enough to mix the entire water column, hypolimnetic water can serve as a source of remineralized nutrients to augment biological production within the epilimnion. As lake depth increases, the potential for convective circulation to mix the entire water column decreases. The increase in depth also implies longer residence times for nutrient remineralization and a larger hypolimnetic volume for nutrient storage. In a large, deep lake such as Lake Pend Oreille, convective circulation of hypolimnetic nutrients into the epilimnion may occur only sporadically. In contrast, in a shallower lake such as Coeur d'Alene Lake, convective circulation of hypolimnetic nutrients into the epilimnion may occur twice a year. Compared with Lake Pend Oreille and Coeur d'Alene Lake, Flathead Lake represents an intermediate example because of its moderate depth and substantial exposure to wind.

A comparison of hypolimnetic enrichment of total nitrogen among the three lakes indicates that annual mean concentrations of total nitrogen were larger in the hypolimnia than in the epilimnia (table 8). The ratios of epilimnetic to hypolimnetic concentrations ranged from 0.67 (Lake Pend Oreille in 1990) to 0.79 (Coeur d'Alene Lake in 1992). The relative difference between epilimnetic to hypolimnetic nitrogen concentrations was smallest in Coeur d'Alene Lake, the shallowest and most likely to undergo full-depth convective circulation. One possible explanation for that lake's enriched hypolimnetic total nitrogen can be derived from the results of a 1999 study of benthic flux in Coeur d'Alene Lake done by the USGS (Kuwabara and others, 2000). Using an *in-situ* benthic flux chamber, the annual flux of dissolved inorganic nitrogen, a component of total nitrogen, from the lakebed sediments to

Table 8. Annual mean concentrations of total nitrogen and phosphorus within the epilimnion and hypolimnion at the deepest limnological stations, Coeur d'Alene Lake and Lake Pend Oreille, Idaho, and Flathead Lake, Montana

[µg/L, micrograms per liter; EPI, epilimnion; HYPO, hypolimnion]

Year	Total nitrogen (µg/L)			Total phosphorus (µg/L)		
	EPI[1]	HYPO[2]	EPI/HYPO	EPI[1]	HYPO[2]	EPI/HYPO
			Coeur d'Alene [3]			
1991	292	375	0.78	4.6	4.8	0.96
1992	216	274	.79	2.9	2.8	1.04
			Flathead [4]			
Sept. 1991–Aug. 1993	128	182	.70	5.1	5.8	.88
			Pend Oreille [5]			
1989	160	212	.75	8	10	.80
1990	110	164	.67	6	10	.60

[1] When water column not thermally stratified, refers to upper water column.
[2] When water column not thermally stratified, refers to lower water column.
[3] Limnological station 3 (fig. 2), data from Woods and Beckwith (1997).
[4] Limnological station 2 (fig. 3), data from Stanford and others (1994).
[5] Limnological station 2 (fig. 4), data from Woods (1993a).

the overlying water column was calculated to be 270 µg/cm^2. On the basis of that result and riverine loading data from Woods (2001), the contribution of nitrogen to Coeur d'Alene Lake from benthic flux was determined to exceed that delivered to the lake from its drainage basin by a factor of 1.5. Comparable studies of benthic flux have not been done for Flathead Lake or Lake Pend Oreille. Relative differences between epilimnetic and hypolimnetic total nitrogen concentrations were similar for those two lakes, regardless of large differences in their depth.

On the basis of epilimnetic to hypolimnetic ratios of phosphorus concentration, which ranged from 0.60 (Lake Pend Oreille in 1990) to 1.04 (Coeur d'Alene Lake in 1992), the three lakes represent a gradient in hypolimnetic enrichment of total phosphorus (table 8). Lake Pend Oreille exhibited a clearly defined case of hypolimnetic enrichment, presumably because of its large depth. Coeur d'Alene Lake exhibited the opposite condition, no enrichment of hypolimnetic total phosphorus, presumably because of its shallow depth and short hydraulic residence time.

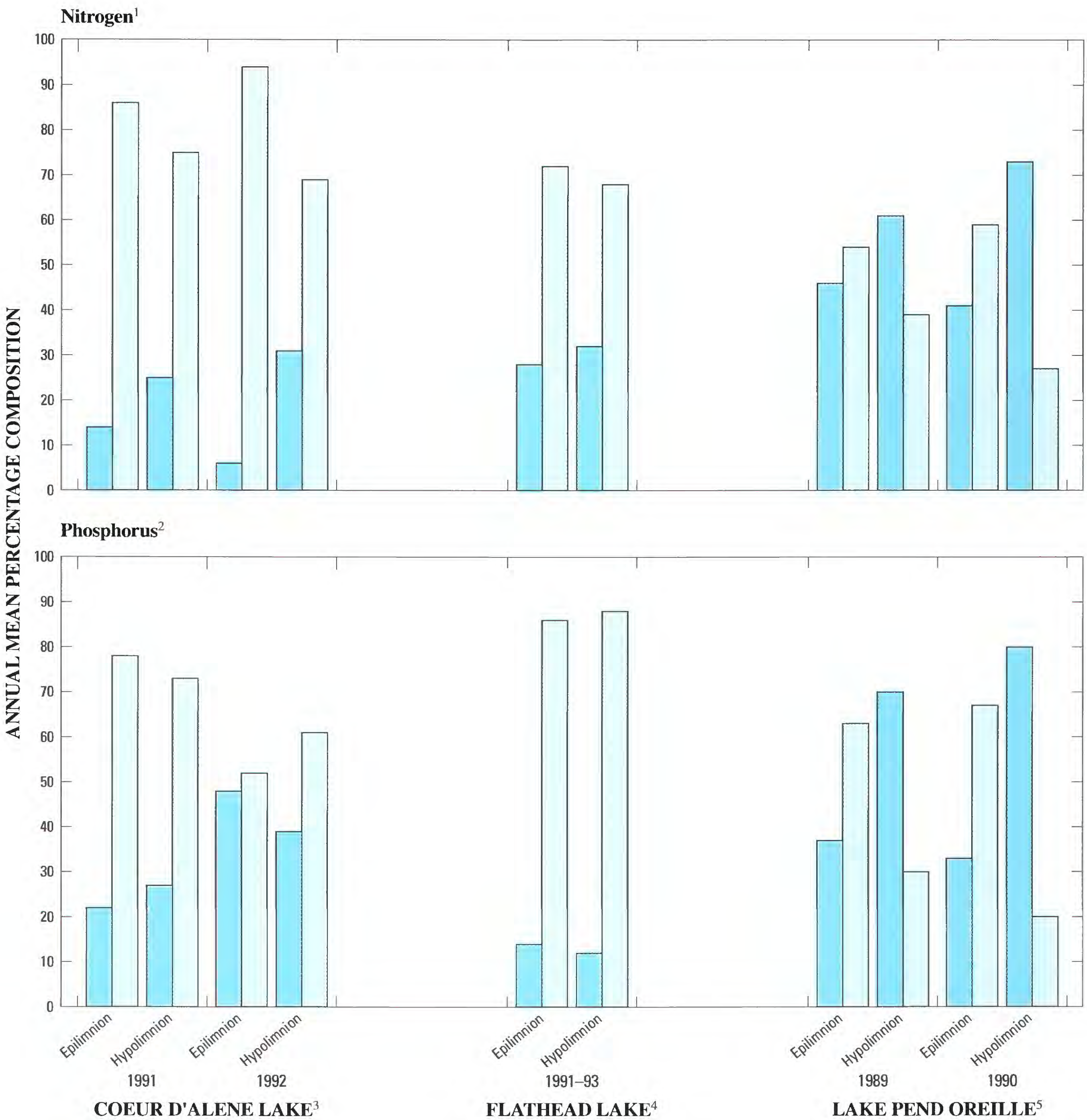
Nutrient Partitioning

Additional insight into chemical and biological limnology can be gained through analysis of the partitioning of nutrients into their bioavailable and particulate fractions. The bioavailable fractions of nitrogen and phosphorus are defined here, respectively, as the sum of dissolved (<0.45 µm) nitrite, nitrate, and ammonia and dissolved orthophosphorus. The following two comparisons were made: (1) epilimnion and hypolimnion, and (2) inflow loads and outflow loads.

