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TOTAL ALKALINITY OF SURFACE WATERS: A MAP OF THE UPPER MIDWEST REGION

by

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Abstract

This map illustrates the regional patterns of mean annual alkalinity of surface water in the northern portions of Minnesota, Wisconsin, and Michigan. As such, it provides a qualitative graphic overview of the relative potential sensitivity of surface waters to acidic input in the upper midwest portions of the United States. The map is based on data from approximately 14,000 lakes and streams and the apparent spatial associations between these data and macro-scale watershed characteristics that are thought to affect alkalinity.

DISCLAIMER

The information in this document has been funded by the United States Environmental Protection Agency. It has been subjected to Agency review and approved for publication.

A major goal specified in the National Acid Precipitation Assessment Plan (Interagency Task Force on Acid Precipitation, 1982) is the quantification of the extent of sensitivity of the nation's lakes and streams to acidification. Most earlier efforts to determine patterns of surface water sensitivity to acidic deposition have relied on interpretations of bedrock distribution and chemistry (Galloway and Cowling, 1978; Likens et al., 1979; Hendrey et al., 1980; National Atmospheric Deposition Program, 1982). One effort was based on soil sensitivity (McFee, 1980) and another on surficial geology (Shilts, 1981). While each of these contributed to the general knowledge of the extent of surface water sensitivity, they are in sharp disagreement for many portions of the country. More importantly, there is a lack of spatial correlation between the patterns drawn by these efforts and the observed patterns of surface water alkalinity.

Although there is general agreement that surface water alkalinity is directly related to mineral availability, it is apparent that maps of rock type or soil type alone are inadequate to express patterns of mineral availability that are meaningful in terms of surface water sensitivity. For instance, results from several recent studies of patterns of surface water sensitivity in different regions of the United States (Eilers et al., 1983; Haines and Akielaszek, 1983; Twaroski et al., 1984) indicate that no single factor (e.g., bedrock geology) can explain observed patterns of surface water alkalinity. Rather, these studies indicate that one must consider a variety of driving or integrating spatial factors that affect alkalinity such as land use, physiography, and soil type (as well as geology), and that the relative importance of any one, or a particular combination of those factors, may vary within or among regions.

A recent report of the National Academy of Sciences (Environmental Studies Board, 1984) defined several important geochemical and hydrological processes of watersheds that determine whether waters will acidify and the rate at which acidification would proceed. These processes are not yet defined on a regional scale and, therefore, cannot presently be used in a definition of relative sensitivity of regions to acidic deposition.

In light of the above, it is clear that caution must be used in any effort to use a single measure such as alkalinity to assess the sensitivity of surface waters to acidic deposition because the actual response of a given lake or stream is determined by numerous biogeochemical and hydrological factors of the watershed plus chemical processes within water bodies. Alkalinity is certainly the most readily available measure of the acid-neutralizing capacity of surface waters. Although alkalinity measurements do not completely incorporate the influences of all factors into a definition of surface water sensitivity, they do reflect the interactions of biogeochemical and hydrological processes that ultimately influence sensitivity.

With this rationale, we approached the problem of depicting the likely patterns of surface water sensitivity in the conterminous United States by synoptically analyzing spatial patterns of surface water alkalinity as an integrator of the various factors which determine sensitivity. We accomplished this by: (1) assembling available alkalinity data on as many representative surface waters as necessary and/or possible; (2) plotting these data on large-scale maps; and (3) analyzing the patterns of the values of the plotted data for spatial correlations with other characteristics such as land use, geology, and physiography.

A national map compiled earlier (Omernik and Powers, 1983) described the general patterns of surface water alkalinity in the conterminous United States. By comparison, the regional map presented here is based on two orders of magnitude more data (for the Upper Midwest portion of the national map) and depicts the spatial patterns of surface water alkalinity in greater detail and at a greater resolution than was possible in the national map.

The alkalinity ranges of the five map units were chosen to reflect potential sensitivity patterns on a regional scale, as compared with the broader ranges used for the national map. Although it is not possible to define exact break points between sensitive, moderately sensitive, and insensitive waters, it is generally agreed that waters of total alkalinity > 200 ueq/l are relatively insensitive to acidic deposition.

As was the case with the national map, our purpose is to show what range of alkalinity one might expect to find in most of the surface waters most of the time. Relative to the national map, the regional map provides more detailed ancillary information on ranges of conditions, significant apparent regional and local relationships between alkalinity and macro-scale watershed characteristics such as land use and physiography, seasonal variations, and other factors. This information in turn provides a basis for understanding the confidence with which predictions and estimations of potential surface water sensitivity might be made for the region, or parts of the region. We emphasize, however, that the map and the ancillary information are not intended for making precise predictions of sensitivity for individual water bodies or specific locations. Rather, this map and the other regional maps are intended to help fill the urgent need to understand the relative potential sensitivity of surface waters in different parts of the country in order to provide a national perspective of the potential problem, provide rationale for selecting geographic areas for more detailed studies, and allow more accurate regional assessments of acid deposition impacts on aquatic resources.

MAP DEVELOPMENT

The methods used to develop this map were similar to those used to prepare the alkalinity map of the New England and New York Region (Omernik and Kinney, 1985), although the map scales were larger and amount of data used for the Upper Midwest Region was much greater. The alkalinity data were selected and mapped according to several categories, with separate designations given for streams, lakes, and reservoirs, as well as to sites associated with watersheds of less than 260 sq km (100 sq mi). Each data point was scrutinized for representativeness by keeping the watershed size consistent with the relative homogeneity of major watershed features thought to influence surface water alkalinity such as physiography, vegetation type, and land use. In areas of relative heterogeneity, most of the data were associated with small watersheds less than 130 square kilometers. Representative data was imperative for detecting spatial patterns of alkalinity, possible correlations with patterns of other characteristics, and, ultimately, extrapolation of the data. To include non-representative data from sites having large watersheds of widely differing characteristics, or data downstream from major industrial waste discharges, would mask these spatial patterns.

