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Soils, geologic, and hydrogeologic influences on lake water quality in northwestern Wisconsin

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SOILS, GEOLOGIC, AND HYDROLOGIC INFLUENCES ON LAKE WATER QUALITY IN NORTHWESTERN WISCONSIN

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SOILS, GEOLOGIC, AND HYDROLOGEOLOGIC CONTROLS OF WATER QUALITY IN NORTHWESTERN WISCONSIN LAKES

Prepared by

WISCONSIN GEOLOGICAL and NATURAL HISTORY SURVEY
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SOILS, GEOLOGIC, AND HYDROGEOLOGIC INFLUENCES ON LAKE WATER QUALITY IN NORTHWESTERN WISCONSIN

by

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December 1990

ABSTRACT

The Wisconsin Department of Natural Resources (DNR) has determined that 44 percent of Wisconsin's lakes with phosphorus values in excess of 0.035 mg/l are located in the northwestern region of the state. In 1988 the Wisconsin Geological and Natural History Survey (WGNHS) initiated a project to assess the natural occurrence of phosphorus in the geologic materials and groundwater in northwestern Wisconsin and to determine whether these background levels of phosphorus affect lake water quality.

The Pleistocene history of the area indicates that glaciers advancing into the project area from the west and northwest deposited a thick sequence of materials with variable phosphorus concentrations. Bray phosphorus analyses of unlithified sediment samples indicate that Pleistocene units deposited by ice flowing from west are high in phosphorus. Pleistocene units deposited by the Superior Lobe, flowing into the area from the northwest, decrease in phosphorus content with each subsequent glacial advance.

A potentiometric surface map constructed for the area can be used to determine regional groundwater flow patterns. In the process of generating the potentiometric surface map, several areas were identified where surface-water elevations differ from water-level elevations in wells by 50 to 200 ft. In these areas lakes receive minimal groundwater contributions.

Groundwater samples from 109 domestic wells had phosphorus concentrations ranging from <0.004 to 0.298 mg/l with a median concentration of 0.032 mg/l. Groundwater samples collected near earthen-lined manure pits and septic systems suggest that these may be significant point sources of phosphorus to groundwater.

For several lakes in the study area, lake phosphorus concentrations correlate with phosphorus concentrations in upgradient wells. Lakes with phosphorus in excess of 0.050 mg/l tend to be formed in till of the Trade River Formation or meltwater stream sediment of the Sylvan Lake Member. Lakes and groundwater with phosphorus between 0.020 and 0.050 mg/l are located in lake sediment and meltwater stream sediment of the Sylvan Lake Member. Phosphorus and groundwater concentrations < 0.020 mg/l were noted in the eastern portion of the area mapped as Crex Meadows Formation.

Data on the phosphorus content of geologic materials was combined with information on groundwater flow systems to define general "phosphorus provinces" within the study area. Region 1, the area of Trade River till and lake sediments generally has poor lake quality; Region 2, the eastern portion of the area mapped as Crex Meadows Formation, generally has good lake quality. Region 3, an area with two distinct flow systems, has upland lakes with fair to poor water quality while lakes around the margin of region 3 generally are of good quality. Lake quality in region 4, the area mapped as meltwater stream sediment of the Sylvan Lake Member, is quite variable and seems to be influenced by the length of groundwater flow paths discharging to the lakes. Region 5, the area mapped as Poskin till, has few lakes but these seem to have elevated phosphorus values.

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ACKNOWLEDGEMENTS

This study was conducted under a contractual agreement between the Bureau of Research, Wisconsin Department of Natural Resources and the Wisconsin Geological and Natural History Survey. The project was funded from segregated gasoline tax money that is distributed to Wisconsin DNR, Bureau of Water Resources Management, for a comprehensive lake management, demonstration, and research program. We especially thank the Water Resources Research staff members who collected over 200 lake samples in the spring of 1988. Landowners in the area were exceedingly cooperative and we'd like to thank all of the homeowners who allowed us to sample their wells, drill stratigraphic holes on their property, or install monitoring wells on their land. We are grateful to several individuals who helped us gain access to various monitoring sites. Jack Nedland of the Barron County forestry department acquired permission and provided access to the Waterman Lake study site. Jeff Timmins, Polk County Soil and Water Conservationist, identified the manure pit monitoring sites and set up contacts with the landowners. Jim Peterson of the Small-Scale Waste Management Project installed the monitoring wells around the Viola Lake septic system and arranged permission for us to sample there. Finally, several members of the WGNHS staff assisted with the preparation of the final document and we'd like to thank Deb Patterson, Ron Hennings, and Ken Bradbury for the time and effort they put in to this report.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The primary purpose of this study was to assess the natural occurrence of phosphorus in the geologic materials and groundwater in northwestern Wisconsin and determine whether background levels of phosphorus could affect lake water quality. In order to accomplish this goal, the distribution of the Pleistocene materials was mapped and 245 samples were analyzed for available phosphorus. A potentiometric surface map was constructed in order to determine regional groundwater flow directions and samples from 109 domestic wells, four study sites, and several springs were analyzed for dissolved phosphorus. Phosphorus contributions to groundwater were measured near two earthen-lined manure pits and one septic system. The following conclusions can be drawn from the data collected as part of this study.

1. Bray phosphorus analyses of unlithified sediment samples indicate that several units contain significant amounts of "plant available" phosphorus. Pleistocene units deposited by ice flowing from the west (Pierce and Trade River Formations and Crex Meadows sediment) contain high amounts of "plant available" phosphorus whereas those materials derived from a northwestern source area (River Falls, Poskin, and Sylvan Lake tills) decrease in phosphorus content with each subsequent glacial advance. Meltwater stream sediment of the Sylvan Lake Member also has elevated phosphorus levels, perhaps due to incorporation of older till material into the outwash.

2. Groundwater flow systems are somewhat complex in the study area. In several areas, surface-water elevations differ from water-level elevations in wells by 50 to 200 ft. In the southern portion of the area mapped as Trade River till, the water table is steeply mounded under most lakes. In the southwestern part of study area, small upland lakes formed in Sylvan Lake undifferentiated sediment and till are perched. In the northeast part of the study area, two distinct flow systems are present, one shallow and one deep.

3. Samples from 109 domestic wells had phosphorus concentrations ranging from <0.004 to 0.298 mg/l with a median concentration of 0.032 mg/l. The dolomite and basalt aquifers contribute the least phosphorus to groundwater while the sandstone and sand and gravel aquifers may contribute significant amounts of phosphorus. Speciation analyses indicate that hydroxyapatite and iron phosphate, specifically vivianite, are possible sources for the phosphorus.

4. Earthen-lined manure pits and septic systems can be significant point sources of phosphorus to groundwater.

5. The phosphorus concentration of lakes receiving minimal groundwater inputs is affected by the phosphorus content of the surrounding geologic material as well as by land-use activities in the watershed. Some lakes seem to receive significant amounts of phosphorus from upgradient wetlands; limited groundwater samples suggest that wetlands may contribute phosphorus to groundwater.

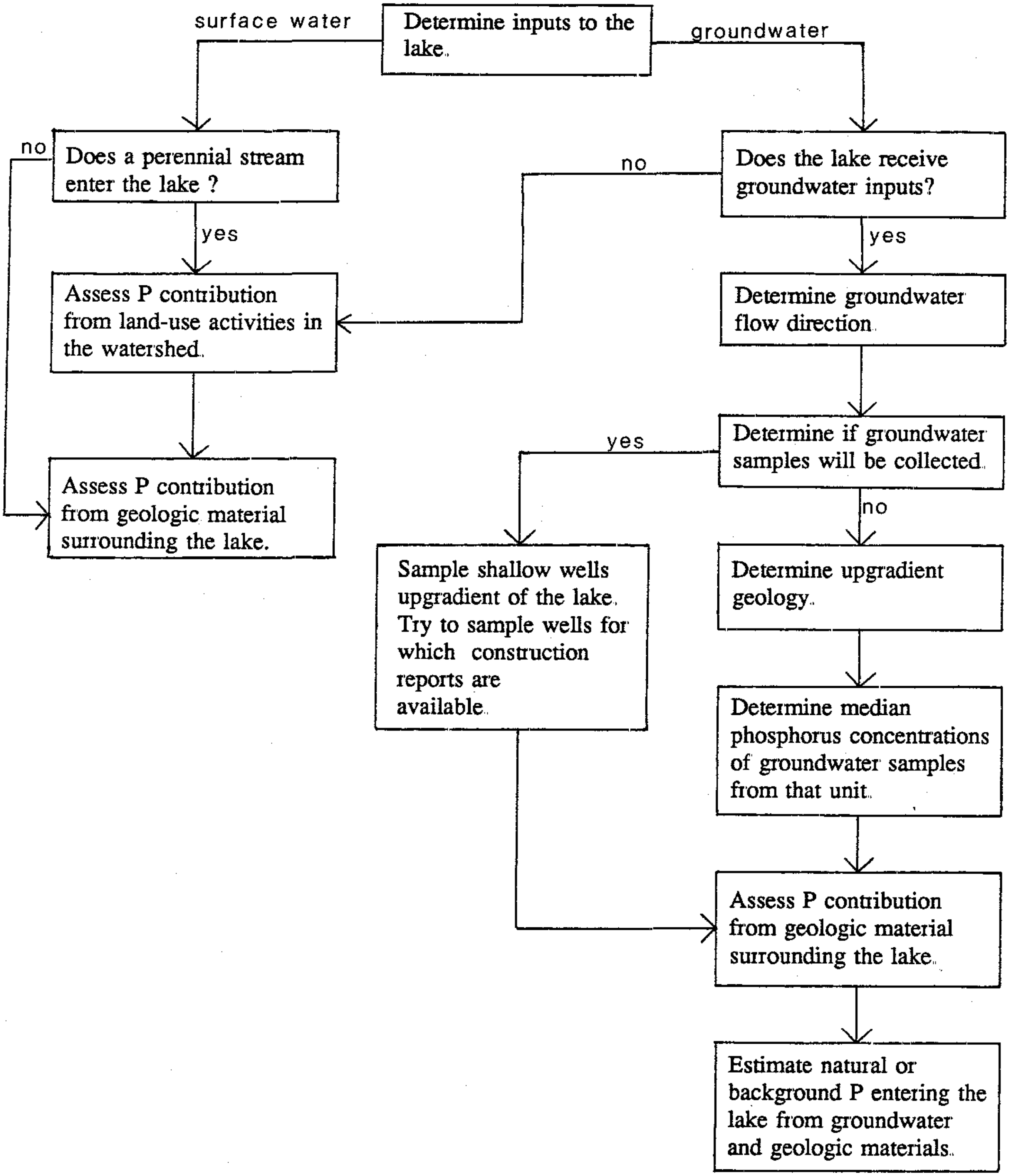
6. For several lakes in the study area, lake phosphorus concentrations correlate with phosphorus concentrations in upgradient wells. These lakes range in quality from high- to low-phosphorus lakes. Lakes with phosphorus in excess of 0.050 mg/l tend to be formed in till of the Trade River Formation or meltwater stream sediment of the Crex Meadows Member. Lakes and groundwater with phosphorus between 0.020 and 0.050 mg/l are located in lake sediment and meltwater stream sediment of the Sylvan Lake Member. Phosphorus and groundwater concentrations < 0.020 mg/l were noted in the eastern portion of the area mapped as Crex Meadows Formation.

7. Lakes with low spring total phosphorus concentrations, yet high summer concentrations indicate that shoreline development may contribute significant amounts of phosphorus to some lakes.

8. Five general phosphorus provinces have been defined for the study area. Region 1, the area of Trade River till and lake sediments general has poor lake quality; Region 2, the eastern portion of the area mapped as Crex Meadows Formation, generally has good lake quality. Region 3, an area with two distinct flow systems, has upland lakes with fair to poor water quality while lakes around the margin of region 3 generally are of good quality. Lake quality in region 4, the area mapped as meltwater stream sediment of the Sylvan Lake Member, is quite variable and seems to be influenced by the length of groundwater flow paths discharging to the lakes. Region 5, the area mapped as Poskin till, has few lakes but these seem to have elevated phosphorus values.

Implications for Lake Management

Based on work in the study area, a general flow chart for assessing phosphorus inputs to a lake has been developed. Determining the natural or background phosphorus contributions to a given lake requires site specific geologic and hydrogeologic information. The potentiometric surface and Pleistocene maps presented in this report provide a good starting point, however, more detailed information is available from the well construction reports on file at the WGNHS. These reports, filed when a domestic well is installed, provide information on geology, depth to groundwater, and well construction. For the study area, this information has been compiled on 1:24,000 USGS topographic maps. For other areas, the reports are filed by township, range, and section and may be requested from the Survey. When developing a management strategy for a given lake, well construction reports can provide useful, site specific geologic and hydrogeologic information.



Flow chart for assessing phosphorus contributions to lakes.

INTRODUCTION

Background

The Wisconsin Department of Natural Resources (DNR) has determined that 44 percent of Wisconsin's lakes with phosphorus values in excess of 0.035 mg/l are located in the northwestern region of the state. The high phosphorus lakes are mostly shallow eutrophic lakes located in Polk, Barron, and St. Croix counties, Wisconsin (Lillie and Mason, 1983).

A variety of factors, both natural and anthropogenic, affect lake phosphorus levels. Omernik and others (1988) have mapped regional variations in summer total phosphorus values for lakes in Minnesota, Wisconsin, and Michigan. In addition to measured phosphorus values, the regions of the map were delineated using data on land use, forest type, geology, potential natural vegetation, and soils. Omernik's 1:250,000 scale map can be used to estimate the present trophic state of a lake or to predict the attainable lake trophic status for a given region. Since a variety of factors affect lake chemistry and because the map was compiled from several data sources, there is a fair bit of variation of lake phosphorus values within given regions. More detailed information on land-use practices, geology, and groundwater flow patterns may be able to explain some of the variation in lake chemistry within a given region.

Purpose and Scope

In 1988 the Wisconsin Geological and Natural History Survey (WGNHS) initiated a project to assess the natural occurrence of phosphorus in the geologic materials and groundwater in northwestern Wisconsin and to determine whether these background levels of phosphorus affect lake water quality. While the project addressed geological and hydrogeological controls on phosphorus distribution, it only briefly considered some of the anthropogenic contributions of phosphorus to lakes from manure pits and septic systems.

In order to assess the phosphorus content of the geologic materials in the region, it was necessary to map the distribution of the Pleistocene deposits. Once the units were defined, samples of subsurface sediments (depth > 3 ft) were analyzed for plant available phosphorus. These samples were collected by hand augering, from stratigraphic drillholes, and from outcrops. The outcrops were primarily gravel pit exposures.

Knowledge of groundwater flow directions and groundwater chemistry are necessary in order to assess how groundwater chemistry affects lake quality. A potentiometric map (1:100,000) was constructed for the study area and it can be used to estimate regional groundwater flow directions. Groundwater samples collected from homeowners' wells, several springs, and from piezometers at four study sites helped determine background phosphorus concentrations. These data provide a general picture of phosphorus distribution in the groundwater of northwestern Wisconsin.

Study boundaries

The study area includes most of Polk County and portions of Barron, Burnett, and St. Croix counties (fig. 1). The study area boundaries were defined using lake chemistry data and the distribution of geologic units. Lake phosphorus values from DNR files were plotted for Polk, Barron, Burnett, Washburn, and St. Croix counties. A majority of the high phosphorus lakes fell within an area outlined by various ice margin positions. Figure 2 (modified from Attig and others, 1985) shows ice-margin positions in northern Wisconsin along with the study area boundaries. The southern and eastern boundaries of the study area roughly parallel the margins of the early St. Croix and the St. Croix advances of the Superior Lobe. The northern boundary of the area corresponds roughly to the valley of the Clam and Yellow rivers. The northwestern boundary of the study area parallels the contact between a region of extensive outwash deposits in the St. Croix valley and a region where till and associated deposits predominate. The western boundary of the study area is the St. Croix River.

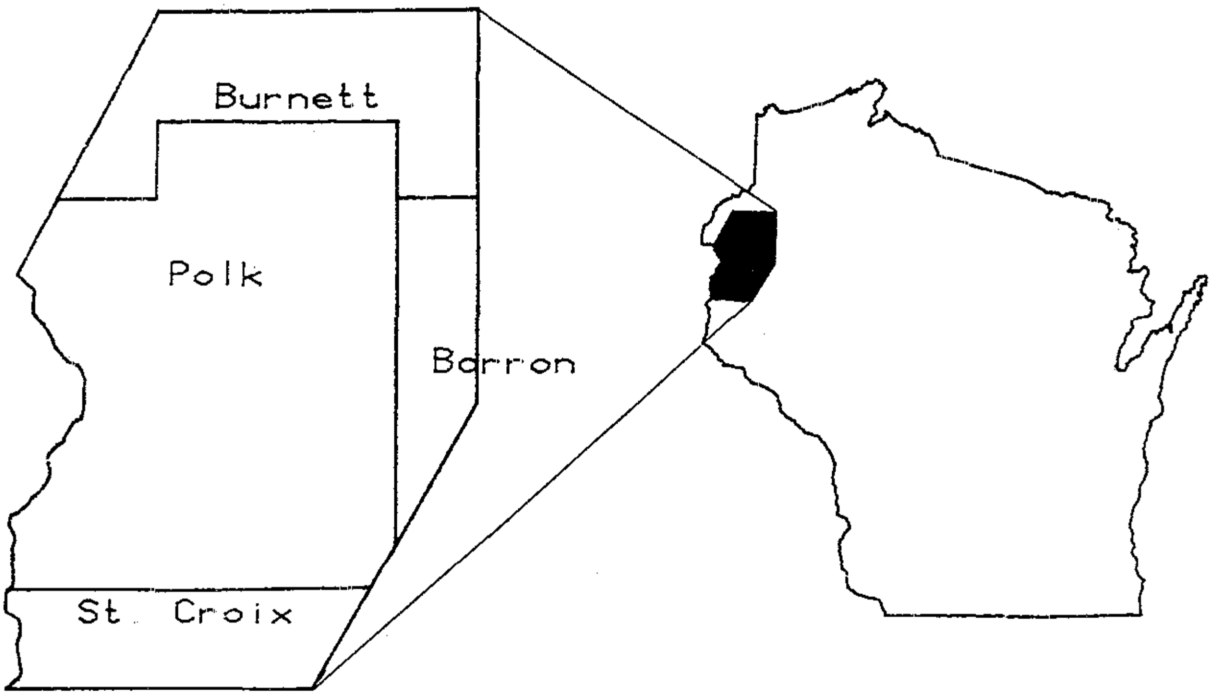


Figure 1. Location of study area.

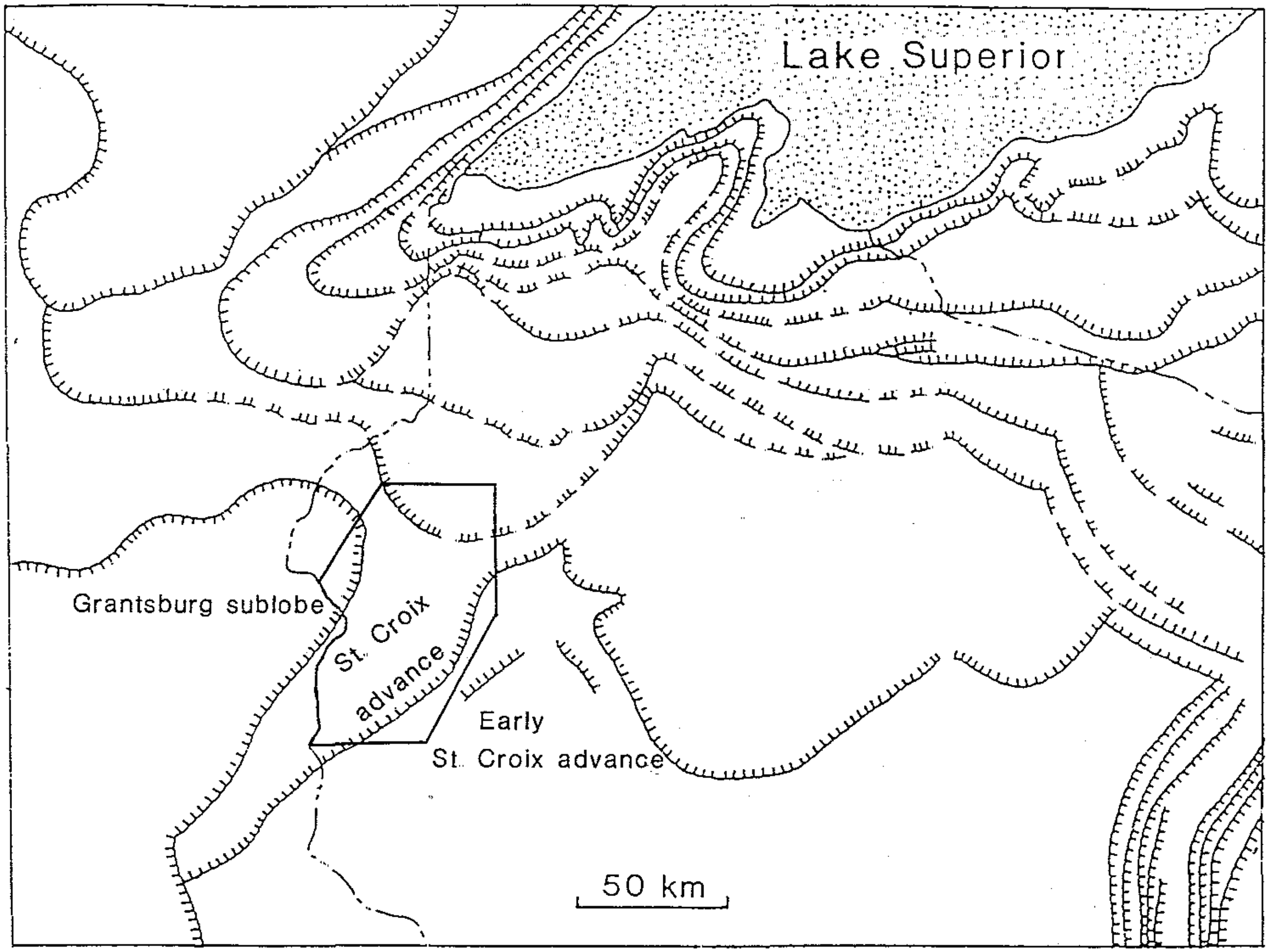


Figure 2. Study area boundaries in relation to ice-margin positions in northern Wisconsin (modified from Attig and others, 1985).

GEOLOGY

The bedrock geology of the study area has been described by Mudrey and others (1987) and the Pleistocene geology was mapped as part of this project (Johnson, in preparation). Prior to this study, Johnson (1986) had mapped the Pleistocene geology of Barron County.

Bedrock Geology

The bedrock in the study area consists of Precambrian basalts overlain by a series of Cambrian and Ordovician rock. Mudrey and others (1987) have mapped the bedrock geology of northwestern Wisconsin and a modified version of their map is shown in figure 3. In areas of thick Pleistocene deposits, no drillholes penetrate to the bedrock; these areas have not been mapped and are shown in white on figure 3.

The Precambrian basalts, emplaced approximately 1.1 billion years ago and locally known as traprock, form a topographic high that runs from west central Polk County into southern Burnett County. The depth to bedrock over this ridge is commonly 50 ft or less and rock outcrops are relatively common. The basalts are contained within the Chengwatana Volcanic Group.

During Cambrian time, approximately 523 to 505 million years ago, a series of sandstones, shales, and dolomites was deposited in the area. The oldest of these units, the Mt. Simon Formation, consists of a thick sequence (> 470 ft) of clean, well-sorted sandstones interbedded with a shale unit.

The Eau Claire Formation overlies the Mt. Simon and is approximately 100 to 150 ft thick. It is a brownish, poorly sorted sandstone with numerous interbedded silty layers. In places in contains abundant fossils and some beds contain glauconite, a green micaceous mineral.

The Wonewoc Formation, which overlies the Eau Claire, is also a sandstone but it consists of two distinct units. The lower unit, the Galesville Member, is a clean, well-sorted white sandstone while the overlying Ironton Member is a poorly sorted white sandstone with extensive iron staining. Both units are 15 to 60 ft thick.

The Tunnel City Group, which is approximately 100 to 185 ft thick, consists of two formations -- the Mazomanie Formation and the Lone Rock Formation. Within these formations there are several recognizable units, however, in general the Mazomanie Formation consists of clean, well-sorted sandstone and the Lone Rock Formation is similar but it contains more shale and a fair bit of glauconite.

Figure 3. Portion of the bedrock geology map of northwestern Wisconsin (from Mudrey and others, 1987). Legend is on next page.

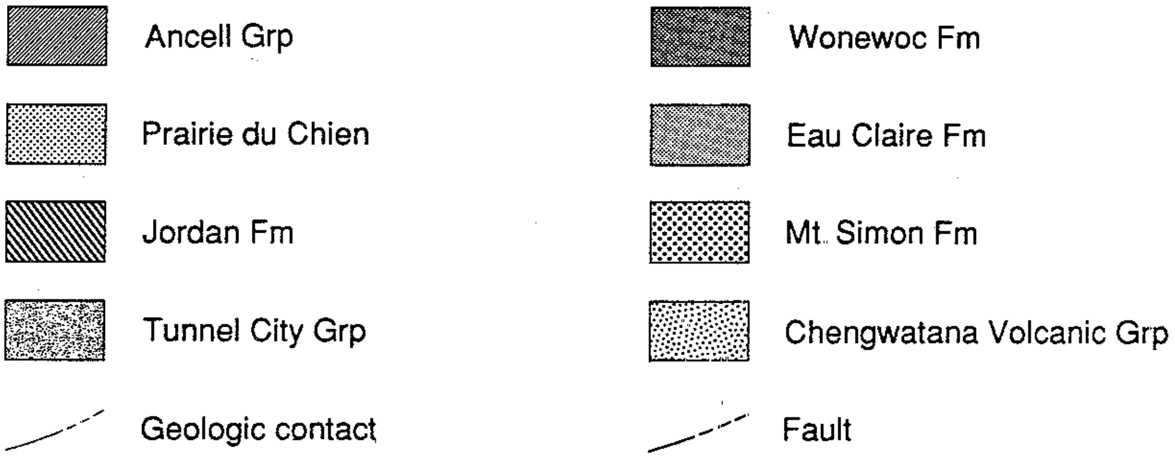


Figure 3. Legend for the bedrock geology map of northwestern Wisconsin.

The Jordon and St. Lawrence Formations were assigned a single map unit. The St. Lawrence is a thin, less than 10 ft thick, siltstone which is overlain by the Jordan Formation. The Jordan contains several recognizable units ranging from a relative clean sandstone to a poorly sorted sandstone to a sandy dolomite. The Jordan is 100 to 155 ft thick.

During Ordovician time, approximately 505 to 468 million years ago, deposition shifted from predominantly sandstone to predominantly carbonate rocks. The Prairie du Chien Group consists of two formations -- the Oneota and the Shakopee. The Oneota is a thick (90 ft) dolomite sequence overlain by 7 to 16 ft of sandstone and siltstone of the Shakopee Formation. Overlying the siltstone is another 50 to 60 ft of dolomite and sandy dolomite, also of the Shakopee Formation.

The youngest bedrock unit in the study area in the Ancell Group. It is a moderately sorted, light colored sandstone approximately 80 ft thick.

Pleistocene Geology

Glacial History

Most of the unlithified sediment in the study area was deposited during the last part of the Wisconsin Glaciation by ice of the Superior Lobe and ice of the Grantsburg Sublobe. Deposits from older glaciations are present in the subsurface, but rarely crop out in the study area. A simplified map of the Pleistocene geology of the study area is shown in figure 4. A brief glacial history of the study area is outlined below, followed by descriptions of the Pleistocene units.

Older Glaciations.--The Des Moines Lobe flowed into Wisconsin from the west over 700,000 years ago (Baker and others, 1983) and deposited till of the Pierce Formation. The early Des Moines Lobe appears to have been quite extensive, and the Pierce Formation extends perhaps as far east as Marathon County (Baker and others, 1987; Attig and Muldoon, 1989).

Following a period of weathering that may have lasted several hundred thousand years, the Superior Lobe advanced into the area flowing towards the southeast and depositing yellowish-red sandy loam till and outwash of the River Falls Formation. The River Falls Formation is probably pre-Wisconsin in age (Baker and others, 1983; Johnson, 1986). A gently rolling landscape with well-developed dendritic drainage and moderate relief characterizes the present day landscape in the region where the River Falls till is at the surface.

Late Wisconsin Glaciation--Superior Lobe. Following perhaps more than 100,000 years of weathering, the Superior Lobe again advanced into the study area, flowing towards the southeast. The sediment associated with this advance is included in the Copper Falls Formation. The Early St. Croix advance of the Superior Lobe, 25,000 to 15,000 years ago, deposited sediment of the Poskin Member. The topography in the region where the Poskin till is at the surface is gently rolling with well-developed dendritic drainage and moderate relief. Drillholes in this region encounter buried outwash, River Falls till, and Pierce till over the regional bedrock. The surface topography is similar to that developed on older the River Falls till, and must have developed relatively quickly, perhaps aided by the presence of permafrost, which was present in the area during and following the deposition of the Poskin till (Johnson, 1986).

Sediment of the Sylvan Lake Member was deposited around 15,000 years ago during the St. Croix advance of the Superior Lobe and is contained in a variety of landforms. Though the landscape left by the retreating Superior Lobe was greatly modified when extensive buried ice melted, the landscape has been altered little by subsequent fluvial or hillslope processes. Permafrost abated and the buried ice melted around 13,000 years ago (Attig and Clayton, 1986), perhaps being totally gone by 10,000 years ago. The landscape underlain by the Copper Falls Formation consists of hummocks, outwash plains, ice-walled lake plains, streamlined hills, tunnel channels, eskers, and ice-margin ridges. The distribution of the glacial landforms in the study area is described briefly in Appendix A.