EPILIMNION AND HYPOLIMNION

In 1991, the mean percentages of bioavailable nitrogen and particulate nitrogen in the hypolimnion of Coeur d'Alene Lake were 25 and 75, respectively; whereas in the epilimnion, the mean percentages were 14 and 86, respectively (fig. 5). The percentage compositions between the epilimnion and hypolimnion were even more dissimilar in 1992. The percentages of bioavailable and particulate nitrogen between the epilimnion and hypolimnion in Flathead Lake were comparable; in both strata, bioavailable nitrogen composed about 30 percent of total nitrogen. As in Coeur d'Alene Lake, percentages of bioavailable and particulate nitrogen between the epilimnion and hypolimnion of Lake Pend Oreille also were dissimilar. However, in contrast to the other two lakes, bioavailable nitrogen in Lake Pend Oreille's hypolimnion composed between 61 and 73 percent of total nitrogen, indicative of extensive remineralization and retention.

Among the three lakes, the overall pattern for bioavailable and particulate phosphorus composition, in relation to total phosphorus, was similar to that for nitrogen (fig. 5). The percentage difference between epilimnetic and hypolimnetic bioavailable phosphorus in Coeur d'Alene Lake was less than 10 percent in 1991 and 1992. Bioavailable phosphorus in both the epilimnion and hypolimnion composed a larger percentage of total phosphorus in 1992 than in 1991 but was still less than 50 percent. In Flathead Lake, bioavailable phosphorus in the epilimnion and hypolimnion composed only 14 and 12 percent of total phosphorus, respectively. In contrast, the percentage composition of phosphorus in the epilimnion and hypolim-



EXPLANATION

Bioavailable

Particulate

1 Bioavailable nitrogen defined as sum of dissolved nitrite, nitrate, and ammonia; particulate nitrogen defined as total minus bioavailable

2 Bioavailable phosphorus defined as dissolved orthophosphorus; particulate phosphorus defined as total minus bioavailable

3 Limnological station 3 (fig. 2), data from Woods and Beckwith (1997)

4 Limnological station 2 (fig. 3), data from Stanford and others (1994)

5 Limnological station 2 (fig. 4), data from Woods (1993a)

Figure 5. Annual mean percentage composition of bioavailable and particulate nitrogen and phosphorus concentrations, in relation to total nitrogen and phosphorus concentrations, respectively, within the epilimnion and hypolimnion at the deepest limnological stations, Coeur d'Alene Lake and Lake Pend Oreille, Idaho, and Flathead Lake, Montana.

nion of the deepest of the three lakes, Pend Oreille, was substantially different. Within the epilimnion, bioavailable phosphorus composed 35 percent, on average, of total phosphorus; that percentage increased to 75 within the hypolimnion. As with nitrogen, this increase was indicative of significant remineralization and retention of phosphorus within the hypolimnion of Lake Pend Oreille.

INFLOW LOADS AND OUTFLOW LOADS

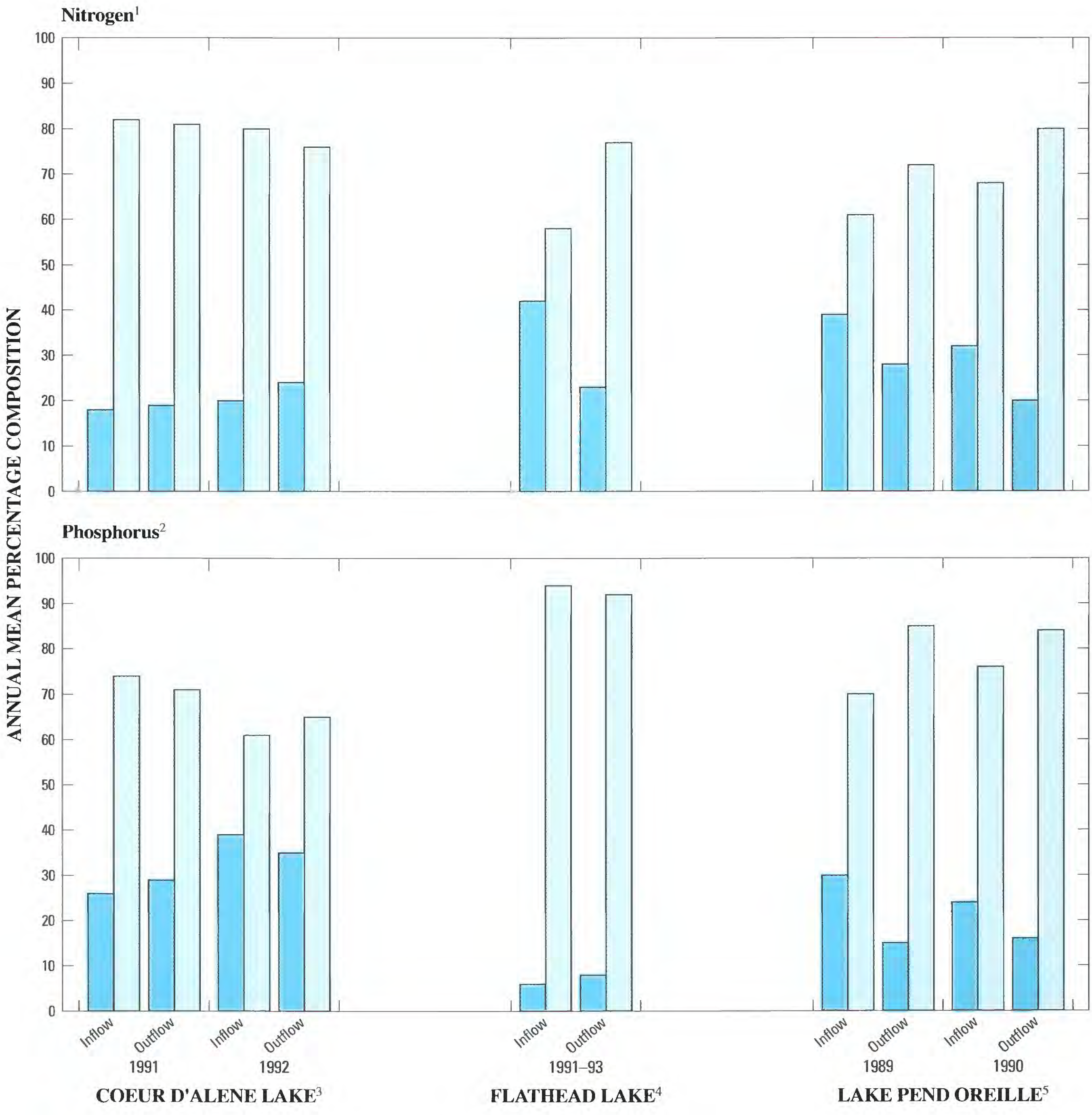
The annual mean percentage composition of bioavailable and particulate nitrogen and phosphorus, in relation to total concentrations of nitrogen and phosphorus in inflow and outflow loads for the three lakes, are listed in figure 6. The information in figure 6 was combined with that in tables 1–3 to produce figures 7–11, which were used to help separate physical limnological processes from those of a chemical and (or) biological nature.

