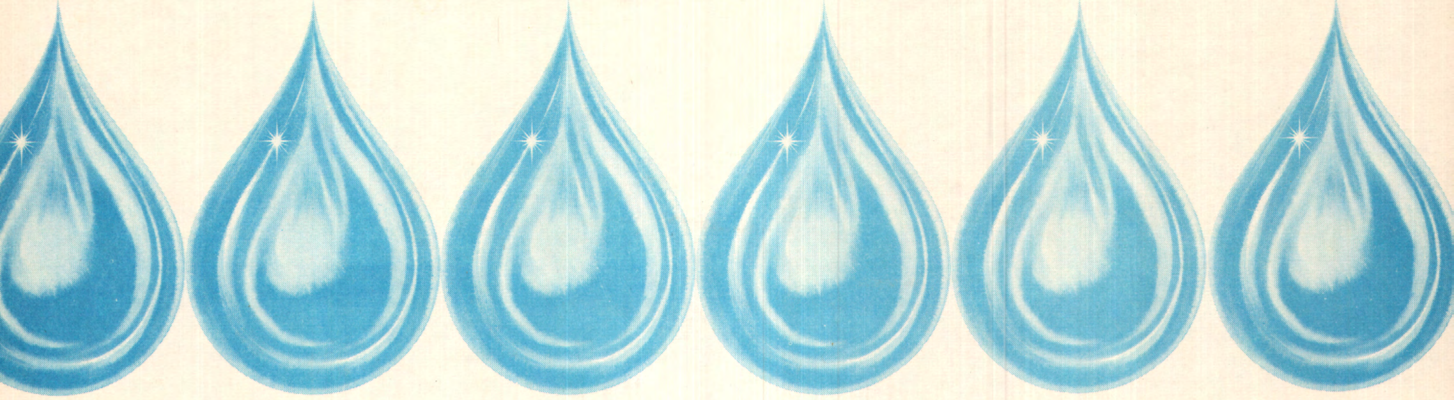

COMPARISON OF SELECTED CULTURAL, PHYSICAL, AND WATER-QUALITY CHARACTERISTICS OF LAKES IN WASHINGTON

U.S. GEOLOGICAL SURVEY

Water-Resources Investigation 77-62

Prepared in Cooperation With
State of Washington Department of Ecology

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Lakes, State of Washington

17c. COSATI Field/Group

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1979

UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, Secretary

GEOLOGICAL SURVEY

H. William Menard, Director

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METRIC-ENGLISH CONVERSION FACTORS

In recognition of a worldwide trend to adoption of the metric system of measurements (SI or System Internationale), metric values are used in this report. However, the following factors are provided for conversion of metric values to English values:

Multiply	By	To obtain
Centimeters (cm)	0.3937	inches (in)
Meters (m)	3.281	feet (ft)
Hectares (ha)	2.471	acres

GLOSSARY

Algae. Simple plants, many microscopic; contain chlorophyll and lack roots, stems, and leaves. Most algae are aquatic and may become a nuisance when environmental conditions are suitable for prolific growth.

Algal bloom. A large number of a particular algal species. A condition when water looks green because of the abundance of planktonic algae.

Basalt lava flows. Widespread outpourings of dark-colored fine-grained igneous rock, and the resulting solidified layers of the rock.

Bathymetric. Relating to the measurement of water depths, as for a lake. A bathymetric map shows contours of the lake bottom.

Channeled scablands. Areas of the Columbia Plateau where the underlying rock, chiefly basalt lava flows, has been exposed and channeled by catastrophic flood-waters.

Coulee. A steep-sided gulch or water channel.

Eutrophication, eutrophic. The enrichment of water, a natural process that may be accelerated by the activities of man; pertains to waters in which productivity is generally high as a consequence of a large supply of available nutrients.

Fecal-coliform bacteria. The fecal-coliform group is defined as all organisms that produce blue colonies when grown on a specified medium at 44.5°C for 24 hours. Fecal coliforms are that part of the total-coliform group present in the gut or feces of warmblooded animals. The total-coliform group (not reported in this survey) is defined as any colony that exhibits a characteristic golden metallic sheen when grown on a specified medium at 35°C for 18 to 24 hours. The presence of total coliforms may suggest contributions from sources of nonfecal origin as well as fecal.

Intermontane. Lying between mountains.

Mean depth. The volume of the lake divided by the area.

Nutrient. Any chemical element, ion, or compound that is required by an organism for the continuation of growth, for reproduction, and for other life processes.

Photosynthesis. A biochemical synthesis of carbohydrates from water and carbon dioxide in the chlorophyll-containing tissues of plants in the presence of light.

Pleistocene Epoch. A period of increased glacial activity, also known as the "ice age."

Respiration. A life process in which carbon compounds are oxidized to carbon dioxide and water and the liberated energy is used in metabolic processes.

Secchi disc. A circular metal disc 20 centimeters in diameter used to measure the transparency or clarity of water. The disc is usually painted in alternating black and white quadrants. When suspended to various depths by means of a graduated line, its point of disappearance indicates the limit of visibility.

Thermal stratification. A temperature distribution characteristic of many lakes in which the water is separated into three horizontal layers: (1) an upper zone (epilimnion) of generally warmer water in which temperature is more or less uniform throughout; (2) an intermediate zone (metalimnion) in which temperature decreases rapidly with depth; and (3) a lower zone (hypolimnion) of colder water in which temperature is again more or less uniform throughout.

Trophic. Relating to the degree of production in a lake. Lakes in which productivity is low are called oligotrophic; lakes in which productivity is high are called eutrophic. Lakes in which productivity is moderate are called mesotrophic.

COMPARISON OF SELECTED CULTURAL, PHYSICAL,

AND WATER-QUALITY CHARACTERISTICS OF LAKES

IN WASHINGTON

By G. C. Bortleson and N. P. Dion

ABSTRACT

This report presents comparisons and a graphical overview of the relative magnitude and the regional and statewide distribution of 19 selected cultural, physical, and water-quality characteristics measured in a reconnaissance study of several hundred lakes in Washington. The selected characteristics presented for each lake include types of land use in the lake drainage basin, shoreline residential development, altitude of lake, mean lake depth, nitrogen and phosphorus concentrations in upper and bottom waters, specific conductance, temperature and dissolved-oxygen concentration of bottom water, Secchi-disc visibility, emersed macrophytes covering shoreline and lake surface, and fecal-coliform bacteria.

Statewide, about two-thirds of the lake drainage basins studied have more than half their land in forest. Urban and suburban developments of the basins are highest in the more populated western Washington counties near Puget Sound, whereas most land in the drainage basins of lakes in the Columbia Plateau of eastern Washington is used for agricultural purposes. Statewide, almost one-fourth of the lakes are shallow (mean depth 2.0 meters or less) and only 7 percent of the lakes have mean depths greater than 20 meters. Dissolved-oxygen layering in summer was detected in many lakes throughout the State. The oxygen concentrations in the upper waters of these lakes were typically near saturation, but the bottom waters of many were severely depleted. Statewide, about one-third of the lakes had Secchi-disc readings of 2.0 meters or less, a value often considered characteristic of eutrophic lakes. The poorest water clarity was observed in the Columbia Plateau, where 68 percent of the lakes had Secchi-disc readings of less than 2.0 meters. Statewide, the median concentration of total phosphorus in the upper waters of lakes was 20 micrograms per liter. More than one-third of the lakes in the State had total phosphorus concentrations in their upper waters that exceeded 30 micrograms per liter, a concentration that is often considered characteristic of eutrophic lakes.

INTRODUCTION

In 1973-74 a reconnaissance study of 760 lakes and reservoirs in Washington was made by the U.S. Geological Survey in cooperation with the State of Washington Department of Ecology. In general, the statewide reconnaissance consisted of a data-collection program designed to document the status of lakes in terms of their cultural, physical, and water-quality characteristics. The need to document the water-quality and overall lake conditions is specifically required of each State in the "Clean Lake" section of the 1972 Amendments to the Federal Water Pollution Control Act. In partial response to this need, this report was prepared to (1) provide a simple, comparative overview of the large amount of information obtained from the lake reconnaissance, and (2) describe noticeable regional and statewide trends and patterns. The data used for this analysis were obtained from a seven-volume series of reports that present basic data for each lake (Bortleson and others, 1976a-1976d; Dion and others, 1976a-1976c). The individual lake data are grouped in this report for the purpose of providing the lake manager with descriptive statistics necessary to determine whether a given value of a characteristic for a certain lake is medium, high, or low compared with values of other lakes.

Lakes covered by the State Shoreline Management Act of 1971 served as a basis for lake selection (Washington Department of Ecology, 1973a). These lakes number about 760 and include those greater than 8 hectares in area and not situated entirely on Federal lands, such as national forests, national parks, Indian reservations, and wilderness areas. The data are representative of both high- and low-altitude lakes throughout the State; however, most of the lakes in the State are at low altitude and consequently they are more vulnerable to the effects of man's activities.

For purposes of this report, the counties of the State were grouped into seven numbered regions (fig. 1). The distributions of ranges in values are given for 19 types of characteristics describing the cultural, physical, and water-quality conditions of the lakes in these seven regions, and in the State as a whole.

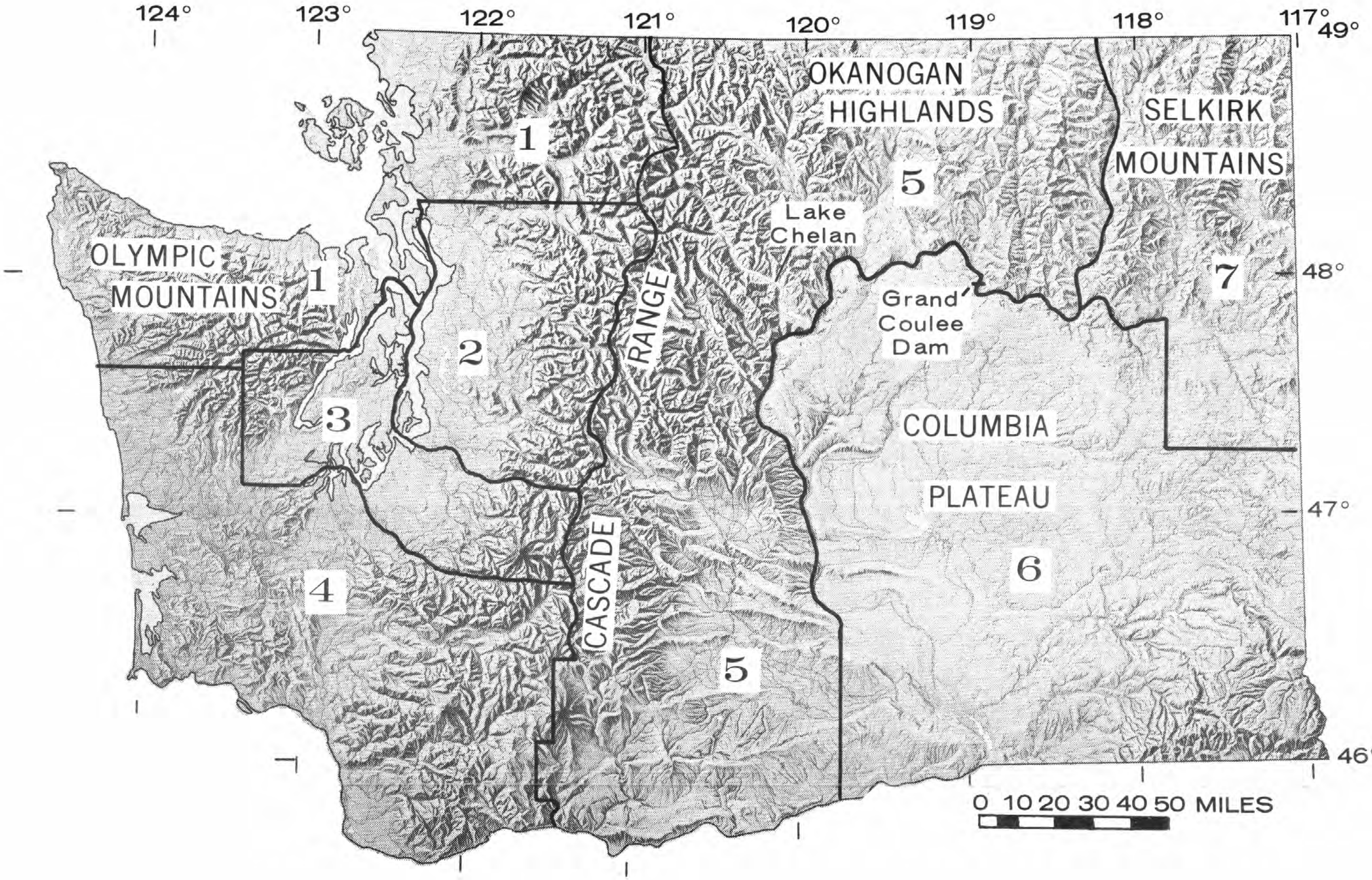


FIGURE 1.--Locations and numbers of regions discussed in report.

Formation of Lakes in Washington

Lakes are bodies of water formed in depressions of the earth's surface in response to various climatic, hydrologic, and geologic conditions. The majority of Washington lakes were formed as the result of glacial activity that occurred during the Pleistocene Epoch, which ended about 10,000 years ago.

In the Puget Sound Lowland of western Washington most lakes occupy depressions in the surface of glacial drift--the gravel, sand, silt, and clay laid down by continental glaciers during the ice age. These depressions are either elongate troughs cut by the passing ice sheet or are kettles, the more nearly circular depressions formed by the melting of stagnant ice blocks buried or submerged in the glacial drift.

In the western foothills of the Cascade Range and the foothills of the Olympic Mountains, lakes in areas of glacial drift occupy depressions left by the melting of stagnant remains of the continental glacier, whereas lakes in areas of bedrock occupy depressions cut into the rock by the passing continental glacier. Lakes in the higher mountains are in basins cut by local alpine glaciers.

In eastern Washington, lakes in the higher northern areas--the Okanogan Highlands and Selkirk Mountains--and on the eastern slope of the Cascade Range generally were formed in glacier-cut depressions in bedrock. The deep excavation of a valley by vigorous glacial erosion produced Lake Chelan, which is more than 490 meters deep and the largest natural lake in Washington. In the semiarid Columbia Plateau, underlain by basalt lava flows, most lakes occupy the more deeply cut parts of some coulees of the channeled scablands. Most of these coulees were cut by gigantic, catastrophic floods (Bretz, 1959) resulting from the breaking of ice dams and the rapid emptying of large glacial lakes.

Many lakes have been formed, or increased in size, by man's activities. Numerous reservoirs are located in mountain valleys and serve a variety of purposes, including municipal water supply, irrigation, electrical-power generation, flood control, and recreation. In lowland areas some natural lakes have been enlarged or new lakes have been formed by small dams; many such lakes were created for the purpose of enhancing real-estate developments. In the Columbia Basin Irrigation Project area of eastern Washington, several lakes have been enlarged and reservoirs have been constructed for the storage of irrigation water diverted from the Columbia River at Grand Coulee Dam. Also, numerous small lakes and ponds have formed in the Columbia Basin from the seepage of irrigation water applied in that area.

Source of Lake Data

The analysis of cultural and physical characteristics was based on data from 671 lakes of the total of 760 lakes originally studied. Analysis of the water-quality data was based on 617 lakes. The reduced number of lakes resulted from editing and screening of data to obtain a complete data set, one with no missing or indeterminate values. The regional distribution of lakes for the physical-cultural and water-quality data sets is shown in table 1.

Cultural and physical characteristics were determined from aerial reconnaissance, aerial photographs, topographic maps, and bathymetric maps. Water-quality data for most of the lakes were collected during the periods July-September 1973 and May-September 1974. All the water-quality data represent samples taken on a single occasion. Prior to 1973, some of the lakes were sampled four times during the year by Collings (1973) and Bortleson and others (1974 and 1976). For those lakes sampled four times during a year, the data from the midsummer sampling period were used.

Water samples for chemical analyses were collected at depths of 1 meter below the water surface and 1-2 meters above the lake bottom. Lakes too shallow to sample at these depths were sampled at about one-third and two-thirds the depth of the lake. Additional details of the data collection are given in the reports by Bortleson and others (1976a-1976d) and Dion and others (1976a-1976c).

TABLE 1.--Regional distribution of lakes in data sets

Region	Number of lakes in physical-cultural data set	Number of lakes in water-quality data set
1	89	73
2	153	136
3	90	60
4	68	57
5	72	73
6	113	143
7	86	75
State	671	617

REGIONAL AND STATE DISTRIBUTION OF SELECTED LAKE CHARACTERISTICS

Cultural and Physical Characteristics

The nutrient and mineral loads that reach a lake largely determine its water quality and are a function of the geochemistry of the drainage basin, the climate and hydrology of the region, and other natural conditions. Superimposed on these natural physical factors may be a variety of human and cultural effects. The influence of man on the watershed of a lake can result in an increased rate of nutrient input to the lake, which may bring about an accelerated rate of generally undesirable chemical, physical, and biological effects (Lee, 1972, p. 39). Thus, lakes cannot be regarded as isolated, unchanging entities because the interactions of the entire watershed must be taken into account.

The cultural and physical characteristics that were evaluated in the reconnaissance study (Bortleson and others, 1976a-1976d; Dion and others, 1976a-1976c) are listed below:

Cultural data

*Predominant land use in drainage basin
- residential urban
- residential suburban
- agricultural
- forest or unproductive

*Degree of residential development of shoreline
Number of nearshore homes
Public boat access to lake

Physical data

Drainage area
*Altitude
Lake area
Lake volume
*Mean depth
Maximum depth
Shoreline length
Relative depth
Development of volume
Shoreline configuration
Basin geology
Inflow (perennial, intermittent, or none visible)
Outflow channel (present or absent)

Those characteristics marked above by asterisks have been selected as the best descriptors of cultural and physical conditions of lakes for the purpose of this report. Graphs showing the comparisons of the ranges in the values of these selected lake-basin characteristics, regionally and statewide, are shown in figures 2-8. Each figure compares a single characteristic over the seven geographic regions and the State as a whole. Within the outline of each graph is shown the median value for the particular physical or cultural variable. The significance of these data and noticeable patterns and trends are discussed below.

Land uses.--Consideration of land uses is important to assess the potential impact of nonpoint, or dispersed, loadings into a lake from natural and artificial sources in the drainage basin. Several studies have indicated that there is a positive correlation between the amounts of nitrogen and phosphorus originating in the watershed and the trophic state of lakes or streams (Vollenweider, 1968; Brezonik and Shannon, 1971; Patalas, 1972; Omernik, 1976). Therefore, for this report the drainage basins of the lakes were classified into various generalized land-use categories as described below:

a. Forest and unproductive land. Public and private forest lands and tree farms. Unproductive lands include cleared or fallow land, meadows, wetlands, and seasonal recreational areas.

b. Agricultural land. Pasture or cropland.

c. Urban land. Predominant use is for single-family residences, where apartment complexes and substantial commercial or industrial activities also may be present.

d. Suburban land. All use is single-family residences, but a small amount of commercial use may be present.

Also included in the drainage-basin consideration is the surface area of the lake, which must be taken into account relative to the percentage of the drainage basin in each of the above land-use categories.

The percentages of the drainage basin used primarily for forest or for agricultural, residential urban, or residential suburban development are shown in figures 2-5. Statewide, about two-thirds of the lake basins have more than 50 percent of their land in the forest and unproductive category (fig. 2). In Region 6, the Columbia Plateau, 74 percent of the lakes have more than 90 percent of their basins in agricultural use (fig. 3), most of which is used for grazing rather than intensive agriculture.

Graphs of the percentages of the drainage basin used by urban and suburban residential development are shown in figures 4 and 5, respectively. For most lake basins in the State, the area occupied by urban and suburban residential development is a relatively small fraction of the total drainage basin (drainage basin including lake surface). Statewide, only 4 percent of the lakes studied exceeded 10 percent urban development and 8 percent exceeded 10 percent suburban development in their basins. Suburban residential development is highest in populated western Washington, in regions 2 and 3. In eastern Washington, no lake basin contained more than 10 percent suburban residential development, whereas in western Washington 59 lake basins (15 percent) exceeded 10 percent suburban residential development.

Residential development of shoreline.--The development of shoreline for residential use is an important consideration in the potential for nutrient loading from cultural sources. Graphs showing residential development of shoreline (fig. 6) indicate that throughout the State (all regions) most of the lakes had 1 percent or less of their shorelines developed. Many of these lakes are in forested areas accessible only by trail. If the shoreline is developed to an extent greater than 1 percent, the most frequent pattern is 1 to 10 percent of the total shore developed. The most populous areas of the State (regions 2 and 3) had the highest percentage of lakes with 90 to 100 percent of their shorelines developed.

Altitude.--Lake altitude is important because of its relation to seasonal cycles of temperature and precipitation. Colder water temperatures and shorter growing seasons at high altitudes generally result in lower aquatic-plant productivity.

Most of the lakes studied in western Washington (regions 1, 2, 3, and 4) are below 200 meters altitude (fig. 7). Region 2 has the largest percentage of high-altitude lakes in western Washington, with 21 percent of its lakes above 1,000 meters altitude, the approximate altitude of separation of intermontane and high-altitude lakes.

In eastern Washington the overall terrain is higher and most lakes are above 400 meters altitude. In Region 5, which borders the eastern Cascades, 28 percent of the lakes are above 1,000 meters altitude.

Mean depth.--One of the most significant physical features affecting the ability of a lake to produce and utilize nutrients is its mean depth. In shallow lakes--those having mean depths of 2.0 meters or less--nutrient-rich bottom water can readily mix with water at the surface, thereby supplying algal populations with the nutrients needed for continued reproduction, and oftentimes prolific growth.

