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Geography of Alaska Lake Districts: Identification, Description, and Analysis of Lake-Rich Regions of a Diverse and Dynamic State

Scientific Investigations Report 2008–5215

U.S. Department of the Interior
U.S. Geological Survey

Cover: Photograph of lakes and land in the Minchumina Lake District in Denali National Park and Preserve, Alaska. (Photograph taken by Chris Arp, U.S. Geological Survey Research Ecologist, 2008.)

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Conversion Factors

Multiply	By	To obtain
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
square kilometer (km^2)	0.3861	square mile (mi^2)
hectare (ha)	0.003861	square mile (mi^2)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32.$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8.$$

Datums

Vertical coordinate information is referenced to the, North American Vertical Datum of 1988 (NAVD 88). Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83). Altitude, as used in this report, refers to distance above the vertical datum.

Acronyms

ECA	external contributing area
DEM	digital elevation models
dL	lake density
DNR	Department of Natural Resources
GLWD	Global Lakes and Wetlands Database
GIS	geographic information systems
HI	hypsometric index
HUC	hydrologic unit code
LR	limnetic ratio
LTER	long-term ecological research stations
NHD	National Hydrography Dataset
PCA	principal components analysis
USGS	U.S. Geological Survey
WDC	World Digital Chart

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Abstract

Lakes are abundant landforms and important ecosystems in Alaska, but are unevenly distributed on the landscape with expansive lake-poor regions and several lake-rich regions. Such lake-rich areas are termed lake districts and have landscape characteristics that can be considered distinctive in similar respects to mountain ranges. In this report, we explore the nature of lake-rich areas by quantitatively identifying Alaska's lake districts, describing and comparing their physical characteristics, and analyzing how Alaska lake districts are naturally organized and correspond to climatic and geophysical characteristics, as well as studied and managed by people.

We use a digital dataset (National Hydrography Dataset) of lakes greater than 1 hectare, which includes 409,040 individual lakes and represents 3.3 percent of the land-surface area of Alaska. The selection criteria we used to identify lake districts were (1) a lake area (termed limnetic ratio, in percent) greater than the mean for the State, and (2) a lake density (number of lakes per unit area) greater than the mean for the State using a pixel size scaled to the area of interest and number of lakes in the census. Pixels meeting these criteria were grouped and delineated and all groups greater than 1,000 square kilometers were identified as Alaska's lake districts. These lake districts were described according to lake size-frequency metrics, elevation distributions, geology, climate, and ecoregions to better understand their similarities and differences. We also looked at where lake research and relevant ecological monitoring has occurred in Alaska relative to lake districts and how lake district lands and waters are currently managed.

We identified and delineated 20 lake districts in Alaska representing 16 percent of the State, but including 65 percent of lakes and 75 percent of lake area. The largest lake districts identified are the Yukon-Kuskokwim Delta, Arctic Coastal Plain, and Iliamna lake districts with high limnetic ratios of 19, 17, and 21 percent, respectively. The three smallest districts we considered were Tetlin in the eastern interior, Menhiskof on the Alaska Peninsula, and Matanuska–Susitna at the head of Cook Inlet with limnetic ratios of 14, 9, and 9 percent, respectively. Lake density and limnetic ratio were poorly related among lake districts, such that some districts had a few large lakes like Iliamna with Lakes Iliamna and Becharof—the two largest in the State, compared to other districts with many very small lakes like Yukon-Kuskokwim Delta with 111,130 lakes and 63 percent of these less than 10 hectares. Most lake districts are in regions with relatively low precipitation, but temperature regimes varied widely among lake districts. Approximately one-half of lake districts were glaciated during the Pleistocene and similar numbers occur in regions classified as having continuous, discontinuous, and sporadic permafrost, or perennially unfrozen soils. Most districts are at low elevations (less than 250 meters) with two important exceptions being Tetlin with a mean elevation of 530 meters and Ahtna with a mean elevation of 760 meters. These higher elevation districts, particularly Ahtna, had distinct characteristics from other lake districts such as continuous permafrost and Pleistocene glaciation. Several lake districts share similar boundaries to defined ecoregions with lake districts occurring in less than one-half of these 32 ecoregions of Alaska.

Most lake districts are lands fully or partly managed by the U.S. Fish and Wildlife Service and the National Park Service, with other land management by the Bureau of Land Management and State and borough government. Much of the U.S. Geological Survey's lake water-quality sampling efforts has been done in the Arctic Coastal Plain, Matanuska-Susitna, and Iliamna districts but no recorded collections in nine lake districts. Similarly, most lake limnological studies in Alaska were site-specific and represent only a small portion of Alaska's lake districts. This identification, characterization, and analysis of lake-rich regions may help provide a template to guide future limnological and other scientific research for Alaska.

Introduction

Interest and study of the distribution of lakes has a long history dating back to the early 1800s primarily among geographers (Meybeck, 1995). More recently, interest in the geographic distribution of lakes regionally and globally has reemerged among physical and biological scientists interested in landscape-scale processes (for example, Lehner and Döll, 2004; Downing and others, 2006; Smith and others, 2007), such as water, sediment, and carbon storage (Vorosmarty and others, 2000; Jackson and others, 2001), regulation of biogeochemical cycles (Cole and Caraco, 2001; Melack and Forsberg, 2001), climate interactions (Bonan, 1995), and biological diversity and habitat provision (Abell, 2002; Baron and others, 2002). Limnologists are particularly interested in how lakes within a region respond to and integrate the effects of human land-use and climate change (Webster and others, 2000; Carpenter and others, 2007). Thus, limnologists, who are ecosystem ecologists studying lakes and other inland waters, are increasingly focused on the study of regional characteristics and processes of lakes and how multiple lakes vary naturally and respond to anthropogenic land-use and climate change (Magnuson and Kratz, 2000; Webster and others, 2000; Walter and others, 2006; Carpenter and others, 2007). Alaska has a history of limnological research dating back to the 1880s and that continues with much contemporary research (Hobbie, 1997). Limnologists are also increasingly focused on lake studies at the landscape scale (for example, Hershey and others, 1999; Edmundson and Mazumder, 2002; Smith and others 2007; Walter and others, 2007). As landscape-scale limnological studies increase in Alaska and elsewhere, there is a need to recognize and consider regions where lakes are the dominant landforms on the landscape, how such regions operate and vary, and what makes them different from landscapes with few lakes. Such new and spatially explicit frameworks often can be useful for organizing studies and facilitating communications among multiple scientific disciplines, policy makers, and land managers (Likens, 1998), along with making new discoveries. Naturally, lake-rich regions, commonly referred to as lake districts, are a logical unit for landscape limnological analysis and have been the recent focus of intensive limnological study, primarily in the mid-western United States and Canada (Magnuson and others, 2006). Such lake district studies have helped limnologists better understand patterns of spatial and temporal coherence among lakes within a district and how these patterns relate to varying climate and geology between lake districts (Soranno and others, 1999; Webster and others, 2000; Carpenter and others, 2007). This recent interest in lake districts by some limnologists may seem long in coming, as lake districts were clearly identified and described by G.E. Hutchinson in his classic 1957 work “A Treatise on Limnology” on page 1 where he writes:

> *The catastrophic origin of lakes, in ice ages or periods of intense tectonic or volcanic activity, implies a localized distribution over the land masses of the earth, for the events, however grandiose, that have produced the basins have never acted on all the lands simultaneously and equally. Lakes therefore tend to be grouped together in* ***lake districts****; within each district the various basins may resemble each other in certain general character yet differ markedly in size and depth and so in their rate of maturation and senescence. It is this diversity in unity that gives the peculiar fascination to limnology. A group of lakes confronts the investigator as a series of complex physiochemical and biological systems, each member of which has its own characteristics and yet also has much in common with the other members of the group. Moreover, the whole group of lakes of a given* ***lake district*** *may be compared with another group, often under widely different geographical and climatic conditions. In this way it is possible to identify the causal factors producing the differences between lake and lake or* ***lake district*** *and* ***lake district****.*

Even now, more than 50 years after this foundational limnological work was published, little if any quantitative work has been done to identify and delineate lake districts regionally or globally, thus limiting the types of comparisons and identification of causal factors suggested by Hutchinson (1957).

Alaska offers an optimal landscape to undertake such an effort to better integrate lake districts into limnology and other natural sciences. Even though the State of Alaska is a geopolitical unit, its vast size (1.5 million km^2), expansive latitudinal extent (18°), wide longitudinal extent (58°), lengthy coastline (54,500 km), and complex tectonic setting create a largely contiguous landscape with several large mountain ranges and expansive river valleys. These geographical attributes of Alaska interact with climate, glacial history, and soil conditions (particularly permafrost) to create many lakes (> 400,000). Lakes in Alaska are unevenly distributed and thus can be grouped into districts and readily compared and contrasted—a process that should help devise new questions of interest to basic and applied science. Alaska presents an important opportunity to begin studying the diversity in unity that provides a particular fascination to the field of limnology (Hutchinson, 1957).

An example of such diversity in unity is the study of lake origins, where 76 modes of lake basin genesis are described by Hutchinson (1957) that can be categorized as formed by constructive, destructive, and obstructive processes. Principal lake types of Alaska include thermokarst lakes formed in depressions created by permafrost degradation (destructive), glacial lakes including kettles and tarns (destructive), and moraine-dammed lakes (destructive / obstructive), and fluvial lakes such as oxbows formed by meander cut-offs (obstructive) (Milner and others, 1997). Volcanic activity can form crater and maar lakes (constructive), as occur on the Seward Peninsula (Begét and others, 1996). Investigations recognizing the genetic composition of lakes within lake districts may provide a useful basis for better understanding the role of lakes on the landscape in the present and over long time-scales. First, however, there is a need to identify where these lake districts occur and what landscape and climate elements these lake districts have in common.

In Alaska, there are many lake-rich areas present, yet these areas have not been formally described nor compared and analyzed as distinct natural units on the landscape—lake districts. This presents an opportunity for basic scientific discovery that may eventually be of interest to those conducting basic science in other disciplines, such as geology, hydrology, and biogeography, and potentially even disciplines such as climatology and anthropology. For example, the sedimentological records of lakes are of interest to limnologists for understanding ecosystem succession (Holtham and others, 2004), but these records also are of interest to many other disciplines because they provide diverse insights into numerous natural phenomena at wide temporal and spatial scales (for example, Anderson and others, 2001; Smol and Douglas, 2007b). Organizing limnological research by lake districts may present a useful framework for these other disciplines as well. For example, applied research has recently been focused on landscape-scale lake processes in Alaska and other high-latitude regions related to climate change (Yoshikawa and Hinzman, 2003; Klein and others, 2005; Smith and others, 2005; Riordan and others, 2006; Walter and others, 2006; Smol and Douglas, 2007a) with important implications to wildlife habitat, particularly migratory fish and birds. Yet few limnologists or other scientists have directly considered lake change or other ecological patterns and processes in the context of lake districts.

To our knowledge, lake districts have not previously been quantitatively delineated for any particular region of the world (for example, continents or biomes). Formally named lake districts include the English Lake District in the United Kingdom, Northern Highland and Yahara Lake Districts in Wisconsin (Carpenter and others, 2007), and Sawtooth Lake District in Idaho (Arp and others, 2007), and other lake-defined regions include the Great Lakes and Prairie Pothole regions of the northern Midwest United States and southern Canada. Yet to our knowledge, these lake districts and other lake regions are not distinctly bounded geographically. Our primary goal in this work was to quantitatively identify and delineate lake districts for a geopolitical region in Alaska. We have developed a relatively simple approach for identifying lake districts within a select region using the combination of lake density and lake area extent. Our goal is that others interested in the topic of lake distribution and lake districts will use a similar approach for other areas to identify and better understand lake-rich regions in other parts of the world.

Methods

Study Area, Lake Abundance, and Data Sources

The study focused on the entire State of Alaska, which is one-fifth the size of the conterminous United States. Unlike most U.S. state boundaries, most Alaska's borders are determined naturally by coastlines with the exception of the U.S.-Canadian border on the east side. Thus, Alaska largely represents a naturally bounded land unit.

An important premise of this paper is that lakes are unevenly distributed on the landscape due to varying and interacting geologic, hydrologic, and climatic conditions, which can be observed at various scales from global to continental and national (figs. 1 and 2). Lake abundance is most commonly described by lake density (d_L) (Meybeck, 1995):

$$d_L = \frac{\text{Number of Lakes}}{\text{Land Area}} \times \frac{10^6}{\text{Land Area}}, \quad (1)$$

where d_L is scaled to 1 million km^2 in order for comparability among regions of differing size with land area in square kilometers, and lake abundance is described by percentage of lake surface-area or the limnetic ratio (LR):

$$LR = \frac{\text{Land Surface Area}}{\text{Land Area}} \times 100 \cdot \quad (2)$$

Although LR is the most commonly used metric of lake extent, lake surface-area provides only two dimensions of a lake, the third being depth distributions or bathymetry giving lake volume. Over several orders of magnitude lake-surface area can be closely related to lake volume (fig. 3), however, this may vary considerably among lakes within a size-class (for example, 100 to 1,000 km^2) and among regions with lakes of contrasting origin. Despite this limitation, most lake geographic analyses use these metrics of lake abundance, d_L and LR, as common descriptors. The basic description of lake number versus extent allows for general comparison of landscape units at scales ranging from local to global (fig. 2). Such comparison describes, for example, that places like India and China have very few lakes of small size, while Canada and Russia have many small and large lakes.

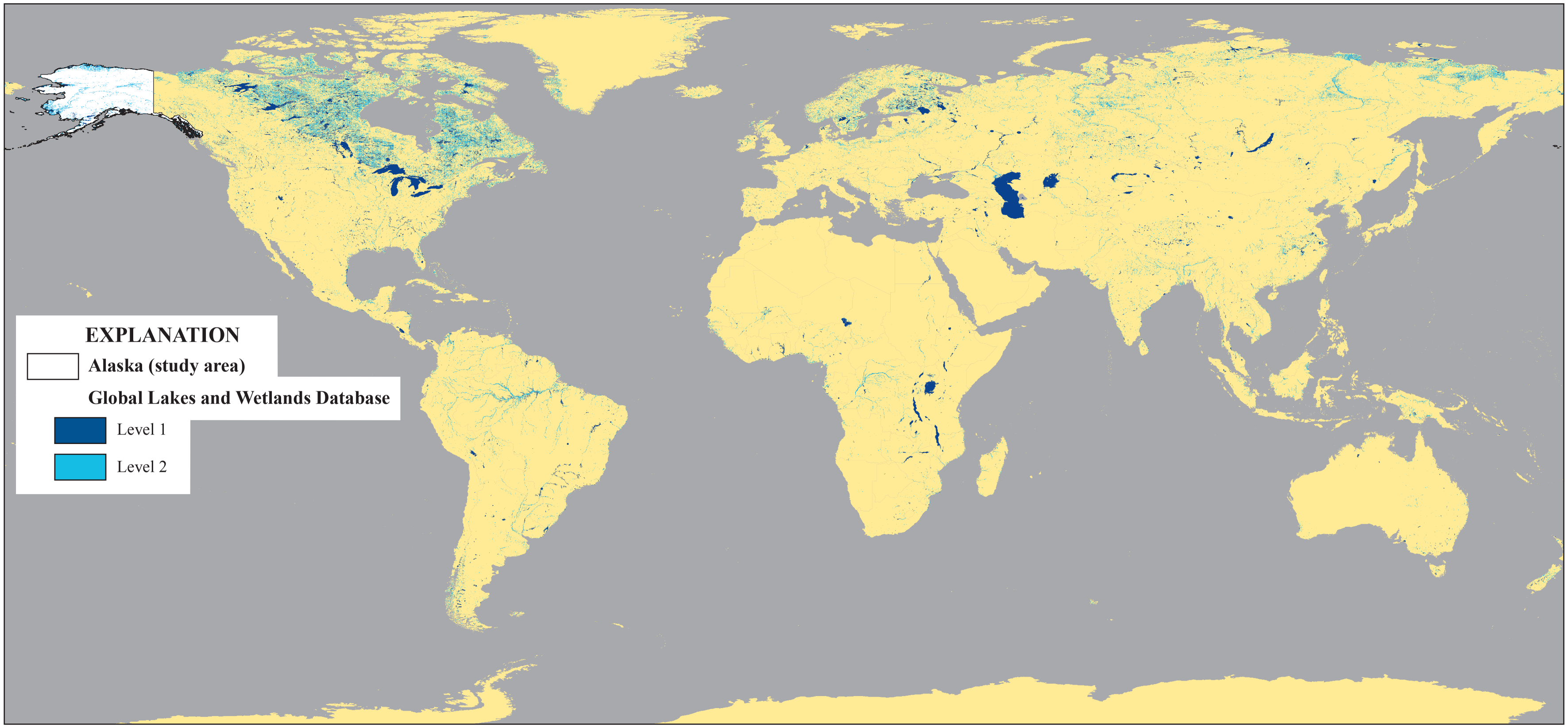

Figure 1. Worldwide map of lakes from the Global Lakes and Wetlands Database (GLWD; Lehner and Döll, 2004) showing lakes larger than 50 km^2 (level 1) and 0.5 km^2 (level 2) showing the study area of Alaska in white (Mercator projection).