Inflow and outflow loads of bioavailable and particulate nitrogen for Coeur d'Alene Lake showed little difference in their percentage composition with respect to total nitrogen; the percentages were comparable between 1991 and 1992 (figs. 7 and 8). Such results might indicate that the lake merely passed its inflow nitrogen load through to its outlet relatively unaltered; the lake retained less than 10 percent of the nitrogen it received as input in both years. However, other data suggest chemical and biological alteration of the lake's inflow load of nitrogen. Phytoplankton assimilation of bioavailable nitrogen was evident from changes in dissolved inorganic nitrogen concentrations periodically measured at limnological stations 1 through 6 (fig. 2) during 1991–92. Within the lake's upper water column, dissolved inorganic nitrogen concentrations ranged from less than 7 to 234 μg/L during 1991 and from less than 7 to 98 μg/L during 1992 (Harenberg and others, 1992, 1993). During both years, the minimum concentrations were measured during May through September, the period of thermal stratification and summer phytoplankton production. The aforementioned addition of dissolved inorganic nitrogen from benthic flux from the lakebed sediments provided an internal source of bioavailable nitrogen that replaced part of the influent bioavailable nitrogen that was converted to particulate nitrogen within the lake.

Similar to nitrogen loads, the inflow and outflow loads of bioavailable and particulate phosphorus for Coeur d'Alene Lake showed little difference in their percentage composition with respect to total phosphorus (figs. 7 and 8). However, unlike its retention of nitrogen, the lake's retention of phosphorus was about two-thirds of its input in 1991 and about one-third in 1992. If physical settling were the only limnological process affecting influent phosphorus loads, then the percentage of bioavailable phosphorus would have increased at the lake's outlet; however, such was not the case. Chemical and biological processes within the lake also affected the influent phosphorus loads. The propensity to sorb to particulate matter probably converted part of the bioavailable phosphorus to particulate phosphorus. Phytoplankton assimilation also converted bioavailable phosphorus into particulate phosphorus. Dissolved orthophosphorus concentrations within the upper water column of limnological stations 1 through 6 (fig. 2) ranged from less than 1 to 11 μg/L in 1991 and from less than 1 to 6 μg/L in 1992 (Harenberg and others, 1992, 1993). The minimum concentrations of dissolved orthophosphorus were measured during the summer months of both years, indicative of phytoplankton assimilation.

In contrast to Coeur d'Alene Lake, Flathead Lake retained about 36 percent of its influent nitrogen load from drainage basin and atmospheric sources during 1978–82 (fig. 9). The percentage of bioavailable nitrogen, in relation to total nitrogen, for Flathead Lake's drainage basin input was 42; that declined to 23 at the lake's outlet (fig. 9), indicative of in-lake conversion of bioavailable nitrogen to particulate nitrogen by chemical and biological processes. These results are consistent with seasonal dynamics of dissolved nitrite plus nitrate concentrations at Flathead Lake's deepest limnological station, 2 (fig. 3), as presented by Stanford and others (1997) for water years 1990–96. Within the upper water column, concentrations ranged from less than 1 to 63 μg/L; the smallest concentrations were measured during the summer months of elevated phytoplankton production.

Flathead Lake retained about three-fourths of the phosphorus it received from drainage basin and atmospheric sources (fig. 9). The percentage composition of inflow and outflow loads of bioavailable phosphorus in relation to total phosphorus were nearly equal—both were less than 10 percent. As mentioned previously, if physical settling were the only limnological process affecting influent phosphorus loads, then the percentage of bioavailable phosphorus would have increased between the lake's inlet and outlet. Given the likelihood of a substantial removal of sediment-associated phos-



EXPLANATION

Bioavailable

Particulate

1 Bioavailable nitrogen defined as sum of dissolved nitrite, nitrate, and ammonia; particulate nitrogen defined as total minus bioavailable

2 Bioavailable phosphorus defined as dissolved orthophosphorus; particulate phosphorus defined as total minus bioavailable

3 Inflow concentrations from Coeur d'Alene and St. Joe Rivers; outflow concentrations from Spokane River

4 Inflow and outflow concentrations from Flathead River

5 Inflow concentrations from Clark Fork; outflow concentrations from Pend Oreille River

Figure 6. Annual mean percentage composition of bioavailable and particulate nitrogen and phosphorus concentrations, in relation to total nitrogen and phosphorus concentrations, respectively, for inflows and outflows, Coeur d'Alene Lake and Lake Pend Oreille, Idaho, and Flathead Lake, Montana.

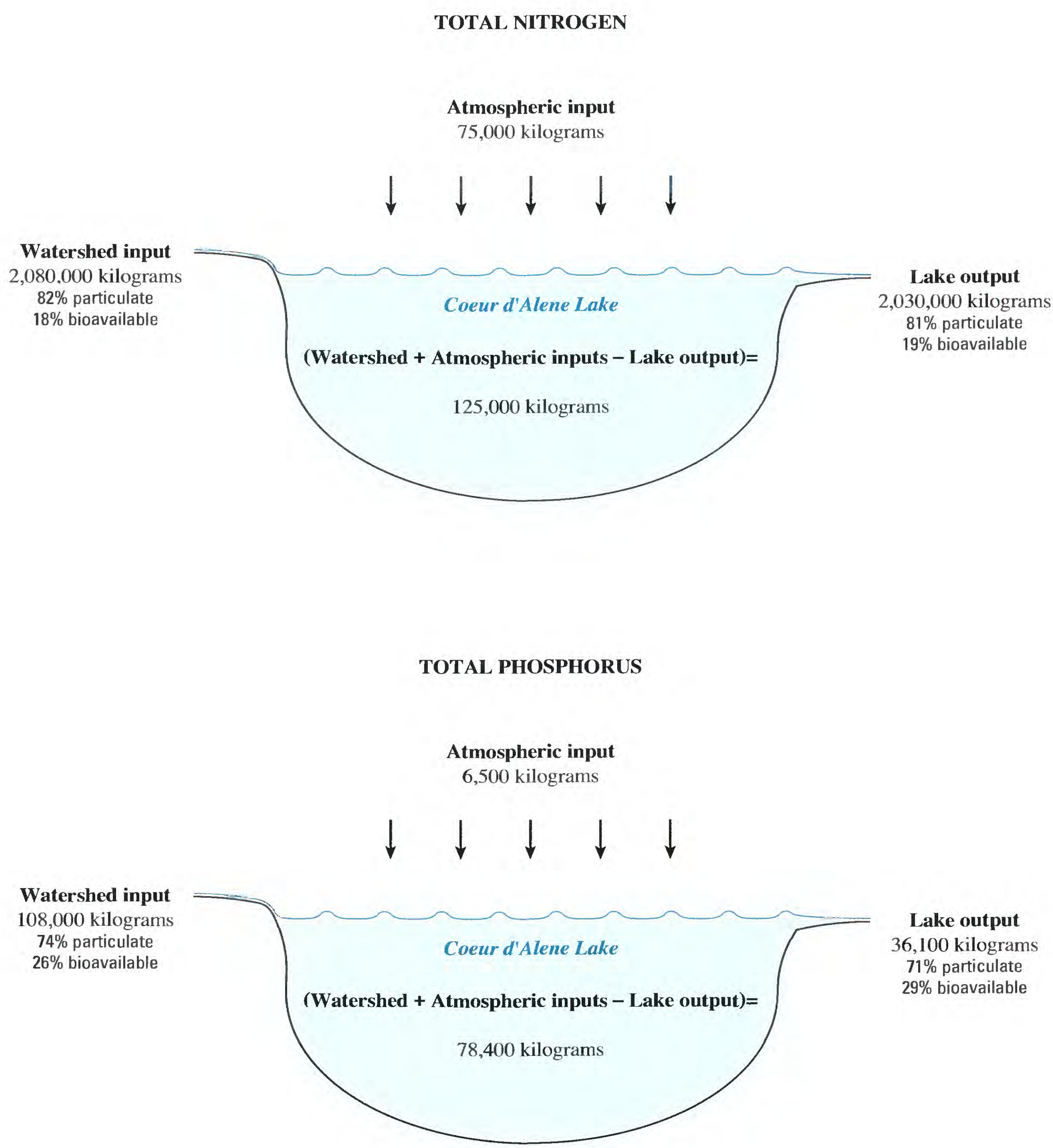
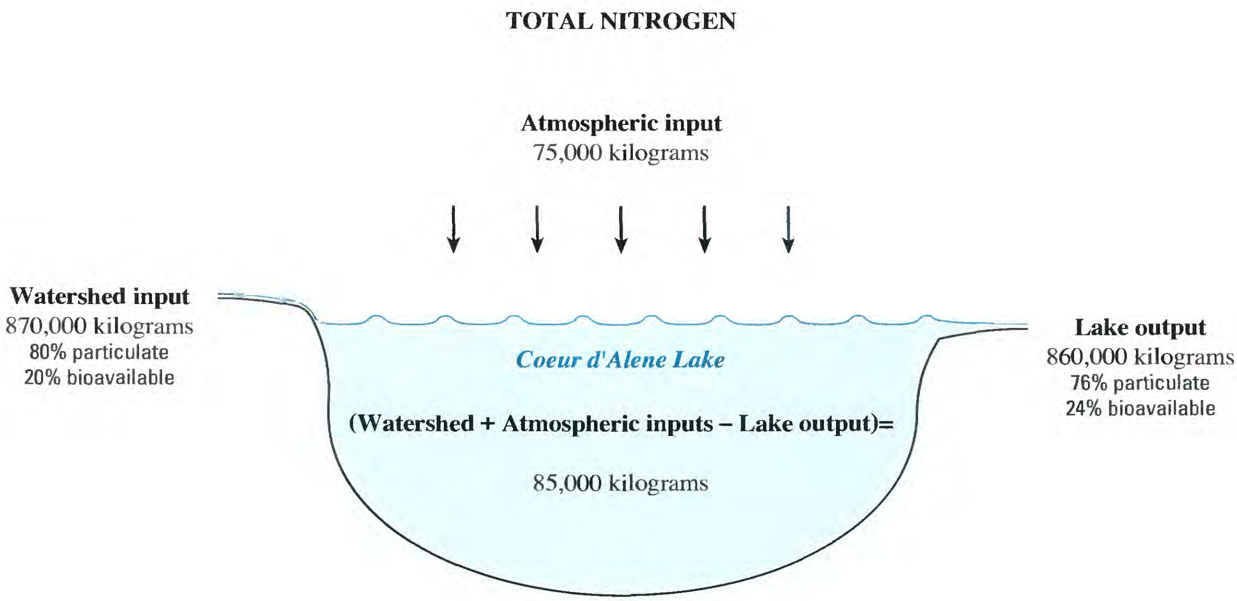