Graphs of mean depth (fig. 8) indicate that statewide, 22 percent of the lakes have mean depths of 2.0 meters or less. Only 7 percent of the lakes have mean depths greater than 20.0 meters, and 50 percent of the lakes have mean depths in the range of 2.1 to 8.0 meters.

In region 6, the Columbia Plateau, 61 percent of the lakes had mean depths of 2.0 meters or less. The shallowness of these lakes reflect, in part, the low relief of the region.

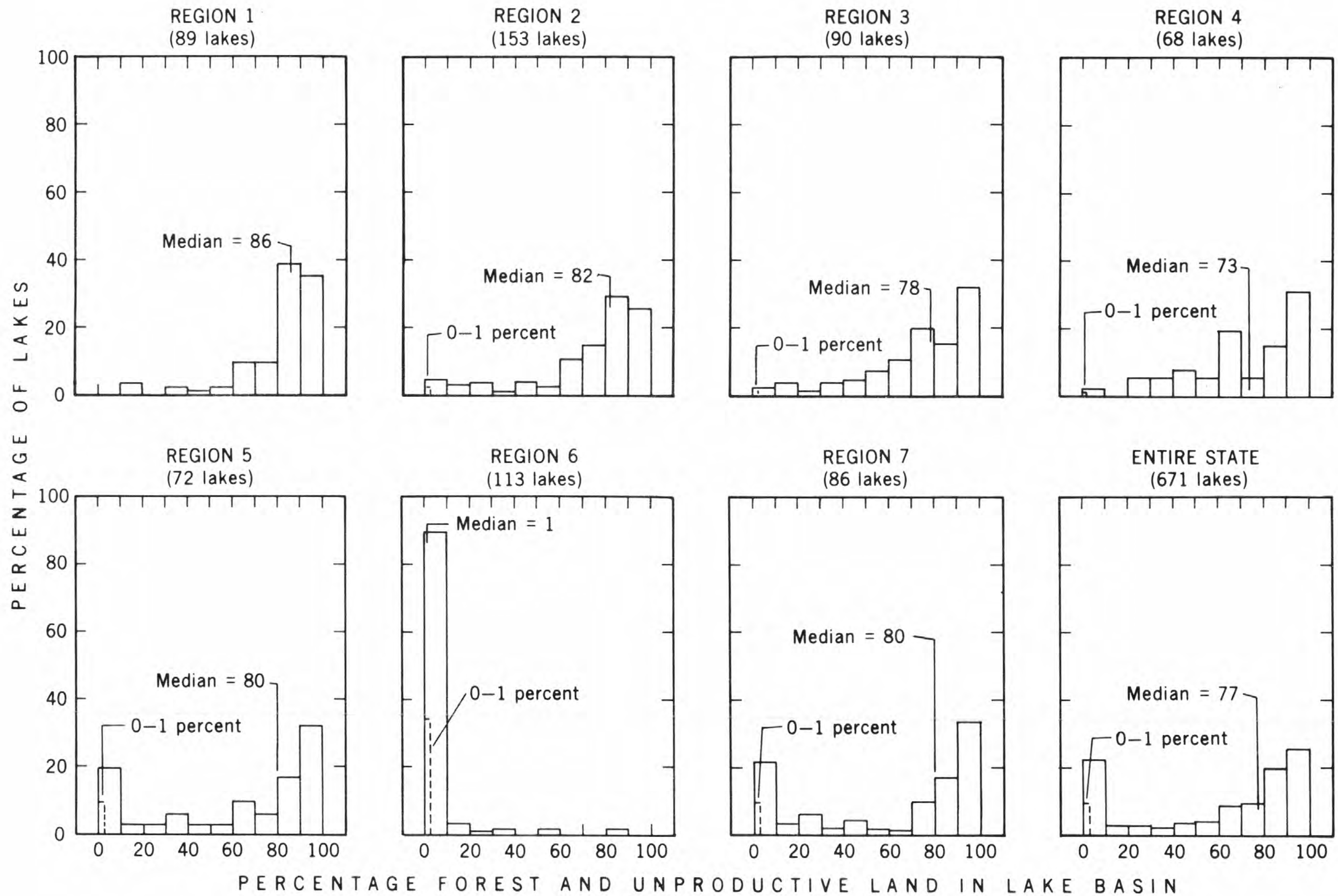


FIGURE 2.—— Regional and state distributions of percentage forest and unproductive land in lake basin.

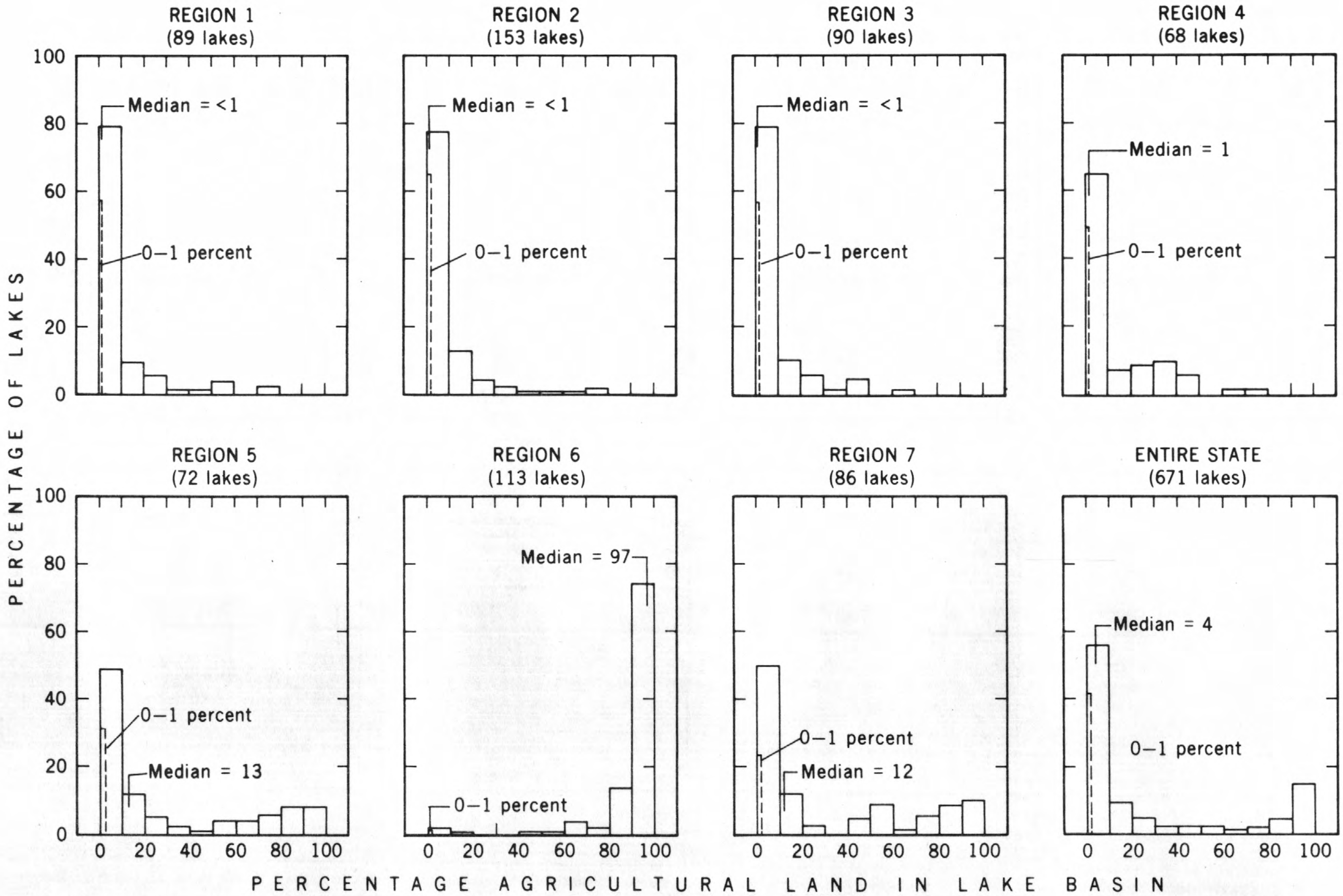


FIGURE 3.—— Regional and state distributions of percentage agricultural land in lake basin.

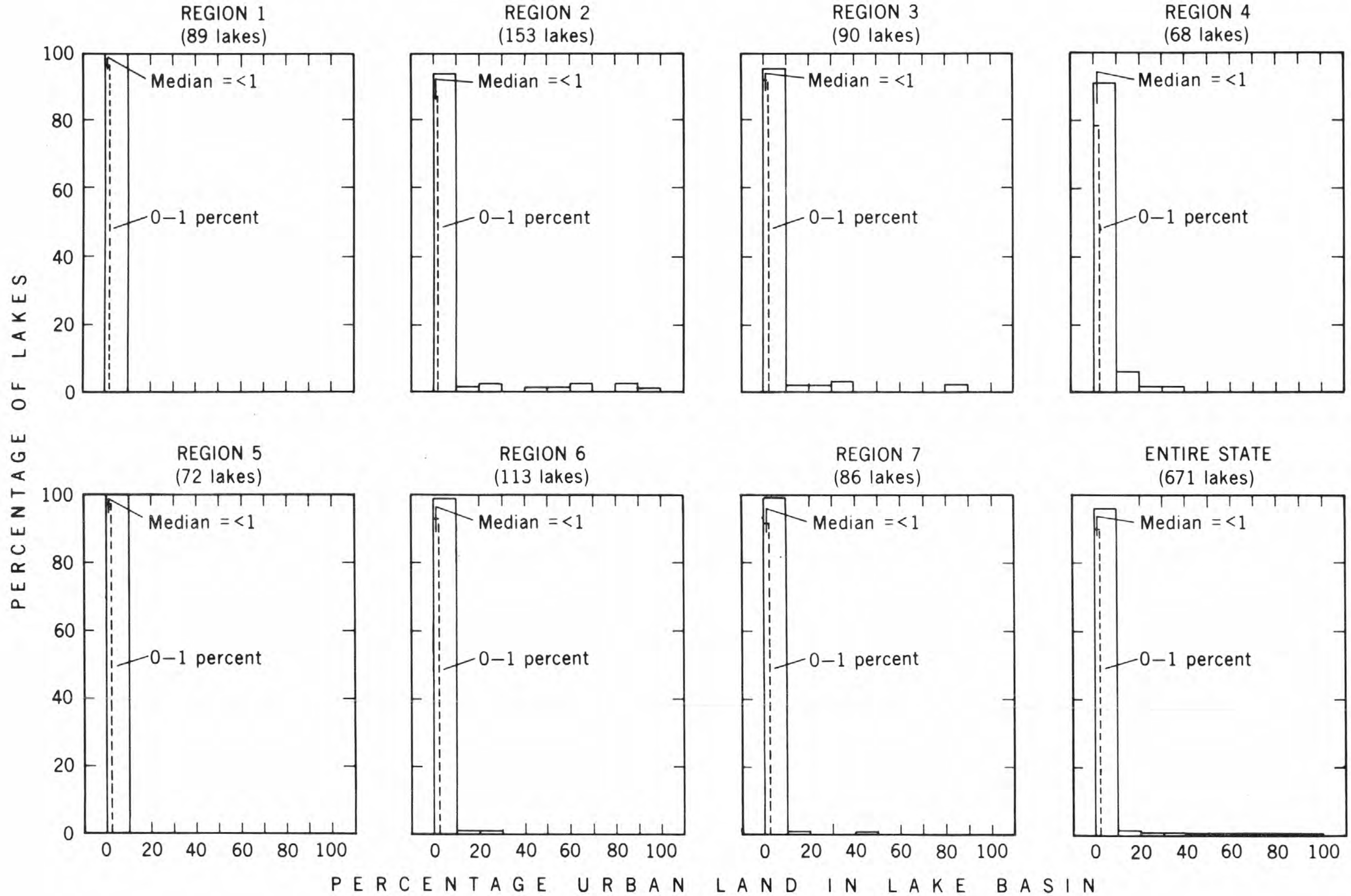


FIGURE 4.—— Regional and state distributions of percentage urban land in lake basin.

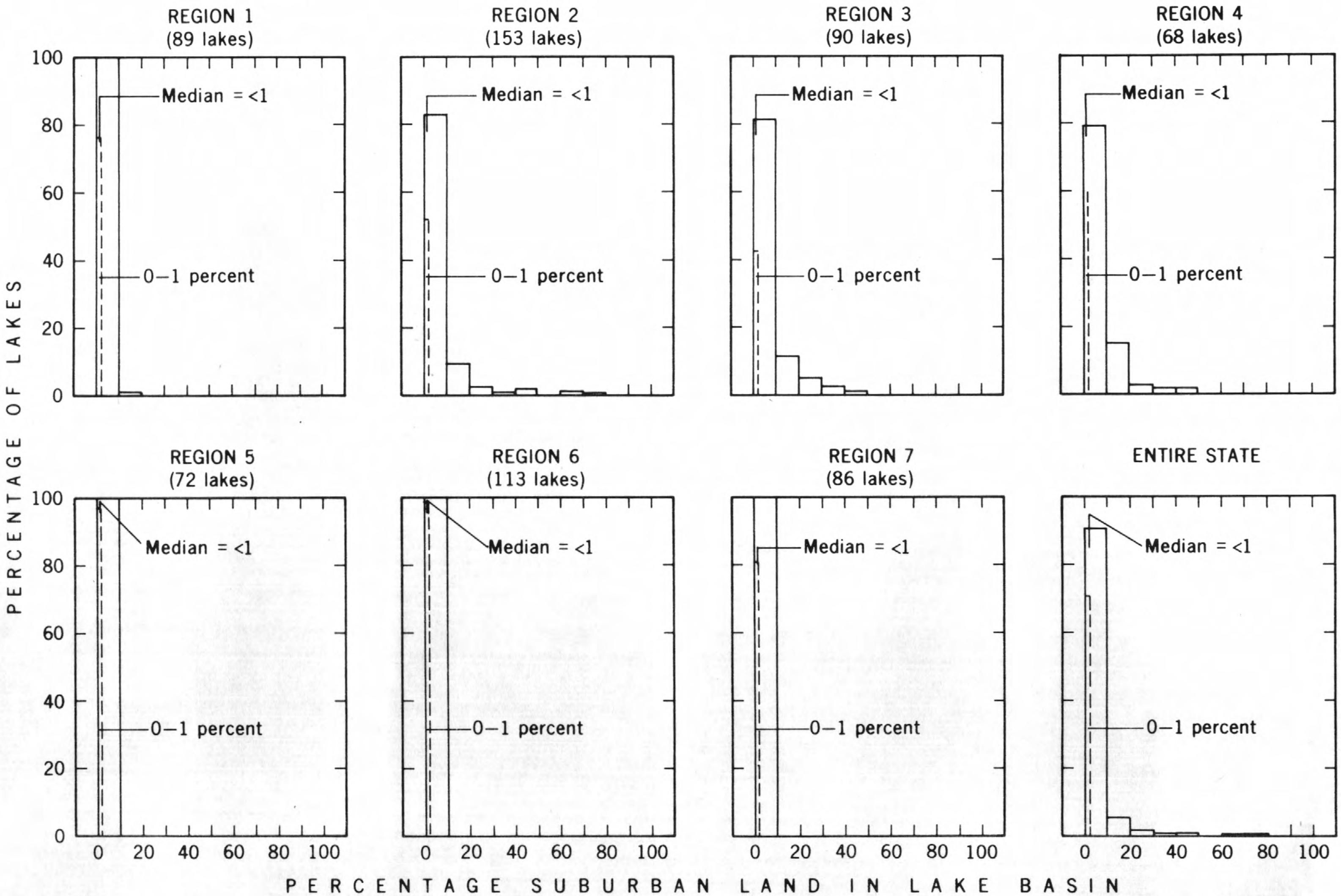


FIGURE 5.—— Regional and state distributions of percentage suburban land in lake basin.

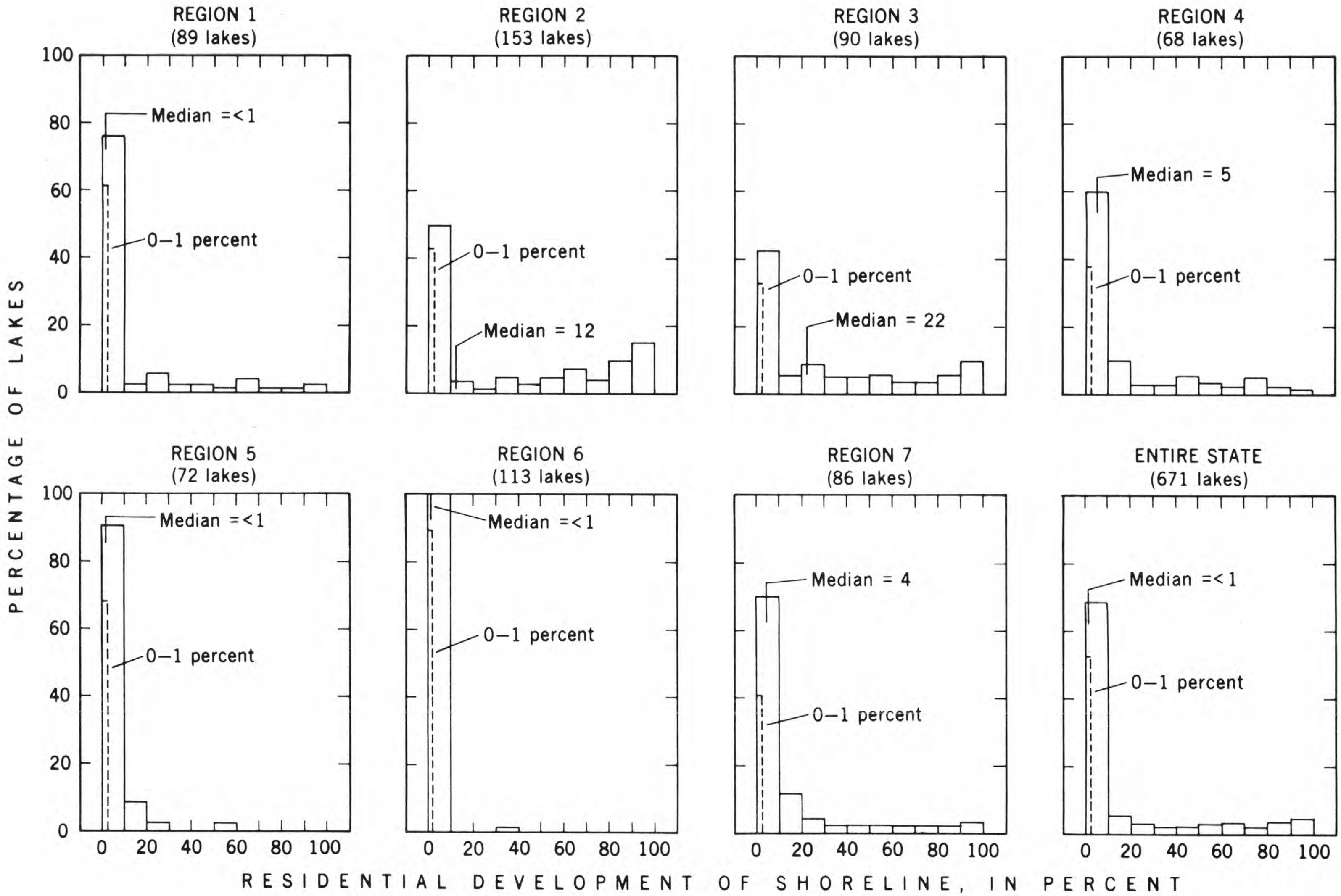


FIGURE 6.—— Regional and state distributions of residential development of shoreline.

