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# Sedimentation analysis of Iowa lakes

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Sedimentation analysis of Iowa lakes

by

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# INTRODUCTION

## Problem Statement

Excess sedimentation in natural and artificial lakes decreases depths, hinders fish populations, and is detrimental to recreation and aesthetics. Deposition of sediment in a lake occurs as soon as the lake is formed and continues throughout the life of the lake. Iowa's natural lakes, formed by glaciation, have been experiencing sedimentation for thousands of years. Artificial lakes, reservoirs formed by the damming of streams, are recent features on the landscape and have experienced sedimentation for decades. Natural and artificial lakes will continue to be supplied with sediment as watershed erosion continues.

## Objectives

1. Provide a more accurate method to predict lake sedimentation rates. Accurate prediction of sedimentation rates can provide valuable information to lake developers and a community supporting construction of a new lake or restoration of an existing lake. Lake origin and watershed geology, flood characteristics, and morphology

are studied in the thesis in an attempt to provide a better method of estimating lake sedimentation rates.

2. Provide a more accurate method of estimating lake sediment unit weights. An accurate method for estimating lake sediment unit weights can be beneficial to designing lake dredging operations. Unit weights of lake sediments are correlated with particle size, depth of sediment, and distance from the dam.
3. Historic sedimentation rates of Iowa's natural lakes are studied to examine the impact of agriculture and settlement on lake sedimentation.

# LITERATURE REVIEW

## Background Information

Sedimentation of lakes in the United States has been studied by Brune (1948) and Glymph (1951) in the 1940's and 1950's. Recent sedimentation studies have been done by Dendy (1968), Livesey (1972), and Stall (1981). Erosion prediction methods, suspended solids and bed load measurements in streams, and lake bathymetric surveys have been used to estimate lake sedimentation rates. The United States Soil Conservation Service established Land Resource Areas (LRA's) in 1965 to characterize land use, relief and topography, climate, water, and soil types. Flood magnitude and frequency data for streams in Iowa have been studied by Schwob (1953, 1963) and Lara (1973, 1987). Streams in Iowa have been classified into regions according to flood characteristics by Lara (1987). Basin morphology and its effect on lake sedimentation has been studied by Dragoun and Miller (1966), Parker (1977), and Schumm, Mosley, and Weaver (1987). Methods for estimating the unit weight of lake sediments have been developed by Lane and Koelzer (1943) and Koelzer and Lara (1958).

## Lake Sedimentation Terminology

Net drainage area is the part of the drainage basin which contributes sediment to the lake and excludes the lake area and the drainage areas of any upstream reservoirs which act as effective sediment traps (Dendy, 1968). The terms drainage area, watershed area, and drainage basin in the thesis are synonymous with net drainage area (DA). The effectiveness of a lake to capture sediment is measured by the trap efficiency (TE) of the lake; i.e., the ratio of sediment deposited to the sediment entering the lake, expressed as a percent. A low trap efficiency indicates a large percentage of sediment is being transported through the lake.

Brune (1948) and Stall (1981) use the term specific weight and Heinemann (1962) uses the term volume-weight to express the weight of lake sediment per unit volume. The weight of solid material per unit volume is elsewhere described as the sediment density (Koelzer and Lara, 1958). Spangler and Handy (1982) define density of soil as the mass per unit volume and unit weight of soil as the body force per unit volume. This thesis uses the term unit weight ($\gamma$) to define the dry weight of sediment per unit volume, expressed in kilonewtons per cubic meter (pounds/cubic foot).

The terms gross erosion, sediment yield, and sediment production rate are defined by Chow (1964). Gross erosion is the total amount of sheet and channel erosion in a watershed. Sediment yield is the quantity of eroded sediment that is transported downstream to a control point, such as a lake, and is expressed in units of weight or volume. The sediment production rate is computed by dividing the annual sediment yield by the area of the watershed and is expressed in terms of weight, or volume, of sediment per unit of drainage area per year (Chow, 1964).

Sediment yield (SY) is elsewhere defined as the amount of sediment that is delivered to a downstream point, such as a lake, and is expressed as a weight of sediment per unit of drainage area per year (Livesey, 1972; Hadley, 1977; Stall, 1981). Dendy (1968) uses the term sediment accumulation rate (SAR) to express the volume of sediment deposited in a lake per unit of drainage area per year.

This thesis uses the term sedimentation rate (SR) to define the volume of sediment deposited in a lake per year and the term sediment accumulation rate (SAR) to define the volume of sediment deposited per drainage area per year. The annual sediment yield (SY) as defined by Livesey (1972), Hadley (1977), and Stall (1981) is calculated by using the sedimentation rate (SR), drainage area (DA), sediment unit weight ($\gamma$), and trap efficiency (TE) expressed as a decimal.

$$SY=\frac{SR}{DA}x\frac{\gamma}{TE}$$

The annual percent storage loss is the ratio of the sedimentation rate to the lake volume at the time of the first lake survey, expressed as a percent (Dendy, 1968). The capacity to watershed ratio is the ratio of the earliest measured lake volume to the drainage area.

## Accepted Sedimentation Relationships

Lake sedimentation studies offer some general relationships between sedimentation and drainage areas. Larger watersheds have higher sedimentation rates than smaller watersheds (Dendy, 1968). Studies show lake sediment accumulation rates and sediment yields decrease as drainage areas increase (Glymph, 1951; Dendy, 1968; Livesey, 1972; Hadley, 1977; Stall, 1981). Hadley (1977) attributed the decrease in sediment yield in larger watersheds to the greater diversity of topography (flatter slopes) and the development of bottomlands in larger basins, thus providing more sites for sediment to deposit as colluvium and alluvium. Annual storage loss rate increases as the capacity to watershed ratio decreases (Glymph, 1951).

# IOWA LAKE SEDIMENTATION

## Methods of Determining Lake Sedimentation Rates

Lake sedimentation for this study is calculated using bathymetric data from sequential lake surveys. The volume of the lake below a certain datum, usually the spillway elevation, is determined. The loss in volume between lake surveys at different dates is the sedimentation the lake has experienced during that time period. The sedimentation rate is calculated by dividing the volume of sediment by the number of years between lake surveys. The lake survey method is the most accurate technique to determine lake sedimentation rates (Holeman, 1972).

The Iowa lake surveys were done three different ways - through the ice surface with a rod, from a boat with rod, and with a sonic sounder or recording fathometer from a boat. Lake surveys done through the ice surface with a rod and from a boat with a rod are performed using standard surveying equipment. Usually a baseline and ranges are laid out across the lake and water depths are taken at intervals along the ranges. The sonic sounder or recording fathometer operates from a boat and continuously transmits sound waves and receives the reflected sound waves. The lake depths are determined using the sound wave velocity through the lake water. Through electronic and mechanical components, the depths are continuously recorded on a chart as the boat crosses the lake on a predetermined course. The ice and rod, boat and rod, and sonic sounder lake surveys use established elevation benchmarks to adjust the lake depths to elevations above mean sea level.

The gross erosion in the watershed, the sediment yield, and the trap efficiency of a lake are sometimes used to calculate lake sedimentation rates. Erosion methods provide only an estimate of lake sedimentation. This thesis does not use erosion methods to estimate sedimentation rates for the Iowa lakes.

The sedimentation rate of a lake is also predicted using the trap efficiency of the lake and suspended solids concentrations, bed loads, and discharges of streams entering the lake. Variations in the relationship between stream discharges and stream sediment loads make the accuracy of using these measurements to predict lake sedimentation questionable (Holeman, 1972). Therefore, this thesis does not use suspended solids and bed load data to estimate sedimentation rates for the Iowa lakes.

**Possible Measurement Problems**

Lake surveys provide reasonably accurate sedimentation rates. However, some problems need to be considered.

1. If a lake has been dredged, records of lake dredging are not always available; therefore lake survey data are sometimes not useful because of unknown amounts of sediments removed by dredging.
2. Lake surveys performed with a sonic sounder or recording fathometer may not record accurate depths due to soft clayey lake bottoms, aquatic vegetation, and schools of fish. Also, the horizontal location of the boat may be in question.
3. Construction and modifications of lakes and watersheds affect lake volumes and sedimentation rates. Shoreline protection with rock rip-rap, installation of boat docks, and changes in park and lake uses affect the lake volume. Water diversion projects and increased tillage in the watershed increase the sedimentation rate; whereas, conservation practices such as terracing and strip cropping in the watershed, decrease the sedimentation rate.
4. Calculated values for sediment yield may not be accurate due to lack of trap efficiency data. The sedimentation

rate, drainage area, sediment unit weight, and trap efficiency are needed to calculate sediment yields. Sediment yields are calculated for 25 Iowa lakes with sediment unit weight data. Trap efficiency data are available for 3 of these 25 lakes and range from 85% to 95%. The midrange value of 90% for trap efficiency is used to calculate the sediment yields for the Iowa lakes without trap efficiency data.

5. The age and development of a lake has an effect on the amount of sediment deposited in a lake. Trap efficiency and sedimentation are believed to decrease as a lake ages.

Lake surveys provide the best information available. It is hoped that sediment measurement errors are reduced in significance by using data from a large number of lakes.

## Iowa Sedimentation Survey Data

Iowa's natural lakes, reservoirs, and farm ponds are referred to as lakes in the thesis. Sedimentation surveys have been completed in 40 Iowa lakes as listed in Tables 1 and 2. The 40 lakes provide the necessary data to analyze lake sedimentation. Each lake has been surveyed at least twice and most of the lakes have been surveyed more than twice. The

Table 1. Iowa lake locations and references

| lake name | Iowa county | dates of surveys used to compute sedimentation | reference |
|---|---|---|---|
| Allerton Reservoir | Wayne | 1913, 1939 | U.S. Dept. of Agriculture, 1975 |
| Backbone Lake | Delaware | 1934, 1942, 1949 | U.S. Dept. of Agriculture, 1975 |
| Barney Mundt | Crawford | 1944, 1949, 1952 | U.S. Dept. of Agriculture, 1975 |
| Beeds Lake | Franklin | 1935, 1946, 1979 | U.S. Dept. of Agriculture, 1975<br>Bachmann et al., 1980 |
| Black Hawk Lake | Sac | 1916, 1935 | Bachmann et al., 1983 |
| Bloomfield | Davis | 1937, 1951 | U.S. Dept. of Agriculture, 1975 |
| C. A. Stiles | Cherokee | 1940, 1949, 1950, 1953 | U.S. Dept. of Agriculture, 1975 |
| Centerville Res. #2 | Appanoose | 1926, 1937 | U.S. Dept. of Agriculture, 1975 |
| Charles Fienhold | Crawford | 1945, 1949 | U.S. Dept. of Agriculture, 1975 |
| Clear Lake | Cerro Gordo | 1935, 1971 | Iowa State Planning Board, 1935<br>Bachmann et al., 1980 |
| CM ST P&P RR Res. | Boone | 1903, 1918 | U.S. Dept. of Agriculture, 1975 |
| Coralville Reservoir | Johnson | 1958, 1968, 1975 | U.S. Dept. of Agriculture, 1975<br>McDonald et al., 1977 |
| Don Williams Lake | Boone | 1974, 1980 | U.S. Dept. of Agriculture, SCS, 1983 |
| Fairfield Res. #3 | Jefferson | 1927, 1934, 1953 | U.S. Dept. of Agriculture, 1975 |
| Farmer's Ditch | Woodbury | 1941, 1945 | U.S. Dept. of Agriculture, 1975 |
| Five Island Lake | Palo Alto | 1935, 1970 | Iowa State Planning Board, 1935<br>Bachmann et al., 1980 |
| Fred Hollrah | Monona | 1944, 1949 | U.S. Dept. of Agriculture, 1975 |
| Honey Creek No. F-1 | Lucas | 1955, 1958, 1959, 1961 | U.S. Dept. of Agriculture, 1975 |
| Jones Creek Res. | Harrison | 1942, 1949, 1950, 1953 | U.S. Dept. of Agriculture, 1975 |
| Lake Icaria | Adams | 1976, 1986 | Adams County, 1989 |

Table 1. (Continued)

| lake name | Iowa county | dates of surveys used to compute sedimentation | reference |
|---|---|---|---|
| Lake Iowa | Iowa | 1978, 1988 | Iowa DNR, 1989 |
| Lake John Deere | Clayton | 1979, 1988 | Clayton & Delaware Counties, 1988 |
| Lake Panorama | Guthrie | 1970, 1980 | Dougal et al., 1981 |
| Lake of Three Fires | Taylor | 1936, 1950 | U.S. Dept. of Agriculture, 1975 |
| Lake Wapello | Davis | 1937, 1951, 1971, 1982 | U.S. Dept. of Agriculture SCS, 1983 |
| Lower Pine Lake | Hardin | 1924, 1932 | U.S. Dept. of Agriculture, 1975<br>Bachmann et al., 1991 |
| Max Miller #5 | Pottawattamie | 1941, 1949, 1952 | U.S. Dept. of Agriculture, 1975 |
| Prairie Rose Lake | Shelby | 1971, 1980, 1985 | _____, 1985 |
| Red Rock Reservoir | Marion | 1977, 1984 | U.S. Army Corps of Engineers, 1988 |
| Silver Lake | Palo Alto | 1935, 1973 | Iowa State Planning Board, 1935<br>Bachmann et al., 1980 |
| Springbrook Lake | Guthrie | 1936, 1946, 1980 | U.S. Dept. of Agriculture SCS, 1983 |
| Swan Lake | Carroll | 1935,1952, 1980 | Iowa State Planning Board, 1935<br>Lohnes et al., 1981 |
| Theobold C | Woodbury | 1948, 1952 | U.S. Dept. of Agriculture, 1975 |
| Theobold Main | Woodbury | 1949, 1952 | U.S. Dept. of Agriculture, 1975 |
| Tracy North | Crawford | 1939, 1949, 1953 | U.S. Dept. of Agriculture, 1975 |
| Tuttle Lake | Dickinson | 1935, 1973 | Iowa State Planning Board, 1935<br>Bachmann et al., 1980 |
| Union Grove Lake | Tama | 1936, 1950 | Bachmann et al., 1983 |
| Upper Pine Lake | Hardin | 1934, 1947, 1961, 1990 | U.S. Dept. of Agriculture, 1975<br>Bachmann et al., 1991 |
| Wilbur Meyer | Crawford | 1944, 1949, 1952 | U.S. Dept. of Agriculture, 1975 |
| William Esbeck | Audubon | 1944, 1949 | U.S. Dept. of Agriculture, 1975 |

Table 2. Iowa lake survey data

| lake name | surface area (hectares) | net drainage area (sq. km) | earliest volume (cubic meters) | sedimentation rate (cubic m/yr) | annual storage loss (%) | sediment dry unit weight (kN/cubic m) |
|---|---|---|---|---|---|---|
| Allerton Reservoir | 41.4 | 12.5 | 630,600 | 5,318 | 0.84 | ----- |
| Backbone Lake | 50.6 | 316.7 | 750,300 | 11,414 | 1.52 | 11.80 |
| Barney Mundt | 1.6 | 0.9 | 51,000 | 1,950 | 3.81 | 8.67 |
| Beeds Lake | 42.9 | 81.8 | 1,424,000 | 8,132 | 0.57 | ----- |
| Black Hawk Lake | 323.0 | 48.7 | 4,948,900 | 41,462 | 0.84 | 6.99 |
| Bloomfield | 31.1 | 5.5 | 1,105,700 | 5,726 | 0.52 | ----- |
| C. A. Stiles | 5.4 | 1.5 | 96,300 | 1,036 | 1.08 | 8.23 |
| Centerville Res. #2 | 20.7 | 6.8 | 1,371,000 | 6,849 | 0.50 | ----- |
| Charles Fienhold | 0.8 | 1.1 | 15,600 | 3,073 | 19.75 | 9.92 |
| Clear Lake | 1,474.3 | 35.5 | 44,954,600 | 55,530 | 0.12 | ----- |
| CM ST P&P RR Res. | 5.2 | 6.5 | 53,100 | 1,480 | 2.79 | ----- |
| Coralville Reservoir | 1,983.0 | 7,900.0 | 66,105,400 | 992,140 | 1.50 | 6.68 |
| Don Williams Lake | 61.5 | 83.7 | 3,212,100 | 17,893 | 0.56 | 5.44 |
| Fairfield #3 | 16.2 | 7.6 | 255,400 | 3,418 | 1.34 | 8.11 |
| Farmer's Ditch | 388.5 | 55.4 | 831,700 | 129,570 | 15.58 | 10.73 |
| Five Island Lake | 401.1 | 34.1 | 5,013,700 | 26,360 | 0.53 | ----- |
| Fred Hollrah | 1.0 | 0.6 | 23,400 | 1,665 | 7.12 | 9.16 |
| Honey Creek No. F-1 | 3.4 | 3.1 | 227,100 | 1,193 | 0.52 | 10.37 |
| Jones Creek Reservoir | 7.8 | 5.8 | 313,700 | 6,232 | 1.99 | 8.61 |
| Lake Icaria | 283.3 | 72.8 | 9,084,700 | 211,880 | 2.33 | ----- |

Table 2. (Continued)

| lake name | surface area (hectares) | net drainage area (sq. km) | earliest volume (cubic meters) | sedimentation rate (cubic m/yr) | annual storage loss (%) | sediment dry unit weight (kN/cubic m) |
|---|---|---|---|---|---|---|
| Lake Iowa | 34.0 | 5.4 | 1,243,900 | 5,676 | 0.46 | ----- |
| Lake John Deere | 5.0 | 3.4 | 201,100 | 6,034 | 3.00 | ----- |
| Lake Panorama | 566.6 | 1,139.6 | 23,871,700 | 657,230 | 2.75 | 11.79 |
| Lake of Three Fires | 39.3 | 15.5 | 1,519,100 | 33,688 | 2.22 | ----- |
| Lake Wapello | 115.3 | 20.2 | 5,324,700 | 16,400 | 0.31 | 5.11 |
| Lower Pine Lake | 26.3 | 39.2 | 910,700 | 28,950 | 3.18 | 12.32 |
| Max Miller #5 | 1.3 | 0.6 | 65,600 | 1,410 | 2.15 | 11.57 |
| Prairie Rose Lake | 88.2 | 18.5 | 2,505,000 | 43,930 | 1.75 | 14.46 |
| Red Rock Reservoir | 4,208.9 | 15,695.9 | 78,272,600 | 2,244,650 | 2.87 | ----- |
| Silver Lake | 269.9 | 32.4 | 4,362,200 | 14,400 | 0.33 | ----- |
| Springbrook Lake | 6.9 | 4.9 | 228,800 | 2,011 | 0.88 | 7.53 |
| Swan Lake | 52.6 | 3.1 | 754,000 | 3,950 | 0.66 | 8.64 |
| Theobold C | 4.1 | 0.6 | 46,300 | 1,419 | 3.07 | 10.67 |
| Theobold Main | 10.6 | 1.1 | 127,300 | 5,230 | 4.11 | 11.36 |
| Tracy North | 1.8 | 0.6 | 60,000 | 1,011 | 1.69 | 8.52 |
| Tuttle Lake | 1,139.6 | 444.4 | 14,456,300 | 104,150 | 0.72 | ----- |
| Union Grove Lake | 47.8 | 27.9 | 1,040,300 | 14,802 | 1.42 | 6.73 |
| Upper Pine Lake | 23.9 | 35.7 | 814,400 | 12,650 | 1.55 | ----- |
| Wilbur Meyer | 1.0 | 0.8 | 54,000 | 1,492 | 2.75 | 8.83 |
| William Esbeck | 1.0 | 0.5 | 15,500 | 1,110 | 7.13 | 8.83 |

sedimentation rates provided in the tables reflect the sediment deposited between the earliest lake survey and the most recent lake survey.

The lakes surveyed can be classified as natural or artificial. Black Hawk Lake, Clear Lake, Five Island Lake, Silver Lake, Swan Lake, and Tuttle Lake are natural lakes formed during the Wisconsin glacial stage and are located on the Des Moines Lobe. The remaining 34 lakes are artificial lakes that are formed on dammed, meandering streams located throughout the state of Iowa. Figure 1 displays the locations of the lakes.

The frequency of Iowa lake surveys, used in this study, varied from 3 years to 56 years. Short time spans may not always reflect true sedimentation rates due to aberrations in climatic conditions. A 5 to 10 year frequency of lake surveys has been suggested as most representative (Vanoni, 1975). The 40 Iowa lakes studied averaged 17.9 years between lake surveys. The average time span between lake surveys for the 34 artificial lakes and the 6 natural lakes was 14.8 years and 35.2 years, respectively.

The 40 Iowa lakes offer a wide range of lake size and drainage basin area as shown in Table 2. The pond of Charles Fienhold has the smallest area (0.8 hectares) and the pond of William Esbeck has the smallest drainage basin (0.5 square kilometers) and volume (15,500 cubic meters). Red Rock

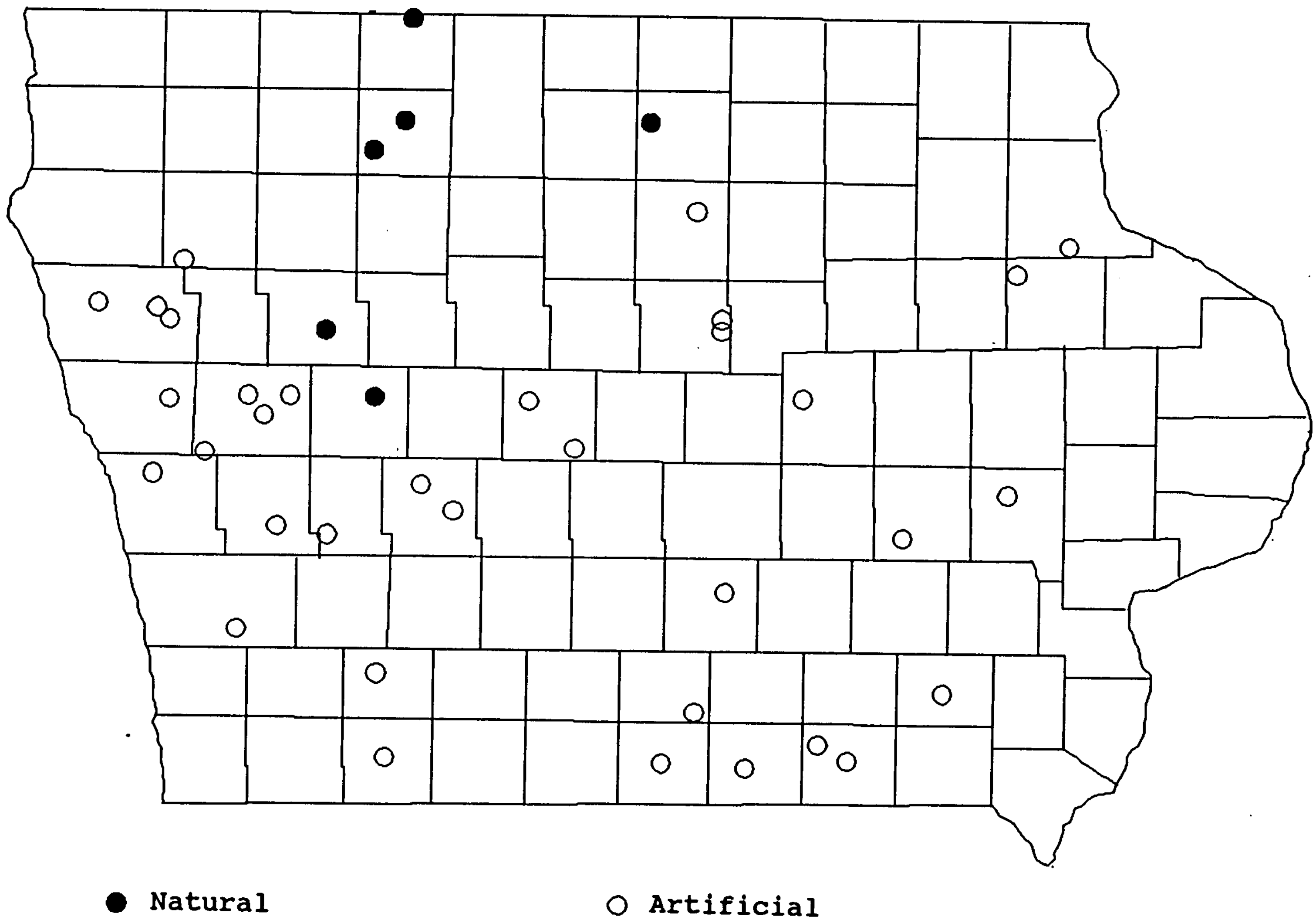


Figure 1. Locations of studied lakes

Reservoir has the largest area (4208.9 hectares), drainage basin (15,695.9 square kilometers), and volume (78,272,600 cubic meters). The sedimentation rates range from 1011 cubic meters per year (Tracy North) to 2,244,650 cubic meters per year (Red Rock Reservoir). Clear Lake has the lowest percent annual storage loss (0.12%) and the pond of Charles Fienhold has the highest percent annual storage loss (19.75%).

## Iowa Climatology and Watershed Land Use Characteristics

The annual precipitation in Iowa varies from 64 centimeters (25 inches) in the northwest to 86 centimeters (34 inches) in the southeast (National Oceanic and Atmospheric Administration, 1980). These differences in annual precipitation within the state of Iowa are small and are assumed to have no effect on any observed differences in sedimentation rates. Rainstorm intensity and duration are assumed not to vary significantly throughout the state.

Watershed land uses for the Iowa lakes reflect the agriculture of the state with 34 of the watersheds consisting of more than 70% row crops. Pastured land, forest, and urban development comprise a low percentage of the watersheds.

# GEOLOGICAL AND LAND RESOURCE AREA CLASSIFICATION

## Geological Setting of Iowa

The effects of glaciers during the Pleistocene Epoch have resulted in a relatively young geological landscape in Iowa. Kansan age glaciers traversed the entire state of Iowa, except the northeast corner, approximately 600,000 to 1,200,000 years before present (Prior, 1976) (see Figure 2). The Kansan glacial stage was followed by the Yarmouth interglacial, Illinoian glacial, and Sangamon interglacial stages. Illinoian glacial deposits occur along a narrow belt in southeast Iowa and overlie the Kansan till. The Wisconsin glacial stage entered Iowa during two substages, the Tazewell and the Cary. The Tazewell extended ice into northern Iowa about 20,000 radiocarbon years ago (Anderson, 1983). The Cary glaciers advanced into Iowa about 14,000 years before present and retreated from the state about 13,000 years before present (Prior, 1976). The Cary glaciers extended into Iowa in a lobelike extension and formed the physiographic region called the Des Moines Lobe (Anderson, 1983). Deposition of Wisconsin loess began approximately 70,000 years before present and continued during and after the deposition of the Tazewell till (Anderson, 1983). The deposits of loess over the Kansan till are thickest in western Iowa along the Missouri River and thin

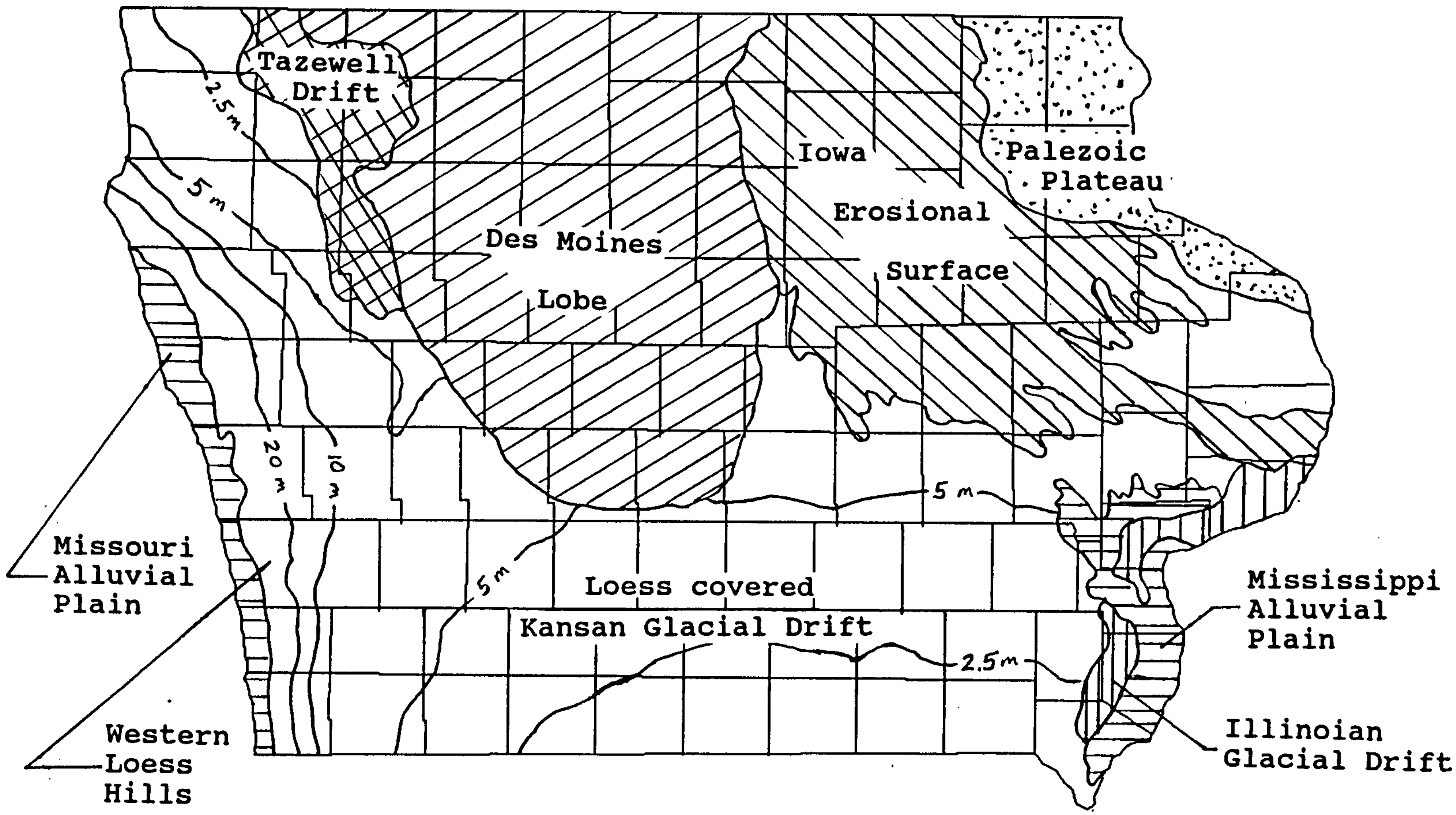


Figure 2. Geological landform regions of Iowa and contours indicating thickness of overlying loess

to the east across the state as shown by the contours in Figure 2. The Wisconsin glaciers in Iowa left relatively flat topographies for new drainage systems to develop and the Des Moines Lobe is the only region of the state where natural glacial lakes are present.