Figure 7. Relation between inputs and outputs of total nitrogen and phosphorus and nutrient partitioning of input and output loads, Coeur d'Alene Lake, Idaho, 1991 calendar year.



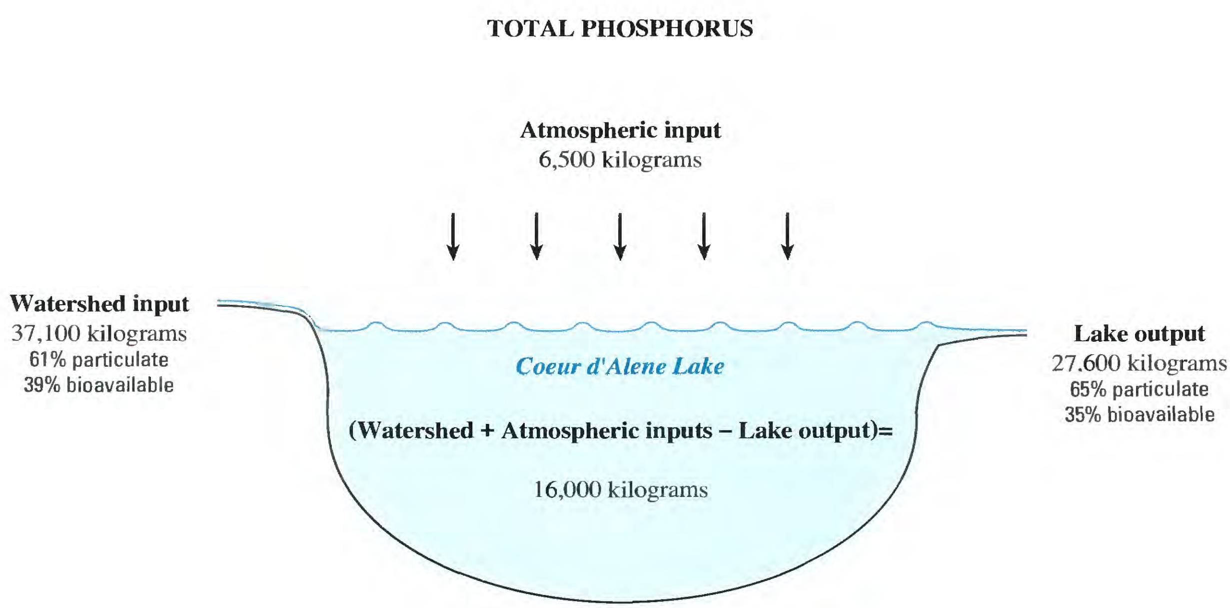


Figure 8. Relation between inputs and outputs of total nitrogen and phosphorus and nutrient partitioning of input and output loads, Coeur d'Alene Lake, Idaho, 1992 calendar year.