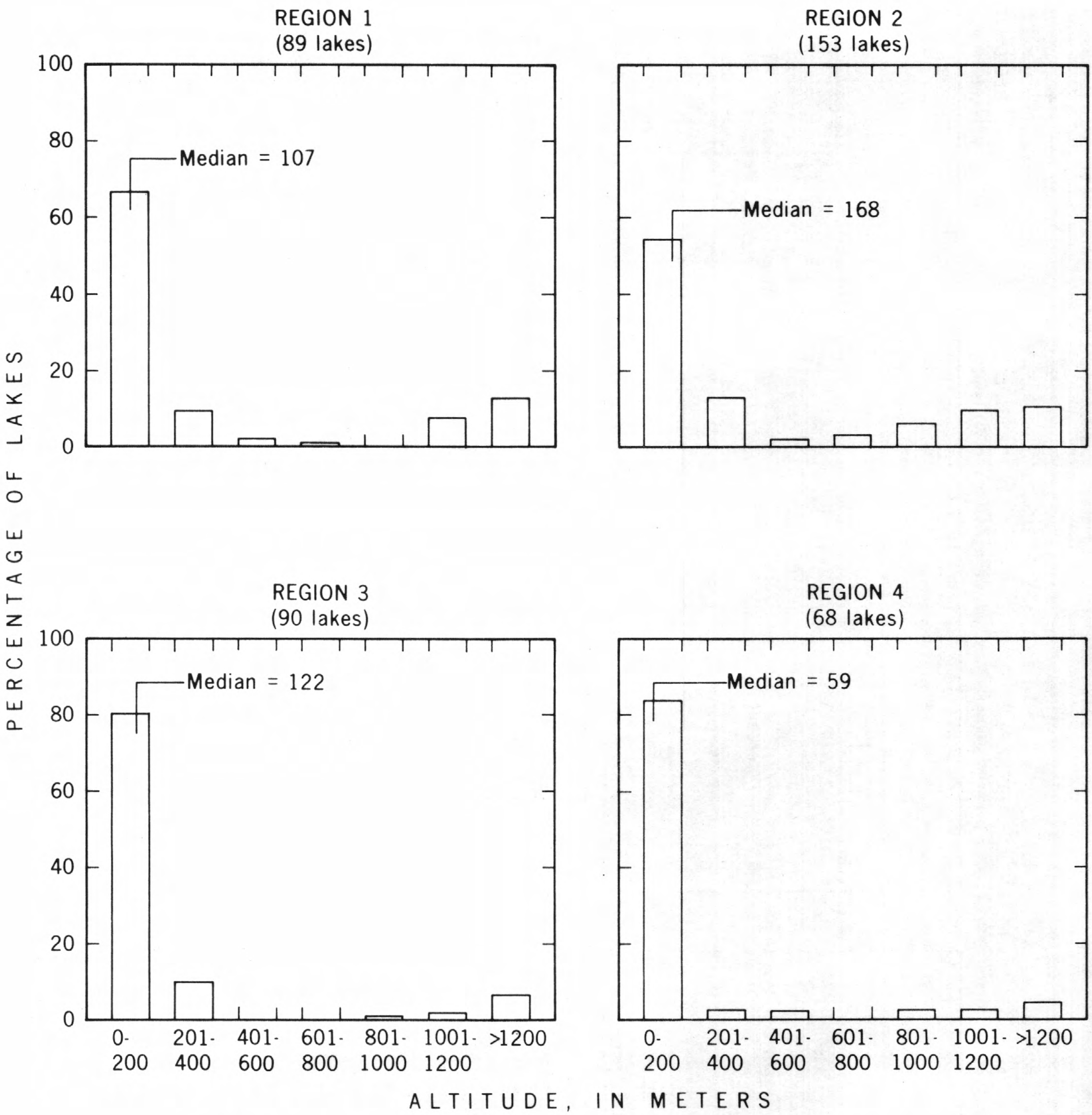
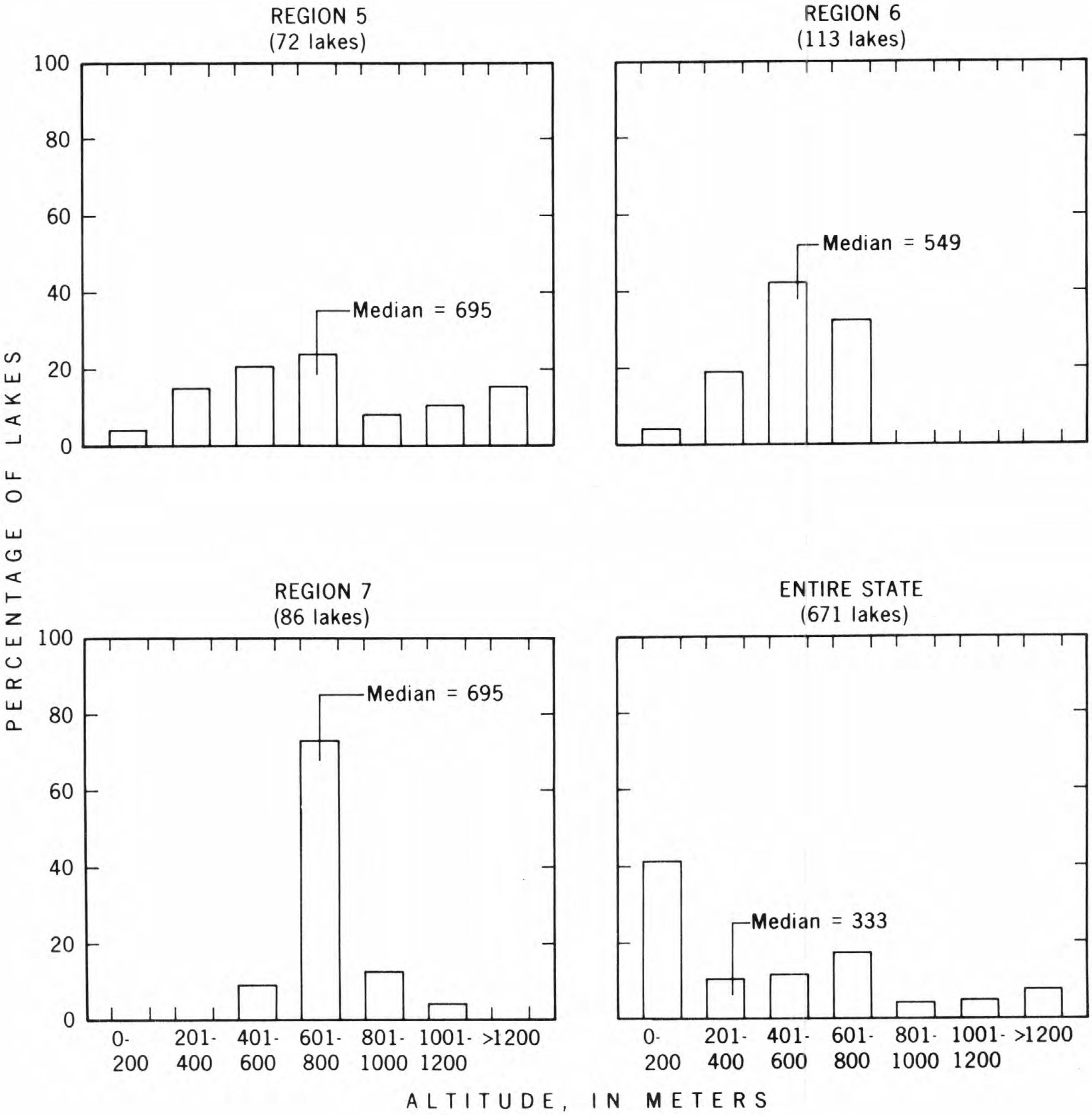


FIGURE 7.—— Regional and state distributions of lake altitude.


REGION 5
(72 lakes)
Median = 695
REGION 6
(113 lakes)
Median = 549
REGION 7
(86 lakes)
Median = 695
ENTIRE STATE
(671 lakes)
Median = 333
PERCENTAGE OF LAKES
100
80
60
40
20
0
0-200
201-400
401-600
601-800
801-1000
1001-1200
>1200
ALTITUDE, IN METERS

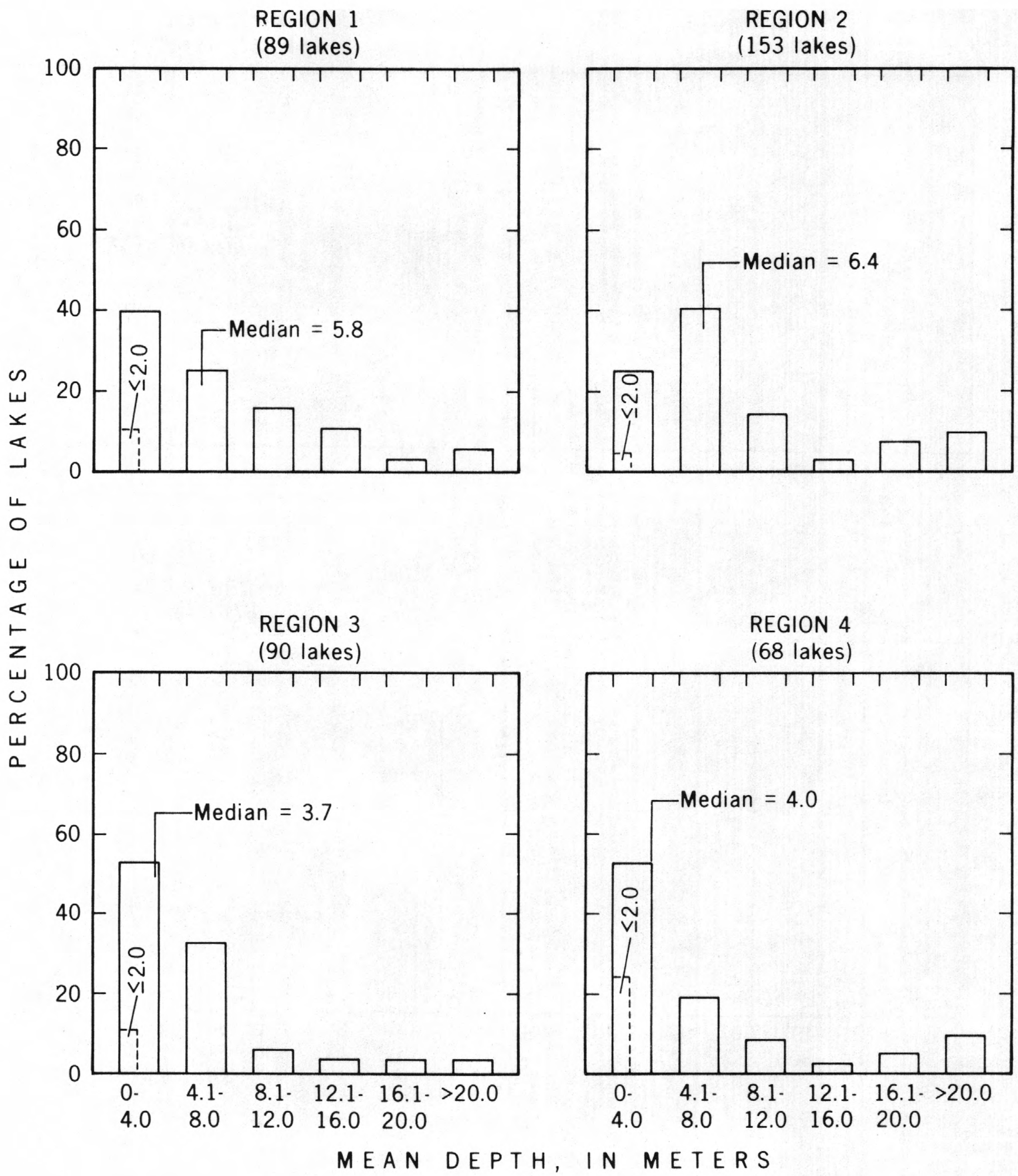
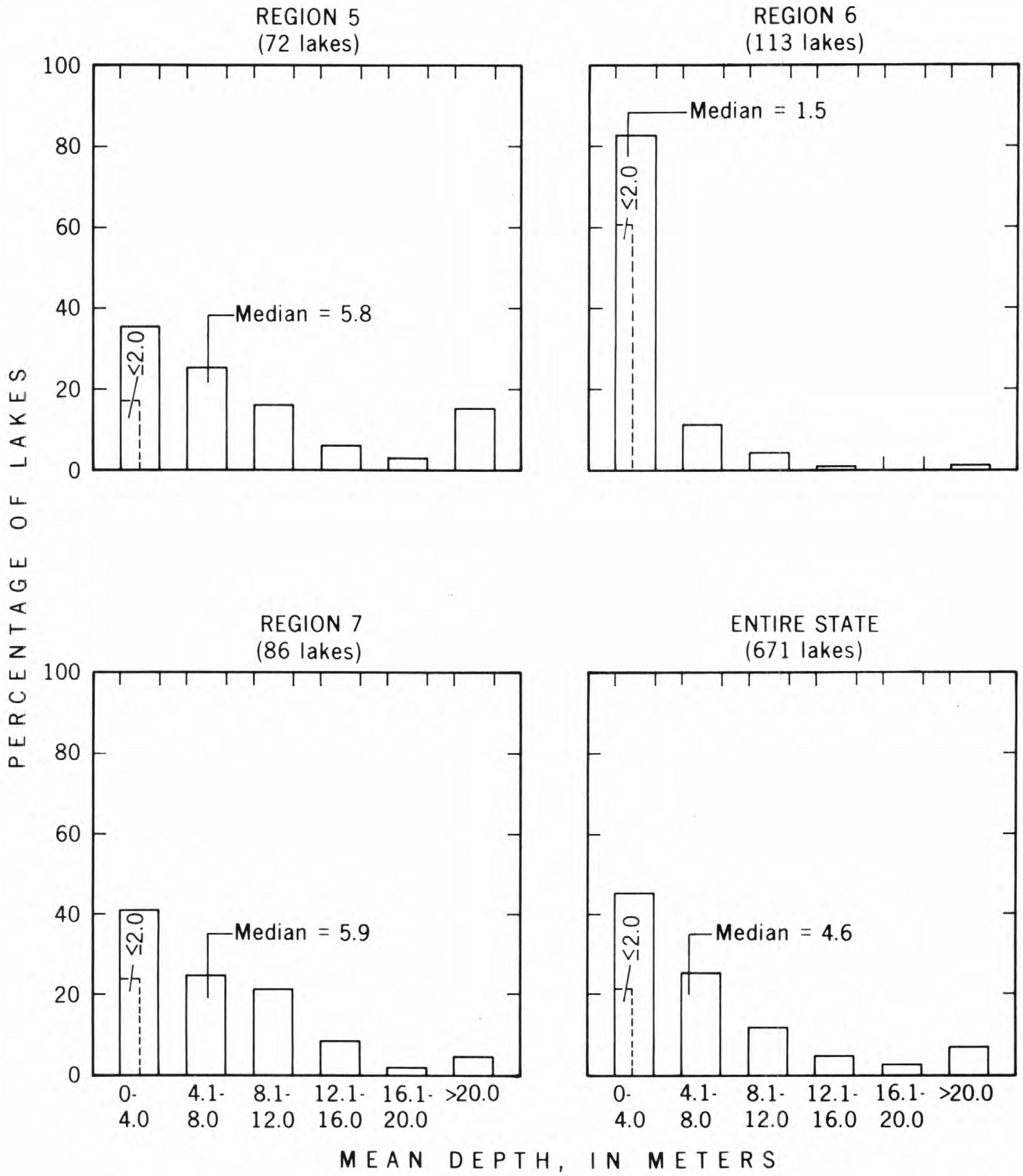


FIGURE 8.—— Regional and state distributions of mean depth of lakes.


REGION 5
(72 lakes)
Median = 5.8
≤2.0
REGION 6
(113 lakes)
Median = 1.5
≤2.0
REGION 7
(86 lakes)
Median = 5.9
≤2.0
ENTIRE STATE
(671 lakes)
Median = 4.6
≤2.0
PERCENTAGE OF LAKES
100
80
60
40
20
0
0-4.0
4.1-8.0
8.1-12.0
12.1-16.0
16.1-20.0
>20.0
MEAN DEPTH, IN METERS

Water-Quality Characteristics

An adequate description of lake-water quality requires consideration of several physical, biological, and chemical characteristics. Concentrations of nitrogen and phosphorus nutrients are especially important because, under most lake conditions, these nutrients are usually responsible for causing a shift from a low to a high lake productivity (Wetzel, 1975, p. 640). Nutrient-rich (eutrophic) waters often sustain excessive growths of algae and other aquatic plants.

In the reconnaissance study of lakes in Washington (Bortleson and others, 1976a-1976d; Dion and others, 1976a-1976c), evaluations were made of the water-quality characteristics listed below:

Total inorganic nitrogen (nitrite, nitrate, and ammonia), upper water
Total inorganic nitrogen, bottom water
Total organic nitrogen, upper water
Total phosphorus, upper water
Total phosphorus, bottom water
Specific conductance, upper water
Temperature, bottom water
Dissolved oxygen, bottom water
Secchi-disc visibility
Shoreline covered by emersed plants (macrophytes)
Lake surface covered by emersed plants (macrophytes)
Fecal-coliform bacteria

Graphs comparing the 12 water-quality characteristics in the regions and statewide are shown in figures 9-20, with each figure applying to a single characteristic. Where appropriate, the median value of each water-quality characteristic is shown in the figures.

Total concentrations of inorganic nitrogen.--The concentration of total inorganic nitrogen is determined by summing total nitrite, nitrate, and ammonia nitrogen. Nitrogen is an essential element to plant growth. Although there are numerous exceptions, a direct correlation has been observed between average concentrations of inorganic and organic nitrogen and high sustained productivity of algal populations (Wetzel, 1975, p. 196). According to Wetzel, lakes of high algal productivity often have average concentrations of inorganic nitrogen that exceed 500 µg/L (micrograms per liter). For the purposes of this report, the distributions of total inorganic-nitrogen and total phosphorus concentrations are examined in two subdivisions: upper lake water and bottom lake water.

Graphs of total inorganic nitrogen in upper lake water (fig. 9) show that the median concentration of inorganic nitrogen for the entire State was 90 µg/L, being highest in region 6 (140 µg/L), and lowest in region 5 (60 µg/L). With the exception of region 6, at least one-half of the lakes in other regions had inorganic-nitrogen concentrations in the range of 0 to 100 µg/L. These concentrations are considered low but are representative of those in summer, a time when nutrient uptake by plants is often pronounced and the inorganic nitrogen in the water is often reduced to low concentrations. Data from intensive lake studies in Washington indicate that inorganic-nitrogen concentrations are commonly several times higher during winter and early spring than during summer (Bortleson and others, 1976; McConnell and others, 1976).

Total inorganic-nitrogen concentrations (especially ammonia nitrogen) often increase in deeper waters during summer thermal stratification (Hutchinson, 1957, p. 876). With the advent of fall, ammonia in the bottom water circulates to the upper water where it may become active in the production of aquatic plants. Graphs of the total inorganic nitrogen in bottom water (fig. 10) show that on a statewide basis the median concentration of inorganic nitrogen in the bottom water (220 µg/L) was about 2.5 times greater than near the surface (90 µg/L). The median concentrations in the bottom water ranged from 110 µg/L in region 3 to 370 µg/L in region 7. In Region 6, lakes had the highest concentrations of inorganic nitrogen at the surface, but did not show pronounced divergence from lakes of other regions in bottom inorganic nitrogen. This is probably due in part to the number of shallow, nonstratified lakes in region 6. Compared to those in western Washington, lakes in all regions of eastern Washington had higher concentrations of bottom inorganic nitrogen.

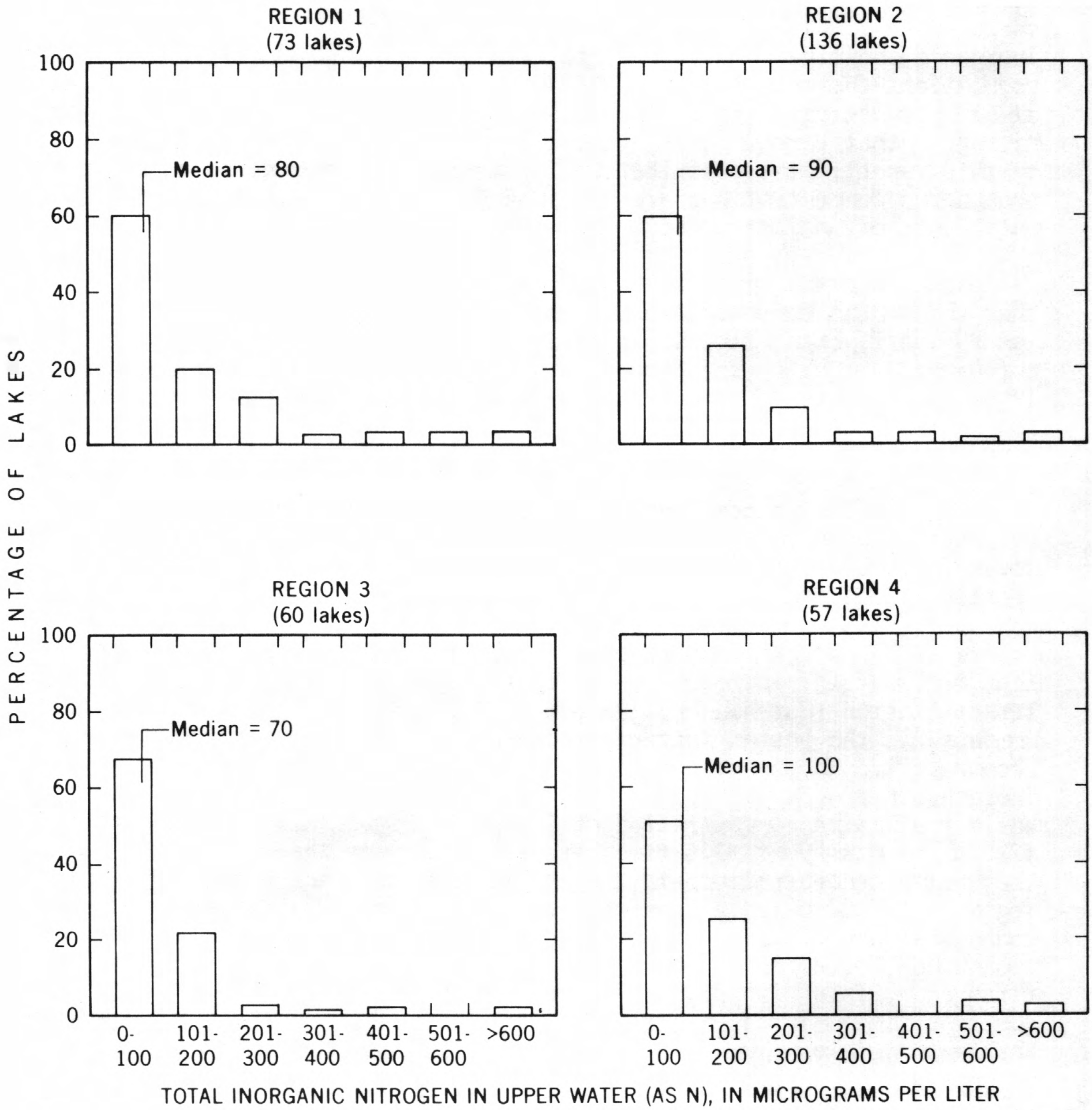
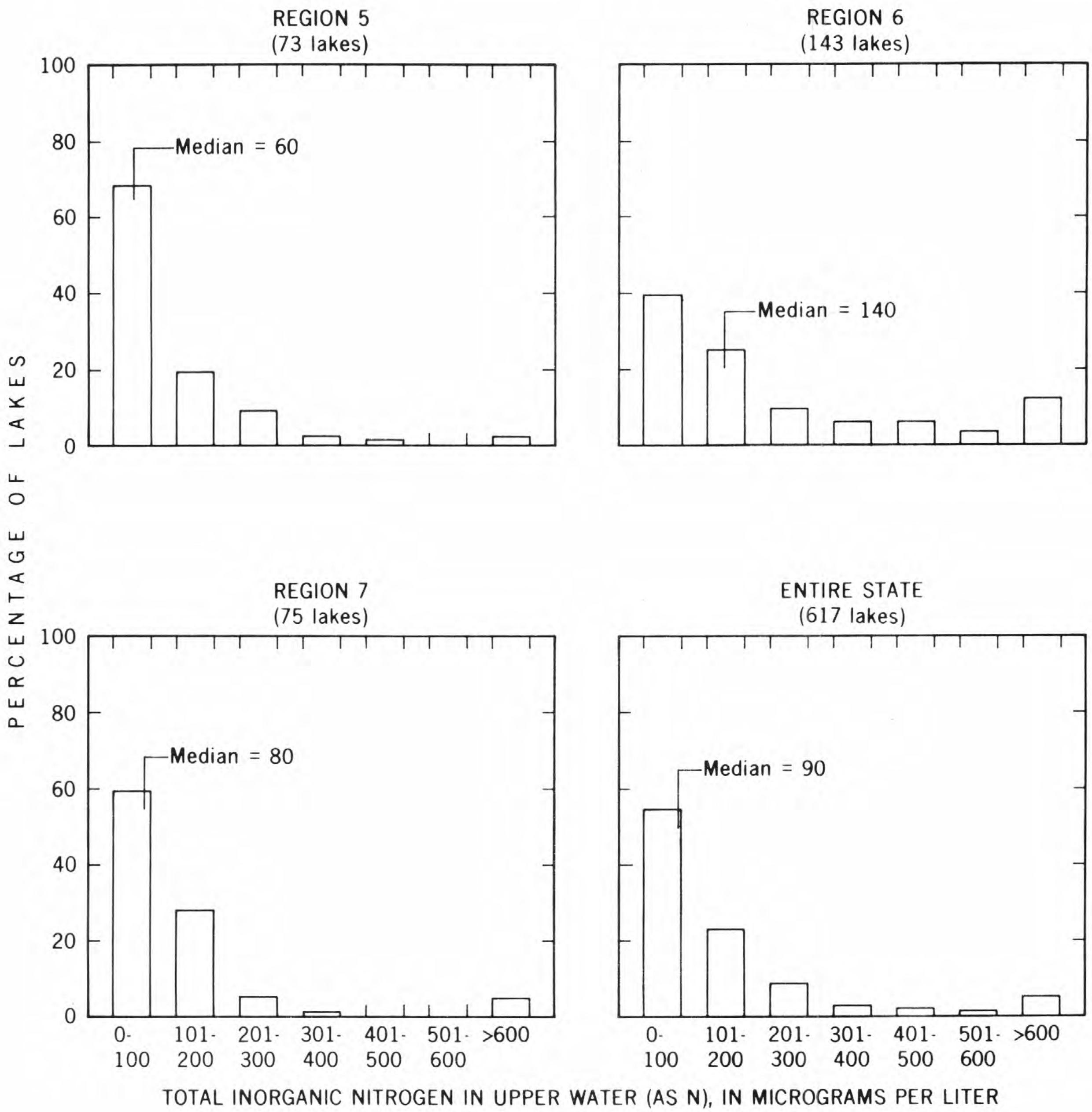


FIGURE 9.—— Regional and state distributions of total inorganic-nitrogen concentration in upper water.