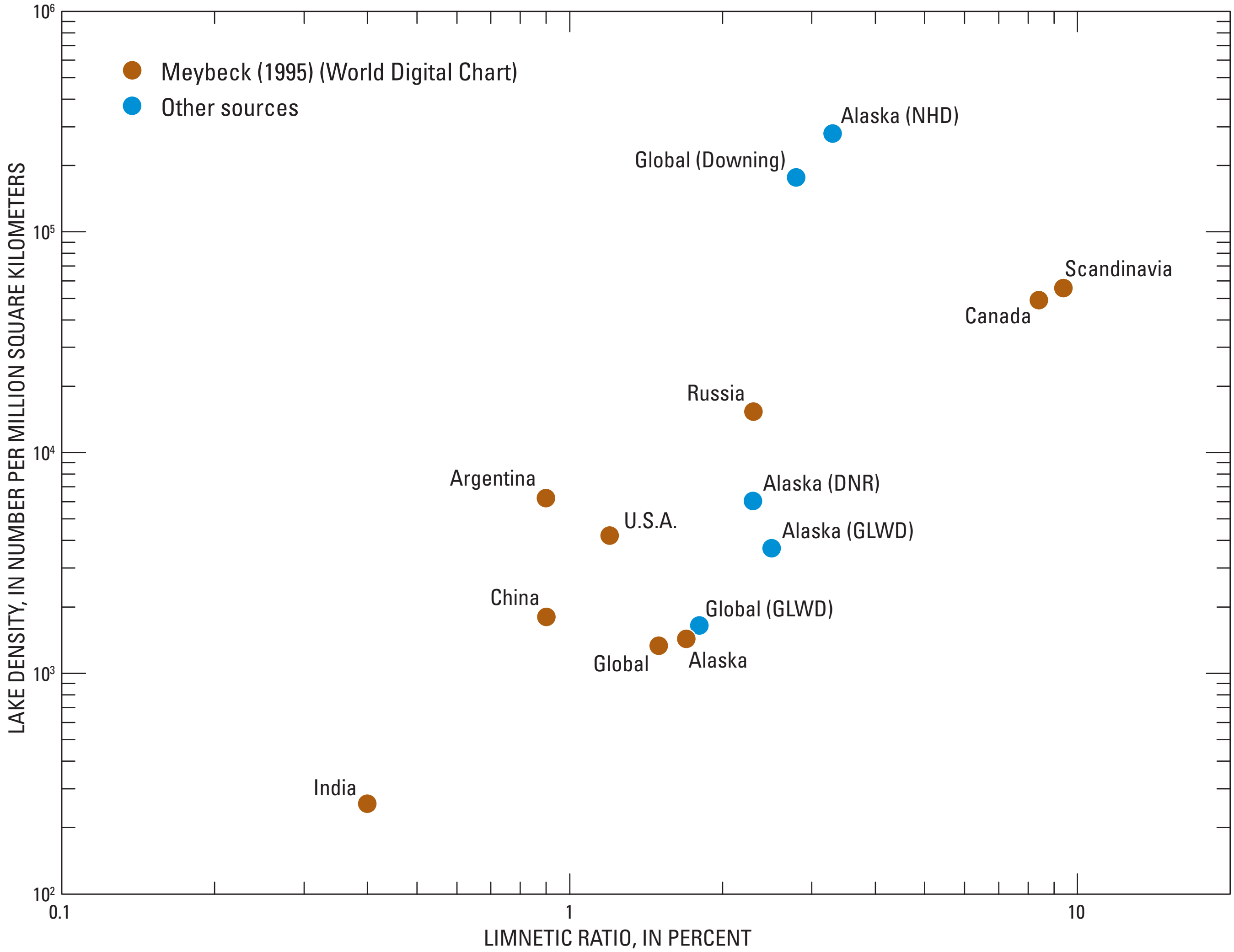

Figure 2. Lake-surface area (limnetic ratio) versus lake density (d_L) for select geographic regions on Earth with emphasis on variations among Alaska and global estimates using differing methods and minimum lake sizes.

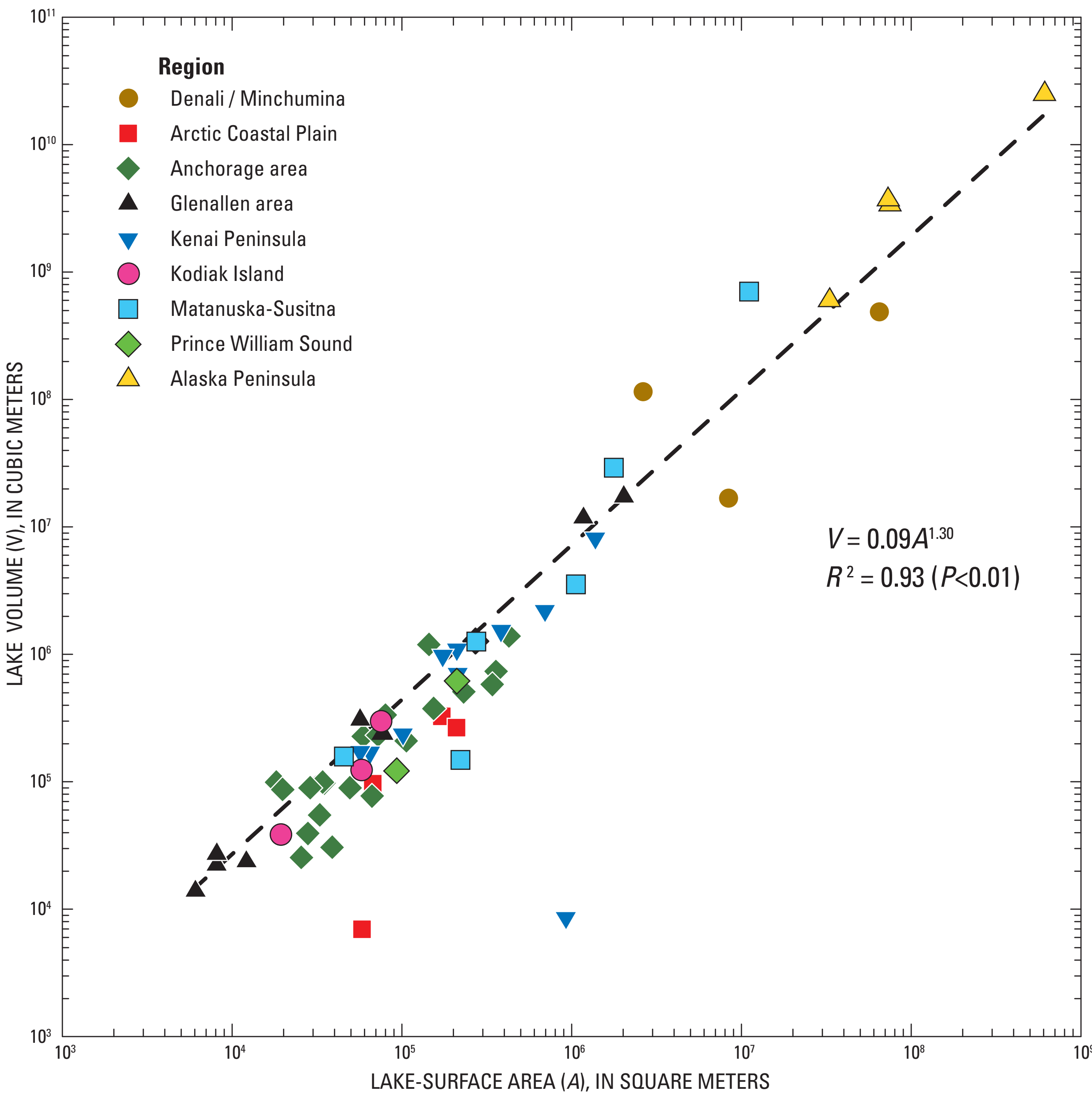

Figure 3. Relations between lake-surface area and volume for 61 select lakes in different regions of Alaska where reasonable bathymetric surveys exist.

The description and comparison of lake geography for a region is of particular importance in order to understand the datasets being used, how they were developed, and the minimum size of lakes considered. For example, most regions plotted in figure 2 are from the World Digital Chart (WDC) (van der Leeden and others, 1989), which only accounts for lakes greater than 1 km^2 with lake censuses for many regions derived from extrapolation based on the abundance of larger lakes; as is the case for Alaska (Meybeck, 1995). Comparison of the WDC to more recent global lake estimates in the Global Lakes and Wetlands Dataset (GLWD) (Lehner and Döll, 2004) shows that lake area increased by 24 and 20 percent, respectively. The GLWD uses the WDC coupled with more recent digital datasets and satellite imagery. Comparison of the WDC to a global analysis based on the Pareto distribution to include much smaller lakes (> 0.001 km^2) (Downing and others, 2006) greatly increased d_L and LR by 131,300 km^2 and 87 percent, respectively. Similarly, varying estimates of lake abundance exist for the State of Alaska, including datasets from the WDC, GLWD, and USGS National Hygrography Dataset (NHD) (table 1). Additionally, defining what constitutes a lake solely according to surface area, instead of calling such a feature a wetland or low-gradient river, also is a consideration worthy of discussion (Meybeck, 1995; Wetzel, 2001; Lehner and Döll, 2004); however, it is a topic that we will not pursue further in this report.

Our analysis here primarily uses the USGS National Hydrography Lakes Dataset (Lake NHD), which was compiled from 7.5-minute USGS topographic maps originally developed from manual delineation of aerial photography conducted between the 1950s and 1990s. The Alaska Lakes NHD includes many very small lakes (<10 ha) and for our use in this analysis we truncated lake size at 1 ha (0.01 km^2) because smaller lakes appeared to deviate from known size-frequency distributions (Meybeck, 1995; Downing and others, 2006). In comparison to other lake census datasets (table 1), the Alaska Lake NHD appears to have been carefully developed and provides for relatively high resolution analysis. However, as with any such census and delineation of water bodies, errors can occur due to varying times of image acquisition relative to seasonal and interannual variation in lake-surface area, along with errors in delineating boundaries related to natural interference (vegetation, topography, cloud cover, etc.), human interpretation, and the spatial resolution of the imagery used. For example, in a small portion of Denali National Park and Preserve with many lakes, lake area is 24.2 km^2 and lake numbers are 154 in the Lake NHD. More recent Landsat imagery for this same location for five individual time periods from 1986 to 2002 indicate that average lake area of 2,320 hectares ranges from 2,180 to 2,650 hectares and that average lake numbers of 129 range from 115 to 156 (fig. 4). This example suggests that Lake NHD estimates of lake numbers (d_L) are more likely subject to natural variability with small lakes disappearing and reappearing with changing seasons and interannual climate conditions, although lake area (LR) tends to be more robust to such variations. Additionally, the Lake NHD was only recently compiled and a few regions still have some delineation errors and a few parts of the State are incomplete, such as Saint Lawrence Island. For such areas, we cross-checked this dataset against the Department of Natural Resources dataset (DNR) to complete the statewide identification of lake districts, but excluded these regions of the State from more detailed lake district comparisons and analysis.

Table 1. Summary of lake hydrography datasets.

[km^2, square kilometer; <, less than]

Dataset	Primary reference	Coverage	Census method	Minimum lake size (km^2)
Global Lake Census (GLC) / Word Digital Chart (WDG)	van der Leeden and others, 1987; Meybeck, 1995	Global	Compilation of multiple datasets with some size-frequency extrapolations	1
Global Lake and Wetland Database	Lehner and Döll, 2004	Global	Compilation of multiple datasets with intensive GIS processing	0.1
Lakes, 1 to 100,000	Alaska Department of Natural Resources http://nrdata.nps.gov/regions/akro/lk1mil.xml	Alaska	Processed Digital Chart of the World	1
USGS NHD Lakes	USGS National Hydrography Dataset http://nhd.usgs.gov/techref.html	Alaska	1:100,000 topographic maps derived from aerial photography (1950s) stereo pairs	<0.1

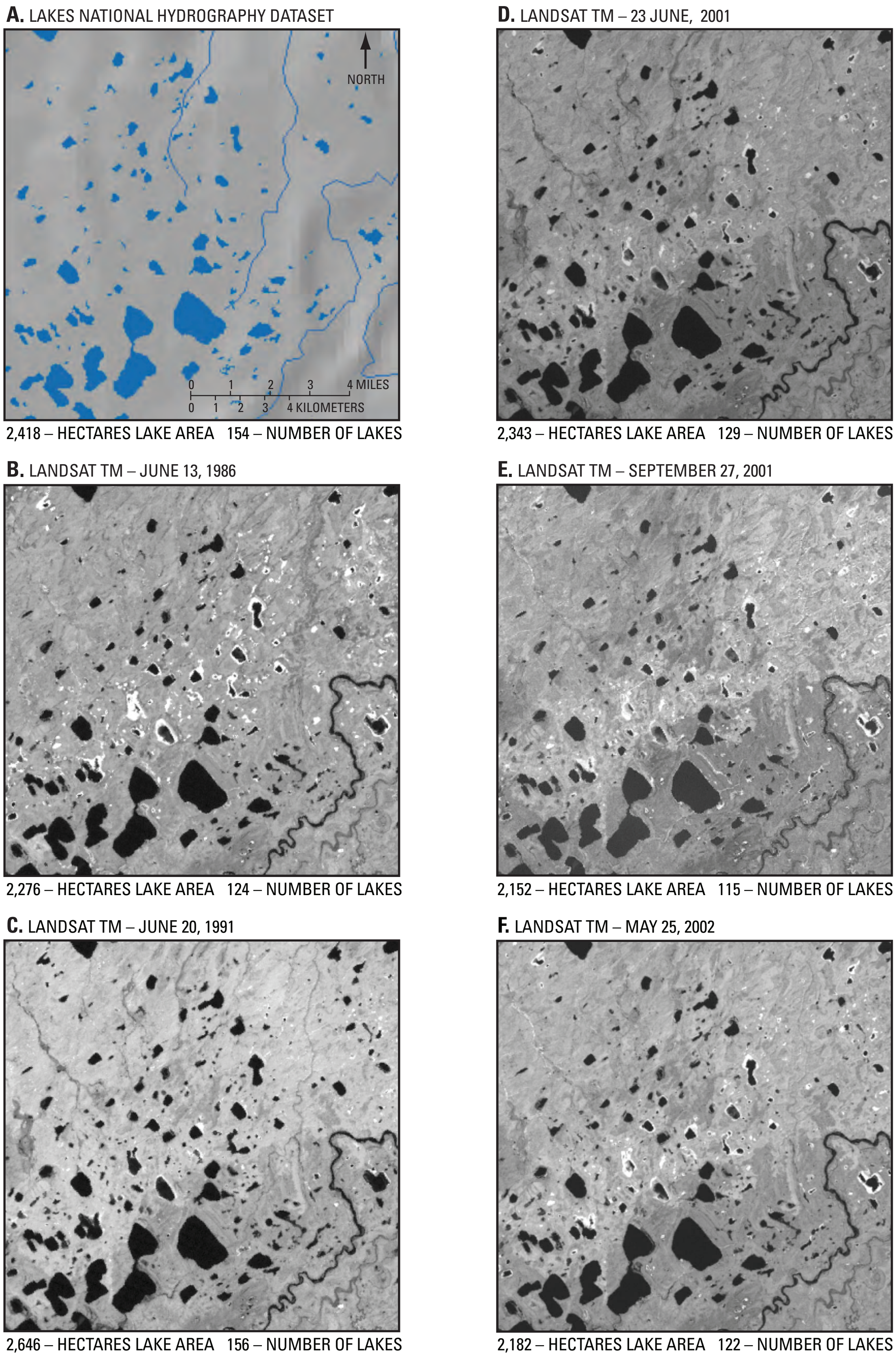

Figure 4. An example of lake-surface area and lake numbers for a portion of Denali National Park and Preserve comparing the Lakes National Hydrography Dataset (NHD) (*A*) to a time series of images acquired from Landsat TM (B-F).

Many other geospatial datasets were used in this paper to characterize and compare lake districts for the State (table 2). These datasets are subject to similar types of error and uncertainty associated with natural variability and geographic analyses of vast inaccessible terrain. To better understand how these datasets were developed and their limitations, we direct the reader to those dataset descriptions, mostly available on-line (table 2), although some of these limitations are discussed in this report.

Lake District Identification and Delineation

The first decision we made in developing this approach was identifying a grid size for spatial analysis of lake abundance. Grid size was defined by calculating the mean land area per lake in the dataset, which takes into account the area of interest and the resolution of the dataset being used:

$$\text{Grid Size} = \frac{\text{Total Land Area}}{\text{Number of Lakes in Area}} \ . \qquad (3)$$

For Alaska, this is 3.8 km^2 at 1:400,000 resolution. Using tools in a geographic information systems (GIS) environment, we developed a 3.8 km^2 grid for the entire State and calculated d_L and LR for each grid cell. We decided that in order for an individual cell to qualify as part of a lake district, the qualifying cell should have d_L or LR values greater than that of the entire region (Alaska), such that;

$$\text{Lake District Qualifying Cell} = d_{Lcell} > \bar{d}_{LAlaska} \cup LR_{cell} > \overline{LR}_{Alaska} \ , \qquad (4)$$

where most cells qualifying by the d_L criteria also qualified by the LR criteria (fig. 5). We think that determining qualifying cells relative to the mean is reasonable based on the observed bimodal distribution of lakes in Alaska and most landscapes (that is, lakes tend to be either abundant or scarce). Next, we spatially joined all adjacent qualifying cells. Visual inspection of these qualifying groups showed that many were actually parts of similar spatial units and joining these together resulted in 281 units greater than100 km^2 where all cells in each group met the criteria in equation 4. We set the lower limit of lake districts at 1,000 km^2 (0.07 percent of Alaska) based on visual inspection of the size distribution of qualifying groups. We set this limit of lake districts size to the major lake-rich land units of the State to arrive at a reasonable number to describe and analyze in this report and suggest that future work focused on particular parts of the State would identify these minor lake districts using the same criteria. These groups of qualifying grid cells were identified as the major lake districts of Alaska. Finally, each district was manually delineated to include all lakes and associated land that appeared to be part of the same landscape unit based primarily on comparisons with digital elevation models (DEMs) and drainage network maps (NHD) to assist in drawing natural boundaries. This aspect of the delineation process is qualitative and based on our professional judgment. Attempts we made at automated delineations typically resulted in boundaries not representing obvious parts of the natural unit of land forming a lake district. Thus, our analysis coupled the lake districts with the landscape unit where they were formed.