The formation of the Iowa Erosional Surface, located to the east of the Des Moines Lobe, has been a controversial subject for years (Prior, 1976). Recent studies reveal the area to be a highly eroded region consisting of glacial till with a thin, discontinuous layer of overlying loess (Prior, 1976).

## Lake Classification

The Pleistocene geology of Iowa is used to categorize the lakes in 3 different regions: the Des Moines Lobe, the Iowa Erosional Surface, and the loess covered Kansan till. The three regions reflect different soil parent materials and ages. The loess covered Kansan till is further subdivided into three regions according to the depth of loess overlying the Kansan till: the loess thickness is greater than 10 meters (32 feet) in the Western Loess Hills along the Missouri River, 5 to 10 meters (16 to 32 feet) from the Western Loess Hills to south central Iowa, and less than 5 meters (16 feet) from south central Iowa east to the Mississippi River.

Land Resource Areas (LRA's) have been used for the grouping and generalization of sediment yields (Stall, 1981). The established LRA's in Iowa coincide closely with the geological regions as shown in Figure 3 (United States Department of Agriculture, Soil Conservation Service, 1970). The Des Moines Lobe coincides with LRA 103; the Iowa Erosional Surface includes LRA's 104, 105, and 108; the Kansan till with less than 5 meters of overlying loess is represented by LRA's 108 and 109; the Kansan till with 5 to 10 meters of overlying loess is divided between LRA's 107 and 108; and the Kansan till with more than 10 meters of overlying loess is associated with LRA 107. LRA 103 is further divided into LRA 103 Bluff Drainage for steep drainage areas occurring along major streams on the Des Moines Lobe (Stall, 1981).

The LRA's do not always coincide with drainage basins; i.e., a lake's drainage area may be divided between more than one LRA. Black Hawk Lake and Swan Lake are natural lakes with watersheds divided between LRA 103 and LRA 107. Since 3/4 of Black Hawk Lake's watershed is located in LRA 103 and 2/3 of Swan Lake's watershed is located in LRA 107, Black Hawk Lake and Swan Lake are grouped in LRA 103 and LRA 107, respectively. The watershed of Lake Panorama is divided nearly equally between LRA's 103, 107, and 108. Therefore, this thesis does not use Lake Panorama in the classification of the

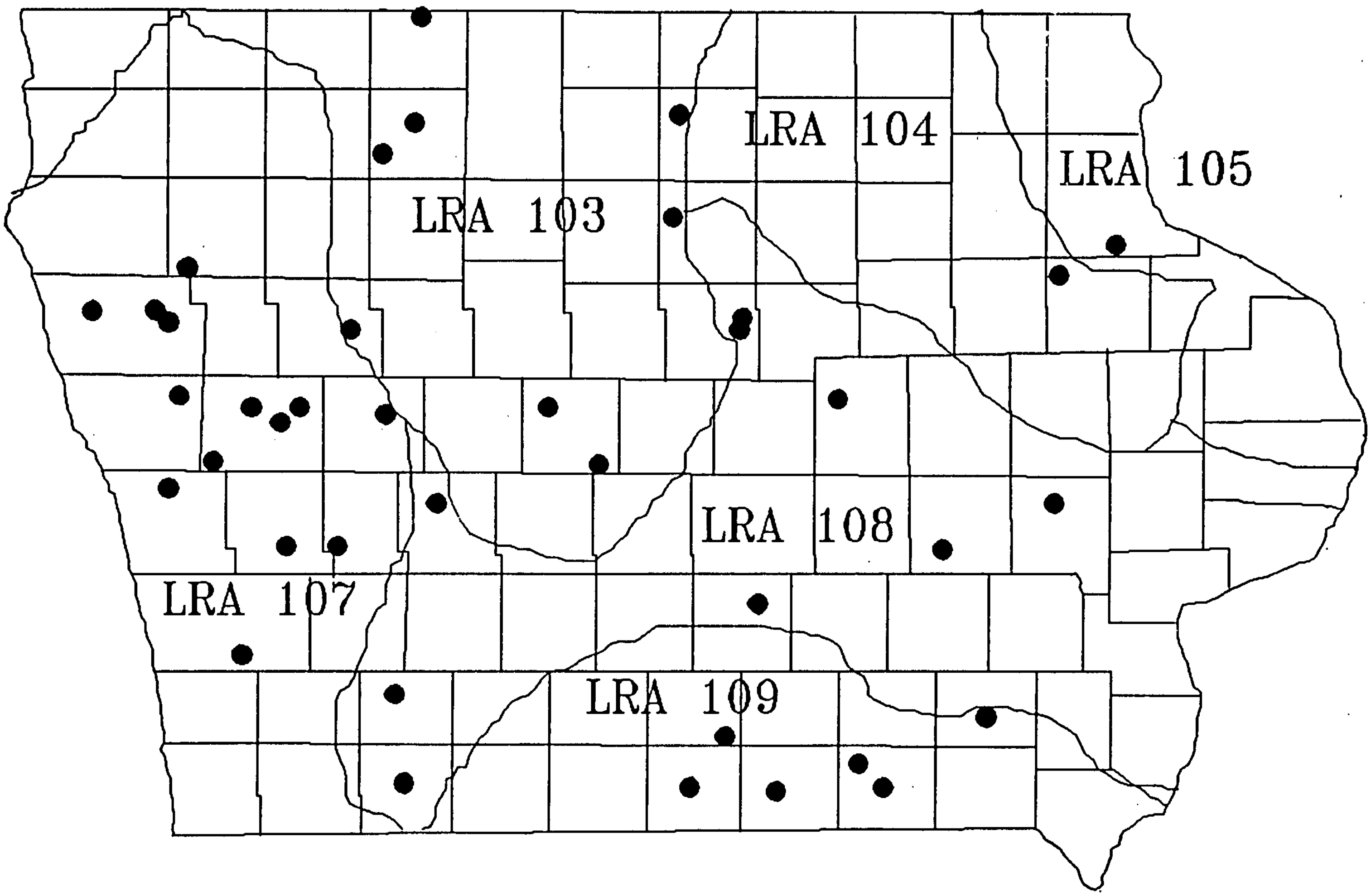


Figure 3. Locations of 39 lakes and Land Resource Areas (LRA's)

Iowa lakes by LRA's. The 39 Iowa lakes shown in Figure 3 are listed in Table 3 according to watershed LRA's.

## Analysis of LRA Classification of Iowa Lakes

Lakes with larger watersheds are expected to have higher sedimentation rates. A graph of the logarithm of sedimentation rate versus the logarithm of drainage area is shown as Figure 4. The 39 lakes show an increase in sedimentation rate with an increase in drainage area. Each Iowa lake is characterized by the LRA that represents its watershed. The variations in lake sedimentation rates for the LRA's at given drainage areas do not allow the sedimentation rates to be more accurately predicted using LRA's and drainage basin size.

Annual sediment yields are calculated for 24 Iowa lakes with sediment unit weight data. Trap efficiency data are available for 2 of these lakes. A trap efficiency of 90% is used for the 22 lakes without trap efficiency data. A plot of annual sediment yields versus watershed areas for 24 Iowa lakes classified by LRA's is shown as Figure 5. Studies by Glymph (1951), Livesey (1972), and Stall (1981) show lake sediment yields decrease as drainage areas increase. Data from the Iowa lakes agree with the accepted relationship of decreasing sediment yield with increasing drainage basin size.

Table 3. Land Resource Area (LRA) classification of Iowa lakes

| LRA 103 | LRA 103 Bluff Drainage | LRA 104 | LRA 105 |
|---|---|---|---|
| Beeds Lake | Don Williams Lake | Backbone Lake | Lake John Deere |
| Black Hawk Lake | | | |
| Clear Lake | | | |
| CM ST P&P RR Res. | | | |
| Five Island Lake | | | |
| Silver Lake | | | |
| Tuttle Lake | | | |

| LRA 107 | LRA 108 | LRA 109 |
|---|---|---|
| Barney Mundt | Coralville Res. | Allerton Res. |
| C. A. Stiles | Lake Icaria | Bloomfield |
| Charles Fienhold | Lake Iowa | Centerville Res. #2 |
| Farmer's Ditch | Lake of Three Fires | Fairfield #3 |
| Fred Hollrah | Lower Pine Lake | Honey Cr. No. F-1 |
| Jones Creek Res. | Red Rock Res. | Lake Wapello |
| Max Miller #5 | Springbrook Lake | |
| Prairie Rose Lake | Union Grove Lake | |
| Swan Lake | Upper Pine Lake | |
| Theobold C | | |
| Theobold Main | | |
| Tracy North | | |
| Wilbur Meyer | | |
| William Esbeck | | |

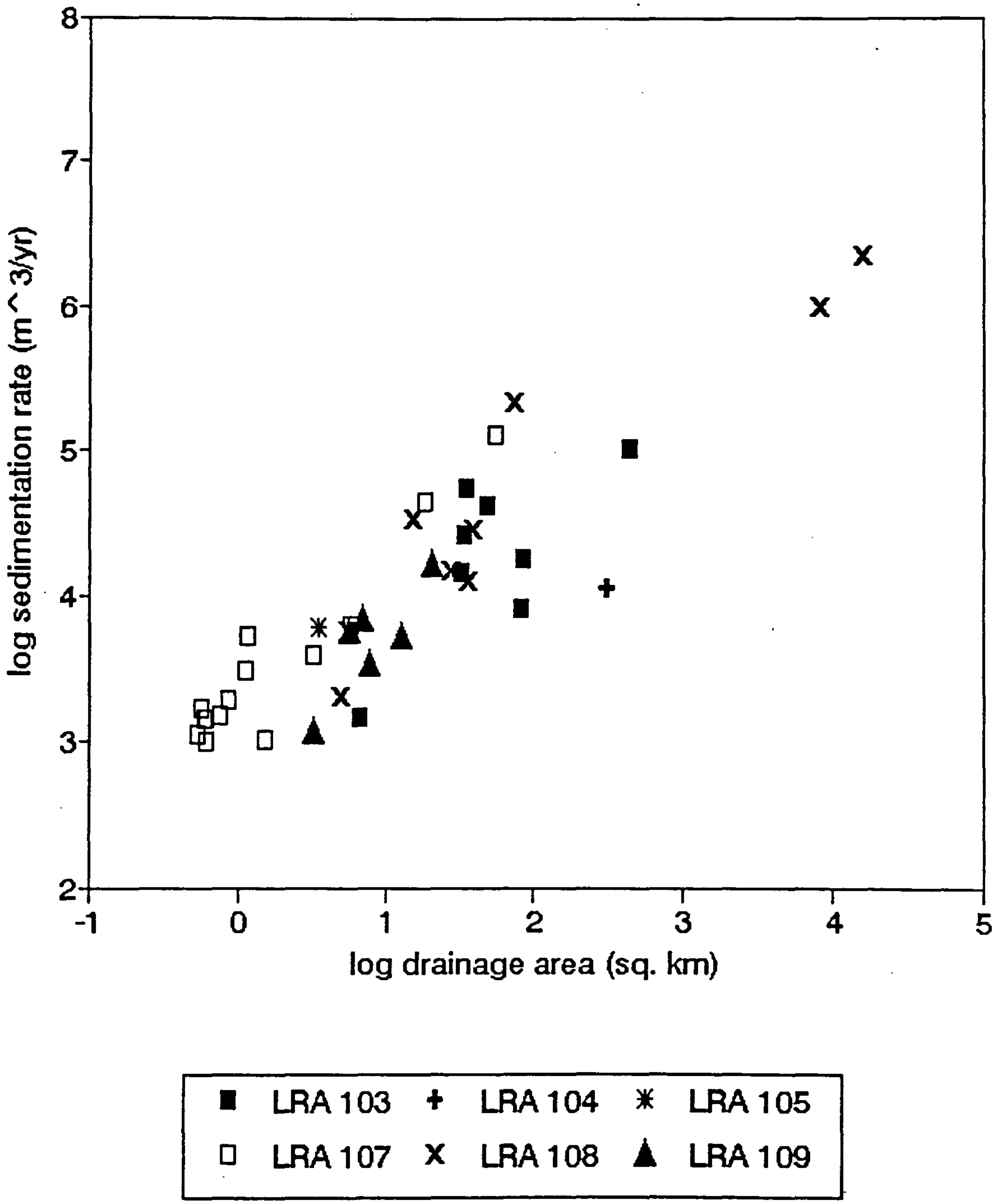


Figure 4. Sedimentation rates for 39 Iowa lakes classified by Land Resource Areas (LRA's)

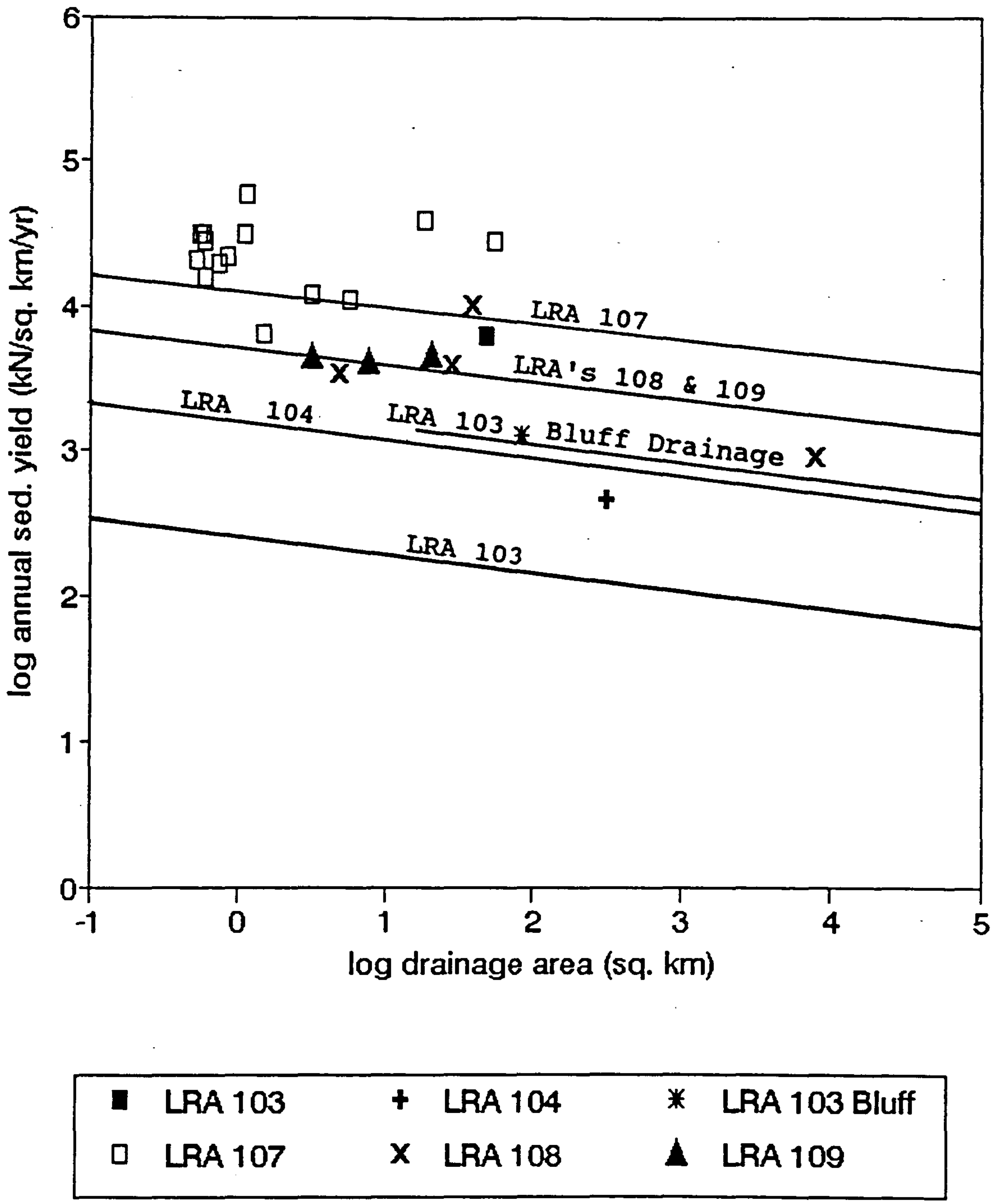


Figure 5. Annual sedimentation yields for 24 Iowa lakes classified by Land Resource Areas (LRA's)

The Army Corps of Engineers analyzed sediment yields from stream suspended solids data and reservoir sedimentation survey records. The LRA lines shown in Figure 5 are developed by the Army Corps of Engineers and represent the average annual sediment yield for each LRA. The change in sediment yield from one LRA to another is shown by the LRA lines in Figure 5; the change may in fact be a wide band of transition (Stall, 1981).

In general, the Iowa lakes fit the accepted Army Corps of Engineer's sediment yield lines for each LRA. The sediment yield for Black Hawk Lake, located in LRA 103, is much higher than the accepted LRA 103 sediment yield line. The high sediment yield for Black Hawk Lake may be the result of approximately 25% of its watershed being in LRA 107. Don Williams Lake is located in LRA 103 Bluff Drainage and the annual sediment yield of 1292 kilonewtons per square kilometer per year (log value of 3.1) agrees with the established line for this region. The annual sediment yield for Backbone Lake in LRA 104 is lower than the average LRA 104 value from the Army Corps of Engineers. Most of the Iowa lakes in LRA 107 have higher annual sediment yields than the established values from the Army Corps of Engineers. One of the 4 Iowa lakes in LRA 108 has a high annual sediment yield that coincides better with the established LRA 107 line. The remaining 3 lakes in LRA 108 correspond with the accepted sediment yields for this region. The annual sediment yields for the 3 Iowa Lakes in LRA 109 compliment the data from the Army Corps of Engineers.

A plot of sediment accumulation rates, calculated on a volumetric basis, versus drainage areas is shown as Figure 6. Each lake is grouped according to the LRA that represents its watershed. Studies by Dendy (1968) and Hadley (1977) show sediment accumulation rates decrease as drainage areas increase. Data from the Iowa lakes agree with the accepted relationship of decreasing sediment accumulation rates with increasing drainage areas. The line in Figure 6 denoting the average value for 1,105 United States reservoirs (Dendy, et al. cited by McHenry, 1974) appears to fit the data from the Iowa lakes.

The annual percent storage loss is related to the capacity to watershed ratio for 39 Iowa lakes as shown in Figure 7. Lakes with lower capacity to watershed ratios have higher annual storage losses. Having the same size watershed and equal annual sediment yield, a lake with a small volume will lose its capacity at a more rapid rate than a lake with a large volume (Glymph, 1951). The range of capacity to watershed ratios from 46 reservoirs located in 18 states (Glymph, 1951) agree with the Iowa lake data as shown in Figure 7. The Iowa lakes in LRA 107 appear to have higher annual storage losses for given capacity to watershed ratios than the Iowa lakes in LRA's 103, 104, and 109.

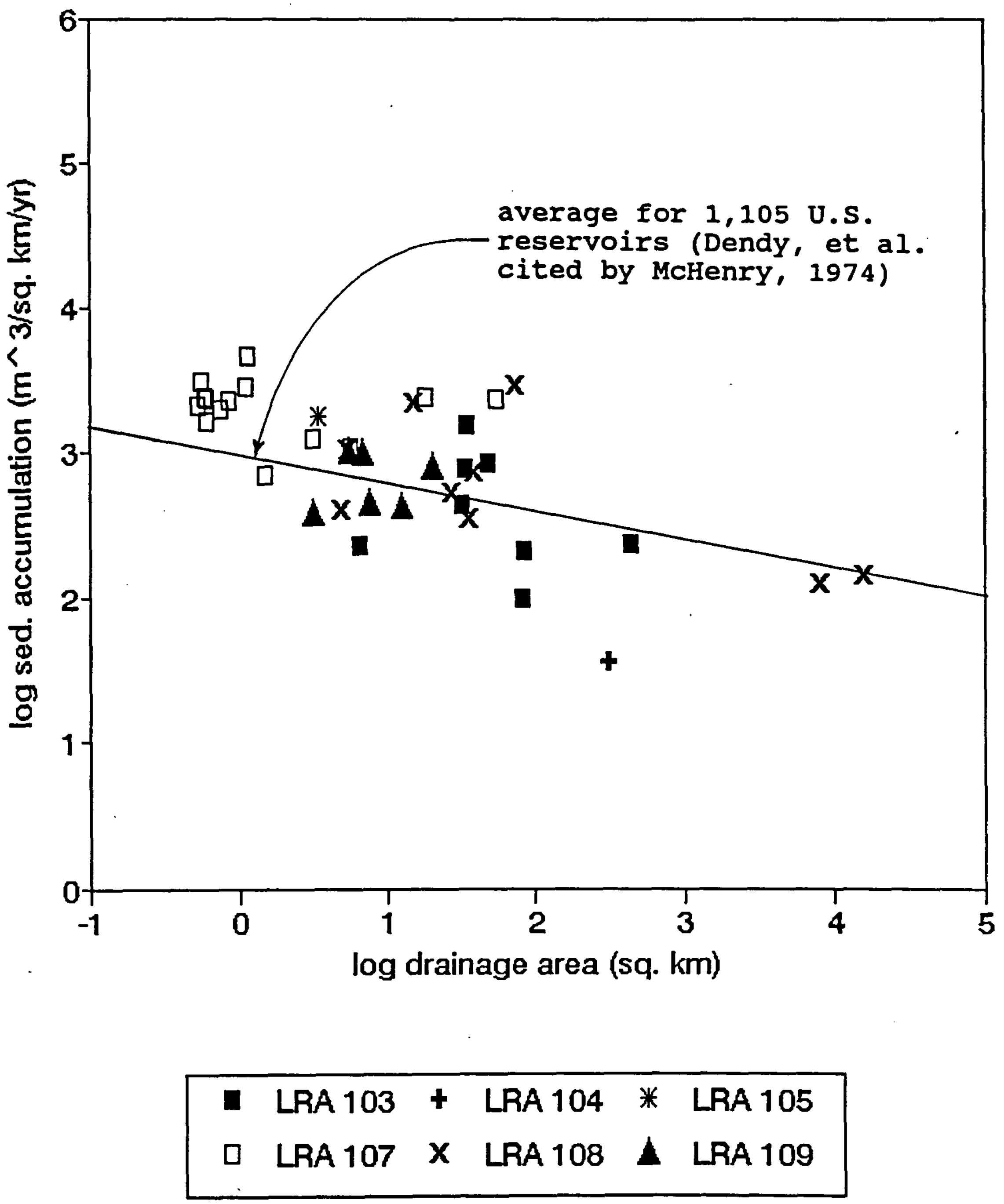


Figure 6. Sediment accumulation rates for 39 Iowa lakes classified by Land Resource Areas (LRA's)

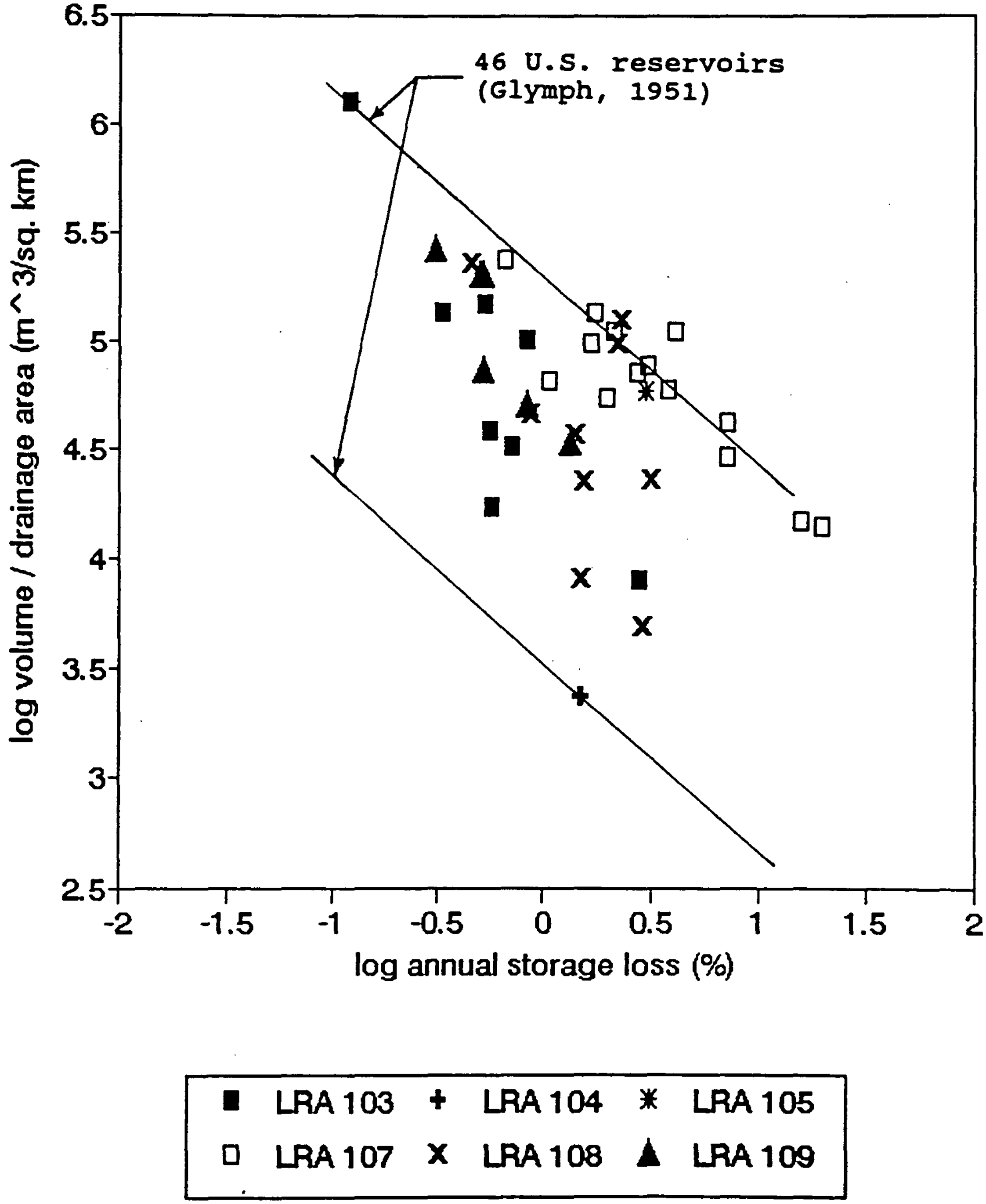


Figure 7. Capacity to watershed ratios versus annual storage losses for 39 Iowa lakes classified by Land Resource Areas (LRA's)

Since smaller drainage areas are found to have higher sediment accumulation rates as shown in Figure 6 and the studied lakes in LRA 107 have small drainage areas, it is interpreted that lakes with small watersheds have higher annual storage losses for given capacity to watershed ratios. Figure 8 differentiates the lakes according to watershed size and clearly supports this interpretation. It is concluded that the differentiation in storage loss between the LRA's in Figure 7 is influenced by watershed size.

Lakes with small watersheds, if they are to have the same useful life, generally will require a larger capacity to watershed ratio than lakes with larger watersheds (Glymph, 1951). Glymph's findings are supported by the Iowa lakes data as shown in Figure 8. For lakes with similar storage losses, smaller watersheds have larger capacity to watershed ratios.

## Conclusions

The sedimentation data from the Iowa lake surveys show similar correlations with lake sedimentation studies by the Army Corps of Engineers (Livesey, 1972), Dendy (cited by McHenry, 1974), and Glymph (1951).