Meltwater drainage patterns changed as the margin of the Superior Lobe retreated. Little outwash is associated with the ice margin indicated by the limit of the Poskin till, while extensive outwash deposits are associated with the Sylvan Lake till. At the limit of the Sylvan Lake deposits, meltwater flowed southeast into the Hay and Red Cedar Rivers in Barron County, but southwest into the Willow River in Polk and St. Croix Counties. Meltwater continued to flow into the Willow River until the margin of the glacier retreated north of the topographic high formed by the knobs of Precambrian basalt. North of this divide, meltwater flowed to the southwest into the St. Croix River. The outwash plain formed by this meltwater was later buried by till of the Trade River Formation.

An outwash plain with a northerly surface slope occurs in the northern part of the study area and was formed by meltwater derived from buried ice. Much of the meltwater flowed in two north trending valleys mapped as Sylvan Lake meltwater stream sediment near Clam Falls and southeast of Indian Creek.

As the margin of the Superior Lobe continued to retreat to the north into what is now Burnett County, a lake formed in the basin of the Clam and St. Croix Rivers. This lake, glacial Lake Lind, extended northward from Wolf Creek to north of the mouth of the Clam River. Red, varved sediment, deposited in glacial Lake Lind, is exposed along the margins of the St. Croix River valley between these two points, as well as along tributaries--the Wood, Trade, and Clam Rivers. This lake may have extended to the southwest as far as the present position of the Mississippi River as indicated by drilling done by the U.S. Geological Survey in the Anoka sand plain (Helgeson and Lindholm, 1977).

Figure 4. Simplified map of Pleistocene geology of the study area (from Johnson, 1986; Johnson, in preparation). Legend is on next page.

Crex Meadows Formation

▒ Fluvial and lacustrine deposits

Trade River Formation

▧ Till

⠿ Meltwater stream sediment

□ Lake sediment

Copper Falls Formation

■ Till

Sylvan Lake Member

▓ Till

▒ Meltwater stream sediment

▨ Undifferentiated sediment

░ Lake sediment

Poskin Member

░ Till

Figure 4. Legend for Pleistocene geology map of the study area.

Exposures of lake sediment along the Wood River contain up to 400 varves consisting of red clay and tan silt with varves 0.5 to 3 cm thick. However, drillholes southwest of Wolf Creek near Sunrise, Minnesota, contain up to 40 m of varved sediment suggesting that up to 2400 varves may have been deposited in parts of glacial Lake Lind. In Wisconsin, Lake Lind sediment is overlain by beach and fluvial sand. Prior to the arrival of the Grantsburg Sublobe in Wisconsin, glacial Lake Lind filled with sediment derived from the retreating Superior Lobe, which lay to the north.

Late Wisconsin Glaciation--Grantsburg Sublobe. The latest glacial advance in the study area is represented by till, outwash, mass-movement sediment, and lake sediment deposited in association with the Grantsburg Sublobe of the Des Moines Lobe, which advanced into the study area from the west. This advance occurred around 12,300 years ago (Clayton and Moran, 1982). The maximum extent of this advance is marked by the limit of the Trade River till, ice-marginal channels, ice-marginal lake plains, and ice-margin ridges. The maximum ice-margin position extended from south of Osceola, where the glacier covered much of the region mapped as Trade River meltwater stream sediment, north through Dresser and St. Croix Falls. In this region, outcrops of the Trade River till are few and the margin is difficult to trace. North of St. Croix Falls, Trade River till is extensive at the surface, forming a 5-km wide arc of hummocky topography from just west of Eureka Center north to Trade Lake.

When the Grantsburg Sublobe was at its maximum extent, it dammed the St. Croix drainageway and formed glacial Lake Grantsburg. The regional extent and duration of Lake Grantsburg is not well known. As the sublobe retreated out of the St Croix drainageway, glacial Lake Grantsburg drained and meltwater followed the course of the present St. Croix River. But when the ice was at its maximum extent and blocked the St. Croix drainageway, it is unclear where glacial Lake Grantsburg drained. Bruck (1979) suggested that water from Lake Grantsburg carved the Horse Creek channel that begins east of Dresser, Wisconsin; however, no channel exists that would connect the Horse Creek channel to glacial Lake Grantsburg, which lay 40 km to the north. Cooper (1935) suggested that water from the lake may have flowed under, through, or over the ice to reach the Horse Creek channel.

Silt and clay, some of it varved, occurs near the former maximum position of the Grantsburg Sublobe, but much of the area inundated by the lake is now covered by sand. A broad fluvial plain composed predominantly of medium sand formed in the St. Croix valley (shown as Crex Meadows Formation on fig. 4). It is not clear if this sand was deposited in Lake Grantsburg or if the sand consists of slightly reworked sediment deposited earlier in Lake Lind. Much of the sand may also have been reworked by streams proceeding and following Lake Grantsburg. The broad sand plain became a terrace following the downcutting of the St. Croix River. The sand on the surface of the terrace became mobilized by westerly and southwesterly winds and long, sinuous transverse dunes were formed.

Late Wisconsin Glaciation--Lake Superior Spillway. The last major event to shape the landscape in the study area was the drainage of water from Lake Superior down the St. Croix valley when the Superior Lobe was blocking the eastern outlets to Lake Michigan and Lake Huron. This spillway formed and was in operation between 10,000 and 12,000 years ago (Clayton, 1983). The added discharge caused the St. Croix to downcut over 35 m to its present level. It was during this event that the Precambrian basalt was exhumed forming the St. Croix Dalles and their famous potholes.

Pleistocene Stratigraphy

Pierce Formation.--The oldest Pleistocene sediment in the study area is till of the Pierce Formation, which occurs only in the subsurface. Characteristics of the Pierce till are described by Baker and others (1983), Mickelson and others (1984), Baker (1988a, 1988b), and Johnson (1986). The type section, located just south of the study area at Woodville, includes lake sediment as well as calcareous, olive-black loam till; no lake sediment was recognized in the study area. Within the study area, Pierce till has patchy distribution occurring only rarely in drillholes in the southern part of the area, and never in outcrop. Well drillers' reports in the vicinity of known occurrences of Pierce till mention "blue clay" or "yellow clay" overlying bedrock or, more rarely, overlying older unconsolidated sediment.

River Falls Formation.--The River Falls till is typical of material deposited from Superior Lobe ice; it is red, sandy, and contains many volcanic clasts. This unit is described by Baker and others (1983), Mickelson and others (1984), Baker (1988a, 1988b), and Johnson (1986). The River Falls till is nearly identical to the younger Copper Falls till; these two units are distinguishable, however, because the mineralogy of the River Falls till has been altered by weathering (Johnson, 1986). Unweathered layers of River Falls till may be present in the subsurface in the central and northern parts of the study area, but they are difficult to differentiate from layers of Copper Falls till. The type section of the River Falls till is located just south of the study area near Baldwin. The till of the River Falls Formation occurs at the surface immediately south of the study area and in the subsurface in the southern part of the study area.

Copper Falls Formation.--During late Wisconsin time (25,000 to 15,000 years ago) ice of the Superior Lobe flowed into the study area from the northwest and deposited sediment of the Copper Falls Formation; two members of this formation occur in the study area. The Poskin Member of the Copper Falls Formation consists predominantly of yellowish-red sandy loam till and occurs at the surface in the southeast part of the study area. The Sylvan Lake Member of the Copper Falls Formation consists of yellowish-red sandy loam till, outwash, mass-movement sediment, and lake sediment; much of the study area is covered by sediment included in this member. Drillholes and well construction logs reveal a complex stratigraphy suggesting that multiple advances or complex depositional environments are represented by the sediments in the Sylvan Lake Member. Characteristics of these two members are described by Johnson (1986, 1988a, 1988b).

Trade River Formation.--The Trade River Formation includes outwash, mass-movement sediment, and lake sediment deposited by the Grantsburg Sublobe. North of St. Croix Falls, the Trade River till is extensive at the surface and the area is characterized by hummocky topography. Within this area, 2 to 10 m of till overlie Copper Falls outwash. Kettles are common in this region and have relief greater than the thickness of the till, indicating that the buried ice was Superior Lobe ice. Ice-marginal channels occur just west and south of Eureka Center. Five small ice-marginal lake plains occur along the eastern edge of the former ice-margin limit.

Crex Meadows Formation.--The Crex Meadows Formation is a term used in this report to include the sand, silt, and clay deposited in Lake Lind and Lake Grantsburg and in the rivers that shortly post-dated Lake Grantsburg. The Crex Meadows sediment exposed at the surface consists mostly of sand with local accumulations of bedded silt and clay. Well construction records in the region report buried clay layers, particularly in the St. Croix River Valley where red clay beds are up to 30 m thick, some of these clay layers may well have been deposited in glacial Lake Lind. Sediment that was deposited in the lakes was derived from the Superior Lobe as well as from the Grantsburg Sublobe.

Phosphorus Content of Unlithified Units

Two hundred forty-five samples of unlithified sediment were analyzed in order to determine the phosphorus content of the Pleistocene lithostratigraphic units. Forty-seven samples of soil parent material (C horizons) were collected along a north-south transect and a northwest-southeast transect across the study area (fig. 5). These materials, collected with a hand auger, came from depths greater than 3 ft to insure that they were unaffected by soil forming processes and land-use activities such as the application of agricultural chemicals or animal wastes. Samples collected as part of the Pleistocene mapping effort were also analyzed; these include 140 samples from drillholes and 58 samples collected from outcrops. Drillhole samples were collected at depths ranging from 3 to 68 ft; most outcrop samples were collected in gravel pits. Figure 5 shows the location of drillholes for which samples were analyzed; locations of outcrop samples are not shown.

Samples were analyzed at the State Soil and Plant Analysis Lab for Bray 1 phosphorus. This analytical procedure measures "plant available" phosphorus rather than total phosphorus and was used as a simple and inexpensive measure of the phosphorus that might be available from the geologic materials.

In the Bray 1 procedure, non-carbonate materials are extracted with 0.1N hydrochloric acid utilizing a 10:1 dilution (volume of acid is 10 times the volume of soil). For carbonate rich sediments, i.e., Pierce and Trade River tills, and lake sediments, a 50:1 dilution was used. The phosphorus identified in the normal Bray 1 procedure is termed "plant available" and is a measure of phosphorus that can be utilized by agronomic crops. As such, it may also serve as a rough assessment of phosphorus that can be fairly easily leached from geologic materials.

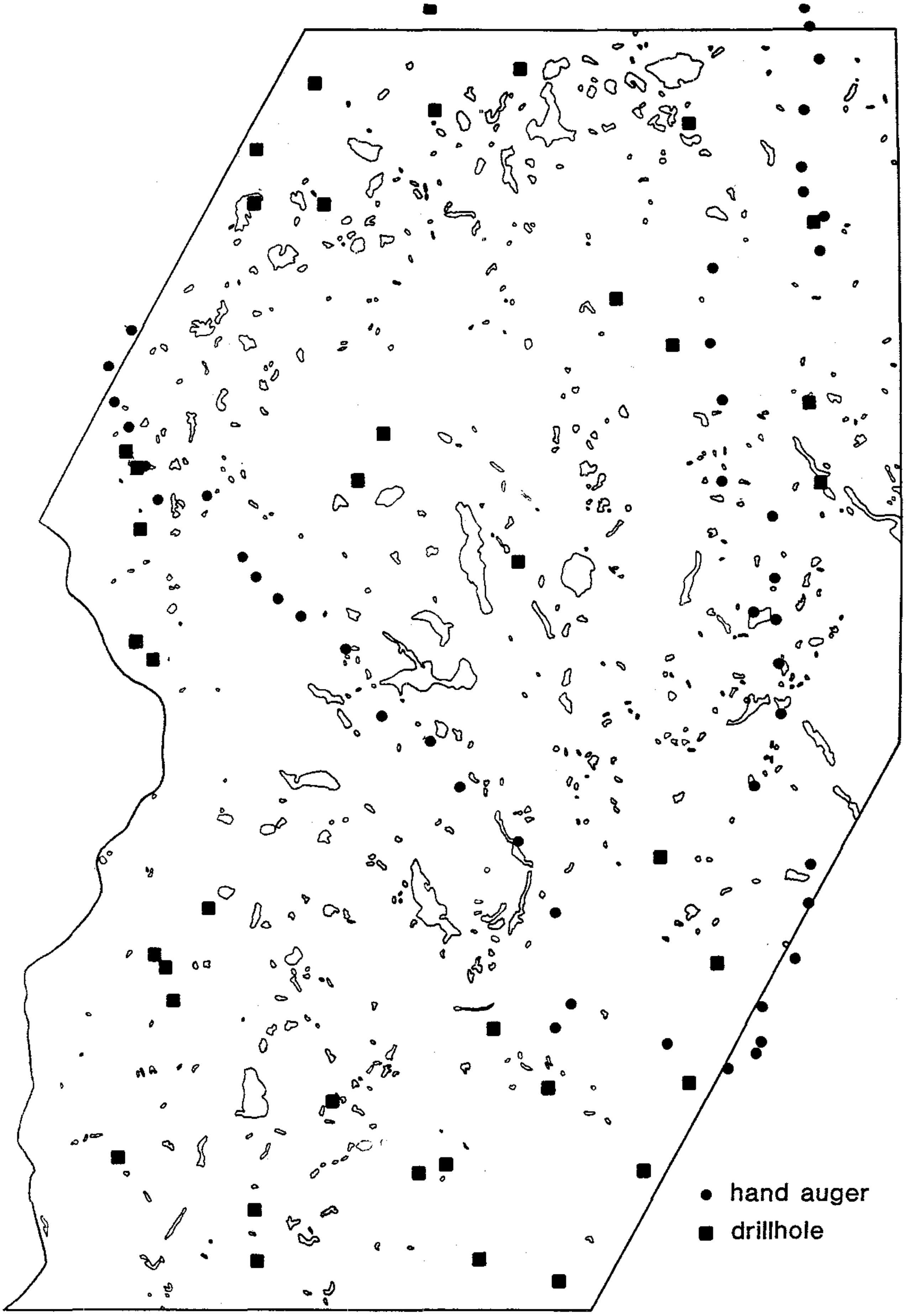


Figure 5. Map showing location of stratigraphic drillholes and subsurface sampling points.

Given the larger volume of acid used in the 50:1 dilution, is not clear that all of the phosphorus measured is necessarily plant available, but the values are still considered to be a reasonable estimate of phosphorus that may be mobile.

From a crop production standpoint, Bray 1 phosphorus values for a medium-textured soil that are less than 30 lbs/acre are considered low, those between 31 and 45 lbs/acre are optimum and those above 46 lbs/acre are high or excessively high (>60 lbs/acre). These comparison values are from surface soils and as a result they reflect agricultural practices including applications of manure and commercial fertilizers. It is assumed that sub-surface samples should have lower phosphorus contents, however, no other sub-surface data are available for comparison.

Data from samples analyzed (fig. 6) show that glacial materials derived from a western source area (Pierce and Trade River tills and Crex Meadows sediment) contain high amounts of "plant available" phosphorus whereas those materials derived from a northwestern source area (River Falls, Poskin, and Sylvan Lake tills) decrease in phosphorus content with each subsequent glacial advance. Cretaceous shales, known to be high in phosphorus, are located to the west of the study area while the bedrock northwest of the study area includes Precambrian igneous and metamorphic rocks, Cambrian sandstones, and Ordovician carbonates. The igneous rocks are not believed to contain much phosphorus, however, the Paleozoic sedimentary rocks are potential phosphorus sources. It appears that the River Falls till, deposited as ice first advanced into the area from the northwest, incorporated bedrock material containing phosphorus. Subsequent ice advances from the northwest were eroding till deposited by the previous ice advance, rather than eroding bedrock material. The lower phosphorus contents on the younger Superior Lobe tills (Poskin and Sylvan Lake) seems to support the idea that each advance reworked previous Pleistocene deposits and incorporated limited amounts of bedrock material.

Data (fig. 6) also show that Pleistocene lake sediments contain high amounts of Bray 1 phosphorus. Lake basins may accumulate organic material and this could be the source of phosphorus in these sediments. The meltwater stream sediment of the Sylvan Lake Member is also high in phosphorus. The extensive outwash deposits associated with the Sylvan Lake till indicate that significant quantities of meltwater were generated during the meltback of Sylvan Lake ice. Large tunnel channels (see Appendix A) suggest that this meltwater may have been eroding material sub-glacially. Incorporation of older material, specifically River Falls and Poskin till, into the meltwater stream sediment may account for its higher phosphorus content.

Many of the lithostratigraphic units in the study area contain significant amounts of "plant available" phosphorus. Certainly, these materials, if saturated for long periods of time (geologic time), would yield dissolved phosphorus to the groundwater.

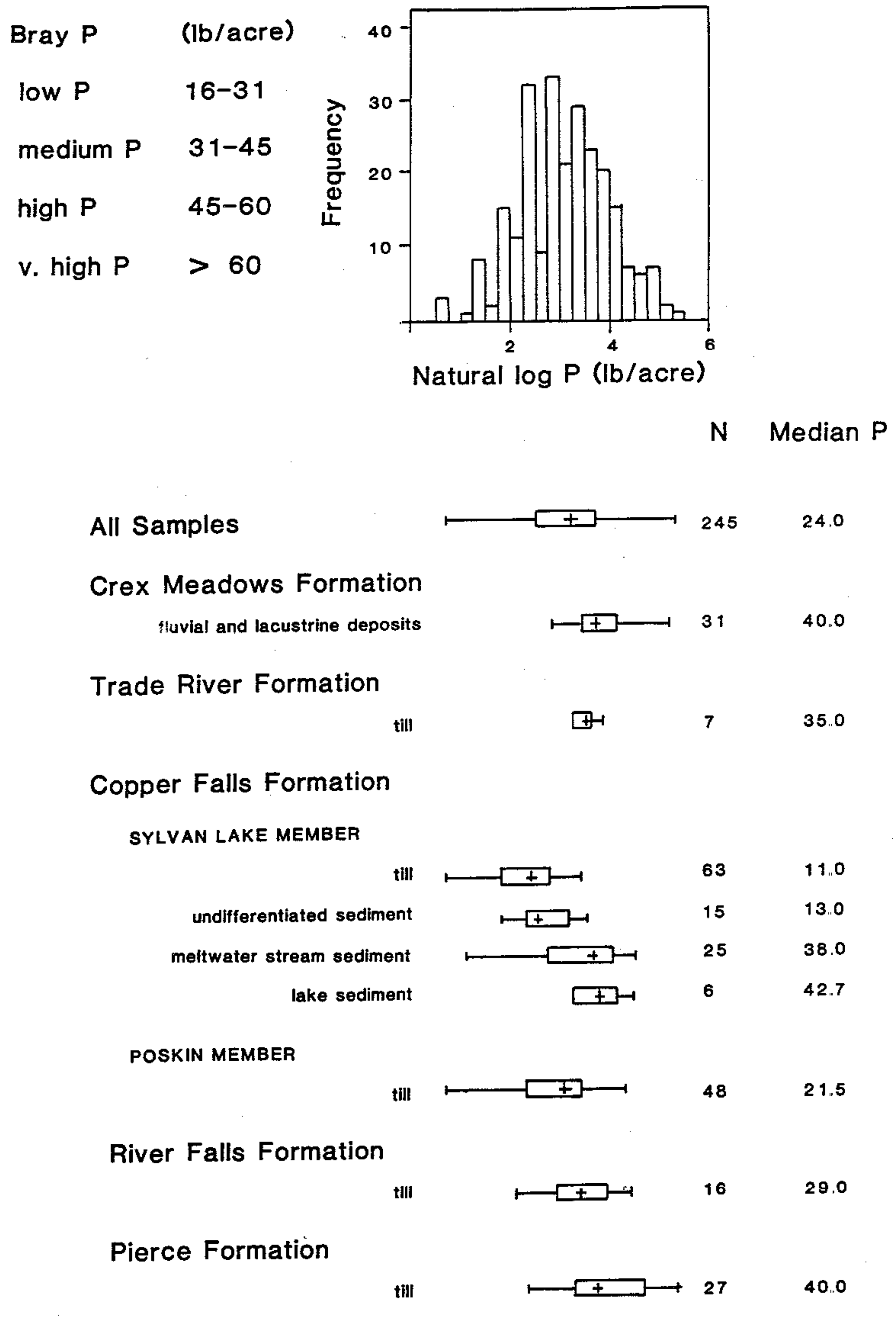


Figure 6. Histogram of the natural log of Bray 1 phosphorus concentrations of subsurface materials (top). Lower portion of the figure shows boxplots of results from specific Pleistocene units, median concentration is listed for each boxplot (shown by +), box encloses values between the first and third quartiles, line represents the entire range of values.

HYDROGEOLOGY

Major Aquifers

Water supply wells in the study area tap a variety of aquifers including the sand and gravel aquifer, the Prairie du Chien dolomite, the Cambrian sandstones, and the Precambrian basalt. Over much of the area the Pleistocene deposits are more than 100 ft thick. While these deposits are quite variable in composition, they commonly contain enough coarse-grained sediment to provide adequate water supply for domestic wells.

In areas where Pleistocene deposits are thin or absent, wells are completed in the bedrock aquifers. A general depth to bedrock map for the study area is shown in figure 7 (modified from Mudrey and others, 1987). The band of near-surface bedrock that runs from west central Polk county into southern Burnett County is underlain by the Precambrian basalt and some Cambrian sandstones. The sandstones usually provide dependable water supplies, but the basalt is typically a very low-yielding aquifer that is only utilized when the overlying Pleistocene materials cannot supply adequate yield. Water quality from both the sandstone and basalt is generally good, however, some wells completed in the Cambrian sandstones yield water that is high in iron.

A second area of near-surface bedrock occurs in north-central St. Croix County and south-central Polk County. Here the underlying bedrock is primarily Prairie du Chien dolomite, although in places it is capped by sandstone of the Ancell Group. The dolomite aquifer is a moderately productive aquifer and it is used extensively for domestic supply.

Regional Groundwater Flow Patterns

In groundwater studies conducted at the regional scale, water-table maps based on office data are frequently used to characterize groundwater flow patterns. The water table is the top of the saturated zone, and is the level at which the pore pressure is equal to atmospheric pressure. Office-derived water-table maps are based on surface-water elevations taken from 1:24,000 USGS topographic maps and depth to water data reported on well construction reports.

Using surface-water data to aid in the generation of a water-table map assumes that the surface-water bodies are surficial expressions of the water table. In order to use water elevations in domestic wells, the assumption that the vertical groundwater gradients are negligible must be made. This is because most homeowners' wells are completed far below the actual water table and are frequently open over relatively long intervals. Water levels in wells of similar depth actually define a potentiometric surface, which is an imaginary surface representing the total hydraulic head in an aquifer. In unconfined aquifers, the potentiometric

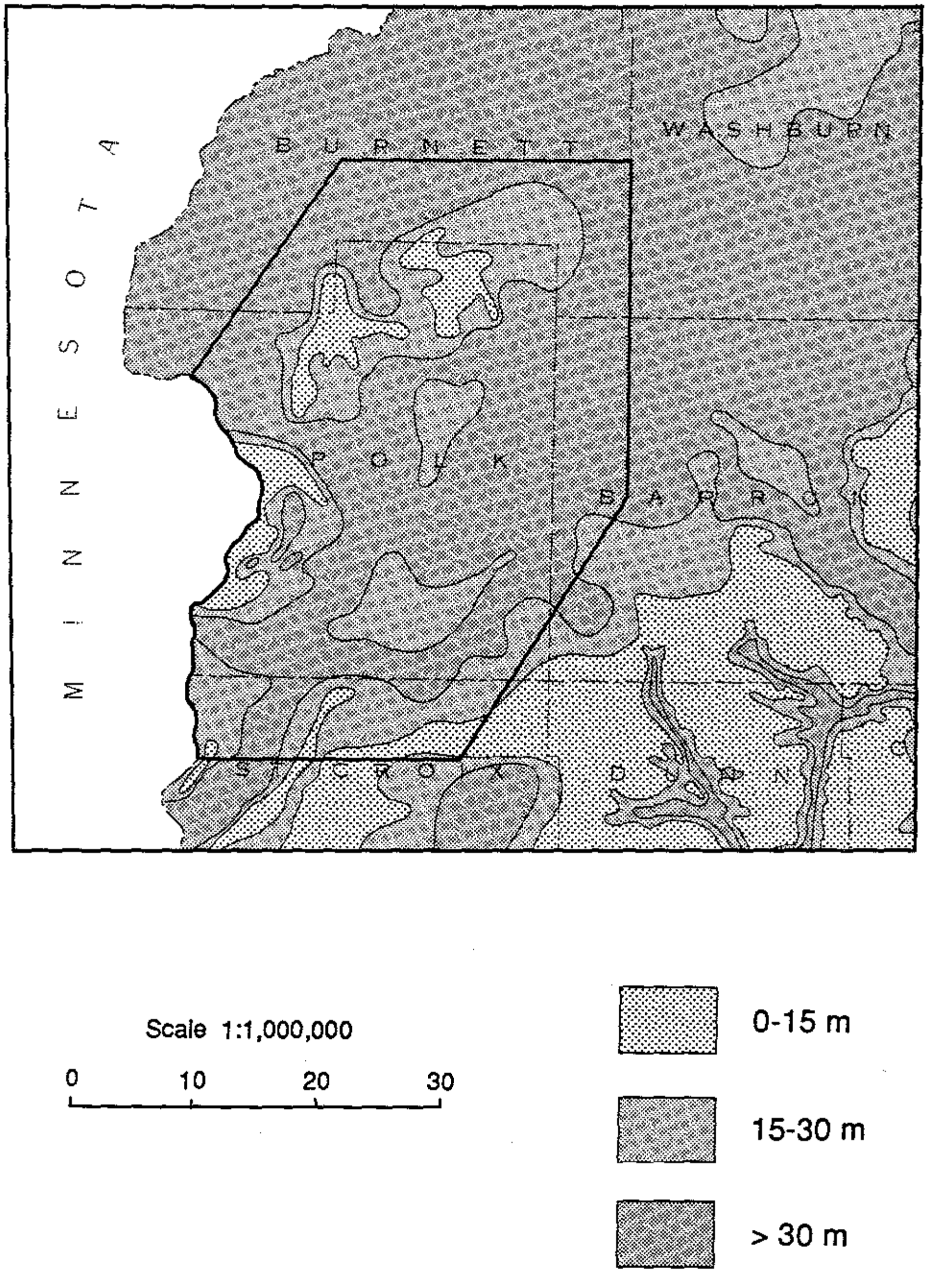


Figure 7. Simplified depth to bedrock map (from Mudrey and others, 1987).

surface frequently coincides with the water table. In some cases, however, these two surfaces do not coincide, such as in areas of strong vertical gradients or perched groundwater systems.

In some geologic settings, the above assumptions about office-derived data are valid. For example, in central Wisconsin an office-derived water-table map of a uniform, sandy, unconfined aquifer was accurate to within 5 ft when compared to field-derived water-table maps (Blanchard and Bradbury, 1987). In other geologic settings, however, these assumptions may not hold. In Door County, Wisconsin, the fractured dolomite aquifer exhibits strong downward hydraulic gradients and multiple saturated zones. In such settings, "water-table" maps based solely on groundwater elevations from wells can incorrectly identify a deeper potentiometric surface as the water table (Bradbury and others, 1988).

Water-table Mapping

Given the variety of aquifers in the study area, it was not clear that an office-derived water-table map would be accurate. In addition, a regional groundwater study conducted in Barron County (Zaporozec and others, 1987) indicated that the hydrogeology in the northeastern portion of the study area was complex. In order to test the accuracy of an office-derived map for the region, two computer-generated contour maps were constructed; one based on surface-water elevations and one based on well-water elevations. Subtracting one surface from the other identified several areas where water levels in wells differed significantly from surface-water elevations. Field investigations in three areas identified specific geologic settings where large discrepancies between surface-water and well-water elevations could be expected.

Surface-water map.--A contour map based on surface-water elevations was constructed using elevations of all lakes, perennial streams, and large wetlands (greater than several mi^2) shown on USGS 1:24,000 topographic maps. Intermittent streams and isolated wetlands were not considered reliable indicators of water-table elevation and so these points were not included in the map. The locations and elevations of the surface-water points were digitized and entered into a database. For large lakes a central point was digitized along with several points delineating the shoreline. The shoreline points were spaced approximately 1/8 to 1/4 mile apart. For smaller lakes a single point was entered and for streams several points, approximately 1/2 mile apart, were entered. The data were contoured using a minimum curvature algorithm. The computed contours compared well with a hand-contoured subsection of the regional map. The resulting contour map of surface-water elevations is shown in figure 8.