The map of the Upper Midwest Region, similar to the national map and the New England/New York map, was based on patterns of the actual alkalinity values and the apparent spatial associations of these values with aerial characteristics that are believed to be driving or integrating factors affecting alkalinity. Driving factors, as used in this paper, refer to those that are generally believed to directly affect alkalinity (e.g., geology and soils). Integrating factors, on the other hand, are considered those that tend to reflect combinations of driving factors; for example, land use and potential natural vegetation reflect regional combinations (or an integration) of driving factors such as soils, land surface form, climate, and geology. We believe that the importance of each of these factors, and the hierarchy of importance relative to the combinations of factors, varies from one region to another and even within regions. Clarifying these regional factors is a major goal of our overall synoptic analyses.

We acquired alkalinity data from a variety of sources. As expected, uniformity of coverage and temporal consistency was lacking. In general, the amount of data we acquired was a function of its availability and, more importantly, the apparent complexity of regional patterns of alkalinity. In some areas, after gathering and plotting a certain amount of data, the spatial patterns became clear enough so that the addition of more data merely supported the patterns already set. In other areas, more data, and/or analyses at increasingly larger scales, were necessary to distinguish the alkalinity patterns.

The most recent data (1979-1983) for the Upper Midwest Region were obtained from STORET, an EPA computer-based water quality data storage and retrieval system. Data collected by the EPA, the University of Minnesota-Duluth, and the Wisconsin Department of Natural Resources (Glass et al., 1983) and the Minnesota Pollution Control Agency (Twaroski et al., 1983; Thornton et al., 1982; Heiskary and Thornton, 1983) from 1978 to 1983, which had not been entered into STORET at the time of our collection, were also used. These data were plotted on 1:250,000 or 1:500,000-scale topographic maps, with each site represented by a small circle color-coded to an alkalinity class value; the exact value and the water body type were noted beside the circle. From STORET data for the earlier period, 1960 to 1975, 108 lake and stream points (mostly from the early 1970s) were determined to be suitable for our mapping purposes and were plotted on overlays. These three sources yielded approximately 1,648 values (86% from lakes and 14% from streams) in the Upper Midwest Region. Of these values, 56% represented one sample only, 8% were the mean of two samples, and 35% were the mean of three or more samples.

For Michigan and Wisconsin, we relied heavily on earlier (1960 to 1975) data, because of a paucity of more recent data and the relatively complex alkalinity pattern. In Michigan's Upper Peninsula, in addition to 306 points from STORET and Glass et al. (1983), small-scale dot maps from Schneider (1975) showing the distribution of lakes by methyl orange alkalinity class were used to aid in the determination of the areal extent of our alkalinity classes. The patterns of these historical data indicated the location of clusters of lakes with less than 400 ueq/l alkalinity. By superimposing these patterns on our 1:500,000-scale maps containing the more recent alkalinity data, and by noting the apparent relationships of lake type to alkalinity, lake size to alkalinity, lake vs. stream alkalinity, and relevant macro-scale watershed characteristics, we were able to interpolate and estimate areas of specific alkalinity classes. This process was also enhanced by transferring and plotting the data by alkalinity class on 1:250,000-scale topographic maps.

For Wisconsin, an abundance of historical alkalinity data was available from that state's Department of Natural Resources (and one of its predecessor agencies, the Wisconsin Conservation Department) in publications of "Surface Water Resources" by county (Various Authors, 1960-1980). These included maps that showed the alkalinity classification for each lake and stream sampled. For the eighteen-county area delineated in the map inset, alkalinity values were given for about 10,500 lakes and 2,500 stream sites. On these large-scale county maps, lake and stream sites were color-coded according to alkalinity class, and the resultant patterns indicated where boundaries might be drawn. The delineation of our alkalinity classes on the county maps was made after noting lake types, lake sizes, stream courses, and physical features from 1:250,000-scale topographic maps as well as consideration of other driving and integrating factors. In addition, comparisons were made to the spatial patterns of recent alkalinity data plotted on the 1:500,000-scale Wisconsin map, which included 537 lake and stream points from STORET and Glass et al. (1983).

The data for Minnesota used in our mapping were primarily of recent origin. Approximately 805 lake and stream values from STORET and Glass et al. (1983) were plotted on 1:250,000-scale topographic maps by alkalinity class (e.g., 1 = < 50 ueq/l, 2 = 50 to 100 ueq/l, 3 = 100 to 200 ueq/l, etc.). Data listed in Twaroski et al. (1983), Thornton et al. (1982), and Heiskary and Thornton (1983) were checked for any lakes not previously plotted or listed in the STORET or Glass et al. (1983) data sets. An interpretive process similar to that used for Wisconsin and Michigan, considering the relevant driving and integrating factors, was also used for Minnesota. Since the relationship between alkalinity and lake type and lake size is quite different in northeast Minnesota than in other parts of the Upper Midwest Region, the final class boundaries there were based largely on the spatial pattern of the alkalinity data itself, but also with some considerations of bedrock type, land surface form, and land use.

Spatial patterns of the alkalinity values were the most important factor for delineating alkalinity map units throughout the Upper Midwest Region. Land use and vegetation information were also useful, but in a more general way of delineating areas where low alkalinity waters were unlikely. Low alkalinity waters are generally found only in predominantly forested or wetland areas. Wherever agriculture (including grazing) occurs, even as a fairly small portion of the land use mosaic, mean annual alkalinity values are commonly well over 400 ueq/l. Geology maps were used to focus our attention and data collection efforts on areas of suspected sensitive rock types. However, final map unit alignments were nearly always based on patterns of alkalinity values or physiographic features. Locally, physiographic and hydrologic features were extremely helpful for map unit delineations (e.g., where strong associations were apparent between lake type and alkalinity or glacial feature and low alkalinity lake type).

DATA ASSESSMENT

The use of historical alkalinity data raises questions concerning the comparability of older and newer methods of measuring surface water alkalinity. Methodologies vary even among recently collected data. For example, of the recent data (1978-1983) used for the Upper Midwest map, alkalinity values for approximately 46% of the sites were determined using the titration method of Gran (1952), 22% were determined by single endpoint titration (potentiometric) (American Public Health Association, 1980), 11% were determined by double endpoint titration (potentiometric) (American Public Health Association, 1980), and 21% were of unknown methodology. While these recent data were of great importance, especially in Michigan and Minnesota, they only represent about one-tenth of all the data points used. For the entire Upper Midwest data set, including the large amount of historical data from Wisconsin, roughly 88% of the alkalinity values were determined by colorimetric methodologies (usually methyl orange or methyl purple); only 5% were determined using the method of Gran (1952), 3% by single endpoint titration (potentiometric) (American Public Health Association, 1980), 1% by double endpoint titration (potentiometric) (American Public Health Association, 1980), and 3% unknown.