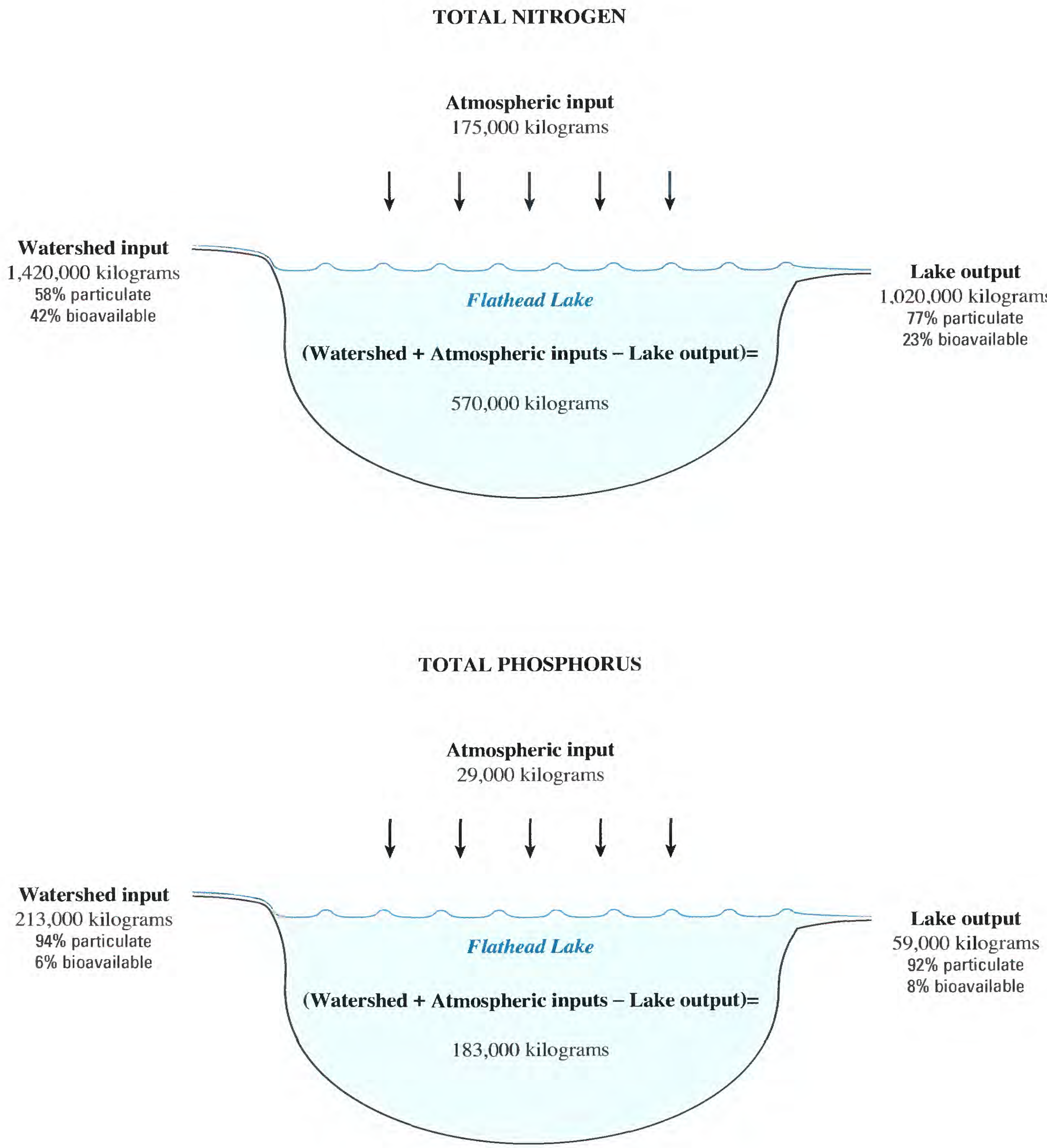


Figure 9. Relation between inputs and outputs of total nitrogen and phosphorus and nutrient partitioning of input and output loads, Flathead Lake, Montana, 1978–82.

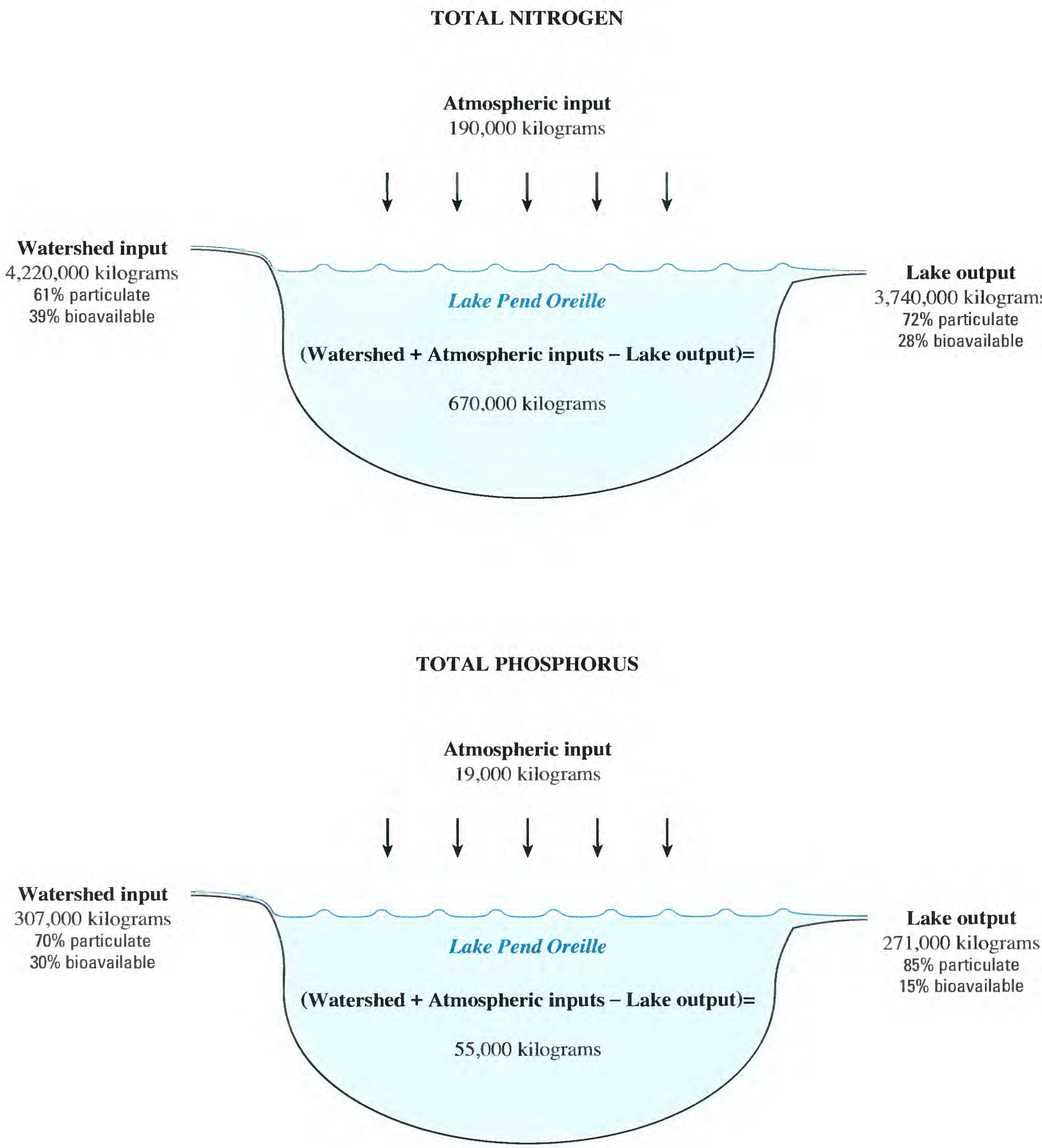


Figure 10. Relation between inputs and outputs of total nitrogen and phosphorus and nutrient partitioning of input and output loads, Lake Pend Oreille, Idaho, 1989 water year.

