WATER, ENERGY, AND BIOGEOCHEMICAL BUDGETS (WEBB) PROGRAM: DATA AVAILABILITY AND RESEARCH AT THE NORTHERN TEMPERATE LAKES SITE, WISCONSIN

By
John F. Elder, David P. Krabbenhoft, and John F. Walker

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

Multiply	*By*	*To obtain*
millimeter (mm)	0.03937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
square meter (m^2)	10.76	square foot
square kilometer (km^2)	0.3861	square mile
hectare (ha)	2.471	acre

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 used in this report

Temperature is given in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by the following equation:

$$°F = 1.8(°C) + 32$$

Specific conductance of water is expressed in microsiemens per centimeter at 25 degrees Celsius (µS/cm). This unit is equivalent to micromhos per centimeter at 25 degrees Celsius (µmho/cm), formerly used by the U.S. Geological Survey.

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ABSTRACT

More than three thousand kettle lakes, widely dispersed within a mixed temperate forest ecosystem, are predominant features of the Northern Highland area of north-central Wisconsin. A hydrological and biogeochemical investigation of seven of these lakes and their watershed area is currently in progress as part of the Water, Energy, and Biogeochemical Budgets (WEBB) program of the U.S. Geological Survey. The objectives of the overall WEBB program are to: (1) improve understanding of processes controlling water, energy, and biogeochemical fluxes in freshwater systems, the interactions among those processes, and their relations to climatic variables; and (2) improve the capability to predict freshwater, energy, and biogeochemical budgets over a range of spatial and temporal scales.

The focus of the WEBB project in Wisconsin is hydrologic research in the Northern Temperate Lakes (NTL) area of the state. Based on the premise that an understanding of hydrologic and biogeochemical cycles in the watershed is predicated on a thorough understanding of the individual components that control the water flow, the project involves a detailed study of the hydrologic budget, including the roles of rainfall, streamflow, ground water, and flow in the unsaturated zone. It also involves investigation of ground-water/surface-water interactions. The objectives of the Northern Temperate Lakes WEBB project are to: (1) describe processes controlling water and solute fluxes in the NTL watersheds; (2) examine interactions among those processes and their relations to climatic variables; and (3) improve the capability to predict changes in water and solute fluxes for a range of spatial and temporal scales.

A variety of procedures will be used to address the objectives of the project including: installation of piezometers, lysimeters, stream-gaging sites, precipitation collectors, climate-monitoring instruments; analysis of transport of nutrients and other solutes through the system; analysis of changes in isotopic composition of water; and temperature profiling. The implementation of these procedures is described in this report.

The NTL–WEBB study area includes seven lakes that are also the site of a Long-Term Ecological Research (LTER) project, sponsored by the National Science Foundation. This project incorporates diverse research investigations conducted by faculty and research associates of the University of Wisconsin-Madison. The research orientation of NTL–LTER is principally toward aquatic ecology and geochemistry of the lakes. The WEBB research plan, with its emphasis on hydrologic processes in the lake watersheds, is designed to complement and enhance the LTER work.

INTRODUCTION

Background

Understanding and predicting global change has become one of the major scientific concerns of the late 20th century. The possibility of global climatic change has mobilized scientists from many disciplines and nations around the world in an effort to improve the ability to model the climate system and to predict its future patterns. During the past three decades, atmospheric scientists have made substantial progress in developing models that account for most of the important components of the climate system. Improvements in understanding of the physical climate system resulting from improved observations, and dramatic advances in computers, have facilitated this progress.

Despite these advances, however, climate models still are not able to adequately simulate atmospheric conditions at regional to local scales. One area in which additional knowledge is needed to enable continued model improvement is the interaction between terrestrial hydrologic processes and the atmosphere. Progress in this area requires research activity by specialists in fields such as hydrology, ecology, geology, and geochemistry, as well as the atmospheric sciences.

A global change research program of the U.S. Geological Survey was initiated in fiscal year 1991 to strengthen terrestrial and hydrologic process research. Entitled "Water, Energy, and Biogeochemical Budgets" (WEBB), the program emphasizes long-term field investigations of interactions and cycles of water, energy, gases, nutrients, and vegetation. The purpose of WEBB is twofold: to improve understanding of processes controlling terrestrial water, energy, and biogeochemical fluxes, their interactions, and their relations to climatic variables; and to improve the capability to predict continental water, energy, and biogeochemical budgets over a range of spatial and temporal scales.

The WEBB study sites are selected on the basis of geographical and environmental diversity. Priority is given to sites where data collection and/or WEBB-related process investigations are already underway, such as the Long-Term Ecological Research (LTER) sites, sponsored and funded by the National Science Foundation. Other similar research programs include the U.S. Forest Service Experimental Forests, and the International Biosphere Reserves designated by the United Nations Educational, Scientific, and Cultural Organization (UNESCO). A major emphasis of WEBB investigations is the development and maintenance of strong collaborative research relationships with scientists involved in these and other related programs.

This report describes the characteristics, data collection, research, and cooperative activities of the Northern Temperate Lakes (NTL) WEBB site in the Northern Highland area of Wisconsin, which officially began operations on October 1, 1990. Located in the north-central part of the state (fig. 1), the NTL site includes five open lakes and two bog lakes. It is also the site of the NSF-sponsored North Temperate Lakes Long-Term Ecological Research (NTL-LTER) project (Magnuson and others, 1984), which has been ongoing since 1980 under the direction of the Center for Limnology, University of Wisconsin-Madison. The WEBB hydrologic and biogeochemical research in the LTER lake watersheds complements the ecological research conducted at the NTL-LTER, which is focused on in-lake processes.

Purpose and Scope

This report describes the characteristics, data collection, research, and cooperative activities of one WEBB site, the Northern Temperate Lakes (NTL) site in the Northern Highland area of Wisconsin. Located in the north-central part of the state (fig. 1), the NTL site includes five open lakes and two bog lakes. It is also the site of the Northern Temperate Lakes Long–Term Ecological Research (NTL–LTER) project (Magnuson and others, 1984), which has been ongoing since 1980 under the direction of the Center for Limnology, University of Wisconsin–Madison.