For low alkalinity waters, the most commonly used fixed endpoint procedures (either potentiometric or colorimetric) often yield overestimates of alkalinity (Dillon et al., 1978; Zimmerman and Harvey, 1979-1980; Jeffries and Zimmerman, 1980; National Research Council of Canada, 1981; Henriksen, 1982; Kramer and Tessier, 1982; Church, 1983). Precision may also be significantly less with colorimetric procedures because of uncertainty as to the exact endpoint (Kramer and Tessier, 1982; Church, 1983). In contrast, the double endpoint procedure and the procedure of Gran are unbiased and more precise for low alkalinity waters (Gran, 1982; American Public Health Association, 1980; Church, 1983).

When making our final interpretations of spatial patterns of the data and subsequent map unit delineations, we attempted to compensate for the probable bias introduced by selected analytical procedures. If actual endpoint pH values of the titrations had been known, then quantitative procedures might have been applied to correct for bias (National Research Council of Canada, 1981; Henriksen, 1982; Kramer and Tessier, 1982; Church, 1983), but because of the lack of such information, adjustments were not possible. However, a comparison of values for a large group of lakes in northern Wisconsin where we obtained recent values determined by Gran's titration, as well as earlier values determined by colorimetric endpoint, indicated a pattern of overestimation by the colorimetric methods of about 30 or 60 ueq/l, depending on the particular colorimetric method used (Figure 1). Haines and Akielaszek (1983) found a similar overestimation (32 ueq/l) in their comparisons of values for a set of New England lakes. Based on these comparisons, we adjusted the earlier Wisconsin data by subtracting 30 ueq/l (if methyl orange) or 60 ueq/l (if methyl purple) when we color-coded the county maps. Elsewhere in the Upper Midwest where representative sites had borderline or slightly above borderline values between alkalinity classes (e.g., 50, 100, 200, and 400 ueq/l) and where the alkalinity methods had been other than double endpoint or Gran's titration, we assigned the respective areas to the lower alkalinity class and drew the map units accordingly. However, in many cases the compensation may not have been

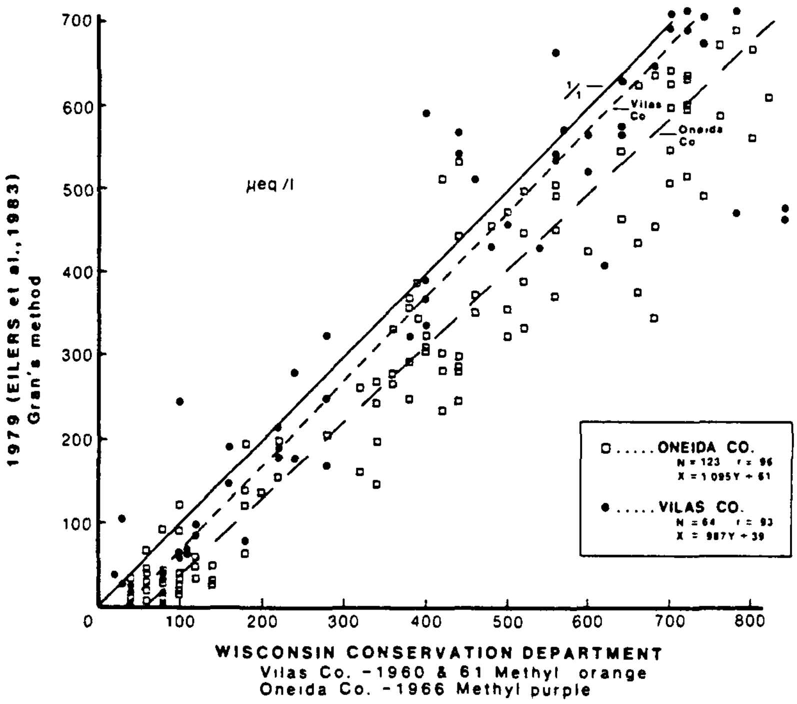

Figure 1. Single sample alkalinity values from two time periods for lakes in Vilas and Oneida counties, Wisconsin. Source: Andrews and Threinen (1966), Black et al. (1963), Depository of Unpublished Data.

enough to account for the bias due to methodology as suggested in the sources cited above. Hence, the areas in the lower alkalinity classes may actually be slightly larger than is shown; e.g., the actual areas shown as map unit #1 (< 50 ueq/l) may include some of the adjacent areas shown as map unit #2 (50 to 100 ueq/l), the areas shown as map unit #2 may include some of the adjacent areas shown as map unit #3, etc.

Another area of concern is the use of single sample values as representative data points. Since the alkalinity of surface waters can fluctuate on a daily, weekly, monthly, and annual basis, a single sample from a water body may not seem to be representative of that lake or stream's average alkalinity. We believe, however, that for the purposes of this map, one-sample data points are sufficiently representative to be used in the assessment of spatial patterns and delineation of the alkalinity class boundaries. The comparison of alkalinity values for northern Wisconsin lakes determined using different laboratory methods and taken during different time periods (Figure 1) also serves as an illustration of the usefulness of single sample values for our purposes.

SEASONAL VARIATION

Surface water alkalinity of lakes and streams is subject to seasonal and annual fluctuations due partially to climatic, meteorologic, and related hydrologic events. Seasonal variations of alkalinity concentrations in the Upper Midwest Region appear to have distinct patterns, due especially to runoff from spring snowmelt.

Recent data showing complete month by month and seasonal trends for surface water alkalinity in the Upper Midwest Region are scarce for lakes and for streams with small watersheds. However, analysis of thirty-one stream sites across the region with long-term monthly data showed an annual pattern of higher alkalinity values in winter; a rapid drop in spring, with the lowest alkalinity values occurring in April; and then another rise with a peak in August (Figure 2). Although this pattern is based on data from mostly higher alkalinity streams, some with very large watersheds, a similar seasonal pattern seemed to occur in most streams throughout the region regardless of alkalinity level or watershed size. For the forty-one year-long data sets, the average difference between the low value month and the mean annual value of each sampled stream was 52% (range 14-87%; median 55; standard deviation 14.8%). Watershed and hydrological characteristics vary greatly from stream to stream, of course, and have different influences on seasonal alkalinity trends. Thornton et al. (1982) found that streams in Minnesota which are highly dependent on runoff tend to have greater fluctuations in flow and greater fluctuations in stream chemistry, while streams with large surface water storage areas will have lesser fluctuations in flow and small fluctuations in stream chemistry.