REGION 5
(73 lakes)
Median = 60
REGION 6
(143 lakes)
Median = 140
REGION 7
(75 lakes)
Median = 80
ENTIRE STATE
(617 lakes)
Median = 90
PERCENTAGE OF LAKES
100
80
60
40
20
0
0-100
101-200
201-300
301-400
401-500
501-600
>600
TOTAL INORGANIC NITROGEN IN UPPER WATER (AS N), IN MICROGRAMS PER LITER

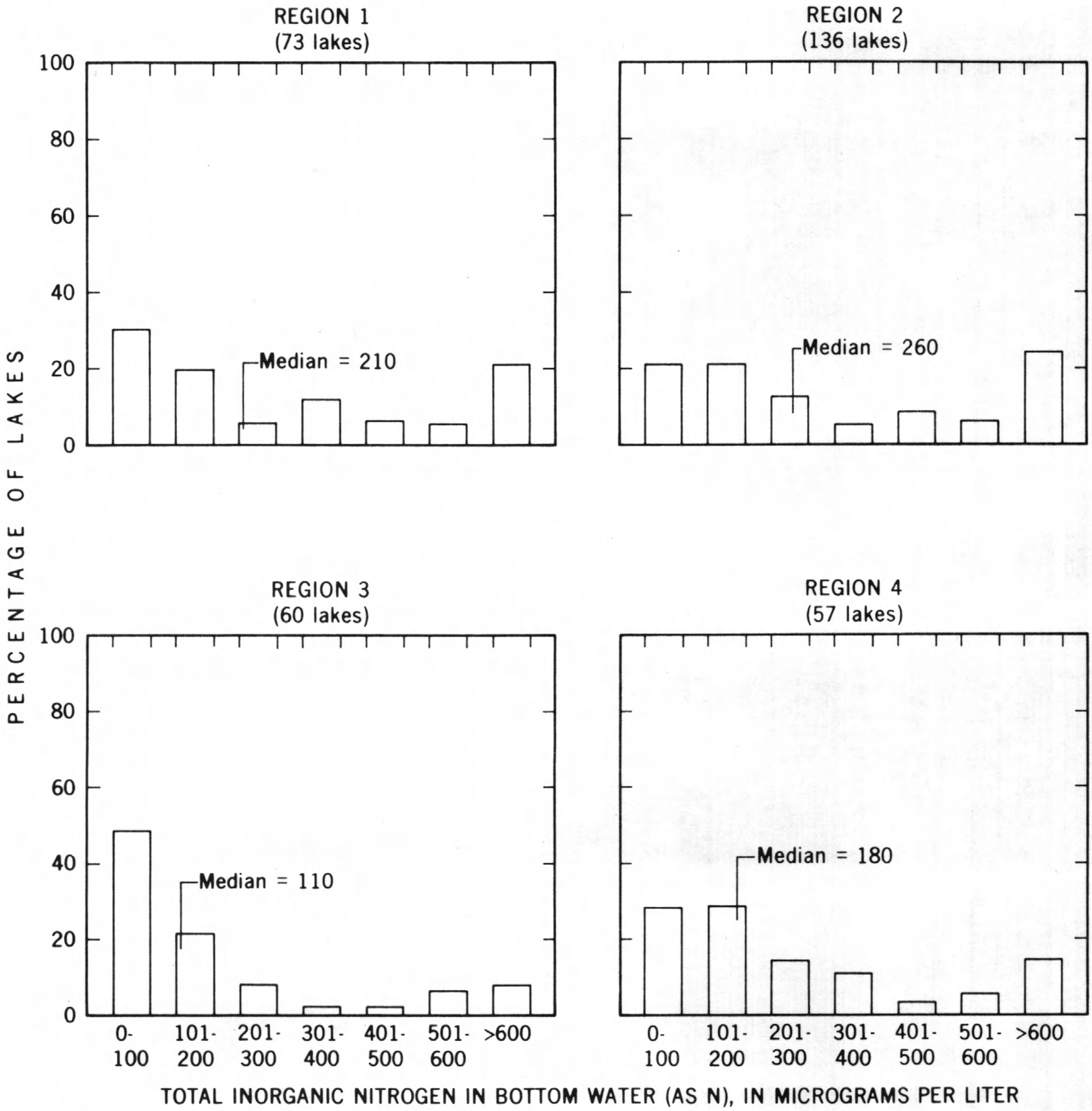
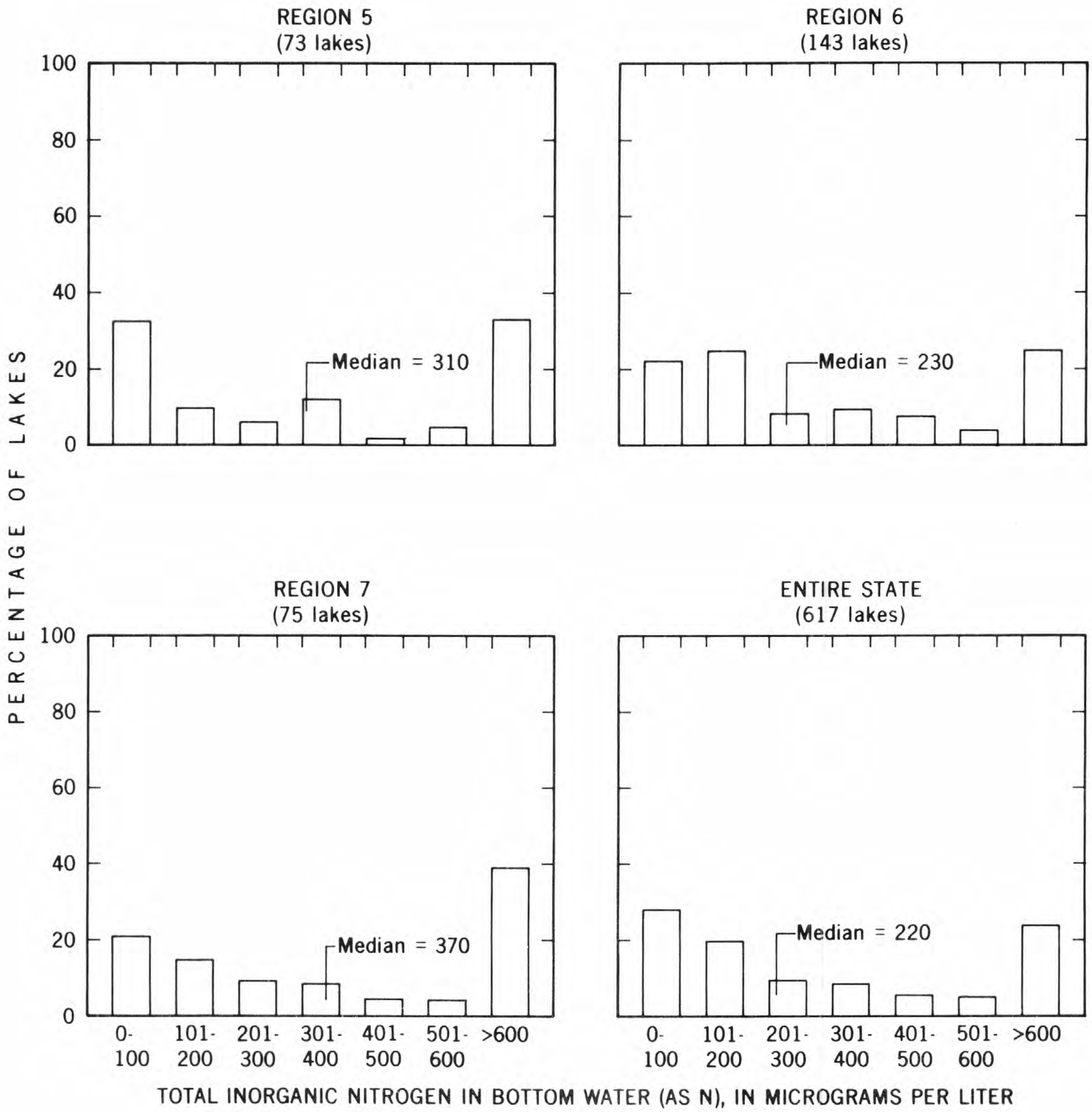


FIGURE 10.—— Regional and state distributions of total inorganic nitrogen in bottom water.


REGION 5
(73 lakes)
REGION 6
(143 lakes)
REGION 7
(75 lakes)
ENTIRE STATE
(617 lakes)
Median = 310
Median = 230
Median = 370
Median = 220
PERCENTAGE OF LAKES
0
20
40
60
80
100
0-100
101-200
201-300
301-400
401-500
501-600
>600
TOTAL INORGANIC NITROGEN IN BOTTOM WATER (AS N), IN MICROGRAMS PER LITER

Total concentrations of organic nitrogen.--Total organic nitrogen is an indicator of the amount of plant and animal matter in the lake. Lueschow and others (1970), studying Wisconsin lakes, found that a lake having an annual mean organic-nitrogen concentration of less than 200 µg/L probably would not have algal nuisances, but that a lake having a concentration of more than 800 µg/L would probably have numerous blooms during most of the growing season. Lakes of high algal productivity often have average concentrations of organic nitrogen exceeding 700 µg/L (Wetzel, 1975, p. 196).

Graphs of total organic-nitrogen concentration in upper water (fig. 11) show that the median concentration was highest in region 6 (1,200 µg/L) and lowest in region 2 (230 µg/L). Lakes in all three regions of eastern Washington had higher median concentrations of organic nitrogen than did those of regions in western Washington. Statewide, 27 percent of the lakes had concentrations of organic nitrogen greater than 800 µg/L.

Total phosphorus concentrations.--The potential degree of algal productivity in lakes is often assessed by the total phosphorus concentration. Phosphorus is an essential element to the growth of aquatic plants, but it is deficient enough in many natural waters to be a limiting factor in algal growth (Lee, 1973, p. 111). Lakes of high algal productivity commonly have average concentrations of total phosphorus that exceed 30 µg/L (Wetzel, 1975, p. 217).

Graphs showing the concentration of total phosphorus in the upper water (fig. 12) indicate that the median concentration for all lakes studied in Washington was 20 µg/L. More than one-third of the lakes in the State had total phosphorus concentrations exceeding 30 µg/L. Region 6 had 127 lakes (89 percent) which had concentrations exceeding 30 µg/L. In contrast, regions 2 and 3, the most populated in western Washington, had only 10 lakes in each region with concentrations exceeding 30 µg/L during the summer sampling. The algal blooms observed in region 6 may be related to high phosphorus concentrations. For example, about one-third of the lakes in region 6 had algal blooms at the time of sampling, compared to 9 percent in region 2, and 13 percent in region 3 (Bortleson and others, 1976a-1976d; Dion and others, 1976a-1976c).

The vertical distribution of phosphorus during summer thermal stratification is variable. In plant-productive lakes, with oxygen depletion in the bottom water, there is often an increase in soluble phosphate near the bottom of the lake (Hutchinson, 1957, p. 751). This results in part from the decomposition of sinking plants and animals, but in most cases it is caused primarily by the release of phosphorus from bottom sediments (Hutchinson, 1957, p. 751).

Graphs showing total phosphorus in bottom water (fig. 13) indicate that on a statewide basis the median concentration of total phosphorus in the bottom water (49 µg/L) was about 2.5 times greater than near the surface (20 µg/L). All eastern Washington lakes had higher total phosphorus concentrations in the bottom waters than did western Washington lakes. Region 6, which did not show a pronounced divergence from other regions for inorganic nitrogen in bottom water, had the highest median total phosphorus concentration in bottom water. Regions 1, 2, and 3 had the lowest median concentrations of total phosphorus.

Specific conductance.--Specific conductance is a unit of measurement of conduction of an electric current in water; its value varies directly with the amount of dissolved solids in the water. The specific conductance values used in this report have been corrected to 25°C (Celsius). An increase in dissolved-solids concentration in a lake often results in increased plant and animal production because more dissolved minerals are available for utilization by those plants and animals (Moyle, 1956; Rawson, 1951; Ryder, 1965).

Graphs of specific conductance (fig. 14) show that median specific conductance ranged from 39 µmho/cm (micromhos per centimeter at 25°C) in region 2 to 640 µmho/cm in region 6. The specific conductance of lakes in eastern Washington was substantially higher than those in western Washington. For example, very few lakes west of the Cascades had a specific conductance greater than 200 µmho/cm whereas more than three-fourths of the lakes in eastern Washington exceeded this value.

Temperature, bottom water.--The temperature of the bottom water during midsummer is of special significance because (1) temperature stratification and water circulation affect the vertical distribution of nutrients, and (2) water temperatures affect the mobility and feeding habits of fish and other animals. Prolonged low concentrations of dissolved oxygen combined with high temperatures may not be favorable to the fish production of a lake. According to Smith and Bella (1973, fig. 11), the most favorable combination of dissolved oxygen and temperature for rainbow trout are dissolved oxygen concentrations greater than 6.0 mg/L (milligrams per liter) and temperatures less than 15°C.

The temperatures shown on the graphs in figure 15 are bottom temperatures and therefore represent the coldest part of the lake. On a statewide basis about one-third of the lakes have temperatures too high to meet the criteria for most favorable conditions for rainbow trout, as described above. Regions 3, 4, and 6 have the largest percentage of lakes with warmer waters. Notably, the same three regions have the shallowest mean depth (fig. 8). Most of the shallow lakes with warm bottom temperatures are mixed thoroughly by wind and by convective heating and cooling, and have uniform temperatures.

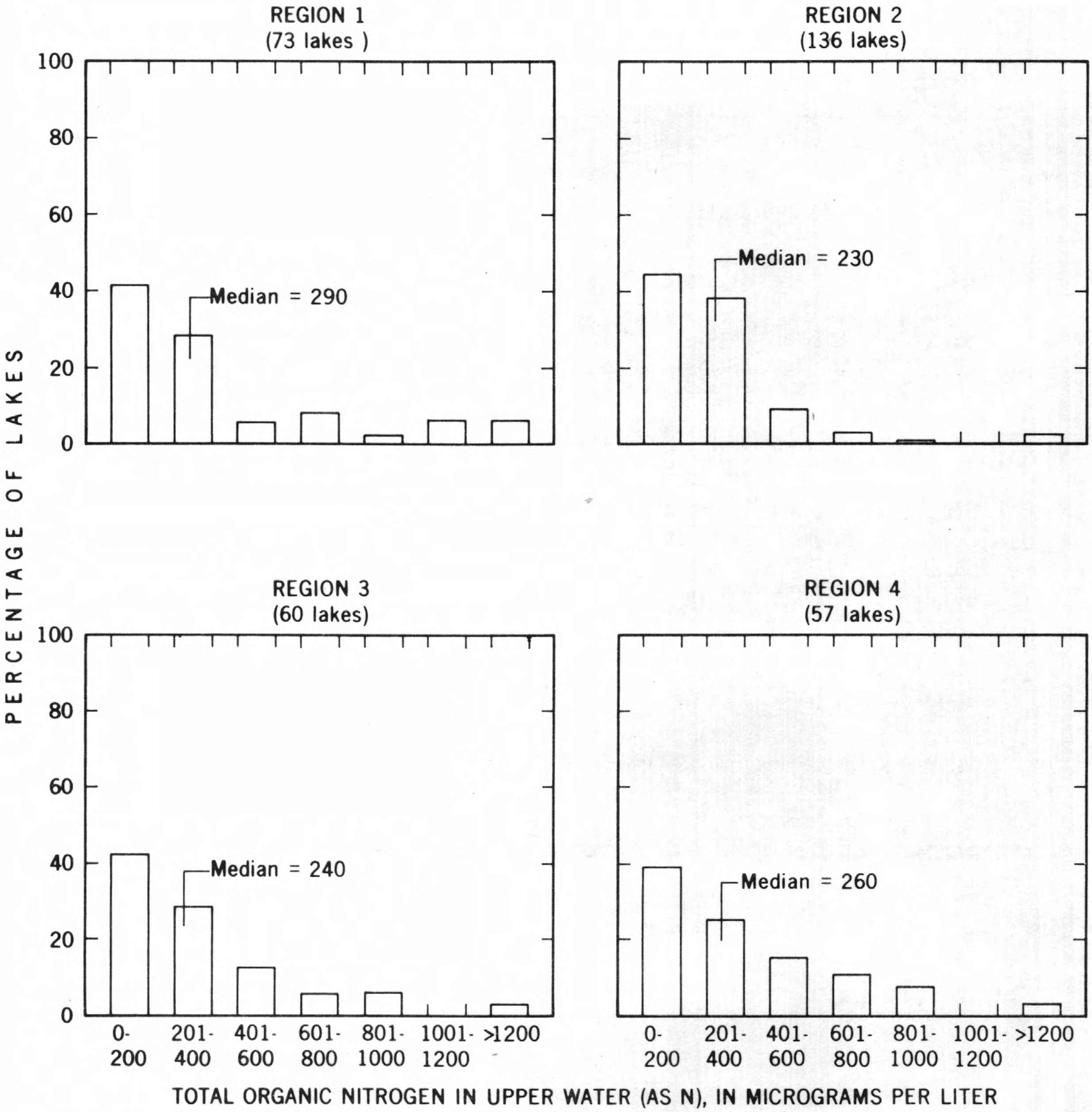
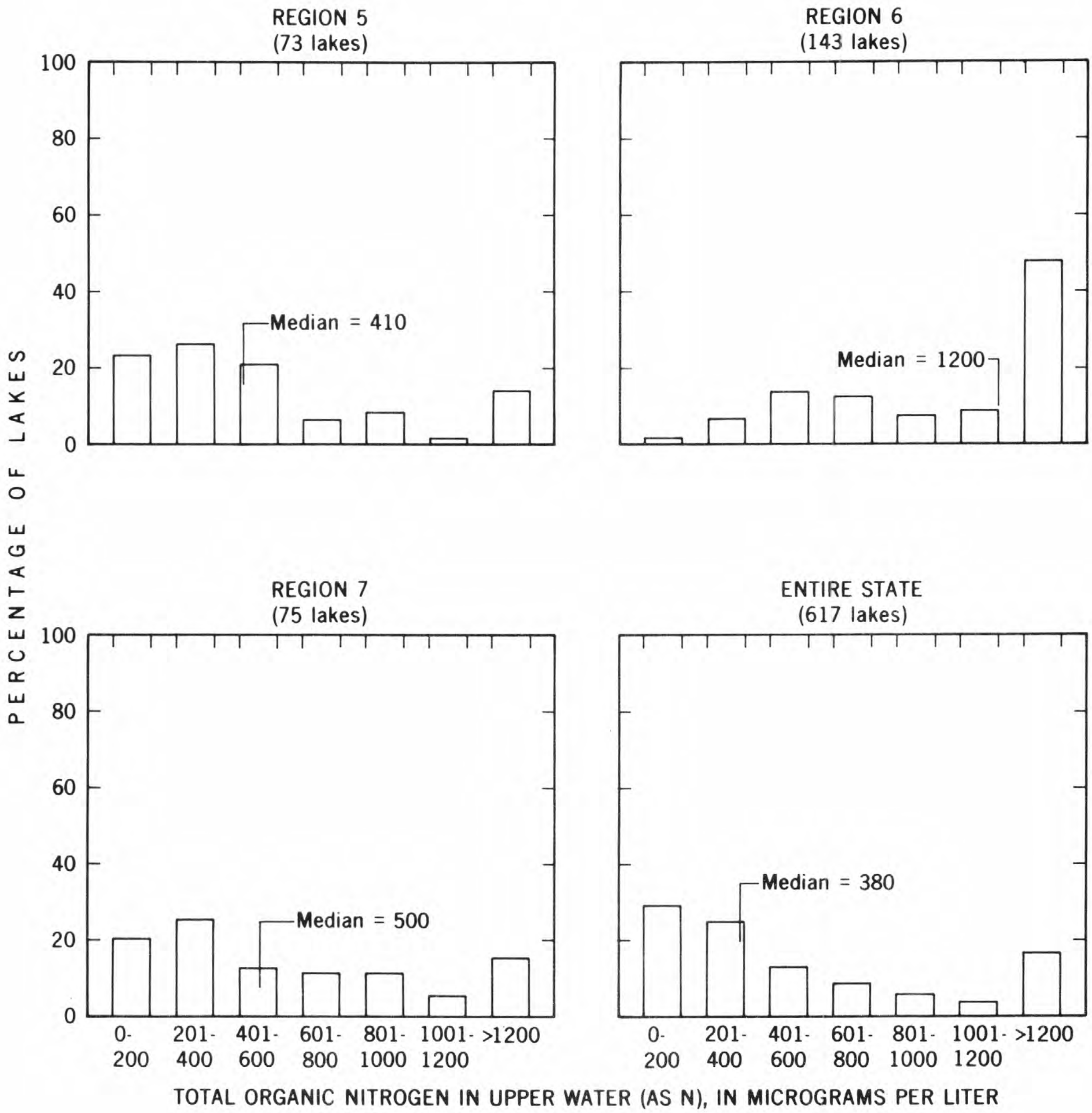


FIGURE 11.—— Regional and state distributions of total organic nitrogen in upper water.