Site Characteristics

More than 3,000 kettle lakes, formed at the end of the last continental glaciation about 10,000 years ago, are concentrated in the Northern Highland area of north-central Wisconsin. The lakes range in area from 0.1 to more than 1,500 ha and in depth from 1 to 33 m. Trophic classifications range from oligotrophic to eutrophic. About 80 percent of the land area and 60 percent of the lake frontage in the WEBB study area lie within two state forests. In this sparsely populated area, many lakes have totally forested watersheds and no private frontage. The forest vegetation consists of a mixture of coniferous and deciduous species.

Geologic features of the area are dominated by a sandy outwash plain consisting of 30 to 50 m of unconsolidated sand and coarser till overlying Precambrian igneous bedrock. The predominant soils are thin forest soils with high organic content in the uppermost horizon. The site is representative of the glacial lake districts common to the upper Midwest and Canada, but certain individual characteristics distinguish it from other nearby lake areas. Among the most important of these characteristics is glacial drift

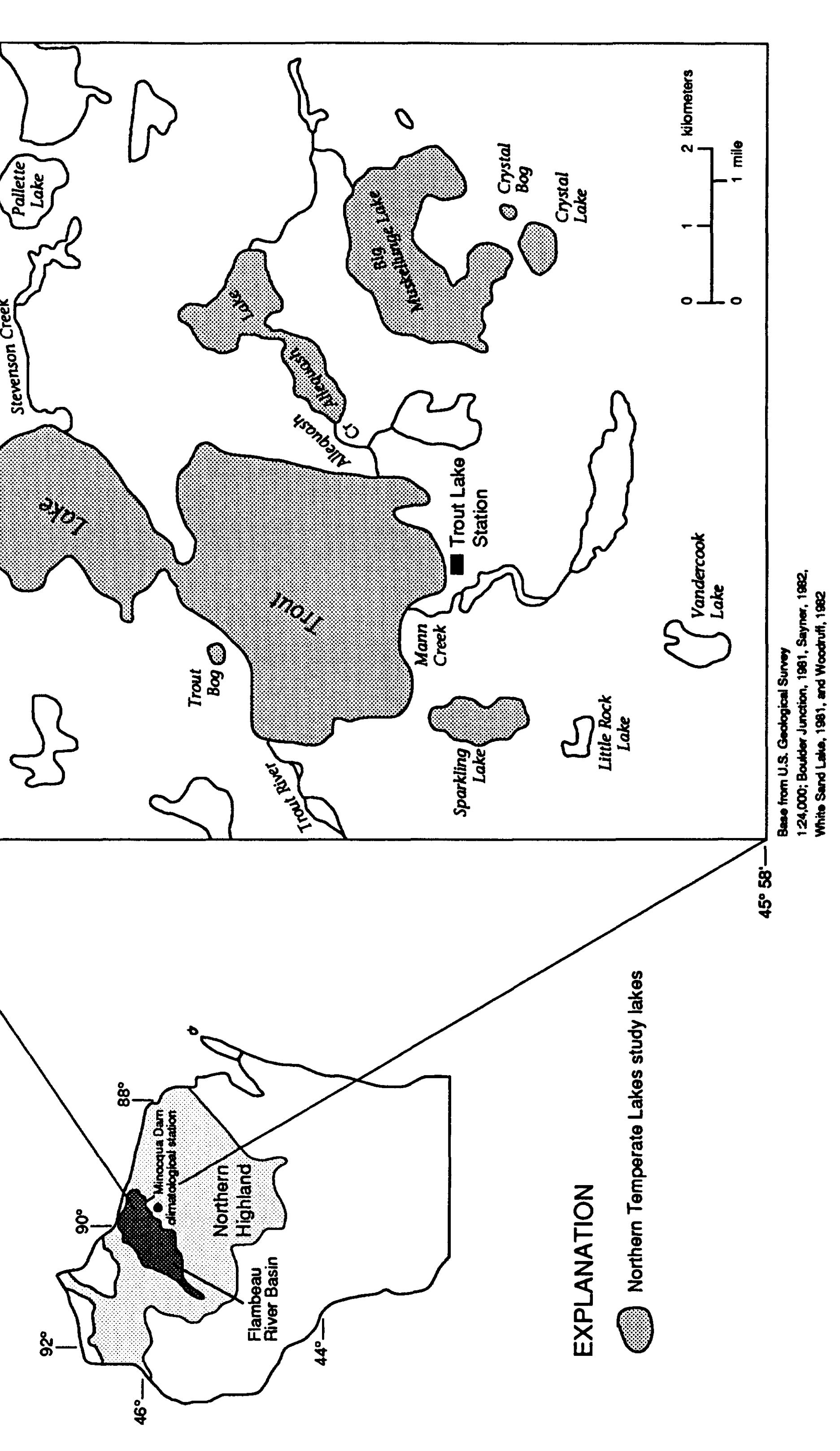

Figure 1. Location of Northern Temperate Lakes Long-Term Ecological Research study lakes in the Northern Highland area of Wisconsin.

that is virtually carbonate free; as a result, the ground-water chemistry is almost entirely controlled by silicate hydrolysis. The lack of carbonate minerals has led to speculation that the area would be subject to rapid lake acidification, but previous LTER work indicates that ground-water inflow can still effectively buffer the lake systems against acid loading (Anderson and Bowser, 1986; Kenoyer, 1986).

The seven study lakes lie within a circle of 10-km radius at an altitude of 492 to 502 m. Climate is uniform throughout the study site. Eighty-two years of record at a weather station 17 km south of the study area demonstrated that mean monthly air temperatures are lowest in January, ranging from -17°C to -6°C, and are highest in July, ranging from +13°C to +26°C, and that precipitation averages 760 mm per year (fig. 2). The lakes are ice free about 7 months of the year, commonly from late April through early December. The climate at the site is influenced by air masses from the North Pacific, the North Atlantic, the Gulf, the Arctic, the High Plains, and the Ohio Valley. Located about 70 km south of Lake Superior and 200 km northwest of Lake Michigan, the study site is also under strong climatic influence from the Great Lakes.