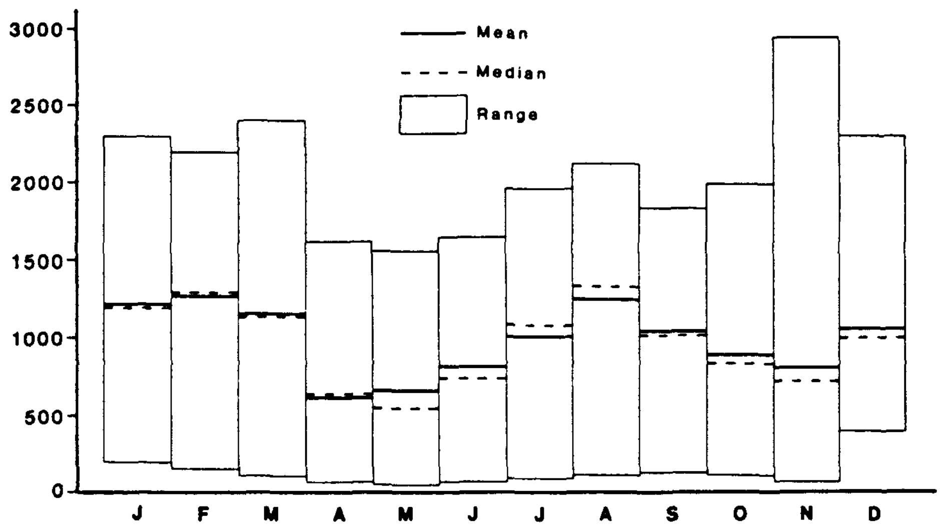

Figure 2. Seasonal variations in alkalinity (ueq/l) at thirty-one stream sites in the Upper Midwest Region (twenty-two in Minnesota, four in Michigan, and five in Wisconsin). Forty-one year-long data sets are represented. Source: STORET 1979-1981.

Declines in alkalinity concentrations during spring snowmelt and in conjunction with precipitation events can be dramatic for streams, but for lakes the seasonal fluctuations appear to be less extreme. Low alkalinity lakes also appear to have lower spring values, but the data are too limited to adequately assess seasonal fluctuations and trends. Most of the low alkalinity lakes are represented by only one or a few alkalinity samples per year. A comparison of spring, summer, and fall alkalinity values for twelve northern Minnesota lakes revealed that, on the average, the spring alkalinities were only 14% lower than the mean values (Heiskary and Thornton, 1983). A greater percentage difference might have resulted had values of the lowest month only (April or May) been compared to mean annual values that included higher winter values as well. However, from our synoptic analyses of alkalinity values from thousands of lakes in the Upper Midwest, seasonal fluctuations do not appear to vary greatly outside the range of values in the classes designated on our alkalinity map.

REGIONAL PATTERNS

The Upper Midwest Region exhibits great diversity and spatial heterogeneity in its patterns of surface water alkalinity. Several factors contribute to the complexity of these patterns, especially lake types, sizes, and their hydrologic characteristics; bedrock geology; land surface forms; and soil characteristics. The formation of these lakes, surface features, and soils reflect the region's glacial history. As a result of glacial action, this region contains one of the densest concentration of lakes in the world.

While nearly all of the streams and a great majority of the lakes in the Upper Midwest Region have high mean annual alkalinity values (> 400 ueq/l), there are several areas where a considerable number of lakes have low alkalinity values (< 50 ueq/l). Although relatively large in number, the lakes in the lowest alkalinity class tend to be small in size and comprise only a small percent of the region's total surface water area (Table 1). The lakes of average alkalinity values < 200 ueq/l comprise only 6.6% of the region's surface water area. Clusters of lakes with alkalinities < 50 ueq/l are found in portions of Vilas, Oneida, Lincoln, and Langlade counties of Wisconsin, as well as Gogebic, Iron, Alger, and Chippewa counties of Michigan.

The map depicts generalized patterns of surface water alkalinity and is intended to show the range of values within which one might expect the mean annual alkalinities for <u>most</u> of the surface waters for each classified area.

Table 1. Area (hectares) in lakes by alkalinity class.*

Alkalinity Class	Wisconsin	Minnesota	Michigan	Total
< 50 ueq/l	6,400	0	1,686	8,086 (0.4%)
50 - 100	5,595	13,982	1,426	21,003 (1.1%)
100 - 200	17,843	68,423	8,948	95,214 (5.1%)
< 200	29,838	82,405	12,060	124,303 (6.6%)

Total lake area in the Upper Midwest Region (Northern Wisconsin, Northeastern Minnesota, and Northern Michigan) 1,868,799 hectares

* Lakes > 6 hectares (15 acres). Based on extent of surface water appearing on 1:250,000-scale USGS topographic maps.

Although some areas are predominantly of low surface water alkalinity, other areas are characterized by wide ranges in alkalinity and contain various lake sizes and lake types that are in close proximity to one another. Thus, care should be taken in interpreting the mapped patterns. Even in areas classified as containing waters of predominantly > 400 ueq/l, there may be a few lakes, but probably no streams, that are of low alkalinity.

Examination of the physical and chemical characteristics of streams and lakes suggests three loosely delineated subregions within the Upper Midwest Region. Distinctions can be made between: (1) most of northern Wisconsin and east central Minnesota; (2) northeast Minnesota comprising Cook, Lake, and St. Louis counties; and (3) the major portion of Michigan's Upper Peninsula and the northern portions of Bayfield, Ashland, and Iron counties in Wisconsin (Figure 3). These subregions, while individually containing variations in surface water alkalinity, can be broadly differentiated by certain physical characteristics that influence the alkalinity patterns. Factors that directly affect alkalinity such as geology, land surface form, and soils, show subtle variations in the different subregions. Integrating factors such as potential natural vegetation, or especially land use, which generally correlated with alkalinity in some other parts of the nation (Omernik and Powers, 1983), were of less significance for determining alkalinity patterns in the Upper Midwest Region.