REGION 5
(73 lakes)
Median = 410
REGION 6
(143 lakes)
Median = 1200
REGION 7
(75 lakes)
Median = 500
ENTIRE STATE
(617 lakes)
Median = 380
PERCENTAGE OF LAKES
0
20
40
60
80
100
0-200
201-400
401-600
601-800
801-1000
1001-1200
>1200
TOTAL ORGANIC NITROGEN IN UPPER WATER (AS N), IN MICROGRAMS PER LITER

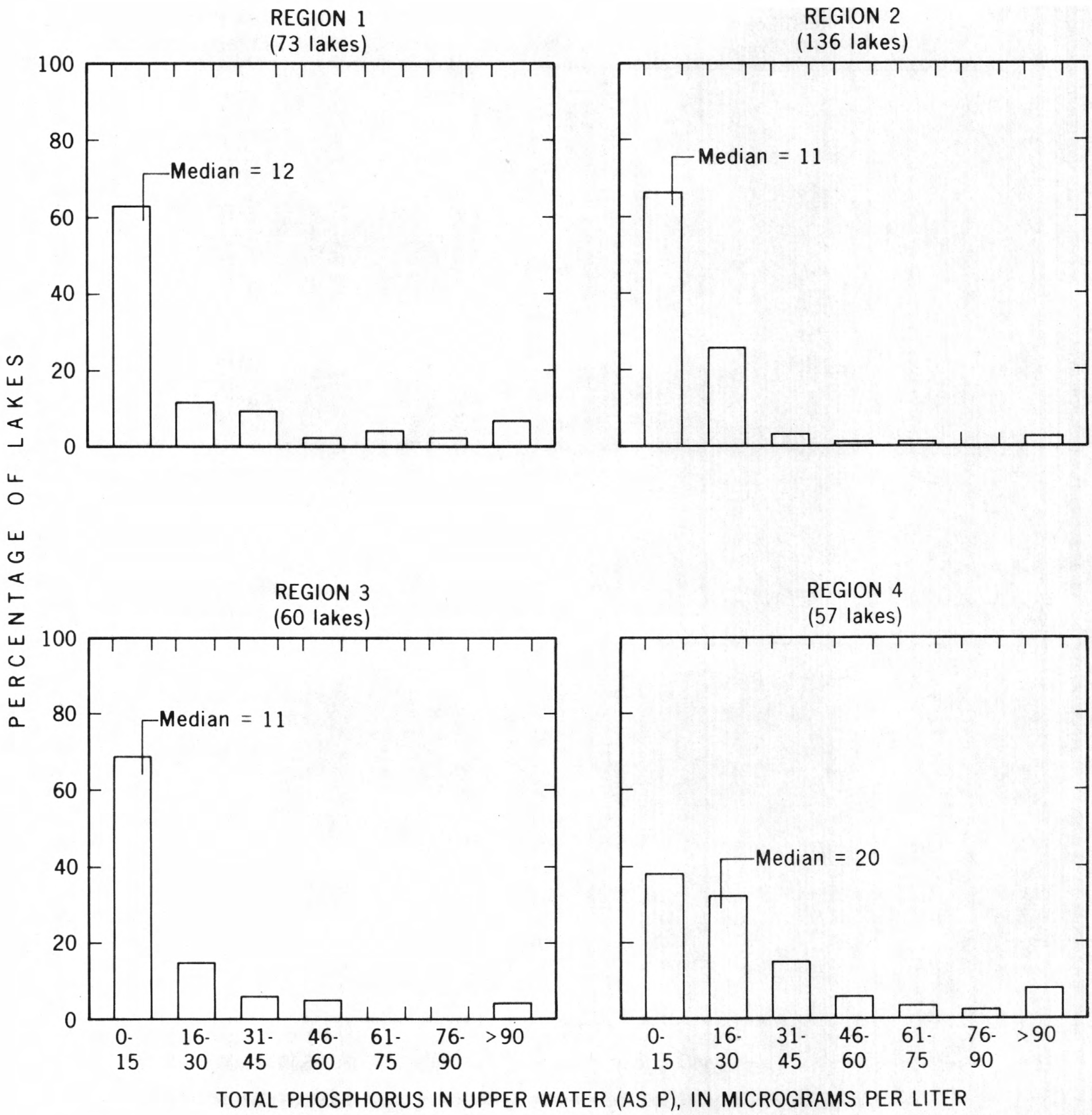
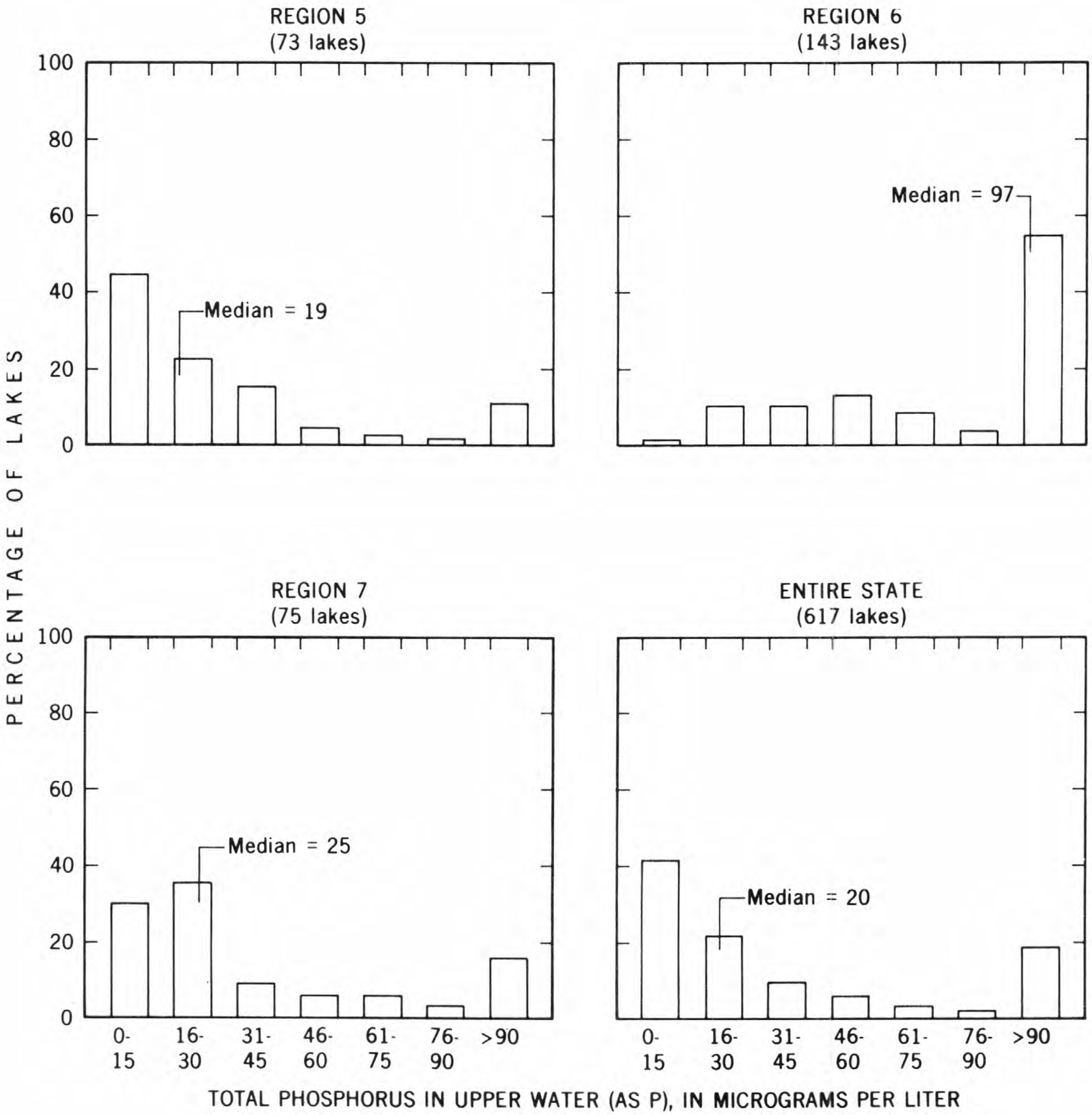


FIGURE 12.—— Regional and state distributions of total phosphorus in upper water.



REGION 5
(73 lakes)
Median = 19
REGION 6
(143 lakes)
Median = 97
REGION 7
(75 lakes)
Median = 25
ENTIRE STATE
(617 lakes)
Median = 20
PERCENTAGE OF LAKES
100
80
60
40
20
0
0-15
16-30
31-45
46-60
61-75
76-90
>90
TOTAL PHOSPHORUS IN UPPER WATER (AS P), IN MICROGRAMS PER LITER

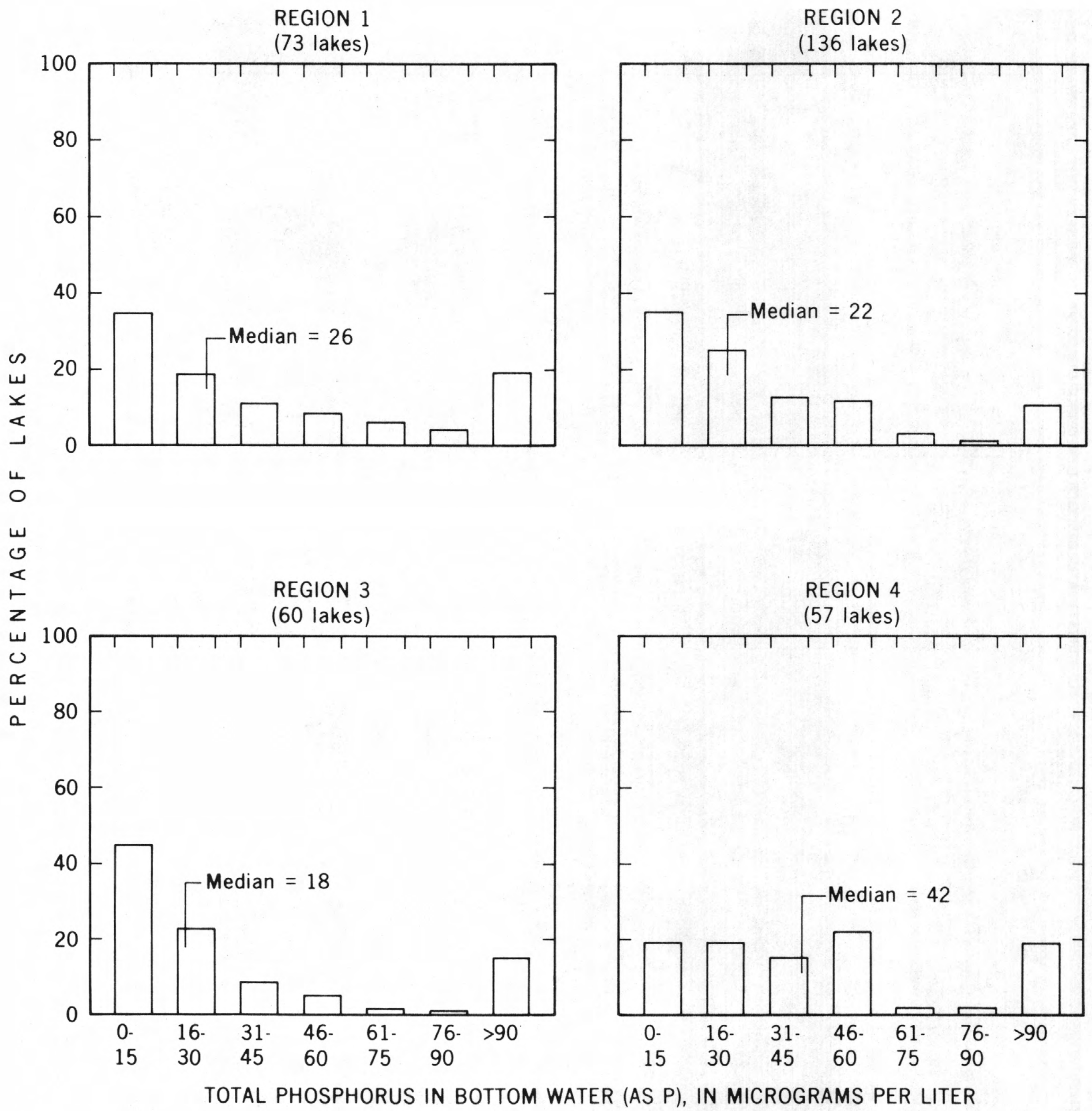
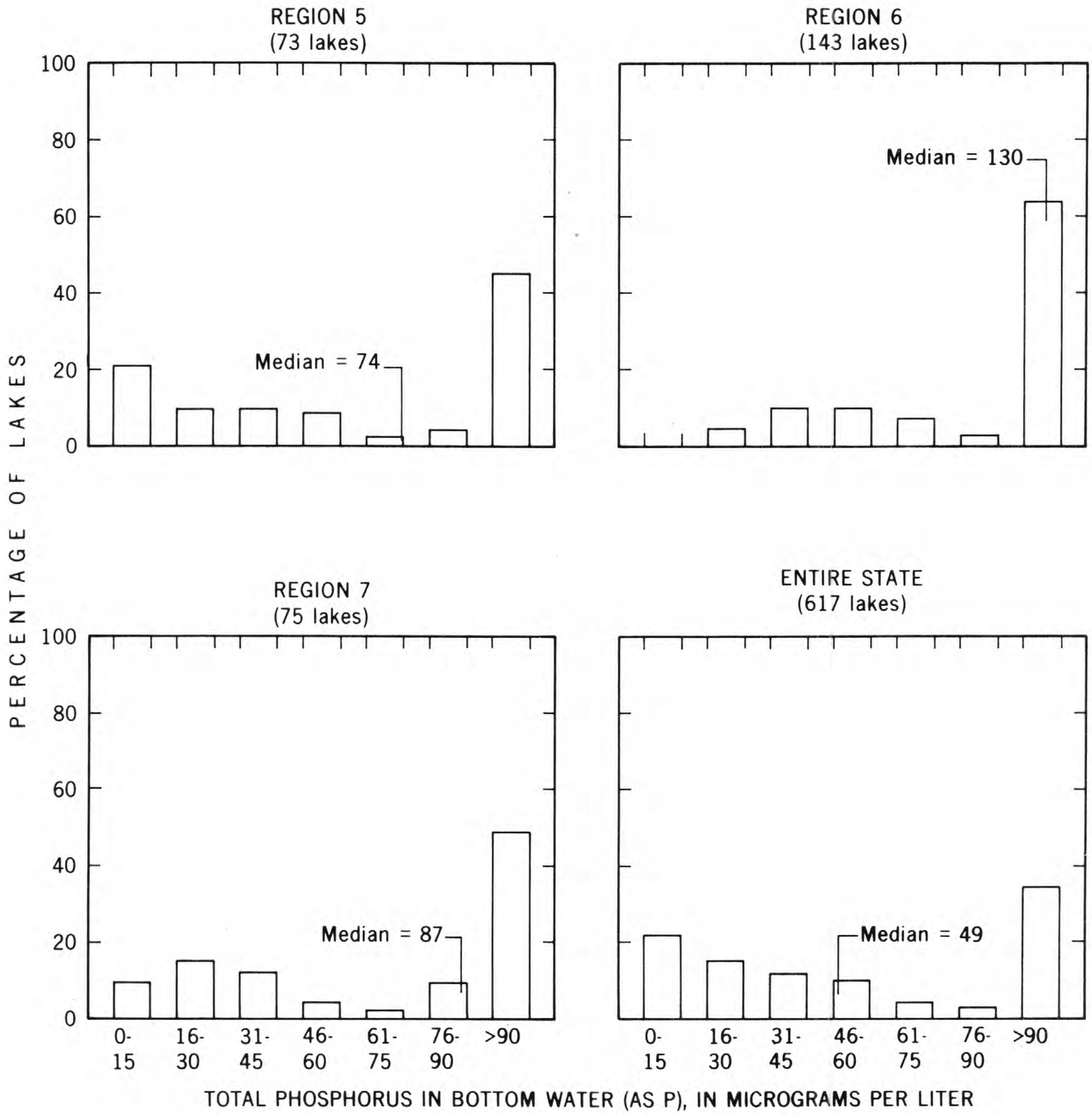


FIGURE 13.—— Regional and state distributions of total phosphorus in bottom water.