Most of the lakes in the Northern Highland area are seepage lakes–they have no surface-water inlets or outlets. Water budgets are thus dominated by direct precipitation, ground-water flow, and evapotranspiration. The seven study lakes, four of which are seepage lakes, are all in the same ground-water-flow system. A close relation between the lake-water ionic concentrations and the topographic settings reflects increasing proportions of ground-water inputs into the lakes from upgradient to downgradient areas. Lakes in topographic highs, such as the two bog lakes and Crystal Lake, receive little ground-water flow and no streamflow and have water with low ionic concentrations (10 to 20 µS/cm). Lakes in topographic lows such as Trout Lake, are dominated by ground-water and stream inputs and have water with higher ionic concentrations (70 to 90 µS/cm). Although linked by a common ground-water-flow system and similar climate, the lakes represent a broad range of size, morphometry, habitat, thermal features, chemistry, biological productivity, and species composition.

Several hydrogeologic studies of single lake basins recently were conducted in the NTL area (Okwueze, 1983; Kenoyer, 1986; Krabbenhoft, 1988; Wentz and Rose, 1989). These studies have led to detailed descriptions of the ground-water-flow network around three of the LTER lakes (Sparkling Lake, Crystal Lake, and Crystal Bog) and two non-LTER lakes in the area (Little Rock Lake and Vandercook Lake). A common conclusion of all of these studies is that the hydraulic conductivity of the unconsolidated aquifer is high; thus, the hydraulic connection between the aquifer and the lakes is substantial. Because surface water readily percolates through the sandy soils of the region, surface-water runoff is thought to be negligible as a hydrologic input to the lakes.

DATA AVAILABILITY

The Northern Temperate Lakes area has been the focus of limnological data collection and research for more than six decades. The data collection of the Wisconsin WEBB project is intended to complement and expand upon previous and ongoing research efforts. This section describes the existing data base and planned data-collection activities for the Wisconsin WEBB project.

Historical and Current Data

Limnological research at Trout Lake Station, directed by limnological pioneers Edward A. Birge, Chaucey Juday, and Arthur D. Halser, began in the 1920's (Beckel, 1987). This work serves as a background for current research at the NTL–LTER site. Data collected since the 1920's include:

- temperature
- pH
- Secchi depth (transparency)
- specific conductance
- free and fixed carbon dioxide
- concentrations of dissolved oxygen
- major ions
- iron
- manganese
- carbon
- color
- chlorophyll
- nitrogen and phosphorus (including different species)
- biological community data (species and biomass of phytoplankton, zooplankton, and fish).

During the 1950's, a number of the lakes in the district were manipulated by liming, phosphate additions, piscivore removal, and addition or removal of