The established Land Resource Areas that are associated with geology provide correlations to predict lake sedimentation. Annual sediment yields for the Iowa lakes compliment

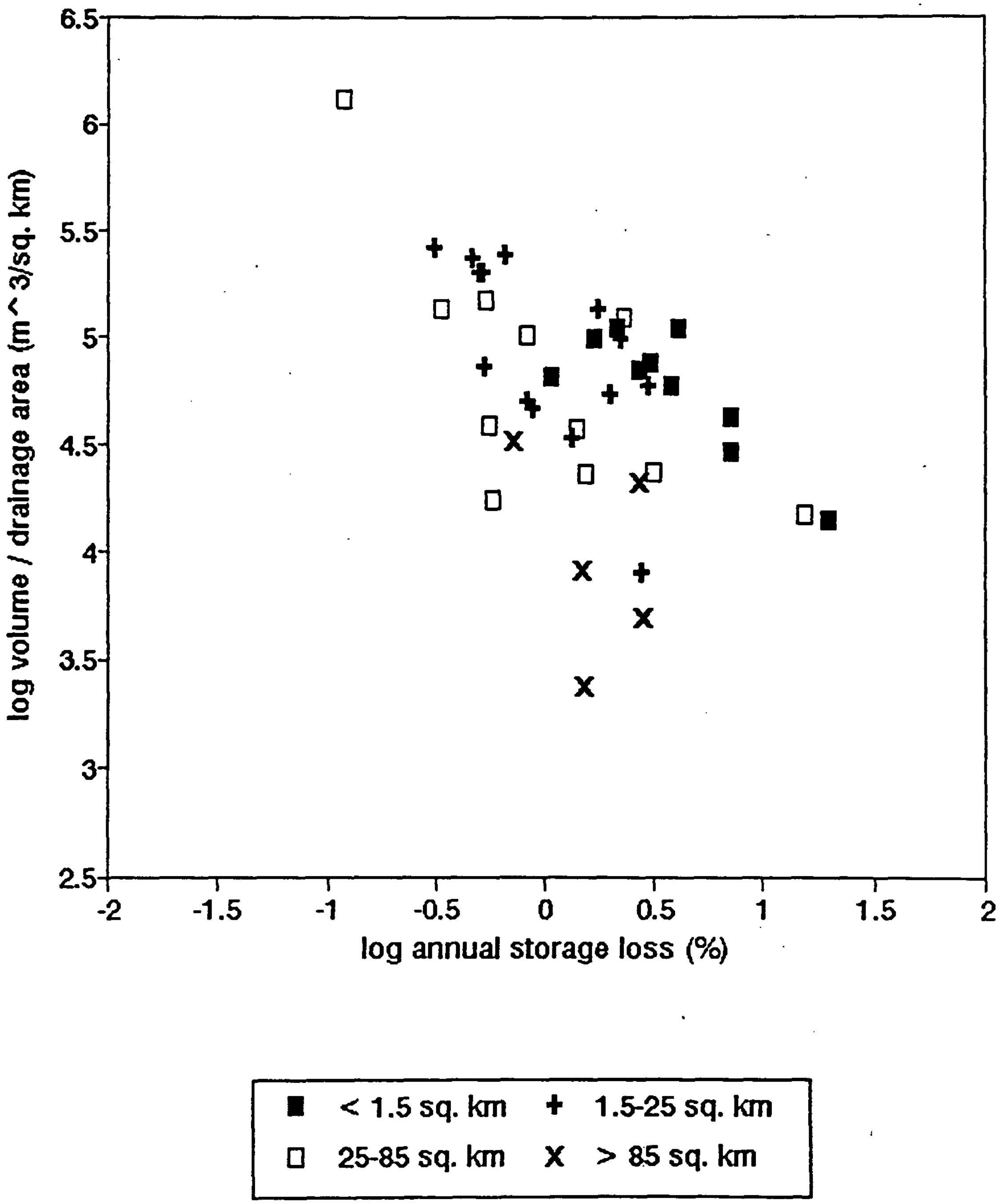


Figure 8. Capacity to watershed ratios for specific watershed sizes

the results from the Army Corps of Engineers for most LRA's. The Iowa lakes with annual sediment yields varying from the LRA lines developed by the Army Corps of Engineers may represent the band of transition that exists between each established LRA line. The sediment yield curves shown in Figure 5 provide a method to estimate annual sediment yields for lakes with known drainage areas. The sedimentation rate of a lake is calculated using the drainage area (DA), estimated sediment yield (SY) from Figure 5, sediment unit weight ($\gamma$), and trap efficiency (TE) expressed as a decimal.

$$SR = \frac{SY}{\gamma} x DA x TE$$

The life of a lake can be estimated using capacity to watershed ratios. However, the use of LRA's to characterize lakes does not prove to be an aid in forecasting the life of a lake using capacity to watershed ratios.

# HYDROLOGIC CLASSIFICATION

## Lara's Hydrologic Regions

A method for estimating the magnitude and frequency of floods at sites on ungaged rural streams in Iowa was developed by Schwob and Lara (Lara, 1987). The magnitude of floods in Iowa vary considerably due to drainage basin efficiency which is dependent on the watershed topography and hydrology (Lara, 1987). Five hydrologic regions have been established to estimate the magnitude and frequency of floods on Iowa streams (Lara, 1987). The hydrologic regions and locations of 38 Iowa lakes are shown in Figure 9.

The topography of each hydrologic region is described as follows (Lara, 1987). Region #1 is the physiographic area known as the Western Loess Hills. The Western Loess Hills are sharp-featured with steep sided slopes making the landscape conducive to runoff. The topography of Hydrologic Region #2 is described as rugged to rolling with rapid runoff. The bluff-like areas of this region are found near the Mississippi River and along the divide between the Mississippi River and Missouri River basins. Hydrologic Region #3 is the largest region and consists of steeply to gently rolling hills interspersed with areas of more subdued topography. This region has a well-developed drainage system. Hydrologic

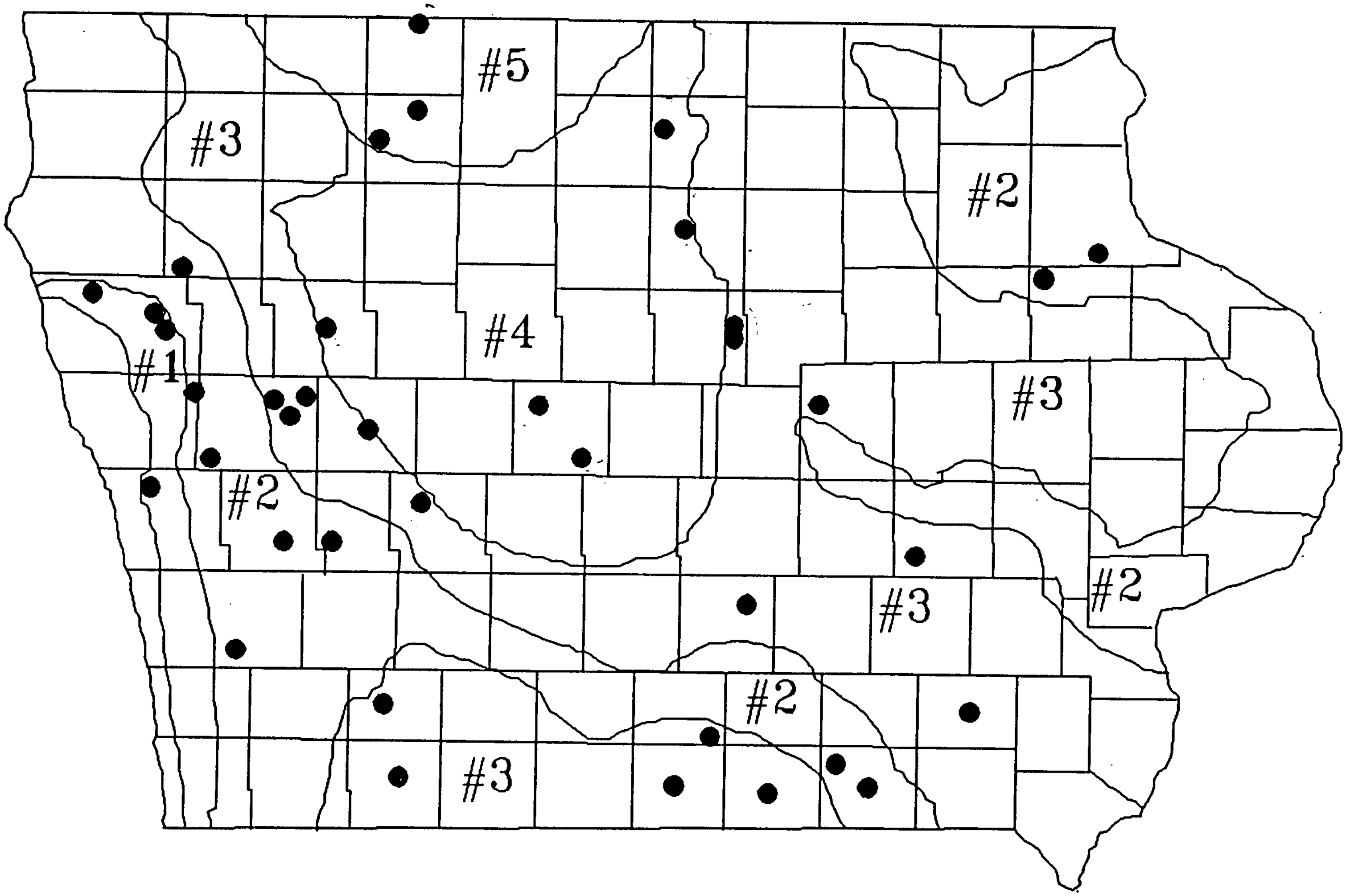


Figure 9. Locations of 38 lakes and Lara's hydrologic regions

Region #4 is located on the southern two-thirds of the Des Moines Lobe and is distinguished by level terrain and a poorly developed drainage system with a high density of ponds and marshes. Hydrologic Region #5, which coincides with the northern part of the Des Moines Lobe in Iowa, has an abundance of bogs, swales, and circular depressions causing the region to have the smallest magnitude of floods per unit area. Each hydrologic region represents the topography and hydrology common to the region; however, within each region small watersheds may exist that have hydrological and topographical characteristics of another region (Lara, 1987). Also, differences in rainfall amounts and rainfall intensities between the hydrologic regions are not significant enough to account for differences in flood magnitudes.

## Classification of Iowa Lakes

Table 4 categorizes 38 Iowa lakes according to the hydrologic regions of their watersheds. The lakes listed for Hydrologic Regions #1, #2, and #3 are artificial lakes. Hydrologic Region #4 is further subdivided into natural and artificial lakes. The 3 lakes listed for Hydrologic Region #5 are natural lakes. Lake watersheds may include more than one of the hydrological regions established by Lara. The watershed of Coralville Reservoir is distributed between

Table 4. Hydrologic classification of Iowa lakes

| Hydrologic Region #1 | Hydrologic Region #2 | Hydrologic Region #3 |
|---|---|---|
| Farmer's Ditch<br>Jones Creek Reservoir<br>Theobold C<br>Theobold Main | Backbone Lake<br>Bloomfield<br>C. A. Stiles<br>Charles Fienhold<br>Fred Hollrah<br>Honey Creek No. F-1<br>Lake John Deere<br>Lake Wapello<br>Max Miller #5<br>Prairie Rose Lake<br>William Esbeck | Allerton Reservoir<br>Barney Mundt<br>Centerville Res. #2<br>Fairfield #3<br>Lake Icaria<br>Lake Iowa<br>Lake of 3 Fires<br>Lower Pine Lake<br>Red Rock Reservoir<br>Springbrook Lake<br>Swan Lake<br>Tracy North<br>Union Grove Lake<br>Upper Pine Lake<br>Wilbur Meyer |

| Hydrologic Region #4 Natural Lakes | Hydrologic Region #4 Artificial Lakes | Hydrologic Region #5 |
|---|---|---|
| Black Hawk Lake<br>Clear Lake | Beeds Lake<br>CM ST P&P RR Res.<br>Don Williams Lake | Five Island Lake<br>Silver Lake<br>Tuttle Lake |

Hydrologic Regions #2, #3, and #4. Lake Panorama's drainage area is split between Hydrologic Regions #3 and #4. The watersheds of Coralville Reservoir and Lake Panorama are not classified by hydrologic regions. Red Rock Reservoir, Swan Lake, and Black Hawk Lake each have watersheds that are located in more than one hydrologic region; however, a high percentage of each of these watersheds is located in one of the regions. Therefore, each of these 3 lakes is grouped in the hydrologic region that best represents its watershed.

## Analysis of the Hydrologic Classification of Iowa Lakes

Lara's hydrologic region classification, based on drainage basin efficiency, is postulated to be a useful mechanism in determining lake sedimentation rates. The effectiveness of a drainage basin to collect and transport water is also expected to be a measure of a basin's effectiveness to collect and transport sediment.

The correlation between the logarithm of the sedimentation rate and the logarithm of the watershed area is shown as Figure 10. Lake sedimentation rates for the various hydrologic regions can not be distinguished on the basis of hydrologic regions. A plot of the sediment accumulation rate versus drainage area is shown as Figure 11. The sediment accumulation rates decrease with increasing drainage areas.

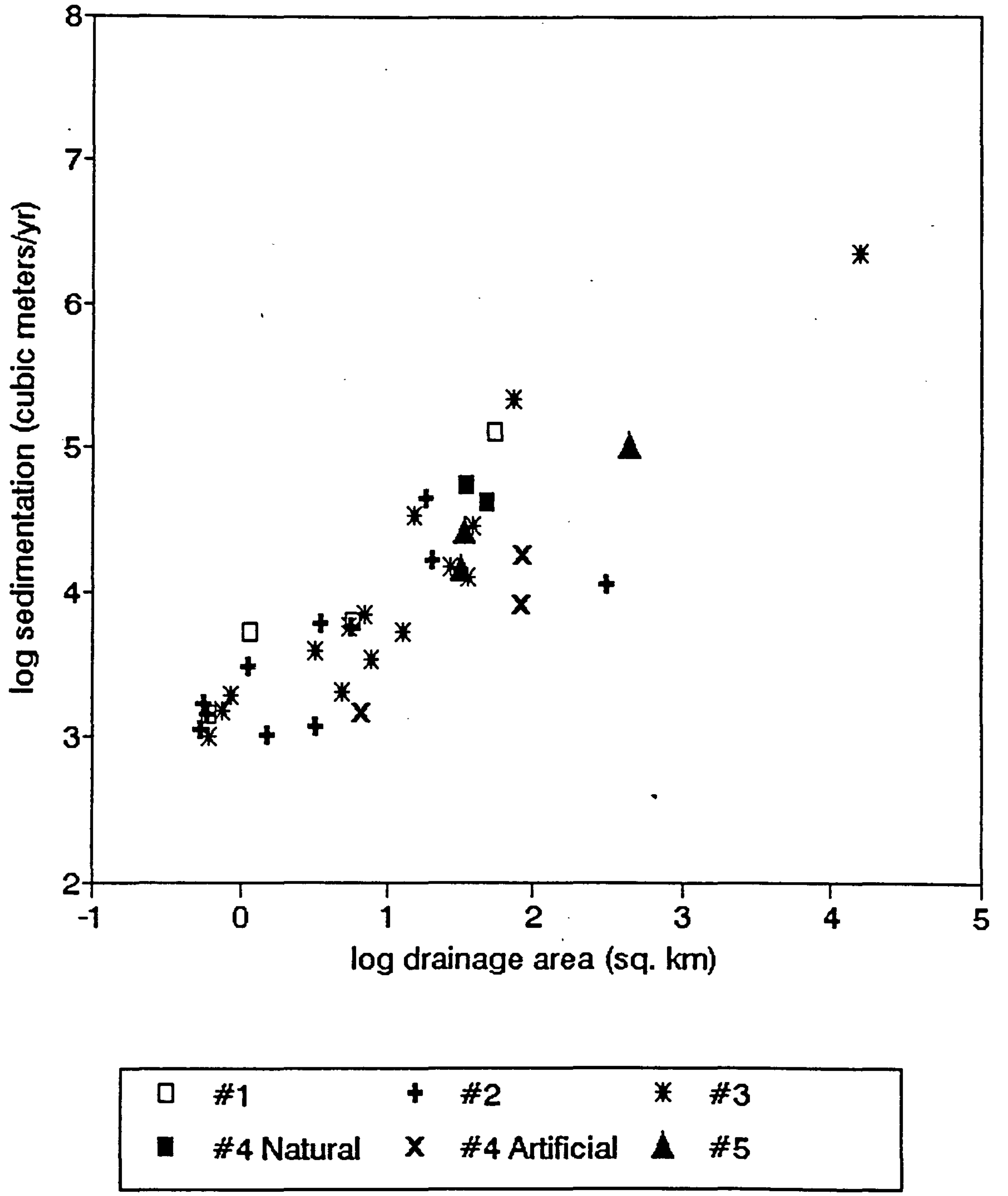


Figure 10. Sedimentation rates for 38 Iowa lakes classified by hydrologic regions

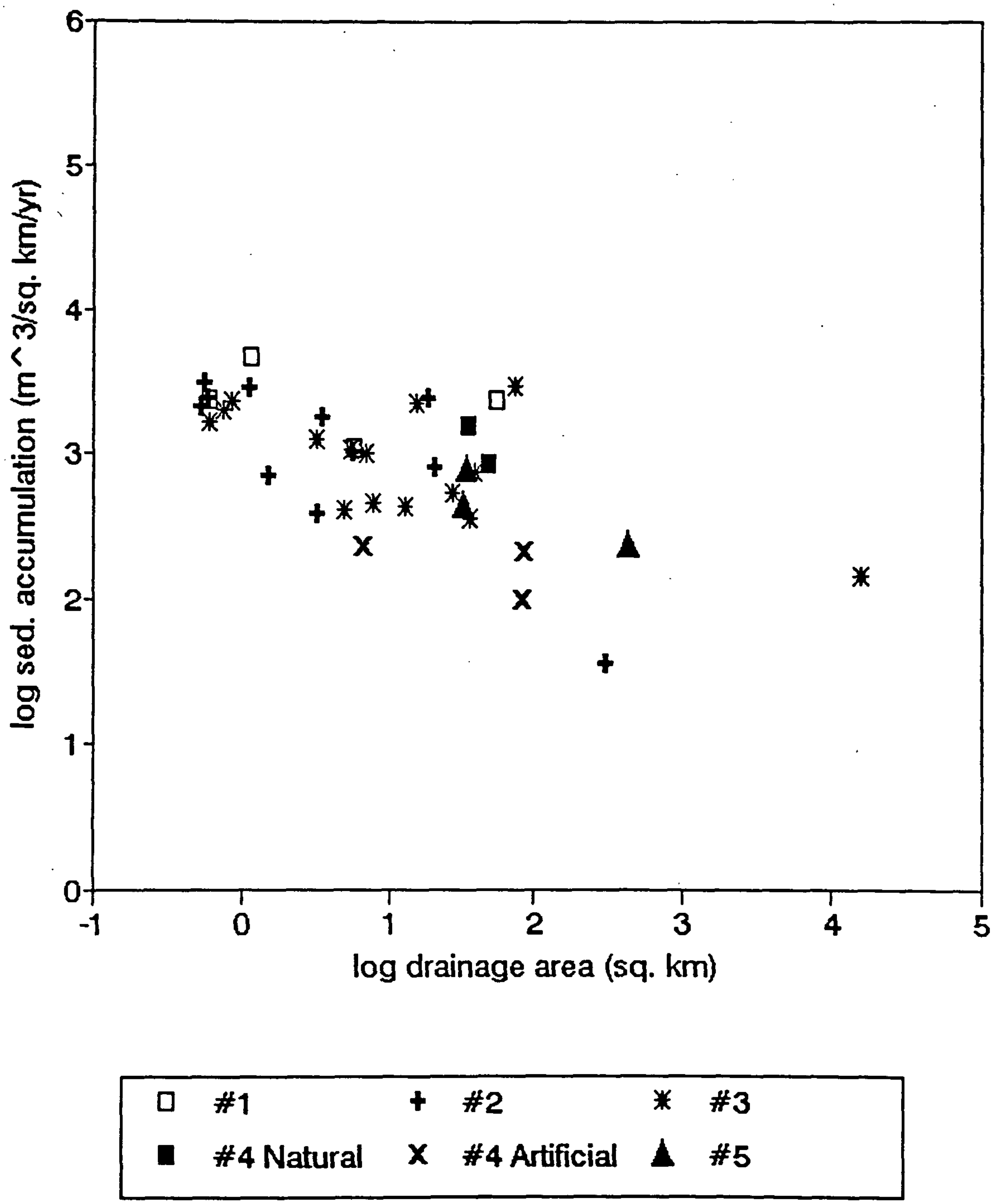


Figure 11. Sediment accumulation rates for 38 Iowa lakes classified by hydrologic regions

The hydrologic regions do not provide a direct method to estimate lake sediment accumulation rates. The relationship between the ratio of the volume to drainage area and the percent annual storage loss is shown as Figure 12. No improvement in estimating lake sedimentation rates is made using the hydrologic regions.

### Flood Discharges Using Hydrologic Regions

Lake sedimentation is hypothesized to be directly related to flood discharges. The rate of water movement from the watershed may also describe the sediment load being transported from the watershed.

Lara (1987) developed equations for each hydrologic region in Iowa to determine the magnitude and frequency of floods. The equations are developed using records of flood peaks at 251 gaged stations in Iowa and adjacent states. The general form of the equations is:

$$\log Q_t = b\log(DA) + \log c$$

Which transforms to:

$$Q_t = c(DA)^b$$

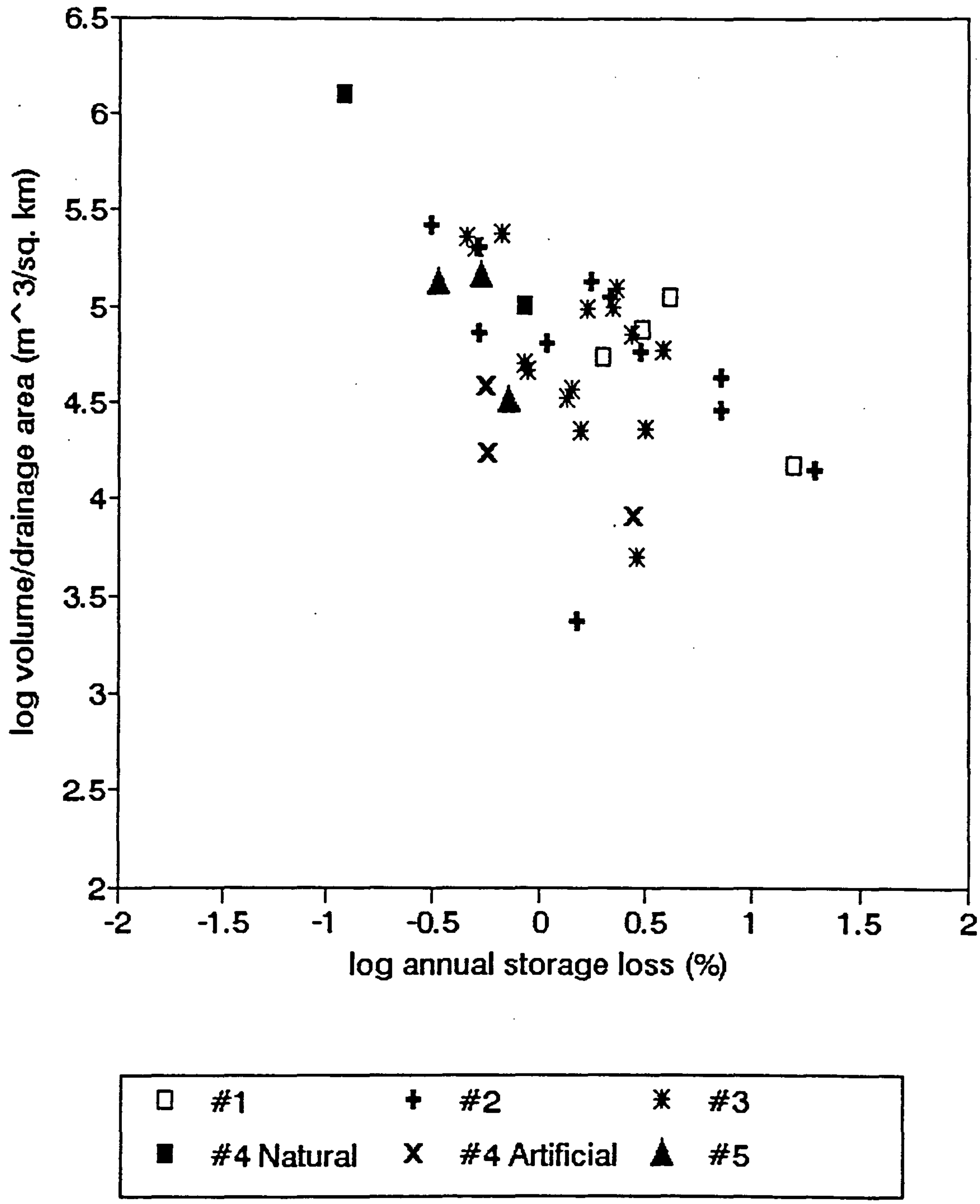


Figure 12. Capacity to watershed ratios versus annual storage losses for 38 Iowa lakes classified by hydrologic regions

where Q is the discharge (cubic feet/second) for the selected recurrence interval t (years), DA is the drainage area (square miles), and b and c are regression equation coefficients.

Flood discharges are calculated for each hydrologic region using a flood recurrence interval (t) of 2 years (see Appendix A for flood discharge equations). Figure 13 shows lake sedimentation rates increase as flood discharges increase. The variations in the plot of sedimentation rates and flood discharges in Figure 13 do not improve the correlation of sedimentation rates and drainage areas as shown in Figure 10. Lake trap efficiency may decrease during peak flow rates and the sedimentation rate may be less than expected. The decrease in trap efficiency is speculated to greatly decrease sedimentation rates in lakes with small volumes and large flood discharges. The ratio of lake volume to flood discharge is shown in Figure 14. No extreme decreases in sedimentation rates can be observed at low capacity to flood discharge ratios. Flood discharges for hydrologic regions do not provide a better method to estimate lake sedimentation rates.

## Conclusions

The classification of lake watersheds using Lara's hydrologic regions does not provide an improved method to

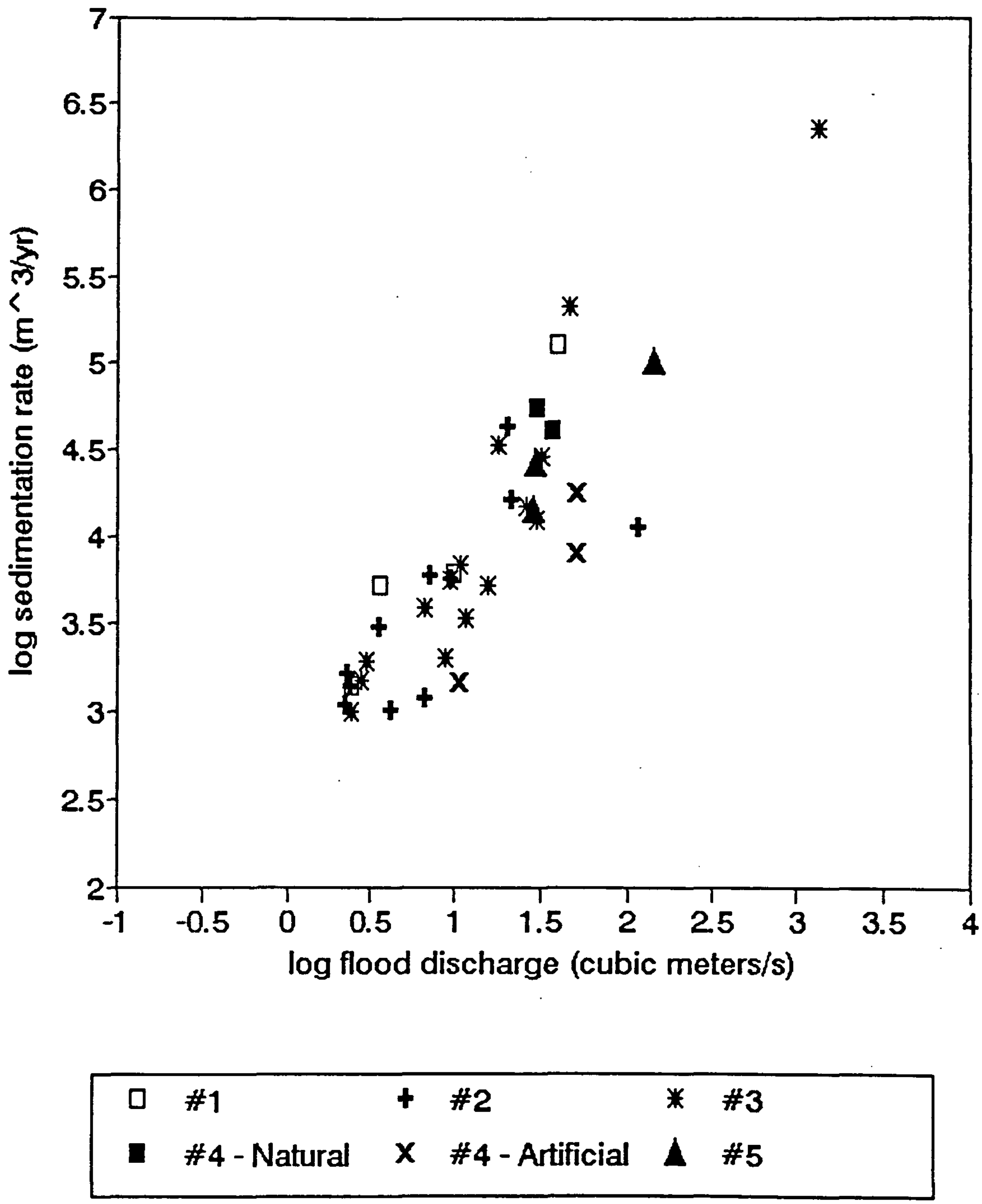


Figure 13. Sedimentation rates versus calculated flood discharges for 38 Iowa lakes classified by hydrologic regions

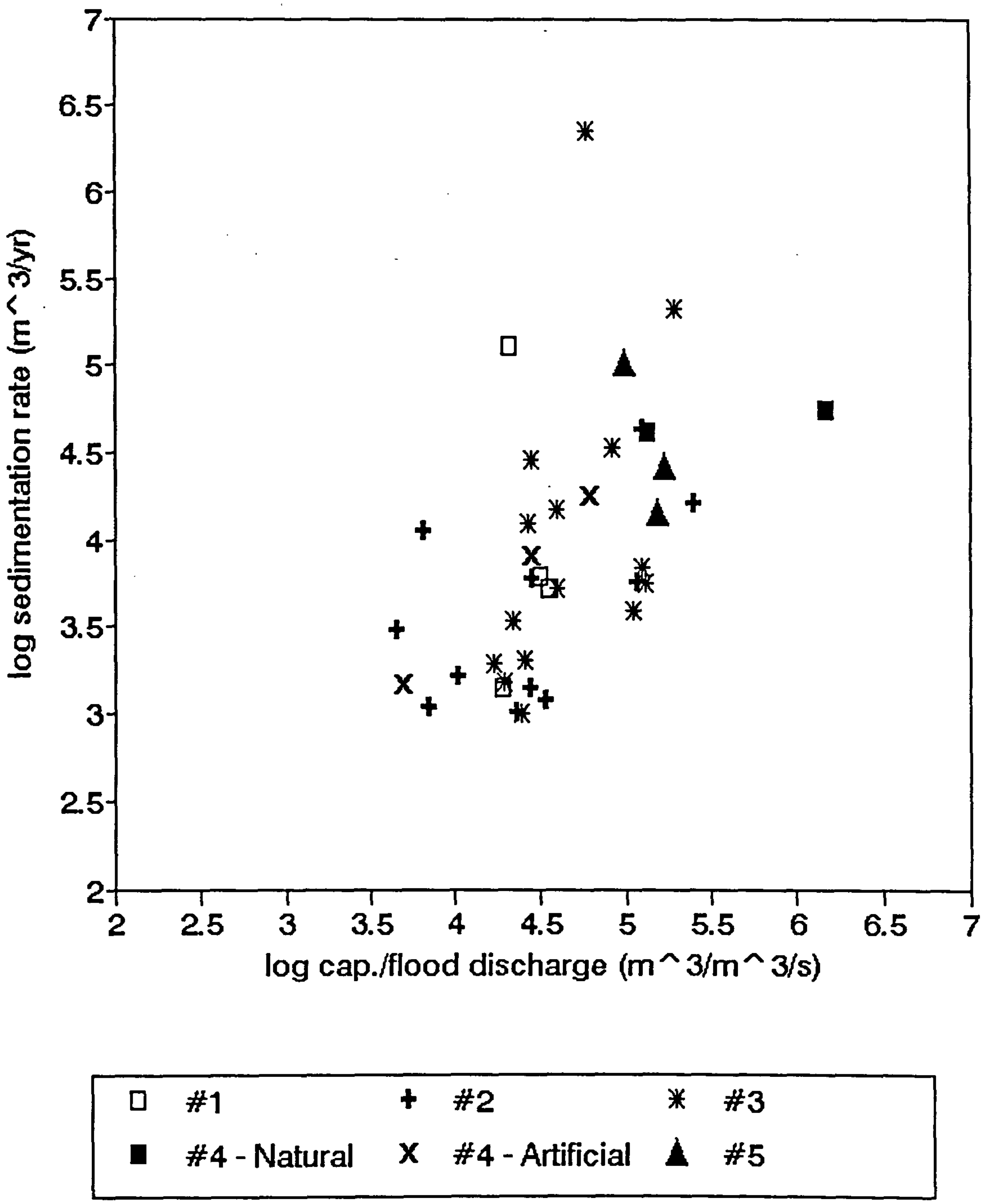


Figure 14. Sedimentation rates versus capacity to flood discharge ratios for 38 Iowa lakes classified by hydrologic region

estimate lake sedimentation rates. The analysis of flood discharges for each hydrologic region shows the rate of water movement from a watershed does not directly describe the amount of sediment being transported from the watershed.