REGION 5
(73 lakes)
Median = 74
REGION 6
(143 lakes)
Median = 130
REGION 7
(75 lakes)
Median = 87
ENTIRE STATE
(617 lakes)
Median = 49
PERCENTAGE OF LAKES
0
20
40
60
80
100
0-15
16-30
31-45
46-60
61-75
76-90
>90
TOTAL PHOSPHORUS IN BOTTOM WATER (AS P), IN MICROGRAMS PER LITER

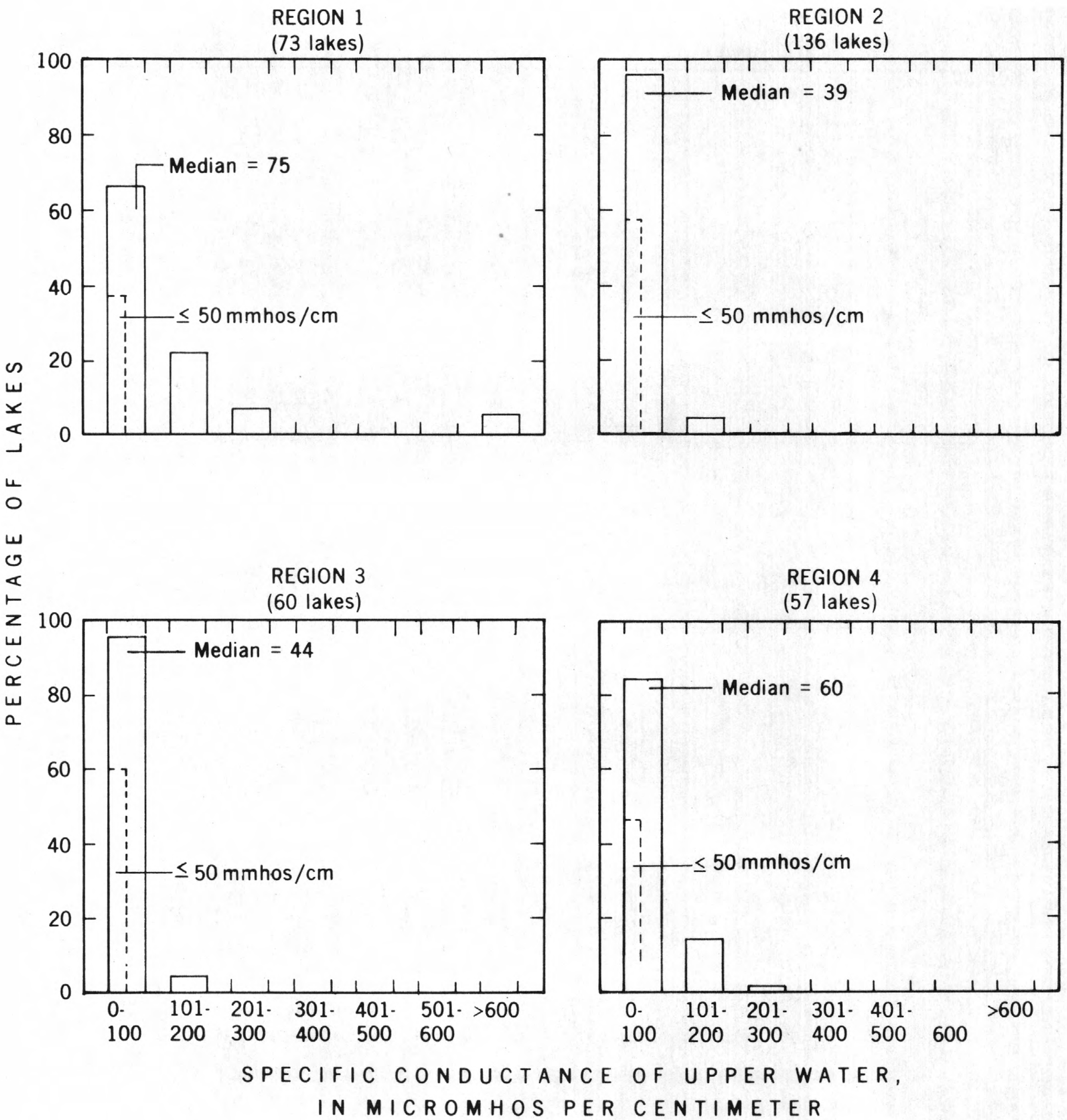
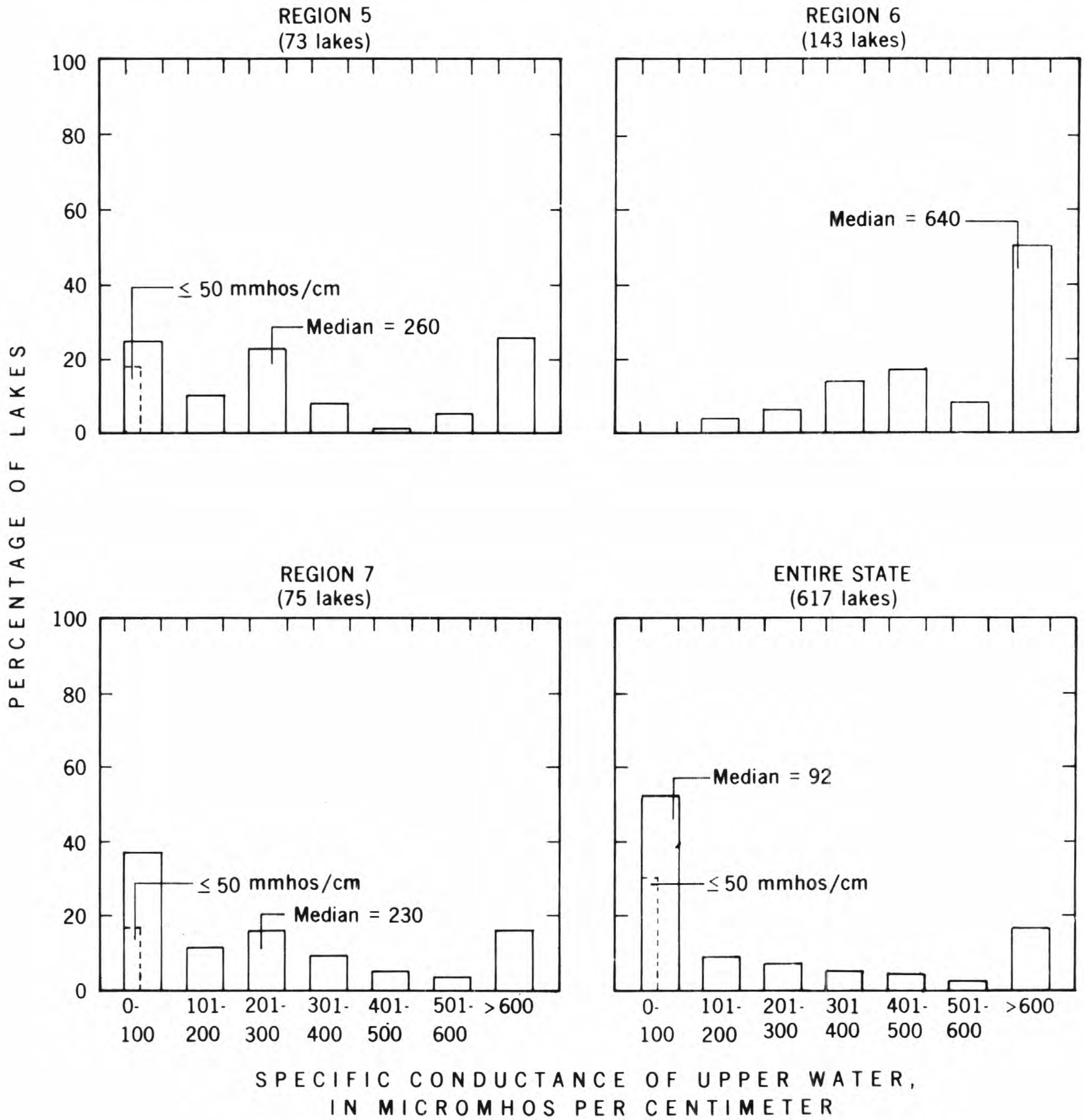


FIGURE 14.—— Regional and state distributions of specific conductance of upper water.


REGION 5
(73 lakes)
≤ 50 mmhos/cm
Median = 260
REGION 6
(143 lakes)
Median = 640
REGION 7
(75 lakes)
≤ 50 mmhos/cm
Median = 230
ENTIRE STATE
(617 lakes)
Median = 92
≤ 50 mmhos/cm
100
80
60
40
20
0
PERCENTAGE OF LAKES
0-100
101-200
201-300
301-400
401-500
501-600
>600
SPECIFIC CONDUCTANCE OF UPPER WATER, IN MICROMHOS PER CENTIMETER

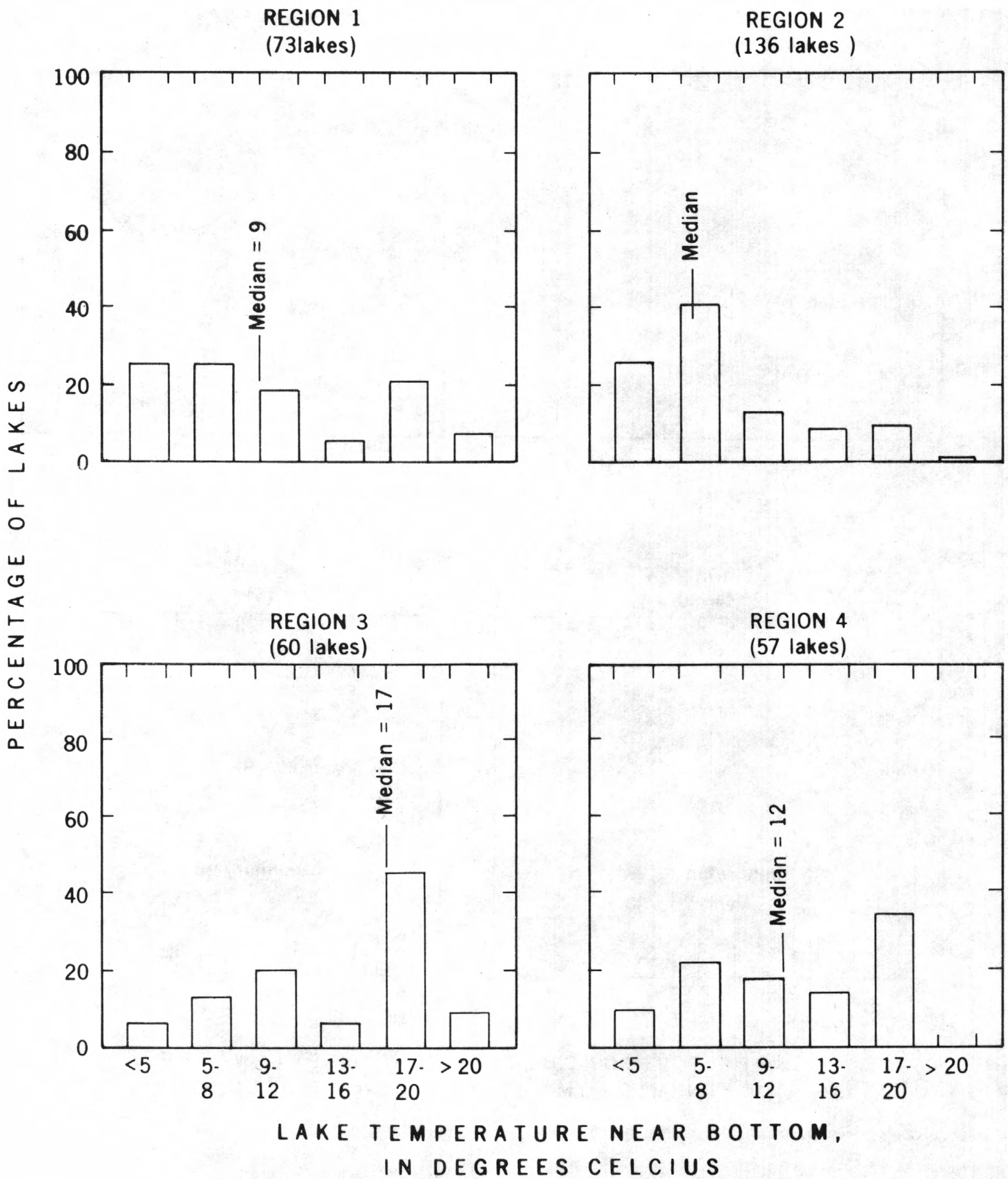
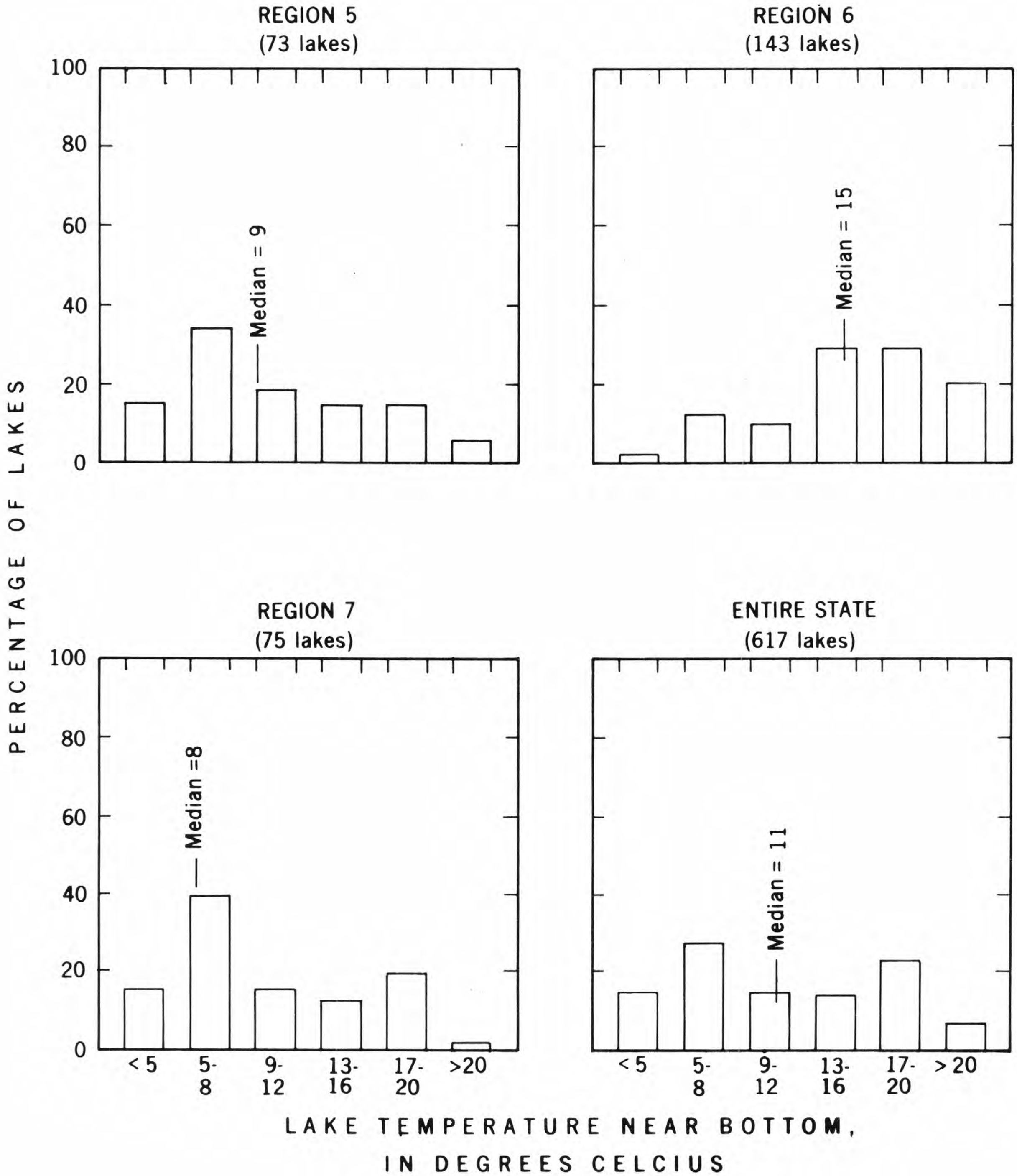


FIGURE 15. –– Regional and state distributions of temperature of bottom water.


REGION 5
(73 lakes)
Median = 9
REGION 6
(143 lakes)
Median = 15
REGION 7
(75 lakes)
Median =8
ENTIRE STATE
(617 lakes)
Median = 11
PERCENTAGE OF LAKES
0
20
40
60
80
100
< 5
5-8
9-12
13-16
17-20
>20
LAKE TEMPERATURE NEAR BOTTOM, IN DEGREES CELCIUS

Dissolved oxygen, bottom water.--The dissolved-oxygen concentration in a lake varies with time of year and is a function of many factors, including the water temperature, atmospheric pressure, and salinity of water. Oxygen concentration in water is continually being altered by life processes, such as photosynthesis and respiration, and by complex chemical reactions. The organisms in the lighted upper layers of water produce organic matter which eventually settles to the bottom. There, bacteria use oxygen to degrade the organic materials, thereby reducing the oxygen concentration in the water. A value of less than 4.0 mg/L dissolved oxygen is generally considered unfavorable to most aquatic organisms, according to the U.S. Environmental Protection Agency (1973, p. 132). Although dissolved-oxygen standards for good growth and general health of fish are not easily defined, a minimum of 5 mg/L for warm-water fish habitats and 6 or 7 mg/L for cold-water fish habitats have been recommended and widely accepted (Bennett, 1970, p. 73).

Graphs of dissolved-oxygen concentration in bottom water (fig. 16) show that, statewide, about 57 percent of the lakes had dissolved-oxygen concentrations of 6.0 mg/L or less in the bottom water, and that nearly one-third had severe bottom-water oxygen depletion, to concentrations of less than 0.5 mg/L. Extreme depletion of dissolved oxygen may cause death to fish.

Region 7 had the highest percentage of lakes with low oxygen concentration near the bottom. In contrast, regions 3, 4, and 6 had the highest concentrations of dissolved oxygen; many of these lakes are shallow (fig. 8) and temperatures were observed to be practically constant from top to bottom. This uniformity of temperature indicates that the waters are well mixed throughout. Under these circumstances the vertical distribution of oxygen is often uniform and near saturation. Region 6 had the highest percentage of lakes with dissolved-oxygen concentrations greater than 12 mg/L. These lakes were supersaturated with respect to dissolved oxygen--that is, the quantity of oxygen in solution for the water temperature was beyond equilibrium concentration. Supersaturation, which apparently occurred in 31 of the 617 lakes statewide, can occur during daytime from the production of oxygen by plants as part of the photosynthetic process. Studies have shown that the growth of fish may be impaired when the fish are subjected to alternately low (nighttime) and high (daytime) oxygen concentrations (Bennett, 1970, p. 73).

Secchi-disc visibility.--Water transparency or clarity can be measured by Secchi-disc readings. Secchi-disc visibility is the depth at which a black and white disc (20 cm in diameter) disappears from view when lowered into the water. Because changes in biological production can cause changes in the color and turbidity of a lake, Secchi-disc visibility often is used as a gross measure of the quantity of algae in the water (Edmondson, 1972, p. 185; Bachmann and Jones, 1974, p. 158). Empirical data suggest that average Secchi-disc depths in eutrophic lakes are mostly less than 2.0 meters, according to the U.S. Environmental Protection Agency (1974, p. 11).

Graphs of Secchi-disc visibility (fig. 17) show that on a statewide basis about one-third of the lakes had Secchi-disc visibilities of 2.0 meters or less and another one-third of the lakes had visibilities of 2.1 to 4.0 meters. The median Secchi-disc visibility ranged from 1.2 meters (region 6) to 3.3 meters (regions 2 and 7). Sixty-eight percent of the lakes in nutrient-rich region 6 had Secchi-disc readings of less than 2.0 meters.

Emersed macrophytes.--Emersed macrophytes are large aquatic plants that can be seen without magnification and that have leaves or other structures extending above the water surface. In this report, however, rooted aquatic plants with floating leaves, such as waterlilies and watershield, also are considered emersed. The extent of emersed aquatic-plant growth was assessed according to the percentage of the lakeshore and water surface covered by emersed and (or) floating plants.

Graphs of shoreline plants (fig. 18) show that 40 percent of the lakes had more than 50 percent of the shoreline covered by emersed plants. There is a tendency for the percentage of shoreline covered by aquatic plants to be either small or large, but not in between.

Graphs of the amount of lake surface covered by plants (fig. 19) show that only 92 of 617 lakes (15 percent) examined had more than 10 percent of the lake surface covered by emersed plants. A lake-surface coverage of as little as 10 percent is commonly considered to be a nuisance condition for users. The distribution pattern of emersed macrophytes, in terms of percentage lake surface covered, appears to be similar for all regions in the State. The median value for plant coverage is not shown in figure 19 because the original data were estimated as a range of values.

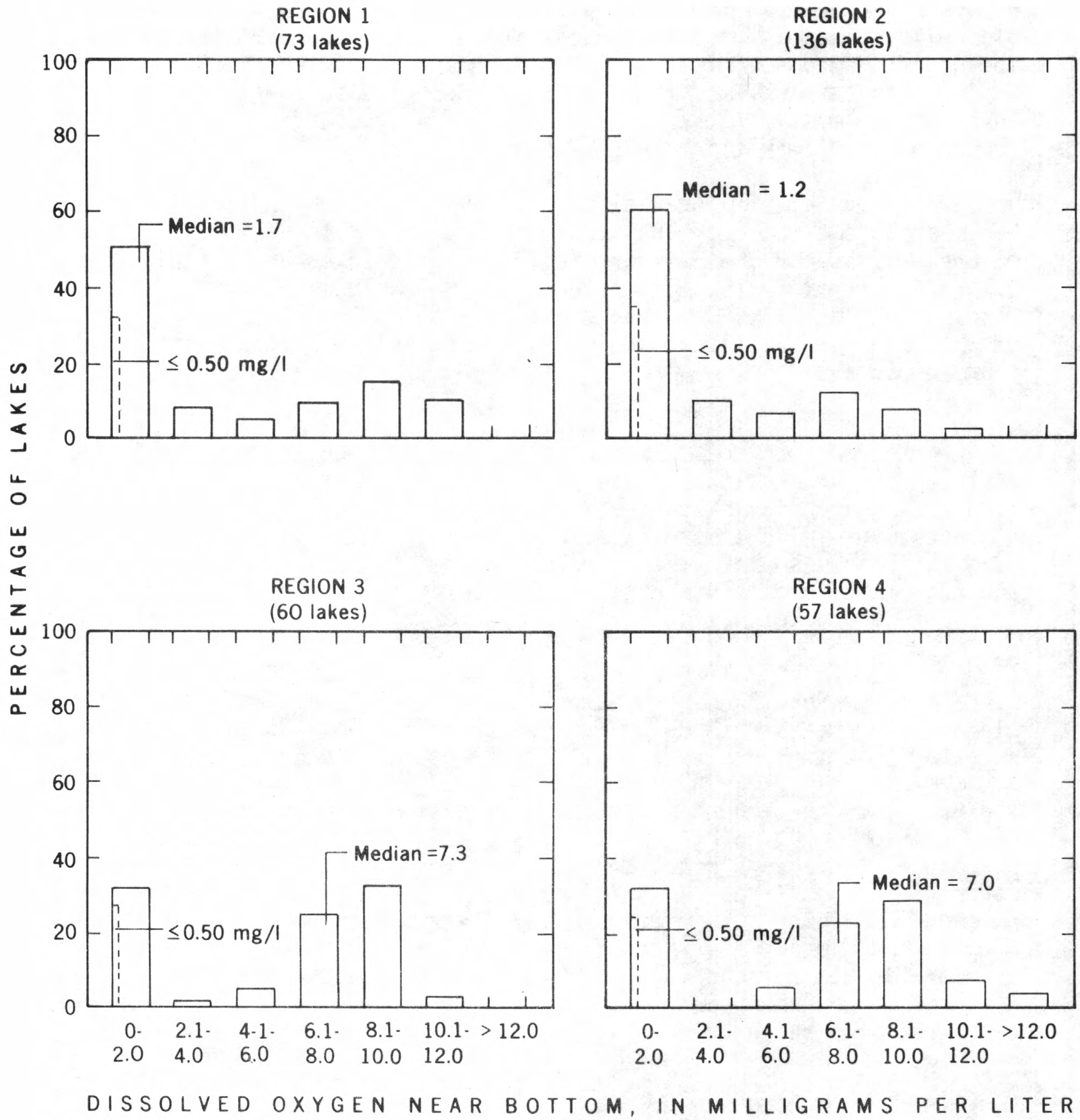
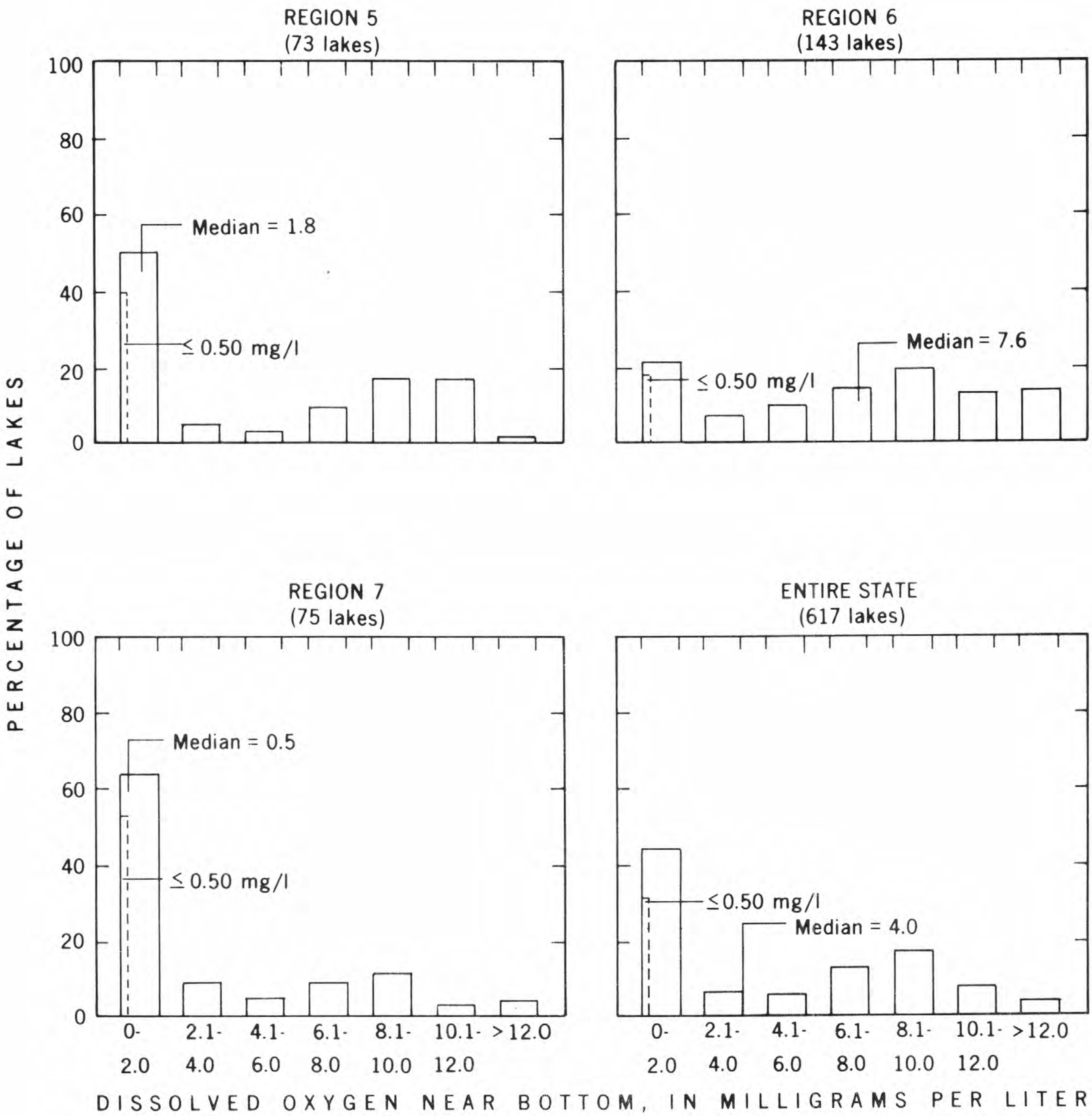