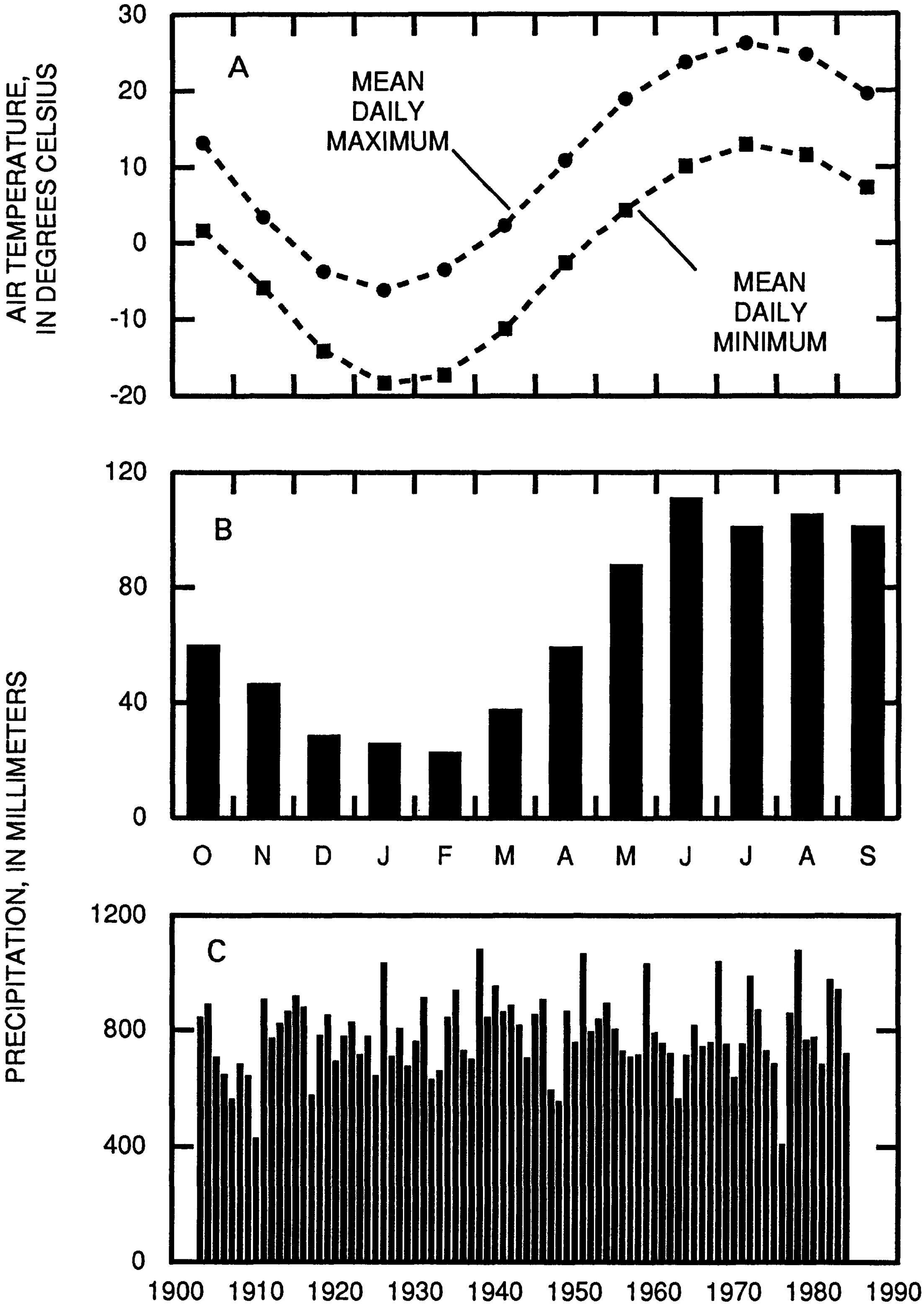

Figure 2. Mean daily air temperatures by month, mean monthly precipitation, and total precipitation at Minocqua Dam climatological station, 1903–84.

planktivores. Chemical and biological responses to these treatments were documented during the experimental work, and some of the results are stored in the lakebed sediment record. Recent studies of lakebed sediments (Kitchell and Kitchell, 1980) showed evidence of immediate and long-term responses to large-scale manipulation.

Data collected for the LTER program have included chlorophyll, primary production, zooplankton biomass, chemical concentrations, and physical characteristics of the seven study lakes. As of 1991, these data have been collected every 2 to 4 weeks during the ice-free period and three times during ice cover. Fish, benthic invertebrates, and macrophytes in the lakes have been sampled each August. Complete ion analyses of lake water have been done quarterly. Ground-water levels have been measured monthly at wells near the study lakes, coincident with ground-water sampling for chemical analysis. The Environmental Remote Sensing Center (ERSC) of the University of Wisconsin–Madison has developed an extensive Geographic Information System (GIS) data base of land use, soils, vegetation cover, and general lake characteristics.

A weather-monitoring station at Woodruff Airport, 10 km south of Trout Lake, has been maintained by the National Weather Service since 1906. Since the initiation of the LTER program, instrumentation has been added to make this site a fully automated land-based weather station. Climatic variables that are monitored at this site include air and soil temperature, precipitation, radiation (longwave, shortwave, and photosynthetically active), wind speed and direction, and relative humidity. The measurement frequency varies depending on the variable and conditions, but it is at least hourly. Additional weather data are collected with the same frequency at a raft-based station on Sparkling Lake that records air and water temperature, wind speed at three elevations, and relative humidity. In addition, numerous National Climate Data Center daily weather stations in the general vicinity collect daily precipitation and maximum and minimum air-temperature data.

A variety of data produced by programs of State and Federal agencies are available. The Wisconsin Department of Natural Resources (WDNR) has conducted surveys that resulted in maps and analyses of surface-water resources of the region. Topographic maps, aerial photographs, and geologic and soil maps are available from the USGS and from State agencies. Fisheries data have been collected continuously since 1946 at a WDNR fish research site 15 km from the Trout Lake station. A sample-collection site for the National Atmospheric Deposition Program is on the east shore of Trout Lake. Several lakes in the area have been monitored since the late 1970's as part of the U.S. Environmental Protection Agency (USEPA) Long-Term Monitoring program.

Streamflow data have been collected at USGS gaging stations at many sites in the Chippewa River Basin. One of the longest records of continuous-streamflow data in the Nation (102 years, 1888-1990) is available for the Chippewa River at Chippewa Falls, 180 km southwest of the study site.

Data to be Collected as Part of the Water, Energy, and Biogeochemical Budgets Project

A summary of the type and frequency of data collection planned as part of the WEBB project is given in table 1. These data will provide some consistency with other WEBB projects; the data also are complementary to LTER monitoring and other existing data, and they will be available for analyses to be completed in the NTL–WEBB research. The emphasis of these data is on climate, hydrology of streams entering and leaving Trout Lake, ground-water/surface-water interactions, and water quality of streams and ground water.

RESEARCH AT THE WISCONSIN NORTHERN TEMPERATE LAKES

WEBB Project

Objectives

The objectives of the Wisconsin NTL–WEBB project are to:

1. Describe processes controlling water and solute fluxes in the NTL watersheds.

2. Examine interactions among those processes and their relations to climatic variables.

3. Improve the capability to predict changes in water and solute fluxes for a range of spatial and temporal scales.

An understanding of the mass flux of water through the watershed is predicated on a thorough understanding of the individual processes that control water flux. The WEBB study will initially focus on two areas of research that will provide information on water flux–rainfall, streamflow, and recharge; and interchanges between ground water, lakes, and other surface water. Data from these studies will serve as a framework for future research on hydrologic, chemical, and biological responses to changing environmental conditions. The development of a comprehensive modular hydrologic modeling system is a long-range goal of this project.

Plan of Study

All seven NTL study lakes of the LTER and WEBB projects are in a relatively small watershed (120 km^2) that has its discharge point at the outlet from Trout Lake (fig. 1). The NTL–LTER research has identified distinct differences between the various lakes within the watershed and is based on the assumption that many of these differences are controlled by hydrologic processes. Nevertheless, little is known about the processes that control the fluxes of water, nutrients, and solutes throughout this watershed.

Rainfall, Streamflow, and Recharge Processes

One element in understanding the flow paths and residence times within the hydrologic system is the streamflow-generation mechanism. For some of the study lakes, streamflow can contribute significantly to the fluxes of water and solutes. Furthermore, areas adjacent to the streams can be crucial in generating quick-response streamflow by rapid local recharge to the water table and (or) by interflow. Complexities of streamflow generation and recharge are compounded by low-relief, complex topography and by interactions between surface water and ground water. Precipitation is the primary source of water for the seven-lake watershed; understanding the partitioning of precipitation to streamflow, recharge, and evapotranspiration requires further research.