## BASIN MORPHOLOGY AND DRAINAGE DENSITY

Lake sedimentation is closely related to drainage basin morphology, both because its magnitude is controlled by erosion, which is influenced by morphology, and because erosion and sediment transport are mechanisms whereby drainage basins are molded (Schumm, Mosley, and Weaver, 1987). Lake drainage basins have distinct shapes, slopes, and networks of tributary streams. The drainage areas of Iowa lakes are studied to determine correlations of watershed morphology with lake sedimentation. The sedimentation of a lake may be influenced by one or more factors that include: major river basin, watershed shape ratio, drainage density, basin relief ratio, and ruggedness number.

### Missouri River and Mississippi River Basins

Differences in major drainage basin morphometric parameters are used to classify the lakes according to their sedimentation. The two major river basins that drain the state of Iowa are the Missouri River basin and the Mississippi River basin shown in Figure 15. Table 5 lists the lakes according to major river basins. All 18 lakes in the Missouri River basin and 16 of the 22 lakes in the Mississippi River

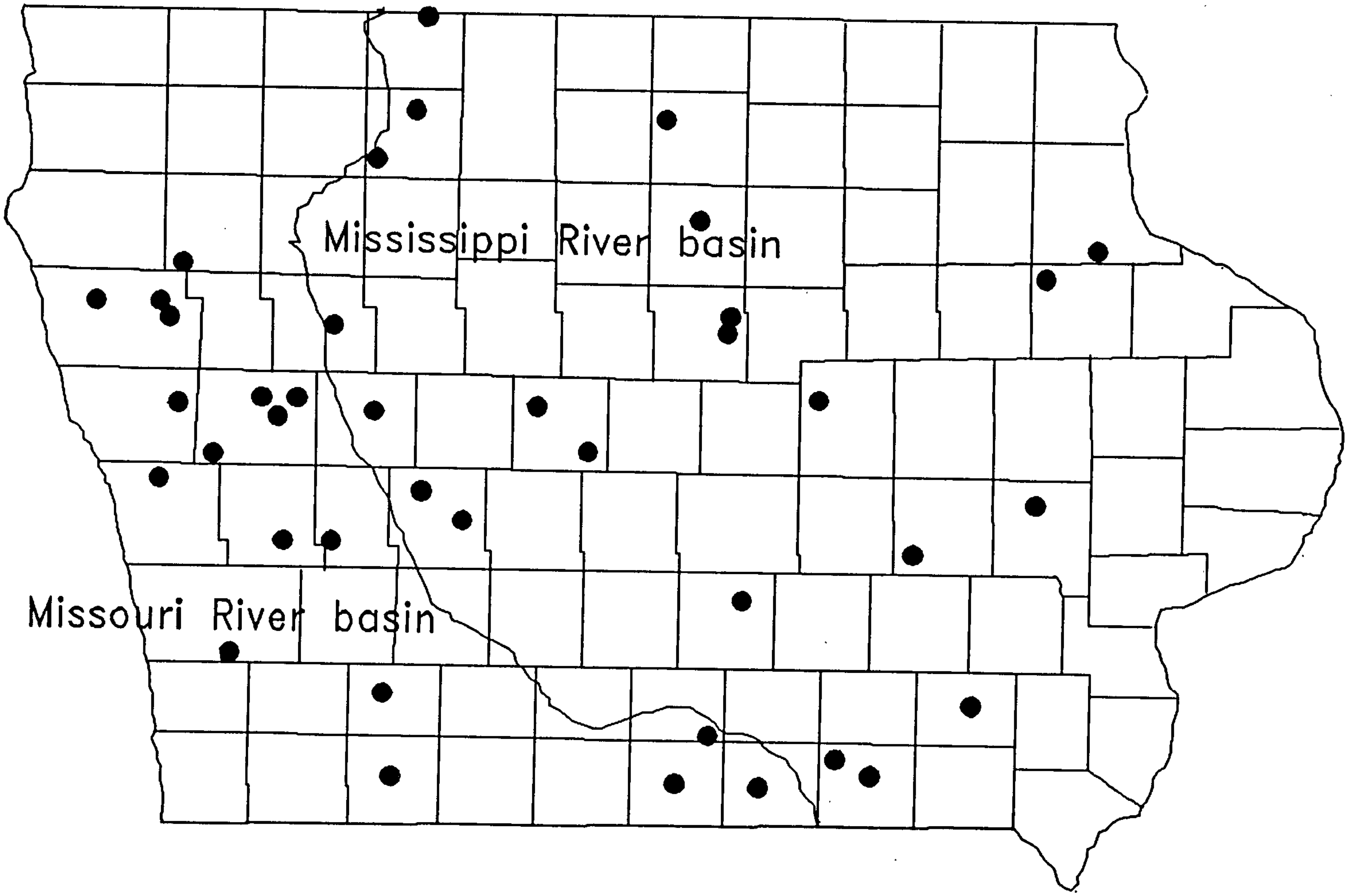


Figure 15. Locations of 40 lakes and the Missouri River basin and Mississippi River basin divide

Table 5. Major river basin classification of Iowa lakes

| Missouri River Basin (artificial) | Mississippi River Basin (artificial) | Mississippi River Basin (natural) |
|---|---|---|
| Allerton Reservoir | Backbone Lake | Black Hawk Lake |
| Barney Mundt | Beeds Lake | Clear Lake |
| Centerville Reservoir #2 | Bloomfield | Five Island Lake |
| C. A. Stiles | CM ST P&P RR Reservoir | Silver Lake |
| Charles Fienhold | Coralville Reservoir | Swan Lake |
| Farmer's Ditch | Don Williams Lake | Tuttle Lake |
| Fred Hollrah | Fairfield Reservoir #3 | |
| Honey Creek No. F-1 | Lake Iowa | |
| Jones Creek Reservoir | Lake John Deere | |
| Lake Icaria | Lake Panorama | |
| Lake of Three Fires | Lake Wapello | |
| Max Miller #5 | Lower Pine Lake | |
| Prairie Rose Lake | Red Rock Reservoir | |
| Theobold C | Springbrook Lake | |
| Theobold Main | Union Grove Lake | |
| Tracy North | Upper Pine Lake | |
| Wilbur Meyer | | |
| William Esbeck | | |

basin are artificial lakes. The 6 natural lakes in the Mississippi River basin are located on the Des Moines Lobe.

Sedimentation Analysis of Iowa Lakes

The correlation of lake sedimentation rates with areas of watersheds draining into the lakes is shown as Figure 16. The lakes in the Missouri River basin appear to have greater increases in sedimentation rates for given increases in drainage areas than the artificial and natural lakes in the Mississippi River basin.

A regression analysis is performed for the Missouri River basin lakes and the artificial and natural Mississippi River basin lakes. The statistical procedures and computations are in Appendix B. The statistical tests reveal there is a significant difference in the relationship of sedimentation rates and drainage areas for the Missouri River basin lakes and the artificial and natural Mississippi River basin lakes. The slopes of the regression line for the Missouri River basin lakes and the regression line for the artificial and natural Mississippi River basin lakes are distinct at a 70% confidence interval. The equations of the regression lines provide a practical means to estimate sedimentation rates for Iowa lakes. The sedimentation rate (SR), expressed in cubic meters

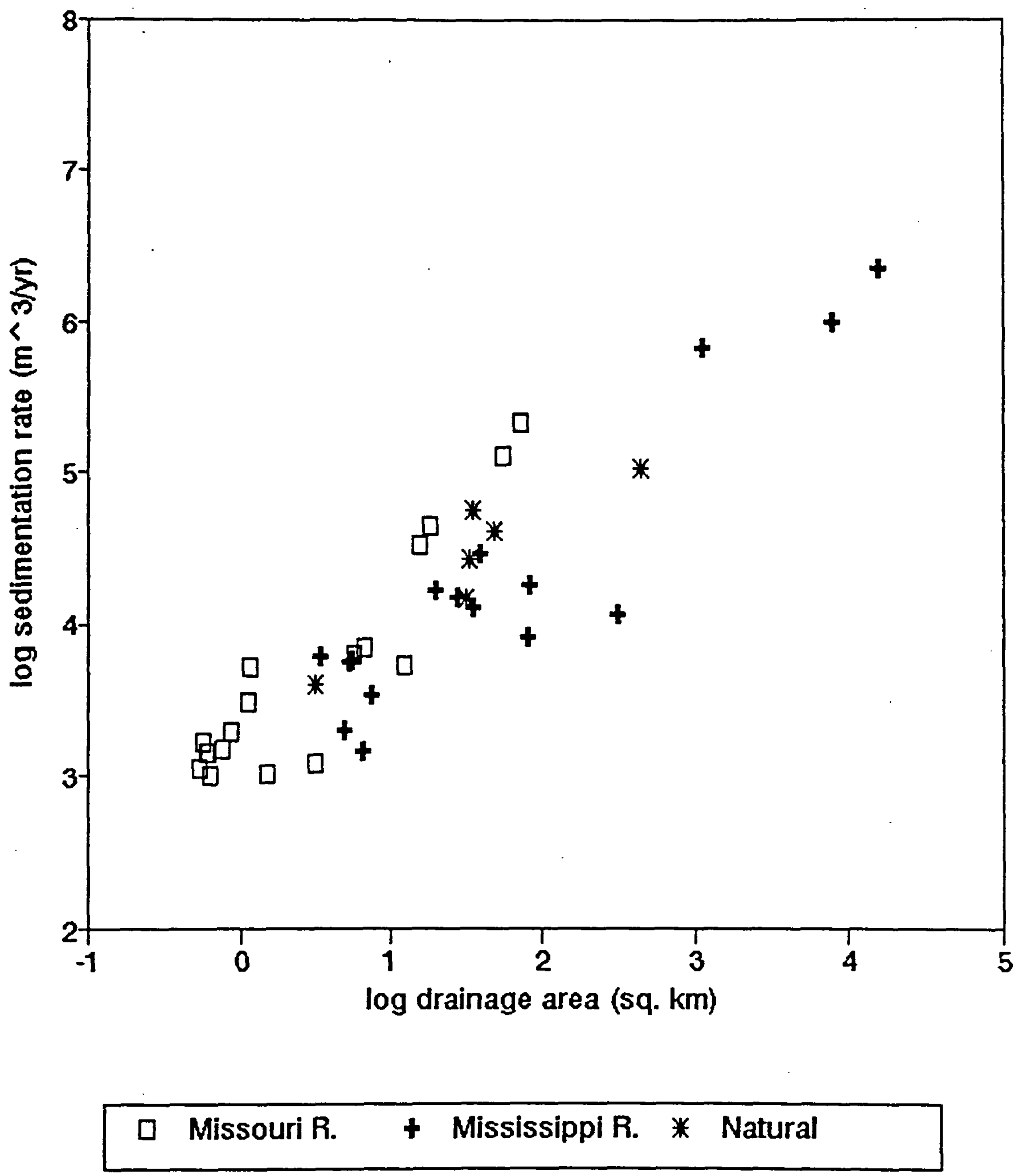


Figure 16. Sedimentation rates for 40 Iowa lakes classified by major river basins

per year, can be estimated knowing the drainage area (DA), expressed in square kilometers, using the following equations.

Missouri River basin lakes:

$$SR - 1811(DA)^{0.940}$$

Artificial and natural Mississippi River basin lakes:

$$SR - 1153(DA)^{0.748}$$

The correlation of actual sedimentation rates and calculated sedimentation rates using the equations are shown in Figures 17 and 18. The true sedimentation rates, in general, agree with the calculated sedimentation rates.

Classifying the Iowa lakes according to major river basins is hypothesized not to improve the correlation of sedimentation rates and drainage areas. A regression analysis performed on the sedimentation rates and drainage areas for all 40 Iowa lakes provides the following equation:

$$SR - 1710(DA)^{0.710}$$

A plot of actual sedimentation rates and calculated sedimentation rates using the equation for all 40 Iowa lakes is shown as Figure 19. Further statistical analysis (see Appendix B) shows that grouping all 40 Iowa lakes together provides a

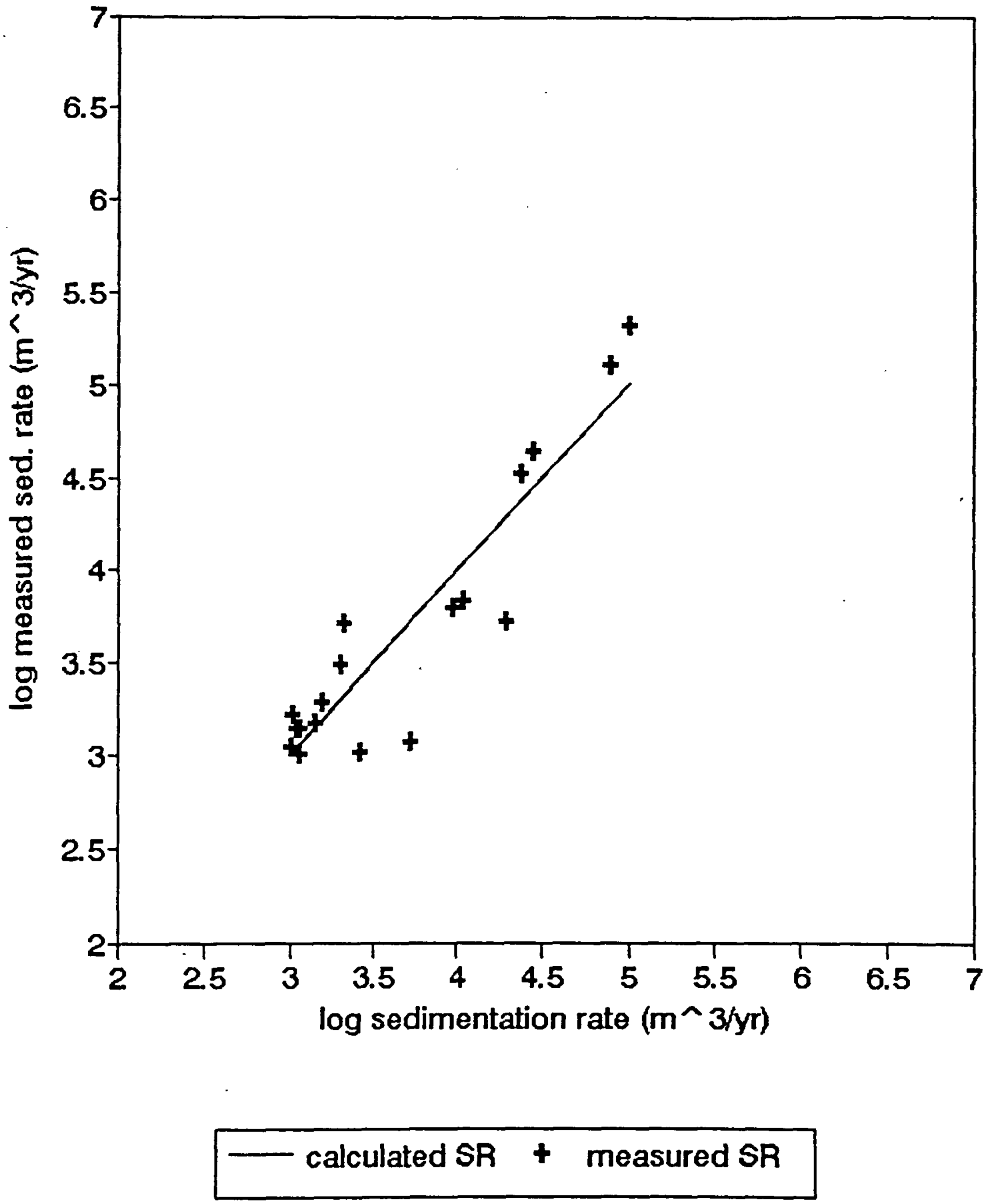


Figure 17. Missouri River basin lakes

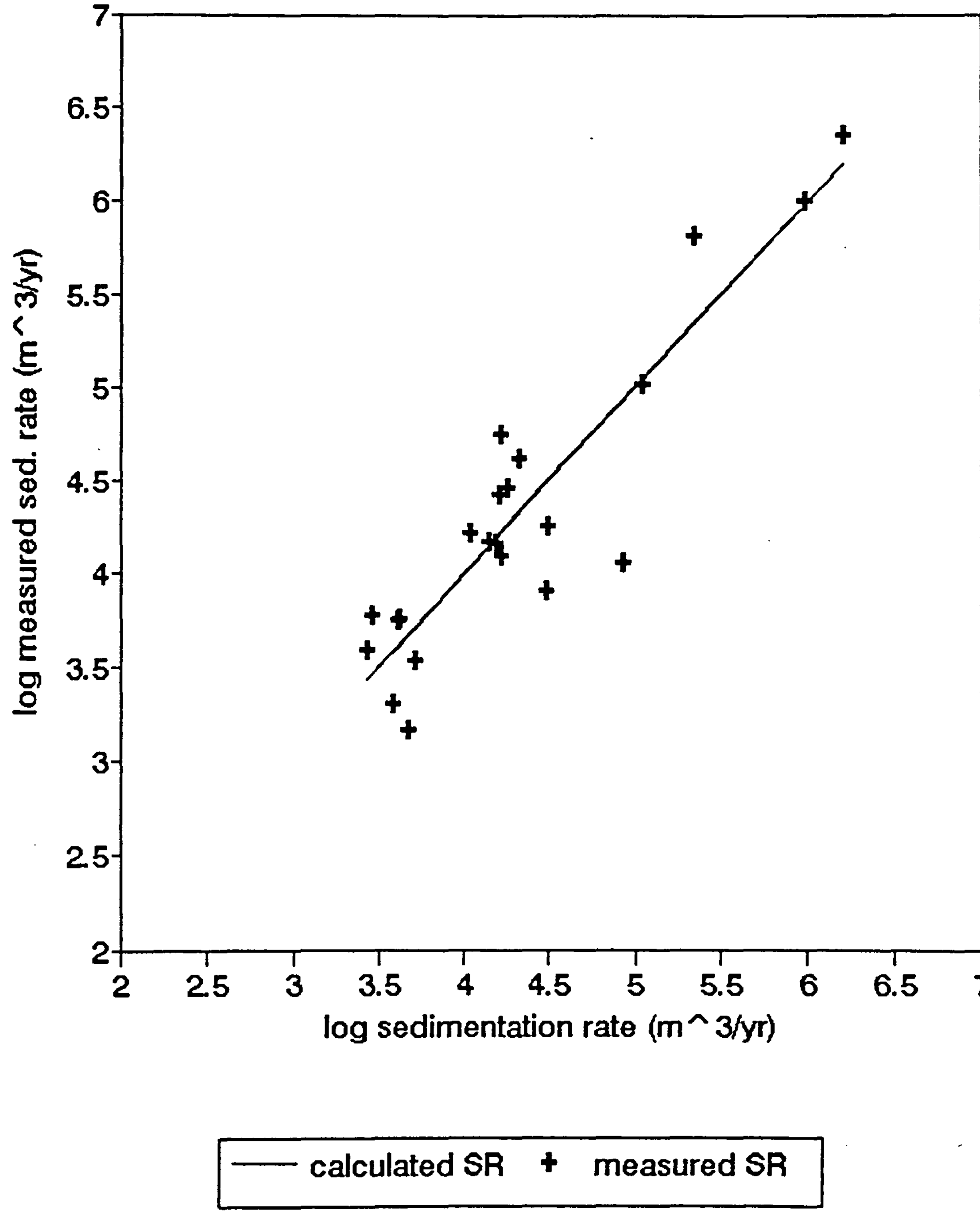


Figure 18. Artificial and natural lakes in the Mississippi River basin

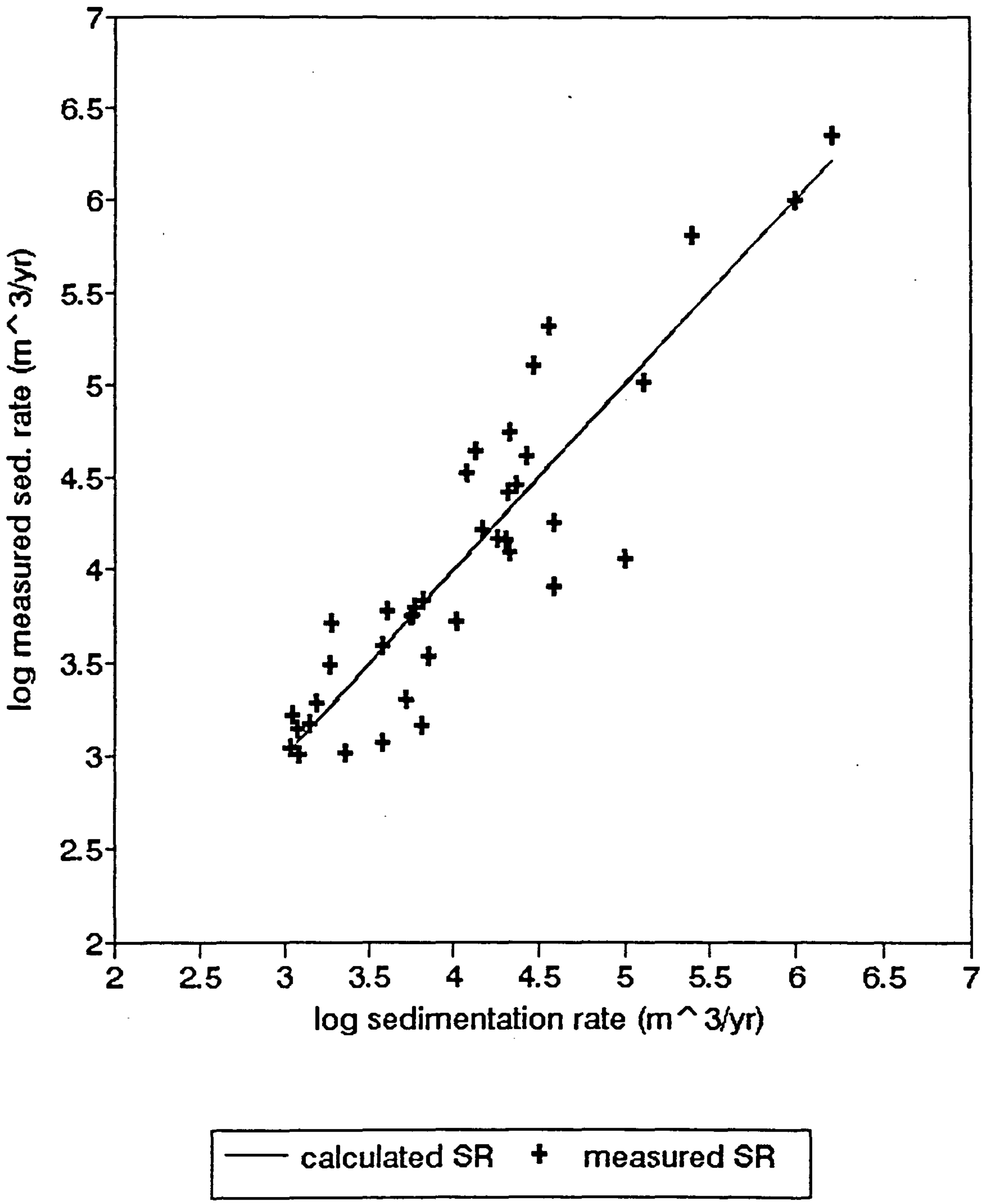


Figure 19. 40 Iowa lakes (Missouri River and Mississippi River basin lakes)

correlation that allows sedimentation rates to be estimated as accurately as the classification of lakes by the two major river basins.

Sediment yields, expressed in weights, for 25 Iowa lakes with sediment unit weight data are displayed in Figure 20. The 14 Iowa lakes in the Missouri River basin have an average sediment yield of 24,113 kilonewtons per square kilometer per year (7026 tons/square mile/year) and the Iowa lakes in the Mississippi River basin have an average sediment yield of 4923 kilonewtons per square kilometer per year (1434 tons/square mile/year). The Missouri River basin lakes in Iowa have sediment yields almost 5 times greater than the Mississippi River basin lakes in Iowa. The incorporation of all 40 Iowa lakes by expressing lake sedimentation on a volumetric basis is shown as Figure 21. The Missouri River basin lakes have higher sediment accumulation rates than the Mississippi River basin lakes.