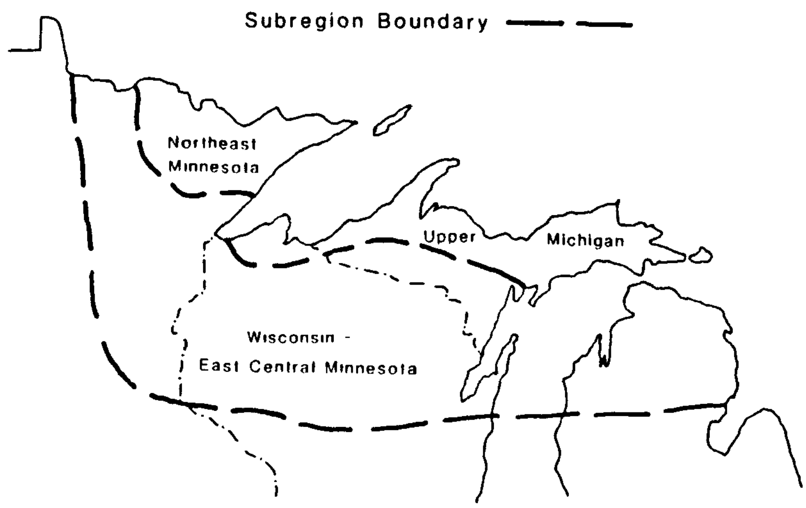

Figure 3. Subregions of the Upper Midwest Region.

Wisconsin-East Central Minnesota

In the northern Wisconsin-east central Minnesota subregion, the differences in lake types [without inlets or outlets (Type A), with inlets or outlets (Type B), spring-fed, acid bog, alkaline bog], and the large number of lakes of each type, contribute to the extreme heterogeneity of surface water alkalinity. While most of the lakes without inlets or outlets are of low alkalinity, the streams, spring-fed lakes, and lakes with inlets or outlets are generally of high alkalinity. The continental glaciation left a relatively thick layer of glacial drift over this part of the Upper Midwest, and most of the lakes occur in pitted outwash and end moraines. These lakes are usually situated well above bedrock and are relatively shallow. For example, in Oneida County, Wisconsin, 88% of the lakes are less than 7.6 meters deep (Andrews and Threinen, 1966). Apparently, for much of this subregion, bedrock has very little influence on lake chemistry and lake morphology.

The major land forms in this subregion include outwash plains, ground moraines, end moraines, lacustrine plains, and drumlins. In the Minnesota portion, in particular Carlton, Crow Wing, and Itasca counties, Twaroski et al. (1984) concluded that lake forms seem to exert a greater influence on lake chemistry and lake morphology than does bedrock. They found that, based on slope and soils, moraine areas are most likely to contain low alkalinity lakes. These lakes are generally small, with no inlets; are located in interfluvial areas; are surrounded by steep slopes and soils that create a quick release of water to the lake; and receive no groundwater inflow (Twaroski et al., 1984). While they found that lakes tended to have high alkalinities in outwash plains in east central Minnesota, many of those portions of Wisconsin within our map unit #1 (< 50 ueq/l) and map unit #2 (50-100 ueq/l) are found in outwash plains and in end moraines. The general difference between moraines or outwash plains appears to be of less significance than more specific factors that influence lake alkalinity in this subregion. Of more importance seem to be groundwater contact, lake size, watershed size, stream inflow and outflow, as well as the texture and mineralogy of the soil and the local relief. High alkalinity lakes tend to be large, with significant inlets and outlets, with large watersheds, and with substantial groundwater contact. A key factor affecting the alkalinity of lakes in this subregion is hydrology, or the route and residence time of water in the watershed (Eilers et al., 1983; Twaroski et al., 1984). The relationship of groundwater to lakes is of major importance and helps to explain why high alkalinity lakes are found in close proximity to low alkalinity lakes, but it is the least known aspect of lake hydrology (Winters, 1977).

Several areas of surface waters with mean annual alkalinity < 50 ueq/l are found in this subregion, centered around Vilas and Oneida counties, Wisconsin. Including all of the low alkalinity areas in Wisconsin, as well as the area in southern Gogebic and Iron counties, Michigan, this subregion has roughly 7,250 hectares of lakes (> 6 hectares) that fall within the map unit #1 boundaries. These areas predominantly contain clusters of low alkalinity lakes without inlets or outlets (Type A). Although the number of lakes in these areas is generally large, the total area of surface water is relatively low since Type A lakes tend to be small in size. For example, of the 1,327 lakes in Vilas County, Wisconsin, 776 (59%) are Type A lakes of less than eight hectares in size, but these account for only 4% of the county's lake area (Table 2). On the other hand, only 88 (7%) of the lakes in the county are Type B lakes or spring lakes greater than 80 hectares, yet these types comprise 63% of the county's lake area. Thus, for Vilas County, the greatest extent of lake area is in the higher alkalinity classes, and the average (uncorrected methyl orange) alkalinity of 298 ueq/l (Black et al., 1963) is skewed downward by the large number of low alkalinity but small Type A lakes.

Table 2. Characteristics of lakes in Vilas County, Wisconsin. Alkalinity values were determined by single endpoint titration (colorimetric -- methyl orange) and, although reported in mg/l, have been converted to ueq/l in the table. Source: Black et al. (1963).