Evaluating the effects of changes in climatic factors on the flow paths and residence times within the system requires the examination of processes at moderately large spatial scales and relatively long temporal scales. Because of the variability of climatic factors and basin characteristics, extrapolation of results to larger scales generally involves use of models rather than a simple dimensional transformation of results.

A primary research consideration, therefore, is proper representation of rainfall, streamflow, and recharge processes at the scale of the NTL system. Most rainfall-runoff models currently in use are based on a representation of hillslope processes, hence the application of these models to low-relief basins is questionable. A secondary research consideration is representation of the various processes that occur in large basins that contain a mixture of low- and moderate-relief topography.

The traditional concept of basinwide overland flow (Horton, 1933) typically does not occur in the usual hillslope setting. Instead, many researchers have argued that smaller parts of the basin are the source areas for overland flow. The concept that such source areas can vary in size in response to rainfall intensity and antecedent soil moisture has been verified by numerous field studies, such as Betson and Marius (1969) and Dunne and Black (1970). In low-relief watersheds as well, one might expect that source areas would be variable and that most would be adjacent to the stream. Numerous isotopic tracer studies have indicated that response of streamflow to rainfall is primarily derived from subsurface water (for example, Bottomley and Johnston, 1984; Pearce and others, 1986).

As water from precipitation enters the unsaturated zone, several transport mechanisms can operate to deliver recharge to the saturated zone. For instance, unsaturated-zone water could move uniformly, or as channelized flow through hydraulically preferential areas, or a combination of the two.

The research on rainfall, streamflow, and recharge is designed to describe streamflow-generation mechanisms and to develop procedures to predict the effects of changing exogenous variables on the surface-water-flow system. Specific objectives of this research include:

1. Investigate the processes controlling streamflow generation in response to rainfall for low-relief hydrologic settings.
2. Investigate the processes that lead to ground-water recharge in the NTL basin.
3. Develop appropriate predictive capabilities for the identified streamflow-generation and ground-water-recharge processes.
4. Investigate the implications of increases in spatial and temporal scale on the predictive capabilities mentioned in objective 3.

Table 1. Data to be collected as part of the Northern Temperate Lakes–Water, Energy, and Biogeochemical Budgets project

[LTER, Long-Term Ecological Research; NCDC, National Climate Data Center; NA, not applicable]

Item	Measurement or Sampling Frequency	Sites
	BASIN CHARACTERISTICS	
Digital terrain map	NA	Basinwide
	SURFACE WATER	
Base-flow measurements	Semiannual	Stream networks
Stage (discharge)	Every 15 minutes	3 Streams
	Daily	2 Streams
	GROUND WATER	
Aquifer characteristics	NA	Basinwide
Representative ground-water levels	Daily	Field-site nests
	Weekly	Areal coverage
	WATER QUALITY	
Field water-quality determinations	Monthly and quarterly	5 streams plus LTER lakes
Alkalinity	Quarterly and during storms	5 streams plus LTER lakes
Major ions	Quarterly and during storms	5 streams plus LTER lakes
Nutrients	Quarterly and during storms	5 streams plus LTER lakes
Isotopes (oxygen-18 and deuterium)	Quarterly and during storms	5 streams
Biological data		
Biota (fish, zooplankton, benthos, macrophytes)	Annual	Lakes (LTER)
Chlorophyll and primary production	2 weeks (summer); 6 weeks (winter)	Lakes (LTER)
	CLIMATIC FACTORS (collected at climate-monitoring sites within NTL watersheds)	
Precipitation quantity		
Continuous	Every 5 minutes	6
Total	Daily	6 plus NCDC sites
Air temperature		
Maximum, minimum, mean	Daily	2
Mean	Hourly	2
Wind speed		
Maximum, minimum, mean	Daily	2
Total travel	Daily	2
Wind direction	Hourly	2
Air moisture content		
Maximum, minimum, mean	Daily	2
Mean	Hourly	2

Table 1. Data to be collected as part of the Northern Temperate Lakes–Water, Energy, and Biogeochemical Budgets project (continued)

Item	Measurement or Sampling Frequency	Sites
	CLIMATIC FACTORS (continued)	
Incoming radiation		
Shortwave	Hourly and daily total	1
Longwave	Hourly and daily total	1
	OTHER	
Soil temperature, at two depths		
Maximum, minimum, mean	Daily	1
Mean	Hourly	1
Snowpack moisture	Bimonthly total	Areal coverage

Researchers in this study will use stable isotopes of water (oxygen-18 and deuterium) to identify unsaturated-zone transport mechanisms by examining the isotopic evolution of unsaturated-zone waters after rainfall events. The evolution can be affected by several processes, including the exchange and mixing of mobile water with less mobile water, the exchange of soil water with atmospheric vapor, and the exchange of unsaturated-zone water with ground water.

As many as three reaches of streams flowing into Trout Lake will be isolated and monitored before, during, and after rainfall events. Discharge measurements will be made and samples for isotopic analysis will be collected at the upstream and downstream ends of each stream reach. A series of nested piezometers and lysimeters will be placed on a transect along the most likely flow path on both sides of the stream. The lysimeters will be sampled periodically to examine the evolution of the isotopic composition of the infiltrating water as it moves toward the saturated zone and then to the stream. A general mixing model will be used to determine the temporal distribution of the source contributions to streamflow. In addition to the isotopic sampling, several gain-loss studies will be done to evaluate ground-water/surface-water interaction at base-flow conditions.

Recently, several rainfall-runoff models have been developed to account for the spatially dynamic variation in runoff generation. An example is TOPMODEL, which is based on the assumption of constant soil characteristics and which relies on variability in topography to describe the variability in source areas (Beven and Kirkby, 1979). The model has been modified to include the effects of spatially variable soil characteristics (Beven, 1986). For some hillslopes, topography is the dominant factor in controlling source areas of runoff (Wood and others, 1990); for low-relief basins, however, it is likely that soil characteristics would dominate. The current literature will be thoroughly searched to identify representative model formulations. A model formulation will probably need to be modified to properly describe the appropriate processes for low-relief basins. The resulting model will be verified by use of data collected for the streams tributary to Trout Lake.