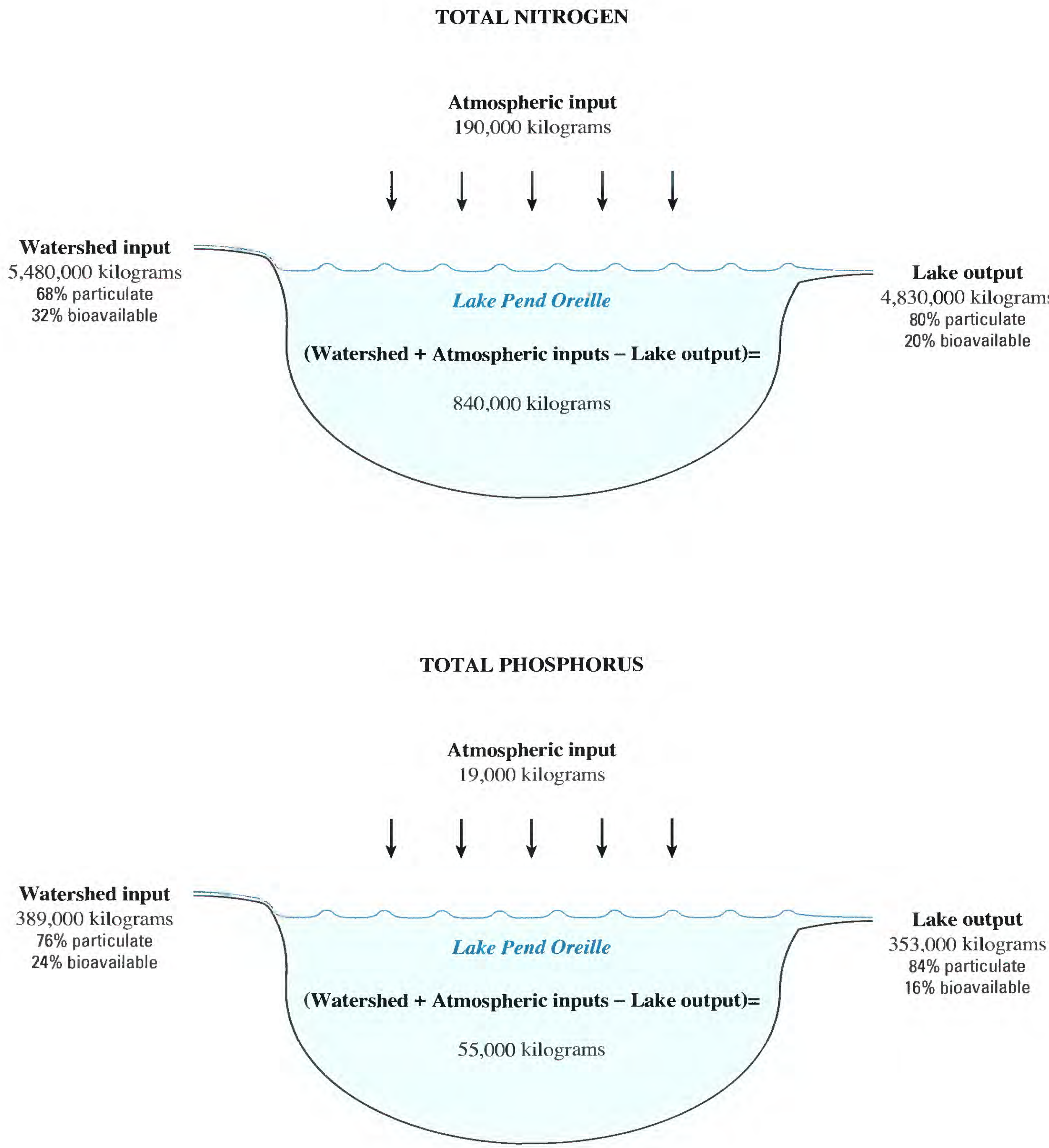


Figure 11. Relation between inputs and outputs of total nitrogen and phosphorus and nutrient partitioning of input and output loads, Lake Pend Oreille, Idaho, 1990 water year.

phorus by physical settling, the large percentage composition of particulate phosphorus output from the lake indicates conversion of bioavailable phosphorus into particulate phosphorus by adsorption and phytoplankton assimilation. These results are consistent with the seasonal dynamics of bioavailable phosphorus concentrations at Flathead Lake's limnological station 2 (fig. 3) during water years 1990–96 (Stanford and others, 1997). Within the upper water column, bioavailable phosphorus concentrations ranged from 0.4 to 4.1 μg/L; the smallest concentrations were measured during the summer months of elevated phytoplankton production.

During water years 1989 and 1990, Lake Pend Oreille retained about 15 percent of the nitrogen load it received from drainage basin and atmospheric inputs (figs. 10 and 11). Phytoplankton assimilation of bioavailable nitrogen was indicated by the reduction in the percentage of bioavailable nitrogen at the lake outlet compared with that from drainage basin inflow (between 11 and 12 percent) (figs. 10 and 11). Again, these results are consistent with upper water-column concentrations of dissolved inorganic nitrogen at limnological stations 2 and 3 (fig. 4), which ranged from 10 to 144 μg/L over the 2-year period (Harenberg and others, 1991, 1992); the smallest concentrations were measured during the summer months of elevated phytoplankton production.

Of the three lakes, Lake Pend Oreille retained the smallest percentage of its input total phosphorus load; about 17 in 1989 and 13.5 in 1990 (figs. 10 and 11). In both years, the percentage of bioavailable phosphorus, in relation to total phosphorus, input to the lake was reduced at the lake outlet by 15 percent in 1989 and by 8 percent in 1990 (figs. 10 and 11). As in the other two lakes, that shift in percentage composition indicated conversion of bioavailable phosphorus to particulate phosphorus by processes such as adsorption and phytoplankton assimilation. Upper water-column concentrations of dissolved orthophosphorus at limnological stations 2 and 3 (fig. 4) ranged from less than 1 to 7 μg/L over the 2-year period (Harenberg and others, 1991, 1992). As with dissolved inorganic nitrogen, the smallest concentrations of dissolved orthophosphorus were measured during the summer months.

FATE AND TRANSPORT OF NUTRIENT LOADS

Overview

Coeur d'Alene and Flathead Lakes and Lake Pend Oreille received, discharged, and retained a wide range of nitrogen and phosphorus loads, in an absolute and relative sense (tables 1–3). The three lakes also displayed a wide range of physical limnological characteristics (table 5); selected values from those four tables are summarized in table 9. If only morphometric and empirically derived values such as mean and maximum depth, hydraulic residence time, and trap efficiency were considered, the lake with the largest values, Lake Pend Oreille, would be expected to retain the largest percentage of the total nitrogen and phosphorus load received. However, that was not the case—Flathead Lake retained the largest loads of total nitrogen and phosphorus relative to what it received. Coeur d'Alene Lake, with the smallest values for mean and maximum

Table 9. Summary of retained load/input load for total nitrogen and phosphorus and selected physical limnological characteristics, Coeur d'Alene Lake and Lake Pend Oreille, Idaho, and Flathead Lake, Montana

[m, meters; cy, calendar year; wy, water year; yr, year]

Variable, unit	Coeur d'Alene [1,2]		Flathead [1,2]	Pend Oreille [1,2]	
	1991 cy	1992 cy	1978–82	1989 wy	1990 wy
Retained load [3]/input load, percent					
Total nitrogen	6	9	36	15	15
Total phosphorus	69	37	[4]76	17	14
Mean depth, m	21.7		50.2	164	
Maximum depth, m	63.7		113	357	
Hydraulic residence time, yr	.50		2.2	2.4	
Trap efficiency, percent	93		97	98	

[1] Data from tables 1–3.
[2] Data from table 5.
[3] Input load - output load.

depth, hydraulic residence time, and trap efficiency, retained a larger relative load of total phosphorus than did Lake Pend Oreille; Coeur d'Alene Lake's retention of total nitrogen was slightly smaller than that of Lake Pend Oreille.

The unexpected behavior of Lake Pend Oreille suggests that limnological processes other than simple physical sedimentation affected the fate and transport of nutrient loads delivered to that lake. Likewise, the large sedimentary loss of particulate phosphorus within Flathead Lake is not intuitively obvious if only the lack of change in nutrient partitioning between the lake's inlet and outlet is considered. For each of these lakes, the influence of in-lake chemical and biological processes was evident, on the basis of shifts in nutrient partitioning between the dissolved and particulate fractions for input and output loads. However, a rigorous evaluation of chemical and biological processes was not possible because of the need to focus on mean conditions; sampling intervals were too long to adequately quantify and evaluate the temporal nature of those processes. Regardless, by coordinating the evaluation of shifts in nutrient partitioning with the evaluation of load discharged versus load received, insight can be gained into the importance of interactions among physical, chemical, and biological processes that affect the fate and transport of nutrient loads delivered into the three lakes.

Coeur d'Alene Lake

Among the three lakes, Coeur d'Alene Lake had the smallest input and output loads of total nitrogen and phosphorus. Compared with the other two lakes, it also had the shortest hydraulic residence time, shallowest mean and maximum depths, and narrowest shape. Because these physical factors are associated with an increased potential for turbulent, advective transport of dissolved, colloidal, and particulate constituents, Coeur d'Alene Lake would be expected to retain a smaller proportion of its input loads, compared with those of the other two lakes.