Size Class	Lake Type A (Without inlets or outlets)					Lake Type B (With inlets or outlets)					Spring Lakes				
Hectares	#	Mean Size (ha)	Total Hectares	Sampled lakes: Mean Alk	Sampled lakes: #	#	Mean Size (ha.)	Total Hectares	Sampled lakes: Mean Alk.	Sampled lakes: #	#	Mean Size (ha.)	Total Hectares	Sampled lakes: Mean Alk.	Sampled lakes: #
0-7	776	2.0	1554 (4%)	174	493	31	2.3	72 -	449	23	97	1.6	158 -	693	27
8-23	145	13.6	1969 (5%)	136	145	24	15.1	362 (1%)	546	22	13	15.6	203 -	626	12
24-39	35	31.1	1089 (3%)	172	35	19	30.6	581 (2%)	640	19	12	32.3	388 (1%)	988	8
40-80	32	55.2	1767 (5%)	158	31	27	58.3	1574 (4%)	678	27	8	60.9	487 (1%)	772	8
81-201	13	117.2	1523 (4%)	386	12	38	127.8	4858 (13%)	756	38	9	108.5	977 (3%)	902	9
202-404	6	285.9	1716 (5%)	332	6	26	286.9	7461 (20%)	762	26	2	210.6	421 (1%)	720	2
405-808	1	–	582 (1%)	40	1	9	504.4	4540 (12%)	830	9	–	–	–	–	–
809	–	–	–	–	–	4	1299.6	5198 (14%)	700	4	–	–	–	–	–
Total	1008	10.1	10,200 (27%)	170	723	178	138.5	24,646 (66%)	664	168	141	18.7	2,634 (7%)	755	66

Streams comprise a very small fraction of the surface water area in much of this subregion, and stream alkalinity is, on the average, much higher than that found in lakes. In Vilas County, Wisconsin, streams comprise only 1.4% of that county's total surface water area, and most streams are small, reflecting the general headwater location of the county. The mean methyl orange alkalinity (uncorrected) for the 151 streams in Vilas County was about 794 ueq/l, with a range of 130 to 1840 ueq/l (Black et al., 1963). Only 14 streams (9%) were determined to have alkalinities < 400 ueq/l, and only 5 streams (3%) had alkalinity values < 200 ueq/l. For much of this subregion, stream alkalinity often appears to be twice as high as the mean alkalinity values of nearby lakes. In general, streams have higher alkalinity than lakes as a result of having larger drainage areas and greater contact with buffering materials.

The largest area of lakes with alkalinities < 50 ueq/l is located in Oneida County, Wisconsin, and contains 109 named Type A lakes ranging from 0.8 hectares to 425 hectares in size. The mean size of these 109 lakes is 27 hectares, and the median size is 12 hectares. Most of this area occurs in a pitted glacial outwash plain, with sandy acidic soils of low fertility that typify much of Oneida County. Frequency distributions for recent and historical data sets of thirty-seven representative lakes in this map unit #1 area give a general idea of: (1) the proportion of lakes within the lowest map unit areas of this subregion that have mean annual alkalinity values within the < 50 ueq/l range; (2) the proportion that have higher values; and (3) some notion of central tendency. These frequency distributions also illustrate the differences in alkalinity values due to the different methodologies, and support our adjustment of 60 ueq/l for the data determined by the colorimetric methyl purple methodology (Figure 4). In this comparison, 58 ueq/l was the difference between the mean of the methyl purple alkalinity data and the mean of the data determined by Gran's titration.

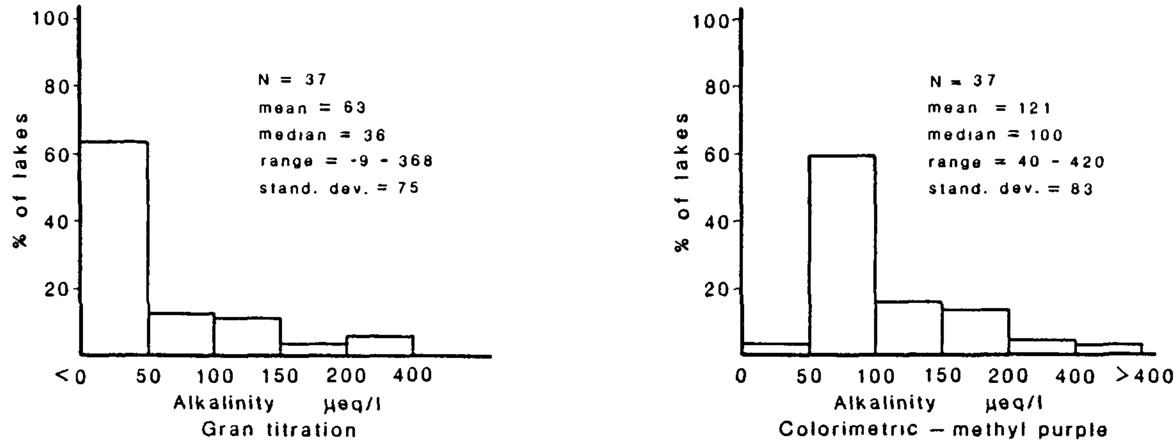

Figure 4. Frequency distributions of thirty-seven representative lakes in an Oneida County, Wisconsin, map unit #1 area. Source: Glass et al. (1983), Andrews and Threinen (1966).

Northeast Minnesota

The northeast Minnesota subregion includes Cook, Lake, and northeastern St. Louis counties, and exhibits considerably more homogeneity in surface water alkalinity than the other subregions. Lakes of various types and sizes, as well as streams, tend to have more similar alkalinity values. The processes of glacial erosion and glacial deposition produced an extremely high density of lakes and extent of area in lakes in this subregion.

A wide variety of bedrock types is found in this subregion, and because the soil and glacial till are relatively shallow, bedrock appears to have a greater influence on lake morphology and lake chemistry. In general, the gabbros, granites, and iron formations contain lakes with relatively lower mean alkalinity values, mostly less than 200 ueq/l (Twaroski et al., 1984). These formations are non-calcareous and resistant to weathering, with thin overlying soils that provide little buffering capacity to the lakes. The slates and greenstone formations contain lakes of higher alkalinity, mostly 400 ueq/l or greater, and, although generally non-calcareous, have some veins of calcite that may greatly influence lake sensitivity (Heiskary and Thornton, 1983). Some calcareous soils are found in the Ely greenstone northeast of Ely, as well as in the large area west of St. Louis County that corresponds to deposits from glacial Lake Agassiz. In addition, the slates and greenstone have faults and fractures which may supply groundwater to these areas of higher alkalinity (Twaroski et al., 1984). For most of this subregion, however, groundwater resources are very limited due to the shallow drift and Precambrian crystalline bedrock types and do not affect alkalinity as in Wisconsin or central Minnesota.

A considerable extent of map unit #2 alkalinity (50-100 ueq/l) occurs in the extreme northeastern part of Minnesota. We estimate that approximately 14,000 hectares in lakes fall within the three areas designated as map unit #2 (of lakes greater than 6 hectares). These three areas are based on data from forty lakes, and were delineated primarily by noting the spatial pattern of these values as well as surrounding lake alkalinity values. Approximately 70% of these forty lakes have alkalinity values less than 100 ueq/l (Figure 5).