Well-water map.--A contour map based on groundwater elevations in domestic wells was also constructed. Well construction reports for wells installed since the late 1930's were used for this map. After confirming the location of each well using current and historic plat maps, the surface elevation was estimated from 1:24,000 USGS topographic maps. The depth to water reported by the driller was then used to calculate a water-level elevation. The

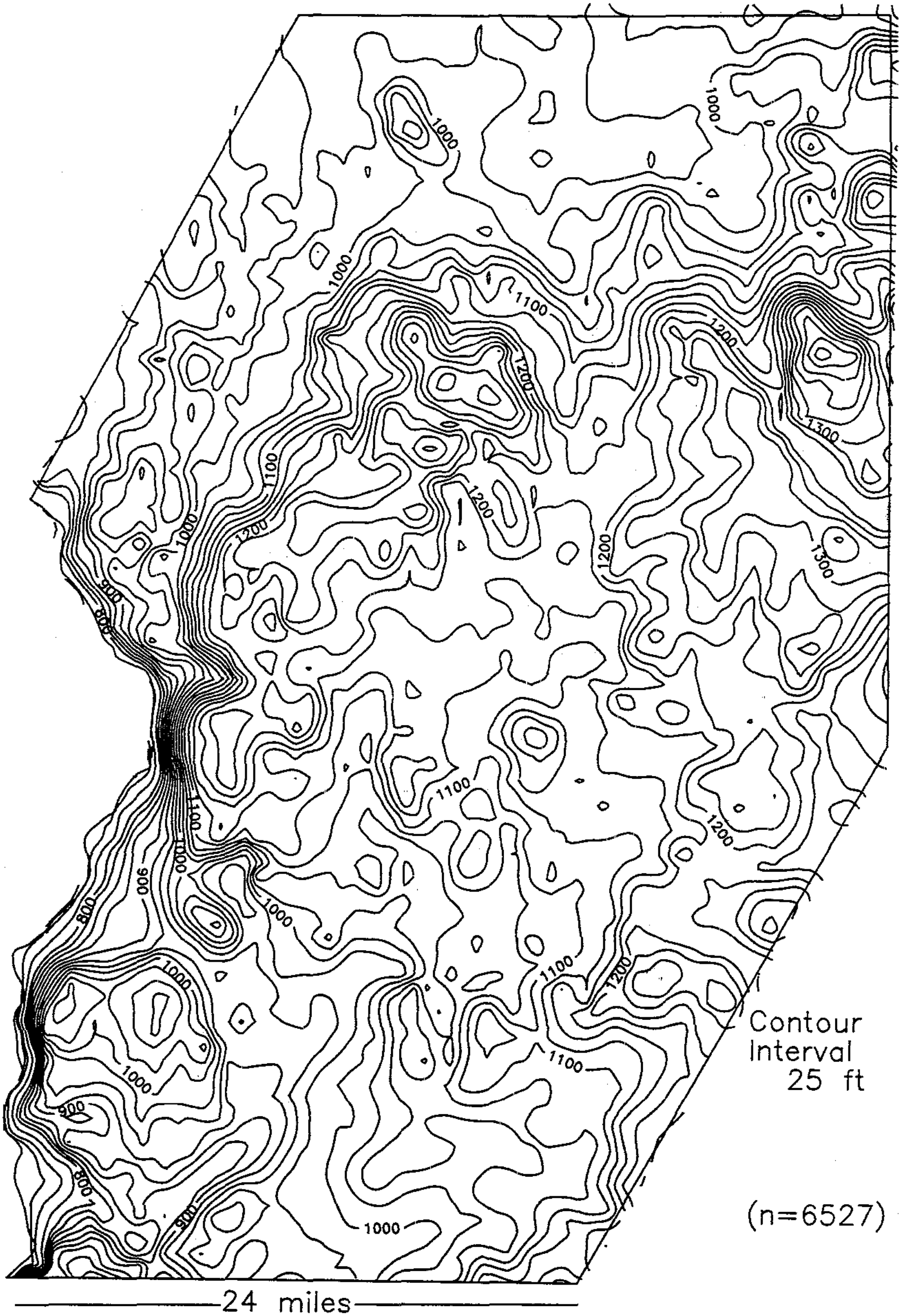


Figure 8. Contour map of surface-water elevations.

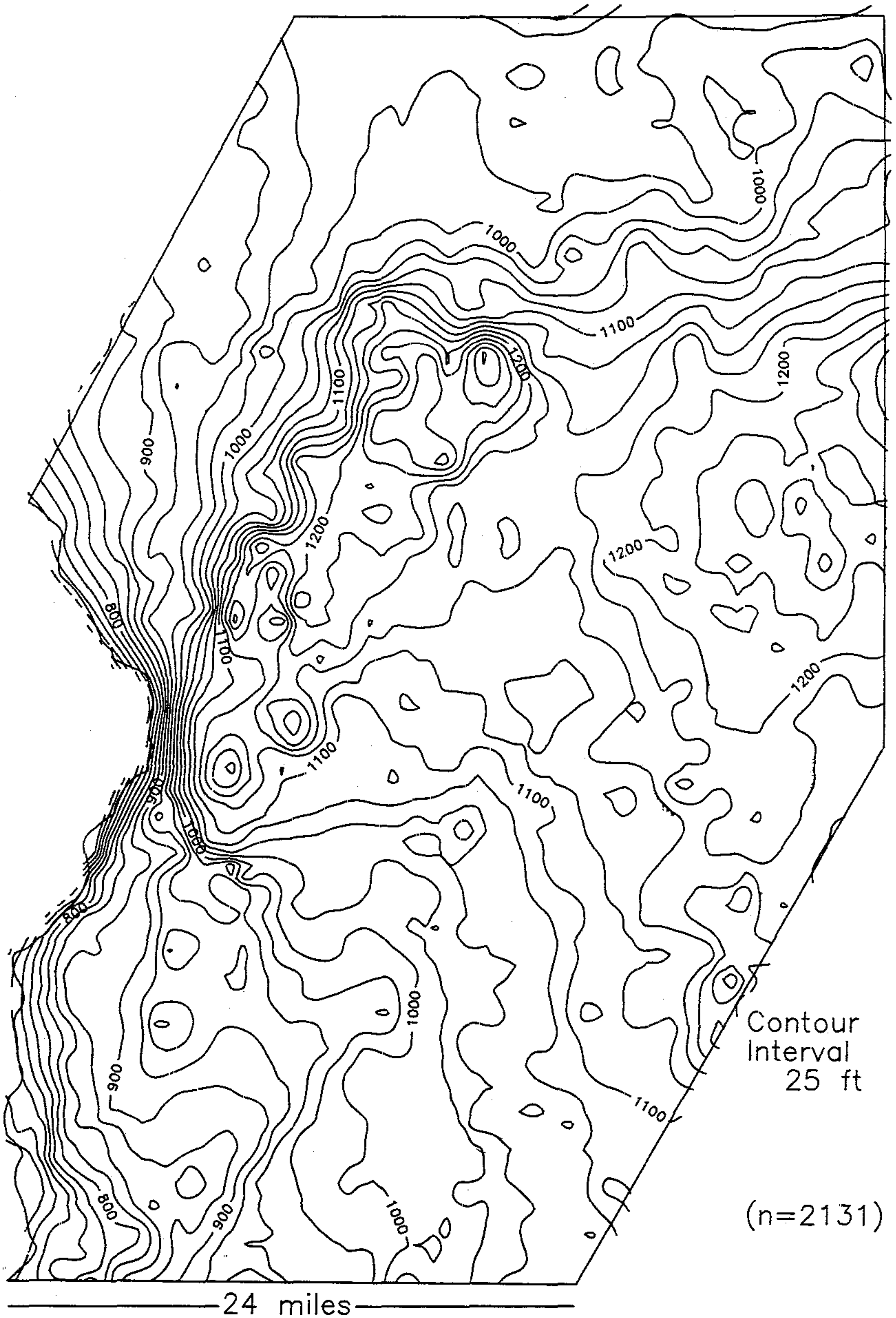


Figure 9. Contour map of well-water elevations.

locations and water levels of 2131 domestic wells were digitized and entered into a database. The data were also contoured using minimum curvature method (fig. 9).

Comparison of maps.--The two maps show similar regional flow patterns; there are potentiometric highs in the west central and northwest portions of each map and water flows in a south-southwesterly direction toward the Apple and Willow rivers, north to Clam and Yellow rivers, and west toward the St. Croix River. In general, the surface-water contour map shows more resolution around small topographic features, probably because of data density; the surface-water map is based upon 6527 points whereas only 2131 points were used to generate the well-water map. The surface-water map indicates a maximum elevation of 1425 ft while the well-water map has a maximum contour of 1300 ft.

Figure 10 was generated by subtracting the interpolated water levels on the well-water map from the interpolated water levels on the surface-water map and contouring the results. This allows a more detailed comparison of the two maps. Over most of the study area, the interpolated surface-water and well-water elevations agree within 50 ft (fig. 10). However, in some areas these water levels differ by 100 ft or more. These differences could be caused by a variety of factors including differing data densities between the two maps, errors in well drillers' records, the existence of complex flow systems or strong vertical gradients in certain areas, or the existence of perched surface-water bodies above a deeper water table.

Field investigations at four study sites (shown on fig. 10) indicate the large differences between the two contour maps result from various hydrogeologic settings in the study area. The settings which exhibit the largest differences between surface-water and well-water elevations include (1) upland areas that contain small perched lakes, (2) areas of hummocky sandy till that develop two distinct saturated zones, (3) areas of silty till where the water table is steeply mounded under lakes. Field data at specific sites illustrate these different conditions.

Study Sites

The four study sites were chosen to represent a variety of geologic and hydrogeologic conditions. Osceola Lake is near an area where there are large differences between surface-water elevations and well-water elevations. In addition, Osceola Lake has somewhat elevated phosphorus concentrations (0.051 mg/l, Spring '88 sampling); it is fed by several springs, and it sits in a small steep watershed that is mainly forested and should not contribute much phosphorus from surface runoff.

Waterman and Sand Lakes were selected as study sites in order to investigate the flow systems in the northeast part of the project area. Groundwater chemistry samples were also collected at these sites and those results are discussed later in the report.

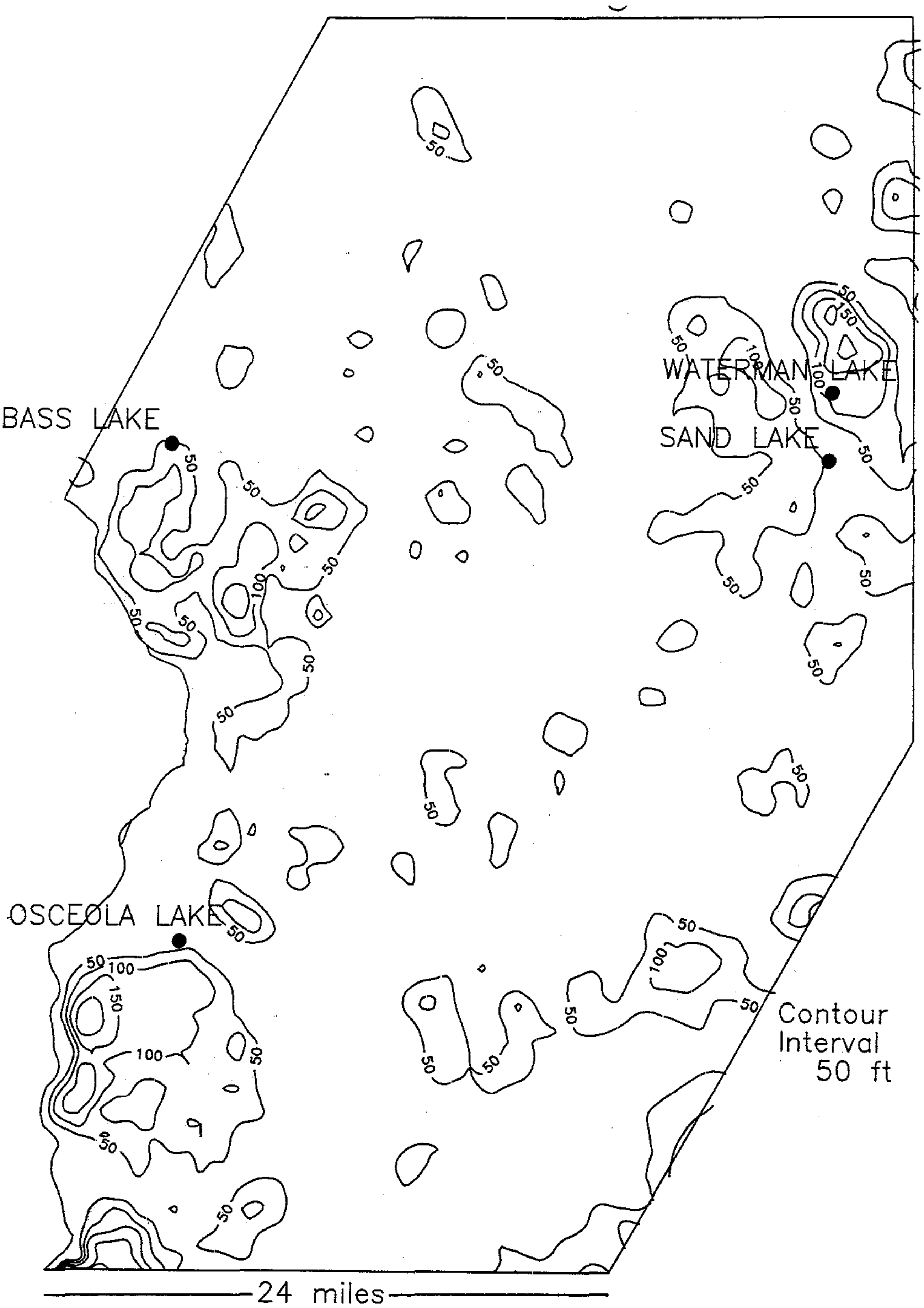


Figure 10. Contour map of the difference between surface-water and well-water elevations; locations of the four study sites are also shown.

Bass Lake is formed in sediments deposited by the Grantsburg Sublobe. Several lakes in this portion of the study area have high phosphorus concentrations; Bass Lake was chosen as a study site because it is accessible, the land use is typical of the area, and the landowners were cooperative.

Each study site contains several $1^1/_4$-inch, PVC piezometers with 3-ft slotted screens completed at various depths. These piezometer nests were used to determine the vertical groundwater gradients. Relative piezometer elevations were determined by rod and level surveying. All piezometers were developed after installation to insure that the screens were open.

Osceola Lake.--Osceola Lake is located at the base of a steep ridge composed of 100 to 150 ft of sand over sandstone and limestone. Loess caps the ridge. Several small lakes on top of the ridge have elevations ranging from 1040 to 1050 ft; while Osceola Lake at the base of the ridge has an elevation of 898 ft (fig. 11). Water levels in monitoring wells (shown as small circles in fig. 11) range from 892 ft near Osceola Lake to 925 ft near the top of the ridge. The well on top of the ridge (DJ) is a domestic supply well while the wells near the lake (OL1 to OL3) were installed by the WGNHS. In addition to the wells near the lake, a drillhole was installed on top of the ridge (marked by X on fig. 11); the hole extended from 1050 to 945 ft and encountered only dry sand. These observations suggest the surface-water features on top of the ridge are small perched lakes.

Osceola Lake is located in a large area of southwestern Polk and northwestern St. Croix counties where differences between surface-water elevations and well-water elevations are on the order of 200 ft (fig. 10). The Apple River valley dissects this area and in the valley, surface- and well-water elevations are similar. The surficial units in most of this area are undifferentiated sediment of the Sylvan Lake Member and meltwater stream sediment of the Sylvan Lake Member (fig. 4). The distribution of these units roughly corresponds to the area where the differences between surface- and well-water elevations are greatest. Note that the northern boundary of the area where water-level differences are large (fig. 10) seems to correspond to the contact between meltwater stream sediment of the Sylvan Lake Member and meltwater stream sediment of the Trade River Formation. On the basis of the data from the Osceola Lake site, the upland surface-water features throughout this area are assumed to be perched, and thus are separated from the underlying aquifers by an unsaturated zone.

Waterman and Sand Lakes.--Waterman and Sand Lakes are both located in a valley that formed when subglacial meltwater discharged to the ice margin. The area is characterized by a broad upland surface with numerous lakes and wetlands at elevations of 1320 to 1340 ft (fig. 12). The upland area is dissected by the valley that contains Waterman, Sand, and Beaver Dam Lakes which range in elevation from 1212 to 1231 ft. The locations of the two study sites are indicated on the map.

The stratigraphy at both sites consists of thin lake sediments over sandy outwash over red sandy till. All of these units are contained within the Copper Falls Formation, and their

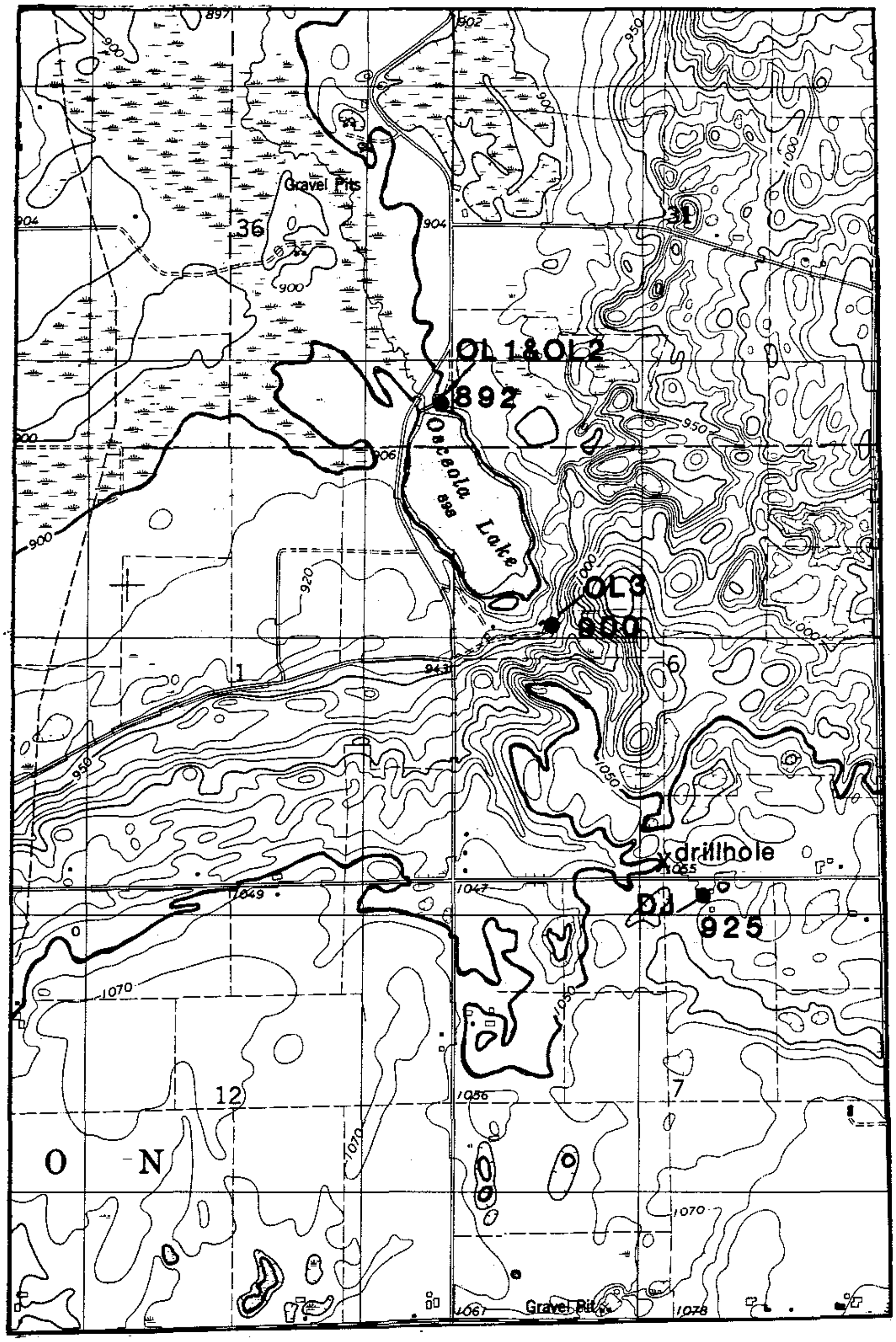


Figure 11. Portion of a 1:24,000 USGS topographic map showing the location of Osceola Lake and water elevations from monitoring wells. Contour interval is 10 ft.; lakes have been outlined and the 900 and 1050 ft contour lines have been highlighted to show relative lake elevations.

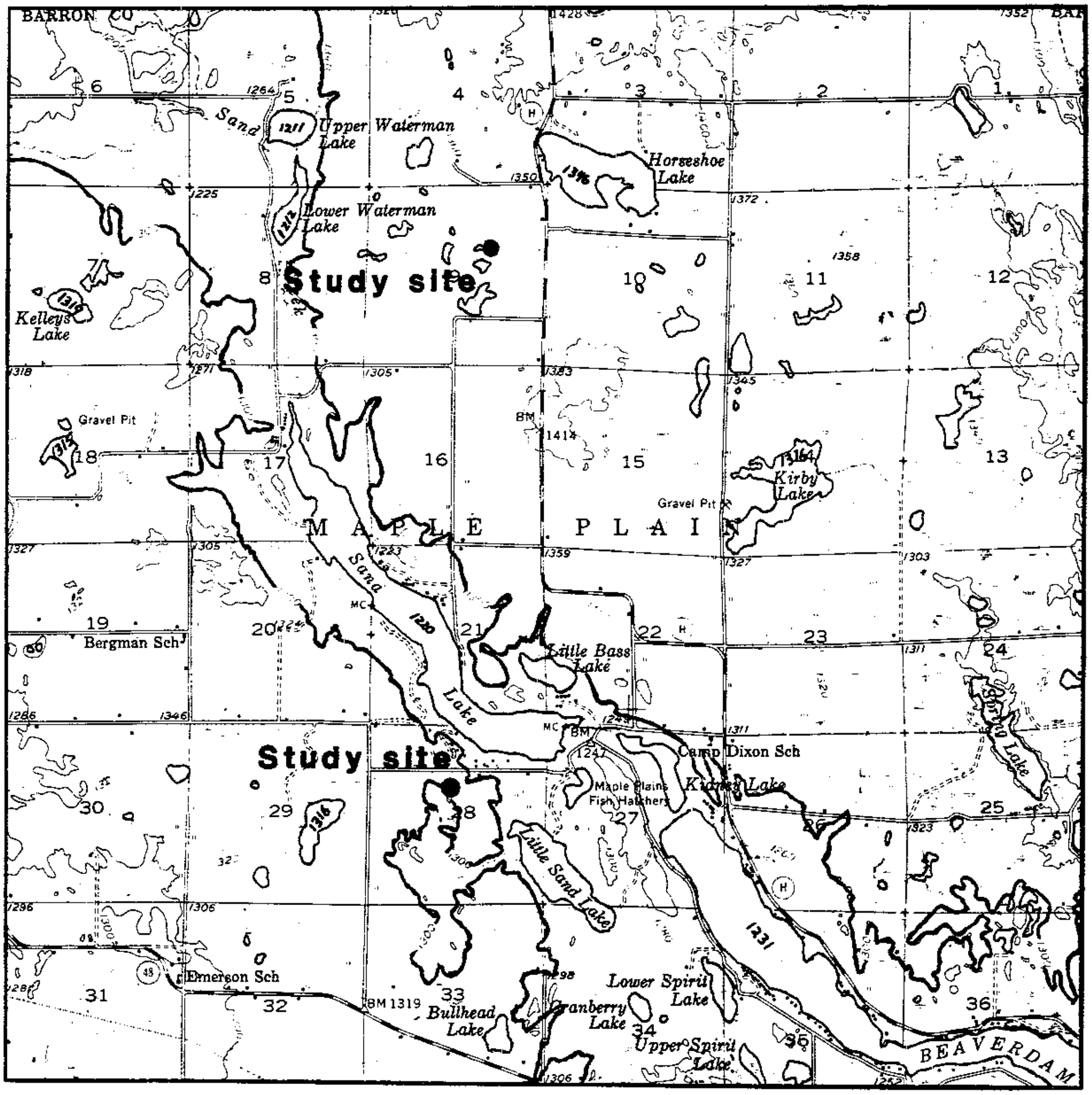


Figure 12. Portion of a 1:62,500 topographic map showing the location of the Waterman and Sand Lake study sites. Contour interval is 20 ft; lakes have been outlined and the 1300 ft contour has been highlighted to show relative lake elevations.

stratigraphic position suggests that they can be included in the Sylvan Lake Member. Cumulative percentages of sand, silt and clay versus depth at the Waterman Lake site are shown in figure 13. The outwash averages 90% sand, 5% silt, and 5% clay. Two grain-size distributions are reported for the till. In general, the till is quite sandy and is best characterized by the grain-size distribution of 81% sand, 13% silt, and 6% clay, however, in places there are some fine-grained layers within the till that are characterized by a grain-size distribution of 35% sand, 46% silt, and 19% clay. The stratigraphy at the Sand Lake site consists of 11 ft of lake sediments, 3 ft of outwash, and 24 ft of till. Samples from the site were not analyzed for grain-size distribution, however, visual examination suggested that the sediments are quite similar to those at the Waterman Lake site.

Vertically nested, $1^1/_4$-inch, PVC piezometers with 3-ft slotted screens were installed at both sites. The shallowest three piezometers at the Waterman Lake site, which are completed in the outwash and the upper portion of the till, contain water (fig. 14a). The two deeper piezometers, which are finished below a depth of approximately 50 ft (elevation 1280 ft), are dry. A similar situation exists at the Sand Lake site. Here, the two shallow piezometers completed in the outwash and till contain water while the deepest piezometer, finished in the till, is dry (fig. 14b). The water-level data at both sites suggest there is an upper saturated zone that is aerially extensive. Below this zone, unsaturated conditions exist until a deeper saturated zone is encountered. Although no piezometers intersect the deeper saturated zone, its elevation has been estimated from the elevations of Waterman, Sand, and Beaver Dam Lakes as well as from water levels in domestic wells.

Both the Waterman Lake and Sand Lake sites lie within a large area where water levels in wells are 100 to 200 ft below surface-water elevations (fig. 10). The valley containing Waterman, Sand, and Beaver Dam Lakes dissects this area and in the valley surface- and well-water elevations are similar. The surficial units in most of this area are till and undifferentiated sediment of the Sylvan Lake Member. In the northeast portion of the study area, the distribution of these units seems to roughly outline areas where the differences between surface- and well-water elevations are greatest. North of Waterman Lake there are several "till islands" separated by meltwater stream sediment (fig. 4). These "till islands" roughly correspond to areas where the surface-water and well-water elevations disagree by more than 50 ft; perhaps fine-grained layers within the till act as the "perching layer". Near the Waterman and Sand Lake sites, the surficial unit is undifferentiated sediment of the Sylvan Lake Member. Piezometer nests at both sites suggests that this unit supports an upper saturated zone which is separated from the deeper saturated zone by a zone of unsaturated sediment.

Bass Lake.--Bass Lake is located in a hummocky till plain that contains numerous lakes and wetlands. Surface-water bodies in this area lie at approximately 995 ft elevation on the eastern side of the till plain and they grade to an elevation of 880 ft on the western edge (fig. 15). Water levels in domestic wells have elevations ranging from 925 ft in the east to 860 ft in the west. Figure 16 is a diagram of the Bass Lake site. The upper portion of the figure shows the locations of the five piezometers installed in and around Bass Lake and the

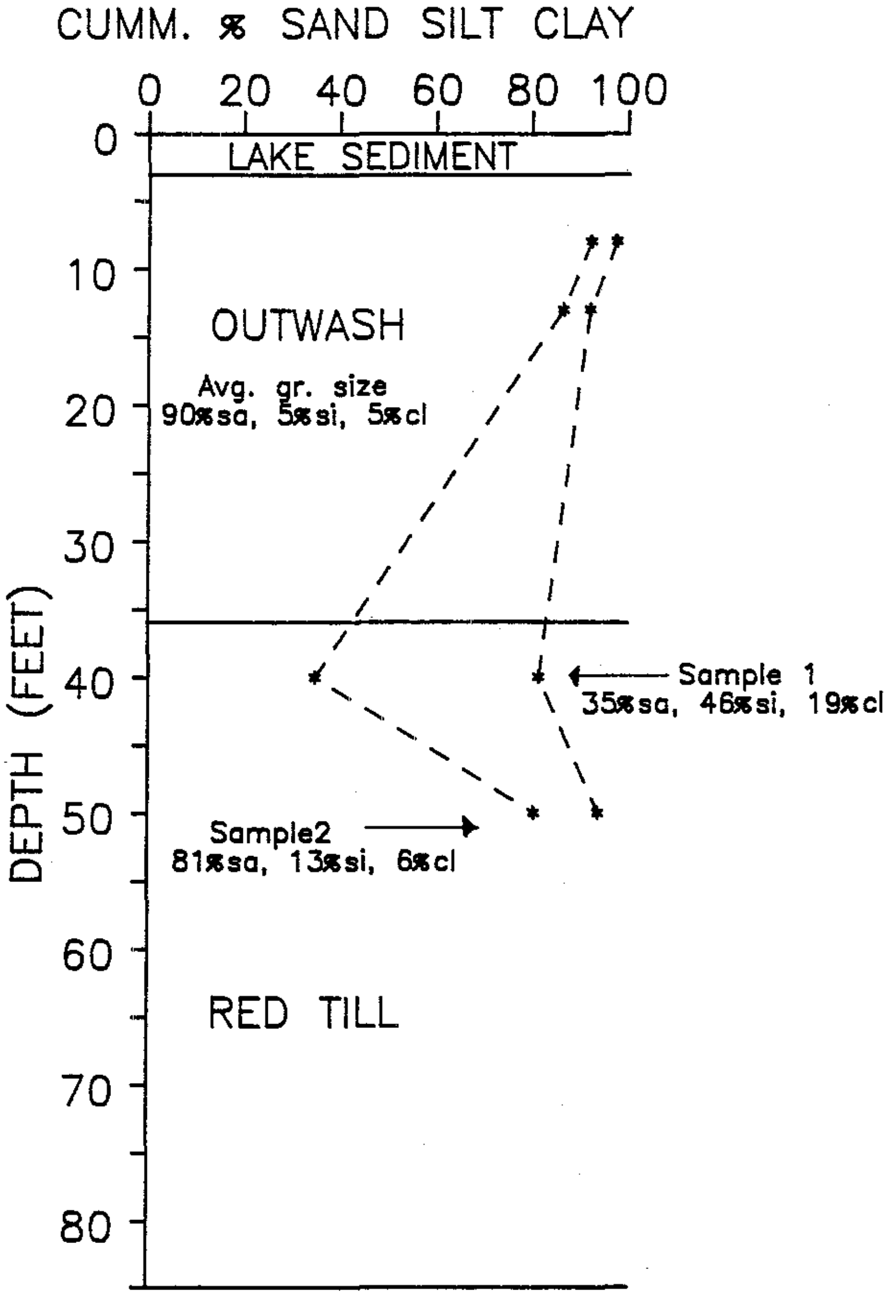


Figure 13. Stratigraphic column for the Waterman Lake study site showing cumulative grain-size percentages versus depth.