Table 2. Summary of geospatial datasets used to characterize and compare lake districts.

[km, kilometer]

Dataset	Source	Description	Resolution
Geologic Map of Alaska	Beikman, 1980 http://agdc.usgs.gov	Major geologic units of Alaska	1:2,500,000
Surficial Geology Map of Alaska	Karlstrom,1964 http://www.nps.gov/akso/gis/	Major surficial geologic features of Alaska	1:1,584,000
Permafrost Map of Alaska	Brown and others, 2001 http://nsidc.org/data/ggd318.html	Permafrost and ground ice data	1:10,000,000
Alaska PaleoGlacier Atlas	Manley and Kaufman, 2002 http://instaar.colorado.edu/QGISL/ak_paleoglacier_atlas	Geospatial summary of Pleistocene glaciation across Alaska	1:1,000,000
Gridded Alaska Climate Data	Leeman and Cramer, 1991 http://agdc.usgs.gov/data/projects/hlct/hlct.html#K	Mean (1961–90) monthly temperature and precipitation for Alaska based on interpolation of National Climate Data Center Global Historical Climate Network	1 km
Unified Ecoregions of Alaska	Nowacki and others, 2003 http://agdc.usgs.gov/data/usgs/erosafo/ecoreg/	Landscape-scale ecological units of Alaska	1:2,500,000

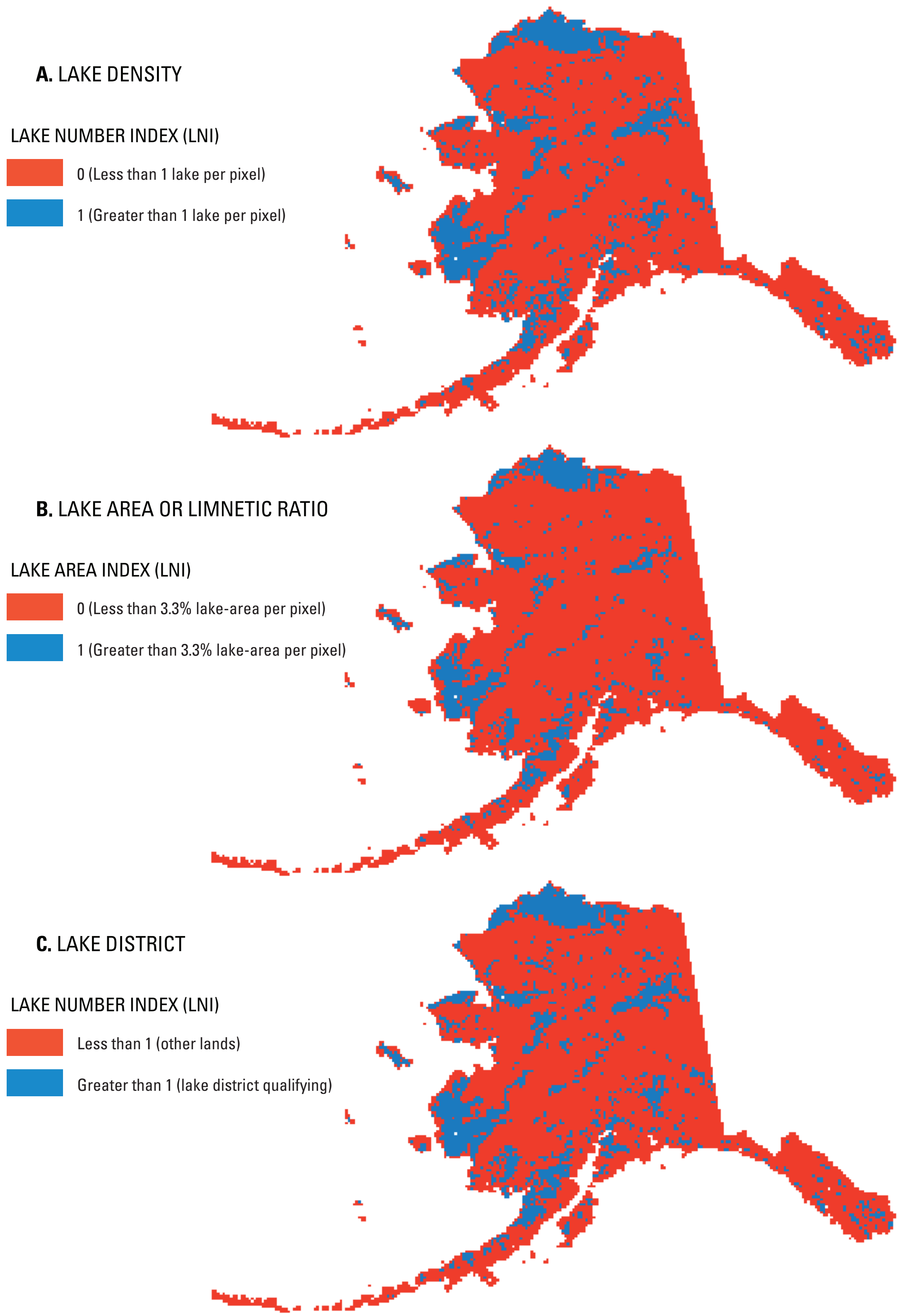

Figure 5. Landscape-scale lake indexes for delineating major Alaska lake districts lake by (*A*) density, (*B*) lake area or limnetic ratio, and (*C*) combined to identify potential lake districts using a 3.8 square kilometer pixel size (number of lakes in Alaska NHD / land area of State).

Lake District Characterization and Analysis

To describe and compare lake districts, we summarized lake densities and spatial extents for each district as in equations 1 and 2 and also calculated the shoreline density.,

$$SD = \frac{\text{Total Lake Perimeter}}{\text{Total Lake Area}}, \quad (5)$$

where perimeter is in kilometers and area is in square kilometers. The elevation for all lake districts lakes and land was calculated from 60-m DEMs and in several cases from 300-m DEMs where obvious errors existed in the finer scale DEM (table 2). We summarized the elevation data using the hypsometric index (HI),

$$HI = \frac{\text{Mean Elevation} - \text{Minimum Elevation}}{\text{Maximum Elevation} - \text{Minimum Elevation}}, \quad (6)$$

where mean elevation is area-weighted (Ritter and others, 1995). This metric is considered a close approximation to the hypsometric integral and describes the elevational distribution of a land area, typically used for drainage basins (Ritter and others, 1995). Drainage area was calculated for each lake district by identifying all higher lands draining into and including each districts from USGS hydrologic unit code (HUC) polygons in GIS. The external contributing area ratio,

$$ECA = \frac{\text{Watershed Area}}{\text{Lake District Area}}, \quad (7)$$

was used to describe the extent to which lake districts are dependent on external land and climate. These continuous lake district variables (d_L, *LR*, elevation, *SD*, *HI*, *ECA*, and drainage area) were summarized and related using principal components analysis (PCA, Proc Princomp in SAS, 2003) and cluster analysis (Proc Cluster in SAS, 2003) to group and compare lake districts.

Other lake district characterization and comparisons that used categorical digital datasets, such as surficial geology, permafrost, and seasonal precipitation, were analyzed qualitatively.

Results and Discussion

Major Alaska Lake Districts and Their Landscape Limnological Structure

Twenty major lake districts were identified in the State of Alaska, which we named according to regionally distinguished landforms such as lakes, rivers, mountain ranges, or coastal promontories (fig. 6). Many smaller lake districts (<1,000 km^2) also were identified, particularly in mountain regions of the Brooks and Coastal Ranges, but are not considered further in this report. Together, these lake districts represent only 16 percent of the total land area, but represent 65 percent of all lakes numerically and greater than 75 percent of lake surface area. The two largest lake districts, Yukon-Kuskokwim Delta at 72,831 km^2 and Arctic Coastal Plain at 55,964 km^2, are expansive coastal lowlands along the Bering Sea and Arctic Ocean, respectively (fig. 6 and table 3) and most lake districts are much smaller. These lake districts are relatively evenly distributed across the State's land mass with the main exceptions being southeast Alaska and the Aleutian Chain where no lake districts were identified, which is not necessarily due to lack of lakes, but rather the land's shape and discontinuity with islands, rough coastlines, and mountainous, tectonically active terrain. Two of the smallest major lake districts, Menhiskof and Rozhnof, occur far out on the Alaskan Peninsula, and the third largest district Iliamna occupies a major portion at the peninsula's base (fig. 6). The Saint Lawrence lake district is on Saint Lawrence Island in the Bering Sea and the only one completely surrounded by ocean. Seven lake districts are associated with the mainstem or major tributaries of the Yukon River, which drains a major portion of Alaska's interior and northwest Canada. Ahtna, at the headwaters of the Copper River and Susitna River basins, is on a paleo-lake bed (fig. 6) and is the only interior lake district not associated with a major river valley.

The major Alaska lake districts were identified by a combination of lake density (d_L) greater than the State total of 279,328 lakes per 10^6 km^2 (409,090 lakes per 1,549,656 km^2 or 1 lake per 3.8 km^2), and surface-area extent or limnetic ratio (*LR*) of 3.3 percent (51,139 km^2 lake-surface area). The lake district average d_L is 858,850 lakes per 10^6 km^2 (1 lake per 1.2 km^2) ranging from 502,193 lakes per 10^6 km^2 (1 lake per 2.0 km^2) in Yukon Flats to 1,789,068 lakes per 10^6 km^2 (1 lake per 0.6 km^2) in Yukon-Kuskokwim Delta. The lake district average *LR* is 11 percent, and ranges from 5.5 percent in Yukon Flats and Kanuti to 20.9 percent in Iliamna (fig. 7 and table 3). The relation between lake district d_L and *LR* is correlated, but relatively weak ($r = 0.49$), indicating a high degree of variability in lake size-frequency distributions among lake districts (fig. 7). Iliamna has the highest lake extent relative to density because of several very large lakes, particularly Lakes Iliamna and Becharof, followed by Arctic Coastal Plain, because of Teshekpuk Lake, and Tikchik, because of its many large moraine-dammed finger lakes, such as Nuyakuk Lake. The lake districts with higher density relative to limnetic ratio include Koyukuk, Kanuti, and Rozhnof due to many small lakes (fig. 7). Another description of lake density that was calculated is shoreline density (*SD*), which is the total length of lake shoreline per unit land area. The lake district average shoreline density is 0.10 km of shoreline per square kilometer land area with the lowest value of 0.04 in Arctic Coastal Plain, likely related in part to the dominance of oriented thermokarst lakes in this district, and the highest value of 0.22 in Menhiskof, where many lakes

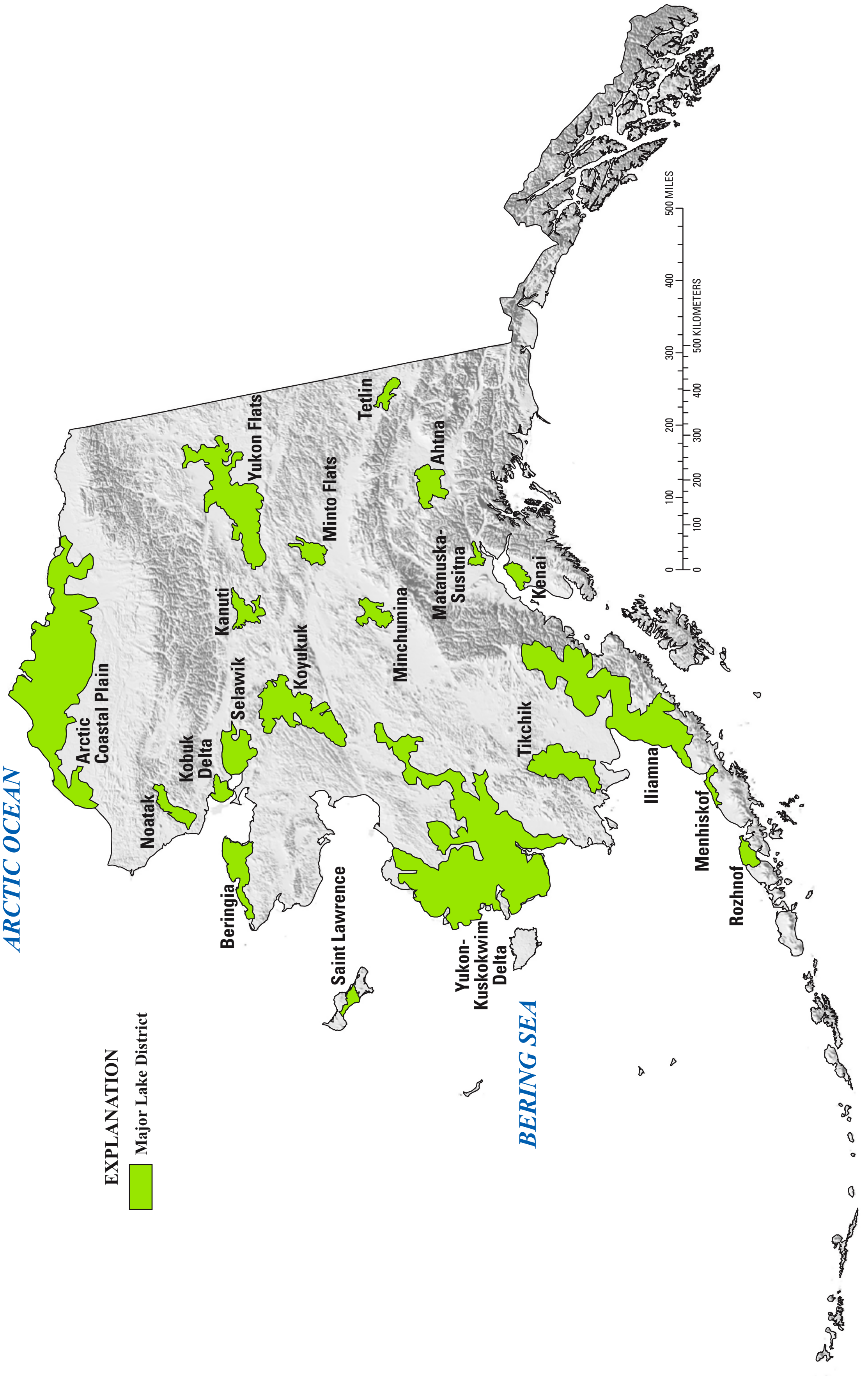

Figure 6. Major lake districts of Alaska.

Table 3. Structural and hydrographic characteristics of major Alaska lake districts.

[**Mean lake elevation**: Surface-area weighted average elevation (NAVD 88). **Large lake limnetic ratio**: Large lakes are > 1 km^2. **Small lake density**: Small lakes are < 0.1 km^2. **Shoreline density**: Defined as total lake perimeter / total area. **External contributing area ratio**: Defined as area draining to the lake district / area of lake district. km^2, square kilometer; m, meter; km, kilometer; >, greater than; <, less than]

District	Total area (km^2)	Mean land elevation (m)	Hypso-metric index	Lake area (km^2)	Mean lake elevation (m)	Limnetic ratio (percent)	Large lake limnetic ratio (percent)	Lake density (d_L)	Small lake density (d_L)	Shoreline density (km)	Drainage area (km^2)	External contributing area ratio
Yukon-Kuskokwim Delta (YKD)	72,831	13	0.02	13,535	–	18.6	9.0	1,789,068	63	0.05	989,687	13.6
Arctic Coastal Plain (ACP)	55,964	28	0.11	9,545	–	17.1	3.0	898,951	54	0.04	111,837	2.0
Iliamna (Ili)	35,403	182	0.10	7,409	146	20.9	17.7	566,393	62	0.05	48,780	1.4
Yukon Flats (YF)	21,006	159	0.15	1,147	–	5.5	1.4	502,193	46	0.07	508,829	24.2
Koyukuk (Koy)	14,658	64	0.08	902	117	6.2	1.2	864,174	57	0.07	69,607	4.7
Tikchik (Tik)	9,349	198	0.18	1,227	100	13.1	11.8	307,643	67	0.06	10,000	1.1
Beringia (Ber)	6,418	15	0.10	456	22	7.1	2.9	632,168	53	0.09	10,000	1.6
Selawik (Sel)	6,112	31	0.12	957	15	15.7	7.4	1,167,042	49	0.07	17,208	2.8
Ahtna (Aht)	4,701	762	0.32	524	726	11.1	5.9	927,399	60	0.08	7,000	1.5
Kanuti (Kut)	3,410	186	0.11	186	173	5.5	3.4	756,115	54	0.14	42,883	12.6
Minchumina (Min)	3,232	247	0.15	249	225	7.7	3.2	663,367	55	0.12	6,000	1.9
Noatak (Noa)	3,199	75	0.11	190	49	5.9	1.6	572,658	51	0.11	32,037	10.0
Minto Flats (MF)	2,787	107	0.07	161	98	5.8	1.7	611,322	53	0.12	77,039	27.6
Kenai (Kai)	2,006	60	0.50	182	60	9.1	2.1	743,226	46	0.11	2,100	1.0
Rozhnof (Roz)	1,903	33	0.14	172	21	9.1	2.7	1,172,103	60	0.11	2,500	1.3
Kobuk Delta (KD)	1,891	8	0.09	358	8	18.9	7.9	1,316,715	47	0.11	31,790	16.8
Tetlin (Tet)	1,867	528	0.10	267	514	14.3	6.2	1,310,848	56	0.15	15,500	8.3
Menhiskof (Men)	1,196	12	0.02	104	8	8.7	2.9	947,152	60	0.22	2,000	1.7
Matanuska-Susitna (Mat)	1,050	77	0.38	92	63	8.8	3.2	569,549	44	0.18	1,200	1.1

have very irregular shapes (table 3). An important landscape-scale description of lake districts missing from our analysis is lake volume per unit land area, which would describe lake water storage on the landscape. Other such landscape analyses of lakes typically lack these data as well, yet such a description would be of great value for many reasons and should be a goal of future work on lake hydrography and any realistic water census for the State.