The higher sedimentation of the Missouri River basin lakes is suggested to be the result of the Missouri River basin lakes having smaller drainage areas. Smaller drainage areas have higher sediment yields and higher sediment accumulation rates as discussed previously. Comparing 5 lakes from the Missouri River basin and 6 lakes from the Mississippi River basin with watershed areas between 10 and 100 square kilometers, the sediment accumulation rates for Missouri River

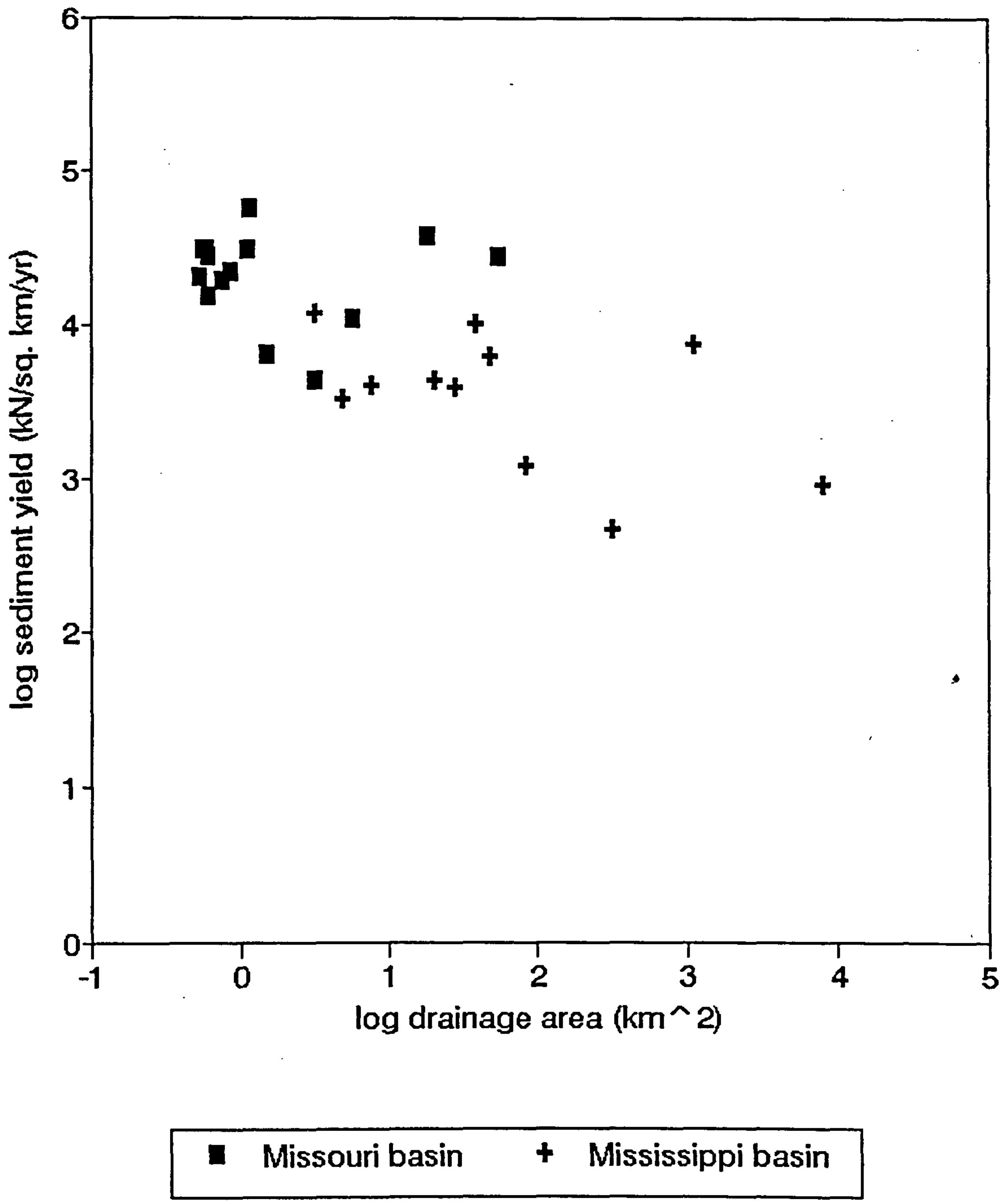


Figure 20. Sediment yields for 25 Iowa lakes classified by major river basin

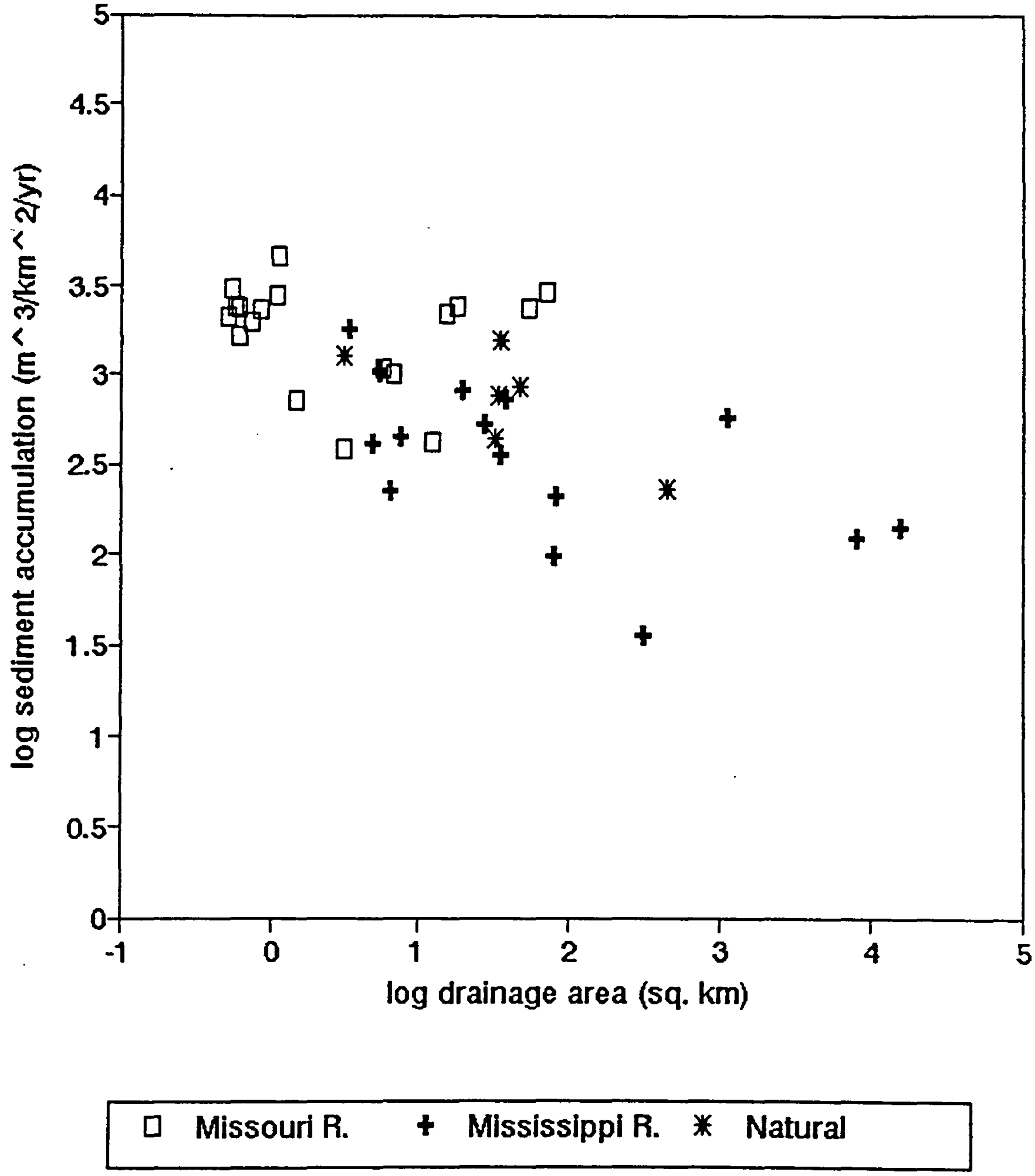


Figure 21. Sediment accumulation rates for 40 Iowa lakes classified by major river basin

basin lakes are 4.5 times greater than the Mississippi River basin lakes. Therefore, the higher sedimentation of the Missouri River basin lakes is not the result of the Missouri River basin lakes having smaller drainage areas.

Watershed Shape Ratio

The geometric shape of a watershed is hypothesized to be related to the quantity of sediment removed from the watershed. The watershed shape ratio is the ratio of the axial length of the watershed to the watershed area (Karsten, 1973). Karsten (1973) found basins on the Tazewell surface to be comparatively circular and those on the thick loess Kansan surface and the Iowa Erosional Surface to be more elongated. Karsten (1973) concludes the differences in basin shapes with geological regions are due to either the maturity and equilibrium condition or the efficiency of the region.

Watershed shape ratios are calculated for 20 of the Iowa lakes using 1:24,000 topographic maps (see Appendix B). The average watershed shape ratio is 0.19 $km^{-1}$ for the artificial lakes in the Missouri River basin, 0.26 $km^{-1}$ for the artificial lakes in the Mississippi River basin, and 0.19 $km^{-1}$ for the natural lakes in the Mississippi River basin. A t-test performed on the watershed shape ratios for the Missouri River basin lakes and the artificial Mississippi River basin lakes (see Appendix B for statistical computations) reveals that the major river basins are not distinguished by watershed shape ratios at a 70% confidence level.

Lake sedimentation rates and drainage areas decrease as watershed shape ratios increase as shown in Figures 22 and 23. Watershed shape ratios reveal no direct correlation to sediment accumulation rates as shown in Figure 24. The shape of drainage basins is concluded not to be an important variable in predicting lake sedimentation.

**Drainage Density**

Drainage density, a morphometric variable invented by Horten (1932), is the quotient of the total stream length in a drainage basin and the drainage basin area (Patton, 1988). Horten reasoned that watersheds with low drainage densities are products of processes dominated by infiltration and subsurface flow; rather than erosion and dissection by overland flow (Patton, 1988). Higher drainage densities reflect a more efficient drainage basin; i.e., the runoff is more rapid and the quantity of water leaving the basin is greater (Hadley and Schumm cited by Chorley, Schumm, and Sugden, 1984). Sediment yields are greater in regions with higher drainage densities as shown in Figure 25 using an

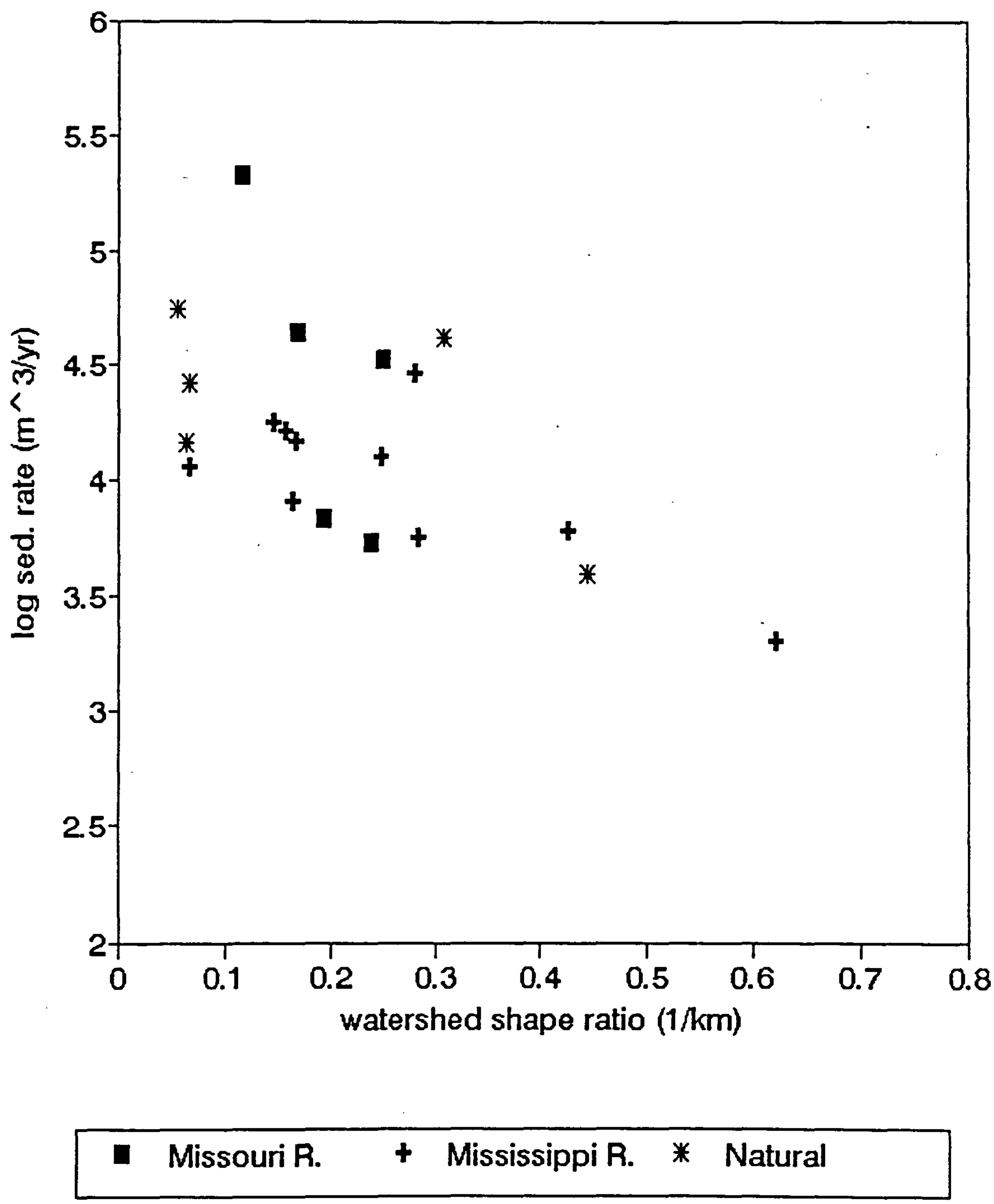


Figure 22. Sedimentation rates versus watershed shape ratios for 20 Iowa lakes

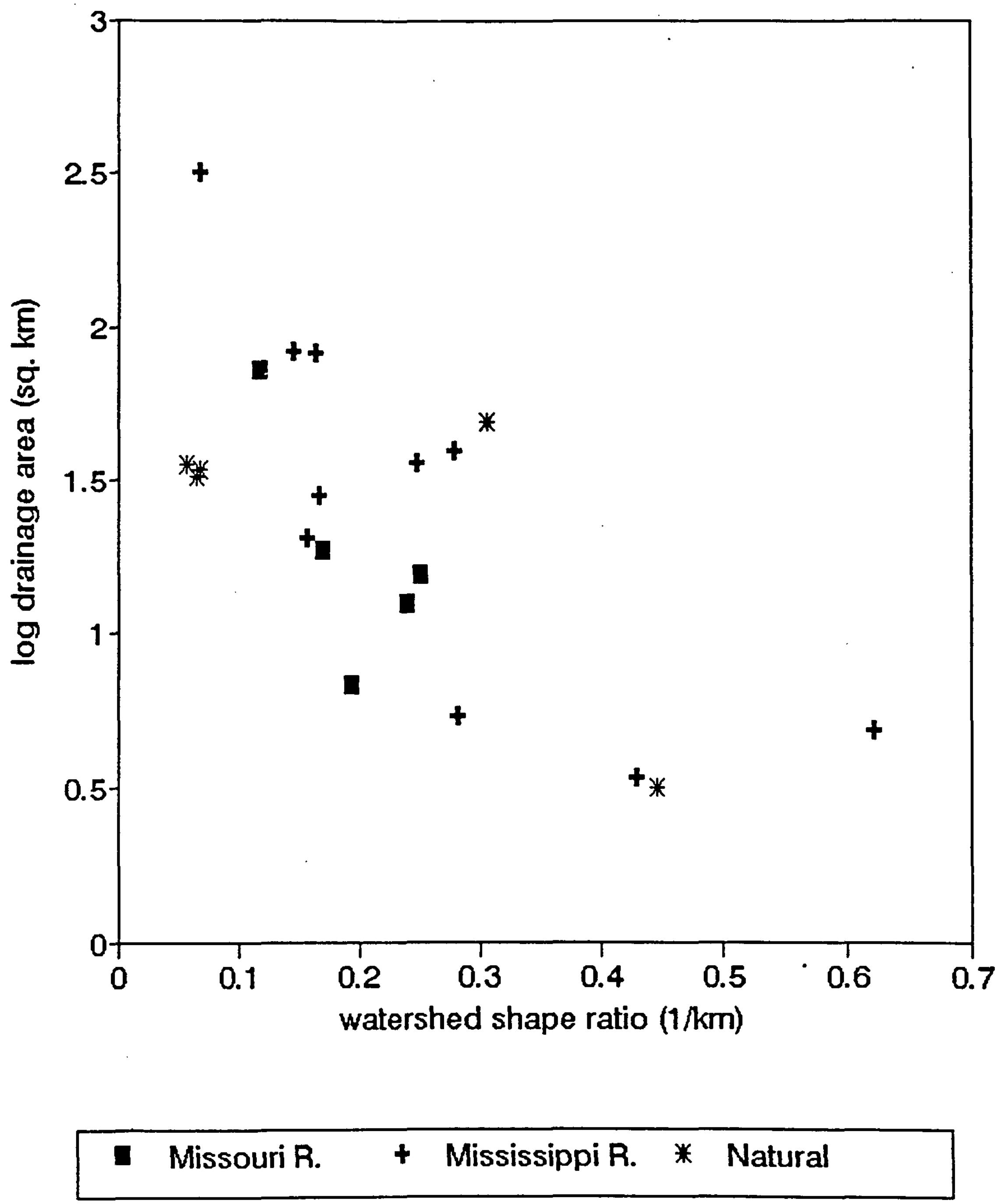


Figure 23. Drainage areas versus watershed shape ratios for 20 Iowa lakes

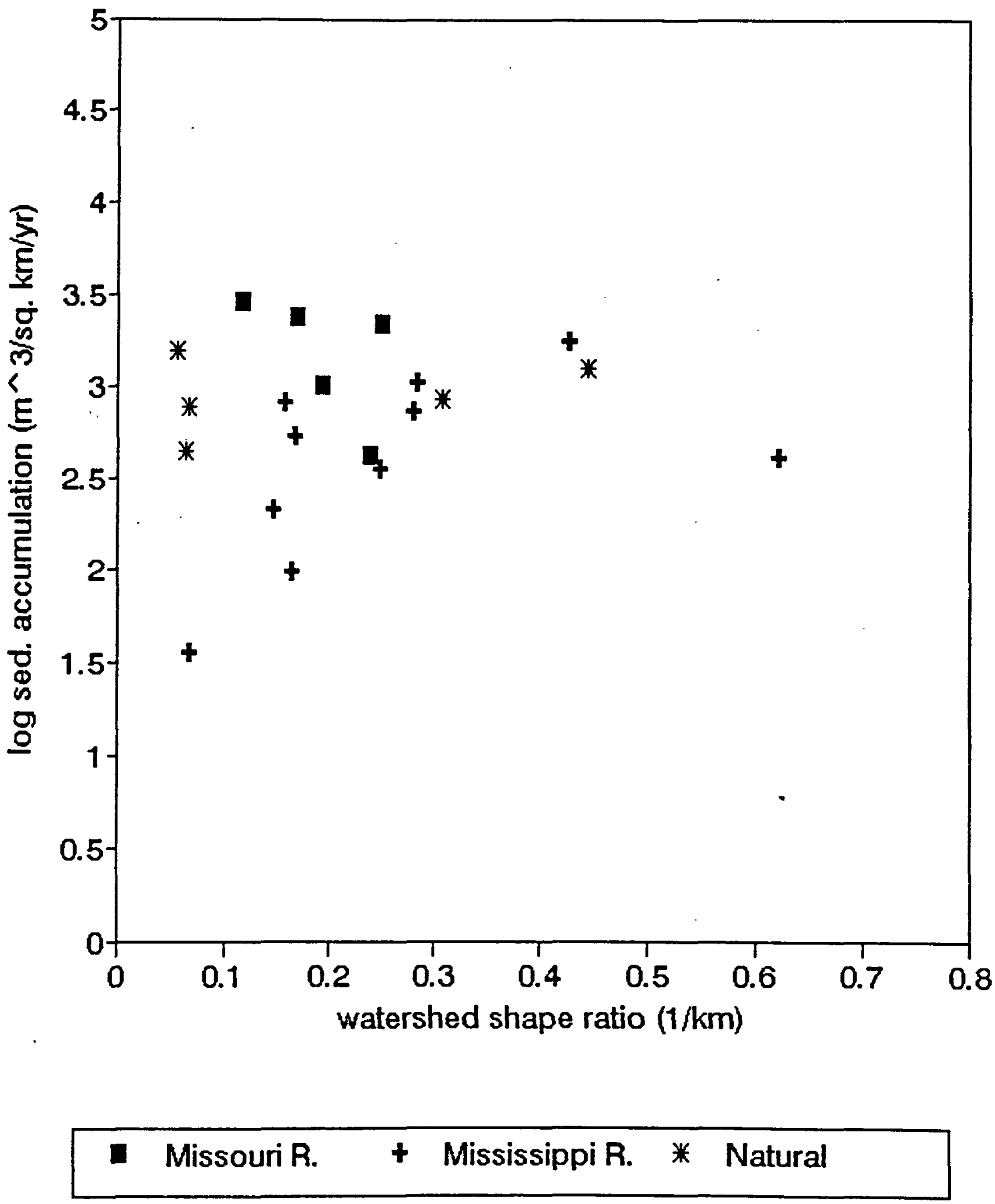


Figure 24. Sedimentation accumulation rates versus watershed shape ratios for 20 Iowa lakes

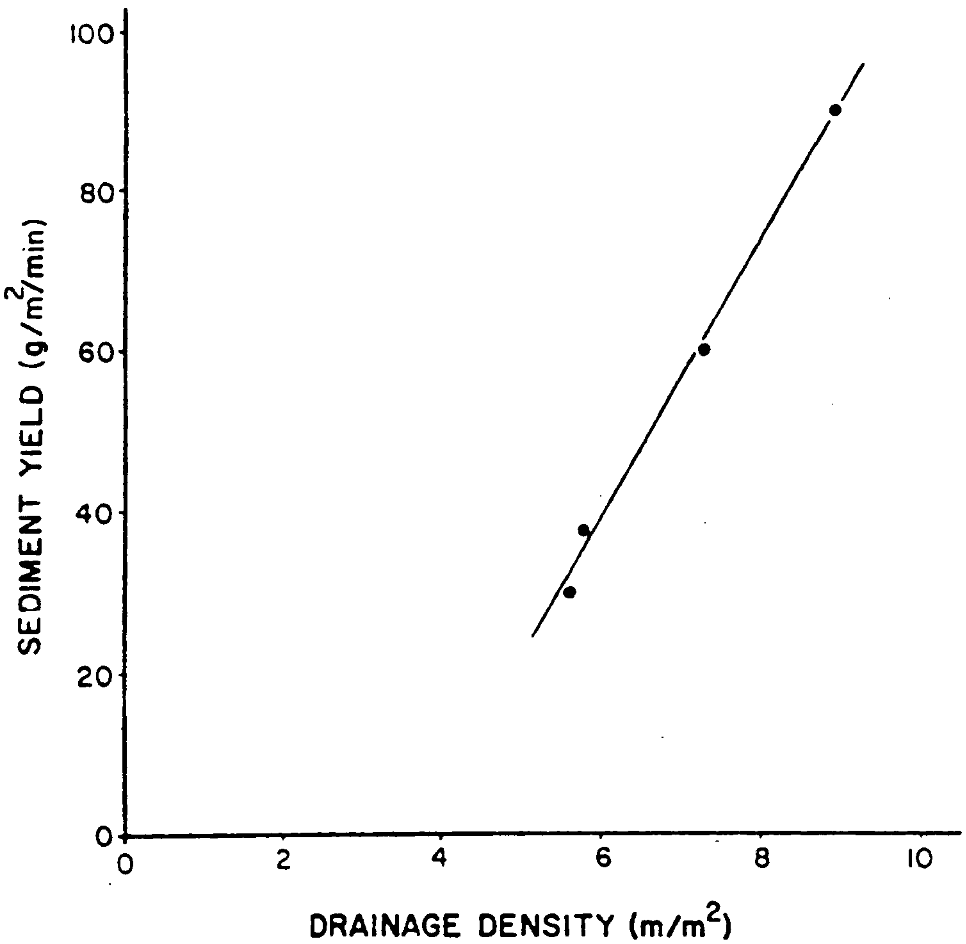


Figure 25. Sediment yield versus drainage density (Mosley cited as Figure 3.11 by Schumm, Mosley, and Weaver, 1987)

experimental study of rill erosion in a rainfall-erosion facility (Mosley cited by Schumm, Mosley, and Weaver, 1987).

## Drainage Density of Iowa Lake Watersheds

Drainage densities of each lake watershed are determined for 20 Iowa lakes using the length of all the streams appearing on the 1:24,000 topographic map (see Appendix B). The drainage density is calculated by dividing the length of contributing streams by the area of the watershed.

Sediment accumulation rates versus drainage densities for 20 Iowa lakes is shown as Figure 26. The Iowa lake data do not show a correlation between sedimentation and drainage density as does Mosley's data from the landscape erosion model.

The 20 lakes with drainage density data are classified according to LRA's based on geology, Lara's hydrologic regions based on floods, and major river basins. A correlation between sediment accumulation rates and drainage densities does not improve when the watersheds are classified with respect to LRA's, Lara's hydrologic regions, or major river basins as shown in Figures 27, 28, and 29. Some distinction between watershed drainage densities and LRA's is observed in Figure 27. The watersheds in LRA 103, the Des Moines Lobe, have lower drainage densities than lake watersheds on Kansan

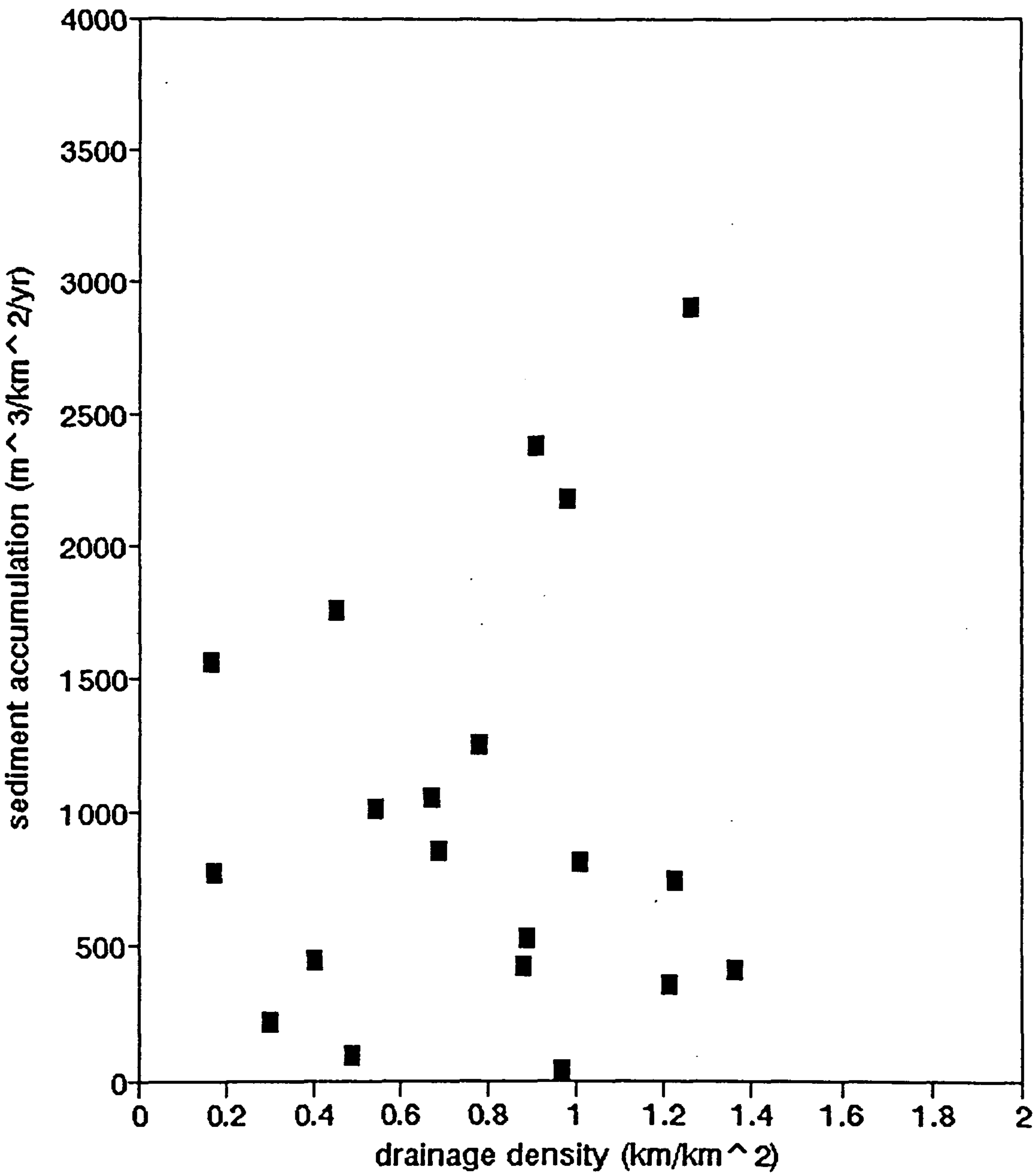


Figure 26. Sediment accumulation rates versus drainage densities for 20 Iowa lakes