Indeed, Coeur d'Alene Lake retained less than 9 percent of the total nitrogen it received (table 9). An important factor in the lake's small retention of its input load of total nitrogen was the temporal distribution of input loads. On the basis of graphical plots of daily loads delivered into Coeur d'Alene Lake over the 1999 water year, Woods (2001) reported that about 56 percent of the annual load of total nitrogen was delivered during April through June, the period of snowmelt runoff during which advective transport through the lake as overflow is most likely. The narrowness of the lake's main channel (fig. 2) and the location of the two primary tributaries near the lake's southern end are likely to enhance advective transport, compared with transport expected in a more circular lake basin. Physical sedimentation of total nitrogen does occur; the mean concentration of total nitrogen in lakebed sediments from 20 sampling locations throughout Coeur d'Alene Lake was 2,100 mg/kg (Woods and Beckwith, 1997). Even in the absence of large shifts in partitioning between bioavailable and particulate nitrogen for input and output loads (fig. 6), the biological process of phytoplankton assimilation was indicated by decreases in upper water-column concentrations of dissolved inorganic nitrogen.

Chemical processes, in the form of hypolimnetic remineralization of particulate to bioavailable nitrogen and the addition of dissolved inorganic nitrogen from the lakebed sediments by benthic flux, also affected total nitrogen concentrations and partitioning in the lake. The effect of hypolimnetic enrichment of bioavailable nitrogen by remineralization and benthic flux was evaluated for the 1999 water year as part of a joint EPA/USGS assessment of trace-element and nutrient loading for Coeur d'Alene Lake (URS Greiner Inc., and CH2M-Hill Inc., 2001b). Input loads substantially exceeded output loads of bioavailable nitrogen during December and January but were about equal during May through November. During February through April, the lake discharged substantially more bioavailable nitrogen than it received. The net loss of bioavailable nitrogen during those 3 months was a consequence of full-depth convective mixing, which was associated with advective transport and discharge of part of the bioavailable nitrogen produced in the hypolimnion by remineralization and benthic flux.

The propensity for phosphorus to sorb to inorganic and organic particles suggests that Coeur d'Alene Lake would retain a larger proportion of its input load for phosphorus than for nitrogen. Such was the case; the lake retained between one-third and two-thirds of its annual input load of total phosphorus (table 9). About 80 percent of that annual input was delivered during April through June, on the basis of graphical plots of daily loads delivered into Coeur d'Alene Lake over the 1999 water year (Woods, 2001). The results of lakebed sediment analyses in Coeur d'Alene Lake clearly indicate that sedimentation of total phosphorus occurs; the mean concentration of total phosphorus in lakebed sediments was 940 mg/kg (Woods and Beckwith, 1997). Nonetheless, sedimentation and advective transport were not the only limnological processes in Coeur d'Alene Lake that affected phosphorus loads delivered to the lake. Part of the bioavailable phosphorus was converted into particulate phosphorus by the chemical process of adsorption and the biological process of phytoplankton assimilation, as indicated by minimal shifts in partitioning between inflow and outflow loads (fig. 6), despite the reduction in total load magnitude.

The adsorption of bioavailable phosphorus in the lake was postulated as an important chemical process because the lakebed sediments are rich in iron oxides and hydroxides, for which bioavailable phosphorus has a high adsorption affinity (Wetzel, 1975; Elder, 1988). The mean concentration of total iron measured in about 150 surficial lakebed samples from Coeur d'Alene Lake was 51,000 mg/kg (Horowitz and others, 1993). Only 14 percent of 1,317 analyses of soils in the conterminous United States (Shacklette and Boerngen, 1984) contained iron concentrations in excess of those measured in the lakebed of Coeur d'Alene Lake. The lake receives abundant amounts of iron in the inflow from the Coeur d'Alene River. According to Hem (1985), flowing, well-aerated, nonacidic surface water generally contains less than 10 μg/L dissolved iron. During the 2001 water year, however, dissolved iron concentrations in the Coeur d'Alene River ranged from 20 to 190 μg/L (O'Dell and others, 2002). The lake's retention of one-third to two-thirds of its influent phosphorus load, in spite of its short hydraulic residence time and shallow depths, may have been increased by its potential to form particulate phosphorus within the water column.

Flathead Lake

Both input and output loads of total nitrogen and phosphorus for Flathead Lake were intermediate between those of the other two lakes. Flathead Lake's hydraulic residence time and trap efficiency were comparable to those of Lake Pend Oreille, whereas mean and maximum depths were about twice those of Coeur d'Alene Lake and only about one-third those of Lake Pend Oreille. Of the three lakes, Flathead had the longest dimensions for length and width, both maximum and effective, and had the largest surface area. Because of its empirically determined ability to retain dissolved, colloidal, and particulate constituents, Flathead Lake would be expected to retain a large proportion of its input loads.

Consistent with this expectation, Flathead Lake retained the largest proportion of its input load of total nitrogen, 36 percent (table 9). About 60 percent of that input load was delivered to the lake during April through June, the period of snowmelt runoff (Stanford and others, 1997). Although the lake's inflow plume has been routed in a rather complex fashion in some years, in other years, the plume has been routed more directly to the lake's southern outlet (Stuart, 1983). The predominance of overflow during snowmelt runoff favors the potential for discharge of part of the influent nitrogen load delivered by snowmelt runoff. However, the large central basin of Flathead Lake and the long distance between the lake's primary tributary and outlet (fig. 3) are likely to hinder advective transport through the lake, especially during periods of low inflow. The lake's large surface area also favors trapping of nitrogen delivered by atmospheric deposition, especially when such deposition occurs in conjunction with minimal advective transport within the lake. During the period analyzed, atmospheric deposition accounted for about 11 percent of the total nitrogen input to the lake (Stanford and others, 1983).

In addition to physical processes, differences in partitioning between bioavailable and particulate nitrogen for both the epilimnion and hypolimnion (fig. 5) and input and output loads (fig. 6) indicate that chemical and biological processes affected the in-lake fate and transport of nitrogen delivered to the lake. The lake's moderate depth, in conjunction with long distances for effective width and length, allows full-depth convective mixing of nitrogen (nitrite plus nitrate) during periods without thermal stratification (Stanford and others, 1997). When such mixing is coincident with advective transport, then part of the lake's nitrogen could be discharged. However, the lake's ability to discharge convectively circulated nitrogen is hampered by its physical characteristics of long hydraulic residence time, moderate depths, and large surface area.

Of these three lakes, Flathead Lake retained the largest proportion of its input load of total phosphorus, about 75 percent (table 9). Comparable to total nitrogen, about 60 percent of the input load of total phosphorus was delivered to the lake during April through

June, the period of snowmelt runoff (Stanford and others, 1997). The retention of phosphorus resulted from a combination of physical, chemical, and biological processes. Ample evidence demonstrates that Flathead Lake is an efficient trap for particulate matter, including particulate phosphorus. The spatial distribution of mean annual concentrations of total phosphorus (vertically integrated data) in Flathead Lake from its inlet area to its outlet illustrates the lake's ability to retain phosphorus (Stanford and others, 1983). On the basis of data from 1977–80, the average annual concentration at the inlet was 15 μg/L; 7.5 km south, at limnological station 1 (fig. 3), the concentration had declined to 9 μg/L. At limnological station 2 (fig. 3), 23 km south of the inlet, the concentration had declined to about 7.5 μg/L, which was comparable to the concentration at the lake outlet. Additionally, Stuart (1983) presented a mass balance budget for total suspended solids (which include sediment-associated phosphorus) in Flathead Lake for 1977–79. Of the 292,000,000 kg of suspended solids input to the lake, less than 4 percent was discharged from the lake. Lakebed sediment analyses for Flathead Lake also clearly indicate that sedimentation of total phosphorus occurs; the mean concentration of total phosphorus from 70 surficial lakebed samples was about 2,300 mg/kg (Moore and others, 1982). That concentration was substantially larger than the mean concentration of 940 mg/kg noted previously for Coeur d'Alene Lake.