A network of streamflow-gaging stations will be installed to support the streamflow-generation research effort. The streamflow-gaging stations will be used in conjunction with a network of existing and proposed climatological sites for calibration and verification of a rainfall-runoff model. The streamflow-gaging network will be confined to the Trout Lake basin initially, with the prospect of expansion to other basins as the study progresses. The inflow-gaging sites are on Stevenson Creek and Allequash Creek, and the outflow-gaging site is on Trout River (fig. 1). Streamflow data will be determined by use of the continuous gage-height records from the gaging stations and by correlation with less frequently made discharge measurements (for example, midmonthly measurements) of the other two tributary streams.

The LTER meteorological raft on Sparkling Lake (fig. 1) and existing National Climate Data Center daily weather stations will be supplemented by the addition of weather stations at each of the three subbasins. A complete weather station at the Trout Lake National Acid Deposition Program site will collect air temperature, soil temperature, air moisture content, incoming longwave and shortwave radiation, and precipitation (table 1). Additional gages in each subbasin will collect air-temperature and precipitation data to assess spatial variability.

The implications of increasing the scale of investigation can be tested in the future by applying the rainfall-runoff model to several spatial scales; the basins comprising Trout Lake tributary streams, three subbasins of the Flambeau River, and the outlet of the Flambeau River. The existing GIS data base will be used in conjunction with Digital Elevation Model (DEM) data to aid in defining model parameters. One challenge to the modeling efforts will be to mathematically represent a mixture of low-relief and hillslope systems at the intermediate and larger scales. The variability of basin characteristics and streamflow-generation processes will be evaluated in the perspective of the increased scales of modeling.

Ground-Water/Surface-Water Interactions

One of the most important unifying themes of past NTL–LTER biological and hydrological research has been investigation of processes that occur at the lake-aquifer interface. Equally important, but as yet completely unknown, is the effect of streamflow on the chemical and water budgets for the drainage lakes. On a system level, a very important question remains unanswered: what is the total mass flux of water and solutes out of the watershed?

Past studies of ground-water/lake interactions have used a variety of methods to estimate mass exchange rates of water and major ions (Kenoyer and Anderson, 1989; Krabbenhoft, 1988). Several unanswered research questions are vital to the full understanding of these interactions and the prediction of changes in these interactions as environmental conditions change. Among these questions are the following:

1. What specific processes control the flux of biogeochemical solutes, and what are the temporal and spatial variations in these processes?
2. How accurate are estimates of rates of water flux between lakes and underlying aquifers?
3. How does streamflow affect the solute budgets of the three drainage lakes (Big Muskellunge, Allequash, and Trout)?

Redox reactions that occur just below the aquifer-lake interface in littoral areas have a profound effect on the flux rate of several key major ions and nutrients (nitrate-nitrogen, total nitrogen, sulfate, and alkalinity). Krabbenhoft (1988) demonstrated that greater than 95 percent of the dissolved nitrate and sulfate in inflowing ground water are removed from solution or transformed to other chemical species before the ground water discharges to the lake. Corresponding rises in pH and alkalinity were also noted. Dissimilatory nitrate reduction or denitrification are likely to be the processes responsible for the nitrate transformation and (or) loss, and sulfate reduction is the most likely process for sulfate removal. The specific biogeochemical processes that control the flux of these important ions are still unresolved. Identification of these processes is important because denitrification would result in a net loss of nitrogen from the system, whereas dissimilatory nitrate reduction would involve a species change to ammonia and would leave nitrogen in the system for biological uptake. In addition, the spatial and temporal variation of these processes is unknown; subsequent oxygenated conditions may prevail in the littoral sediments, which would tend to release retained sulfur and nitrogen to the lake.

Another area of ground-water/lake interaction that requires further research is the accuracy of estimated water-flux rates. New methods need to be developed that will provide estimates of water-exchange rates that are more accurate than those presently available. One potential method of estimation is the use of temperature profiles in the lakebed to detect seasonal and (or) daily heat pulses from the lake into the aquifer. Lapham (1990) developed this method for river systems with marked success; however, the instrumentation design and data analysis will have to be modified to account for two dimensions if the method is applied to lake systems.

The importance of surface water in the water and solute budgets for the three drainage lakes (Big Muskellunge, Allequash, and Trout) has not been determined. These mass fluxes are important for determining flushing rates for the lakes. Furthermore, the variations in streamflow will affect the distribution of residence times in a lake. This effect of streamflow needs to be determined.

The research on ground-water/surface-water interactions is designed to gain a better understanding of the influence of these interactions on the water and chemical budgets of northern temperate lakes. Specific objectives of this research include:

1. Determine the water and solute yields for the Trout Lake Basin and determine the relative importance of streamflow to the water and solute budgets for Trout Lake.

2. Identify the geochemical processes that control the flux of major chemical species (such as nitrogen and sulfur species) at the aquifer-lake interface and the temporal and spatial variability of these processes.

3. Develop the temperature-profiling method for use in lake systems as means of improving estimates of ground-water/lake-water exchange.

4. Investigate methods for estimating the distribution of residence times within the drainage lakes.

Streams tributary to Trout Lake will be sampled periodically (in association with the streamflow-gaging effort for the rainfall-streamflow-recharge research element) to allow the computation of solute fluxes from streams into and out of Trout Lake. The samples will be analyzed for nutrients and major ions. The importance of surface-water sources to the complete hydrologic and chemical budget of Trout Lake will be determined from the estimated surface-water fluxes and the existing NTL–LTER data base.