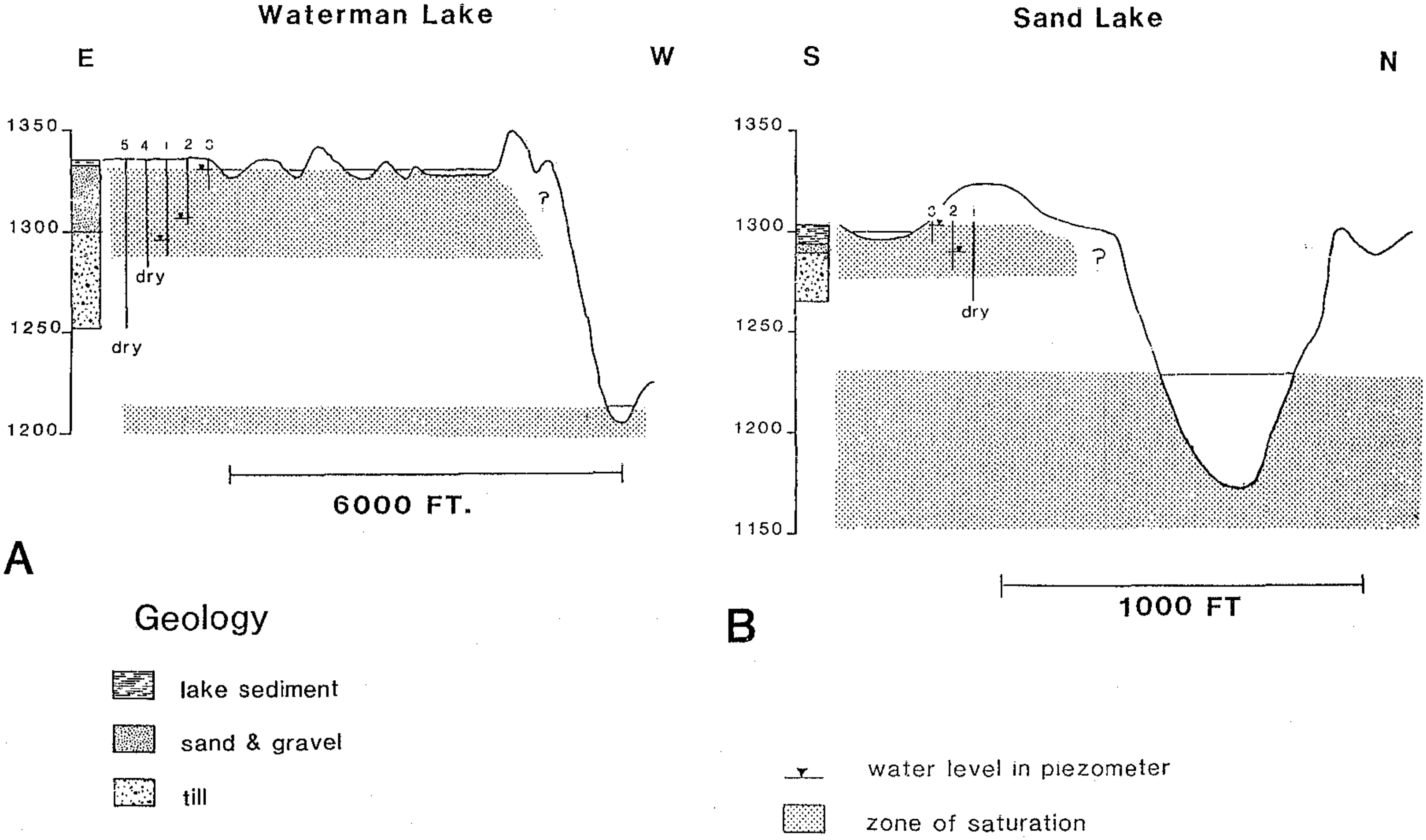


Figure 14. Cross sections for the Waterman and Sand Lake sites showing site geology and water-level elevations measured in vertical piezometer nests.

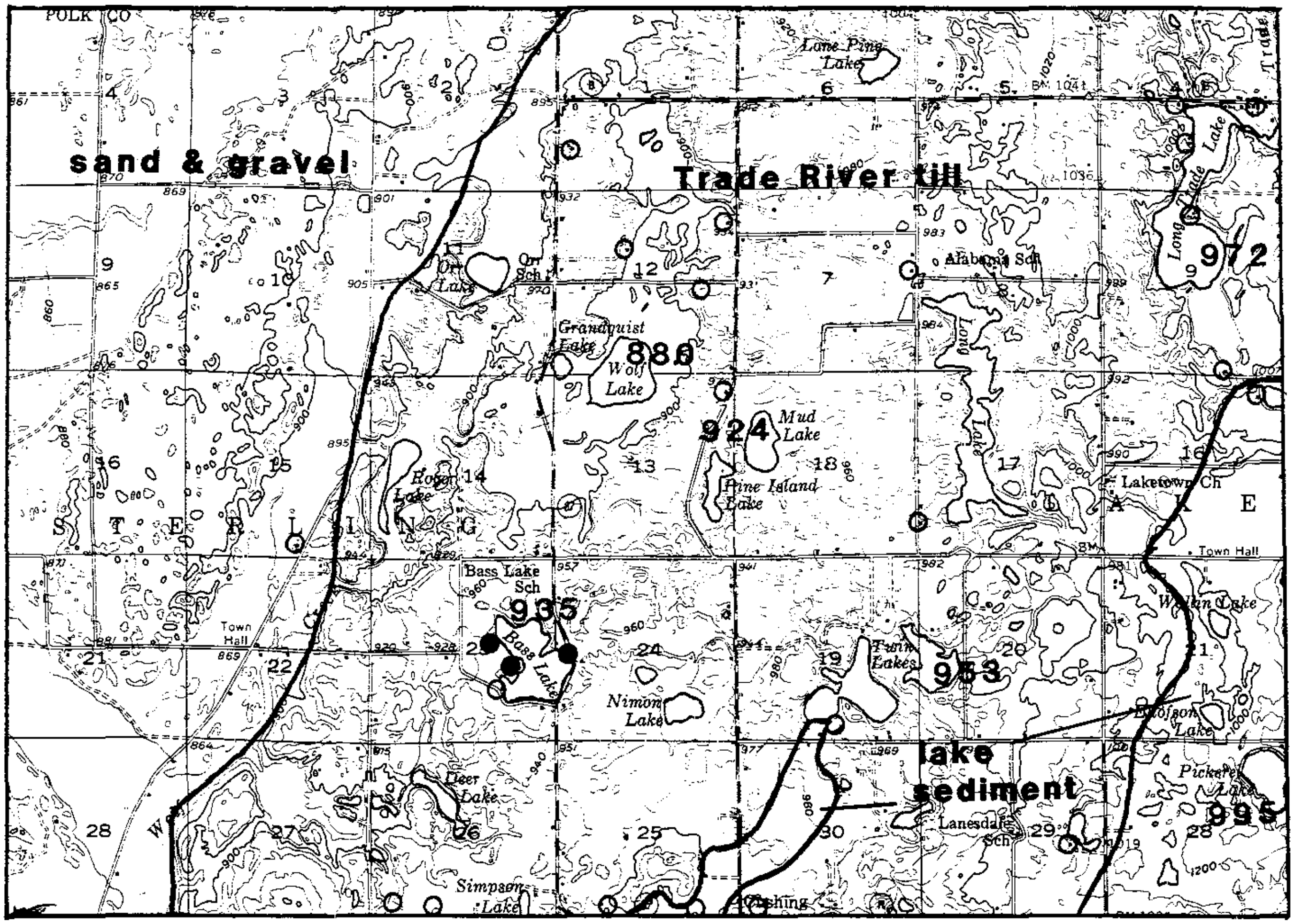


Figure 15. Portion of a 1:62,500 USGS topographic map showing the location of Bass Lake, and a sketch of surficial geologic units. Lakes have been outlined for clarity and selected lake elevations are noted. Solid black circles indicate monitoring well locations around Bass Lake; open black circles indicate domestic wells for which water-level elevations are available.

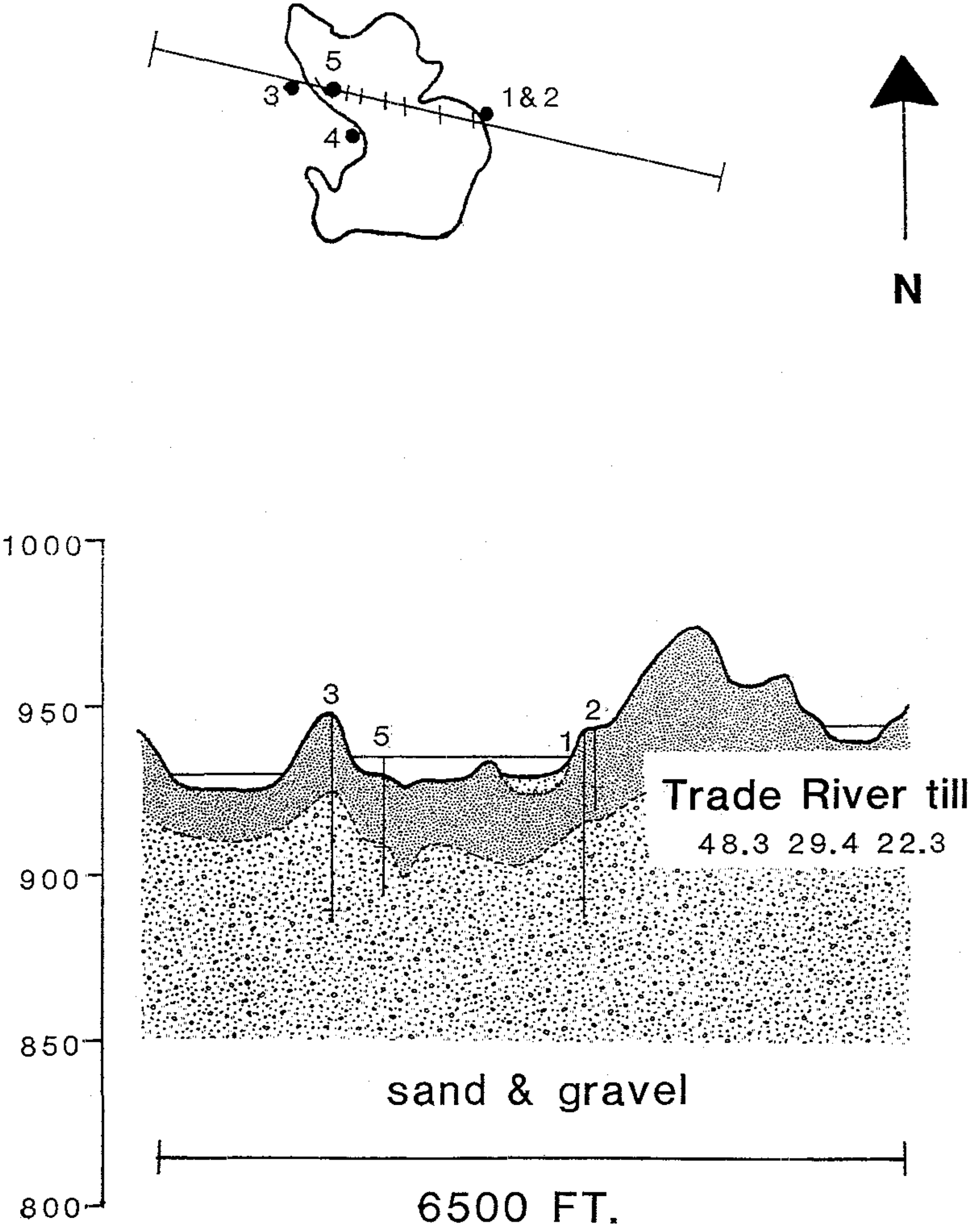


Figure 16. Diagram of the Bass Lake site showing locations of piezometers and a geologic cross section.

location of the line along which a geologic cross section was constructed. The cross section, shown in the lower half of the diagram, was constructed with geologic information obtained from the four drillholes and with data collected from an electrical resistivity survey performed while the lake was ice-covered. Small vertical dashes on the cross-section line in the upper figure indicate sites of vertical resistivity profiles.

The stratigraphy of the site consists of till deposited by the Grantsburg Sublobe that is underlain by sand and gravel of the Copper Falls Formation. Seven samples of the till indicate that it has an average grain-size distribution of 48.3% sand, 29.4% silt, and 22.3% clay. The till seems to have been deposited while buried ice was still present in the underlying sand and gravel. As the ice blocks melted out, the overlying till collapsed into the resulting depressions. These till-lined ice-block depressions now contain lakes and wetlands.

Five piezometers have been installed in and around Bass Lake. Piezometers 1 to 4 consist of $1^1/_4$-inch PVC pipe with 3-ft slotted screens while piezometer 5 is $1^1/_4$-inch steel pipe with a 3-ft sand point as a screen. Figure 17a shows water-level elevations in piezometers 1 to 4. Water levels in the piezometers finished in the sand (1, 3, shown on cross-section and 4 which is not shown) are much lower than the lake elevation while the water level in piezometer 2, completed in the till, is only slightly below lake level. While installing piezometer 1, the till seemed moist and piezometer 2 was installed at the base of the till unit. Below the moist till, the drillhole again encountered dry sand until finally penetrating saturated sand at a depth of approximately 60 ft. Piezometers 3 and 4 encountered only dry powdery till and unsaturated sand until a depth of 60 to 70 ft. The water-level data from piezometers 1 to 4 were not sufficient to determine if two saturated zones were present at the site (fig. 17a) or if the water table was steeply mounded under the lake (fig. 17b). Piezometer 5 was installed in order to determine whether the saturated zone present in the till under the lake continued into the underlying sand and gravel. The piezometer was driven to a depth of 41 ft below the lake surface which placed the screen in the sand and gravel but above the zone of saturation indicated in figure 17a. The continual presence of water in piezometer 5 suggests that Bass Lake is not actually "perched", rather the water table is steeply mounded under the lake (fig. 17b). The water level in piezometer 5 was 28 ft below the lake's surface suggesting strong vertical hydraulic gradients exist under Bass Lake but continuous saturation does exist between the lake and the underlying sand and gravel.

Bass Lake lies on the northern edge of a large area where differences between surface-water elevations and well-water elevations range from 100 to 150 ft (fig. 10). At Bass Lake, a mounded water table explains the discrepancy between surface- and well-water elevations. The water table may also be mounded under other lakes in the area while some lakes may be perched. Gathering the site-specific data necessary to make this determination for each lake was beyond the scope of this study.

Bass Lake is located in an area where till of the Trade River Formation (fig. 4) is the surficial unit. The area of disagreement between surface-water and well-water elevations lies

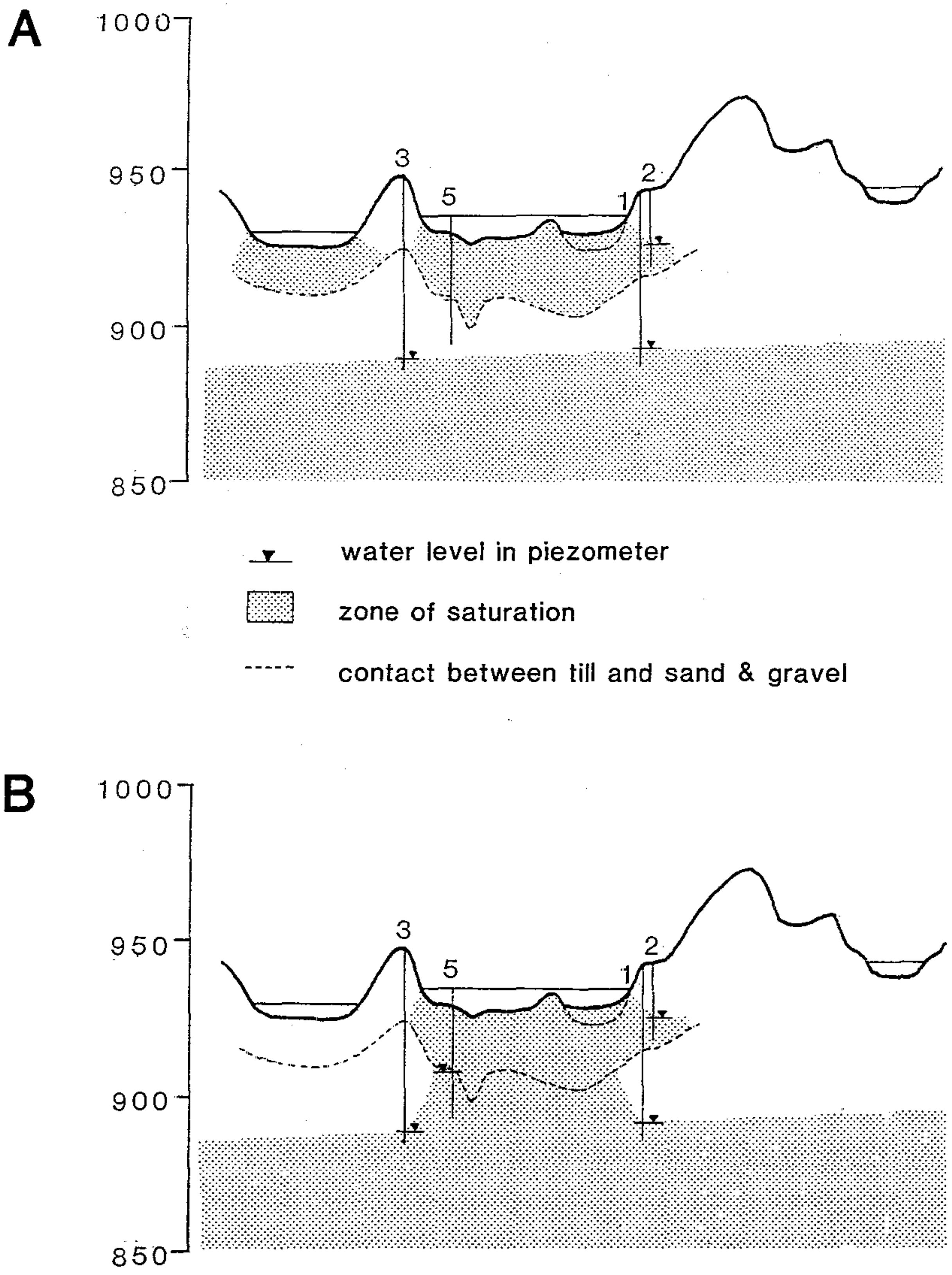


Figure 17. Cross sections showing the water-level elevations in piezometers around Bass Lake. **A.** Water levels in piezometers 1 to 3 suggested that Bass Lake may be a perched lake and that an unsaturated zone existed underneath the till. **B.** The water level in piezometer 5 indicates that the water table is steeply mounded under Bass Lake.

almost entirely within the area mapped as till of the Trade River Formation and nearshore lake sediment of the Trade River Formation. The extent of the till unit, however, is greater than the area where water levels do not agree. In the northern portion of the area mapped as Trade River till, surface-water elevations are similar to well-water elevations. The reasons for this are not clear. One possible explanation is that lakes such as Bass Lake do not "bottom out" in the saturated sand and gravel, while lakes that are deeper or are located in areas where the till is thinner may intersect the saturated zone of the underlying sand and gravel. Water levels of such lakes would reflect the elevation of the saturated zone of the sand and gravel. Manitou Lake, in the southern portion of the area mapped as Trade River till, seems to support this theory. Manitou Lake sits in a steep-walled ice-block depression that penetrates the thickness of the Trade River till. The elevation of this lake is similar to water-level elevations in domestic wells of the area while all the nearby lakes are formed on top of the Trade River till and these lakes have elevations that are 50 to 100 ft greater than water levels in wells.

Potentiometric Surface Map

The four study sites suggest that some groundwater flow systems in the project area can be quite complex, however, regional groundwater flow patterns can be estimated using the existing office data. The regional groundwater flow patterns shown on the contour map of surface-water elevations are quite similar to those on the contour map of well-water elevations. Data from the study sites, coupled with the map showing differences between surface- and well-water elevations (fig. 10) and the map of Pleistocene geology (fig. 4) can be used to delineate areas where surface-water features are not reliable indicators of water-table elevation and areas where well-water elevations do not reflect the water table.

In order to produce an accurate potentiometric map of the region, the surface-water and well-water points that were not representative of the water table were deleted. After editing, the data files contained 5257 surface-water points (1270 points deleted) and 2056 well-water points (75 deleted). These points were combined into one large file and contoured to produce a map of the potentiometric surface (fig. 18). This map is more accurately called a potentiometric map rather than a water-table map because it depicts the deeper saturated zone in areas where perched or mounded groundwater flow systems exist (depicted with stipple pattern in fig. 18). For example, in the Waterman-Sand Lake area, the surface-water points from the upland lakes and wetlands were deleted and the points representing the valley lakes and the wells in the area were retained. In the Bass Lake area, the surface-water points were eliminated and the deeper well-water elevations were retained.

The potentiometric map (fig. 18) is a computer-contoured map which has not been edited to take into account surface topography or hydrographic features. Since the computer has only water-level elevations it may generate contours that actually exceed the elevation of the ground surface in places where topography changes rapidly (such as river valleys) or in areas where the water table is quite shallow. In addition computer-generated contours frequently

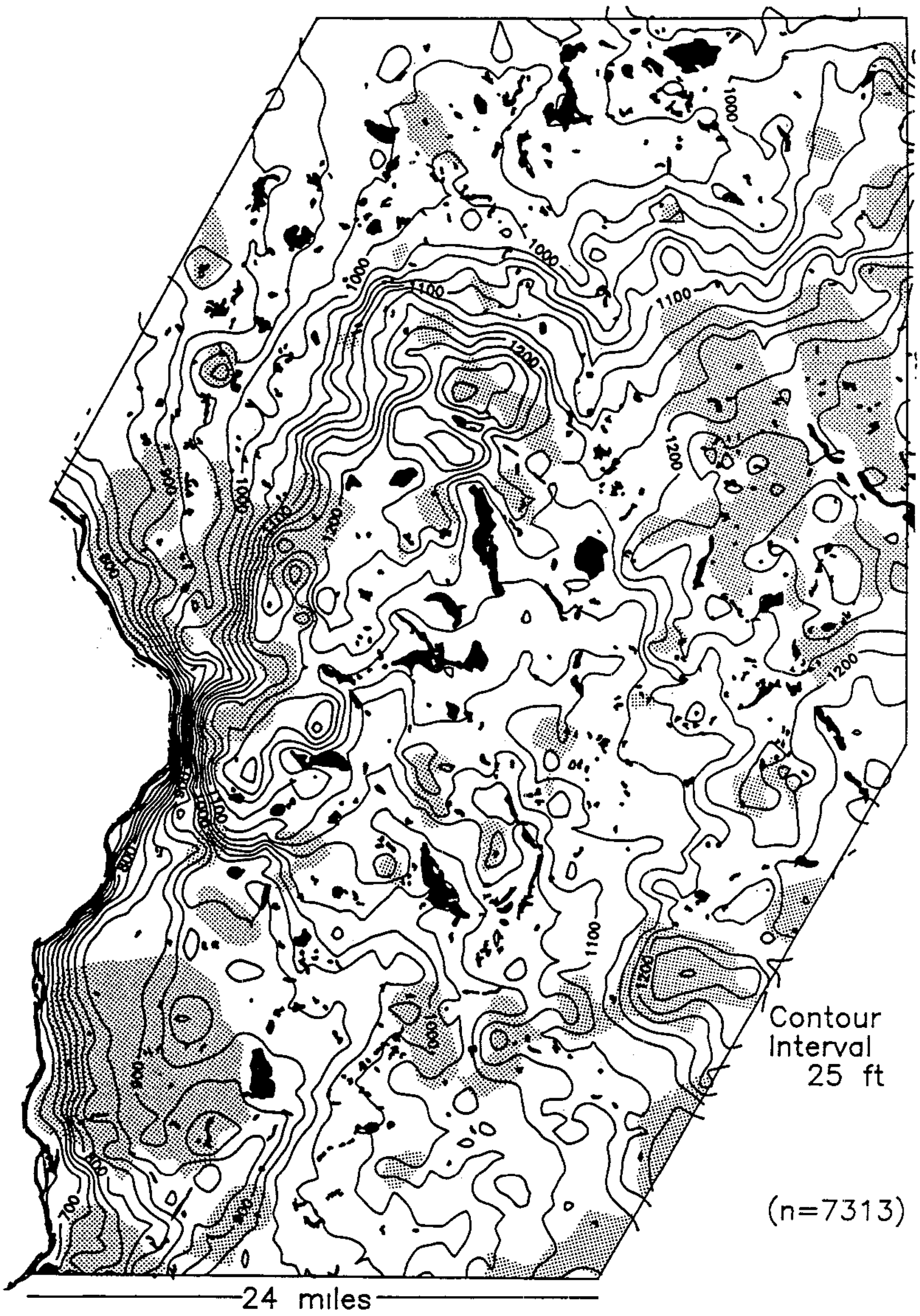


Figure 18. Computer-contoured potentiometric map of the study area. Stippled pattern indicates areas where surface-water elevations are more than 50 ft above groundwater elevations in domestic wells.

cross-cut lakes and streams. If the lake is connected to the groundwater system, contours should not cross it since the lake has a uniform elevation, but since the computer has only point data it may interpolate a contour that "cuts off" a corner of the lake. A final potentiometric map (Plate 1) was hand-edited to correct such errors.

PHOSPHORUS INPUTS AND SOURCES

Groundwater Chemistry

Although phosphorus is only a trace constituent in most natural waters, it plays an important role in limnological studies for it is frequently the limiting nutrient in aquatic systems. Phosphorus is a common element in igneous rocks and it is also relatively common in some sediments. Phosphorus can precipitate directly from ocean water and some shales contain phosphorus rich strata. In addition, since calcium phosphate precipitates under the same general conditions as calcium carbonate, phosphate is a minor constituent in most limestones and dolomites. Phosphate beds consisting of shell fragments suggest that calcium carbonate is sometimes replaced by calcium phosphate after deposition (Krauskopf, 1979).

Most phosphorus in natural waters exists as phosphate (PO_4^-). It can be derived from the weathering of phosphorus minerals, soil erosion, fertilizer runoff, and the disposal of human and animal wastes. In natural surface waters, total phosphorus concentrations are usually less than a few tenths of a milligram per liter but much of this may be due to particulate forms (i.e. phosphorus absorbed onto soil particles) (Hem, 1985).

The most common mineral containing phosphorus is apatite, or calcium phosphate with variable amounts of OH^-, Cl^-, and F^- (hydroxy-, chloro-, and fluoroapatite). Of these various forms, hydroxyapatite is likely the stable solid phase in many natural waters (Stumm and Morgan, 1970). Phosphate is also known to form complexes with a number of metal ions. For ions present in concentrations comparable to that of phosphorus, notably ferric iron, manganous manganese, zinc or copper, the formation of complexes might significantly affect the distribution of the metal ion as well as the distribution of the phosphates (Stumm and Morgan, 1970). Hem (1985) and Drever (1982) both report studies that indicate that vivianite, a ferrous phosphate, can be a major control on the concentration of iron and magnesium in the interstitial waters of lake sediments.

Few data exist on the natural concentrations of phosphorus in groundwater. Stumm and Morgan (1970) note that phosphorus concentrations in groundwater seldom exceed a few µg/l. Data from the Wisconsin State Laboratory of Hygiene suggest that most groundwater samples in this state have phosphorus concentrations less than 0.02 mg/l (G. Bowman, verbal communication).

Methods

In order to assess the background concentration of phosphorus in groundwater of the study area, samples were collected from 109 homeowners' wells, four springs and several sets of samples were collected from each of the research sites described above (fig. 19). Samples were analyzed for total dissolved phosphorus, major ions, alkalinity, nitrate, and chloride.