An interesting attribute of lake districts is their topography and how lake elevations are distributed relative to upland and watershed areas. Lakes are assumed to occur at lower elevations than the surrounding landscape. Accordingly, lake district topography was described by land and lake elevation as area-weighted means and distributions using the hypsometric index (*HI*) (Ritter and others, 1995). Mean lake elevation is 146 m and ranged from 8 m at Kobuk Delta to 726 m at Ahtna (table 3). The mean lake surface elevation for all districts is 9 percent lower than the total land-surface elevation of these districts with several districts excluded due to missing or incomplete data because of poorly developed DEMs. Two exceptions where mean lake elevations were higher than mean land elevations are Koyukuk, 53 m higher, and Beringia, 7 m higher (table 3). These districts with surface-water storage perched higher than most of the land appear related to lake-rich plateaus occuring well above regional low areas—the Koyukuk River flood plain and Bering Sea coastal plain, respectively. *HI* describes the relative elevational distribution of land surfaces, typically calculated for watersheds, where 0.5 indicates even amounts of land above and below the mean land surface for an area.

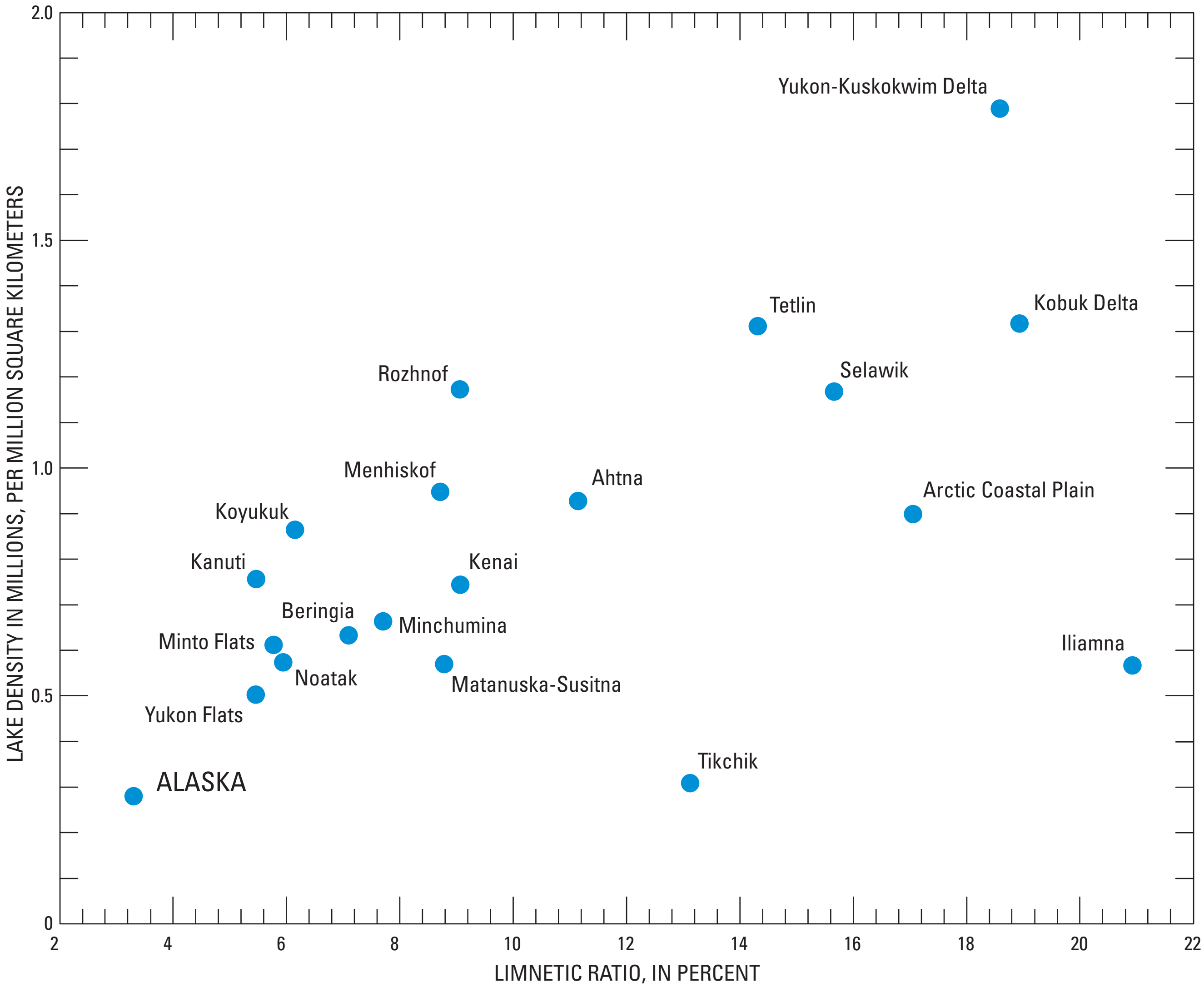

Figure 7. A comparison of major Alaska lake districts by limnetic ratio (percent lake-surface area) and lake density (d_L).

The average lake district *HI* is 0.15 and ranges from 0.02 in Menhiskof and Yukon-Kuskokwim Delta to 0.50 in Kenai. The very low *HI*s appear to be related in part to their expansive lowlands with very large external contributing area (*ECA*, portion of watershed area outside of district) (for example, Yukon-Kuskokwim Delta occurs at the mouth of the Yukon and Kuskokwim River Basins), although high *HI*s appear to be related to lake districts set in sloping terrain mostly within entire watersheds, such as Kenai, Matanuska-Susitna, and Ahtna (fig. 6 and tables 2 and 4). The drainage areas of these lake districts varied by three orders of magnitude and had contributing areas ranging from entirely within lake districts (that is, Kenai, Matanuska-Susitna, and Tikchik) to lake districts with large *ECA*s (that is, Yukon Flats, Yukon-Kuskokwim Delta, Minto Flats, Kobuk Delta, and Kanuti) (table 3).

As a quantitative step to organizing and grouping these lake districts, we performed a cluster analysis using the metrics in table 3. Cluster analysis results suggested three major distinctions or groupings and two minor groupings among lake districts with many finer distinctions of potential interest (fig. 8). The first major distinct grouping is among lake districts in south-central Alaska, the Bristol Bay region, and the paleo Lake Ahtna basin with lake districts in the interior, the North Slope, and western Alaska (fig. 8). The second major distinction is that Lake Ahtna lake district separates strongly from others in this group likely owing to its high elevation and high watershed position, presence of continuous permafrost and recent glaciation, and its unique association with a large ancient lake basin. The third distinct grouping is Iliamna and Tikchik lake districts with high *LR* due to many large and moderately high elevation lakes compared to the other lake districts with smaller and

Table 4. Mean climatic conditions of major Alaska lake districts from 1961 to 1990 based on 1-km interpolation of climate station data (Leeman and Cramer, 1991).

[km, kilometer; cm, centimeter; °C, degrees Celsius]

District	Precipitation (cm)				Mean temperature (°C)			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
Yukon-Kuskokwim Delta (YKD)	7	6	17	13	-12	-4	10	0
Arctic Coastal Plain (ACP)	1	1	7	4	-26	-15	6	-9
Iliamna (Ili)	15	13	21	22	-9	0	11	2
Yukon Flats (YF)	1	1	9	4	-24	-5	12	-6
Koyukuk (Koy)	5	4	14	9	-23	-6	13	-5
Tikchik (Tik)	10	9	20	17	-13	-2	12	0
Beringia (Ber)	5	4	12	9	-18	-9	8	-4
Selawik (Sel)	3	3	11	7	-22	-8	10	-5
Ahtna (Aht)	11	9	21	16	-18	-3	10	-5
Kanuti (Kut)	5	4	15	9	-9	1	12	2
Minchumina (Min)	7	5	17	11	-23	-4	13	-7
Noatak (Noa)	3	3	10	6	-18	-3	12	-4
Minto Flats (MF)	3	3	16	7	-21	-11	9	-5
Kenai (Kai)	10	6	14	17	-19	-2	14	-4
Rozhnof (Roz)	18	14	19	27	-4	1	10	4
Kobuk Delta (KD)	3	2	10	6	-20	-9	10	-5
Tetlin (Tet)	5	5	16	8	-24	-3	13	-6
Menhiskof (Men)	17	14	21	26	-5	1	11	3
Matanuska-Susitna (Mat)	8	5	17	15	-11	1	13	1

lower elevation lakes. A fourth minor grouping is Kenai and Matanuska-Susitna with moderate *LR*, many medium-sized lakes (0.1 – 1.0 km^2), and high *HI*s. A fifth minor grouping distinguishes between lake districts associated with large coastal plains (deltas and marine transgressions), which are Yukon-Kuskokwim Delta, Arctic Coastal Plain, Selawik, and Kobuk Delta. The remaining 11 districts are mostly associated with interior river floodplains with the exception of Menhiskof, Rozhnof, and Ahtna (fig. 8). Finer distinctions of interest include the grouping of Minchumina and Tetlin lake districts (fig. 8), which are relatively distant, but both interior and associated with toe-slopes of the Alaska Range. In general, this analysis suggests that lake districts show most similarity by proximity and large-scale landscape features, such as river floodplains and deltas, and that simple metrics of lake density and lake size help express much of this variation.

Lake District Physical Setting and Ecological Characteristics

The State of Alaska represents a vast and diverse landscape with many important physical gradients and transitions, such as elevation, distance from the coast, and latitude, which interactively drive seasonal energy budgets, climate, hydrologic regimes, glacier and permafrost extent, and vegetation patterns. The hydrogeomorphic landscape generally is a function of bedrock and surficial geology, topography, and drainage networks, which similarly interact with these physical gradients to create and maintain Alaskan ecosystems. In this section, we use existing geospatial datasets of physical and ecological landscape attributes to better characterize the Alaska lake districts to understand the settings where they occur and the processes that create and maintain these particular landscape units.

Geology

Alaska has extremely complex geologic structures with many active faults and volcanoes and more than 50 terranes created by coalesced plates. We characterized the dominant bedrock types of each lake district (table 5 and fig. 9) following mapped units by Beikman (1980) that were condensed to seven general bedrock types for simplicity of description, although many of these districts are across multiple bedrock types. Most lake districts are on sedimentary bedrock, both marine and continental of recent Quaternary and more distal formation. Exceptions to sedimentary bedrock dominance are Iliamna, Beringia, Koyukuk, Selawik, and

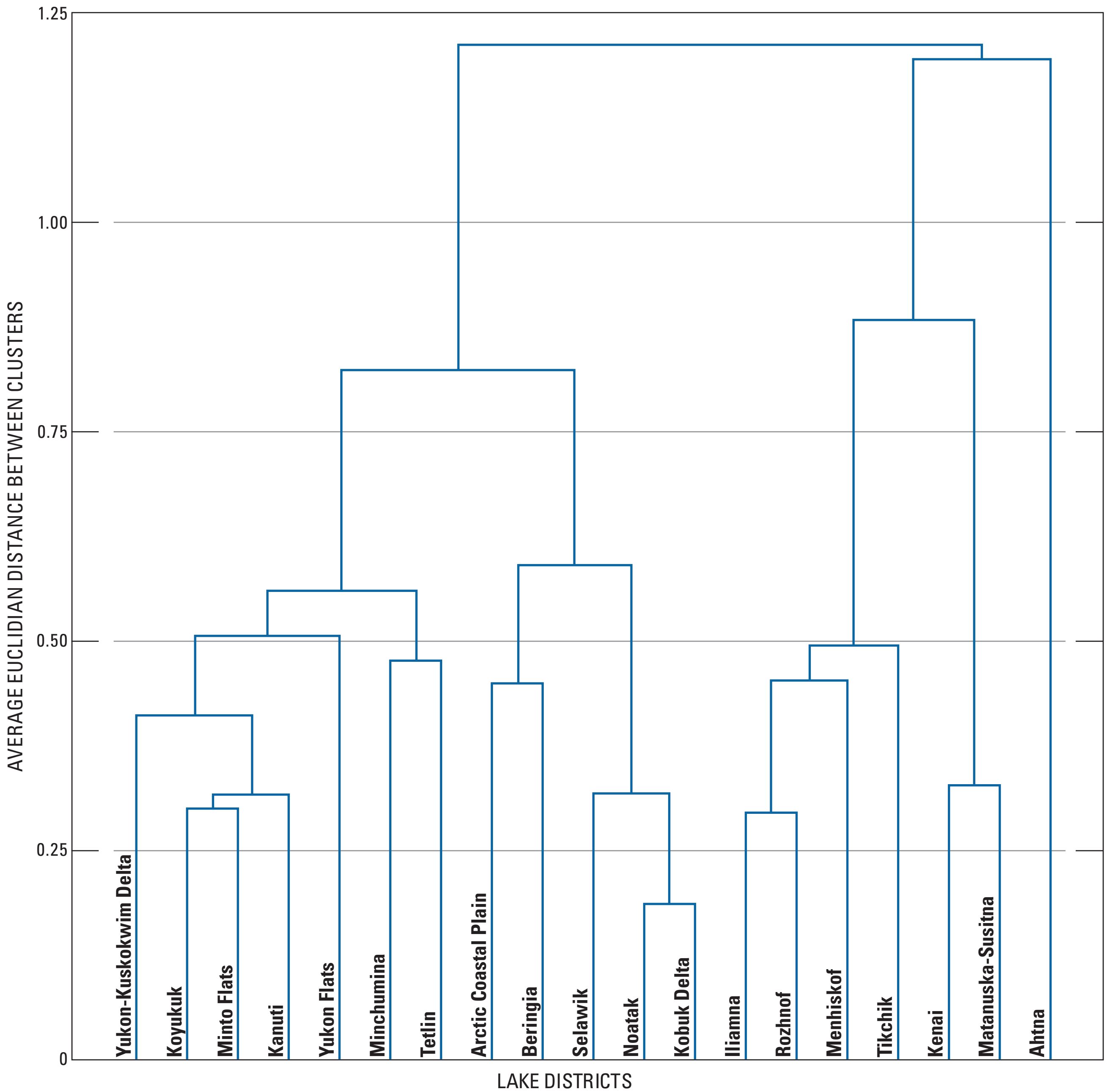

Figure 8. Clustering of major Alaska lake districts by structural characteristics.

Noatak that are predominantly on igneous rocks, primarily extrusive, and Tetlin that is predominantly on metamorphic rock. The lake districts Koyukuk, Beringia, Noatak, and Selawik in northwest Alaska all are on similar extrusive igneous units with similar boundaries indicating some relation between bedrock units and lake districts. In Beringia Lake District, several large maar lakes are found that were created by volcanism eruptions through deep permafrost (Béget and others, 1996). The degree to which other lakes in Beringia and other districts underlain by igneous bedrock relate to volcanic processes is uncertain, but is of interest and may relate to the higher elevational distribution of lakes found here (tables 3 and 4). In Iliamna, the largest lakes are all on mapped metamorphic bedrock surrounded by varying igneous and sedimentary bedrock (fig. 9).

The surficial geology of Alaska also is complex like bedrock geology and is likely more closely related to the formation of most individual lakes and lake districts overall (fig. 10). Lake districts occur almost equally on areas dominated by coastal, fluvial, and glacial deposits (table 5). An interesting observation is that lake district boundaries match closely with these mapped deposits, such as Arctic Coastal Plain occurring on coastal deposits and bounded to the south by a band of eolian deposits, and the Yukon-Kuskokwim Delta occurring on coastal deltaic deposits bounded by mountains and colluvial aprons (fig. 10). Minchumina, Minto Flats, Koyukuk, and Tetlin are across mosaics of fluvial, eolian, and other deposits, possibly suggesting multiple origins and successional processes within lake districts. Ahtna and Kenai lake districts are on glacio-lacusterine deposits related in part to ancient glacial lakes and surficial landforms, the former associated with the massive glacial Lake Ahtna that formed and drained during the late Pleistocene. It would be of great interest to better understand how the lakes occurring across these surficial and subsurficial geologic units vary within and among lake districts.

The occurrence of perennially frozen substrates, or permafrost, has profound influences on the hydrology and vegetation of major portions of Alaska with many influences on lakes related to surface storage and formation of thermokarst depressions, given adequate ground-ice content. Permafrost generally is characterized laterally as continuous, discontinuous, and sporadic, and these distinctions are considered very important to the formation, behavior, and permanence of many Alaskan lakes (Livingstone and others, 1958; Yoshikawa and Hinzman, 2003; Smith and others, 2005).