Processes that control the mass flux of chemical species across the aquifer-lake interface will be identified by means of fine-scale sampling (that is, less than 1 cm). Methods used for chemical sampling will likely be dictated by the sediment type; however, use of close interval membrane equilibrators ("peepers"), core squeezing, and microelectrodes are probable. In addition, seepage meters can be used to collect samples of ground water that passes through the aquifer-lake interface (Krabbenhoft, 1988). High-performance liquid chromatography of sediment extracts (Hurley, 1988), and epifluorescence microscopy will be used to identify the organisms mediating the reactions. The samples will be collected at various times of the year at several locations within the lakes to determine the spatial and temporal variability of these processes.

The temperature-profiling method can be used at different temporal scales (daily and yearly) to estimate ground-water-discharge rates. Daily rates are determined by driving metal pipe (sealed on the bottom end) into littoral-zone sediments to a relatively shallow depth (less than 3 m). As diurnal heating and cooling of the lake's surface waters occurs, an oscillating temperature wave transmitted through the sediments can be measured in the metal pipe. The response of the sediments at a given depth to this temperature wave is a function of three characteristics only: thermal conductivity of the sediments, direction of ground-water flow, and velocity of ground-water flow. Because the thermal conductivity of unconsolidated sandy sediments does not vary by more than about 15 percent (Lapham, 1990) and because the direction of flow is easily determined by a piezometer, ground-water velocity is the only unknown variable. Analytical expressions that describe the transfer of a heat wave into the sediments can then be used with varying ground-water velocities to determine the best match to the observed heat-wave response.

The heat wave generated from the yearly fluctuation in lake temperature can be used in the same manner as daily temperature fluctuations to estimate rates of ground-water flow; however, because the amplitude of the annual heat wave is much larger than that of a daily heat wave (25°C compared to about 4°C), the depth of measurement must be correspondingly increased.

As of 1991, the utility of the temperature-profiling method for estimating ground-water-flow rates into lakes was being tested at Pallette Lake (fig. 1). More research is necessary before the applicability and accuracy of the method can be judged.

One generally uses the average volume and average inflow rates to estimate the mean residence time of a lake; however, in terms of lake chemistry and biology, the residence time distribution (RTD) can be more important. The RTD–the frequency distribution of residence times for individual water parcels in the lake–can vary considerably, depending on hydrologic conditions and physical characteristics of the lake. The concept of RTD was first introduced for wetland studies by Kadlec (1990), who used the approach taken for designing chemical reactors to estimate the RTD in a wetland. The RTD of Trout Lake will be estimated from surface- and ground-water-flow information and one of several techniques. One possible approach is to use a simple multiple-source mixing model. Another possibility is to modify the chemical reactor approach taken by Kadlec (1990) to account for diffuse sources of ground water. A third approach is the application of a two or a three-dimensional hydrodynamic model to Trout Lake. The implications of the estimated RTD for the chemistry of Trout Lake will be assessed by means of the existing NTL–LTER water-chemistry data base for Trout Lake.

Work Plan

The work plan for the NTL–WEBB research activities described previously is shown in figure 3. The time-line chart identifies specific tasks for the initial phase of the NTL–WEBB study (Fiscal Years 1991–93) and provides some detail of the work schedules for accomplishing those tasks.

Collaborative Research

Numerous research projects in the Northern Temperate Lakes area are currently being done by a variety of State and Federal agencies and universities. Because of the similarity of the NTL–LTER and WEBB study areas, the NTL–LTER program will be discussed separately from other ongoing investigations.

Northern Temperate Lakes–Long-Term Ecological Research Program

The NTL–WEBB and NTL–LTER project personnel have been in close communication since the beginning of the WEBB program. In recognition of the opportunities and mutual benefits of collaborative research, the two groups try to coordinate research efforts so that the studies complement–but do not duplicate–each other.

The NTL–LTER program includes hydrologic research; however, the scope of these research activities has been limited to small-scale, site-specific studies in areas immediately adjacent to the lakes and has focused on ground-water/lake-water interactions (Hurley and others, 1985; Anderson and Bowser, 1986; Lodge and others, 1988; Kenoyer and Anderson, 1989; Marin and others, 1990; Krabbenhoft, Bowser, Anderson, and Valley, 1990; Krabbenhoft, Anderson, and Bowser, 1990). Although these studies have been successful, hydrologic studies of the streamflow system have not been done.

The NTL–LTER group consists of 12 principal investigators from the University of Wisconsin–Madison, whose specialties include water chemistry, geochemistry, hydrogeology, remote sensing/GIS, and several branches of ecology. In addition, a number of research associates and graduate students work in the program. Some of the specific projects currently in progress include: (1) analyses of ecological disturbances caused by rapid population growths of particular plant or animal species in the study lakes; (2) development of measurement techniques that may be applied to many different variables for determining temporal variability of ecosystems, and use of such techniques to compare the variability of divergent ecosystems through time; (3) analyses of temporal coherence of divergent lake ecosystems; (4) assessment of responses of lake chemistry to weather-induced alteration of ground-water input; and (5) paleolimnological study of ground-water input to lakes since the end of Wisconsin glaciation, in which siliceous sponge spicules and lake silica are used as ground-water tracers.

An essential part of the LTER concept is collaborative research with other investigators involved in hydrologic, limnological, or ecological research at the site. This type of interaction, which has been ongoing throughout the LTER study, is enhanced further by the addition of the WEBB study at the seven-lake LTER site.

Among the benefits of cooperative interaction with NTL–LTER is access to the Trout Lake Biological Research Station on the south shore of Trout Lake (fig. 1). Owned and operated by the University of Wisconsin–Madison, the station serves as a home base for many limnologists working in the area, regardless of their affiliations. Since its establishment in 1925, the station has expanded to include a chemistry laboratory, five research laboratories, a library, conference room, computer room, and eight offices. Specialized instruments and equipment provide the capability for high-performance liquid chromatography, liquid-scintillation counting, auto analysis of nutrients, pH, and alkalinity measurement, incubations, and microscopy. Cabins on the station grounds provide year-round temporary housing for more than 30 people.