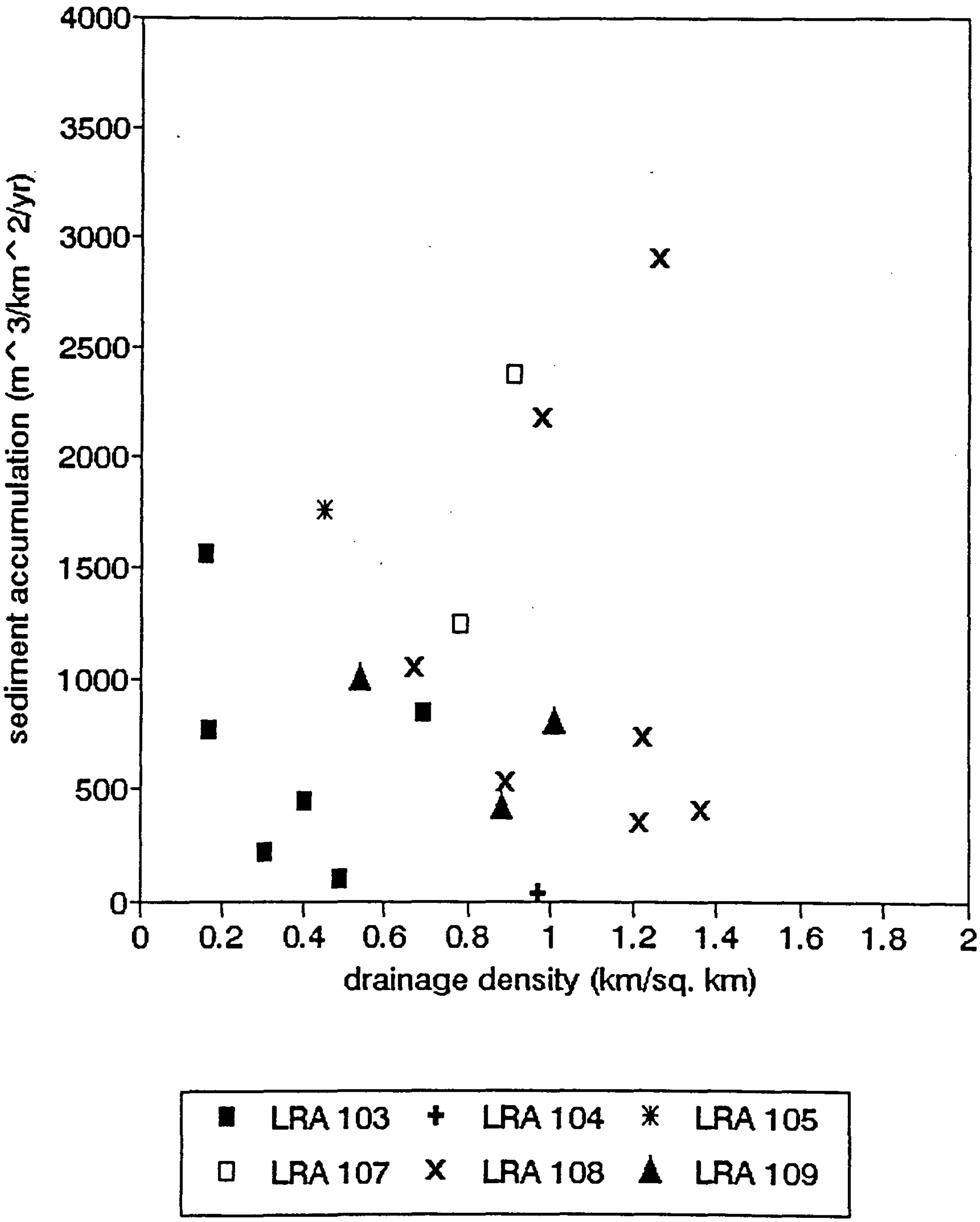


Figure 27. LRA classification for 20 Iowa lakes

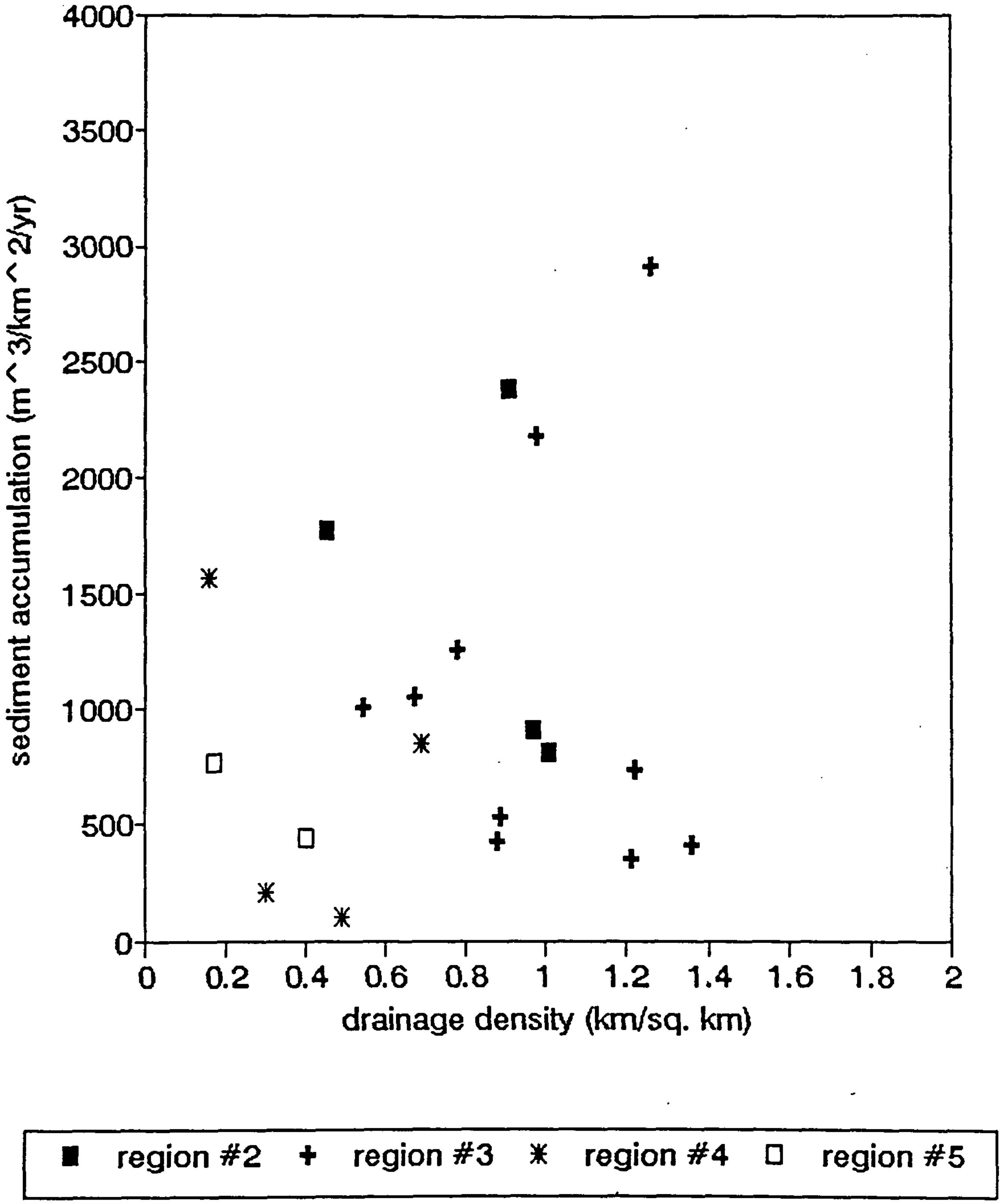


Figure 28. Lara's hydrologic region classification for 20 Iowa lakes

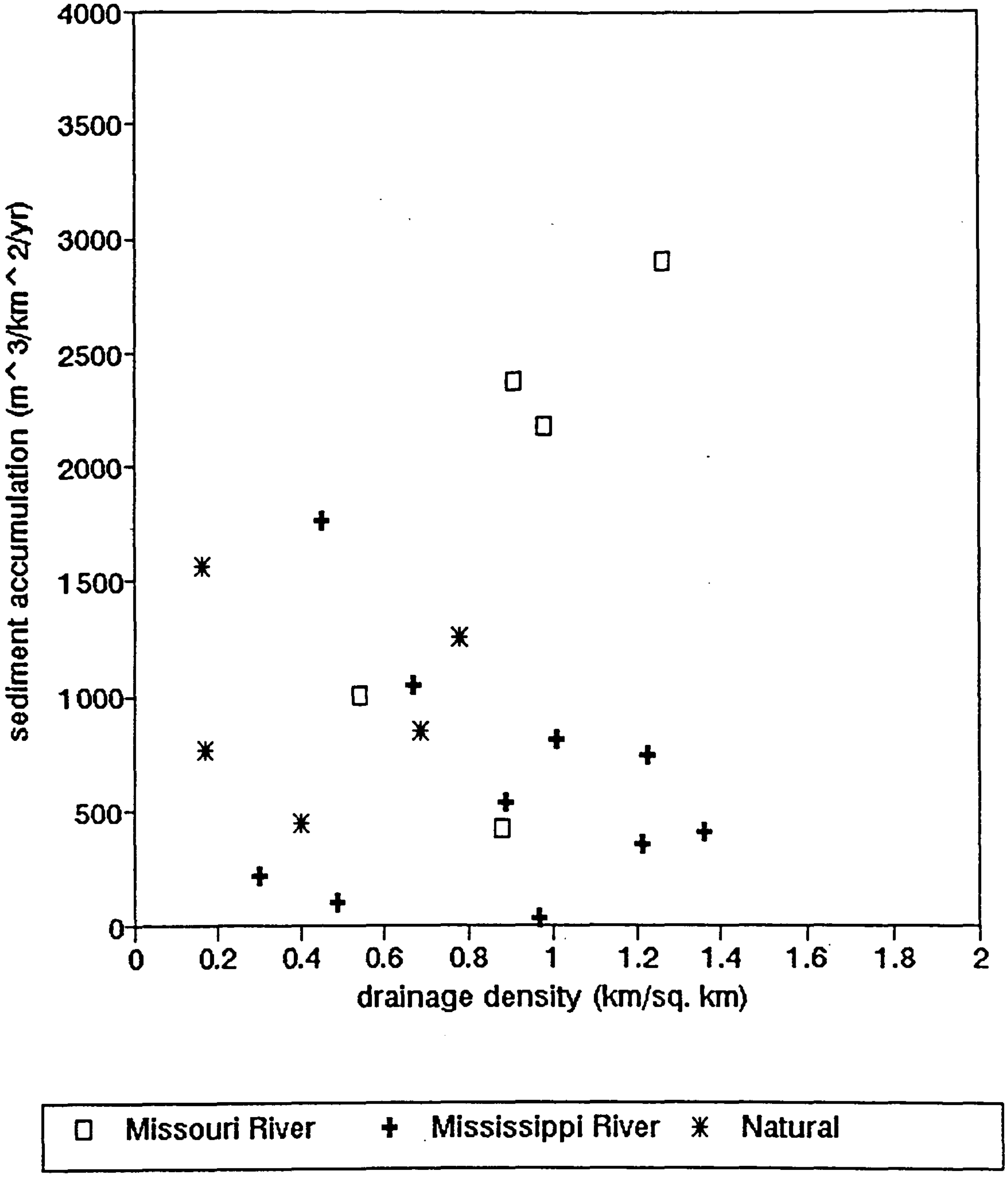


Figure 29. Major river basin classification for 20 Iowa lakes

till represented by LRA's 107, 108, and 109. Ruhe (1975) also found drainage densities to be lower on the Des Moines Lobe than on the Kansan till. The correlation between LRA's and lake sedimentation is not improved by using watershed drainage densities.

## Slope Length and Slope Gradient

Slope length is measured from the drainage divide to the base of the slope (Holy, 1980). Field tests reveal longer slopes have higher soil losses per unit area as rainfall, slope gradient, soil type, and land use remain constant (Bennet cited by Holy, 1980). Doubling the slope length increases the soil loss by 3.03 times when all other factors are held constant (Zingg, 1940). The runoff volume, intensity, and tangential stress increase with increasing slope length, provided the rainfall duration is longer than the time for the water particles to travel the length of the slope (Holy, 1980).

The gradient of slopes in a watershed is one of the major erosion factors (Holy, 1980). The slope gradient controls the tangential stress of the water on the soil and the velocity of the runoff. Field measurements performed at constant rain-fall, slope length, soil type, and land use reveal increases in slope gradient cause increases in soil loss per unit area

(Bennet cited by Holy, 1980). Data from several midwestern United States Soil Conservation Service experiment stations having the same plot size, type of soil, rainfall intensity, and rainfall amount show doubling the slope gradient increases the total soil loss by 2.80 times (Zingg, 1940).

## Basin Relief Ratios

The basin relief ratio is the difference in elevation between the lake surface and the basin divide, divided by the basin length measured in a straight line approximately parallel to the major drainage channel (Hadley and Schumm cited by Miller and Dragoun, 1966). Maner (1958) studied 25 watersheds in Texas, Oklahoma, and Kansas and found smaller watersheds have higher relief ratios than larger watersheds.

Basin relief ratios are determined for 22 Iowa lakes using 1:24,000 and 1:250,000 topographic maps (see Appendix B). The basin relief ratios, expressed as a percent, represent the slopes of the lake watersheds. Sediment accumulation rates increase with increasing basin relief ratio for ratios less than 0.6% and remain constant with increasing basin relief ratios for ratios greater than 0.6% as shown in Figure 30. Drainage areas decrease with increasing basin relief ratios for ratios less than 0.6% and remain constant with increasing basin relief ratios for ratios greater than

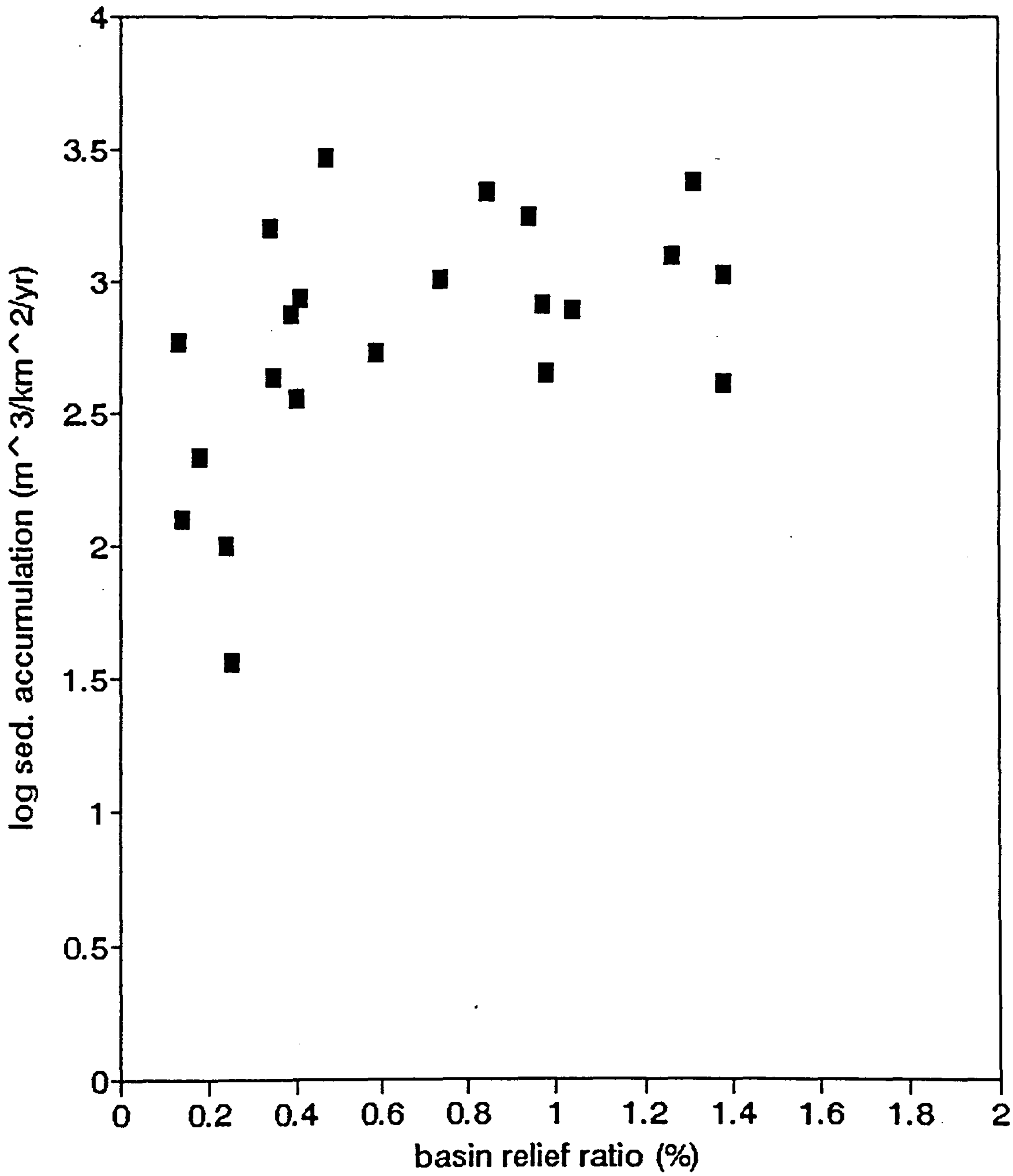


Figure 30. Sediment accumulation rates and basin relief ratios

0.6% as shown in Figure 31. The Iowa lakes agree with Maner's (1958) finding that smaller drainage areas have higher basin relief ratios as shown in Figure 31. Since smaller drainage areas have higher sediment accumulation rates as discussed previously, the increases in sediment accumulation rates with increasing basin relief ratios in Figure 30 reflect decreases in drainage areas with increasing basin relief ratios in Figure 31. Therefore, basin relief ratios are concluded not to have significant, direct influences on sediment accumulation rates.

**Ruggedness Number**

The ruggedness number is the product of the basin relief ratio and the drainage density. Sediment yields increase as ruggedness numbers increase as shown as Figure 32 (Parker cited by Schumm, Mosley, and Weaver, 1987). A study of the Cheyenne River basin in Wyoming reveals higher drainage densities and greater basin relief ratios result in more erosion and greater sediment yields (Hadley and Schumm cited by Chorley, Schumm, and Sugden, 1984).

A plot of sedimentation rates and ruggedness numbers for the Iowa lakes are shown as Figure 33. Sedimentation rates do not appear to be influenced by ruggedness numbers. The

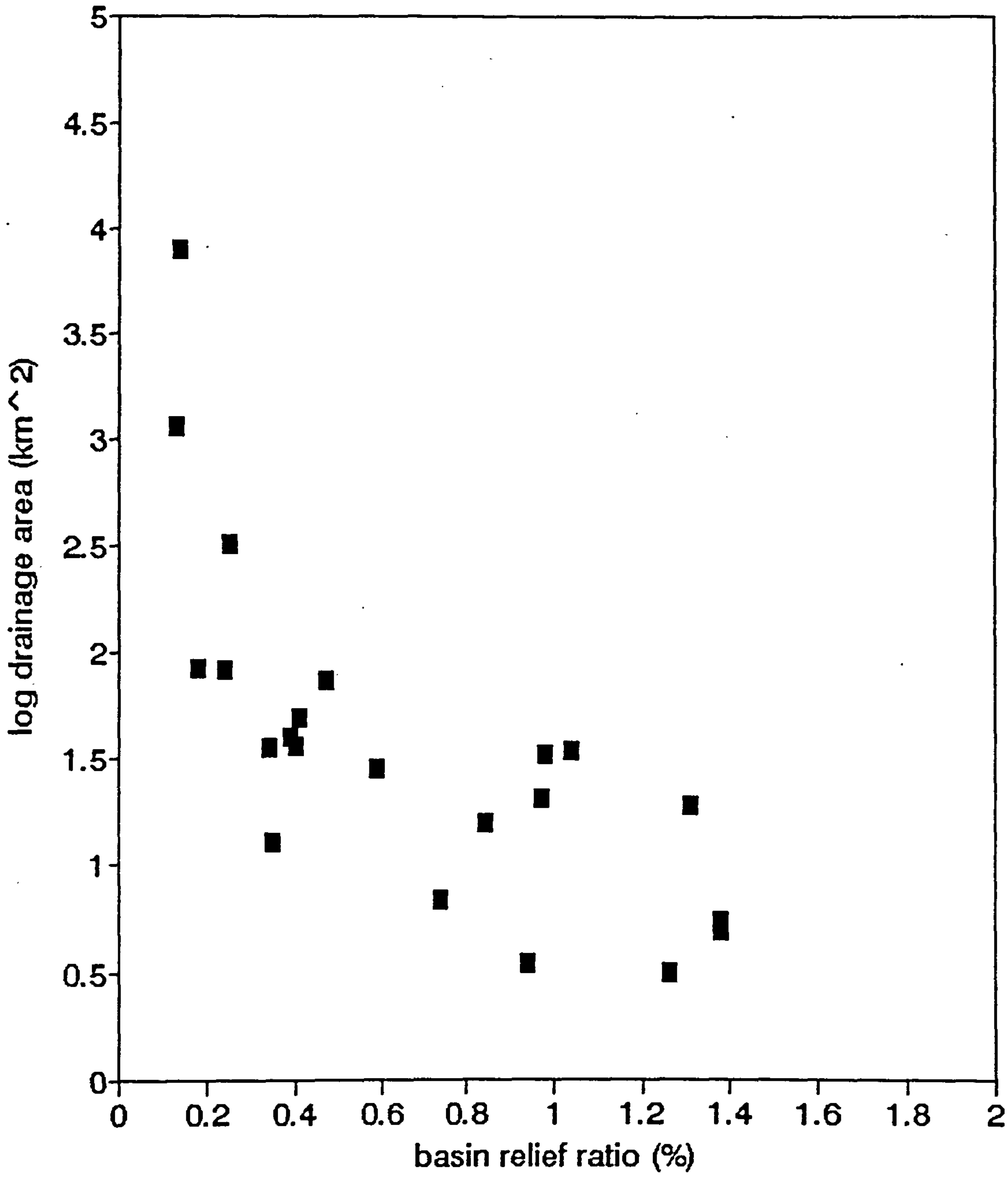


Figure 31. Drainage areas and basin relief ratios

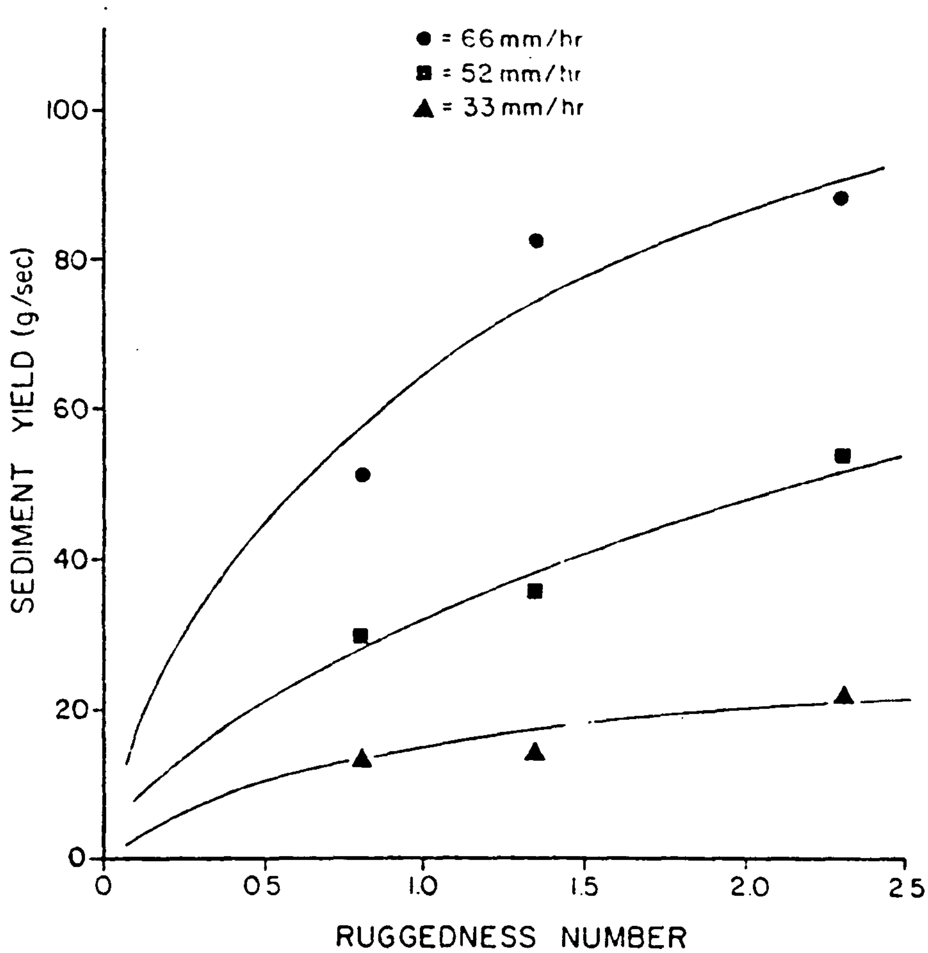


Figure 32. Sediment yield versus ruggedness number (Parker cited as Figure 3.12 by Schumm, Mosley, and Weaver, 1987)

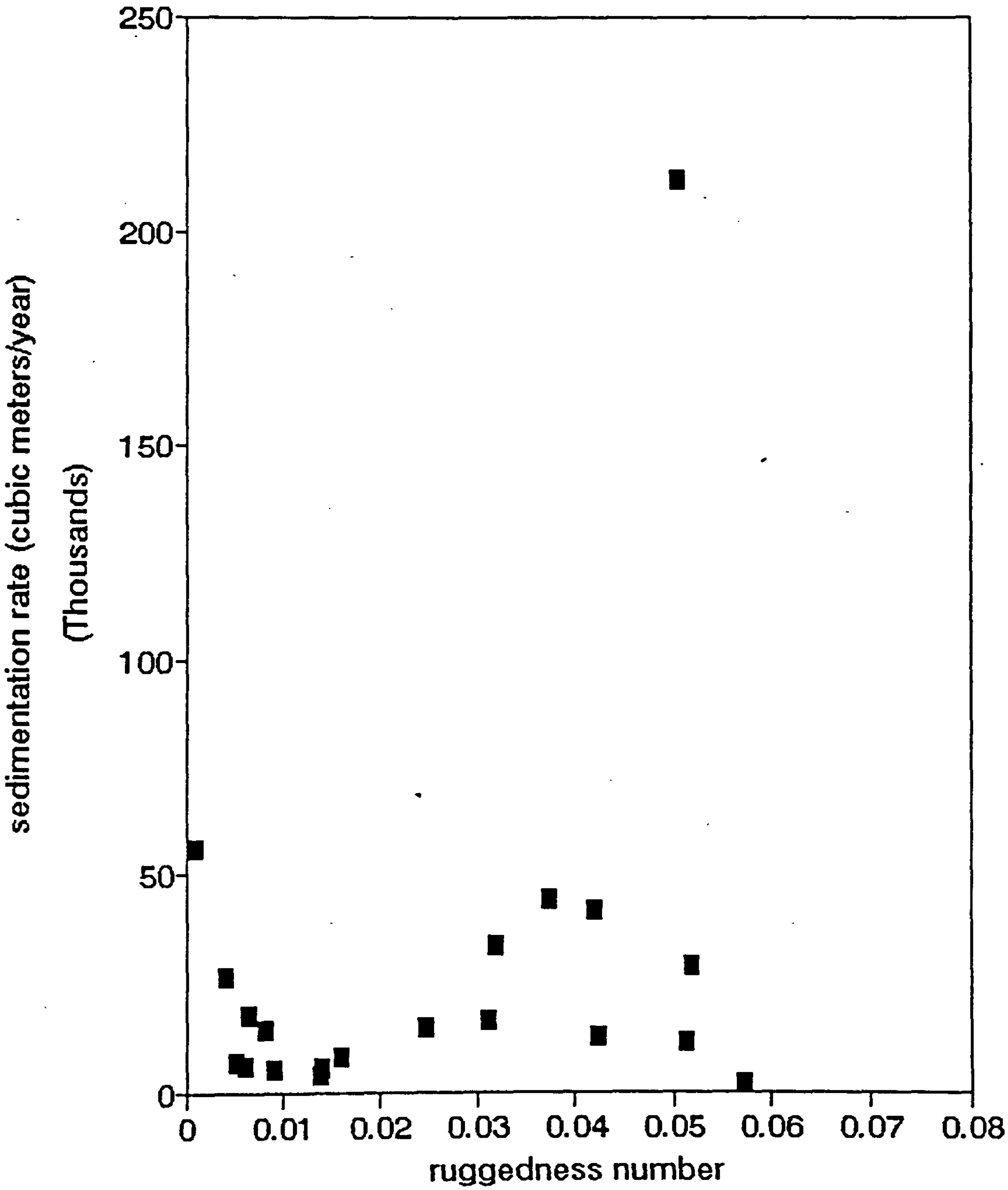


Figure 33. Sedimentation rate versus ruggedness number for 20 Iowa lakes

ruggedness number of a watershed is concluded not to be related to Iowa lake sedimentation.

## Conclusions

Sedimentation rates for Iowa lakes can be estimated using the correlation of sedimentation rates and drainage areas. The classification of Iowa lakes according to major river basins (Missouri River basin and Mississippi River basin) does not provide a more refined method to estimate sedimentation rates. For given drainage areas the sediment accumulation rates of the Missouri River basin lakes are estimated to be 4.5 times greater than the sediment accumulation rates of the Mississippi River basin lakes.

Watershed shape ratios, drainage densities, basin relief ratios, and ruggedness numbers do not show correlations that improve the estimation of lake sedimentation rates.

## ESTIMATING UNIT WEIGHTS OF LAKE SEDIMENTS

Unit weight is previously defined as the weight of sediment per unit volume (Spangler and Handy, 1982). Lake sediment unit weights in the world range from 2.83 to 19.64 kilonewtons per cubic meter (18 to 125 pcf) and are influenced by the size and gradation of sediment particles (sand, silt, and clay) and the amount of consolidation that has occurred (Koelzer and Lara, 1958).

In Sabetha Lake, located in northeast Kansas, Heinemann (1962) found sediment unit weights increase with sediment depth to a depth of 1.1 to 1.2 meters (3.5 to 4 feet) and remain constant for depths greater than 1.2 meters (4 feet). Studies elsewhere show sediment unit weights increase with sediment depth to 0.76 to 1.83 meters (2.5 to 6 feet) and remain constant for depths greater than 0.76 to 1.83 meters (2.5 to 6 feet) (Vanoni, 1975). The percent clay in lake sediments decreases and the unit weight increases with increasing distance upstream from the spillway (Heinemann, 1962). The unit weight of Sabetha Lake deposits at a sediment depth of 30 centimeters (12 inches) increases from 8.48 kilonewtons per cubic meter (54 pcf) near the dam to 13.20 kilonewtons per cubic meter (84 pcf) 1524 meters (5000 feet) upstream from the dam.

## Unit Weights of Iowa Lake Sediments

Lake sediment unit weight data are available for 25 of the 40 Iowa lakes previously studied in this thesis (see Table 2) and also for Lake McBride studied by Lane and Koelzer (1943) and Lake Laverne studied by Tso Wang Lin (1982). Lake Mcbride is in Johnson County, Iowa (LRA 108) and Lake Laverne is in Story County, Iowa (LRA 103). The data are studied in hopes of providing a more reliable and economical method to estimate the unit weight of lake sediments for dredging operations.

The sediment unit weight for each Iowa lake is the average unit weight of all sediment samples taken from the lake. The sediment unit weight for 27 Iowa lakes range from 5.11 kilonewtons per cubic meter (32.5 pcf) in Lake Wapello to 14.46 kilonewtons per cubic meter (92.0 pcf) in Prairie Rose Lake. The average sediment unit weight for the 27 Iowa lakes is 9.14 kilonewtons per cubic meter (58.2 pcf).