Nearly one-half of the lake districts are in continuous permafrost zones and five others are on discontinuous or sporadic permafrost (table 5). Several lake districts are on and share mapped boundaries with isolated regions of continuous permafrost, particularly Yukon-Kuskokwim Delta, Kobuk Delta, Beringia, Selawik, and Ahtna (fig. 11). Minchumina, Minto Flats, and Tetlin occur entirely in expansive zones of discontinuous permafrost and Tikchik entirely in the band of sporadic permafrost stretching from Bristol Bay across the southeast to Yakutat. Rozhnof, Menhiskof, Kenai, and Matanuska-Susitna occur entirely in zones without mapped permafrost soils (fig. 11). The permafrost map used in this comparison has recently been updated (Jorgensen and others, 2008) and new permafrost zones are somewhat different than previously mapped.

More recent Late Wisconsinan glacial extents covered much of the Brooks, Alaskan, and Coastal Ranges with the Pleistocene maximum extending beyond these mountain ranges to lowlands of Bristol Bay, the Alaskan Peninsula, Cook Inlet, Prince William Sound, and Southeast Alaska (fig. 12). Lake districts are commonly assumed to be of glacial origin (Hutchinson, 1957; Magnuson and Kratz, 2000); however, eight of the major Alaska lake districts occur on unglaciated terrain (table 5).

Most lake districts with glacial influence are in late Wisconsinan glaciated terrain where permafrost is absent or sporadic. All lake districts with more ancient glaciation (maximum Pleistocene extent) are in zones of continuous permafrost; these include Kobuk Delta, Noatak, and Selawik (fig. 12 and table 5).

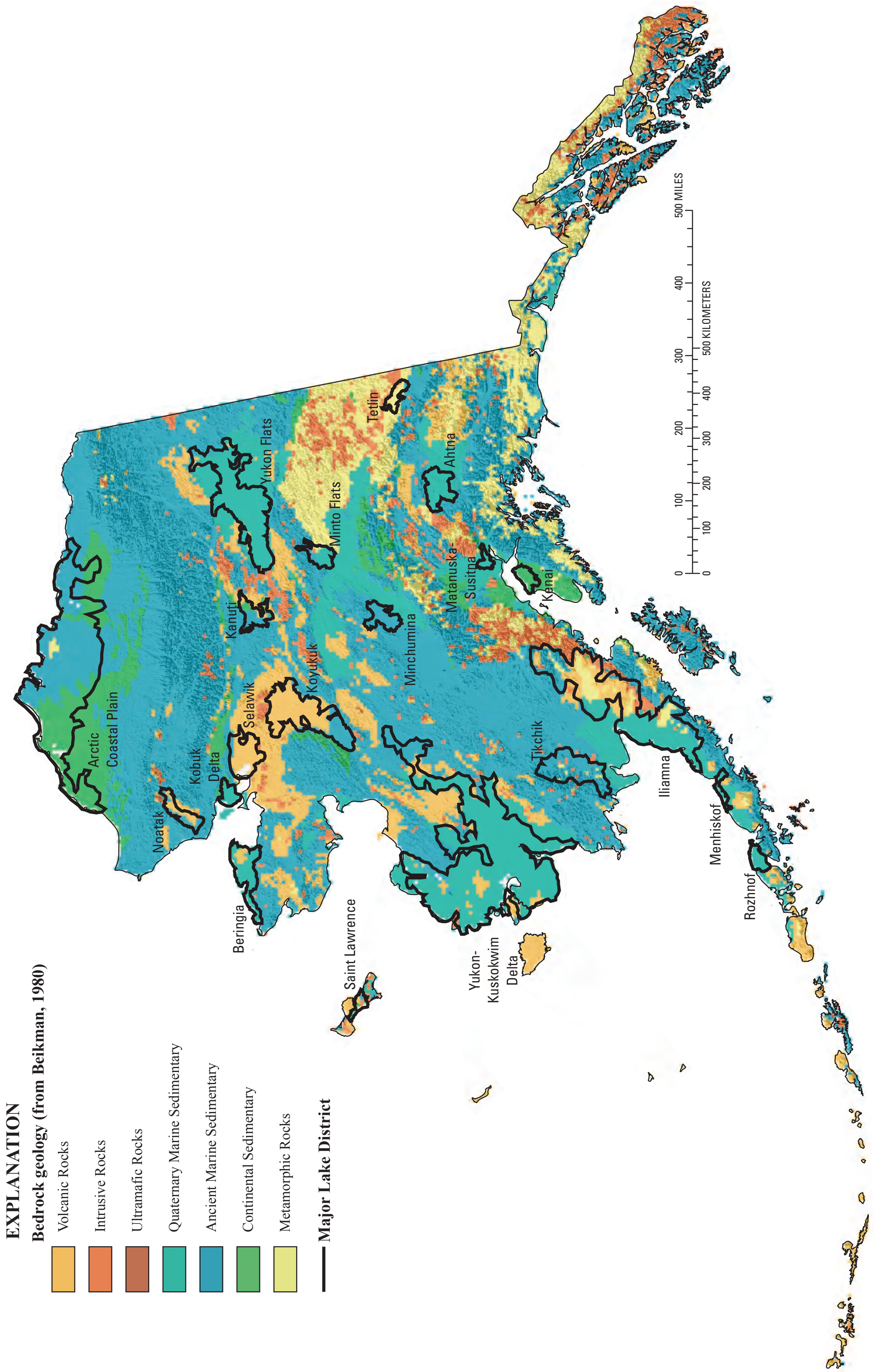

Figure 9. Generalized bedrock geology of Alaska in relation to major Alaska lake districts.

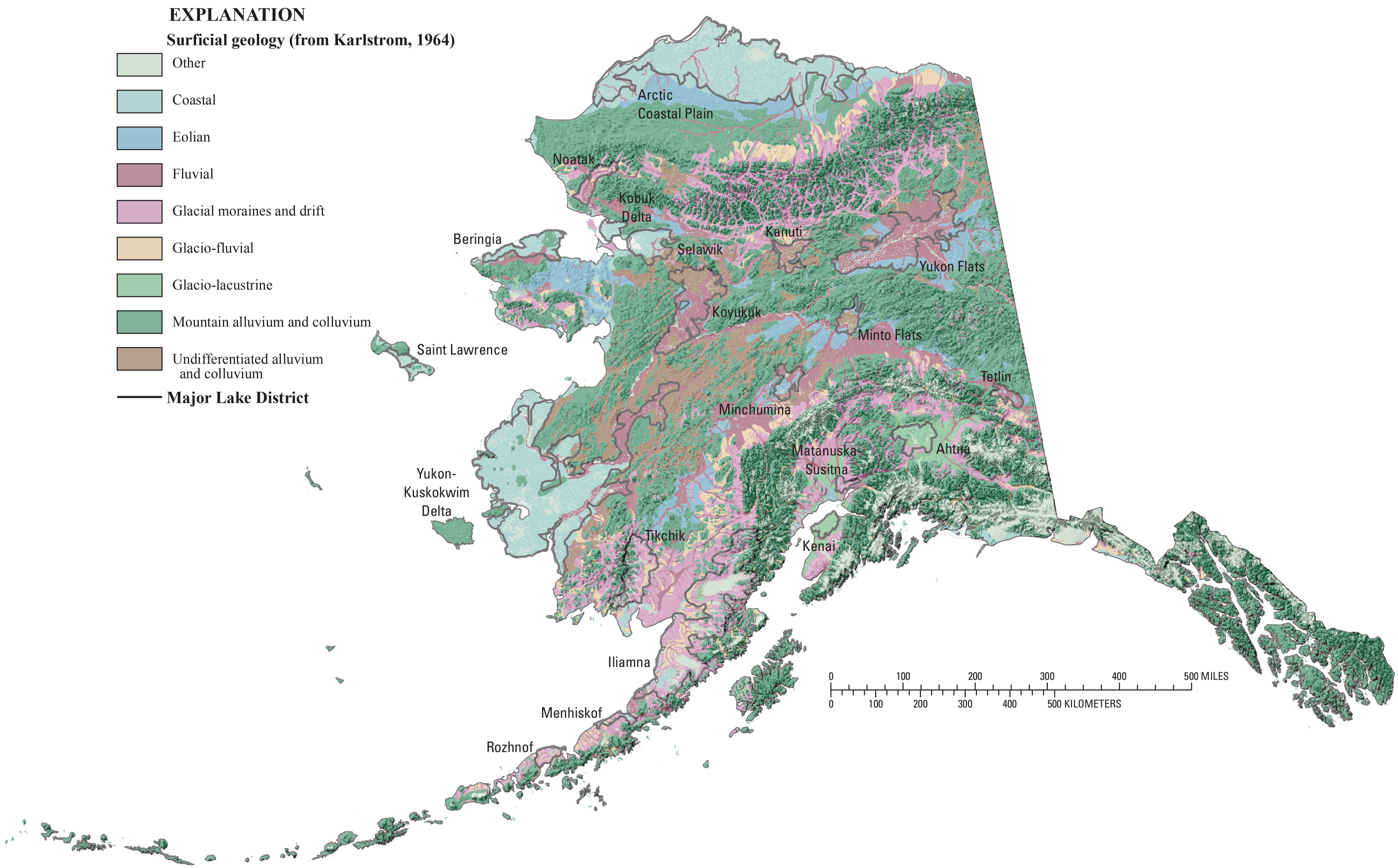

Figure 10. Surficial geology of Alaska and the major Alaska lake districts.

Table 5. Geophysical characteristics of major Alaska lake districts.

District	Dominant bedrock geology (Beikman, 1980)	Dominant surficial geology (Karlstrom, 1964)	Permafrost (Brown and others, 2001)	Glacial history (Manley and Kaufman, 2002)	Unified ecoregions (Nowacki and others, 2003)	
					Level I	Level II
Yukon-Kuskokwim Delta (YKD)	Marine Sedimentary	coastal	continuous	Unglaciated	polar	Bering taiga
Arctic Coastal Plain (ACP)	Marine Sedimentary	coastal	continuous	Unglaciated	polar	Arctic tundra
Iliamna (Ili)	Igneous	glacial	sporadic	Late Wisconsinan glaciers	maritime	Aleutian meadows
Yukon Flats (YF)	Quaternary Marine Sedimentary	fluvial	discontinuous	Unglaciated	boreal	Intermontane boreal
Koyukuk (Koy)	Igneous	fluvial	continuous	Unglaciated	boreal	Intermontane boreal
Tikchik (Tik)	Marine Sedimentary	glacial	sporadic	Late Wisconsinan glaciers	polar	Bering taiga
Beringia (Ber)	Marine Sedimentary	coastal	continuous	Unglaciated	polar	Bering Tundra
Selawik (Sel)	Igneous	coastal	continuous	Maximum Pliestocene extent	polar	Bering Tundra
Ahtna (Aht)	Quaternary Marine Sedimentary	glacio-lacusterine	continuous	Maximum Pliestocene extent	boreal	Pacific mountain transition
Kanuti (Kut)	Marine Sedimentary	undifferentiated alluvium / colluvium	continuous	Late Wisconsinan glaciers	boreal	Intermontane boreal
Minchumina (Min)	Marine Sedimentary	fluvial / eolian	continuous	Unglaciated	boreal	Intermontane boreal
Noatak (Noa)	Igneous	glacial / fluvial	continuous	Maximum Pliestocene extent	boreal	Intermontane boreal
Minto Flats (MF)	Marine Sedimentary	undifferentiated alluvium / colluvium	discontinuous	Unglaciated	boreal	Intermontane boreal
Kenai (Kai)	Continental Sedimentary	glacio-lacusterine	absent	Late Wisconsinan glaciers	boreal	Alaska Range Transition
Rozhnof (Roz)	Quaternary Marine Sedimentary	glacial	absent	Late Wisconsinan glaciers	maritime	Aleutian meadows
Kobuk Delta (KD)	Quaternary Marine Sedimentary	coastal	continuous	Maximum Pliestocene extent	maritime	Bering Tundra
Tetlin (Tet)	Metamorphic Rocks	fluvial / eolian	discontinuous	Unglaciated	boreal	Intermontane boreal
Menhiskof (Men)	Quaternary Marine Sedimentary	coastal / glacial	absent	Late Wisconsinan glaciers	maritime	Aleutian meadows
Matanuska-Susitna (Mat)	Quaternary Marine Sedimentary	glacial	absent	Late Wisconsinan glaciers	boreal	Alaska Range Transition

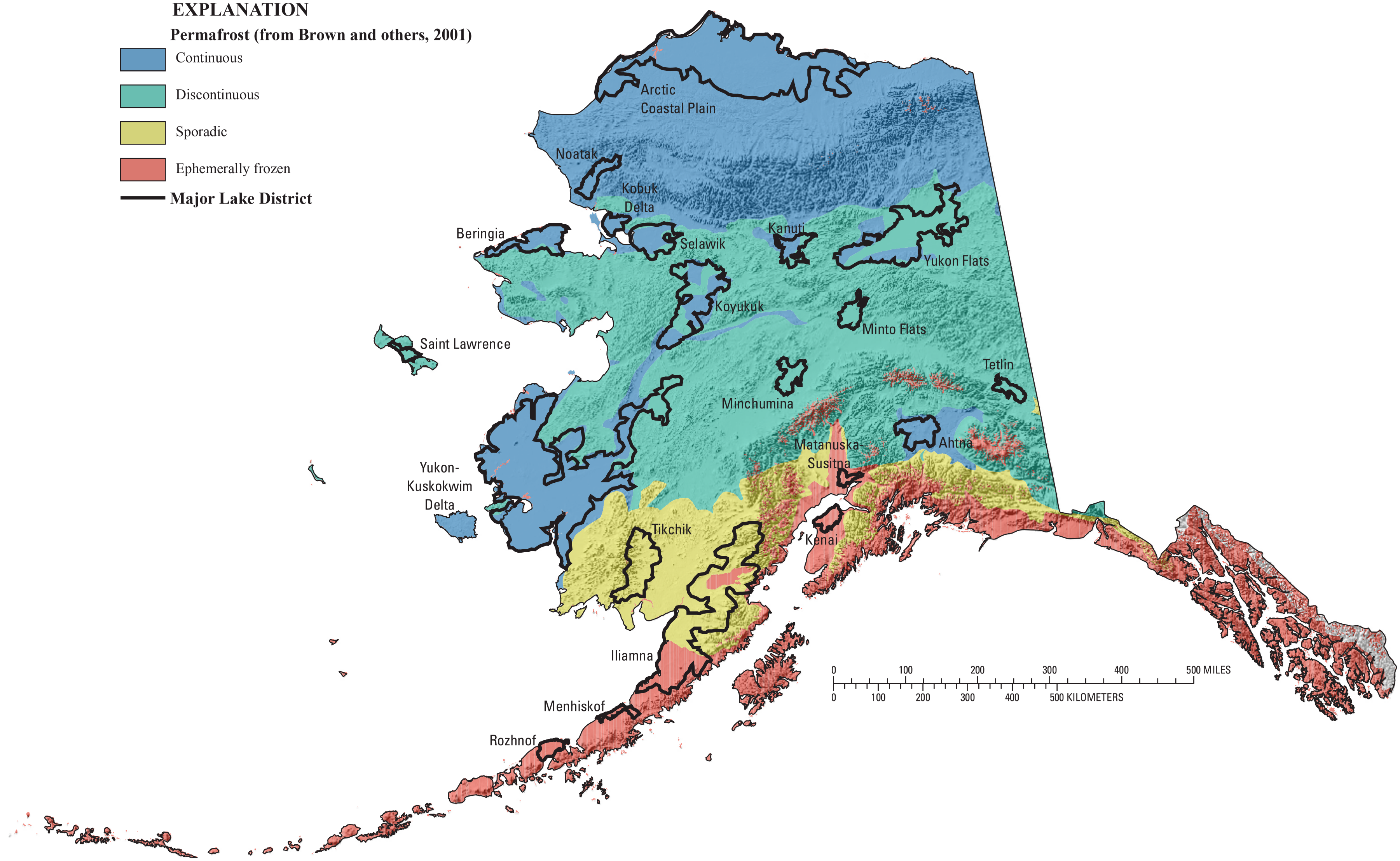

Figure 11. Soil permafrost characteristics in Alaska and location of major Alaska lake districts.