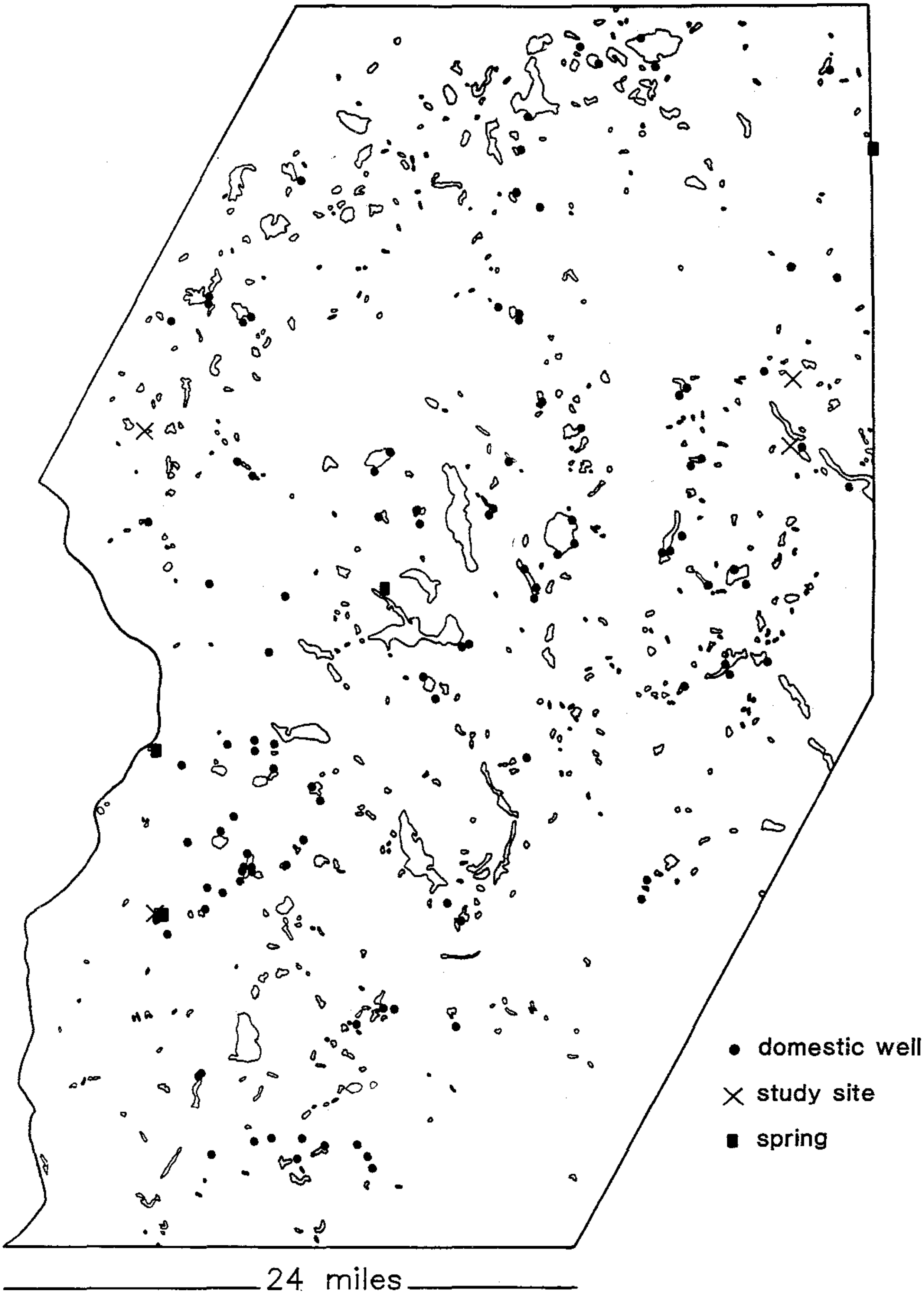


Figure 19. Locations of groundwater sampling points.

Rigorous sampling procedures were followed in order to assure the accuracy of the results. All sampling and filtration equipment was acid rinsed with 10% hydrochloric acid and deionized water prior to sample collection. Bottles for the phosphorus samples were also acid rinsed. Samples for phosphorus and major ions were field-filtered through .45 micron membrane filters, acidified, and kept on ice until analysis. An unfiltered sample was collected for the nitrate, chloride, and alkalinity analyses. Temperature, conductivity, and pH were determined in the field. The major ion samples and the unfiltered samples were analyzed at the UW-Madison Soil and Plant Analysis Laboratory while the phosphorus samples were analyzed at either the UW Soils Department Greenhouse Laboratory or the State Laboratory of Hygiene. Several blank samples of deionized water were filtered and submitted for analysis. Blanks submitted to all three laboratories had concentrations below the detection limits for most parameters measured.

The results from each sample were analyzed using the geochemical speciation program PHREEQE (Parkhurst and others, 1980) which uses the results of a water analysis, temperature, and pH to calculate the concentration of species in solution, the activities and activity coefficients of dissolved species, and the saturation indices of a variety of solid and gaseous phases. The results of the chemical analyses and PHREEQE saturation indices for calcite, dolomite, PCO_2, hydroxyapatite and vivianite are presented in Tables 1 and 2. A general discussion of the groundwater chemistry follows.

Results

Groundwater in the study area is generally of very good quality; only five of the homeowners' samples and two of the research site samples equal or exceed the drinking water standard for nitrate (10 mg/l NO_3^-N), a common contaminant in areas impacted by agricultural practices. Twenty-three homeowners' wells exceed the drinking water standard for iron (.3 mg/l). Iron concentrations range from 9.993 mg/l to below detection (<.011 mg/l). The wells high in iron draw water from the basalt, the Cambrian sandstone, or the sand and gravel aquifer.

Phosphorus concentrations are quite variable, ranging from below detection (<.004 mg/l) to .298 mg/l. Figure 20 is a histogram of the natural log of the phosphorus concentration for the 109 domestic wells. The values are log-normally distributed and the median phosphorus concentration is .032 mg/l which is considered high for groundwater. Of the 109 wells sampled, 9 were completed in basalt, 8 in dolomite, 16 in sandstone and 75 in sand and gravel and we could not determine the unit for one well. Table 3 presents the range of values and the median phosphorus concentration for groundwater samples from each of these geologic units.

Table 3 suggests that the basalt and dolomite contribute the least phosphorus to groundwater while the sandstone and sand and gravel aquifers may contribute significant amounts of phosphorus. There are several sandstone units in the area and it was not always

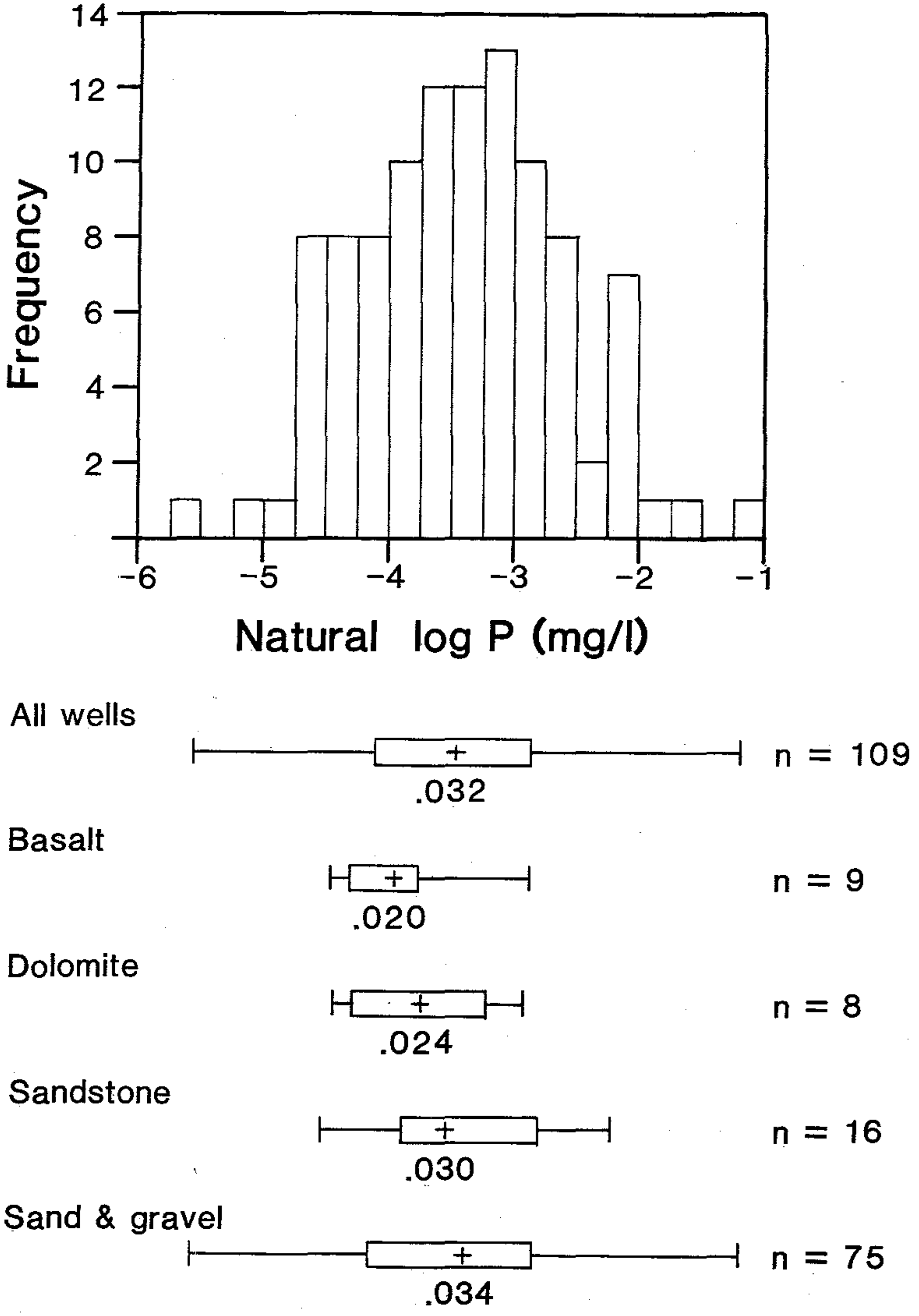


Figure 20. Histogram of the natural log of phosphorus concentration for samples from domestic wells (top). The lower portion of the figure shows boxplots of results for specific geologic units, median concentration is listed for each boxplot (shown by +), box encloses values between the first and third quartiles, line represents the entire range of values.

TABLE 1

CHEMICAL ANALYSES FROM HOMEOWNERS' WELLS (values are in mg/l)

			Temp	Cond.														SATURATION INDICES				
RockType	Name	P	deg. C	umhos	pH	HCO3-	Cl	NO3	K	Ca	Mg	Na	Fe	Zn	Mn	B	S	Calcite	Dolomite	PCO2	HydroxyAp	Vivianite
BASALT	Berry	0.019	11.0	170	8.39	103.6	5.5	1.2	1.299	23.58	8.23	6.81	0.046	0.114	-0.003	0.069	3.64	0.168	0.021	-3.465	-1.954	-4.746
	Bowen	-0.004	11.0	417	7.69	219.5	21.0	-0.5	2.973	59.08	12.18	6.12	0.024	0.147	0.020	0.056	5.21	0.151	-0.245	-2.441		
	Chaffee	0.058	14.3	271	7.75	134.1	-1.0	-0.5	-0.621	35.29	11.68	3.21	-0.011	0.097	0.005	0.033	3.35	-0.138	-0.559	-2.690	-2.158	
	Cousins	0.012	13.1	262	7.62	140.2	-1.0	-0.5	1.219	31.43	9.89	3.46	1.159	0.258	0.194	0.055	0.39	-0.306	-0.938	-2.544	-5.099	-2.565
	Gionness,L	0.015	9.6	154	6.70	146.3	2.0	1.0	-0.621	24.78	9.34	4.17	1.893	-0.010	0.058	0.036	0.67	-1.357	-3.025	-1.619	-10.484	-4.398
	Hansen	0.020	13.4	327	7.48	146.3	15.5	1.5	-0.621	38.70	12.86	3.29	-0.011	-0.010	0.394	0.036	1.68	-0.348	-0.992	-2.387	-4.706	
	Palmer	0.031	10.7	377	6.58	121.9	43.5	2.2	-0.621	41.71	13.78	5.94	0.042	0.209	0.012	0.034	3.99	-1.343	-3.033	-1.580	-9.188	-9.212
	Sellers	0.022	12.9	122	6.48	67.1	5.5	0.8	0.969	17.34	5.22	2.40	0.060	0.076	0.025	0.032	2.43	-1.991	-4.330	-1.714	-11.607	-9.149
	Walker,H	-0.004	10.1	373	7.80	219.5	7.5	-0.5	-0.621	17.06	5.60	57.08	-0.011	0.040	0.023	0.435	1.60	-0.262	-0.885	-2.546		
DOLOMITE	Berget	0.021	9.7	435	7.76	189.0	14.0	8.1	0.719	44.76	21.35	3.68	0.114	0.022	-0.003	0.060	4.17	0.022	-0.162	-2.582	-3.624	-5.031
	Friday	0.012	9.4	355	7.01	207.3	3.5	1.9	-0.621	39.73	18.46	2.38	0.034	-0.010	-0.003	0.032	1.86	-0.729	-1.683	-1.787	-8.184	-8.963
	JohnsonD	0.041	10.8	218	7.60	152.4	5.5	6.0	-0.621	36.72	13.07	2.29	0.039	0.089	-0.003	0.053	3.25	-0.273	-0.860	-2.503	-3.559	-6.056
	JohnsonJW	0.041	10.6	362	7.59	201.2	11.0	4.7	0.781	42.10	18.44	3.26	0.039	-0.010	0.005	0.035	2.54	-0.125	-0.477	-2.377	-3.487	-6.177
	Pepiau	0.024	14.5	390	7.74	207.3	13.5	7.2	0.673	48.43	22.42	5.54	0.024	0.136	-0.003	0.034	4.08	0.142	0.152	-2.499	-3.002	-6.960
	Simon	0.014	10.3	355	7.68	189.0	6.5	3.8	-0.621	39.20	19.46	3.94	0.026	0.013	-0.003	0.031	2.95	-0.096	-0.370	-2.496	-4.650	-7.426
	Wells	0.055	10.5	576	7.67	237.7	33.5	11.4	-0.621	73.91	23.32	9.24	0.042	0.042	-0.003	0.042	6.49	0.230	0.089	-2.396	-1.870	-5.848
	Wickline	0.025	10.3	363	7.67	201.2	4.5	3.3	0.790	39.41	19.12	4.55	0.030	0.012	-0.003	-0.029	3.54	-0.079	-0.346	-2.459	-3.937	-6.762
SAND & GRAVEL	Aleckson	0.015	11.4	186	7.43	97.5	-1.0	-0.5	-0.621	24.12	7.66	2.01	-0.011	0.199	0.052	0.037	1.01	-0.773	-1.899	-2.515	-6.235	
	Almen	0.009	11.5	267	6.97	164.6	-0.5	-0.5	1.034	30.85	11.19	3.25	0.139	0.761	0.716	0.051	1.08	-0.923	-2.138	-1.832	-8.951	-7.356
	Barland	0.018	10.3	323	6.85	182.9	-1.0	-0.5	-0.621	41.14	12.72	2.69	1.528	0.209	0.081	0.037	3.01	-0.907	-2.197	-1.675	-8.361	-4.113
	Barnes,Bruce	0.058	7.9	204	7.39	103.6	1.0	-0.5	0.952	25.32	5.77	1.79	4.680	0.843	0.307	0.032	0.28	-0.823	-2.209	-2.466	-5.049	-0.019
	Behling, R	0.033	11.2	309	7.35	201.2	1.5	1.0	-0.621	38.70	13.86	1.60	-0.011	-0.010	-0.003	-0.029	0.94	-0.377	-1.059	-2.130	-4.912	
	Buss	0.071	10.4	415	7.67	189.0	11.5	10.3	-0.621	63.71	13.63	7.64	0.030	-0.010	0.008	-0.029	5.82	0.090	-0.361	-2.489	-1.636	-5.926
	Carlson	0.017	12.5	368	7.21	213.4	7.5	-0.5	-0.621	41.00	16.94	3.08	3.522	1.194	0.225	-0.029	1.73	-0.459	-1.136	-1.960	-6.406	-2.049
	Carpentier	0.222	12.0	309	7.71	140.2	5.5	1.0	-0.621	45.37	10.18	3.26	-0.011	-0.010	0.138	0.038	3.48	-0.093	-0.677	-2.645	-0.316	
	Chinander	0.035	12.8	249	7.91	164.6	2.0	-0.2	-0.621	39.74	9.14	4.14	0.038	0.099	-0.003	-0.029	3.30	0.131	-0.204	-2.771	-2.030	-5.482
	CumberlandGC	0.041	11.3	220	6.23	147.5	4.0	0.5	-0.621	27.16	8.32	1.34	-0.011	0.012	0.901	0.030	0.79	-1.756	-3.883	-1.137	-11.764	
	Davis,C	0.050	11.4	290	7.58	207.3	1.5	1.0	1.224	31.90	12.18	9.87	-0.011	-0.010	0.030	0.120	0.25	-0.212	-0.697	-2.345	-3.616	
	Douglass	0.115	9.8	294	8.05	189.0	0.5	-0.5	0.869	38.43	11.80	5.19	0.256	0.067	0.124	-0.029	1.40	0.264	0.133	-2.869	-0.289	-1.742
	Frazer	0.094	11.5	219	7.26	115.8	8.0	-0.5	0.921	20.48	8.60	1.95	9.993	0.013	0.364	0.068	0.16	-0.947	-2.122	-2.271	-5.362	0.992
	Fredericks,D	0.060	13.7	251	6.70	176.8	2.5	1.0	-0.621	26.61	8.97	2.63	7.432	0.178	0.216	-0.029	2.21	-1.193	-2.672	-1.518	-8.281	-1.426
	Graves	0.023	11.0	208	8.15	158.5	-0.5	1.0	3.917	33.38	10.61	2.37	0.033	-0.010	-0.003	-0.029	1.72	0.254	0.150	-3.039	-2.078	-5.534
	Haaf,R	0.110	10.1	209	7.20	140.2	-0.5	0.5	-0.621	29.11	5.82	0.63	-0.011	-0.010	0.096	-0.029	0.23	-0.792	-2.161	-2.135	-4.566	
	Haight,E	0.106	12.9	358	7.65	231.7	4.0	0.5	-0.621	47.37	14.94	2.31	0.515	-0.010	0.386	0.043	1.27	0.081	-0.167	-2.365	-1.529	-1.821
	Harris	-0.004	13.5	193	6.82	97.5	-1.0	0.5	-0.621	23.52	8.69	3.07	0.653	-0.010	0.110	0.029	4.57	-1.370	-2.990	-1.894		
	Hawkins	0.079	13.0	251		141.4	-1.0	-0.1	1.151	37.74	10.80	6.00	1.334	0.123	0.178	0.036						
	Heichel	0.121	11.8	268	7.26	158.5	1.5	-0.2	1.376	33.57	7.55	2.91	7.196	0.044	0.136	0.077	0.23	-0.607	-1.709	-2.137	-3.966	0.777
	Hilltop	0.058	11.4	261	7.95	158.5	-0.5	-0.5	-0.621	31.15	10.43	2.62	0.049	-0.010	0.020	-0.029	1.58	0.038	-0.252	-2.833	-1.773	-4.596
	Holst,A	0.034	12.1	357	7.87	160.9	8.5	6.5	-0.621	43.65	14.61	1.41	-0.011	0.210	0.004	-0.029	3.38	0.102	-0.112	-2.747	-2.222	
	Jacobsen	0.009	11.3	185	7.42	97.5	-1.0	-0.5	-0.621	24.23	7.41	2.93	-0.011	2.724	0.014	0.038	4.45	-0.793	-1.955	-2.507	-6.994	
	Jansen	0.011	11.1	242	7.85	146.3	2.5	-0.2	0.702	31.00	9.28	2.63	0.050	0.025	0.090	0.036	1.82	-0.099	-0.580	-2.767	-4.370	-6.214
	Jantz	0.060	9.5	327	7.70	182.9	3.5	1.1	-0.621	48.12	11.98	3.70	0.044	0.037	-0.003	0.042	4.28	-0.012	-0.517	-2.533	-2.251	-5.415
	Jasper	0.041	10.0	304	8.24	115.8	8.0	7.9	-0.621	36.60	13.84	3.19	0.042	0.016	-0.003	0.039	8.24	0.217	0.134	-3.275	-0.975	-4.642
	Jensen,H.	0.012	10.1	432	7.09	134.1	6.0	2.5	1.034	35.03	10.74	2.86	0.060	0.260	0.004	0.032	3.34	-0.861	-2.113	-2.048	-7.795	-7.882
	JohnsonE	0.016	13.6	168	6.28	61.0	11.5	1.7	0.880	18.04	5.94	3.35	0.204	0.012	0.008	-0.029	2.02	-2.206	-4.710	-1.553	-13.181	-8.560
	Johnson,R	0.043	10.8	360	7.56	121.9	13.0	12.0	-0.621	38.23	13.67	2.62	-0.011	0.201	0.005	-0.029	1.81	-0.388	-1.088	-2.559	-3.585	
	Johnson,W	0.012	10.6	129	6.43	91.4	1.5	-0.5	-0.621	17.35	4.12	-0.61	0.372	0.134	0.334	-0.029	0.79	-1.939	-4.371	-1.542	-12.937	-7.519
	Josephs,T	0.069	11.2	340	7.90	189.0	16.0	-0.5	-0.621	37.82	15.80	1.52	0.247	-0.010	0.118	-0.029	4.83	0.120	0.004	-2.713	-1.585	-2.585
	Kohman	0.024	11.6	272	7.75	158.5	1.5	0.4	0.631	35.05	10.85	5.21	0.022	0.017	-0.003	-0.029	1.76	-0.110	-0.579	-2.631	-3.556	-6.871
	Kusteiski	0.026	10.3	255	7.70	158.5	-1.0	0.5	-0.621	31.66	9.70	2.60	-0.011	-0.010	0.005	0.035	3.20	-0.221	-0.829	-2.586	-3.966	
	Langeness	0.010	9.5	382	7.60	231.7	-1.0	-0.5	0.868	47.89	16.32	3.30	0.115	0.167	0.083	0.034	3.36	-0.021	-0.398	-2.332	-5.131	-6.000
	LuckGolfCourse	0.046	9.8	327	7.95	146.3	1.0	-0.5	0.870	34.38	10.89	2.41	0.041	0.157	-0.003	0.036	3.06	0.017	-0.348	-2.877	-2.047	-5.080
	Lundeen,N	0.004	12.9	433	7.28	262.1	1.0	-0.5	-0.621	54.82	20.71	0.87	-0.011	0.010	0.082	-0.029	3.11	-0.186	-0.622	-1.943	-7.345	
	Martineau	-0.004	14.7	118	6.95	48.8	-1.0	1.0	-0.621	11.03	4.07	2.77	0.178	4.035	0.013	0.041	2.12	-1.813	-3.856	-2.310		
	Mauie,J	0.008	14.5	277	7.40	128.0	7.0	2.5	-0.621	30.24	12.91	3.22	-0.011	0.300	-0.003	0.036	2.99	-0.566	-1.302	-2.356	-6.636	
	McGinnity,R	0.141	13.4	218	6.85	97.5	6.0	3.0	-0.621	22.19	9.78	1.01	-0.011	0.470	-0.003	-0.029	2.68	-1.364	-2.903	-1.924	-6.455	
	McKinleyCem	0.010	14.5	455	6.96	146.3	41.5	10.0	-0.621	50.59	16.81	3.05	-0.011	-0.010	-0.003	-0.029	2.98	-0.753	-1.783	-1.864	-7.733	

TABLE 1 (continued)

CHEMICAL ANALYSES FROM HOMEOWNERS' WELLS (values are in mg/l)