Given the substantial sedimentation of particulate phosphorus, in conjunction with minimal changes in nutrient partioning between inflow and outflow loads (fig. 6), some of the bioavailable phosphorus must have been converted into particulate phosphorus by the chemical process of adsorption and the biological process of phytoplankton assimilation. As discussed previously, phytoplankton assimilation of bioavailable phosphorus was readily evident from time-series data for upper water-column concentrations of dissolved orthophosphorus (Stanford and others, 1997). Similar to Coeur d'Alene Lake, Flathead Lake also contains iron-rich lakebed sediments; the mean concentration of total iron measured in 70 surficial lakebed samples was 44,200 mg/kg (Moore and others, 1982). The presence of these iron-rich sediments indicates that adsorption of bioavailable phosphorus to iron oxides and hydroxides may be an important chemical process favoring the lake's retention of phosphorus.

Lake Pend Oreille

Lake Pend Oreille was the outlier among these three lakes with regard to the fate and transport of its input loads of nitrogen and phosphorus. Input and output loads for Lake Pend Oreille were the largest, as were hydraulic residence time, trap efficiency, and both mean and maximum depths. However, the percentage of retained nitrogen was only slightly larger than that of Coeur d'Alene Lake, and the percentage of retained phosphorus was the smallest among the three lakes.

The small retention of total nitrogen for Lake Pend Oreille, about 15 percent for water years 1989 and 1990 (table 9), can be attributed primarily to a combination of physical limnological processes; chemical and biological processes apparently were less important. About 80 percent of the lake's annual load of total nitrogen was delivered by the Clark Fork and, on the basis of graphical output from the load model FLUX, about one-half of that load was delivered during April through June, the period of snowmelt runoff. During snowmelt runoff, two physical processes were likely to have routed most of the influent nitrogen load through the lake's northern basin: the coincident occurrence of inflow-plume routing as overflow and the postulated presence of a thermal bar between the lake's deep southern basin and its shallow northern basin. The role of sedimentation of nitrogen in the lake could not be evaluated because of an absence of nutrient data for lakebed sediments.

Because of the lake's large values for hydraulic residence time, trap efficiency, and depth, and the propensity for phosphorus to sorb to inorganic and organic materials, it is logical to expect that Lake Pend Oreille would retain a substantial part of its input load of total phosphorus. However, the lake retained less than about 17 percent of the input load of total phosphorus (table 9). Similar to nitrogen, retention of total phosphorus was largely the result of physical limnological processes related to inflow-plume timing and routing within the lake, rather than to chemical and biological processes. Graphical output from the load model FLUX indicates that the Clark Fork, which delivered about 70 percent of the lake's annual load of total phosphorus, delivered about one-half of that load during April through June, the period of snowmelt runoff. Similar to nitrogen, most of the phosphorus load was routed through the lake's northern basin by the combination of inflow-plume routing as overflow and the postulated presence of a thermal bar between the lake's deep southern basin and its shallow northern basin. Unlike Coeur d'Alene and Flathead Lakes, the adsorption of bioavailable phosphorus to iron oxides and hydroxides apparently played a minimal role in retention of phosphorus in Lake Pend Oreille. Surficial lakebed samples from the outlet arm of Lake Pend Oreille contained a mean concentration of 28,500 mg/kg of total iron (G.M. Clark, U.S. Geological Survey, written commun., 2002), about one-half of the mean concentrations of iron in the other two lakes. Evaluation of long-term sedimentation as an indicator of retention was not possible because lakebed sediment analyses for phosphorus were not available.

SUMMARY AND CONCLUSIONS

The purpose of this report was to describe the role of limnological processes in determining the fate and transport of nutrients delivered into and discharged from Coeur d'Alene and Flathead Lakes and Lake Pend Oreille. These three large, natural lakes within the NROK study area represented a broad range in physical limnological characteristics that could be expected to exert substantial influences upon the fate and transport of nutrients delivered into them. The large amount of limnological and riverine loading data historically available for these lakes was used to evaluate how interaction among physical, chemical, and biological processes within each lake produced quantitative differences between inflow and outflow loads of nutrients.

The outcome of these interactions over a wide range of spatial and temporal scales determines the quantity and nature of nutrients discharged from each lake at its surface-water outlet. Each lake discharged a smaller nutrient load than it received; retentions of nitrogen loads tended to be smaller than retentions of phosphorus loads. Coeur d'Alene Lake, which received and discharged the smallest nutrient loads among the three lakes, retained about 8 percent and 50 percent, respectively, of its input loads of nitrogen and phosphorus. Flathead Lake retained about one-third of its input load of nitrogen and about three-fourths of its input load of phosphorus. Unlike the other two lakes, Lake Pend Oreille retained only about 15 percent of its input load of nitrogen and less than about 17 percent of its input load of phosphorus; among the three lakes, it received and discharged the largest nutrient loads.

In general, the role of physical limnological processes such as circulation and sedimentation accounted for much of the measured differences in the retention of nutrients among the three lakes. Because of its small propensity to sorb to inorganic and organic particles, nitrogen was less prone to sedimentation and was more responsive to advective circulation. Accordingly, the retention of nitrogen among the three lakes ranged from 5.6 to 36 percent. In contrast, the retention of phosphorus among the three lakes ranged from 13.5 to 75.5 percent, reflecting its strong propensity to sorb to inorganic and organic particles. Comparisons of nutrient partitioning between bioavailable and particulate fractions in the epilimnia and hypolimnia, as well as in input and output loads, provided evidence that chemical and biological processes such as adsorption, remineralization, and phytoplankton assimilation affected the quantity and form of nutrients ultimately discharged from the lakes.

Limnological processes were evaluated retrospectively and, therefore, required a fair degree of postulation about the interactions among physical, chemical, and biological processes because past studies of these lakes were more descriptive than process oriented. One aim of such postulation was to identify important limnological characteristics that might be incorporated into future studies of lakes and reservoirs. For example, the postulated existence of a thermal bar in Lake Pend Oreille and its role in that lake's small retention of nutrients indicates the importance of delineating physical processes related to inflow-plume routing, overall lake circulation, and convective circulation. The importance of also addressing chemical and biological processes can be illustrated with the following example from Flathead Lake: The substantial sedimentation of particulate phosphorus within Flathead Lake, coupled with the lack of changes in partitioning between bioavailable and particulate phosphorus in input and output loads, indicate that part of the input load of bioavailable phosphorus was converted into particulate phosphorus by the chemical process of adsorption and the biological process of phytoplankton assimilation.

Empirical relations were combined with extensive historical data to evaluate the role of limnological processes in the fate and transport of nutrient loads in these three lakes. If this evaluation had been undertaken with a purely empirical approach and without knowledge of historical inflow and outflow nutrient loads, the results would not have correctly predicted these lakes' nutrient retention. Using variables such as areal water load, hydraulic residence time, trap efficiency, and mean depth, the empirical approach likely would have predicted that the magnitude of nutrient retention would progress from small in Coeur d'Alene Lake to large in Flathead Lake and Lake Pend Oreille. That prediction would be correct only for Flathead Lake. If the empirical approach were augmented with knowledge of nutrient loads, then the major discrepancy between predicted and measured nutrient retention would become evident for two of the lakes. Namely, Lake Pend Oreille deviated sharply from its predicted large retention of nutrients and Coeur d'Alene Lake retained about one-half of its phosphorus input.

This evaluation of the role of limnological processes in the fate and transport of nutrients delivered into and discharged from three large, natural lakes within the NROK study area provides an example of the enhanced scientific understanding to be gained if lakes and reservoirs were incorporated into basin-scale national water assessments. For example, in a report evaluating the NAWQA Program, the National Research Council (2002) stated that, "In terms of scientific understanding and management capability, the exclusion of lakes and reservoirs precludes an opportunity to understand significant physical, chemical, and biological processes that alter water quality." Data acquisition programs designed with the capability to unravel the interplay of physical, chemical, and biological processes would benefit future limnological studies of the fate and transport of constituents, whether initiated by the NAWQA Program or other entities.

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