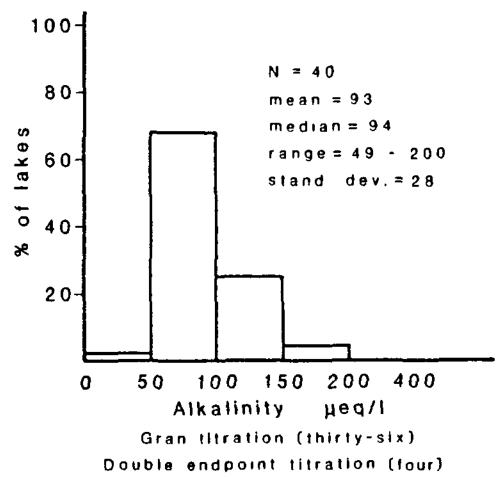

Figure 5. Frequency distribution of Minnesota lakes in areas shown by map unit #2 (50-100 ueq/l). Source: Glass et al. (1983) and STORET 1980-1981.

Alkalinity values within each of our four classes appear to be independent of lake type and lake size in the northeast Minnesota subregion. Whereas we found that the larger lakes tended to be of higher alkalinity in Wisconsin, Heiskary and Thornton (1983) showed no significant correlation between lake surface area and alkalinity in their northeast Minnesota study area. A mix of lakes with inlets and outlets, with outlets but not inlets, and without inlets or outlets are found in our map unit #2 areas (50-100 ueq/l), and for thirty-two of the forty lakes sampled, the sizes ranged from 8 hectares to 1,255 hectares. The mean lake size was 242 hectares. The median size was 156 hectares, and the standard deviation was 272.

The two smaller areas classified in the 50-100 ueq/l alkalinity range class on our map are located on the Duluth gabbro bedrock, which Heiskary and Thornton (1983) showed to have the lowest mean alkalinity of the various "bedrock geoprovinces" in the northeast subregion. The third 50-100 ueq/l class area is located on the Algoman granite bedrock, another non-calcareous area where surface water alkalinity is generally low. In northeast Minnesota, soil and glacial till are very shallow, and there appears to be some correlation between alkalinity and bedrock type, although variations exist within each bedrock geoprovince. Small amounts of limestone, veins of calcite, or ancient glacial lake deposits may increase the buffering of otherwise sensitive bedrock. We found that for most of the Upper Midwest Region, bedrock by itself was not a good indicator of surface water alkalinity.

Upper Michigan

The third subregion -- most of the Upper Peninsula of Michigan, and the extreme northwest portion of Wisconsin in Bayfield, Ashland, and Iron counties -- is physically more heterogeneous, with fewer lakes than the other subregions, and wide variations in surface water alkalinity. Most of the lakes occur in glacial outwash plains and moraines, although a few are found on bedrock outcrops and on ancient lacustrine deposits.

The eastern part of the peninsula varies from smooth plains to irregular plains with hills. This area is characterized by sandy and silty surficial features from the predominant ancient glacial lake bed deposits, with a mixture of alkalinity values. In the southeast part of the peninsula, some lakes are located on bedrock, but the presence of limestone results in high surface water alkalinities. The areas of lowest surface water alkalinity appear to be located in areas of glacial till, and the chemical and physical nature of this till, along with the amount of groundwater contact, drainage basin size, and lake type, greatly influence the degree of buffering capacity. The streams and lakes in these lower alkalinity areas are also located in the uppermost reaches of the watersheds, where topographic watersheds are even roughly definable. [Surface and subsurface watersheds frequently are difficult or impossible to define, particularly in areas of continental glacial topography (Hughes and Omernik, 1981)]. Many of the low alkalinity lakes are without outlets. For the two areas within map unit #1 (< 50 ueq/l) in the eastern portion of the Upper Peninsula there are recent alkalinity values for four lakes and two streams (Table 3).

In the western half of the Upper Peninsula, most of the lakes occur in glacial till, and, as in Wisconsin, alkalinity values appear especially related to lake and watershed size, lake type, and the amount of groundwater contact.

Table 3. Alkalinity (ueq/l) values in map unit #1 in the Upper Michigan Subregion. Source: Glass et al. (1983). Methodology: Gran titration.

Mean:	-2.7 ueq/l
Median:	-8.0
Range:	-36 to 34
Standard Deviation:	29
List of Values:	-36, -27, -15, -1, 29, 34

A few lakes are located on bedrock in Baraga and Marquette counties, and these tend to be moderately low in alkalinity (100-200 ueq/l).

Summary

Our map of total alkalinity of surface waters in the Upper Midwest Region of the United States illustrates the general patterns of the relative potential sensitivity of surface waters to acidic input in that region. The map was developed through analysis of the spatial patterns of alkalinity values from over 14,000 representative lakes and streams, as well as through determination of apparent spatial associations between these data and various watershed characteristics believed to be causal. We found alkalinity patterns in the region to be extremely varied and complex. Many lakes in the region have relatively low alkalinities, but they tend to be small in size, comprise a small percent of surface water area, and occur in relatively small clusters. Most streams exhibit high alkalinities. In northeastern Minnesota, however, there are areas of relatively low alkalinity in which all lakes regardless of size, and even streams, have similar values.