The classification by LRA's for 26 Iowa lakes with sediment unit weight data is shown in Figure 34. The sediment unit weight for each lake is plotted with respect to LRA's as shown in Figure 35. LRA 107 appears to have higher sediment unit weights than LRA's 108, 109 and 103. The average unit weight for the 14 lakes in LRA 107 is 9.87 kilonewtons per cubic meter (62.8 pcf). The average sediment unit weight for

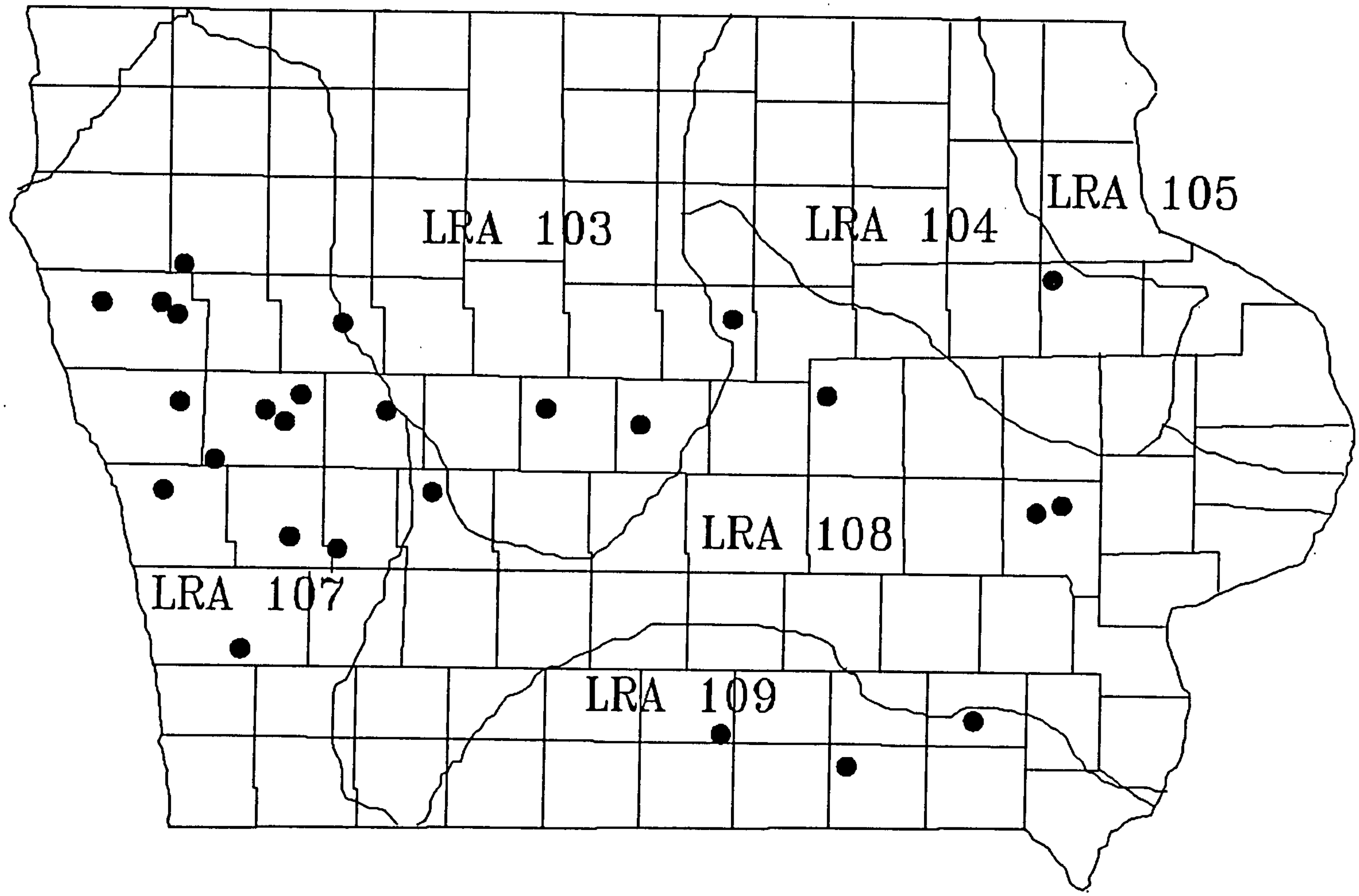


Figure 34. Locations of LRA's and 26 lakes with sediment unit weight data

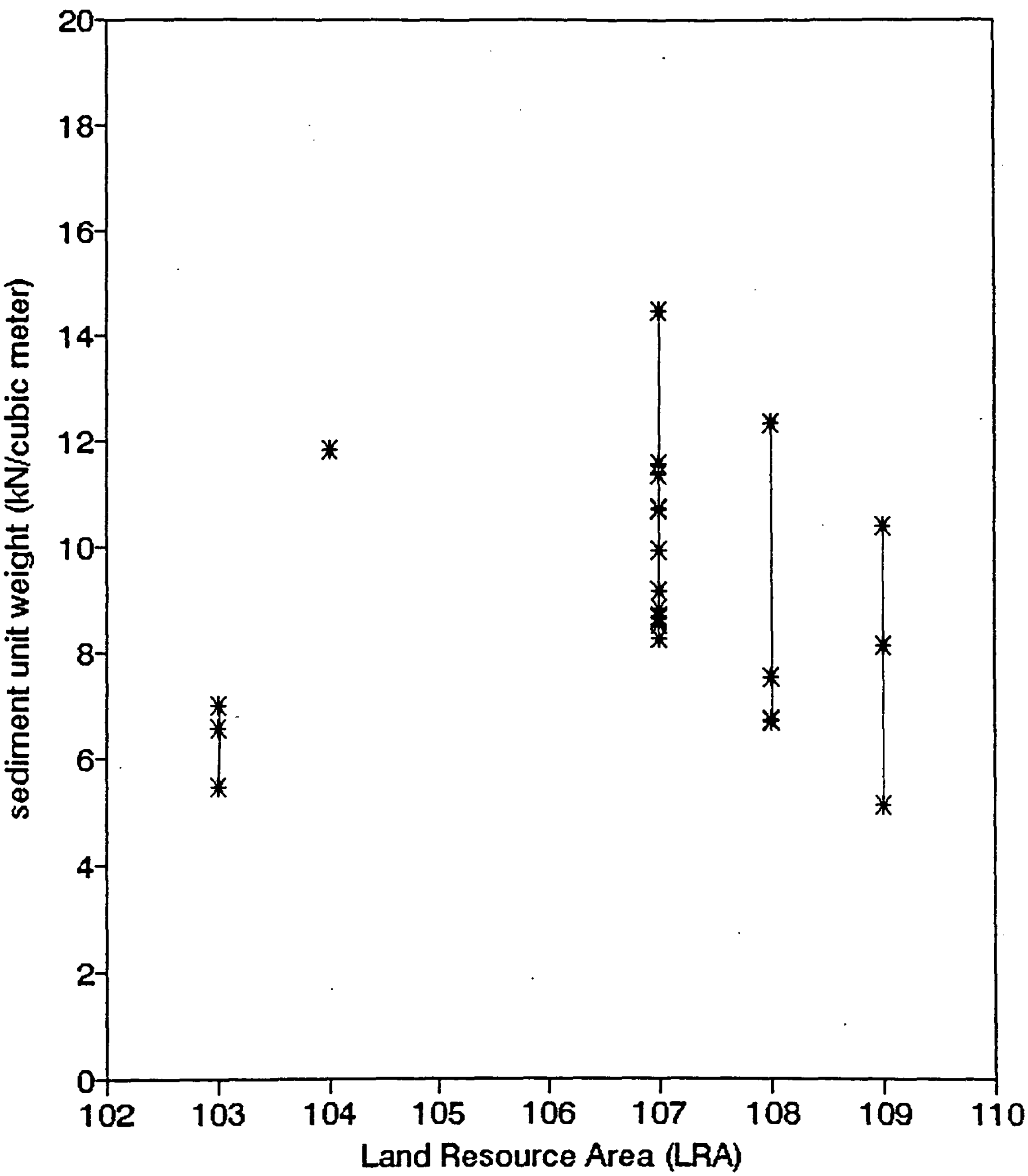


Figure 35. Sediment unit weights classified by LRA's

the 5 lakes in LRA 108, 3 lakes in LRA 109, and 3 lakes in LRA 103 is 8.31 kilonewtons per cubic meter (52.9 pcf), 7.86 kilonewtons per cubic meter (50.0 pcf), and 6.33 kilonewtons per cubic meter (40.3 pcf) respectively. The one lake in LRA 104 has a sediment unit weight of 11.80 kilonewtons per cubic meter (75.1 pcf). The variation in sediment unit weight for each LRA shows the complexity of estimating unit weights. It is concluded that more lakes with sediment unit weight data are needed to verify a correlation between sediment unit weight and LRA's.

The unit weight data for the lake sediments in the artificial lakes are from recent deposits; i.e., the sediments have accumulated in the last 70 years. The two natural lakes, Black Hawk Lake and Swan Lake, have Pleistocene age lake sediments; i.e., sediment accumulations since the Wisconsin glacier retreated 13,000 years before present. The sediment unit weights for Black Hawk Lake and Swan Lake are 6.99 kilonewtons per cubic meter (44.5 pcf) and 8.64 kilonewtons per cubic meter (55.0 pcf) respectively. The sediment unit weights for the 25 artificial lakes range from 5.11 kilonewtons per cubic meter (32.5 pcf) to 14.46 kilonewtons per cubic meter (92.0 pcf) and average 9.25 kilonewtons per cubic meter (58.9 pcf). Comparison of sediment unit weights for artificial and natural lakes shows no distinction between sediment unit weight and geological age of the deposit.

Sediment unit weights may be influenced by depths and locations of samples as found in Sabetha Lake (Heinemann, 1962). Sediment borings from Swan Lake show sediment unit weight increases with depth down to 100 to 110 centimeters (3.3 to 3.6 feet) and the unit weight remains constant at depths greater than 110 centimeters (3.6 feet) as shown in Figures 36 and 37. The unit weight versus depth relationship for Swan Lake is consistent with Sabetha Lake where Heineman (1962) found unit weights increase to a depth of 107 to 122 centimeters (3.5 to 4.0 feet) and remain constant for depths greater than 122 centimeters (4.0 feet). A plot of sediment unit weights and distances upstream from the dam in Black Hawk Lake and Union Grove Lake is shown as Figure 38. The sediment unit weights in Black Hawk Lake and Union Grove Lake do not increase with distance upstream from the dam as found in Sabetha Lake (Heinemann, 1962). Appendix C contains the unit weight data for Swan, Black Hawk, and Union Grove lakes.

Lane and Koelzer (1943) developed equations for computing the unit weight of lake sediments. Lakes are classified by 4 types according to lake operation. Type I lakes are usually full and the sediments are submerged; whereas, Type IV lakes are normally empty and the sediments are exposed to drying. The sediments in the studied Iowa lakes are considered to be always or nearly always submerged and the equation to compute sediment unit weight for Type I lakes is:

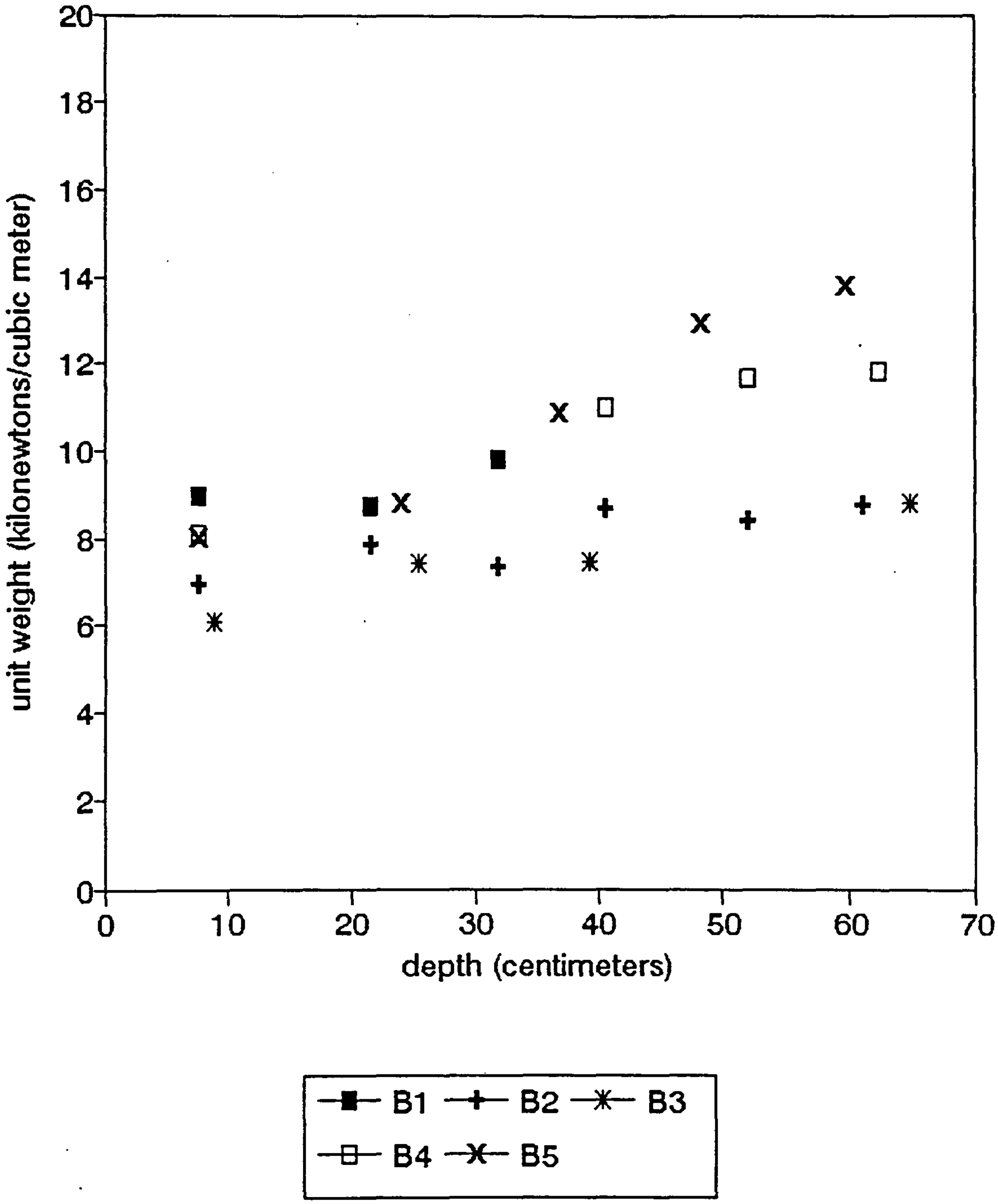


Figure 36. Shallow sediment borings from Swan Lake

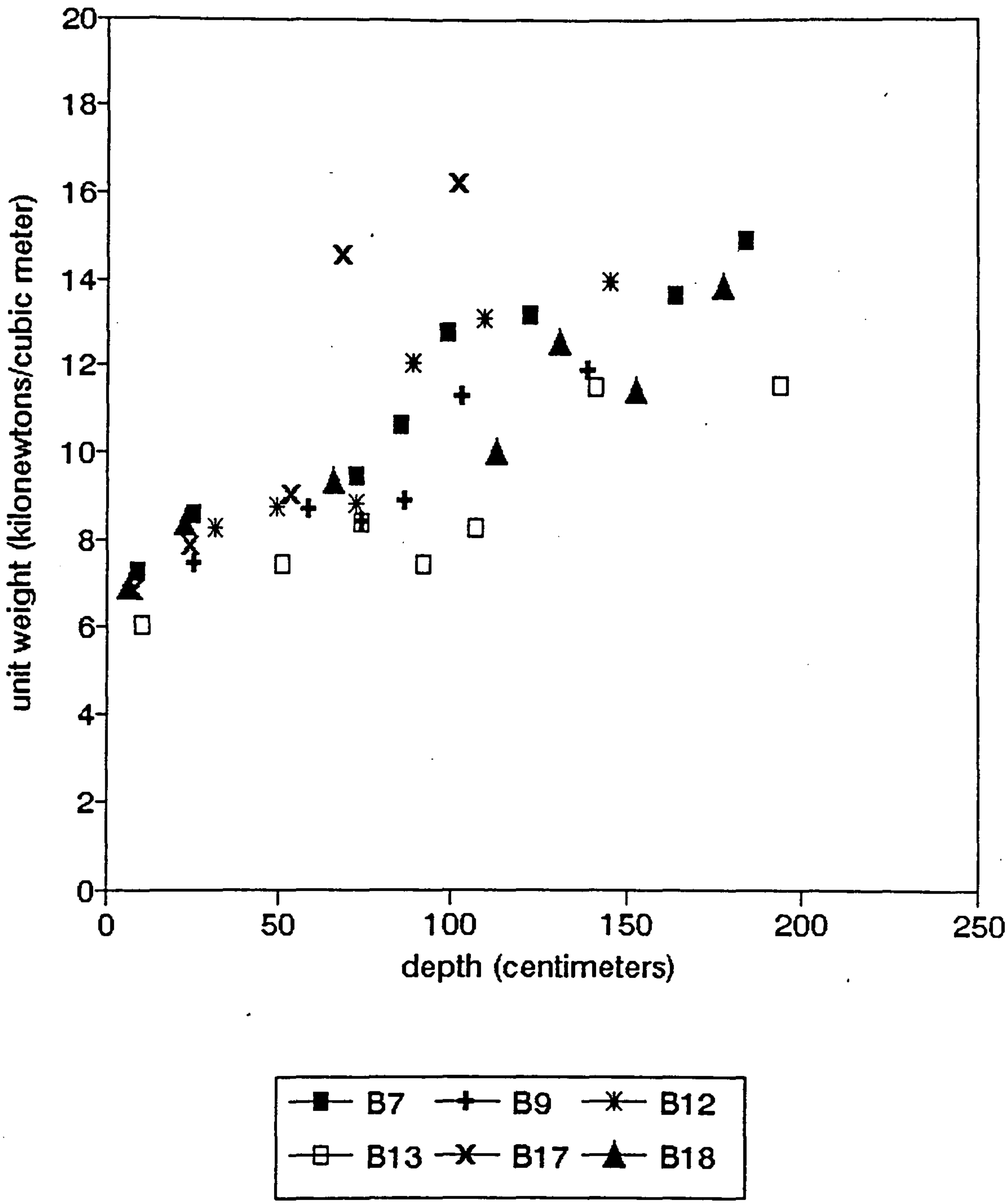


Figure 37. Deep sediment borings from Swan Lake

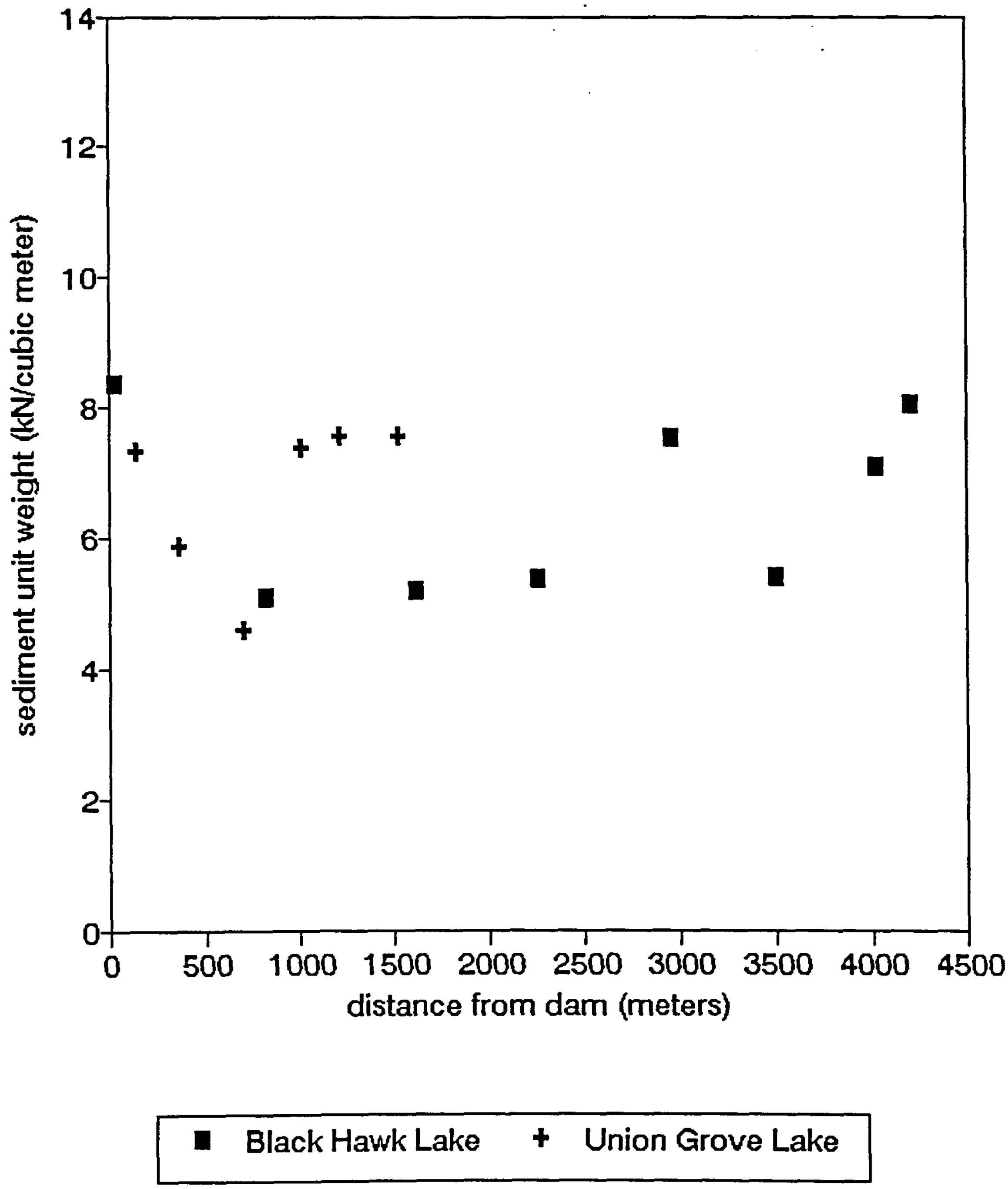


Figure 38. Change in sediment unit weight in relation to distance from dam

$$W = 93ps + (65 + 5.7 \log T)pm + (30 + 16 \log T)pc$$

where

W = unit weight of sediment in pounds per cubic foot

ps = percent sand (0.05 to 1.0 mm)

pm = percent silt (0.005 to 0.05 mm)

pc = percent clay (less than 0.005 mm)

T = time span sediment has been deposited in years

Lane and Koelzer's equation is used to calculate sediment unit weights for 8 Iowa lakes with sediment particle size data. The calculated unit weights are compared to measured unit weights in Figure 39. Sediment particle size classification has been done by Iowa State University for 4 lakes (Black Hawk Lake, Lake Panorama, Lower Pine Lake, and Union Grove Lake), United States Department of Agriculture for 3 lakes (Don Williams, Lake Wapello, and Springbrook), and Lane and Koelzer for 1 lake (Lake McBride) (see Appendix C for data). The calculated unit weights, in general, are higher than the measured unit weights. The variance may be the result of the depth of samples and different particle size classifications. Different soil particle size classifications have been used by different agencies (Spangler and Handy, 1982). The sediment particle size classification used by Lane and Koelzer is from the United States Bureau of Soils. The United States Department of Agriculture classifies clay as less than 0.002

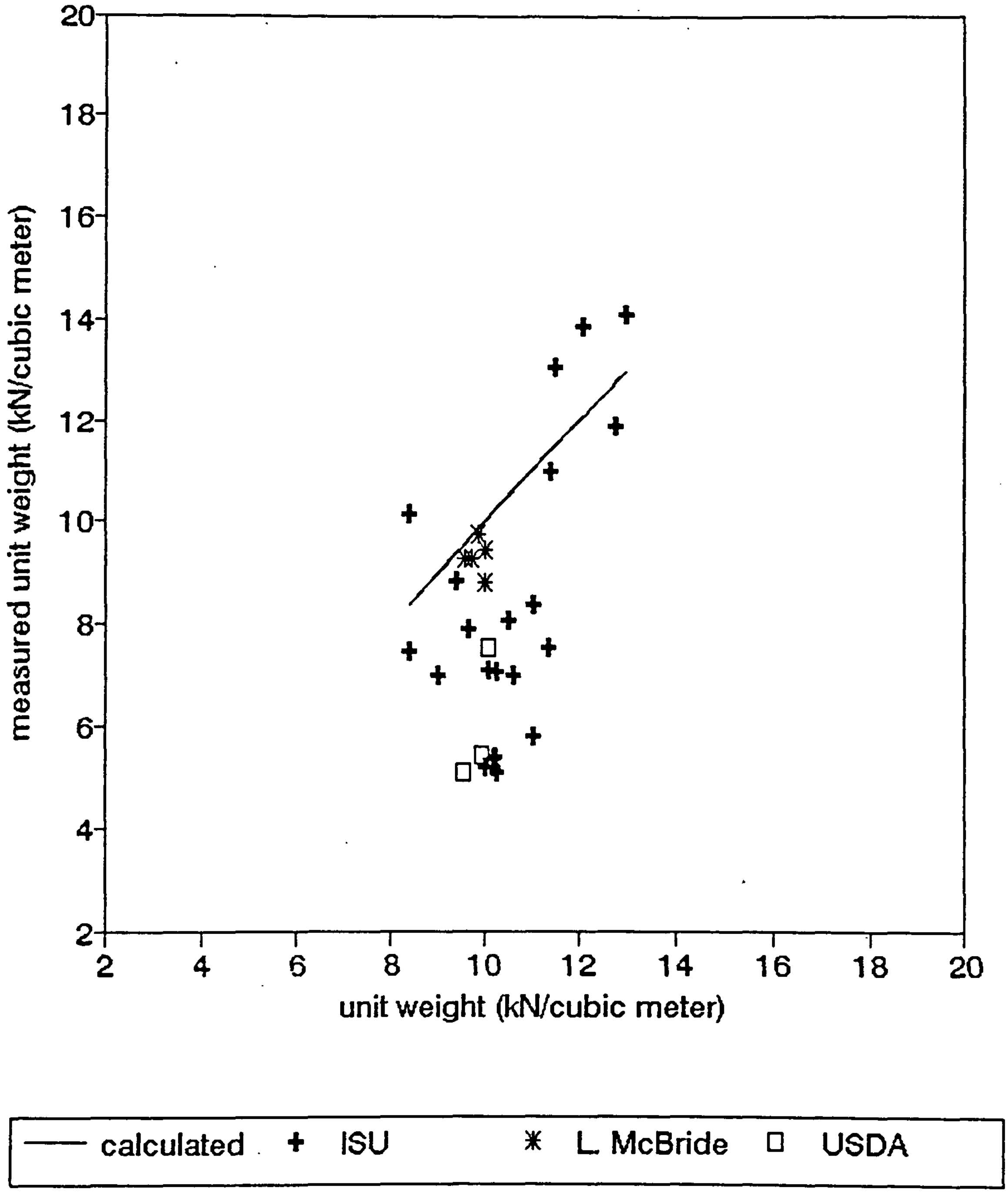


Figure 39. Sediment unit weights for 7 Iowa lakes using Lara and Koelzer's particle size equation

millimeters and the Lane and Koelzer equation uses 0.005 millimeters. Iowa State University employs the ASTM classification which uses 0.074 millimeters to separate silt from sand and the Lane and Koelzer equation uses 0.05 millimeters.

## Conclusions

More lakes with sediment unit weight data are needed for accurate correlations between sediment unit weight and watershed geology. Sediment unit weight in Swan Lake increases with depth to a depth of approximately 1.0 meter (3.3 feet) and remains constant for depths greater than 1.2 meters (4 feet) as found by Heinemann (1962) in Sabetha Lake. Data from Black Hawk Lake and Union Grove Lake do not show increases in sediment unit weight with distance upstream from the dam as found by Heinemann (1962) in Sabetha Lake. Sediment unit weights calculated from the equation developed by Lane and Koelzer (1943) do not correlate well with measured sediment unit weights for 8 Iowa lakes.

# HISTORIC SEDIMENTATION RATES OF IOWA NATURAL LAKES

## Iowa History and Lake Management

The state of Iowa was extensively settled by 1870 (Schwieder, Morian, and Nielsen, 1989). It is hypothesized the sedimentation rates from 1870 to present (post-settlement) are higher than the sedimentation rates from the retreat of the Wisconsin glaciers (13,000 years before present) to 1870 (pre-settlement). Higher post-settlement sedimentation is believed to be caused by increases in water and wind erosion in the drainage basin, bank erosion, and decaying vegetation (Iowa State Planning Board, 1935). Settlers plowed the grassland prairies exposing the soil to water and wind erosion. Settlers contributed to bank erosion by cutting trees surrounding the lakes and allowing livestock to trample vegetation along the shores (Iowa State Planning Board, 1935). Few measures were taken to protect lake shorelines until the 1930's.

## 1935 Lake Surveys

The Iowa State Planning Board surveyed 18 natural lakes in 1935 using soundings and borings. Lake volumes were determined from soundings taken from the water surface to the lake bottom and the original lake volumes were determined by boring through the lake sediments into the glacial till. The Iowa State Planning Board computed the original lake volume by adding the 1935 lake volume to the volume of deposited sediment. Table 6 lists 17 natural lakes with the 1935 survey data. Mud Lake and High Lake are separated by a large swamp and are listed as one lake with a combined surface area, drainage area, and volume. The 17 lakes are located on the Des Moines Lobe as shown in Figure 40.

Sedimentation rates from the time the glaciers retreated, approximately 13,000 years before present, to 1935 can be calculated using data from the 1935 Iowa State Planning Board sediment borings. Lake sedimentation rates are computed dividing the volume of deposited sediment by 13,000 years. The historic sedimentation rates are listed in Table 6. The volume of sediment dredged before 1935 in Five Island Lake (called Medium Lake before 1944) is thought to be insignificant in respect to the lake's total sedimentation.