FIGURE 16.——Regional and state distribution of dissolved oxygen in bottom water.


REGION 5
(73 lakes)
Median = 1.8
≤ 0.50 mg/l
REGION 6
(143 lakes)
Median = 7.6
≤ 0.50 mg/l
REGION 7
(75 lakes)
Median = 0.5
≤ 0.50 mg/l
ENTIRE STATE
(617 lakes)
≤0.50 mg/l
Median = 4.0
PERCENTAGE OF LAKES
100
80
60
40
20
0
0-2.0
2.1-4.0
4.1-6.0
6.1-8.0
8.1-10.0
10.1-12.0
>12.0
DISSOLVED OXYGEN NEAR BOTTOM, IN MILLIGRAMS PER LITER

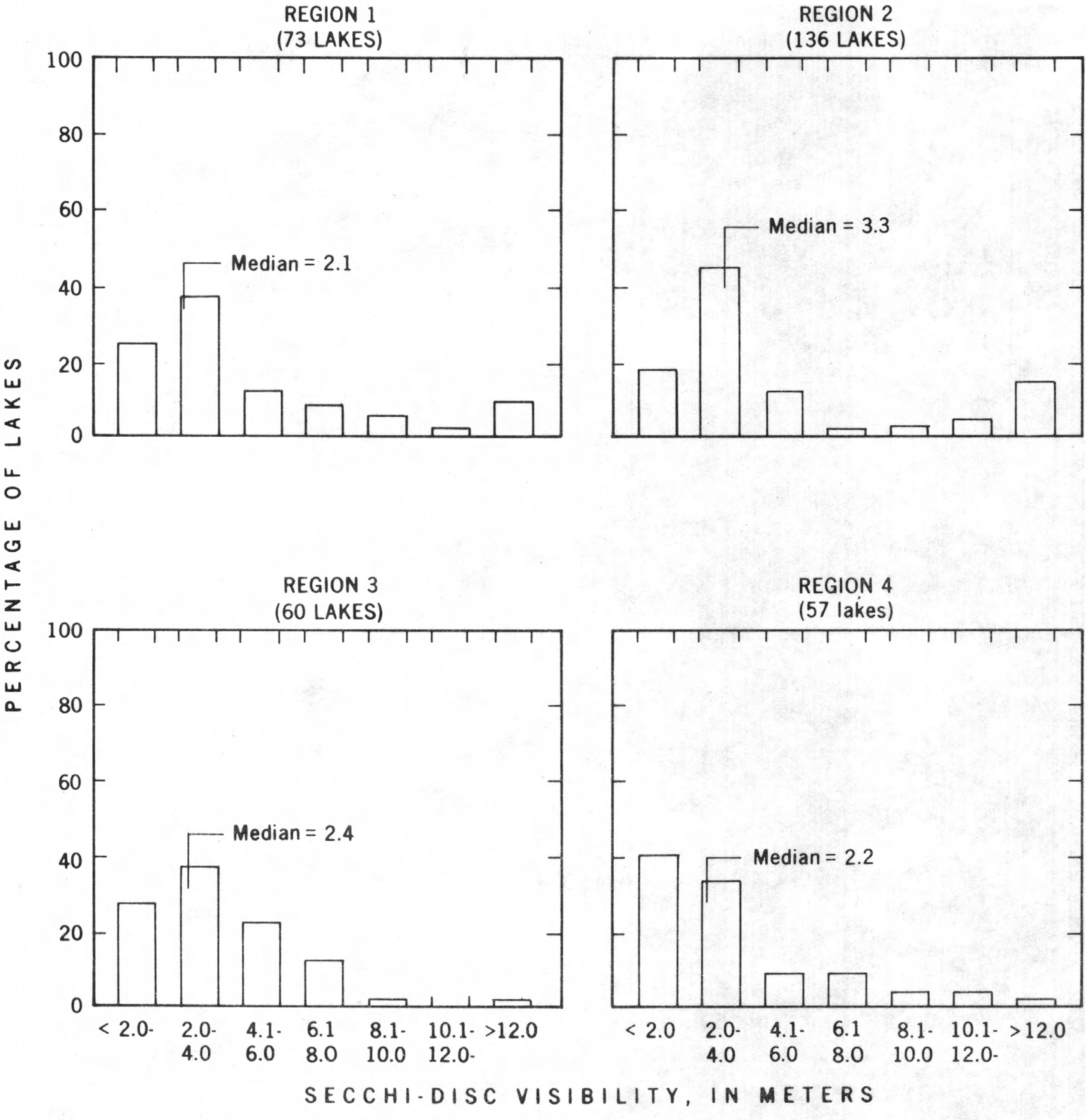
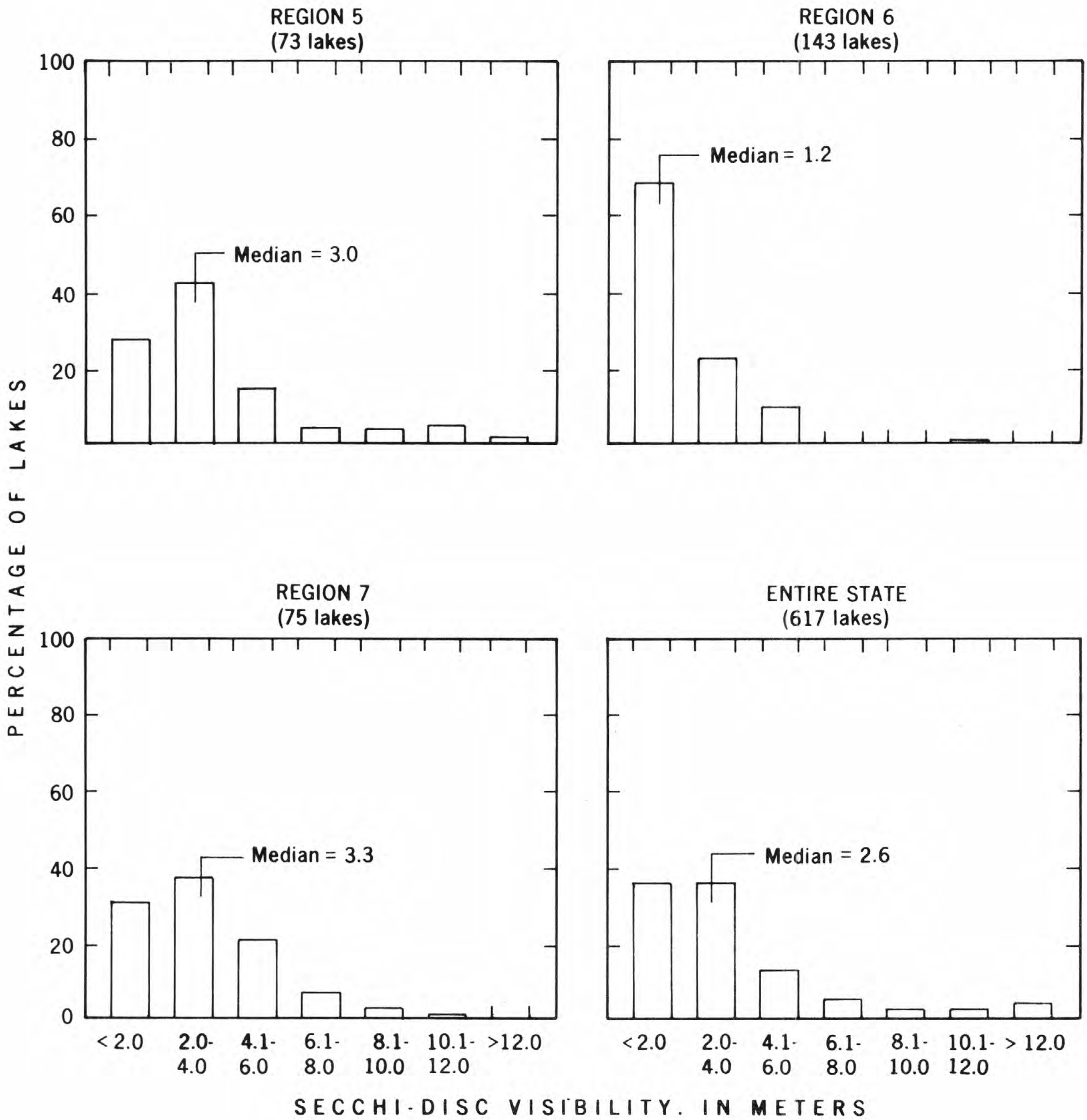


FIGURE 17.——Regional and state distributions of Secchi-disc visibility.


REGION 5
(73 lakes)
Median = 3.0
REGION 6
(143 lakes)
Median = 1.2
REGION 7
(75 lakes)
Median = 3.3
ENTIRE STATE
(617 lakes)
Median = 2.6
PERCENTAGE OF LAKES
0
20
40
60
80
100
< 2.0
2.0-4.0
4.1-6.0
6.1-8.0
8.1-10.0
10.1-12.0
>12.0
SECCHI-DISC VISIBILITY, IN METERS

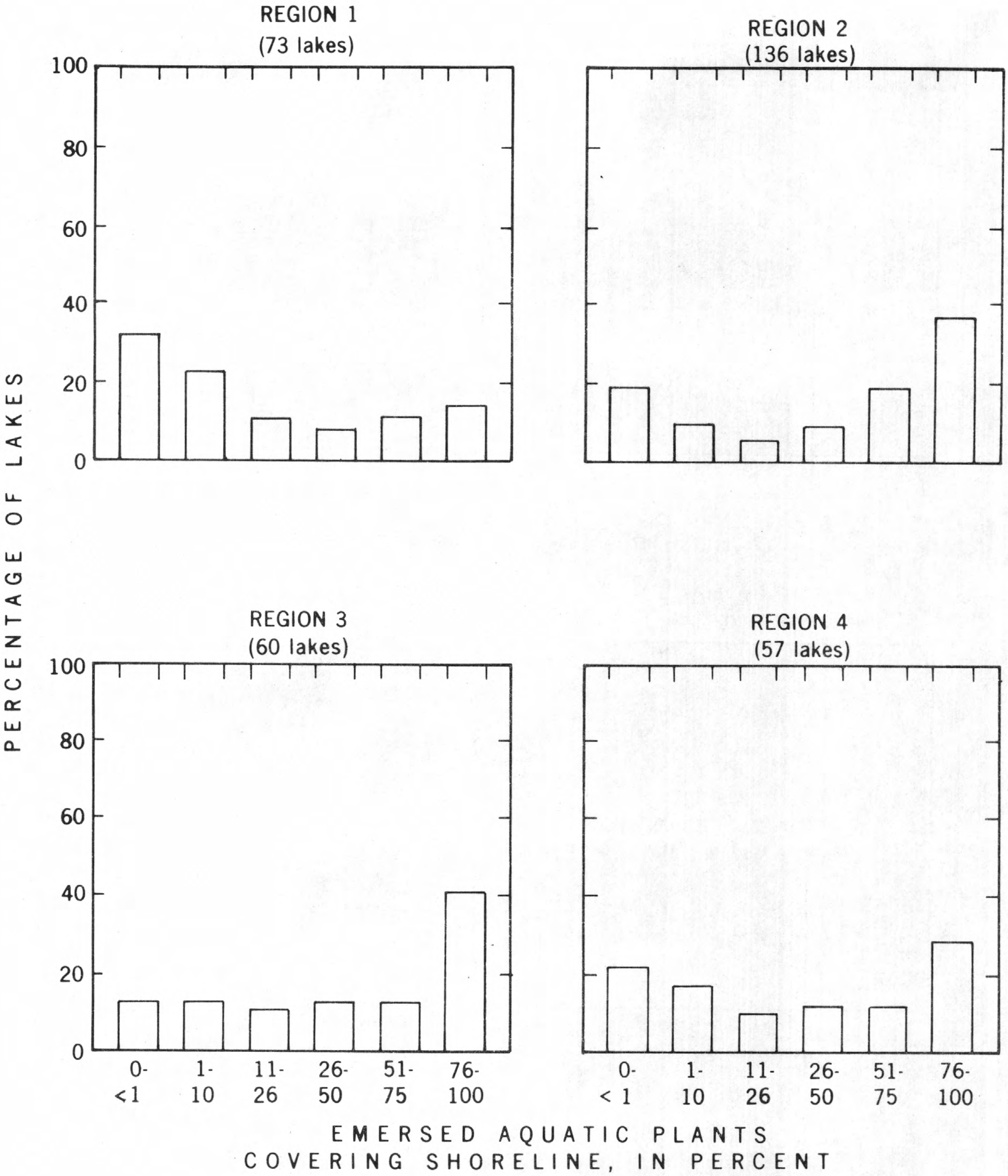
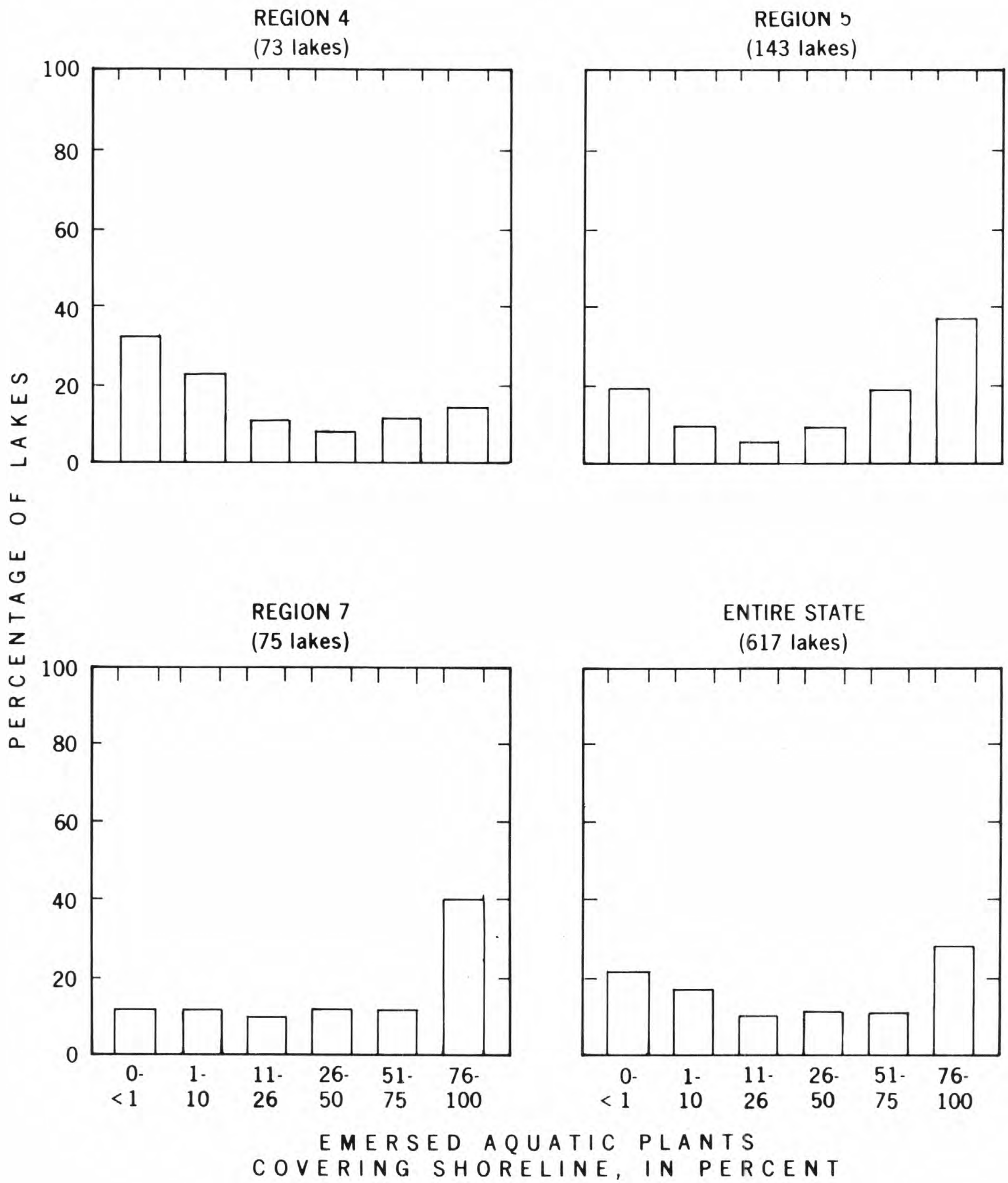


FIGURE 18.—— Regional and state destribution of emersed aquatic plants covering shoreline.