RockType	Name	P	Temp	Cond.	pH	HCO3-	Cl	NO3	K	Ca	Mg	Na	Fe	Zn	Mn	B	S	SATURATION INDICES				
			deg. C	umhos														Calcite	Dolomite	PCO2	HydroxyAp	Vivianite
SAND & GRAVEl	Mechelke,J	0.125	9.7	234	7.28	152.4	0.5	-0.5	-0.621	31.07	7.41	1.18	0.120	-0.010	0.187	-0.029	1.25	-0.663	-1.835	-2.183	-3.953	-4.356
	Melby	0.029	10.2	469	7.73	249.9	10.0	4.8	-0.621	52.05	23.83	2.84	0.084	0.079	-0.003	0.053	2.73	0.174	0.133	-2.431	-3.068	-5.268
	Moore	0.077	11.0	250	7.46	128.0	9.5	-0.5	1.143	32.27	6.61	2.73	4.005	0.040	0.334	-0.029	0.22	-0.522	-1.594	-2.433	-3.602	0.209
	Nerby,D	0.031	11.0	251	7.15	158.5	-0.5	1.0	-0.621	30.89	9.57	0.92	0.667	-0.010	0.189	-0.029	1.58	-0.763	-1.896	-2.030	-6.389	-3.705
	Nerby,R	0.034	10.3	274	7.40	176.8	-0.5	0.5	-0.621	32.43	11.16	1.93	0.532	-0.010	0.065	-0.029	0.87	-0.462	-1.261	-2.238	-5.004	-3.278
	OsceolaHouse	0.026	10.1	208	6.90	109.7	2.0	2.0	-0.621	24.32	8.99	3.83	-0.011	-0.010	-0.003	0.044	5.44	-1.283	-2.877	-1.941	-8.537	
	Osterbauer	0.025	10.8	247	6.34	61.0	11.0	8.7	0.926	23.62	9.08	5.05	0.054	0.026	-0.003	0.031	4.12	-2.090	-4.459	-1.631	-11.998	-9.800
	O'Rourke	0.034	11.8	282	7.67	170.7	-0.5	0.6	0.910	36.16	12.15	2.81	0.039	0.053	-0.003	0.031	2.29	-0.145	-0.610	-2.518	-3.414	-6.027
	PaulsenG	0.035	10.0	280	7.30	134.1	16.5	5.0	0.722	37.30	12.84	2.53	-0.011	-0.010	-0.003	-0.029	3.64	-0.633	-1.609	-2.261	-5.237	
	Paulsen	0.016	11.0	257		112.2	-1.0	0.4	0.838	30.92	9.57	6.81	0.048	0.051	0.038	0.064						
	Paulson	0.042	9.3	283	7.99	164.6	5.5	1.5	0.777	36.04	13.34	2.74	0.028	0.029	-0.003	-0.029	2.69	0.112	-0.100	-2.871	-2.019	-5.625
	Pearson	0.067	10.8	312	7.04	170.7	-1.0	-0.5	-0.621	42.07	8.75	2.56	2.606	0.045	0.534	0.039	1.52	-0.721	-1.990	-1.891	-5.456	-1.668
	Powers	0.024	11.8	529	7.51	268.2	17.0	6.1	-0.621	68.94	28.40	3.38	0.066	0.262	0.005	0.038	9.40	0.108	-0.015	-2.176	-3.745	-6.353
	Randall	0.045	12.0	277	6.50	115.8	12.5	5.5	-0.620	33.10	12.80	3.10	0.020	0.040	-0.003	0.100	3.76	-1.509	-3.274	-1.512	-9.481	-10.052
	Rasmussen	0.024	11.3	283	8.15	152.4	3.5	-0.2	0.913	36.73	10.21	3.14	0.418	0.051	0.111	0.034	4.79	0.275	0.140	-3.056	-1.852	-2.225
	Raszkowski,H	0.015	12.7	276	7.35	170.7	1.0	0.5	-0.621	34.90	11.43	0.95	-0.011	-0.010	0.003	-0.029	1.77	-0.461	-1.237	-2.191	-5.942	
	Raye	0.015	13.5	174	7.03	91.4	3.5	0.5	0.674	18.90	7.69	2.69	0.028	0.032	0.087	0.036	1.34	-1.269	-2.746	-2.130	-8.607	-8.655
	Roberts,H.	0.006	9.5	362	6.84	115.8	4.5	-0.5	0.879	26.82	9.26	2.42	0.069	0.129	0.067	0.042	2.20	-1.284	-2.919	-1.861	-10.639	-9.023
	Rogers	0.013	9.6	217	6.81	115.8	6.0	-0.2	1.794	25.54	9.18	2.70	0.531	0.053	0.580	0.030	1.48	-1.332	-2.996	-1.831	-9.904	-5.789
	Sagerer,M	0.049	9.9	491	7.94	182.9	13.5	-0.5	-0.621	37.70	15.46	1.51	0.027	-0.010	0.130	-0.029	4.34	0.126	-0.015	-2.773	-1.959	-5.683
	Seiser	0.048	11.6	958	7.73	201.2	6.5	-0.5	-0.621	44.19	13.75	3.99	0.016	0.022	0.052	-0.029	2.23	0.055	-0.247	-2.512	-2.405	-6.827
	Sether,D	0.014	11.0	185	6.60	79.2	3.0	2.5	-0.621	16.34	6.43	6.05	-0.011	0.057	0.011	0.041	4.35	-1.864	-3.993	-1.774	-11.803	
	Sobaski	0.298	12.4	198	7.69	109.7	-1.0	1.0	0.729	26.10	5.37	1.49	1.568	-0.010	0.369	0.032	0.37	-0.415	-1.354	-2.721	-0.904	0.863
	Stachowiak	0.041	13.0	310	7.76	201.2	0.5	-0.5	-0.621	40.19	14.59	3.73	-0.011	0.176	0.006	-0.029	2.20	0.068	-0.130	-2.534	-2.538	
	Strand,M	0.059	9.3	343	7.20	231.7	2.0	0.5	-0.621	44.28	14.07	2.18	0.051	-0.010	0.185	0.037	1.75	0.447	-1.286	-1.930	-4.866	-6.498
	Surbaugh,K	0.021	12.0	324	7.29	158.5	18.5	0.5	-0.621	40.81	13.35	2.93	1.316	-0.010	0.221	-0.029	5.05	-0.511	-1.350	-2.170	-5.675	-2.876
	Taylor,L	0.019	11.4	327	7.05	213.4	-0.5	0.5	-0.621	42.51	12.74	1.30	0.269	-0.010	0.104	0.031	0.33	-0.609	-1.596	-1.803	-6.975	-5.680
	Turner	0.032	11.0	194	7.21	115.8	-0.5	-0.5	0.775	24.86	7.76	2.93	0.026	0.220	-0.003	-0.029	2.23	-0.919	-2.205	-2.223	-6.378	-7.661
	VanStone,R	0.053	10.0	277	6.71	164.6	1.5	0.5	-0.621	32.55	10.28	1.34	4.559	-0.010	0.603	-0.029	0.93	-1.184	-2.748	-1.579	-8.273	-2.193
	Viviano	0.049	11.4	301	7.96	158.5	-1.0	0.5	-0.621	38.51	12.07	2.37	-0.011	-0.010	-0.003	0.034	1.81	0.131	-0.095	-2.846	-1.592	
	Warrington	0.068	9.1	351	7.98	201.2	-1.0	0.5	-0.621	47.95	13.43	2.05	-0.011	0.011	-0.003	0.040	1.95	0.297	0.146	-2.777	-0.948	
	Williamson,G.	0.012	11.0	487	7.65	213.4	5.5	0.5	1.286	49.11	15.97	2.19	0.037	0.320	0.003	0.042	3.18	0.029	-0.290	-2.411	-4.472	-7.180
	Winchell,R.H.	0.117	12.6	280	6.95	152.4	1.5	-0.5	-0.621	34.50	10.28	2.17	0.070	0.125	1.592	0.032	3.67	-0.915	-2.189	-1.840	-5.398	-6.079
	Jones,L	0.027	14.3	266	7.27	140.2	3.5	1.0	-0.621	31.55	10.69	1.03	-0.011	0.011	-0.003	-0.029	2.07	-0.637	-1.548	-2.186	-5.588	
SANDSTONE	Anderson	0.011	10.2	127	6.65	67.1	0.5	0.5	1.154	14.39	4.81	3.05	0.074	0.231	0.019	0.048	2.72	-1.939	-4.230	-1.897	-12.083	-8.913
undiffer.	Borgstrom	0.021	11.3	296	7.82	164.6	6.0	3.0	0.882	33.11	16.05	3.07	0.036	0.353	0.039	-0.029	3.02	-0.063	-0.296	-2.689	-3.671	-6.252
undiffer.	Brown,A.	0.026	15.0	258	8.00	176.8	5.5	-0.5	0.703	32.84	10.65	2.94	-0.011	0.242	-0.003	-0.029	1.37	0.205	0.130	-2.819	-2.228	
undiffer.	Brown,H.	0.011	11.5	398	7.17	268.2	-0.5	-0.5	0.677	53.07	17.33	3.43	0.126	0.085	0.631	-0.029	0.96	-0.315	-0.968	-1.829	-6.724	-6.892
undiffer.	Remund	0.038	9.1	329	7.87	146.3	3.5	1.0	1.599	38.41	12.74	2.69	0.013	0.260	0.003	-0.029	1.96	-0.029	-0.433	-2.801	-2.519	-6.964
AncelGp	Beach	0.021	9.9	395	8.01	164.6	11.5	7.0	2.155	41.15	19.65	4.40	0.056	0.010	-0.003	0.041	6.16	0.179	0.157	-2.892	-2.686	-5.391
AncelGp	Jacobson	0.069	10.2	264	7.90	152.4	5.5	3.5	-0.621	35.84	13.26	3.02	0.040	0.046	0.033	-0.029	2.24	0.005	-0.297	-2.808	-1.663	-4.899
AncelGp	Pickard	0.043	10.1	273	7.68	176.8	5.5	2.7	2.814	36.42	15.86	5.79	0.026	0.043	0.016	-0.029	1.63	-0.150	-0.539	-2.524	-3.274	-6.399
Eau Claire	Boettcher	0.068	10.8	269	7.38	158.5	2.0	0.8	-0.621	34.97	10.24	4.05	0.043	0.038	-0.003	0.035	1.33	-0.488	-1.375	-2.263	-3.972	-5.989
Eau Claire	Centuria	0.022	9.2	391	7.36	176.8	19.5	-0.2	0.796	44.66	16.89	6.44	0.900	-0.010	0.196	0.038	12.33	-0.421	-1.157	-2.210	-5.465	-3.266
Eau Claire	Pepst	0.011	12.5	491	6.61	146.3	35.0	10.9	1.803	54.61	18.69	6.34	0.037	0.041	0.025	0.045	7.69	-1.111	-2.521	-1.526	-9.730	-10.219
Jordan	Gustafson	0.026	10.6	250	8.00	158.5	11.5	3.0	-0.621	35.09	13.13	3.20	-0.011	0.035	-0.003	0.050	1.04	0.118	-0.059	-2.890	-2.520	
Jordan	Hasselquist	0.034	9.4	340	7.05	164.6	15.0	8.5	-0.621	48.87	15.01	5.92	-0.011	-0.010	-0.003	0.031	5.39	-0.704	-1.812	-1.929	-6.186	
Mt.Simon	JohnsonR	0.062	10.0	254	8.17	121.9	4.0	1.9	0.666	30.89	10.34	4.68	0.025	-0.010	-0.003	-0.029	4.58	0.113	-0.126	-3.177	-0.927	-4.992
TunnelCity	Swenson	0.110	9.9	289	7.76	176.8	2.5	0.2	-0.621	37.37	11.86	6.25	0.043	-0.010	0.005	0.034	3.67	-0.062	-0.503	-2.604	-1.616	-4.719
Wonnewoc	Campeau	0.083	10.4	337	7.51	207.3	0.5	-0.2	-0.621	40.34	15.43	3.27	1.524	0.029	0.414	0.037	1.35	-0.206	-0.702	-2.283	-3.022	-0.970
UNKNOWN	Maupin	0.033	10.0	357	7.83	207.3	4.0	1.0	-0.621	41.82	17.90	2.62	-0.011	0.025	-0.003	-0.029	2.80	0.114	-0.020	-2.609	-2.773	
BLANK SAMPLES	05/06/88	-0.010																				
	07/31/89	-0.004							-0.621	-0.04	-0.10	-0.61	-0.011	-0.011	-0.003	-0.029	-0.14					
	09/15/89	-0.004							-0.621	0.05	-0.10	-0.61	0.016	-0.010	-0.003	0.039	-0.14					
	11/19/89	-0.004							-0.621	-0.04	-0.10	-0.61	0.023	-0.011	-0.003	-0.029	-0.14					
	08/06/90	-0.004							-0.621	-0.04	-0.10	-0.61	-0.011	-0.010	-0.003	-0.029	-0.14					
	09/01/90	-0.004							-0.621	-0.04	-0.10	-0.61	-0.011	-0.010	-0.003	-0.029	-0.14					

TABLE 2
CHEMICAL ANALYSES FROM SPRINGS AND STUDY SITES (values are in mg/l)

																		SATURATION INDICES				
Sample	Date	Temp deg. C	Cond. umhos	pH	HCO3-	Cl	NO3	P	K	Ca	Mg	Na	Fe	Zn	Mn	B	S	Calcite	Dolomite	PCO2	HydroxAp	Vivianite
SPRINGS																						
BalsamLkS	04-May-88	11.0	202	6.50				0.035														
BashawSp	14-Sep-89	10.0	143	6.95	79.2	1.5	-0.5	0.005	0.981	16.63	5.30	2.28	0.043	-0.010	-0.003	0.032	2.27	-1.513	-3.402	-2.128	-11.046	-9.327
FolsomSp	10-Dec-87	6.5	355	7.60	201.3	4.5	-0.5	-0.217	0.750	50.15	15.35	9.02	0.016	-0.010	0.004	-0.029	5.68					
OsceolaSp	03-May-89	13.5	304	7.40	158.5	10.5	3.0	0.099	0.750	38.40	13.29	1.97	0.068	0.019	-0.003	-0.029	2.74	-0.397	-1.072	-2.271	-3.029	-5.031
LAKE RESEARCH SITES																						
BassLk1	17-Nov-88	8.3	584	7.20	347.5	12.0	1.0	0.015	1.508	80.81	25.51	4.48	0.067	0.177	0.042	0.039	6.05	-0.080	-0.574	-1.771	-5.853	-7.593
BassLk1	18-Jan-89	8.0	604	7.35	347.5	11.5	1.5	0.004	0.717	85.11	27.76	3.43	0.017	0.133	0.009	-0.029	6.12	0.083	-0.239	-1.924	-6.793	-10.167
BassLk1	06-Apr-89	8.3	524	7.15	353.6	16.0	2.0	0.054	2.084	81.49	26.62	5.42	0.012	0.531	0.013	0.037	6.11	-0.122	-0.642	-1.714	-4.438	-8.868
BassLk2	17-Nov-88	8.9	1030	7.20	359.7	12.0	-0.5	0.039	6.439	106.60	48.01	20.28	0.049	0.286	0.476	0.081	77.91	-0.033	-0.307	-1.765	-4.530	-7.487
BassLk2	18-Jan-89	8.9	1579	7.20	432.8	12.5	-0.5	0.018	6.058	96.03	42.76	55.14	0.185	0.038	0.644	0.069	56.81	0.015	-0.218	-1.684	-5.673	-6.371
BassLk2	06-Apr-89	9.1	1569	7.20	475.5	12.5	-0.5	0.061	5.429	97.03	41.35	52.62	0.061	0.200	0.868	0.078	46.91	0.069	-0.125	-1.642	-4.010	-6.734
BassLk3	17-Nov-88	8.6	415	6.80	262.1	8.0	-0.5	0.024	1.805	54.96	15.87	2.54	0.031	0.069	0.101	0.041	0.83	-0.723	-1.893	-1.482	-7.927	-9.195
BassLk3	18-Jan-89	8.4	460	7.10	280.4	8.0	0.5	0.015	2.179	64.36	18.42	-0.61	0.030	0.071	0.119	0.033	0.79	-0.339	-1.133	-1.757	-6.633	-8.789
BassLk3	06-Apr-89	8.4	461	6.80	286.5	7.0	-0.5	0.063	2.264	63.85	17.84	2.92	-0.011	0.159	0.186	0.034	1.06	-0.633	-1.732	-1.447	-6.437	
BassLk4	18-Jan-89	8.8	534	7.70	225.6	50.5	1.0	0.012	2.172	52.19	18.79	29.36	0.014	0.112	0.080	0.053	3.40	0.074	-0.197	-2.453	-4.453	-8.446
BassLk4	06-Apr-89	8.8	418	7.75	207.3	26.5	1.5	0.053	2.426	46.97	15.79	10.18	-0.011	0.404	0.024	0.039	0.75	0.013	-0.350	-2.485	-2.598	
Osceola1	18-Nov-88	10.5	395	7.20	219.5	7.5	0.5	0.027	2.116	46.06	15.82	7.45	0.030	0.143	0.982	0.039	4.54	-0.444	-1.223	-1.949	-5.747	-7.885
Osceola1	18-Jan-89	8.2	375	7.68	225.6	5.5	0.5	0.016	1.703	50.16	7.80	4.53	0.284	0.145	0.949	0.037	4.48	0.052	-0.618	-2.428	-4.090	-4.190
Osceola1	03-May-89	6.2	382	7.60	219.5	6.5	0.5	0.080	1.630	47.84	15.96	3.81	0.053	0.233	0.236	0.030	4.21	-0.097	-0.625	-2.371	-2.724	-5.253
Osceola1	26-Jul-89	11.7	299	7.75	268.2	4.5	1.0	0.026	1.646	50.86	17.53	4.70	0.125	-0.010	0.245	0.091	3.82	0.240	0.170	-2.411	-2.971	-4.729
Osceola2	18-Nov-88	10.0	314	7.20	164.6	4.5	1.0	0.024	1.099	38.95	13.07	1.88	0.026	0.067	0.041	-0.029	3.92	-0.629	-1.612	-2.072	-6.173	-8.104
Osceola2	18-Jan-89	8.8	295	7.53	164.6	4.0	1.0	0.028	1.032	39.28	6.63	1.22	0.025	0.140	0.117	-0.029	4.15	-0.308	-1.292	-2.407	-4.350	-7.119
Osceola2	03-May-89	6.3	306	7.50	158.5	4.0	1.0	0.091	0.771	37.41	13.00	2.14	0.022	0.093	0.005	-0.029	3.91	-0.421	-1.253	-2.407	-3.375	-6.429
Osceola2	26-Jul-89	11.7	560	7.65	176.8	4.0	1.0	0.071	1.442	37.08	13.30	2.60	0.439	0.228	0.092	0.079	3.88	-0.148	-0.589	-2.485	-2.562	-2.319
Osceola3	18-Nov-88	8.9	235	7.00	146.3	13.5	2.5	0.036	1.018	39.29	12.68	3.91	0.029	0.058	0.020	-0.029	4.42	-0.894	-2.179	-1.929	-6.801	-8.212
Osceola3	18-Jan-89			7.00	152.4	12.0	2.5	0.055	0.969	39.33	4.97	1.97	0.016	0.195	0.025	-0.029	4.45	-0.866	-2.530	-1.908	-6.155	-8.559
Osceola3	03-May-89	9.0	132	7.00	140.2	13.5	3.0	0.033	0.786	38.28	12.68	2.73	0.012	0.103	0.019	-0.029	4.30	-0.919	-2.217	-1.946	-6.947	-9.427
Osceola3	26-Jul-89	10.7	321	7.10	146.3	12.5	3.0	0.021	0.786	35.61	12.05	3.89	0.131	0.017	0.016	0.054	4.20	-0.804	-1.945	-2.019	-6.968	-6.366
SandLk2	07-Apr-89	6.0	131	6.05	42.7	2.5	3.0	0.051	1.248	11.83	3.03	4.99	0.053	0.186	0.018	0.032	2.78	-2.876	-6.303	-1.512	-14.818	-10.299
SandLk2	27-Jul-89	10.5	213	6.15	36.6	8.0	11.5	0.013	1.513	20.19	5.14	5.29	0.339	0.294	0.043	0.045	2.76	-2.555	-5.574	-1.661	-14.378	-8.635
SandLk3	18-Nov-88	7.5	291	6.20	146.3	8.0	0.5	0.059	2.929	35.39	9.12	5.91	0.054	0.326	0.031	-0.029	2.46	-1.749	-4.016	-1.132	-11.381	-9.710
SandLk3	07-Apr-89	3.0	109	6.05	36.6	3.5	1.5	0.146	0.846	7.89	3.24	4.22	0.059	0.565	0.017	0.032	1.78	-3.160	-6.727	-1.590	-14.604	-9.291
SandLk3	27-Jul-89	12.5	222	6.51	103.6	7.5	1.0	0.014	1.337	21.20	7.65	4.92	0.167	0.197	0.049	0.050	2.22	-1.709	-3.695	-1.562	-11.711	-8.166
Waterman1	01-Sep-88	9.0	213	6.65	107.3	1.0	-0.1	0.130	1.857	22.22	7.99	3.81	23.420	0.126	2.056	0.085		-1.600	-3.544	-1.708	-8.618	0.336
Waterman1	18-Jan-89	8.7	352	6.65	97.5	5.0	-0.5	0.172	1.665	19.19	7.80	1.85	14.840	0.366	1.603	-0.029	0.90	-1.702	-3.699	-1.749	-8.432	0.088
Waterman2	01-Sep-88	9.0	195	6.35	102.4	1.0	0.0	0.063	1.424	21.42	8.30	7.32	11.150	0.108	2.693	0.076		-1.932	-4.174	-1.427	-11.304	-2.169
Waterman2	18-Jan-89	9.0	349	6.35	91.4	4.0	-0.5	0.077	1.084	16.87	13.78	3.27	1.063	0.346	2.029	0.030	1.58	-2.080	-4.146	-1.476	-11.406	-4.957
Waterman3	01-Sep-88	15.5	324	6.95	156.1	2.0	-0.1	0.082	1.545	54.92	10.34	5.84	0.297	0.636	0.444	0.148		-0.674	-1.857	-1.819	-4.708	-4.535
Waterman3	18-Jan-89	5.0	170	6.95	67.1	5.0	-0.5	0.009	0.859	14.54	13.29	1.42	0.042	0.255	0.775	-0.029	1.55	-1.734	-3.485	-2.227	-11.169	-9.011
BLANKS																						
Blank	06-May-88							-0.010														
Blank	07-Dec-88							-0.004	-0.621	0.10	-0.10	-0.61	0.042	-0.010	-0.003	0.119						
Blank	31-Jul-89							-0.004	-0.621	-0.04	-0.10	-0.61	-0.011	-0.010	-0.003	-0.029	-0.14					
Blank	19-Nov-89							-0.004	-0.621	-0.04	-0.10	-0.61	0.023	-0.011	-0.003	-0.029	-0.14					

Table 3. Range of phosphorus concentrations in groundwater samples from various geologic units

Geologic Unit	Number of Samples	Minimum (mg/l)	Maximum (mg/l)	Median (mg/l)
Basalt	9	<.004	0.058	0.020
Dolomite	8	0.012	0.055	0.024
Sandstone	16	0.011	0.110	0.030
Sand & gravel	75	<.004	0.298	0.034

possible to determine which unit was contributing water to the well. This is partly due to a lack of detailed geologic information and partly because wells often penetrate more than one unit. Several of the sandstone units contain glauconite and poorly preserved fossils. Glauconite is a green micaceous mineral rich in iron and potash, and "green sands" tend to be enriched in iron, potash, and phosphorus (Pettijohn, 1975, p.426). As noted above, fossils are commonly composed of one of the forms of apatite and this is another potential source for phosphorus. Of all of the sandstone units, the Tunnel City, Wonewoc, and Eau Claire tend to be poorly sorted, glauconite rich, and fossiliferous.

The glacial stratigraphy of the study area is relatively complex and it is difficult to distinguish stratigraphic units based upon drillers' construction logs. As noted in the geology section, the phosphorus content of the surficial materials is quite variable and so it is no surprise that the groundwater sampled from the sand and gravel aquifer shows the widest range of phosphorus concentrations.

Speciation Analyses

Results of the geochemical speciation program PHREEQE (Parkhurst and others, 1980) were used to determine which minerals might be controlling the phosphorus concentrations in groundwater. The program calculates the activities and activity coefficients of dissolved species, and the saturation indices of a variety of minerals, including hydroxyapatite and vivianite.

Results from the homeowners' wells indicate that most dissolved phosphorus is in the form $HPO4^{-2}$ and that the groundwater is generally undersaturated with respect to both hydroxyapatite and vivianite. Histograms of the saturation indices of both hydroxyapatite and vivianite (negative saturation indices indicate undersaturation and positive saturation indices indicate oversaturation) indicate groundwater is more undersaturated with respect to vivianite

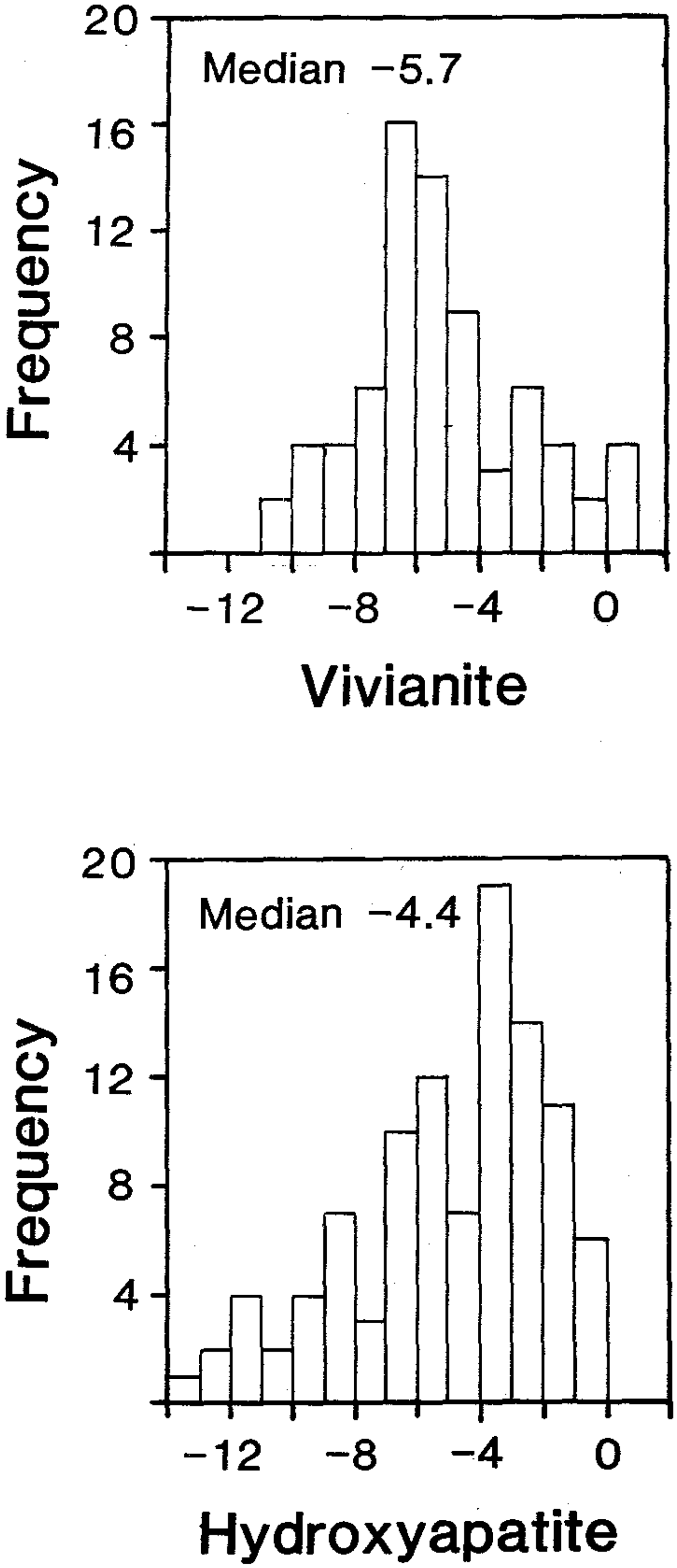


Figure 21. Histograms of saturation indices for hydroxyapatite and vivianite.

than to hydroxyapatite (fig. 21). However, four samples from the sand and gravel were saturated to slightly oversaturated with respect to vivianite while no samples were saturated with respect to hydroxyapatite. Both of these minerals are relatively insoluble and so it is not surprising that most samples are undersaturated with respect to them.

The PHREEQE results were used to examine various chemical controls on the phosphorus system. A plot of pH versus hydroxyapatite saturation index (fig. 22a) indicates that the dissolution of hydroxyapatite is strongly pH dependent. Hydroxyapatite behaves similarly to calcite and a plot of hydroxyapatite saturation index versus calcite saturation index (fig. 22b) indicates that as calcite concentrations increase so do hydroxyapatite concentrations. Since calcite is so ubiquitous and soluble it probably controls the dissolution of hydroxyapatite; once water becomes saturated with respect to calcite it may be difficult to dissolve hydroxyapatite.

The controls on the vivianite system are not as easy to determine. Plots of pH versus vivianite saturation index did not show much correlation, nor did plots of iron versus phosphorus concentrations. Results from the four homeowner wells that were slightly oversaturated with respect to vivianite suggest that vivianite is soluble in the pH range of 7.3 to 7.7; the iron concentrations for these wells were quite high, ranging from 1.6 to 10 mg/l. This suggests that some iron phosphate may contribute significant amounts of phosphorus to the groundwater. Vivianite is the only iron phosphate included in the PHREEQE program but since phosphate forms complexes with a number of metal ions (Stumm and Morgan, 1970) it is possible that other minerals are contributing phosphorus as well.

Neither hydroxyapatite nor vivianite is an abundant mineral but both seem to be present in the study area. Hydroxyapatite is probably present in several of the Cambrian sandstones. These sandstones are frequently iron stained and so may contain iron phosphates as well. Hydroxyapatite is probably present in the Prairie du Chien dolomite since it can substitute for the minerals calcite and dolomite. In this unit the presence of more soluble calcite and dolomite may limit the solubility of hydroxyapatite. Apatite is found in the Precambrian basalt; apatite is less soluble than hydroxyapatite and samples of groundwater from this unit generally contain low concentrations of phosphorus. The Pleistocene materials in the area all contain some locally derived material as well as material derived from rocks to the northwest. These sediments seem to contain enough hydroxyapatite and iron phosphates (vivianite) to contribute significant amounts of phosphorus to the groundwater.

Anthropogenic Contributions of Phosphorus to Groundwater

A variety of factors, both natural and anthropogenic, affect phosphorus concentrations in groundwater. The emphasis of this study was to assess the geologic controls on phosphorus distribution; however, human activities can also contribute significant phosphorus loadings to the groundwater. Potential phosphorus sources include leaching of commercial fertilizers from lawns and agricultural fields, disposal of human and animal wastes, and inputs from

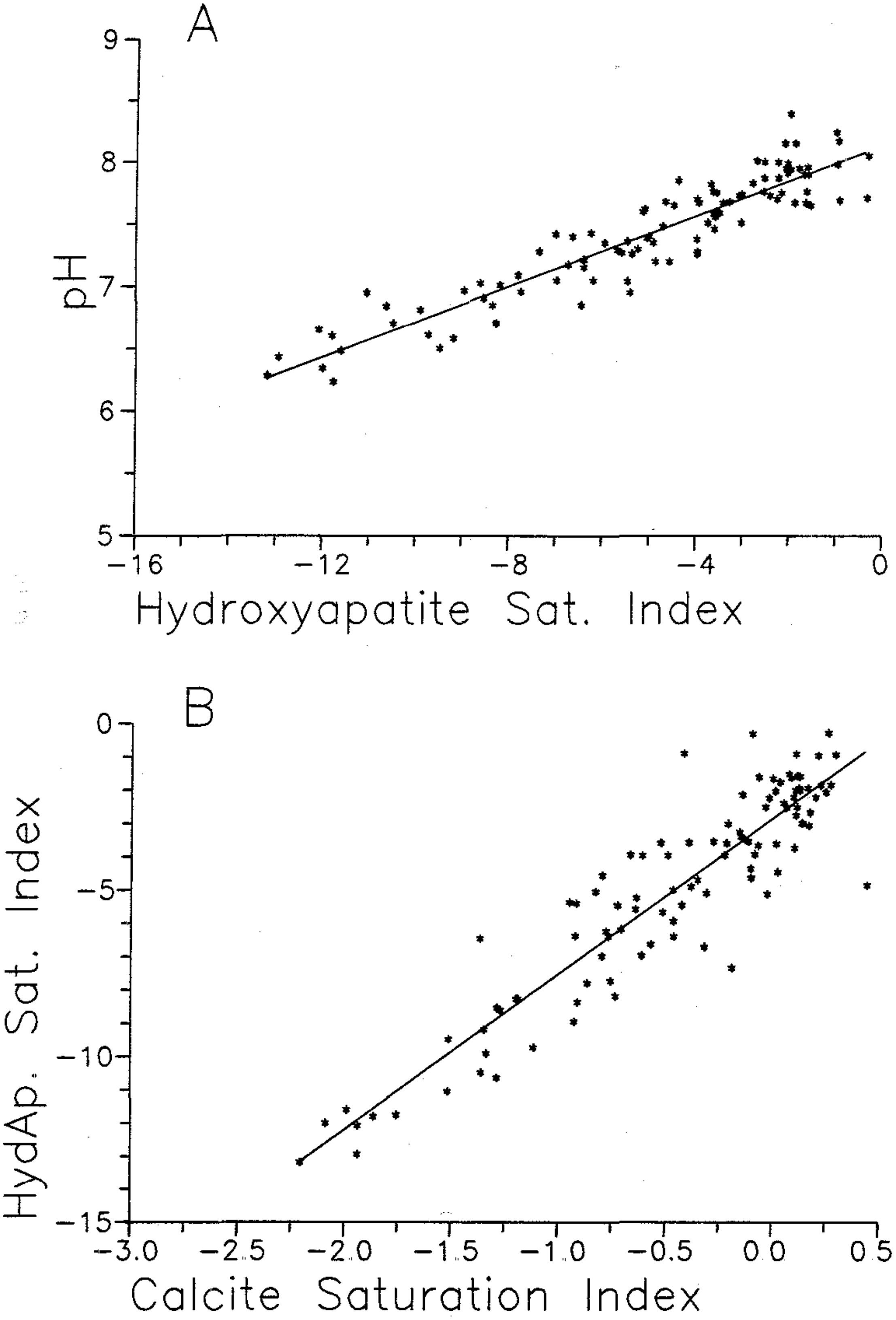


Figure 22. **A.** Plot of hydroxyapatite saturation index versus pH. **B.** Plot of calcite saturation index versus hydroxyapatite saturation index.

agronomic crops such as alfalfa. Since phosphorus contributions from point sources, such as manure pits and septic systems, are more easily quantified than loadings from varying land-use practices, monitoring efforts were focused on two earthen-lined manure pits and one septic system.

Manure Pits

There are approximately 180 earthen-lined manure pits in Polk County while Barron County has over 600. A number of workers have documented nitrogen seepage from earthen-lined manure pits (Cates, 1983; Bickford, 1983), however, phosphorus is more easily adsorbed than nitrogen and few data exist that address the question of whether phosphorus leaches from manure pits. Monitoring wells were installed around two manure pits, located near Balsam and Long Lakes in Polk County, and three rounds of samples were collected and analyzed for total dissolved phosphorus, major ions, alkalinity, nitrate, ammonium, organic nitrogen, and chloride. Sample results are reported in Table 4.