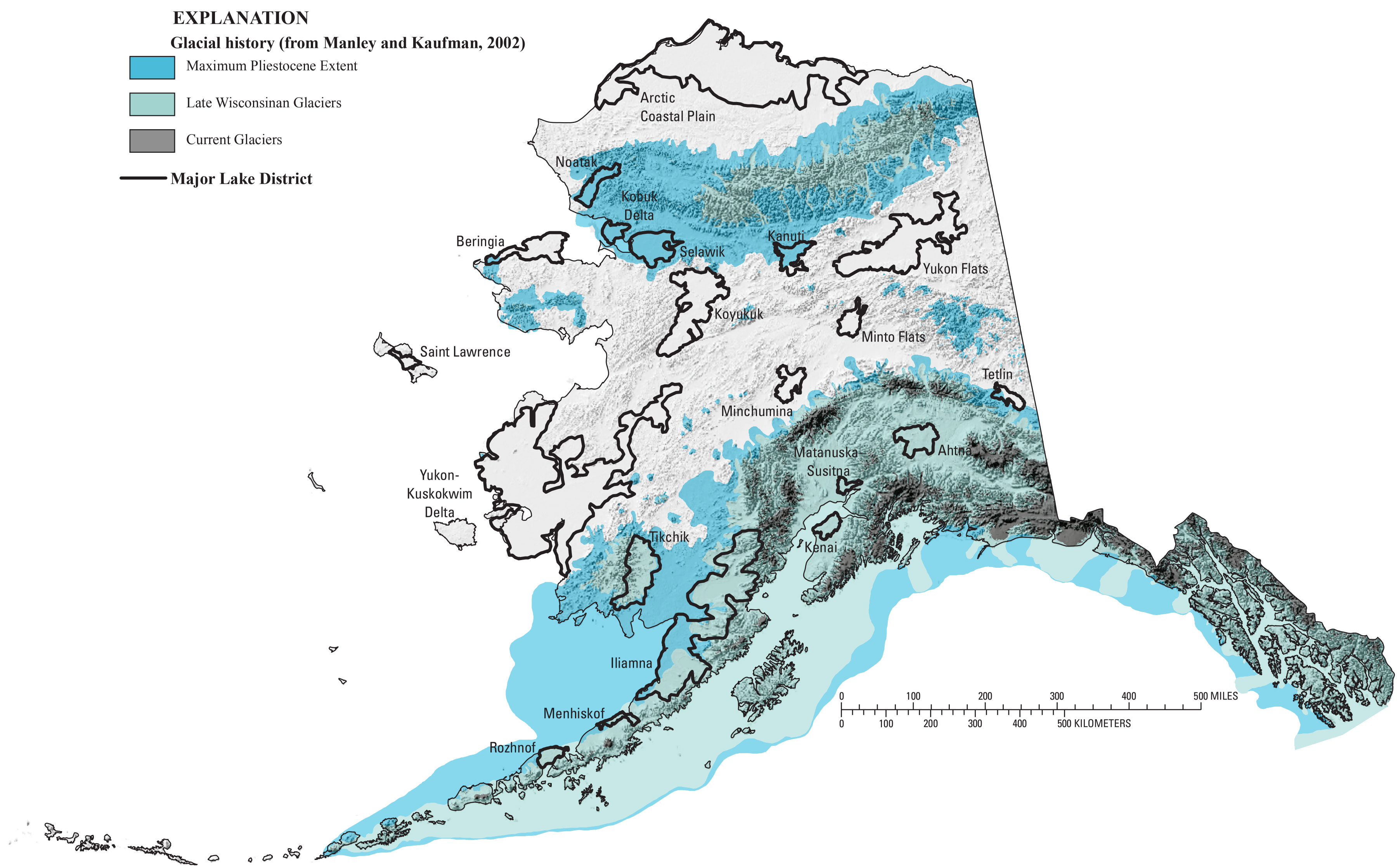

Figure 12. Current and historic glacial patterns in Alaska and location of major Alaska lake districts.

Climate

The Alaskan climate can be coarsely divided into three zones: maritime, continental, and arctic, with transitional zones between the maritime and continental, and a separate transitional / continental zone (Milner and others, 1997). Seven of the major lake districts are fully in the continental zone characterized by low precipitation, cold winters, and warm summers; nine are fully or partly in the transitional / continental zone in western Alaska along the Bering Sea coastline characterized by moderate precipitation and summer temperatures and cold winter temperatures; and two (Kenai and Matanuska-Susitna) are in the transitional zone characterized by moderate precipitation and annual temperatures. The Arctic Coastal Plain is the only lake district in the arctic climate zone occurring north of the Brooks Range, where both precipitation and temperatures are very low. No lake districts are in the maritime zone with very high precipitation and relatively warm winter temperatures. Comparison of global lake distributions to watershed runoff suggests that lake densities increase up to runoff of 1 m yr^{-1} and then lake densities become lower at higher runoff rates likely because of these erosional landscapes (Downing and others, 2006). Such a relation is likely found in mountainous regions of Alaska's maritime zone where rainfall is very high and glaciation is active. We were unable to compare lake districts to mean annual runoff due to lack of spatially representative stream discharge data. However, to provide more quantitative description of the climate regimes of these lake districts, we present spatially interpolated annual and seasonal temperature and precipitation data based on 1961–90 records (table 4).

Principal components analysis (PCA) of mean monthly temperature and precipitation for the Alaska lake districts were used to explore which seasons were most important for differentiating lake district climate regimes. This analysis suggested that temperatures during the seasonal shoulder months of March (fig. 13) and September, and the summer months of June and July (fig. 14), explain most of the variation among lake districts. Mean annual precipitation (fig. 15) helped explain additional variation among lake districts with particular emphasis on the winter (December, January, and February) and summer (June, July, and August) (fig. 16). These seasons or months selected for differentiating lake districts also should factor importantly in controlling local hydrologic conditions of lakes where total precipitation relative to summer evaporation determines the water budget of a lake and surface storage potential on the landscape. However, many lake districts are on floodplains of major rivers systems with distal headwaters, and local climate conditions may play a minor role in lake recharge (table 4). Temperature regimes during the shoulder months also affect lake ice dynamics and flood regimes of the lake districts associated with major rivers (that is,Yukon-Kuskokwim Delta, Yukon Flats, and Minto Flats) or mountain toe-slopes (that is, Tikchik, Matanuska-Susitna, and Iliamna). Cluster analysis using these mean climate summary data distinguished the Alaska Peninsula lake districts (Iliamna, Rozhnof, and Menhiskof) and Arctic Coastal Plain from the other lake districts, which have more similar climate regimes.

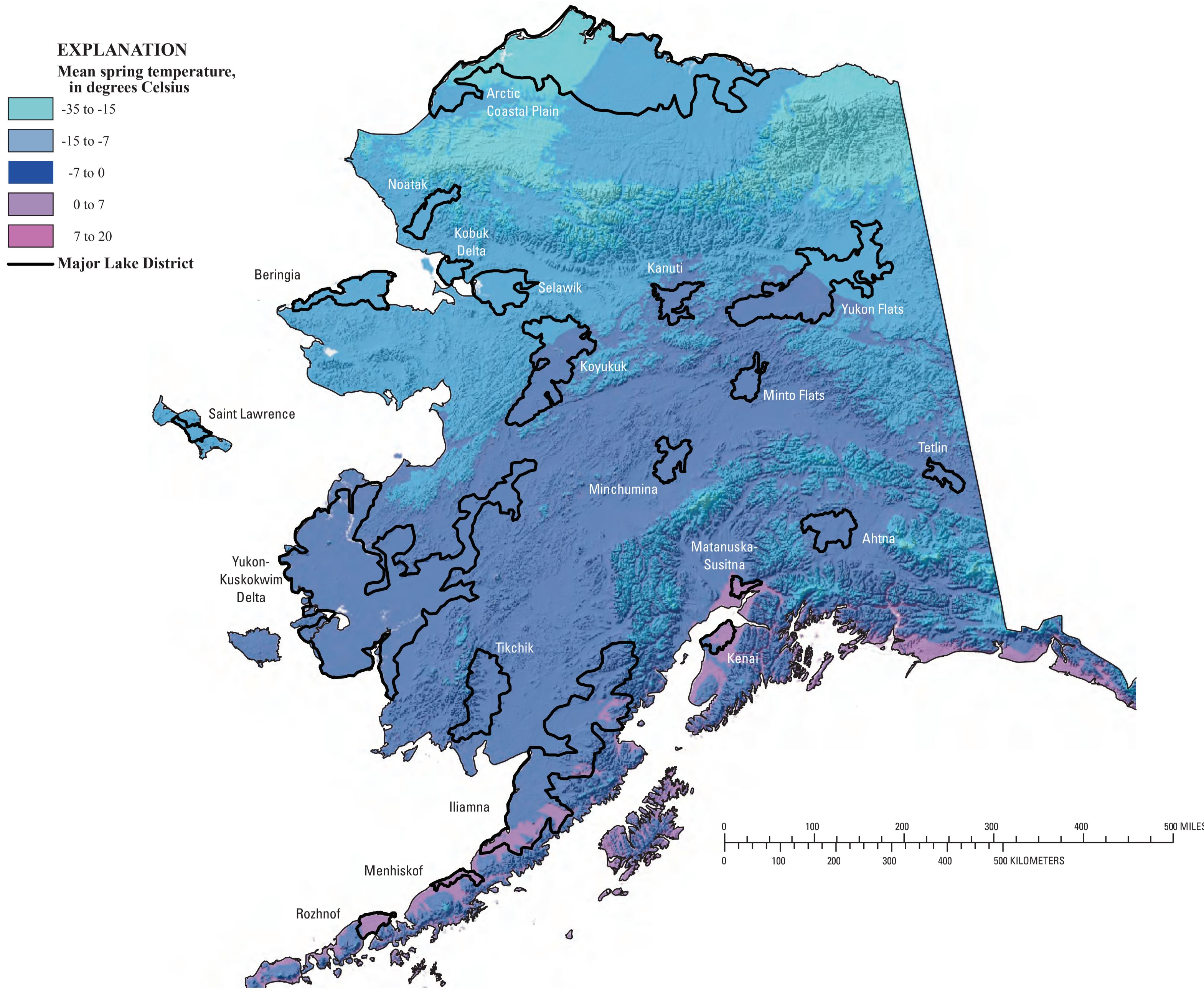

Figure 13. Mean spring temperature (March, April, and May) patterns based on 1-km grid of 1961–90 monthly means from climate station data in Alaska (Leeman and Cramer, 1991) and locations of major Alaska lake districts.

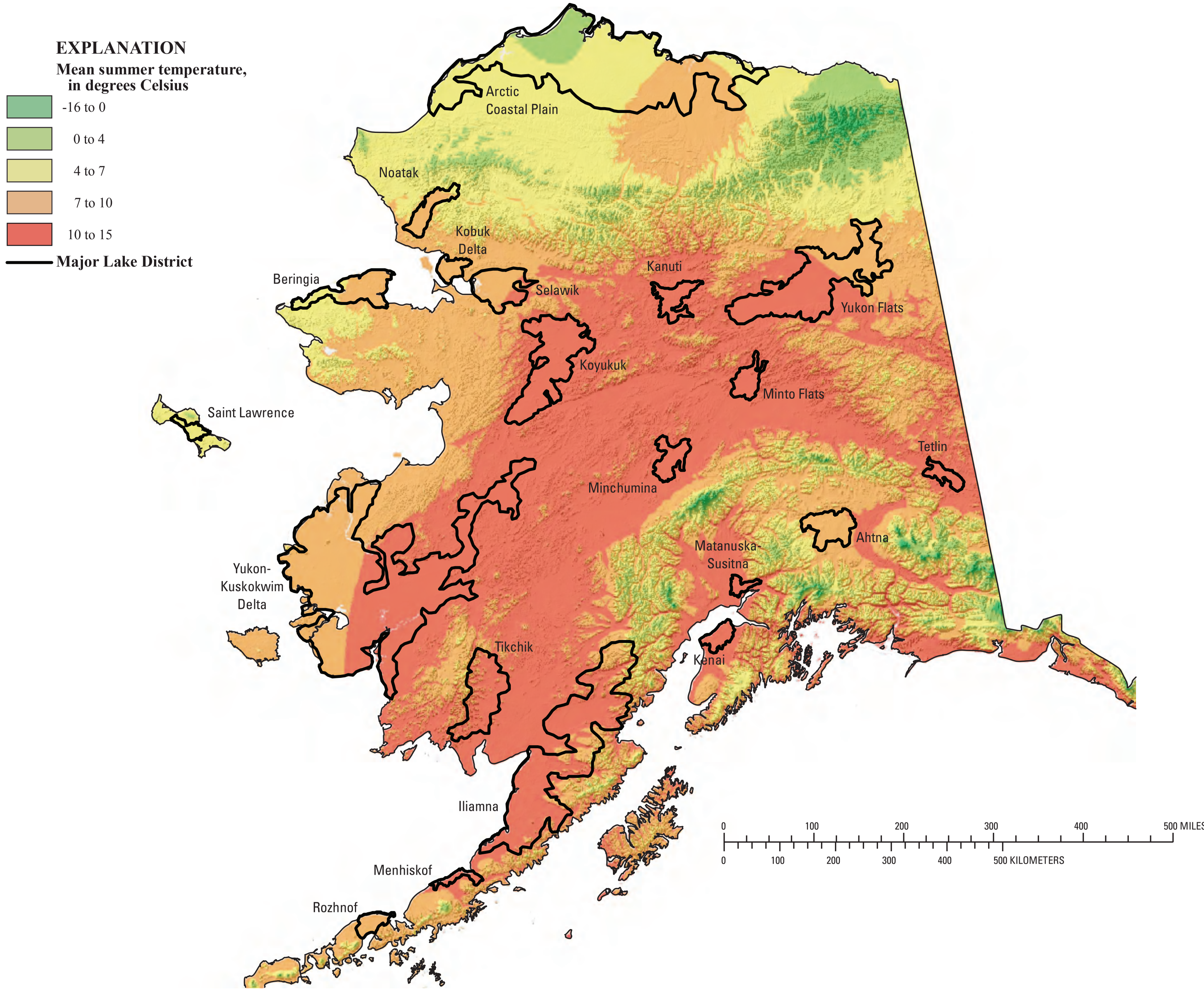

Figure 14. Mean summer temperature (June, July, and August) patterns based on 1-km grid of 1961–90 monthly means from climate station data in Alaska (Leeman and Cramer, 1991 and locations of major Alaska lake districts).

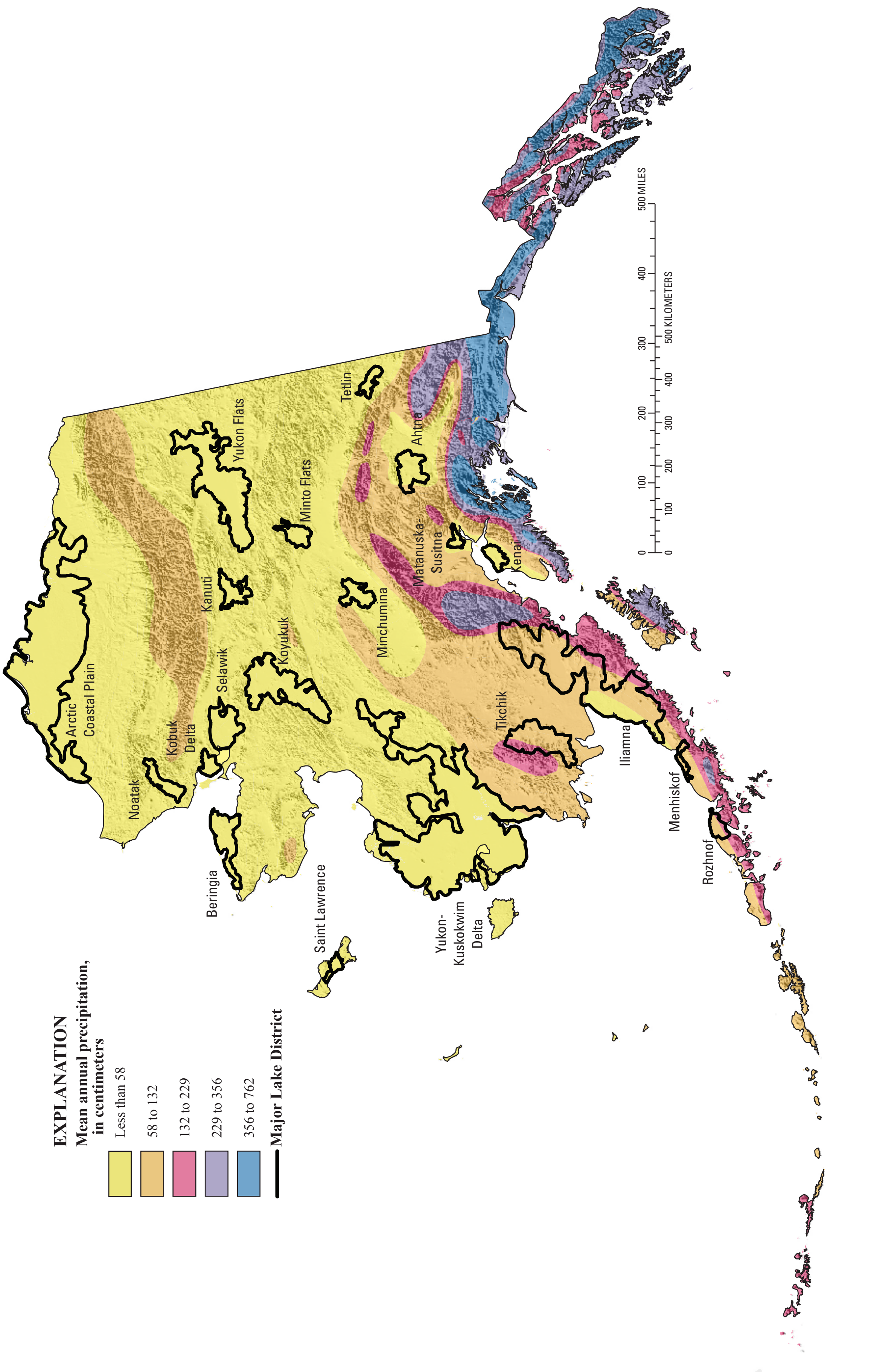

Figure 15. Mean annual precipitation patterns for Alaska (Jones and Fahl, 1994) and locations of major Alaska lake districts.