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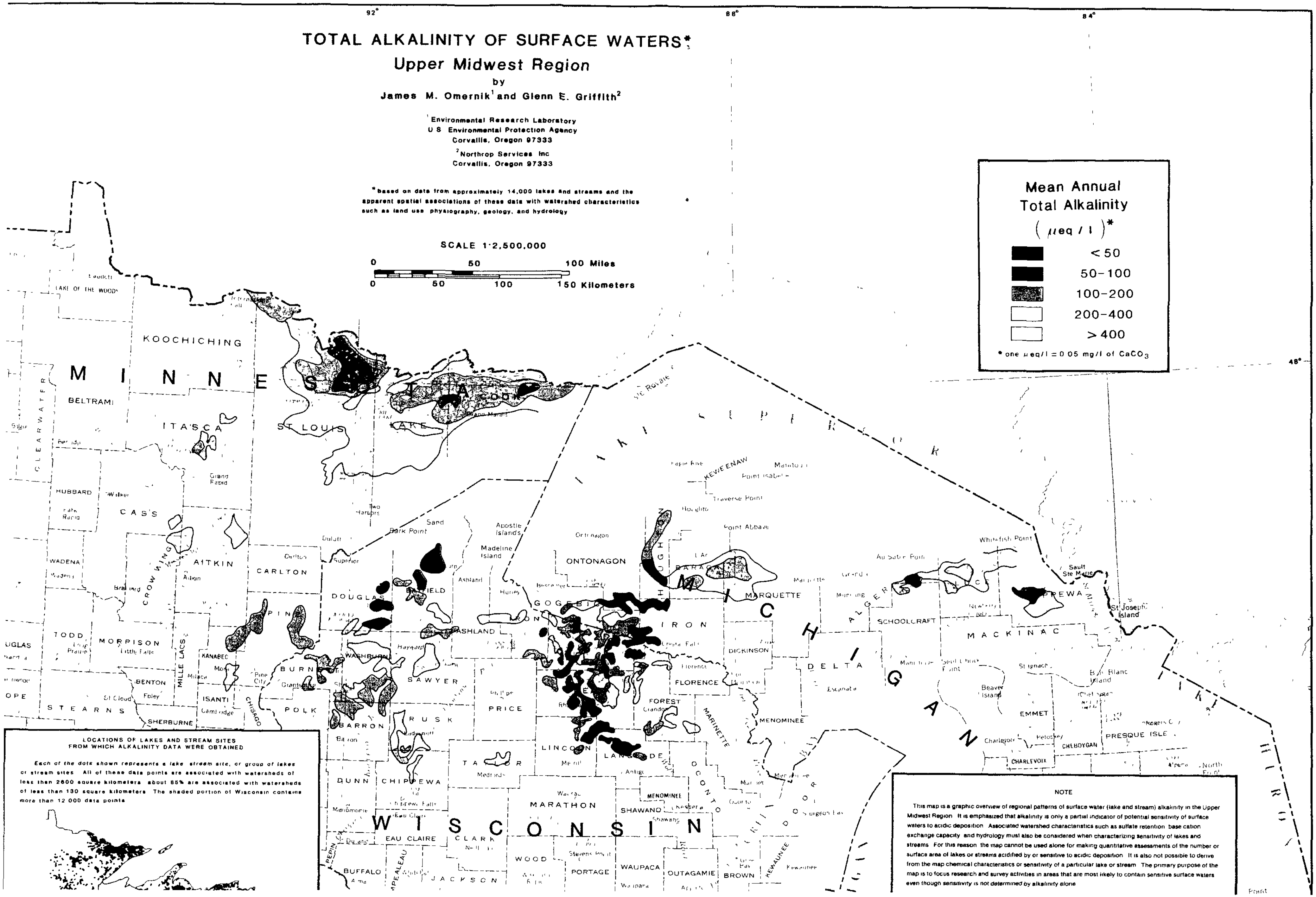
TOTAL ALKALINITY OF SURFACE WATERS*
Upper Midwest Region
by
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*based on data from approximately 14,000 lakes and streams and the apparent spatial associations of these data with watershed characteristics such as land use physiography, geology, and hydrology
SCALE 1:2,500,000
0 50 100 Miles
0 50 100 150 Kilometers
Mean Annual Total Alkalinity (μeq/l)*
<50
50-100
100-200
200-400
>400
* one μeq/l = 0.05 mg/l of CaCO3
92°
88°
84°
48°
MINNESOTA
WISCONSIN
MICHIGAN
LAKE SUPERIOR
KOOCHICHING
BELTRAMI
ITASCA
ST LOUIS
LAKE
COOK
CLEARWATER
HUBBARD
CASS
WADENA
CROW WING
AITKIN
CARLTON
TODD
MORRISON
MILLE LACS
KANABEC
PINE
BENTON
STEARNS
SHERBURNE
ISANTI
CHISAGO
DOUGLAS
BAYFIELD
ASHLAND
BURNETT
WASHBURN
SAWYER
POLK
BARRON
RUSK
PRICE
IRON
VILAS
ONEIDA
GOGEBIC
ONTONAGON
HOUGHTON
KEWEENAW
BARAGA
MARQUETTE
ALGER
SCHOOLCRAFT
LUCE
CHIPPEWA
MACKINAC
DICKINSON
FLORENCE
FOREST
LINCOLN
LANGLADE
TAYLOR
MARINETTE
MENOMINEE
DELTA
EMMET
CHARLEVOIX
CHEBOYGAN
PRESQUE ISLE
DUNN
CHIPPEWA
EAU CLAIRE
CLARK
MARATHON
SHAWANO
OCONTO
WOOD
PORTAGE
WAUPACA
OUTAGAMIE
BROWN
KEWAUNEE
DOOR
BUFFALO
JACKSON
Duluth
Superior
Sand
Bark Point
Two Harbors
Apostle Islands
Madeline Island
Ashland
Isle Royale
Point Abbaye
Traverse Point
Whitefish Point
Au Sable Point
Sault Ste Marie
St Joseph Island
Beaver Island
Grand Rapids
Brainerd
St Cloud
Escanaba
LOCATIONS OF LAKES AND STREAM SITES FROM WHICH ALKALINITY DATA WERE OBTAINED
Each of the dots shown represents a lake, stream site, or group of lakes or stream sites. All of these data points are associated with watersheds of less than 2600 square kilometers, about 85% are associated with watersheds of less than 130 square kilometers. The shaded portion of Wisconsin contains more than 12 000 data points
NOTE
This map is a graphic overview of regional patterns of surface water (lake and stream) alkalinity in the Upper Midwest Region. It is emphasized that alkalinity is only a partial indicator of potential sensitivity of surface waters to acidic deposition. Associated watershed characteristics such as sulfate retention, base cation exchange capacity, and hydrology must also be considered when characterizing sensitivity of lakes and streams. For this reason the map cannot be used alone for making quantitative assessments of the number or surface area of lakes or streams acidified by or sensitive to acidic deposition. It is also not possible to derive from the map chemical characteristics or sensitivity of a particular lake or stream. The primary purpose of the map is to focus research and survey activities in areas that are most likely to contain sensitive surface waters even though sensitivity is not determined by alkalinity alone