REGION 4
(73 lakes)
REGION 5
(143 lakes)
REGION 7
(75 lakes)
ENTIRE STATE
(617 lakes)
PERCENTAGE OF LAKES
100
80
60
40
20
0
0-
<1
1-
10
11-
26
26-
50
51-
75
76-
100
EMERSED AQUATIC PLANTS
COVERING SHORELINE, IN PERCENT

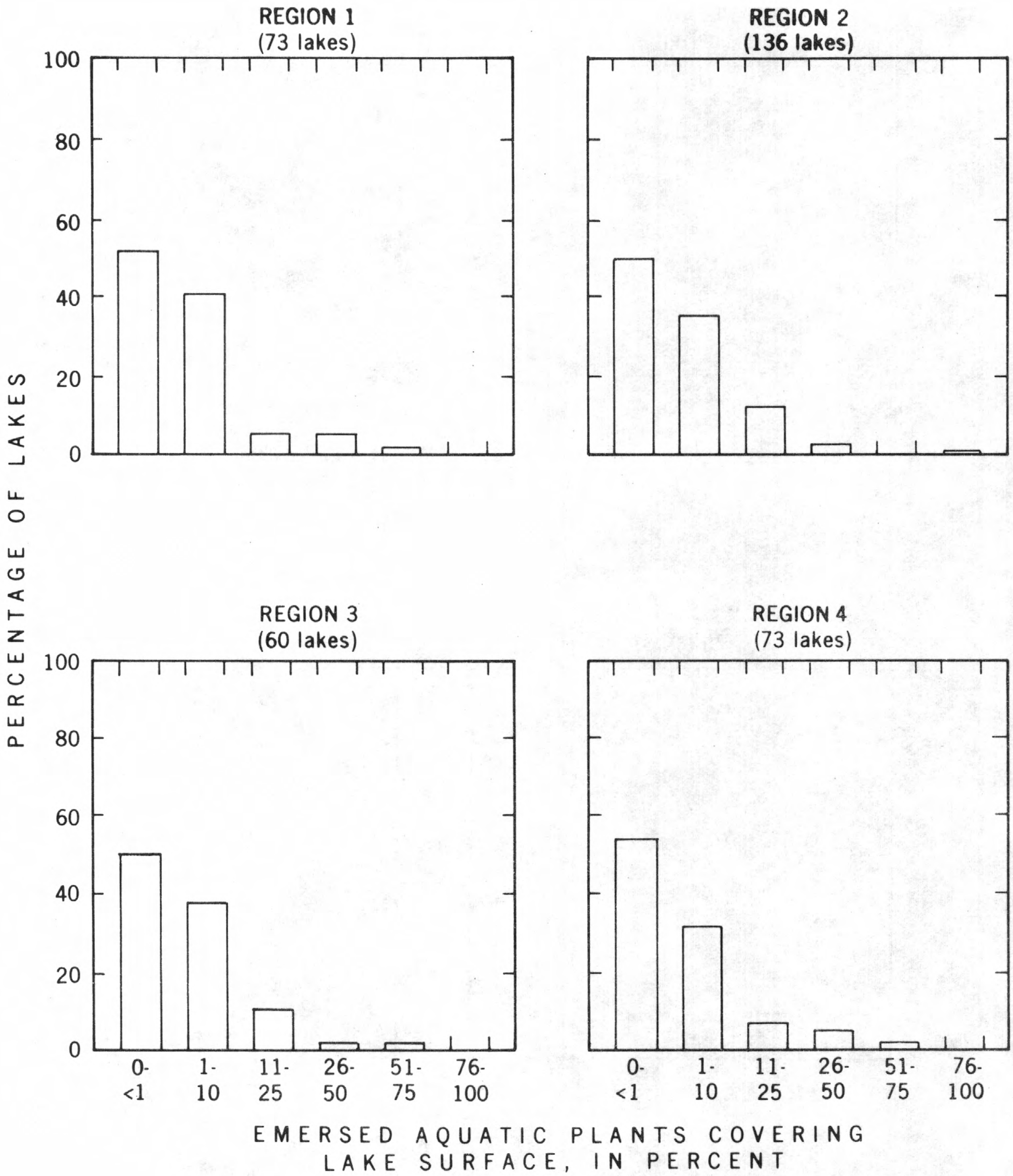
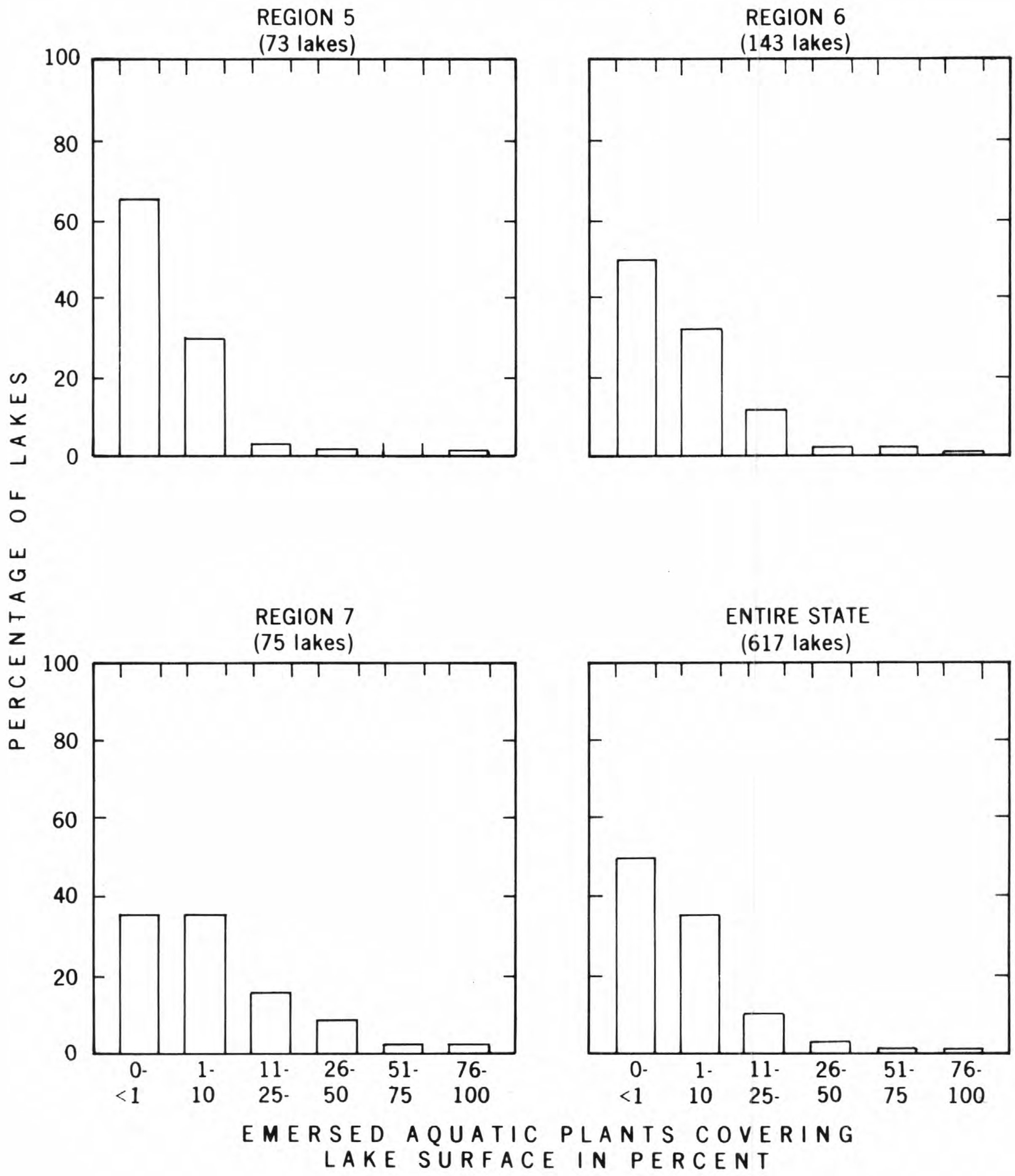


FIGURE 19.—— Regional and state distributions of emersed aquatic plants covering lake surface.


REGION 5
(73 lakes)
REGION 6
(143 lakes)
REGION 7
(75 lakes)
ENTIRE STATE
(617 lakes)
PERCENTAGE OF LAKES
100
80
60
40
20
0
0-
<1
1-
10
11-
25-
26-
50
51-
75
76-
100
EMERSED AQUATIC PLANTS COVERING
LAKE SURFACE IN PERCENT

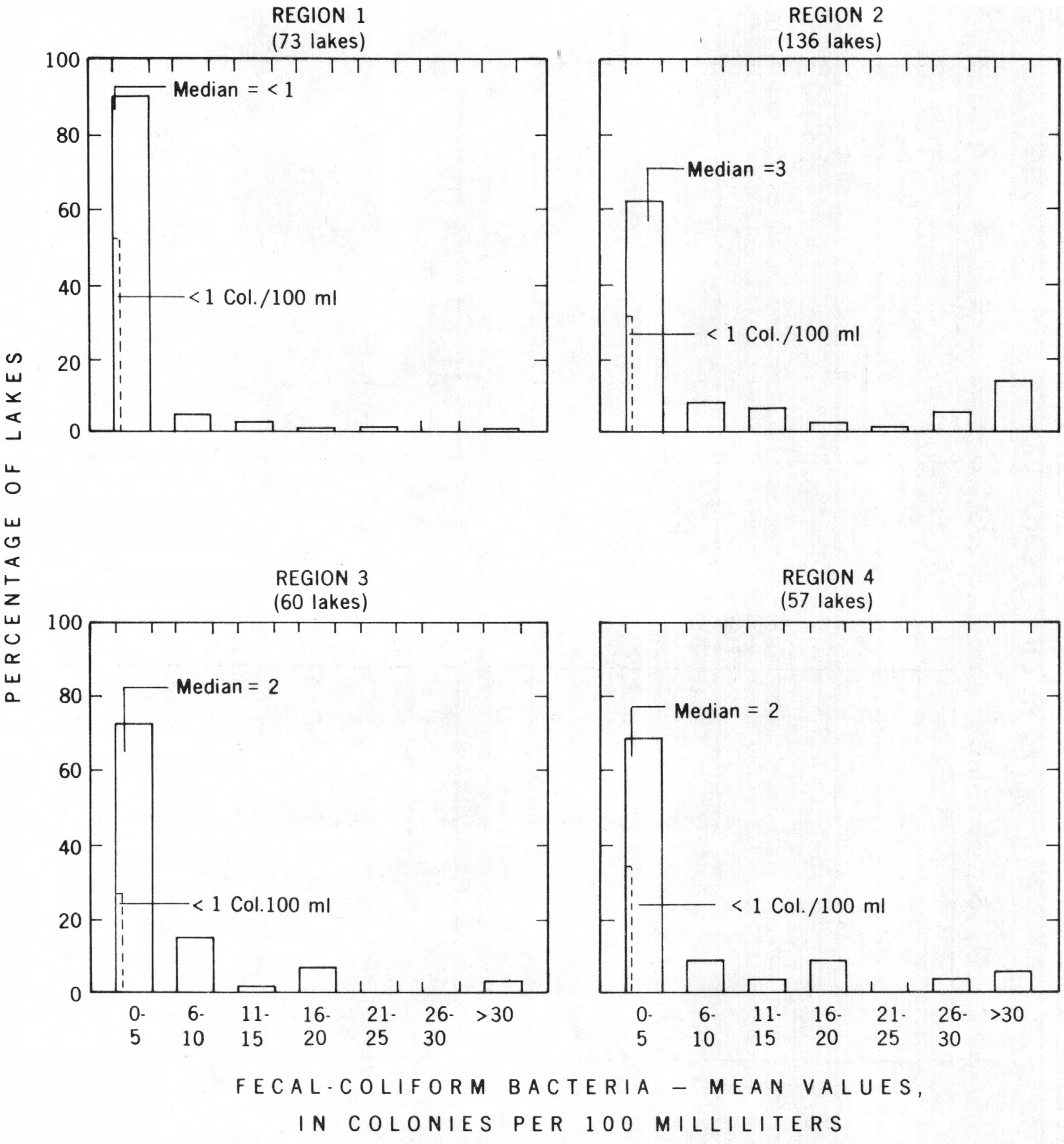
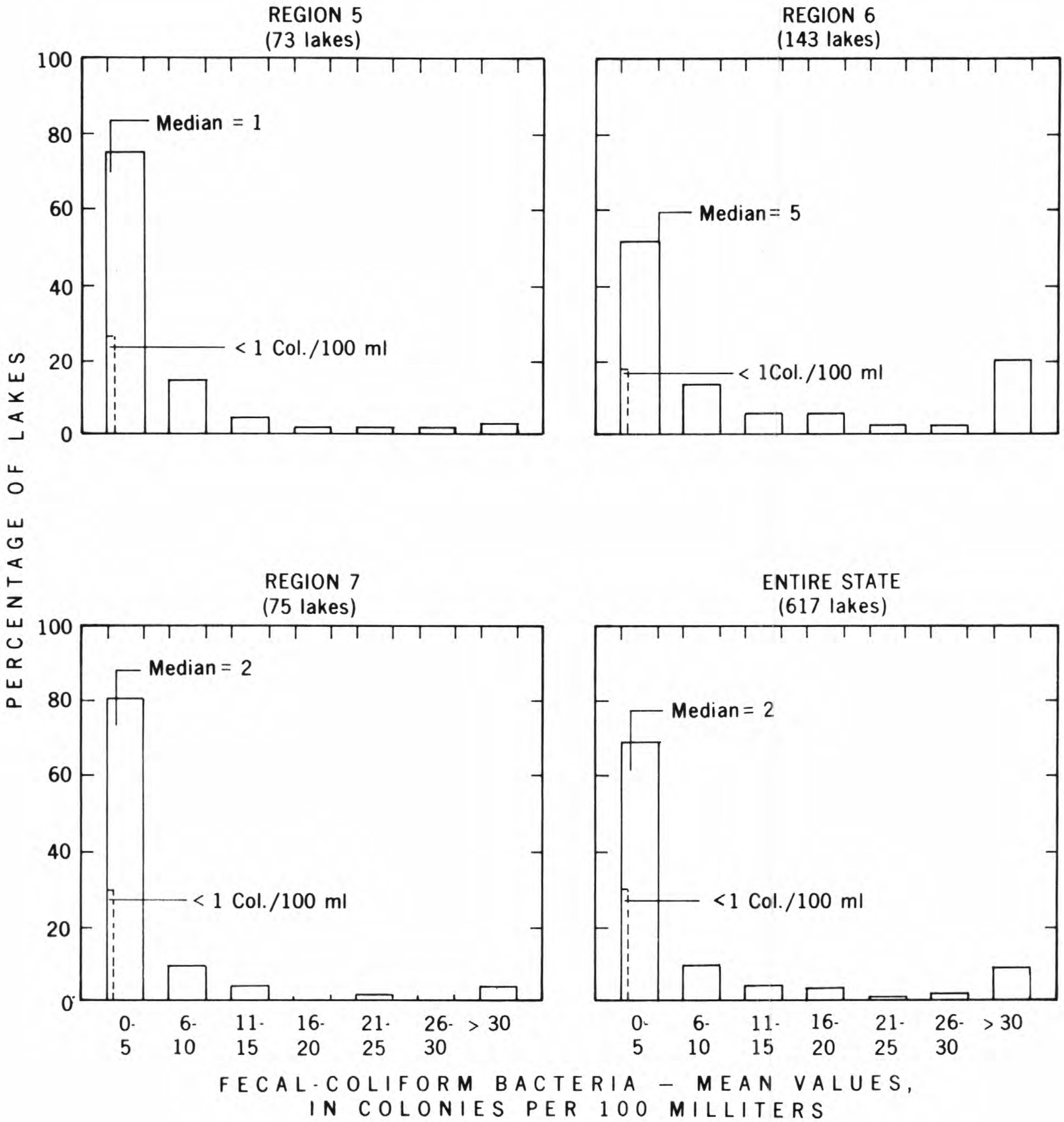


FIGURE 20.—— Regional and state distributions of fecal-coliform bacteria.


REGION 5
(73 lakes)
Median = 1
< 1 Col./100 ml
REGION 6
(143 lakes)
Median= 5
< 1Col./100 ml
REGION 7
(75 lakes)
Median= 2
< 1 Col./100 ml
ENTIRE STATE
(617 lakes)
Median= 2
<1 Col./100 ml
PERCENTAGE OF LAKES
100
80
60
40
20
0
0-5
6-10
11-15
16-20
21-25
26-30
> 30
FECAL-COLIFORM BACTERIA — MEAN VALUES, IN COLONIES PER 100 MILLITERS

Fecal-coliform bacteria.--Fecal-coliform bacteria are present in the feces of warmblooded animals, including man; their presence in water generally is accepted as an indicator of recent fecal-waste contamination (see glossary p. vi). Samples were collected approximately 30 meters offshore at a depth of 0.3 meter at three to five stations around each lake. The reporting unit is the number of colonies per 100 milliliters of water. Although no lake standard has been set by the State for fecal-coliform bacteria, according to Washington Department of Ecology (1973b, p. 5) the "median value of the total count of coliform bacteria (both fecal and nonfecal), should not exceed 240 col/100 mL (colonies per 100 milliliters) of water when associated with a fecal source, and less than 20 percent of the samples should not exceed 1,000 col/100 mL of water." The median fecal-coliform-bacteria concentrations shown by the graphs in figure 20 ranged from less than one (region 1) to 5 col/100 mL of water (region 6). The highest fecal-bacteria counts were observed in regions 2 and 6, which are the regions most heavily influenced by urbanization and agricultural activity, respectively.

SUMMARY

The cultural, physical, and water-quality data shown in figures 2-20 and discussed individually in the text have been summarized in table 2. The relative magnitude of each lake characteristic for each region of the State is indicated by a designation of low, medium, or high, based on whether 30 percent or more of the lakes fall below, within, or above specified limits for that characteristic. Those designations are given only for the purpose of regional comparison and are not necessarily indicative of good or poor conditions. The parameter limits are arbitrary and are not necessarily related to established standards.

Statewide, about two-thirds of the lakes have their drainage basins primarily in forest or unproductive land. In the Columbia Plateau, most of the land in the drainage basins is used for agricultural purposes. Urban development of the drainage basins is generally low throughout the State; suburban development also is low, except in the more populous regions (2 and 3) near Puget Sound, where it is low to moderate. In these same regions, about one-third of the lakes have more than half of their shores developed residentially.

Statewide, 87 percent of the lakes studied are below 1000 meters altitude. The mean depth, probably the most significant physical characteristic affecting lake productivity, is 2.0 meters or less for almost one-fourth of the lakes. Most of the lakes in the Columbia Plateau have a mean depth of 2.0 meters or less. Statewide, only 7 percent of the lakes have mean depths greater than 20.0 meters, and half of the lakes have mean depths between 2.1 and 8.0 meters.

The concentrations of total inorganic nitrogen in the upper water of at least half the lakes were considered low (less than 100 µg/L). Such concentrations, however, are representative of those in summer, a time when nutrient uptake by plants is pronounced and concentrations in the water are consequently reduced. About one-fourth of the lakes had total organic-nitrogen concentrations exceeding 800 µg/L, a concentration that is often characteristic of eutrophic lakes. All regions in eastern Washington had higher concentrations of total organic nitrogen than did those in western Washington. In comparing the relative magnitudes of the inorganic and organic forms of nitrogen, the median total organic-nitrogen concentration (380 µg/L) was about four times higher than the median total inorganic-nitrogen concentration (90 µg/L).

The median concentration of total phosphorus in the upper water of all lakes was 20 µg/L. More than one-third of the lakes had total phosphorus concentrations exceeding 30 µg/L, a concentration that is considered characteristic of eutrophic lakes. Eighty-nine percent of the lakes in the Columbia Plateau exceeded 30 µg/L total phosphorus. Statewide, the median concentration of total phosphorus in the bottom water was about 2.5 times greater than that of the upper water.

About 30 percent of all the lakes, most in western Washington, had specific-conductance values of less than 50 µmho/cm. However, a few lakes west of the Cascades had specific-conductance values greater than 200 µmho/cm although about three-fourths of the lakes in eastern Washington had conductances that exceeded this value.

Summer dissolved-oxygen layering was detected in many lakes throughout the State. The oxygen concentrations in the upper waters of these lakes were typically near saturation but the bottom waters were often severely depleted. One-third of the lakes in the State had bottom-water oxygen depletion, with concentrations of 0.5 mg/L or less.

About one-third of all the lakes had Secchi-disc readings of 2.0 meters or less, a value often considered characteristic of eutrophic lakes. The poorest water clarity was observed in the Columbia Plateau (region 6) where 68 percent of the lakes had Secchi-disc readings of less than 2.0 meters.

The highest fecal-coliform bacteria counts were observed in regions 2 and 6, which are the areas of the State most heavily influenced by urbanization and agriculture, respectively.

TABLE 2.--Relative magnitude of 19 cultural, physical, and water-quality characteristics by region and statewide

Lake characteristic	Lower limit	Upper limit	Units	Relative magnitude[1 2]							
				Region							State-wide
				1	2	3	4	5	6	7	
Cultural											
Percentage forest in lake basin	≤10	>50	Percent	H	H	H	H	H	L	H	H
Percentage agriculture in lake basin	≤10	>50	Percent	L	L	L	L,M	L,H	H	L,H	L
Percentage urban in lake basin	<1	>10	Percent	L	L	L	L	L	L	L	L
Percentage suburban in lake basin	<1	>10	Percent	L	L,M	L,M	L	L	L	L	L
Shoreline residential development	≤10	>50	Percent	L	L,H	L,H	L	L	L	L	L
Physical											
Altitude	≤200	>1,000	Meters	L	L	L	L	M	M	M	L,M
Mean depth	≤4	>16	Meters	L,M	M	L,M	L,M	L,M	L	L,M	L,M
Water quality											
Total inorganic nitrogen, upper water	≤100	>400	µg/L	L,M	L,M	L	L,M	L	L,M	L,M	L,M
Total inorganic nitrogen, bottom water	≤100	>400	µg/L	L,M,H	M,H	L,M	M	L,H	M,H	M,H	M,H
Total organic nitrogen, upper water	≤200	>800	µg/L	L,M	L,M	L,M	L,M	M	M,H	M,H	M
Total phosphorus, upper water	≤15	> 30	µg/L	L	L	L	L,M,H	L,H	H	M,H	L,H
Total phosphorus, bottom water	≤15	> 30	µg/L	L,H	L,H	L,H	H	H	H	H	H
Specific conductance, upper water	≤50	>400	µmho/cm	L,M	L,M	L,M	L,M	M,H	H	M	L,M
Temperature, bottom water	≤8	>16	°C	L	L	H	L,M,H	L,M	M,H	L	L,H
Dissolved oxygen, bottom water	≤ .5	>6	mg/L	L,M,H	L,M	H	H	L,H	H	L	L,H
Secchi-disc visibility	≤2	>4	meters	M,H	M,H	M,H	L,M	M,H	L	L,M,H	L,M
Emersed plants covering shoreline	≤10	>50	Percent	L,H	L	L,H	M,H	L	H	H	L,H
Emersed plants covering lake surface	<1	>10	Percent	L,M	L,M	L,M	L,M	L,M	L,M	L,M	L,M
Fecal-coliform bacteria	<1	>20	Colonies per 100 mL	L,M	L,M	M	L,M	M	M	M	L,M

[1]The respective designations L=low, M=medium, and H=high are used to indicate where 30 percent or more of the lakes are below, within, or above the limits specified.

[2]Designations are given only for the purpose of regional comparison and are not necessarily indicative of good or poor conditions. The limits are arbitrary and not necessarily related to established standards.

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