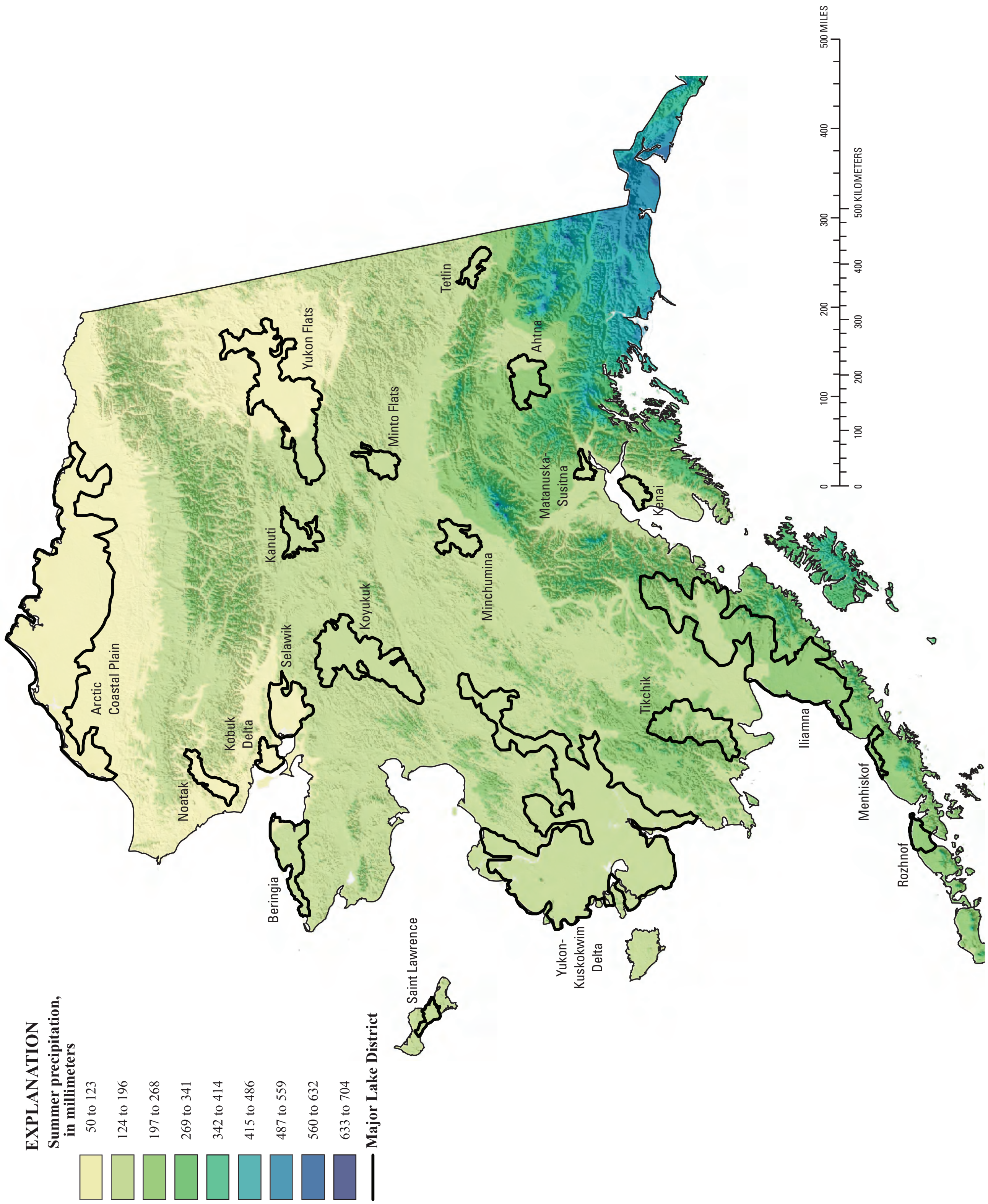

Figure 16. Mean summer precipitation (June, July, and August) patterns based 1-km grid of 1961–90 monthly means from climate station data in Alaska (Leeman and Cramer, 1991) and locations of major Alaska lake districts.

Ecoregions

Efforts to better classify and analyze the vast and diverse landscape of Alaska in an integrated way have resulted in the Unified Ecoregions of Alaska (Nowacki and others, 2003). This approach defines landscape-scale ecosystems based primarily on climate and topography, while also considering vegetation and geology. This system identified ecoregions based on three hierarchical levels of classification, where 31 ecoregions were distinguished at the finest level. Ecoregions are somewhat similar to lake districts in that they introduce a novel way of partitioning the landscape to facilitate scientific description and analysis; however. lake districts are based solely on hydrography relative to region (that is, Alaska) that bifurcate the landscape (lake district versus non lake district), whereas ecoregions are a classification of the entire landscape and utilize multiple natural attributes of the landscape—many of which have already been considered in describing and comparing the major Alaska lake districts independently. Thus, comparison of unified ecoregions to lake districts seems an interesting prospect, as ecoregions exist at multiple scales.

At level I (coarsest) of the ecoregions classification, 10 lake districts are in the boreal region, 5 in the polar region, and Iliamna occurs at the intersection of the boreal, polar, and maritime regions (fig. 17), which roughly follows climate zones. At level II with 9 classes, most lake districts occur within the Intermountain Boreal, Bering Tundra, and Aleutian Meadows classes (fig. 18). At the finest level (III), many lake districts share similar, and in a few cases exact, ecoregions boundaries, particularly lake district Arctic Coastal Plain with the corresponding Beaufort Coastal Plain ecoregion; and lake districts Beringia, Kobuk Delta, and Selawik with corresponding Kotzebue Sound Lowlands ecoregion. Other lake districts occur conspicuously along promontories or margins of particular ecoregions. For example, the Ahtna lake district occupies the western side of the Copper River basin ecoregion and Noatak and Kanuti lake districts occupy a northwestern arm (lower Noatak River drainage) and southeastern corner, respectively, of the Kobuk Ridges and Valleys ecoregion. The only lake districts that substantially overlap multiple ecoregions are Iliamna and Tikchik. All major Alaska lake districts are within just 14 of 32 ecoregions, confirming the importance of particular integrated climatic, topographic, and geologic characteristics associated with lake-rich landscape units.

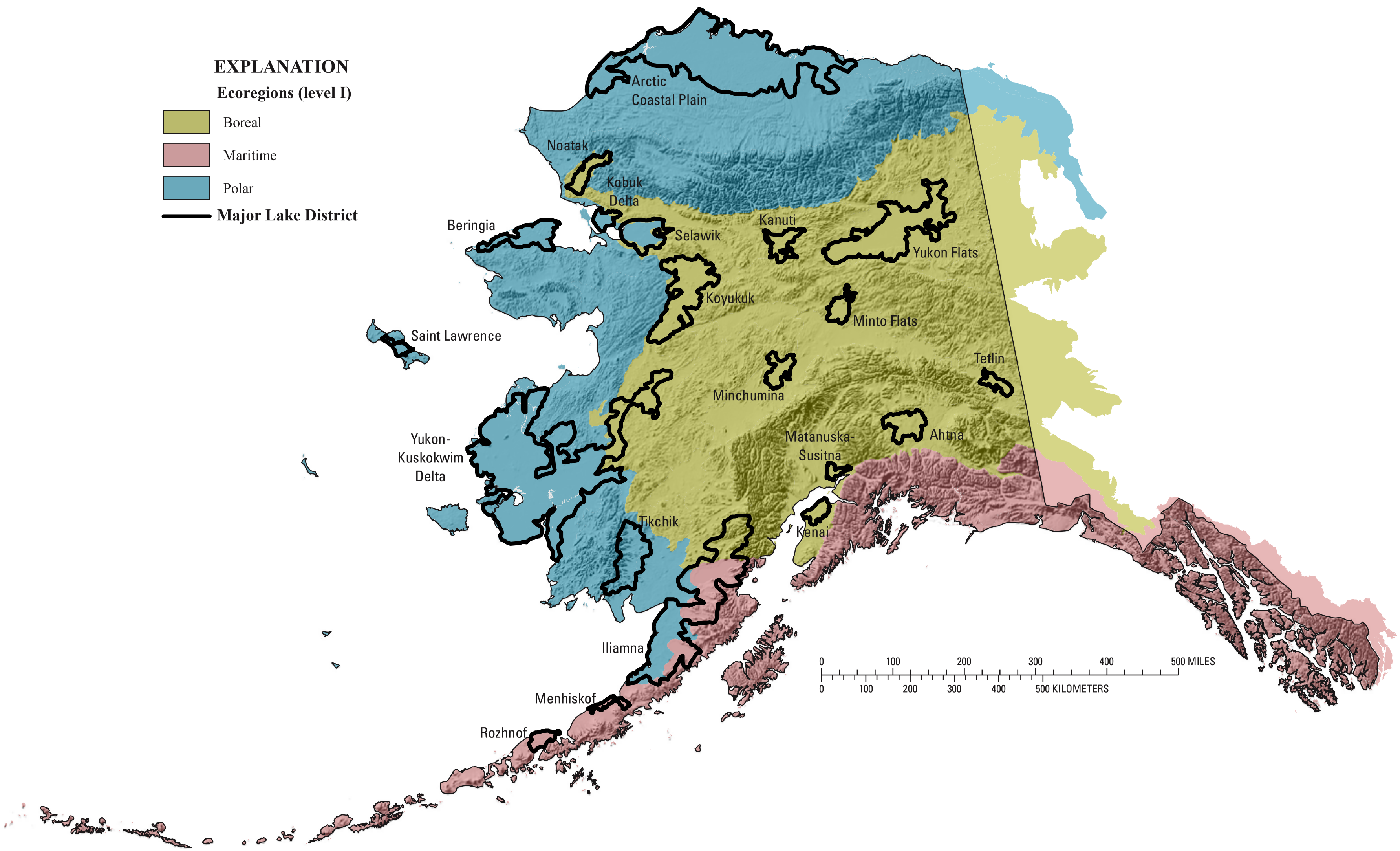

Figure 17. Ecoregions of Alaska (level I) (Nowacki and others, 2003) and locations of major Alaska lake districts.

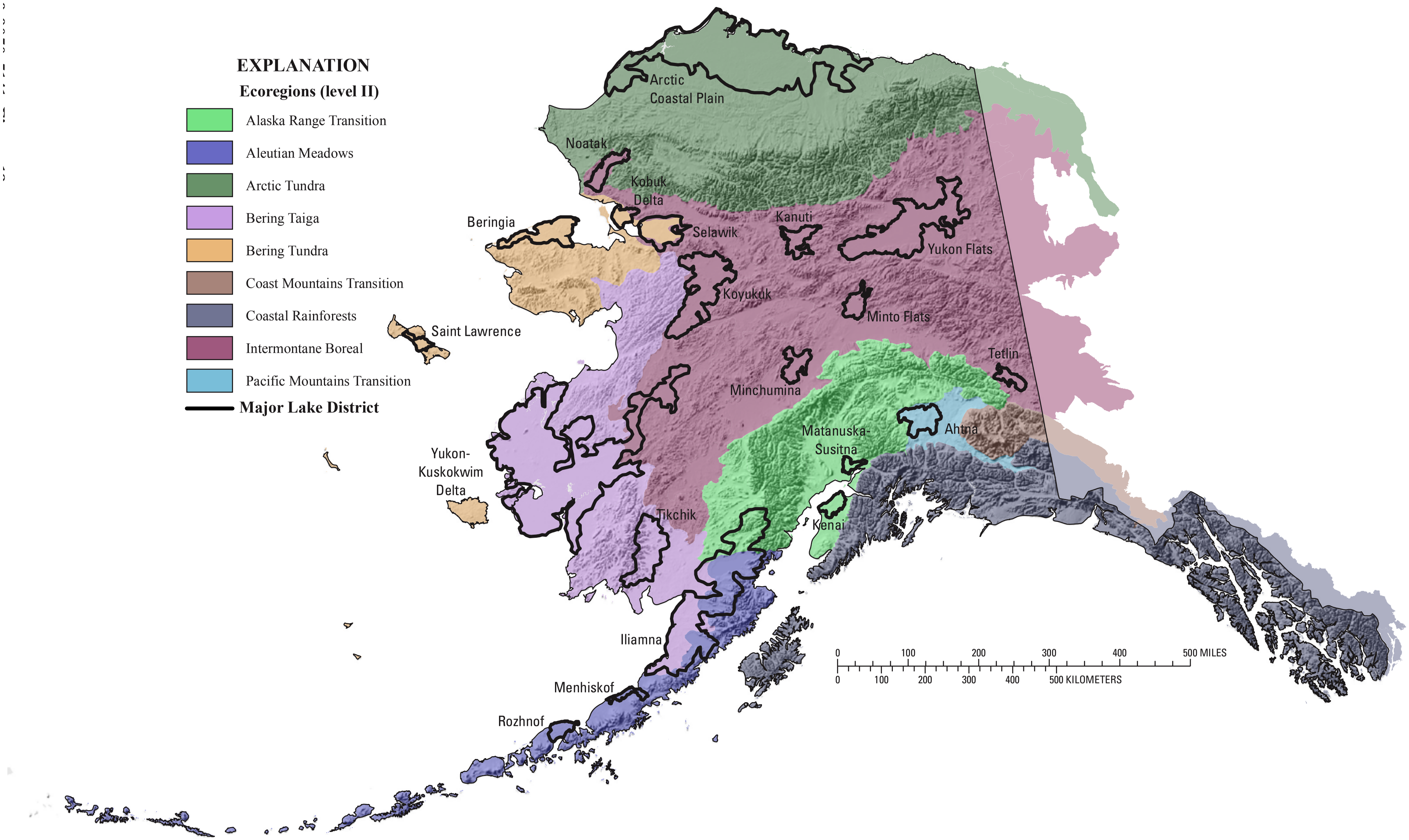

Figure 18. Ecoregions of Alaska (level II) (Nowacki and others, 2003) and locations of major Alaska lake districts.

Scientific Studies, Inventory and Monitoring Networks, and Land Management

Given our identification and description of these lake districts of Alaska, it seems appropriate to consider how these lands have been studied and are presently managed. Such consideration provides an opportunity to assess our current understanding of lake districts, know what information exists that can be brought to bear upon our understanding of lake districts, and help land management agencies realize the nature of lake districts so that they may share efforts with other agencies managing similar lands in Alaska.

As mentioned previously, Alaska has a long history of limnological research including much lake research focused on how lakes function as fish and wildlife habitat and how lakes respond and integrate land and climate change through paleolimnological analysis of sediment records. We chose a cross-section of 25 site-specific Alaska lake studies for geographical comparison relative to the major Alaska lake districts (fig. 19), as well as 10 studies that represent landscape-scale studies of lakes and lake related processes (table 6), to help illustrate where and what lake-focused science has been done in Alaska. Most of these studies are published in peer-reviewed journals that could be easily accessed, whereas much more quality scientific work concerning Alaska lake districts is described in government and consulting reports that is more difficult to access, and thus not included in this paper. A comprehensive annotated bibliography of all types of research in these lake districts would be of great value. A number of these studies represent important contributions to the field of limnology (for example, Goldman, 1960; Likens and Johnson, 1966), biological sciences (for example, Hershey, 1985; Finney and others, 2002), geophysical sciences (for example, Bowling and others, 2003; Jorgensen and Shur, 2007), and particularly climate change and carbon cycling research (for example, Riordan and others, 2006; Walter and others, 2007). However, like much field research and other human activities in Alaska, these have focused on areas where access is more feasible along the road system running from Anchorage to Prudhoe Bay, and large lakes and coastal zones near towns and villages. Much limnological research has focused on lakes in the Arctic Coastal Plain, Matanuska-Susitna, and Iliamna lake districts, while few, if any, such site-specific studies have occurred in the other 17 lake districts. The progressive increase in lake studies using remote sensing techniques, however, is substantially broadening our understanding of less accessible places in Alaska including important work that has focused on and compared a number of lake districts (that is, Riordan and others, 2006). Yet, without corresponding on-the-ground studies, it is highly likely that such remote sensing analyses will yield inaccurate conclusions.

Inventory and monitoring networks show similar patterns as described for lake research in Alaska. We specifically looked at five types of inventory and monitoring programs that relate to lakes in the State: (1) National Oceanic and Atmospheric Administration weather stations, (2) USGS streamflow-gaging stations, (3) USGS water-quality stations, (4) U.S. Fish and Wildlife Service waterfowl breeding populations survey transects, and (5) long-term ecological research stations (LTER) (fig. 20). Weather stations that provide climate data generally are located at airports, thus providing wide and representative distribution for much of the State including lake districts, although Tikchik, Menhiskof, Minto Flats, and Beringia only have adjacent weather stations. Many streamflow-gaging stations are located in Tikchik, Iliamna, Matanuska-Susitna, and Arctic Coastal Plain, although most other lake districts have few current or adjacent gaging stations (fig. 20). This follows a general statewide pattern of patch representation in time and space. An important aspect of lake hydrographic research suggests a relation of d_L and *LR* to regional watershed runoff (Meybeck, 1995); however, lack of spatial coverage of streamflow-gaging stations prohibits such analysis in Alaska. Locations where lake water quality has been sampled by the USGS are also patchy in time and space with five lake districts lacking any USGS water-quality stations, although sampling campaigns have certainly been done in many of these areas by other agencies and researchers (for example, Likens and Johnson, 1968; Edmundson and others, 2000). All three LTER stations in Alaska are located outside lake districts, although lake ecosystems research occurs in each, particularly Toolik Lake LTER. Waterfowl breeding bird surveys are systematically done throughout several lake districts including Beringia, Kobuk Delta, Selawik, Koyukuk, Yukon-Kuskokwim Delta, Iliamna, Yukon Flats, Minto Flats, Minchumina, Ahtna, Matanuska-Susitna, Kenai, and Tetlin, as lake districts represent important waterfowl and other avifauna habitat and often correspond to Federal or State wildlife refuges. Other comprehensive biogeographical inventories of Alaska that pertain to lake-associated organisms generally are lacking or at least not synthesized in a geographic manner. Such biogeographical inventory and analysis of Alaska would be very interesting to compare to the major Alaska lake districts, particularly communities of fish, zooplankton, and aquatic macroinvertebrates and macrophytes, and populations of mammals. The National Park Service Inventory and Monitoring Network has been implementing comprehensive programs in recent years that include monitoring of shallow lakes and large lakes in parks with lands in several Alaska lake districts. Coupling such programs of the National Park Service with the interests of the U.S. Fish and Wildlife Service, which together in Alaska manage most of lake district lands, might be of great value.