Long Lake site.--The manure pit, located south of Long Lake, sits approximately 50 ft above lake level; approximately 40 ft of unsaturated sediment separates the base of the pit from the water table. Groundwater flows from the west-northwest to east-southeast. One upgradient piezometer, PMP1, consists of $1^1/_4$-inch steel pipe with a 3-ft sand point as a screen while three downgradient piezometers, PMP2 to PMP4, consist of $1^1/_4$-inch PVC pipe with 3-ft slotted screens. All piezometers are screened across the water table except for PMP3 which is located next to PMP2 and is screened 10 ft deeper. Figure 23 shows locations of the pit and the monitoring wells in relation to groundwater flow direction.

Both nitrogen and phosphorus concentrations suggest that the manure pit contributes nutrients to the groundwater. The average phosphorus concentration at the upgradient well is 0.006 mg/l while the average downgradient concentrations are 0.019, 0.018, and 0.016 mg/l for wells PMP2, PMP3, and PMP4 respectively. Nitrate averages 2.2 mg/l at the upgradient well and 9.8, 13.5, and 10.0 mg/l at PMP2, PMP3, and PMP4 respectively. The largest input of phosphorus and nitrate seems to occur after the pit has been pumped and while it is being refilled with waste (see May sample, Table 4).

Balsam Lake site.--The manure pit is located east of Balsam Lake and it appears that the water table intercepts the bottom of the pit at some times of the year. The regional groundwater flow direction is from east-northeast to west-southwest, however, local mounding under the manure pit causes reversals of flow in the area immediately adjacent to the pit. Four piezometers have been installed at the site, RMP2 and RMP4 consist of $1^1/_4$-inch PVC pipe with 3-ft slotted screens while PMP1 and RMP3 are 2-inch PVC with 3-ft slotted screens. All piezometers are screened across the water table except for RMP1 which is located next to RMP2 and is screened 20 ft deeper. Figure 24 shows locations of the pit and the monitoring wells in relation to the regional groundwater flow direction.

TABLE 4
CHEMICAL ANALYSES FROM MANURE PITS AND SEPTIC SYSTEM (values sre in mg/l)

Sample	Date	Temp C	Cond umhos	pH	P	TotalN	OrgN	NH4-N	NO3-N	CI	HCO3-	K	Ca	Mg	Na	Fe	Zn	Mn	B	S
LONG LAKE SITE																				
PMP1	14-Nov-89	7.9	335	7.02	0.008	5.0	0.5	1.0	3.5	17.5	91.4	1.93	24.76	7.59	6.22	0.27	10.01	0.21	0.07	5.12
PMP1	21-Feb-90	8.0	397	6.77	0.006	5.0	2.5	2.5	0.0	142.0	377.9	0.95	20.31	6.53	6.67	0.46	5.76	0.08	0.04	4.64
PMP1	24-May-90	9.0	230	6.68	0.004	9.5	5.5	1.0	3.0	17.0	79.2	1.11	19.99	5.96	11.63	0.65	11.21	0.05	0.04	3.72
PMP2	14-Nov-89	7.9	406	6.56	0.008	11.5	0.5	0.0	11.0	39.5	67.1	0.88	43.69	12.71	5.62	0.72	0.48	0.10	0.05	3.86
PMP2	21-Feb-90	8.2	443	6.51	0.023	12.0	1.0	0.0	11.0	38.5	67.1	-0.62	39.35	11.60	6.49	0.01	0.26	0.02	0.05	3.74
PMP2	24-May-90	7.7	394	6.68	0.025	11.5	4.0	0.0	7.5	43.5	54.9	-0.62	40.12	11.49	6.89	-0.01	0.46	-0.00	0.04	3.54
PMP3	14-Nov-89	8.9	425	6.44	0.009	13.0	0.5	0.0	12.5	45.0	67.1	0.88	44.94	13.51	5.77	0.20	0.26	0.02	0.05	4.27
PMP3	21-Feb-90	8.3	495	6.45	0.018	13.5	0.5	0.0	13.0	47.5	61.0	0.66	43.24	13.29	6.83	0.03	0.31	0.01	0.03	4.09
PMP3	24-May-90	9.0	415	6.67	0.026	19.5	4.5	0.0	15.0	164.0	146.3	0.73	42.50	12.68	7.02	0.03	0.43	0.00	0.04	3.38
PMP4	14-Nov-89	8.0	364	6.46	0.009	8.0	0.0	0.0	8.0	27.0	97.5	0.78	39.47	11.84	4.70	0.10	0.19	0.03	0.04	3.63
PMP4	21-Feb-90	8.1	527	6.35	0.017	10.5	0.0	0.0	10.5	38.5	97.5	-0.62	44.69	13.64	6.32	0.02	0.13	0.02	0.04	3.76
PMP4	24-May-90	9.0	443	6.51	0.021	14.0	2.5	0.0	11.5	48.0	97.5	-0.62	46.79	13.79	6.55	-0.01	0.21	-0.00	0.04	3.50
BALSAM LAKE SITE																				
RMP1	15-Nov-89	9.5	1576	6.19	0.090	4.5	2.5	2.0	0.0	130.0	451.1	35.54	124.80	37.94	18.49	5.90	0.19	10.89	0.07	4.35
RMP1	22-Feb-90	6.1	1722	6.06	0.080	5.5	1.0	1.0	3.5	17.0	85.3	41.83	105.30	31.76	17.23	5.35	0.84	10.93	0.08	4.51
RMP1	25-May-90	7.0	1087	6.06	0.075	8.0	7.0	1.0	0.0	124.5	371.9	23.56	91.29	27.72	15.50	3.61	0.32	6.99	0.05	4.00
RMP2	15-Nov-89	10.1	2307	6.53	0.120	34.5	5.5	29.0	0.0	145.5	969.3	200.30	141.40	72.96	20.16	37.30	0.09	12.52	0.12	14.57
RMP2	22-Feb-90	6.0	1815	6.60	0.075	36.0	5.0	31.0	0.0	139.5	993.7	188.20	130.00	66.98	19.85	39.32	0.10	13.46	0.12	11.64
RMP2	25-May-90	6.3	2394	6.62	0.086	46.5	17.0	26.0	3.5	131.0	987.6	184.30	105.70	58.02	31.19	39.46	0.15	8.79	0.14	39.65
RMP3	15-Nov-89	10.5	1542	5.65	0.039	25.5	1.5	0.0	24.0	187.0	103.6	2.80	119.50	35.40	18.14	0.25	0.14	0.07	0.06	10.06
RMP3	25-May-90	6.7	1238	5.85	0.042	13.0	4.0	0.0	9.0	51.0	67.1	1.67	104.90	30.24	17.43	0.15	0.23	0.06	0.06	9.23
RMP4	15-Nov-89	9.1	559	6.42	0.022	2.0	1.0	0.0	1.0	23.0	243.8	1.94	68.01	18.68	9.40	0.13	0.25	3.19	0.07	8.80
RMP4	22-Feb-90	7.5	504	6.52	0.040	3.0	1.5	0.0	1.5	22.0	250.0	1.91	59.73	17.04	9.77	0.57	0.36	3.85	0.08	8.31
RMP4	25-May-90	7.5	474	6.47	0.032	9.5	7.0	0.0	2.5	23.5	201.2	1.09	57.46	16.09	9.45	0.07	0.47	2.13	0.07	7.05
SEPTIC SYSTEM																				
HEW	22-Feb-90	8.8	376	6.86	0.033	0.5	0.5	0.0	0.0	4.0	207.3	-0.62	36.23	19.65	6.92	0.48	0.08	0.12	0.05	5.57
HEW	02-Aug-90	9.0	356	7.03	0.029				0.5	1.0	140.2	0.77	35.65	19.22	6.74	-0.01	0.06	0.03	0.05	4.84
HHouse	22-Feb-90	9.0	169	7.85	0.035	0.5	0.0	0.5	0.0	4.5	67.1	-0.62	20.61	2.67	2.57	0.10	0.04	0.32	0.08	0.82
HHouse	02-Aug-90	11.1	150	8.42	0.029				0.5	4.0	61.0	-0.62	21.45	2.58	1.61	-0.01	-0.01	0.29	0.07	0.90
HNBW	22-Feb-90	8.9	912	6.69	0.015	0.5	0.5	0.0	0.0	13.5	506.0	0.65	88.43	47.94	11.00	0.50	0.06	0.17	0.06	6.21
HNBW	02-Aug-90	9.0	1044	6.93	0.038				16.5	29.0	493.8	1.69	128.80	54.84	9.85	-0.01	0.05	0.03	0.06	8.67
HNW	22-Feb-90	9.1	424	6.24	0.017	4.1	0.5	0.0	3.6	31.0	97.5	0.63	37.06	17.89	10.23	0.50	0.08	0.10	0.04	16.01
HNW	02-Aug-90	9.6	361	6.40	0.009				2.0	25.0	79.2	0.92	32.35	14.13	8.17	-0.01	0.04	0.05	0.04	11.86
HSBW	22-Feb-90	8.4	348	6.85	0.029	0.5	0.5	0.0	0.0	10.5	146.3	-0.62	33.24	16.08	5.45	0.01	0.10	0.05	0.04	8.77
HSBW	02-Aug-90	8.6	404	6.99	0.031				1.5	10.0	189.0	3.03	44.66	21.25	5.58	-0.01	0.03	0.05	0.06	9.26
BLANKS																				
Blank	27-Feb-90				-0.004							-0.62	-0.04	-0.10	-0.61	-0.01	-0.01	-0.00	-0.04	-0.14
Blank	29-May-90											-0.62	-0.04	-0.10	0.87	-0.03	-0.01	-0.00	-0.03	22.45
Blank	06-Aug-90				-0.004							-0.62	-0.04	-0.10	-0.61	-0.01	-0.01	-0.00	-0.03	-0.14

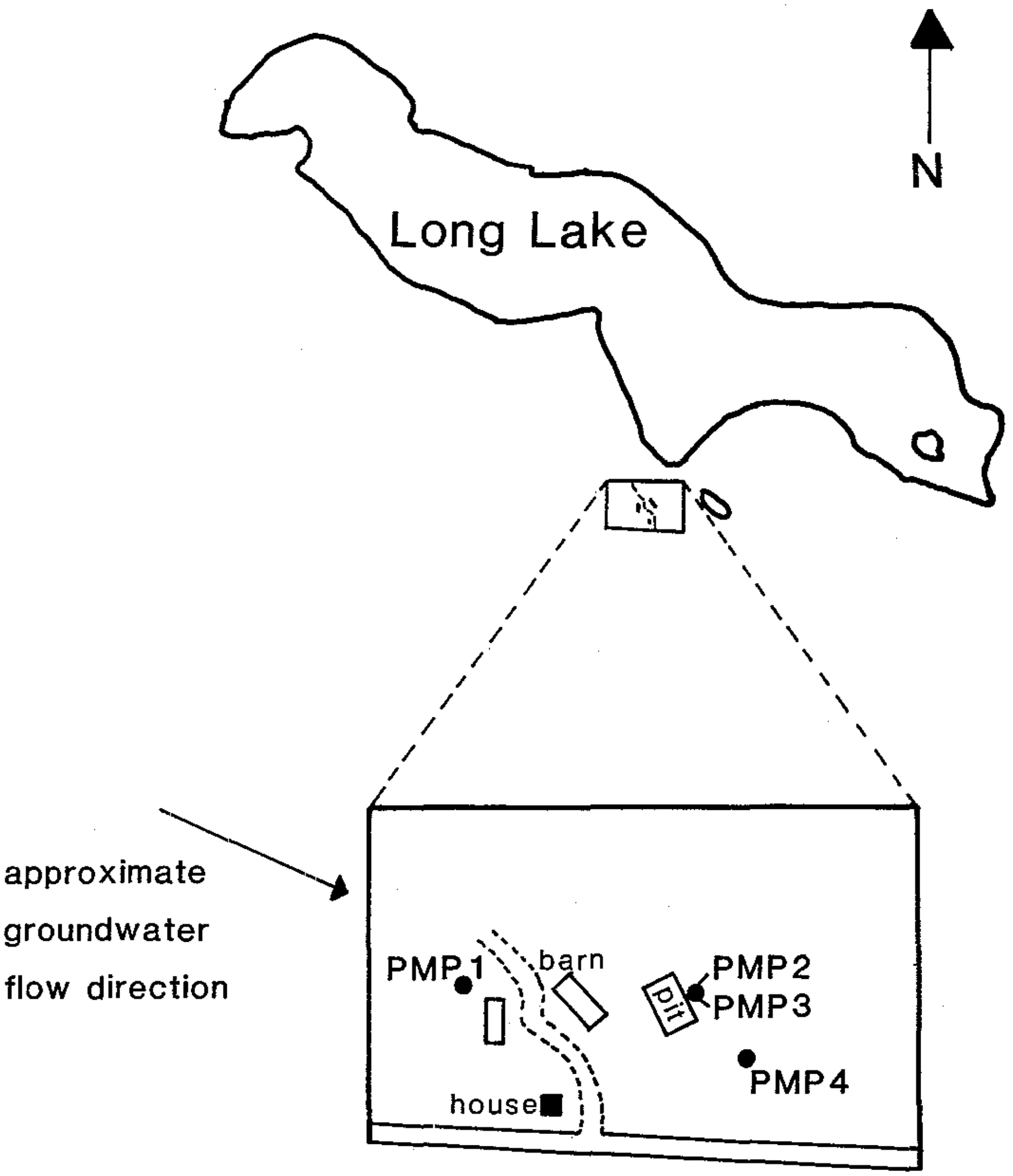


Figure 23. Sketch map of Long Lake site showing location of the manure pit and the piezometers in relation groundwater flow direction.

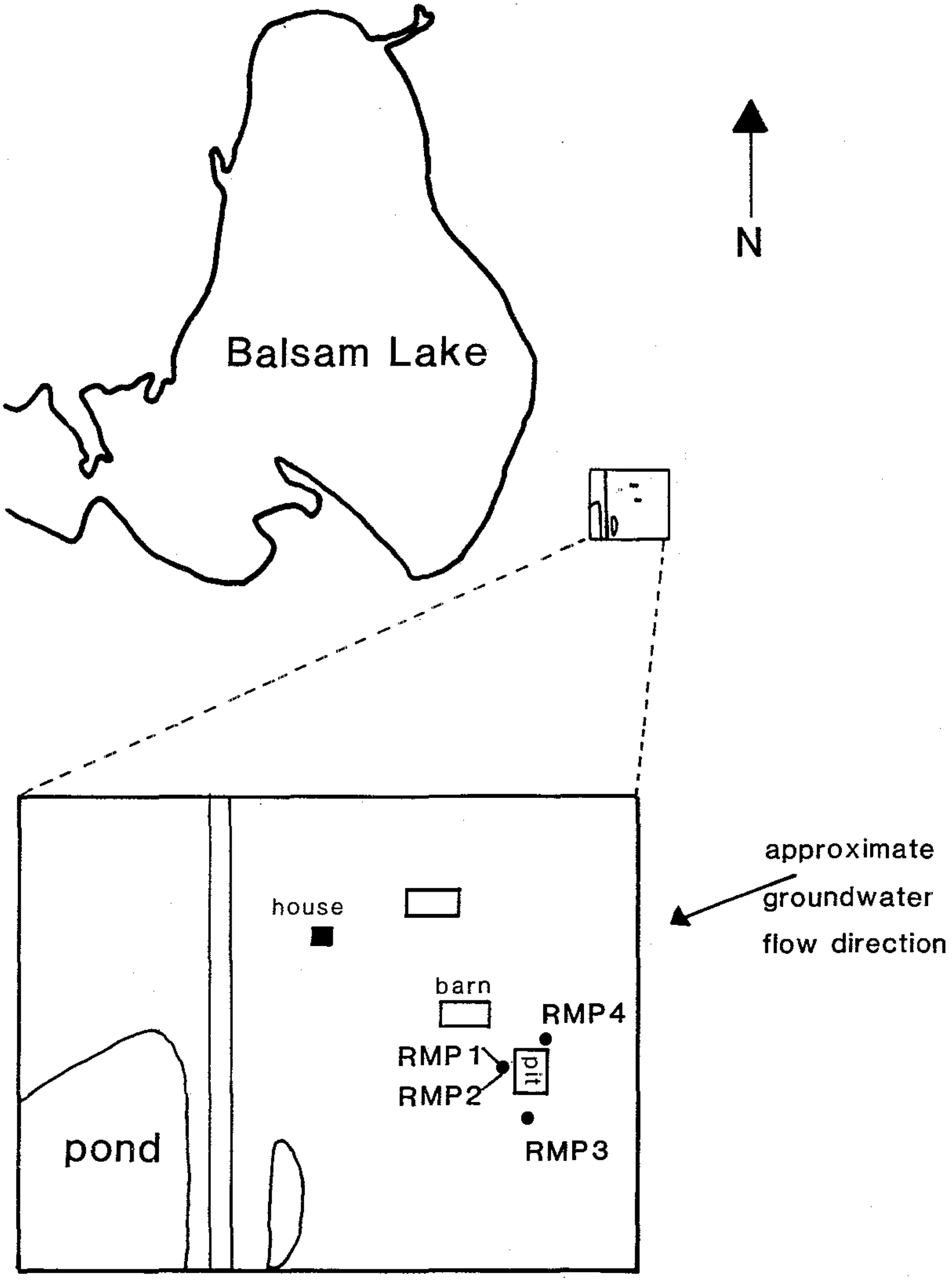


Figure 24. Sketch map of Balsam Lake site showing location of the manure pit and the piezometers in relation to groundwater flow direction.

Local water-table mounding beneath the manure pit causes radial flow from the site; as a result, all four wells receive some nutrient loadings from the pit. Piezometer RMP4 appears to be the least impacted with an average phosphorus concentration of 0.031 mg/l while piezometers RMP2 (shallow) and RMP1 (deep) have average phosphorus concentrations of 0.094 and 0.065 mg/l respectively (Table 4). Piezometer RMP3 has an average phosphorus concentration of 0.041 mg/l based on two samples (piezometer was dry in February, 1990). Total nitrogen (sum of organic N, NO_3-N, and NH_4-N) averages 4.8 mg/l at RMP4, the least impacted piezometer, and 6.0, 39.0, and 19.3 mg/l at RMP1, RMP2, and RMP3 respectively. The high concentrations of NH_4-N at piezometer RMP2 suggest that saturated conditions exist under the pit since NH_4-N quickly converts to NO_3-N under unsaturated flow conditions.

Septic Systems

Many homeowners in the study area rely on septic systems for disposal of their household wastes. Recent research near Stevens Point (Arntsen and others, 1988) and Eau Claire, Wisconsin (Tinker, 1989) suggests that septic systems can contribute significant amounts of nitrate to groundwater. Data on phosphorus contributions from properly functioning septic systems are limited. The Small-Scale Waste Management Project (SWMP) has installed four 2-inch PVC piezometers around a newly constructed septic system near Viola Lake in Burnett County (fig. 25). The system consists of three 10 by 20 ft seepage beds; loadings are alternated between the three beds. Two of the four piezometers, HNBW and HSBW, are completed directly below a seepage bed. HEW is located just east of the driveway while HNW is located north of the seepage beds (fig. 25). All piezometers have 5-ft screens, are completed at 29 ft, and are screened across the water table. The home well is located to the northwest of the seepage beds (labeled HHouse).

Two sets of samples were collected from the site; results are included in Table 4. Samples were analyzed for total dissolved phosphorus, major ions, alkalinity, nitrate, and chloride. These limited data suggest that even well-maintained, properly functioning septic systems can contribute nutrients to the groundwater. The February sample from HNBW has a phosphorus concentration of 0.015 mg/l and a NO_3-N concentration of 0.0 mg/l. The May sample from the same piezometer contains 0.038 mg/l phosphorus and 16.5 mg/l NO_3-N. The rotational loading schedule is not known, however, it appears that in February the north bed (piezometer HNBW) was not receiving waste and nutrient concentrations were low while in May the north bed was receiving waste and nutrient concentrations were elevated.

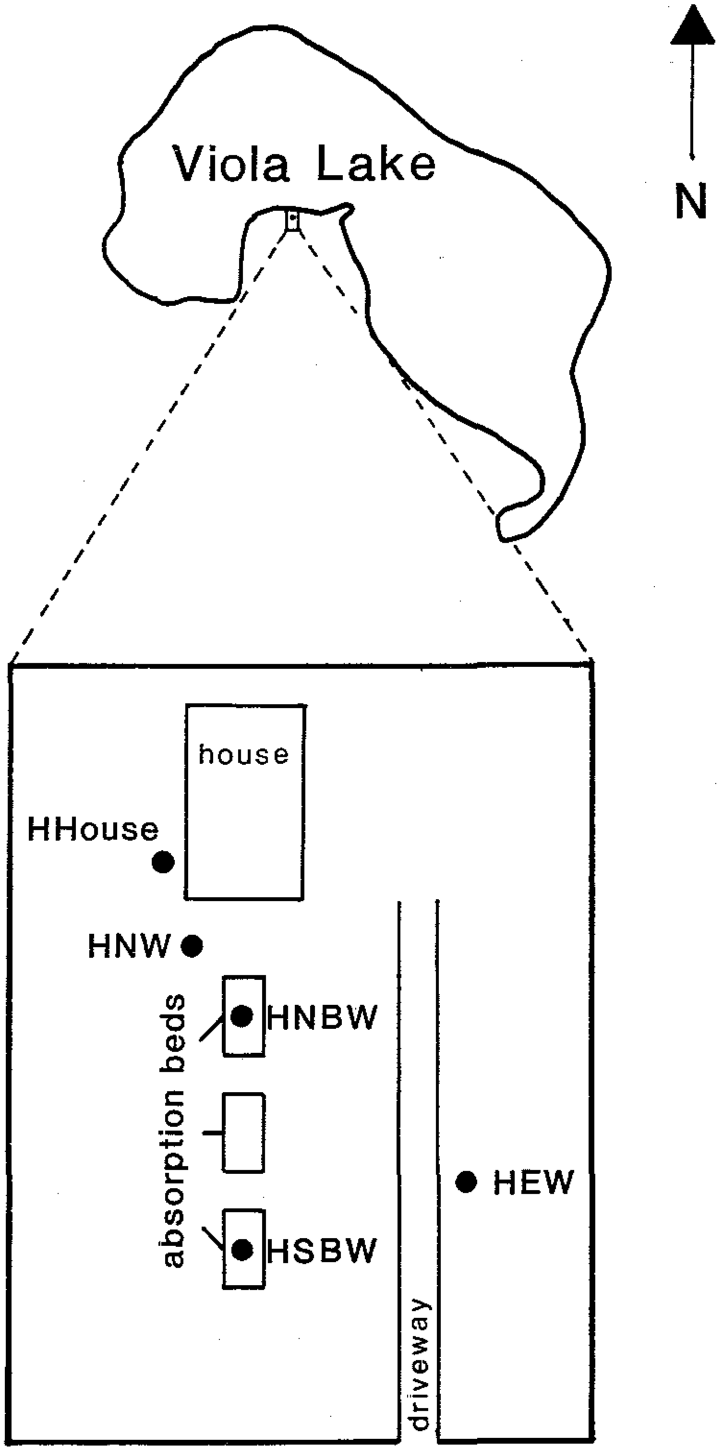


Figure 25. Sketch map of Viola Lake site showing location of the seepage beds, the piezometers, and the house well.

RELATIONSHIPS BETWEEN GROUNDWATER AND LAKE WATER QUALITY

A variety of factors affect lake water quality; these include natural factors such as the size of the watershed, the amount and quality of both the surface-water inputs and the groundwater inputs, the depth of the lake, and the phosphorus content of the geologic materials. In addition to the natural factors that affect a lake, land-use activities in the watershed can also play an important role in determining lake water quality. Due to the variety of factors that control lake water quality, simple comparisons between lake phosphorus concentrations and the type of surrounding geologic material or the upgradient groundwater phosphorus concentration do not show strong correlation when the entire data set is considered. However, lakes may be grouped according to lake/groundwater relationships and several lake settings that are characteristic of the study area are described below.

Lakes Dominated by Surface-water Inputs

Determining detailed lake budgets and calculating relative contributions from surface water and groundwater for various lakes was beyond the scope of this study, however, it is possible to outline areas where the majority of the lakes receive little to no groundwater input. The stippled pattern on the potentiometric surface map (fig. 18) shows areas where surface-water elevations are more than 50 ft above well-water elevations. In these areas, lakes probably receive little to no groundwater input. Specific geologic settings help to explain groundwater flow patterns in some of these areas. In areas where till and lake sediment of the Trade River Formation are the surficial units, the water table tends to be steeply mounded under most lakes (see Bass Lake example). In the southwest part of the study area, small isolated lakes are found in upland areas (see Osceola Lake example). In the northeast part of the study area, till and undifferentiated sediment of the Sylvan Lake Member tend to act as a perching layer, separating a shallow saturated zone from a deeper saturated zone (see Waterman and Sand Lake examples). For all of the above settings, lakes chemistries are dominated by surface-water inputs. A third group of lakes also seems dominated by surface inputs; these are shallow lakes downgradient from wetlands. Examples of lakes located in each of these settings will be discussed below.

Lakes with Steeply Mounded Water Tables

In the southern portion of the area where Trade River Formation till is the surficial unit (fig. 4), lakes have formed in small, till-lined ice-block depressions. The water table tends to be strongly mounded under such lakes and many of these lakes have total phosphorus concentrations in excess of 0.050 mg/l; examples include Manitou, McKeith, Tarbert, Herby, Bass, Roger, Orr, Wolf, Mud, Alabama, and Lone Pine Lakes (DNR, historic data and 1988 sampling). The sediment of the Trade River Formation is relatively high in "plant available" phosphorus and overland runoff entering the lakes can be expected to deliver some phosphorus from the sediment. In addition, runoff from agricultural areas within these watersheds will contribute phosphorus from commercial fertilizers, animal wastes, and alfalfa fields.

Bass Lake chemistry.--Bass Lake appears to be typical of lakes located in the southern portion of the area mapped as Trade River till. It is a relatively small, shallow lake with an enclosed watershed. Groundwater samples collected from piezometers around Bass Lake were analyzed for total dissolved phosphorus, major ions, alkalinity, nitrate, and chloride (see Table 2). In addition, samples from piezometers 1 and 2 (see fig. 16 for location) were analyzed for tritium in order to determine approximate groundwater ages. Tritium (^3H) is a radioactive isotope of hydrogen that is naturally present at low levels in the earth's atmosphere, but tritium in the atmosphere increased dramatically following atmospheric atomic weapons testing from 1952 to the mid-1960s. During this time, all recharging groundwater was enriched with tritium, and groundwater that has entered aquifers since 1952 generally contains elevated tritium levels. The half-life of tritium (12.3 years) is relatively short, making it an excellent indicator of recent groundwater recharge and relative groundwater age where age is defined as the time since the water was in contact with the atmosphere. Hendry (1988) summarized the general qualitative interpretations of groundwater age on the basis of tritium in groundwater (table 5). Tritium analyses are reported in tritium units--a ratio of tritium atoms (^3H) to the much more common ^1H atoms. One tritium unit, or TU, represents one tritium atom per 10^{18} hydrogen atoms.

Table 5. Qualitative interpretations of tritium concentrations in groundwater (from Hendry, 1988).

Concentration (TU)	Interpretation
> 100	Average ground water likely recharged during thermonuclear testing between 1960 and 1965.
10-100	Average ground water less than 35 years old.
2-10	Average ground water at least 20 years old.
< 2.0	Average ground water older than 30 years.
< 0.2	Average ground water older than 50 years.

Piezometer 1, completed in the sand and gravel, contained 22.7 ±1.7 TU suggesting relatively recent groundwater recharge. While piezometer 2, completed in the Trade River till, contained 9.6 ±0.9 TU suggesting somewhat older groundwater. Water levels in piezometers around the lake (see fig. 17b) indicate that water is seeping from the lake to the groundwater system. Both the till and the sand and gravel receive recharge from infiltrating rainfall as well as from seepage out of the lake. The sand and gravel is much more permeable than the till and so rainfall can rapidly recharge the sand and gravel in areas where it is not covered by the till. The fact that piezometer 2 contains older water than piezometer 1 suggests that the residence time of the lake is quite long.

Lakes that are Perched

Data from the monitoring sites suggest that there are at least two distinct hydrogeologic settings in which perched lakes are present -- areas of hummocky till or undifferentiated sediment of the Sylvan Lake Member where two distinct saturated zones develop and upland areas with small isolated lakes. Several lakes are located within areas where surface-water and well-water elevations differ by more than 50 ft (stippled areas, fig. 18). Detailed information describing the groundwater flow systems in all of these areas is not available, however, it is reasonable to assume that the lakes receive minimal groundwater inputs; as a result, no domestic wells were sampled in these areas.

Water levels from the Waterman and Sand Lake study sites, located in the northeast portion of the study area, indicate that a shallow flow system is present over a deeper flow system. Several upland lakes, presumed to be part of the shallow flow system, have moderate to somewhat elevated phosphorus concentrations. Kirby Lake had a spring phosphorus concentration of 0.034 mg/l while three unnamed lakes in the area ranged from 0.026 to 0.53 mg/l (DNR, 1988 sampling). Groundwater samples collected at the Waterman and Sand Lake sites provide information on the phosphorus concentration and the relative age of groundwater in the shallow flow system.