Other Investigations in the Northern Temperate Lakes Area

The Little Rock Lake Experimental Acidification Project (Watras and Frost, 1989) has generated a great deal of multidisciplinary research activity in the area since 1983. The project, which is funded by the

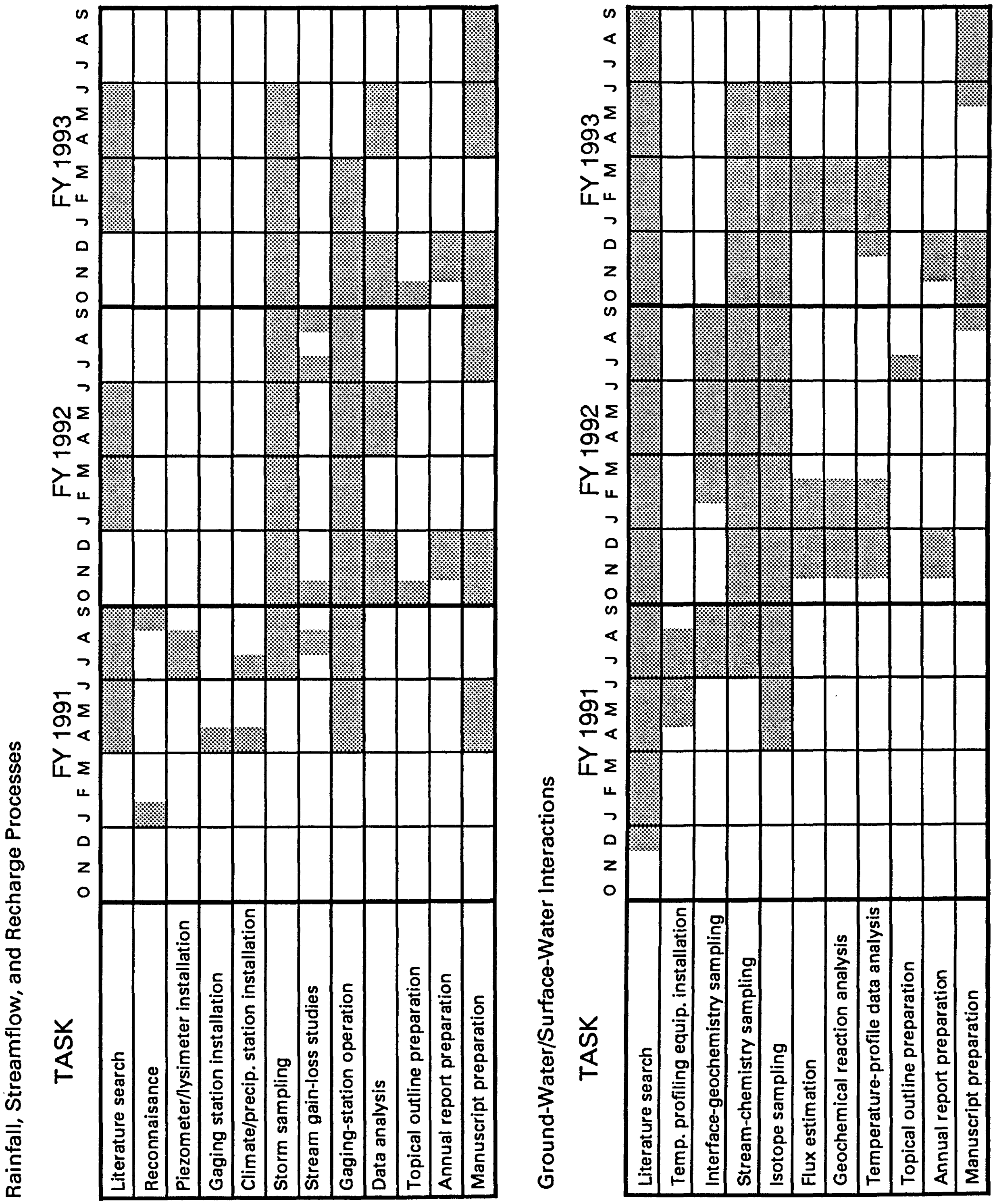

Figure 3. Work plans for the two U.S. Geological Survey research elements for fiscal years 1991-93.

USEPA, includes primary investigators from the University of Minnesota, University of Wisconsin (Madison and Superior), WDNR, and USGS. Little Rock Lake, 3 km southwest of Trout Lake (fig. 1), was divided in half by an impermeable curtain. After a 1-year baseline period, the north basin was artificially acidified with sulfuric acid, causing a pH change from 6.1 to 5.6 for 2 years, then to 5.1 for 2 more years; pH has been maintained at 4.6 for the final 2 years. Limnological responses to this treatment have been monitored closely. The responses have been compared to measurements in the untreated basin, which serves as a control environment. Although Little Rock Lake is not an LTER lake, sampling for the acidification project is scheduled concurrently with sampling of the LTER lakes. Involvement of the USGS in the Little Rock Lake project has included installation of an extensive ground-water monitoring network in the lake basin. Another recent USGS hydrologic investigation was conducted in collaboration with WDNR at Vandercook Lake (fig. 1). A hydrologic budget for the lake was constructed and implications for acid-deposition modeling were discussed (Wentz and Rose, 1989).

Another research effort in the Northern Temperate Lakes area is an interdisciplinary investigation of mercury biogeochemistry. Funded by the Electric Power Research Institute and coordinated by the WDNR, the project includes studies of sources, transport routes, biotransformation, partitioning, and bioaccumulation of mercury in six seepage lakes. These studies are the work of a group of researchers representing different institutions and specialties. Gradients of two factors that are critical influences on mercury speciation–pH and dissolved organic carbon–are found in the study lakes. Most of the work focuses on Little Rock Lake and addresses the important effect that pH can have on the biogeochemical cycle of mercury. Despite low concentrations of total mercury in the water (0.2 to 2 nanograms per liter), methylation in the sediments leads to bioaccumulation of methyl mercury in fish tissue. Both methylation and bioaccumulation seem to be enhanced by low pH.

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