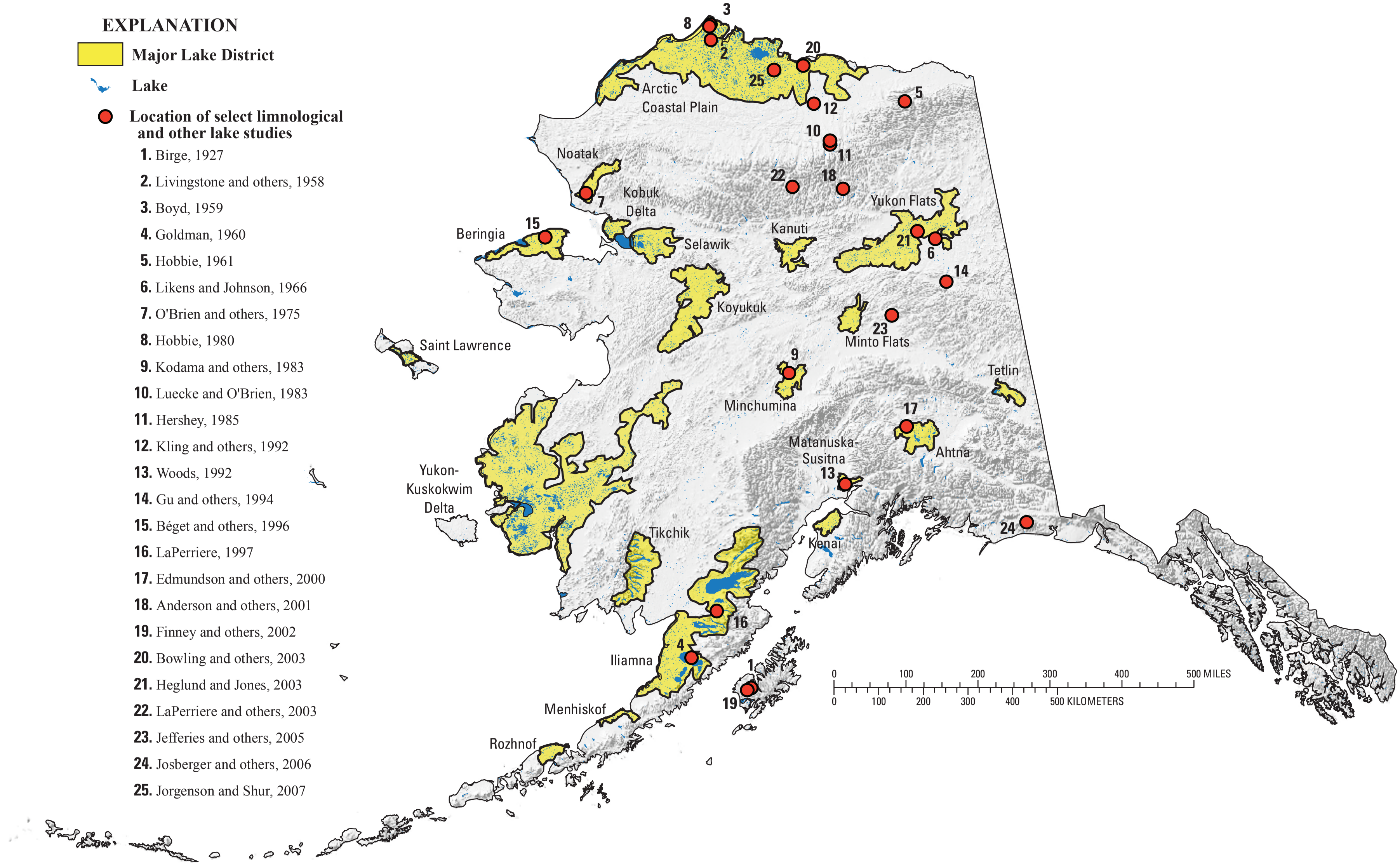

Figure 19. Major Alaska lake districts relative to the location of select limnological and other lake studies .

Table 6. Several regional scale studies focused on varying aspects of Alaska lakes.

Reference	Study area	Research focus
Likens and Johnson, 1968	Interior (Northway and Yukon Flats) and north slope (Barrow) Alaska	Limnological survey with inter-regional comparisons and functional analysis
Sellman and others, 1975	Alaskan arctic coastal plain	Regional analysis of thermokarst lake distribution and geomorphology in landscape context
Landers and others, 1995	Brooks Range, arctic coastal plain, and Denali National Park and Preserve (Wonder Lake)	Inventory and historic deposition. Reconstruction of mercury in lake sediments and vegetation
Jefferies and others, 1996	North Slope (Barrow and Meade River)	Analysis of lake ice dynamics in the context of climate and lake morphology
Edmundson and Mazumder, 2002	Southeast, South-central, and Kodiak Islands	Characterization of lake responses to climate based on source-waters
Sturm and Liston, 2003	North Slope (transect from Barrow to Brooks Range)	Characterization and analysis of snow on lakes
Holtham and others, 2004	Kodiak Island, Alaska and Vancouver Island, British Columbia, Canada	Paleolimnological analysis of salmon populations
Hinkel and others, 2005	Inner Arctic Coastal Plain (North Slope)	Geographic analysis of thermokarst lake morphology and abundance
Riordan and others, 2006	Interior and Arctic Coastal Plain	Lake change in relation to climate change
Walter and others, 2007	Northern Alaska, Siberia, and Canada	Patterns of methane release from thermokarst lake in the Arctic

Most of Alaska lake districts correspond to lands of high natural resource value (for example, wildlife and recreation) and low potential for urban or transportation development due to abundant lakes and associated wetlands that make development difficult. Nine lake districts are associated with National Wildlife Refuges, particularly Yukon-Kuskokwim Delta, Koyukuk, Selawik, Kobuk Delta, Kanuti, Yukon Flats, Kenai, and Tetlin that occur almost fully within National Wildlife Refuge boundaries (fig. 21). Minto Flats and significant parts of Menhiskof and Rozhnof are part of State wildlife protected lands, and Tikchik is mostly part of the Wood-Tikchik State Park. Four lake districts occur partly in National Parks and Preserve lands. Most of the Arctic Coastal Plain Lake District is part of the National Petroleum Reserve – Alaska, which is administered by the Bureau of Land Management, and the remainder of the district is State and refuge land (fig. 21). The only major lake districts we identified without land management designations based on natural resources management were Ahtna and Matanuska-Susitna located in the Matanuska – Susitna Borough. A better understanding of lake districts in Alaska could usefully serve the many agencies charged with management of these lands and waters and facilitate more coordinated management of lands rich in lakes.

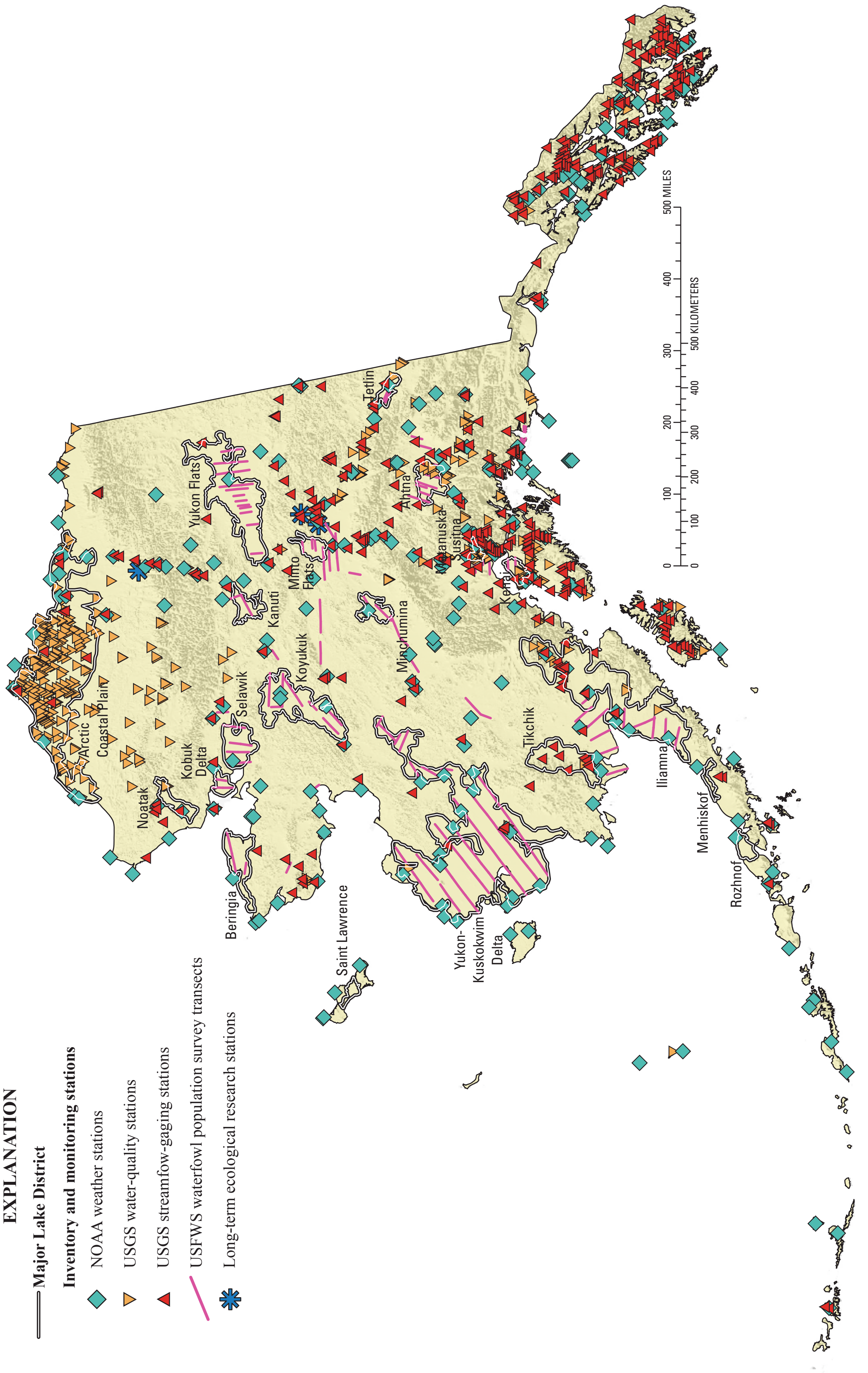

Figure 20. Locations of several types of inventory and monitoring stations and major Alaska lake districts.

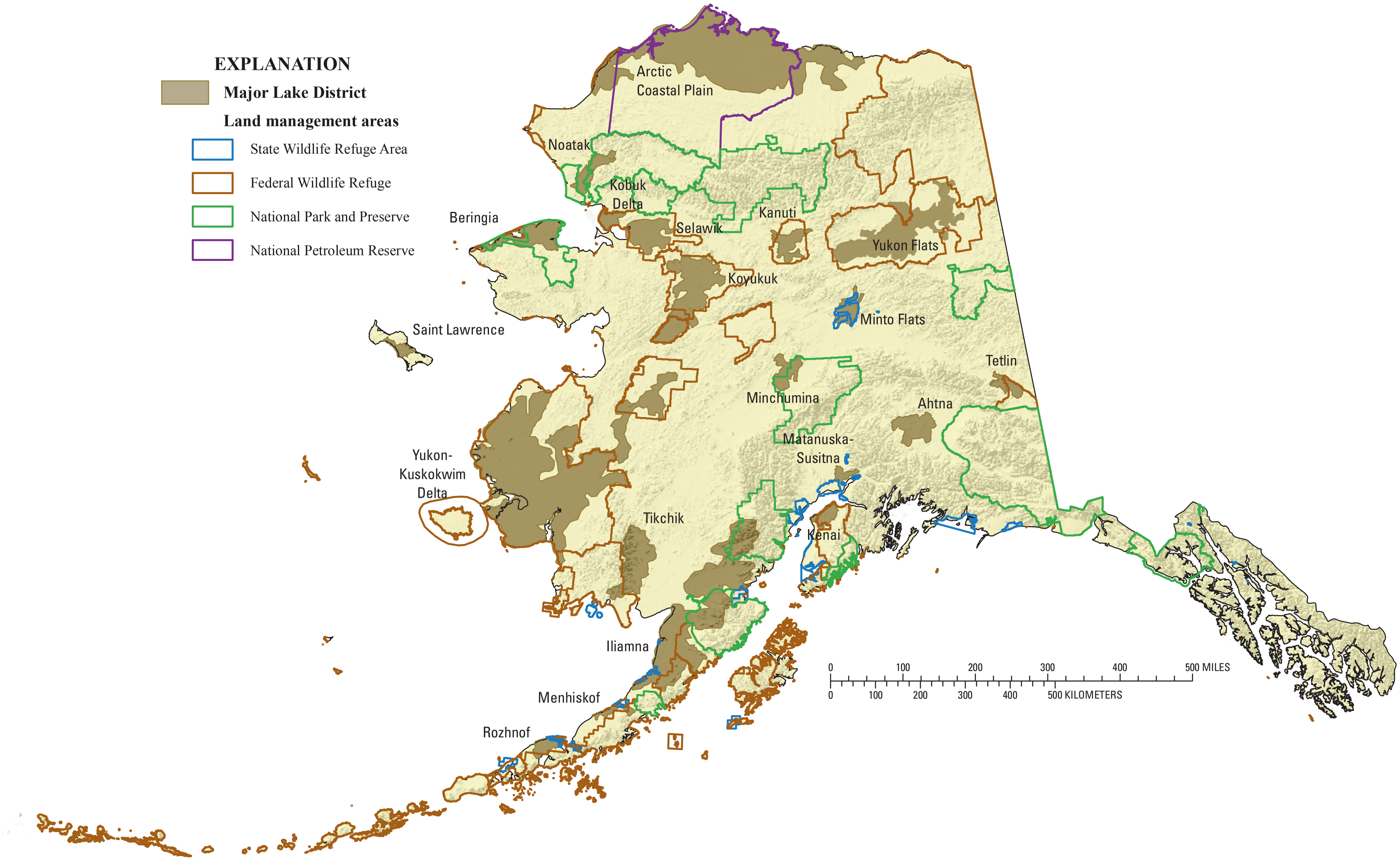

Figure 21. Land management designations and locations of major Alaska lake districts.

Summary and Future Work

In this work, we have identified and delineated 20 major lake districts of Alaska using a simple, quantitative approach that scales with the region of interest and resolution of lake geography dataset. Lake districts are common features of many regions of the world, particularly permafrost and paraglacial environments at high latitudes and riverine and deltaic landscapes worldwide, yet little scientific attention has been given to lake districts as distinct landscape units. By formally identifying and describing Alaska lake districts, it is our goal that this will foster multi- and inter-disciplinary scientific investigation of these landscape units in the future.

We conclude here by offering several questions concerning Alaska lake districts that may serve as interesting and useful lines for future research:

- What are the major processes and times of lake formation within and among lake districts?
- Do lake districts share a common spatial organization of lakes by morphometry, origin, and succession?
- What is the temporal coherence (synchronicity) of hydrologic and thermal regimes and annual events, such as freeze-up and ice-out, thermal stratification and mixing, chlorophyll maxima, and arrival and departure of migratory fish and waterbirds, within and among lake-district lakes?
- What is the total lake-water stored in lake districts, how does this change seasonally and interannually, and by what processes and to what effects?
- How do lake districts affect regional climate regimes and how do such processes interact with climate change and decadal oscillations?
- Do lake districts serve as net sources or sinks for carbon, nutrients, and other elements, at what time scales, and how do such biogeochemical processes interact with land and climate change?
- How do water, sediment, and biota in lakes respond to and integrate atmospheric deposition of pollutants and contaminants within and among lake district?
- How do the insights into climate, land, and biological change from sedimentological (lake core) studies vary and improve with analysis of multiple lakes in a district or when compared among lake districts?
- What are the biological community properties and processes within and among lake districts, and how does biodiversity, endemism, and species abundance vary among lake districts and why?
- What is the hydrologic connectivity (surface and subsurface) of lakes within lake districts, how does this vary over time, and what are the implications of hydrologic connectivity and isolation on biogeography and biological evolution?
- What role have lake districts played in pre-historic human colonization and migration patterns?
- What are the critical ecosystem services provided and hazards created by lake districts with respect to modern human communities and economies, and how do such services and hazards interact with local resource uses and climate change?

These are a few general questions to consider for future research in Alaska and elsewhere. Many of these ideas focus directly on many lakes within a land unit, but we stress here that lake districts are intended to be considered as land units without the need for consideration and study of lakes directly (that is, lake districts can be studied without studying lakes). Most of the State, 84 percent, is not part of a major lake district, but still have lakes, which individually may have greater intrinsic value that serve vital functions to the surrounding landscape and people due to their lower abundance. Comparison of lakes within lake districts to lakes outside of lake districts, and similarly upland attributes and processes inside and outside of lake districts, may prove of equal interest for pursuing these types of questions for Alaska research.

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