Waterman and Sand Lake chemistries.--The piezometers at Waterman Lake are completed in till and meltwater stream sediment of the Sylvan Lake Member (see fig. 14a). The two deepest piezometers, 1 and 2, are consistently high in phosphorus, with concentrations ranging from 0.063 to 0.172 mg/l (see Table 2). The shallowest piezometer, 3, is only 14 ft deep and phosphorus concentrations range from 0.009 to 0.082 mg/l. The shallow piezometer may be influenced by water recharging from the nearby unnamed lake but the deeper piezometers seem to suggest that phosphorus concentrations tend to increase with depth. Sylvan Lake meltwater stream sediment contains 38 lbs/acre of "plant available" phosphorus (see fig. 6), however, the Sylvan Lake till is consistently low in phosphorus (11 lbs/acre). Downward hydraulic gradients indicate that groundwater must recharge through the sand and gravel before reaching the till; it is likely that the meltwater stream sediment is the source of most of the phosphorus in the groundwater at this site.

The piezometers at Sand Lake are completed in till and lake sediment of the Sylvan Lake Member (see fig. 14b). Phosphorus concentrations are more variable than at the Waterman Lake site; samples from piezometer 3, completed in the lake sediment, range from 0.014 to 0.146 mg/l while samples from piezometer 2, completed in the till range from 0.013 to 0.051 mg/l.

Tritium analyses indicate that groundwater is relatively young at both sites. At Waterman Lake, tritium values were 22.5 ±1.7 TU for piezometer 1 and 20.3 ±1.5 TU for piezometer 2. At Sand Lake, tritium values were 22.5 ±1.7 TU and 22.2 ±1.6 TU for piezometers 2 and 3 respectively. All samples indicate that groundwater in the shallow flow system is < 35 yr old. Since samples from piezometer 1 at Waterman Lake are slightly oversaturated with respect to vivianite this suggests that groundwater can reach local equilibrium with respect to vivianite within 35 years; or since vivianite is relatively insoluble, it is possible that a more soluble iron-phosphate complex may be present. Equilibrium constants are not available for any iron phosphate other than vivianite.

Lakes Dominated by Upgradient Wetlands

A number of small, shallow lakes in the southern portion of the study area, located downgradient of wetland areas, have phosphorus concentrations in excess of 0.075 mg/l. Examples include Horseshoe Lake (on the Nye Quadrangle), Kinney Lake, North Fish Lake, Island Lake, Hatfield Lake, and several unnamed lakes in T31N, R17W; T32N, R17W; and T32N, R16W.

Many of these lakes are located in waterfowl production areas; as a result there were few homes with existing wells that could be sampled for groundwater chemistry. Two wells located near North Fish Lake, but not directly upgradient from the lake, had phosphorus concentrations of 0.025 and 0.041 mg/l. In the 1988 sampling, North Fish Lake had a phosphorus value of 0.146 mg/l (DNR data), much higher than would be expected from the groundwater values.

Some groundwater samples, collected downgradient from wetlands in other parts of the study area, suggest that wetlands can contribute phosphorus to the groundwater. Two samples collected from homes downgradient of a small wetland near Staples Lake had phosphorus concentrations of 0.049 and 0.069 mg/l while one spring sample collected downgradient from a small wetland near Balsam Lake had a phosphorus concentration of 0.035 mg/l. The source of the phosphorus is probably the wetlands themselves rather than the material in which the wetlands are formed. Presumably wetland vegetation takes up phosphorus during the summer but when the plants die back in the fall the phosphorus is released through decay. This phosphorus may be transported to the groundwater system by water seeping from the wetlands or it may stay available in the surface water until it is utilized the following summer. Lakes downgradient of wetlands may also receive significant amounts of phosphorus during the seasons when wetland vegetation is dormant.

Lake Chemistries Which Reflect Groundwater Chemistry

Samples from monitoring sites and domestic wells indicate that there are several lakes in the study area where lake phosphorus concentrations are similar to phosphorus concentrations in upgradient wells. These lakes range from good quality, low-phosphorus lakes (phosphorus < 0.020 mg/l) to lakes with phosphorus values in excess of 0.050 mg/l.

High-Phosphorus Lakes

Lakes with phosphorus concentrations in excess of 0.050 mg/l are considered high-phosphorus lakes. Detailed sampling around Osceola and Horse Lakes identified specific geologic settings that contribute significant phosphorus to groundwater. These lakes are discussed in more detail below. Trident and Big Trade Lakes are also examples of high-phosphorus lakes with elevated phosphorus concentrations in upgradient wells. Trident Lake, also called King Lake on some maps, had 0.063 mg/l total phosphorus in the 1988 sampling (DNR data) while the groundwater from an upgradient well had 0.094 mg/l. Trident Lake is downgradient from areas of undifferentiated sediment and lake sediment of the Sylvan Lake Member. Sylvan Lake undifferentiated sediment is relatively low in available phosphorus while the lake sediments are somewhat high (see fig. 6). It is possible that the source of the phosphorus near Trident Lake may be lake sediment of the Sylvan Lake Member. Big Trade Lake, however, illustrates a geologic setting that is clearly capable of providing significant amounts of natural or background phosphorus. Big Trade Lake's phosphorus concentration was 0.076 mg/l during the 1988 sampling period (DNR data). Two wells upgradient from the lake had phosphorus concentrations of 0.106 and 0.059 mg/l. The lake is formed in the northern portion of the area mapped as Trade River till and lakes in this area appear to receive groundwater inflow. The Trade River till has a median Bray phosphorus value of 40 lbs/acre (see fig. 6); this available phosphorus can be carried to the lake with sediment runoff or by groundwater flow.

Osceola Lake.--Osceola Lake sits at the base of a steep ridge; its watershed is relatively small and mainly forested suggesting that the lake receives little phosphorus from land-use activities. It appears that Osceola Lake receives significant groundwater inputs; several springs discharge along the southeast shore of the lake. In addition, the lake has no inflowing stream and yet it serves as the headwaters for Osceola Creek.

The lake's phosphorus concentration is 0.051 mg/l (DNR, 1988 sampling). Piezometer 3, located upgradient from the lake and completed in meltwater stream sediment of the Sylvan Lake Member, had phosphorus values ranging from 0.021 to 0.055 mg/l (see fig. 11 and Table 2). The average concentration of 0.036 mg/l is probably representative. A spring, located on the southeast shore of Osceola Lake, had a phosphorus concentration of 0.099 mg/l. Both Osceola Spring and piezometer 3 are along flow paths that discharge to the lake. The potentiometric surface map (fig. 18) indicates that the recharge area for both of these points is probably the top of the ridge just southeast of the lake (see fig. 11). The surficial unit on the ridge is meltwater stream sediment of the Sylvan Lake Member. Given that the two sampling points tap the same geologic unit, it is surprising that the phosphorus concentrations are so different. The difference could be due to length of flow path or possibly to small local differences in materials. For instance, a small patch of buried organic sediment near the lakeshore could increase the phosphorus concentration of the spring but not of piezometer 3. Since the concentrations of most other ions are quite similar, this explanation seems plausible. A phosphorus concentration of 0.035 mg/l is probably representative of groundwater in the area and this may be high enough to impact lakes that receive significant groundwater inputs.

Tritium samples collected from wells upgradient of Osceola Lake contained 32.0 ±2.2 to 44.2 ±3.0 TU indicating that groundwater is less than 35 years old. Samples were collected from the domestic well on top of the ridge (well DJ on fig. 11), piezometer OL3, and the house well immediately south of the lake (not labeled on fig. 11).

Horse Lake.--Horse Lake, located near Nye in southern Polk County, receives groundwater inputs from the west, north, and east; groundwater discharges from the lake along its southern shore (see fig. 18). Groundwater samples were collected from six domestic wells around the lake all of which draw water from meltwater stream sediment of the Sylvan Lake Member. The phosphorus content of the groundwater varied from 0.016 to 0.121 mg/l. This variation in phosphorus concentrations may be due to well depth. Construction reports are not available for all wells, however, the highest phosphorus concentration came from a 121-ft well, while the lowest value was from a 50-ft well. The average phosphorus concentration of the six upgradient wells was 0.056 mg/l, which is quite high for groundwater. Horse Lake had a phosphorus concentration of 0.062 mg/l in the 1988 sampling (DNR data). It is not known what percentage of the lake's water budget is supplied by groundwater, however, the lake is located in a groundwater discharge area and phosphorus levels in groundwater are quite high suggesting that Horse Lake's high phosphorus content is due, in part, to background concentrations of phosphorus in the groundwater.

Lakes With Elevated Phosphorus Levels

Lake phosphorus values between 0.020 - 0.050 mg/l were considered elevated. Many lakes in the study area fall within this range and for several of those lakes the samples from upgradient domestic wells also had phosphorus concentrations between 0.020 and 0.050 mg/l. Specific examples include Godfrey Lake in Burnett County (lake 0.030, upgradient well 0.034), Little Wood (lake 0.033, well 0.027), Silver (lake 0.022, well 0.023), Paulsen (lake 0.043, well 0.042), Largon (lake 0.044, well 0.053) and Lamont and Little Pine Lakes (Lamont 0.024, Little pine 0.031, well between the two 0.058).

Almost all of these lakes are formed in sediment of the Sylvan Lake Member. Godfrey, Little Wood, and Lamont and Little Pine Lakes receive groundwater inflow from areas where Sylvan Lake meltwater stream sediment is the surficial unit. Largon Lake receives groundwater from areas covered by till as well as from areas covered by meltwater stream sediment. Groundwater recharging Paulsen Lake has traveled through Sylvan Lake lake sediments, while areas upgradient from Silver Lake contain undifferentiated sediment as well as lake sediment of the Sylvan Lake Member. Both meltwater stream sediment and lake sediment of the Sylvan Lake Member are relatively high in phosphorus (see fig. 6) and these sediments are probably the source of the phosphorus in the groundwater.

Low-Phosphorus Lakes

Few lakes in the study area exhibit phosphorus concentrations of <0.020 mg/l. For some of these lakes the upgradient groundwater concentrations are also low in phosphorus. Sand Lake, in Barron County, has a total phosphorus concentration of 0.009 to 0.012 mg/l (DNR, 1988 sampling). This lake sits in a tunnel channel cut through undifferentiated sediment of the Sylvan Lake Member. Most groundwater reaching Sand Lake recharges through this unit which has a median "plant available" phosphorus content of 13 lbs/acre (see fig. 6). The well upgradient from Sand Lake had a phosphorus concentration of 0.012 mg/l which fits with low background phosphorus concentrations.

Several lakes formed in the Crex Meadows Formation, specifically Big Sand Lake, Pike Lake, and Sand Lake, all in Burnett County, also have phosphorus values below 0.020 mg/l (DNR, 1988 sampling). The Crex Meadows Formation has a median Bray phosphorus content of 40 lbs/acre which is quite high and seems to conflict with low phosphorus concentrations in the lakes and groundwater. The Crex Meadows Formation, however, has a complex depositional history. The formation contains sediment deposited in glacial Lake Lind as well as sediment deposited much later in glacial Lake Grantsburg. The sediment supplied to glacial Lake Lind was derived from the north, off the Precambrian Shield and these sediments are probably relatively low in phosphorus. Some of the sediment entering glacial Lake Grantsburg was derived from the west and northwest and may be high in phosphorus, while some of the sediment came from the north and presumably is low in phosphorus. The phosphorus content reported in figure 6 is based on 31 samples, the majority of which came from drillholes located on the western end of the Lake Grantsburg basin. It is possible that sediment in the eastern end of the basin, away from the influence of the Grantsburg Sublobe, contains less phosphorus. The three low-phosphorus lakes discussed above are all located near the eastern end of the glacial lake basin.

Lake Chemistries Affected by Lakeshore Development

Several lakes, with relatively dense home development along the shorelines, appear to receive significant phosphorus contributions from those homes. The phosphorus is probably derived from runoff of lawn fertilizers and contributions from septic systems. The clearest examples of lakes impacted by development are those lakes that have low spring phosphorus concentrations and low phosphorus concentrations in upgradient wells, yet summer phosphorus concentrations are quite high. Data from lake feasibility studies and historic lake data help illustrate three such lakes.

Big Round Lake had a spring total phosphorus concentration of 0.017 mg/l (DNR, 1988 sampling), yet the lake, at one point, had a summer total phosphorus concentration of 0.100 mg/l in (DNR, pre-1979 data). A lake feasibility study for Big Round Lake, conducted in 1978, reported an average groundwater phosphorus concentration of 0.026 mg/l based on 47 samples from 18 wells. Bone Lake has had summer phosphorus total concentrations of 0.054 mg/l (DNR, pre-1979 data), the 1988 spring sample indicated phosphorus of 0.008 mg/l (DNR data). Groundwater discharging to Bone Lake has an average of 0.020 mg/l of phosphorus; according to data from the lake feasibility study for which 181 samples were collected from 31 wells. A recent USGS study of Balsam Lake also indicates that lakes receiving low phosphorus groundwater may have high summer lake phosphorus vales. Samples from 11 piezometers upgradient of Balsam Lake averaged 0.014 mg/l phosphorus. Historic lake data indicates that Balsam Lake has had summer phosphorus values as high as 0.032 mg/l (DNR, pre-1979 data). For all of these lakes, low phosphorus concentrations in the groundwater support the idea that the phosphorus entering the lakes in not due to natural or background sources. There are several other lakes for which no groundwater data was collected which exhibit the same pattern of low spring and high summer total phosphorus values. These lakes include Big Blake, Half Moon, and Wapogasset.

Impacts from development are not limited to low phosphorus lakes, however, the seasonal variation in phosphorus values is most easily seen in these lakes. Several lakes with elevated to high spring phosphorus concentrations are also highly developed. Examples include Round and Big Trade Lakes in Burnett County and Big Butternut Lake in Polk County.

PHOSPHORUS PROVINCES

Data on the phosphorus content of geologic materials was combined with information on groundwater flow systems to define general "phosphorus provinces" within the study area. These general provinces can be used as guidelines to estimate the attainable trophic status for lakes within a given area. Five general provinces are shown on figure 26 and outlined below.

Region 1.--A majority of lakes formed in the till and lake sediment of the Trade River Formation have elevated phosphorus values; much of this phosphorus may be due to natural or background levels of phosphorus in the sediments. Both the till and the lake sediments of the Trade River Formation contain elevated levels of "plant available" phosphorus which can be delivered to lakes either by sediment runoff or as dissolved phosphorus in the groundwater. Lakes in the southern portion of the Trade River province, such as Bass Lake, receive minimal groundwater inputs and lake water quality is dominated by the quality of the surface water entering the lake. Lakes to the north, such as Big Trade Lake, receive phosphorus from both groundwater and surface water. The relative contribution of lake phosphorus from surface water versus groundwater is not known.

Region 2.--Lakes in the eastern portion of the area mapped as Crex Meadows Formation generally have phosphorus concentrations below 0.020 mg/l and groundwater samples in the area have similar concentrations. When all samples are considered, the sediment of Crex Meadows Formation is relatively high in phosphorus. However, given the depositional history of the basin, it is possible that sediment on the eastern end of the basin is lower in phosphorus (discussed in "Low-Phosphorus Lakes" section).

Region 3.--This region is defined as the northeast portion of the study area where surface-water elevations are 50 to 200 ft higher than water levels in domestic wells (fig. 26). Two distinct flow systems are present in this area, a shallow upland flow system and a deeper, more regional flow system. The surficial units in this region are mapped as undifferentiated sediment (a mixture of meltwater stream sediment and till) and lake sediment of the Sylvan Lake Member. While the till is relatively low in phosphorus, the meltwater stream sediment has higher phosphorus levels; the Sylvan Lake lake sediments are also high in phosphorus.

Upland lakes in this region receive minimal groundwater input and their phosphorus concentrations are controlled by the surface-water runoff in to the lakes. Some of these lakes, such as Kirby Lake, have elevated phosphorus concentrations. For lakes formed in meltwater stream sediment or lake sediment, some of the phosphorus entering the lake may come from the geologic materials.

Lakes located around the margins of region 3 receive groundwater from the deeper, more regional flow system and these lakes generally have good water quality. Examples include Pipe Lake in Polk County and Sand Lake and Upper Waterman Lake in Barron County.

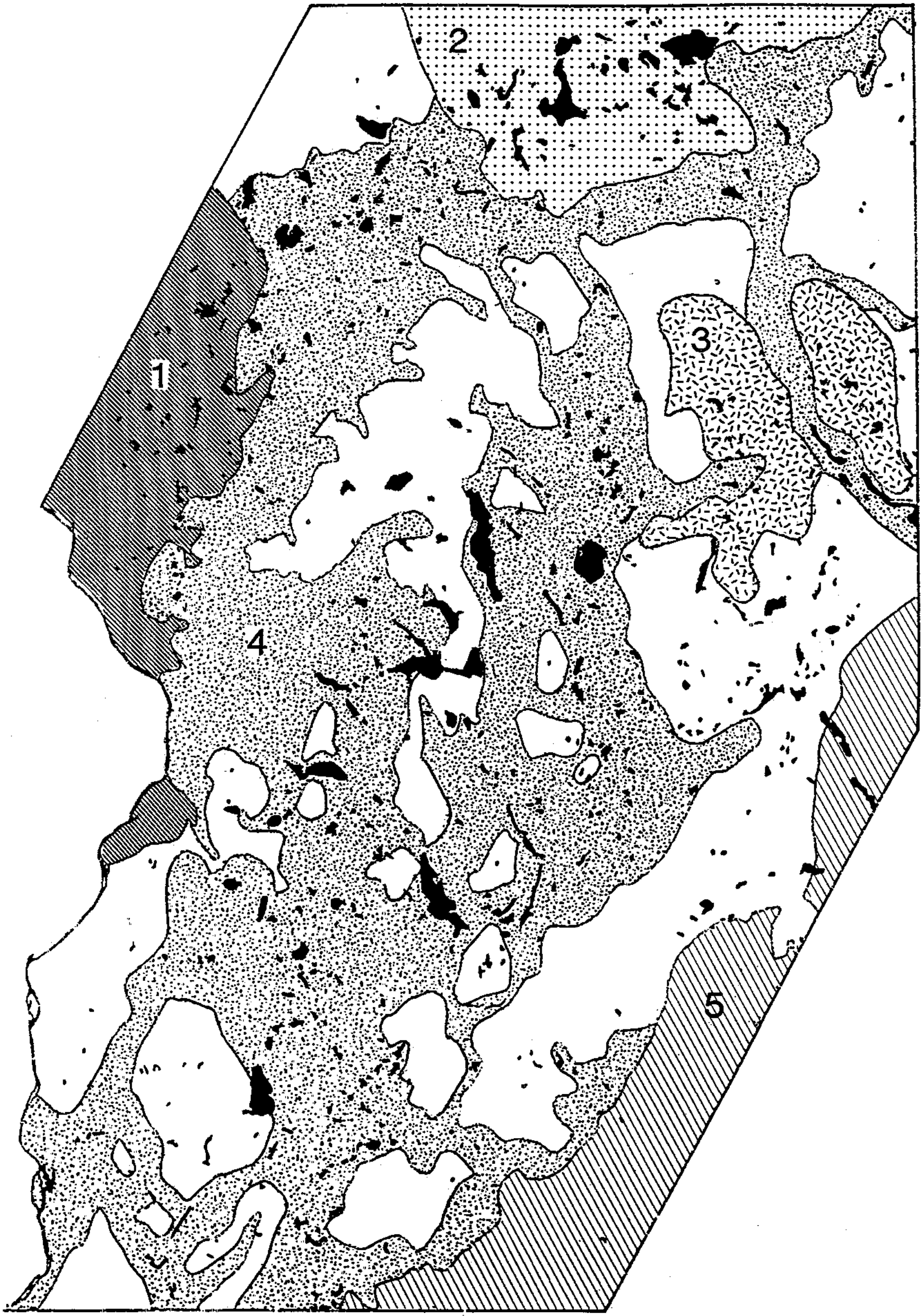


Figure 26. Map of phosphorus provinces within the study area.

Region 4.--A large number of lakes in the study area are formed in meltwater stream sediment of the Sylvan Lake Member; the distribution of this unit defines region 4 (fig. 26). The phosphorus content of the meltwater stream sediment is moderately high, yet lake and groundwater phosphorus concentrations within this region are extremely variable. Phosphorus concentrations in groundwater may be controlled by length of flow path. Groundwater samples from the Waterman Lake study site and from domestic wells near Horse Lake suggest that phosphorus concentrations increase with depth for wells completed in Sylvan Lake meltwater stream sediment. At both sites, the deepest well had phosphorus concentrations in excess of 0.100 mg/l, suggesting that groundwater can dissolve significant amounts of phosphorus from this unit, given long enough travel times.

Hydrogeologic setting must be considered when assessing the potential natural phosphorus contributions to lakes within this region. In the central portion of the study area, the topographically low meltwater stream is flanked to the east and west by topographic highs composed of undifferentiated sediment of the Sylvan Lake Member (see fig. 4). Groundwater tends to flow from these topographically high areas and discharge into lakes formed in the meltwater stream sediment (see fig. 18). Several lakes in this area, specifically Balsam, Bone, Half Moon, Big Round and Big Blake Lakes had spring phosphorus concentrations less than 0.020 mg/l (DNR, 1988 data). Lake feasibility studies for Bone and Big Round Lakes, completed in the 1970's, and a recent USGS study of Balsam Lake indicate that average phosphorus concentrations in groundwater are $\leq$0.025 mg/l (discussed in "Lakes affected by Lakeshore Development").

Groundwater data is also available for the Amery Chain of lakes, located in the southern portion of the study area. Lake feasibility studies indicate that groundwater discharging to Pike Lake, North Twin Lake and South Twin Lake averaged 0.030, 0.035 and 0.032 mg/l. Groundwater entering the lakes from the northeast travels a relatively long flow path (see fig. 18) through meltwater stream sediment of the Sylvan Lake before discharging to the lakes. The longer flow may be responsible for higher phosphorus concentrations in the groundwater.

Region 5.--The area mapped as till of the Poskin Member has few lakes formed in it yet these lakes have somewhat elevated phosphorus values. The Poskin till, deposited by ice flowing from the northwest, has moderately high levels of "plant-available" phosphorus. No domestic wells were sampled in this area and phosphorus concentrations in groundwater are not known. The sediment phosphorus concentration and the presence of lakes with elevated phosphorus concentrations suggest that the Poskin till may contribute natural or background phosphorus to lakes.

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APPENDIX A

Landforms of the Copper Falls Formation*

Hummocks are the most common landform in the county and are composed of outwash (map unit C2sh) or mixtures of outwash, till, mass-movement sediment and lake sediment (unit C2uh). Within map unit C2uh, hummocks are composed solely of till, or solely of outwash, or of mixtures of several types of sediment interbedded with each other. Hummocks formed as a result of the melting out of underlying buried ice. Areas of C2sh represent outwash that was underlain by extensively buried ice; these areas are essentially collapsed outwash plains.

Outwash plains with scattered ice-block depressions are mapped as C2sp. Several separate outwash plains indicate that outwash surfaces were formed as the Superior Lobe retreated, or each outwash plain may reflect a separate advance of the Superior Lobe during overall retreat. Much of the sediment in the outwash plains is horizontally bedded to cross-bedded slightly gravelly sand with most of the sand consisting of pebbles. Adjacent to former ice-margin positions, outwash plains terminate in an outwash head. In these positions, the sediment is gravelly sand to gravel with the gravel consisting of pebbles, cobbles, and boulders with some boulders up to 0.5 m in diameter. Surface slopes on outwash plains are generally to the south.

Ice-walled-lake plains form in topographic lows on the ice; when the ice melts the lake sediments are left as flat plains of sediment. Ice-walled-lake plains are common in the eastern part of the study area, occurring almost entirely within areas mapped as C2uh. The rims of ice-walled-lake plains are composed of beach sediment, outwash, and mass-movement sediment (C2ni) whereas the centers are composed of lacustrine silt (C2oi). Copper Falls till lies beneath the lake-plain sediment.

Streamlined hills are not common in the study area, but characterize some upland surfaces composed of till. These hills indicate ice-flow direction to the southeast, as shown by arrows within map unit C2tn.

Thirteen *tunnel channels* are indicated on Plate 1. Tunnel channels form near the margin of the ice in places where the glacier is frozen to its bed. With frozen bed conditions, subglacial meltwater cannot discharge easily. It builds up under the ice and then catastrophically cuts a subglacial channel and drains. All the tunnel channels in the study area are bounded on their southern end by outwash fans or outwash plains. *Eskers* occur in the central parts of five of the tunnel valleys. Eskers are composed of gravelly sand to gravel. The coarsest fluvial sediment in the study area occurs in eskers. In places, boulders

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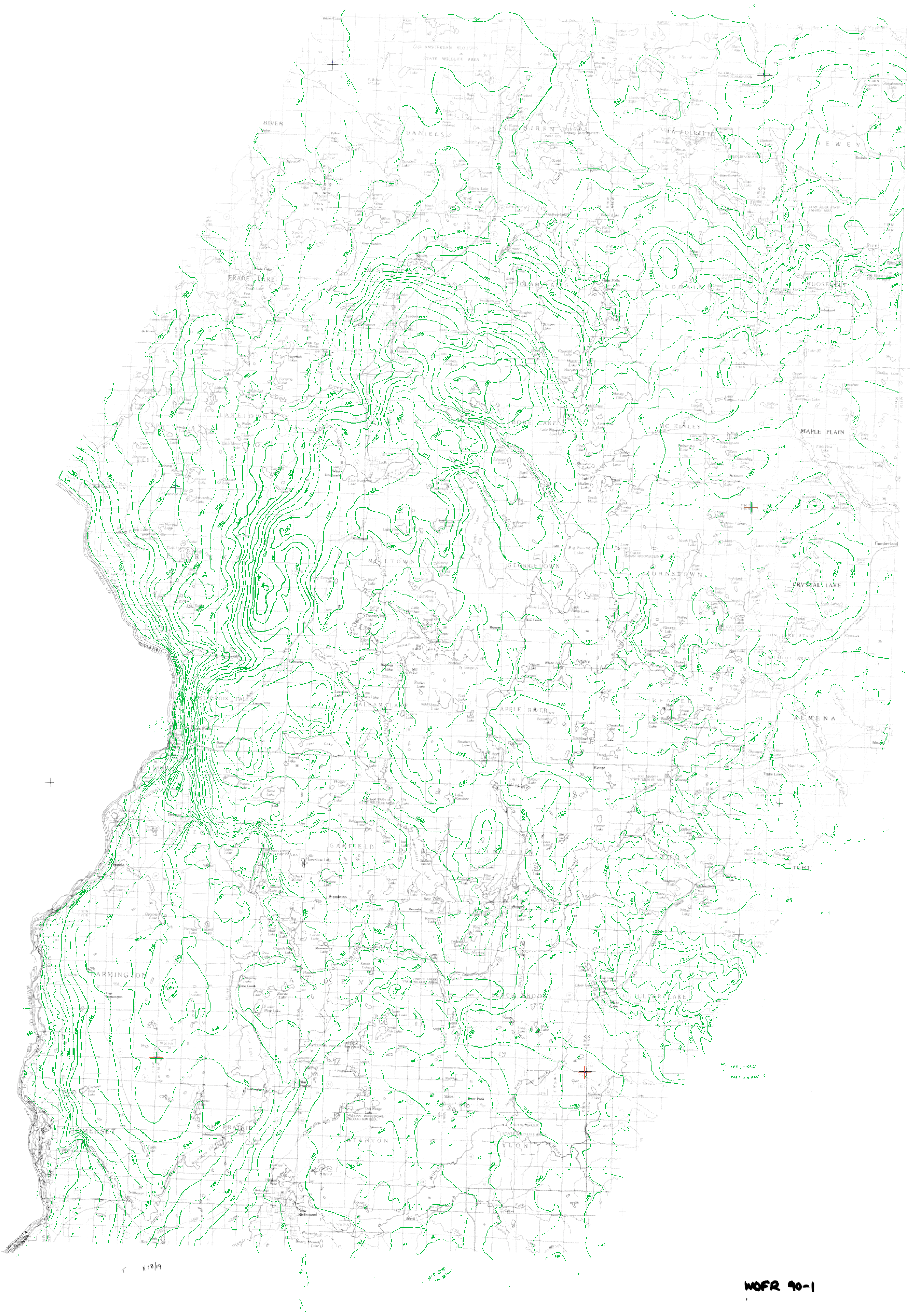
* Map units refer to a preliminary 1:100,000 scale map of Pleistocene geology, on file at the WGNHS.

are up to 1 m in diameter. Several other eskers occur in the study area that are not confined to tunnel valleys.

Isolated *ice-margin ridges* occur in several places in the study area. They are composed of till, mass-movement sediment, and coarse fluvial sediment. Few of these ridges are laterally extensive for more than a kilometer.

Former *ice-margin positions* of the retreating Superior Lobe are indicated by abrupt changes in topography, outwash heads, ice-margin ridges, and coarse fluvial sediment. These ice-margins may represent recessional positions marked during meltback of the glacier, or they may represent re-advances of the Superior Lobe during overall ice retreat. The geomorphic and sedimentological features that suggest the former ice-margin positions are not laterally extensive along a given margin, thus it is difficult to trace isochronal ice-margin positions across the study area.

At least ten different former ice-margin positions are recognized in the study area. The oldest is represented by the southern limit of the Poskin till, just south of the study area. The southern limit of the Sylvan Lake deposits are represented by four or five *en echelon* ice-margin positions. Later ice-margin positions are marked by outwash heads at Range, Balsam Lake, northeast of Big Round Lake, west of Centuria, Frederic, east of Spirit Lake, south of Pokegama Lake, and east of Big Sand Lake.


RIVER
DANIELS
SIREN
LA FOLLETTE
TRADE LAKE
LORAIN
ROOSEVELT
MC KINLEY
MAPLE PLAIN
MILLTOWN
GEORGETOWN
JOHNSTOWN
CRYSTAL LAKE
Cumberland
APPLE RIVER
ALMENA
GARFIELD
FARMINGTON
CLEAR LAKE

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