Figure 41 is a plot of sedimentation rates versus drainage areas of Iowa natural and artificial lakes and shows sedimentation rates since 1935 are higher than sedimentation rates before 1935. Sedimentation rates since 1935 are 20 to 45 times higher than sedimentation rates from the retreat of the glaciers to 1935. The graph of the logarithm of sediment accumulation rates versus the logarithm of drainage areas

Table 6. 1935 survey data (Iowa State Planning Board, 1935)

| lake name | Iowa county | area (ha) | drainage area (sq. km) | 13,000 yr sed. rate (m^3/yr) | original volume (m^3) |
|---|---|---|---|---|---|
| Black Hawk | Sac | 374 | 51.4 | 1393 | 23,796,000 |
| Clear | Cerro Gordo | 1474 | 19.3 | 2720 | 80,303,000 |
| Cornelia | Wright | 106 | 1.8 | 209 | 5,333,000 |
| Five Island | Palo Alto | 401 | 26.1 | 1020 | 18,275,000 |
| Four Mile | Dickinson | 75 | 12.2 | 168.5 | 2,830,000 |
| Lost Island | Palo Alto | 436 | 19.5 | 1102.7 | 29,864,000 |
| Mud/High | Emmet | 329 | 21.6 | 1017 | 18,783,000 |
| North Twin | Calhoun | 206 | 6.7 | 640 | 11,364,000 |
| Rush | Osceola | 128 | 6.6 | 165 | 2,620,000 |
| Rush | Palo Alto | 186 | 90.4 | 519 | 8,262,000 |
| Silver | Dickinson | 444 | 62.5 | 1199 | 25,052,000 |
| Silver | Palo Alto | 270 | 26.1 | 766 | 14,315,000 |
| Storm | Buena Vista | 1247 | 69.4 | 2133 | 57,749,000 |
| Swan | Carroll | 53 | 3.4 | 106 | 2,133,000 |
| Swan | Dickinson | 144 | 38.6 | 812.7 | 12,409,000 |
| Tuttle | Emmet | 1140 | 361.6 | 2420 | 45,922,000 |
| West Swan | Emmet | 420 | 19.4 | 1240 | 20,871,000 |

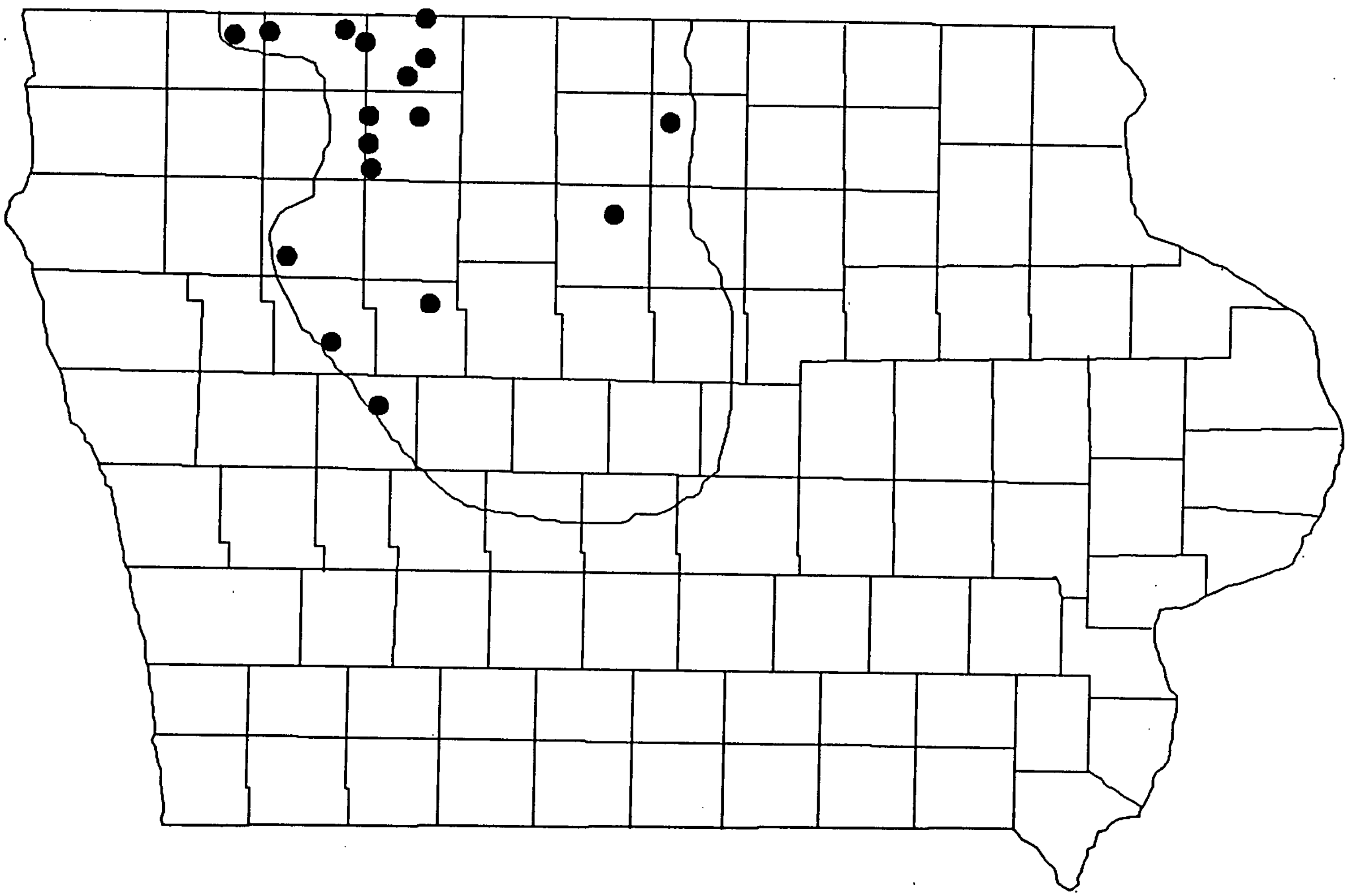

Figure 40. 17 natural lakes on the Des Moines Lobe with sediment borings taken in 1935

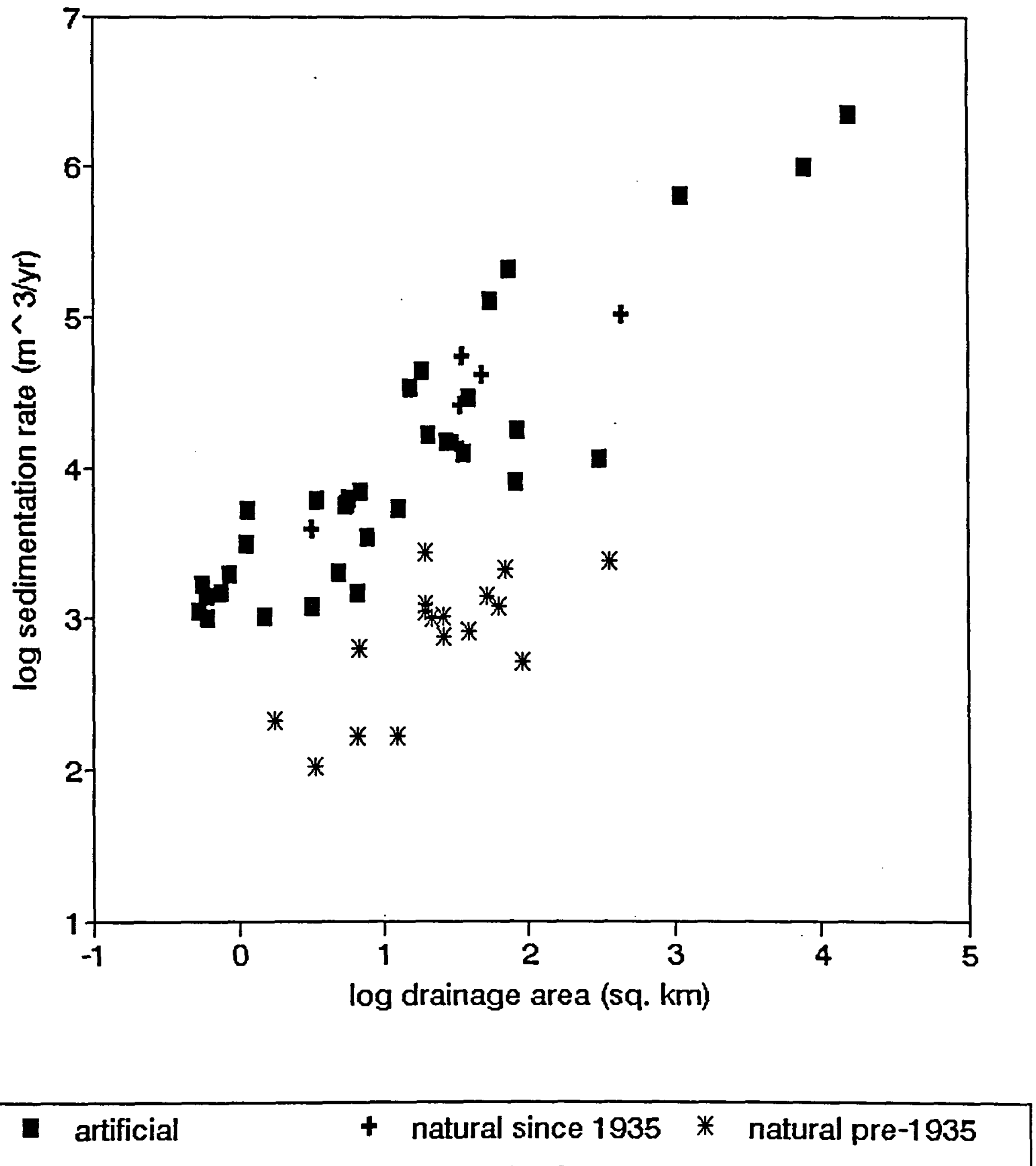


Figure 41. Sedimentation rates before and after 1935

reveals that sediment accumulation rates since 1935 are higher than the pre-1935 sediment accumulation rates as shown as Figure 42. The volume to drainage area ratios versus percent annual storage loss is plotted as Figure 43. The pre-1935 storage losses are 2 logarithmic cycles (100 times) lower than storage losses since 1935. The apparent increase in lake sedimentation since 1935 is beleived to be the result of changes in land use imposed by settlement and consolidation of sediment particles from the weight of overlying layers through geological time.

## Calculating Historic Sedimentation Rates

Data for 6 natural, glacial lakes from the 1935 Iowa State Planning Board sediment borings and post-settlement lake surveys can be used for further analysis of historic sedimentation rates. The volumes of Black Hawk, Clear, Five Island, Swan (Carroll County), Silver, and Tuttle lakes in 1870 can be calculated using the 1935 lake volume and the post-settlement sedimentation rate. The post-settlement sedimentation rates are assumed to represent the rate of sediment deposition from 1870 to present. The sedimentation rate before 1870 is the difference between the original lake volume and the 1870 volume, divided by 13,000 years.

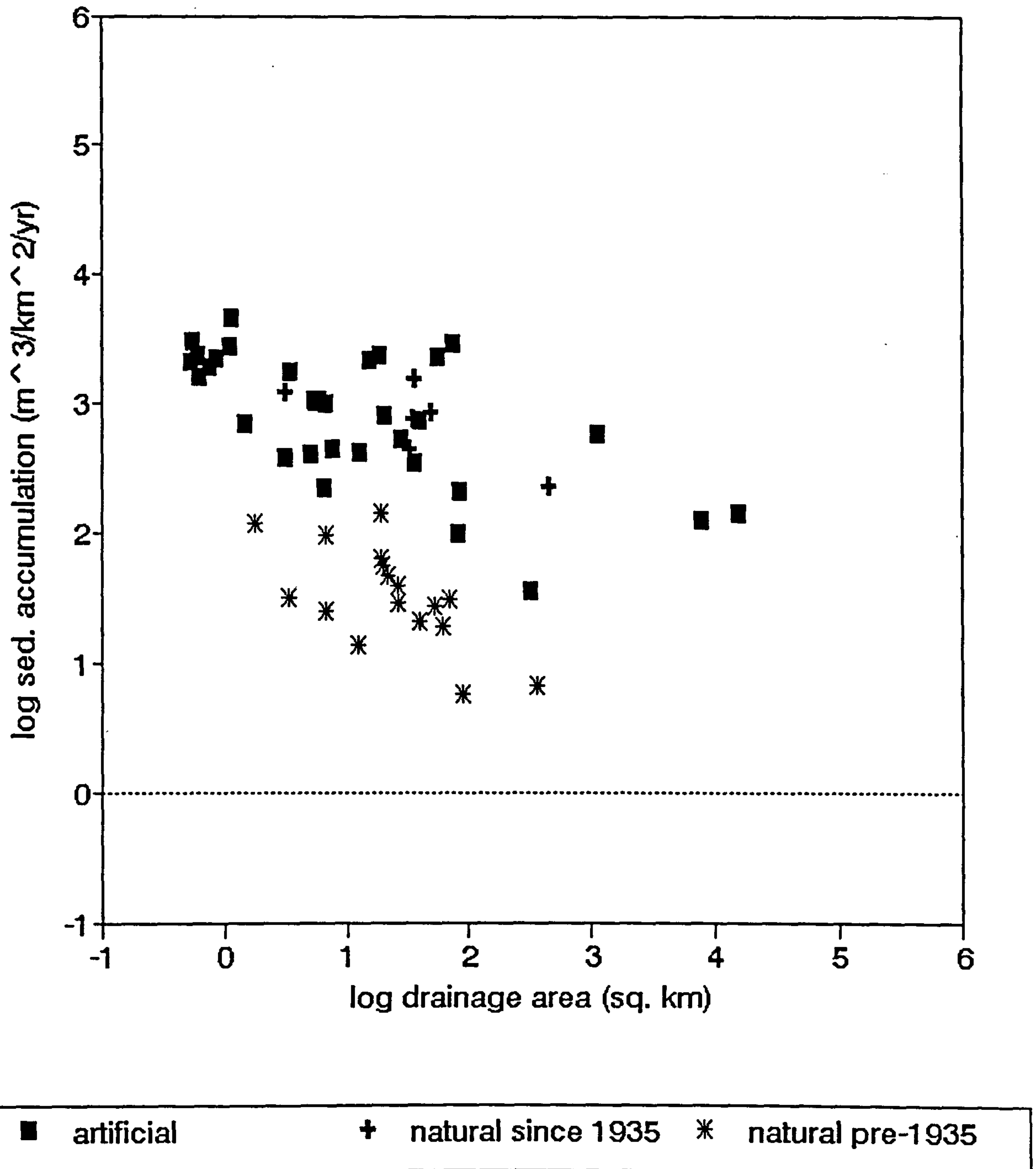


Figure 42. Sediment accumulation rates before and after 1935

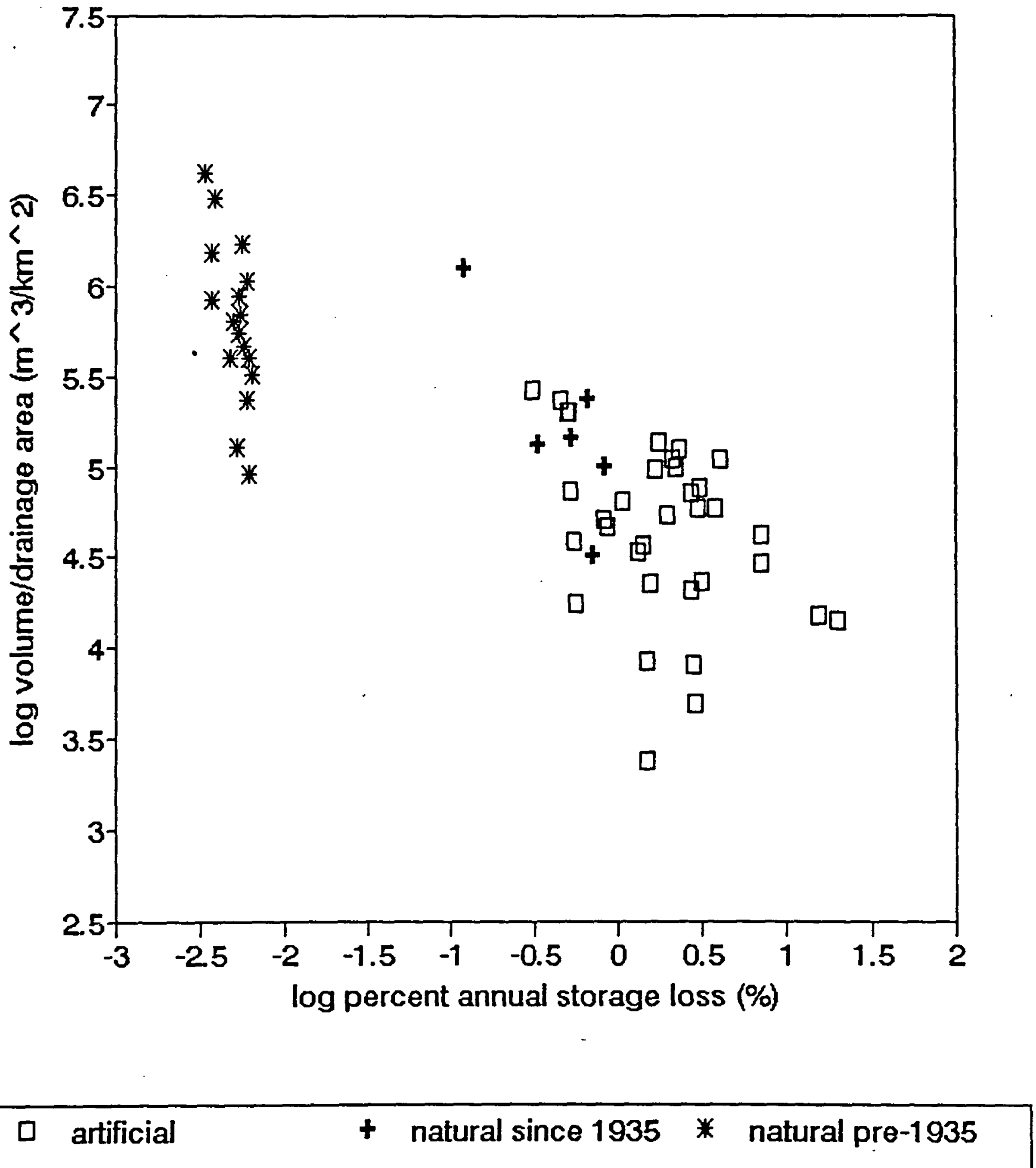


Figure 43. Volume to drainage area ratios versus annual storage losses before and after 1935

Adjustment for Consolidation of Sediment

Sediment borings from Swan Lake (Carroll County) in 1980 found sediment unit weight increases with depth to a depth of about 100 to 110 centimeters (3.3 to 3.6 feet) and remains constant for depths greater than 110 centimeters (3.6 feet) (shown previously in Figure 37). The sedimentation rate in Swan Lake from 1935 to 1980 (3947 cubic meters/year) is also assumed to represent the rate of sediment deposition in Swan Lake from 1870 to 1935. The depth of sediment in Swan Lake deposited since 1870 is computed using the post-settlement sedimentation rate (SR = 3947 cubic meters/year), time span (110 years), and lake surface area (SA = 52.6 hectares).

$$depth=\frac{SR x 110 years}{SA}$$

The depth of sediment deposited between 1870 and 1980 is calculated to be 82.5 centimeters. The sediment unit weight in Swan Lake increases from 8.0 kilonewtons per cubic meter (50.9 pcf) at a sediment depth of 80 centimeters (2.3 feet) to 12.8 kilonewtons per cubic meter (81.5 pcf) at a sediment depth of 100 centimeters (3.3 feet). Assuming the unit weight of sediment deposited before 1870 is 12.8 kilonewtons per cubic meter (81.5 pcf), the volume of sediment deposited before 1870 can be adjusted to a post-settlement sediment volume by a compaction factor of 1.6; i.e., 12.8 kilonewtons (81.5 pcf) of sediment deposited before 1870 would require a volume of 1 cubic meter (35.3 cubic feet) and the same 12.8 kilonewtons of sediment deposited after 1870 would require a volume of 1.6 cubic meters (56.5 cubic feet).

The change in unit weight with depth and time for the other 5 natural lakes (Black Hawk, Clear, Five Island, Silver, and Tuttle) is assumed to be similar to Swan Lake. The pre-settlement sedimentation rates are increased by 1.6 times to account for the compaction of sediment. The post-settlement sedimentation rates and adjusted pre-settlement sedimentation rates are plotted versus drainage areas in Figure 44. The adjustment for compaction of sediments does not appear to cause a significant change in the results. The post-settlement sedimentation rates are approximately 15 to 30 times greater than the pre-settlement sedimentation rates.

## Conclusions

Increases in lake sedimentation have occurred since Iowa was extensively settled in 1870. Post-settlement sedimentation rates are estimated to be 15 to 30 times greater than the pre-settlement sedimentation rates. The increases in lake sedimentation are believed to be the result of agricultural practices and bank erosion.

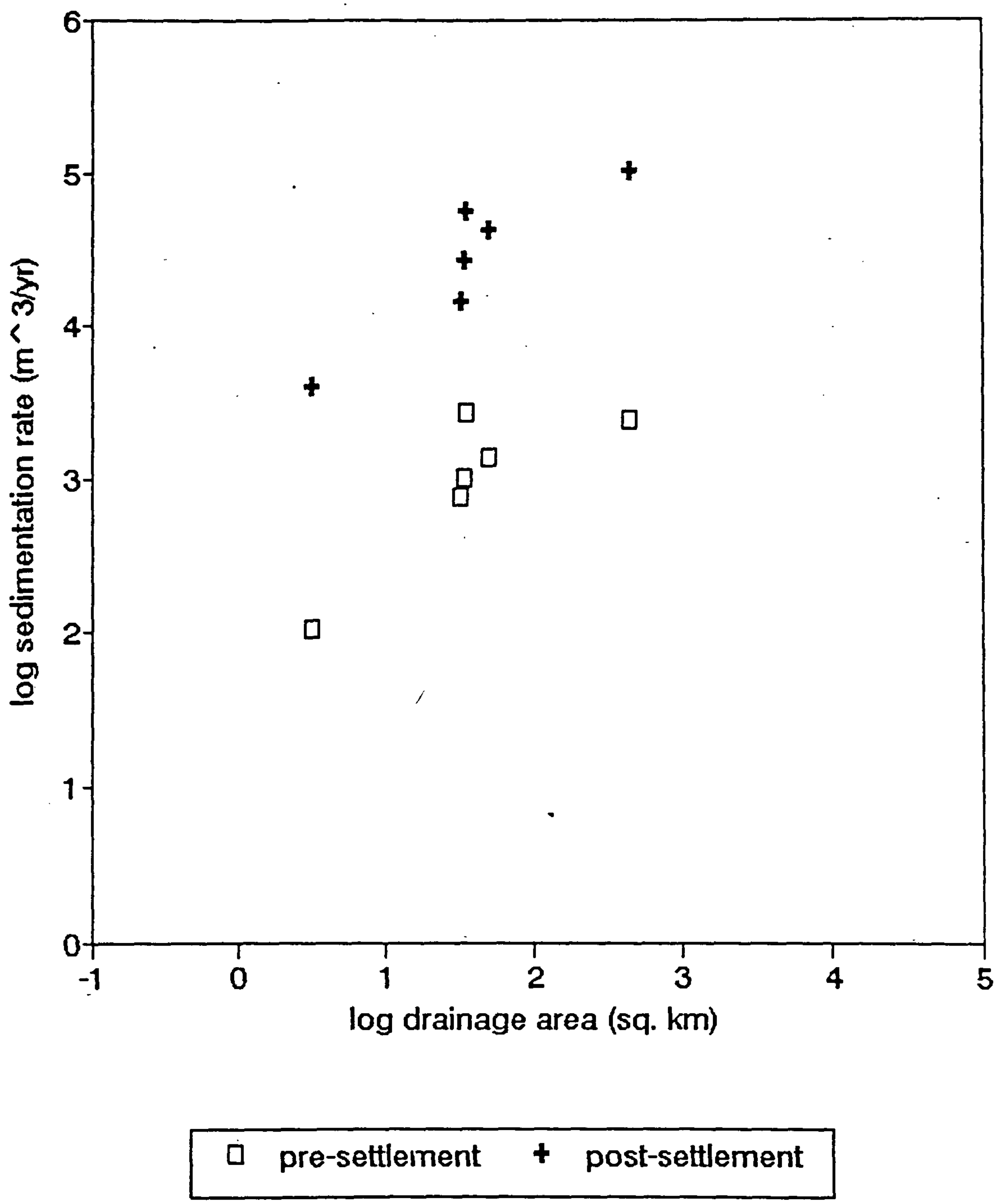


Figure 44. Comparison of pre-settlement sedimentation rates adjusted for compaction and post-settlement sedimentation rates for 6 natural Iowa lakes

## FINAL SUMMARY

1. Attempts to improve estimates of lake sedimentation rates are made using watershed characteristics. The classification of Iowa lakes by Land Resource Areas (LRA's), based on geology, compliments the established method used by the Army Corps of Engineers for estimating sedimentation rates of lakes with known drainage areas.

   The classification of lake watersheds according to Lara's hydrologic regions does not provide an improved method to estimate sedimentation rates. Flood discharges calculated for each hydrologic region using equations determined by Lara (1987) do not prove to be beneficial in forecasting lake sedimentation rates.

   The correlation of sedimentation rates and drainage areas using all 40 Iowa lakes provides a method to estimate sedimentation rates for lakes with known drainage areas.

   The classification of lakes according to major river basins (Missouri River and Mississippi River) does not improve the correlation of sedimentation rates and drainage areas.

   Basin morphology parameters of watershed shape ratio, drainage density, basin relief ratio, and ruggedness number do not provide improved methods to estimate sedimentation rates.

2. Sediment unit weights are studied to provide a more accurate method of estimating unit weights for dredging operations. Sediment unit weight data from 27 Iowa lakes show promising correlations between unit weight and LRA's. Lane and Koelzer's (1943) equation, using sediment particle size, overestimates sediment unit weights for 8 Iowa lakes. The relationship between sediment unit weight and sediment depth for Swan Lake is consistent with data from Sabetha Lake studied by Heinemann (1962). Sediment unit weights increase with depth to a depth of about 1.0 to 1.1 meters (3.3 to 3.5 feet) and remain relatively constant for depths greater than 1.1 meters (3.5 feet). Sediment unit weights remain constant with distance upstream from the dam for Black Hawk Lake and Union Grove Lake which is inconsistent with the results from Sabetha Lake (Heinemann, 1962), where sediment unit weights increase with distance upstream from the dam.
3. The analysis of historic sedimentation rates for Iowa's natural lakes reveals sedimentation rates are 15 to 30 times higher since 1870, the time Iowa is considered to have been extensively settled, than earlier sedimentation rates. Agricultural practices and bank erosion induced by settlement are believed to have greatly increased lake sedimentation.

## ADDITIONAL INFORMATION FOR FUTURE STUDIES

Future sedimentation studies of Iowa lakes may benefit from lake survey data in this thesis and lake survey data from 4 additional lakes not included in the thesis. The sedimentation of the 4 additional lakes could not by studied due to the lack of previous lake surveys. Iowa lakes with volume and date of the most recent lake survey are listed in Appendix D.

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# APPENDIX A: LARA'S FLOOD DISCHARGE EQUATIONS

Lara's regional flood-frequency equations (Table 2 from Lara, 1987).

Hydrologic region 1
(19 stations)

| Equation for indicated recurrence interval | Standard error (percent) |
|---|---|
| $Q_2 = 211A^{0.62}$ | 61 |
| $Q_5 = 502A^{0.60}$ | 37 |
| $Q_{10} = 757A^{0.60}$ | 28 |
| $Q_{25} = 1,140A^{0.57}$ | 24 |
| $Q_{50} = 1,500A^{0.60}$ | 21 |
| $Q_{100} = 1,880A^{0.60}$ | 24 |

Hydrologic region 2
(81 stations)

| Equation for indicated recurrence interval | Standard error (percent) |
|---|---|
| $Q_2 = 196A^{0.57}$ | 55 |
| $Q_5 = 402A^{0.55}$ | 39 |
| $Q_{10} = 570A^{0.55}$ | 34 |
| $Q_{25} = 821A^{0.54}$ | 32 |
| $Q_{50} = 1,020A^{0.53}$ | 33 |
| $Q_{100} = 1,230A^{0.53}$ | 36 |

Lara's regional flood-frequency equations (Table 2 from Lara, 1987).

**Hydrologic region 3**
**(119 stations)**

| Equation for indicated recurrence interval | Standard error (percent) |
|---|---|
| $Q_2 = 129A^{0.62}$ | 44 |
| $Q_5 = 265A^{0.59}$ | 36 |
| $Q_{10} = 381A^{0.57}$ | 35 |
| $Q_{25} = 555A^{0.55}$ | 37 |
| $Q_{50} = 695A^{0.54}$ | 39 |
| $Q_{100} = 851A^{0.53}$ | 41 |

**Hydrologic region 4**
**(24 stations)**

| Equation for indicated recurrence interval | Standard error (percent) |
|---|---|
| $Q_2 = 31A^{0.77}$ | 40 |
| $Q_5 = 67A^{0.72}$ | 33 |
| $Q_{10} = 98A^{0.70}$ | 31 |
| $Q_{25} = 145A^{0.68}$ | 29 |
| $Q_{50} = 180A^{0.66}$ | 30 |
| $Q_{100} = 227A^{0.65}$ | 30 |

Lara's regional flood-frequency equations (Table 2 from Lara, 1987).

**Hydrologic region 5
(8 stations)**

| Equation for indicated recurrence interval | Standard error (percent) |
|---|---|
| $Q_2 = 30A^{0.66}$ | 27 |
| $Q_5 = 37A^{0.71}$ | 21 |
| $Q_{10} = 41A^{0.74}$ | 20 |
| $Q_{25} = 45A^{0.77}$ | 24 |
| $Q_{50} = 47A^{0.79}$ | 24 |
| $Q_{100} = 50A^{0.80}$ | 26 |

# APPENDIX B: BASIN MORPHOLOGY AND DRAINAGE DENSITY DATA

## Slope Significant Test

A regression analysis and a slope significant test for the logarithm of sedimentation rate versus logarithm of drainage area for Missouri River basin lakes and Mississippi River basin lakes are performed. The regression analysis procedures are from Neville and Kennedy (1964).

1.) Obtain slope and intercept from regression analysis.
2.) Use the appropriate regression equation to estimate sedimentation rates for the lakes.
3.) Calculate the estimate of standard deviation for the sedimentation rates as follows:

$$S_y = \frac{(y_i - Y_i)^2}{\sqrt{n-2}}$$

where

$S_y$ ==> estimate of standard deviation for sedimentation rates

$y_i$ ==> logarithm of the measured sedimentation rates

$Y_i$ ==> logarithm of the calculated sedimentation rates

$n$ ==> number of lakes

4.) Calculate the estimate of standard deviation for the slope.

$$S_b = \frac{S_y}{\sqrt{\sum (x_i - X)^2}}$$

where

$S_b$ ==> estimate of standard deviation for the slope

$x_i$ ==> logarithm of the drainge area

X ==> mean value of the logarithm of drainage areas

5.) A t value from the t-distribution table is chosen according to degrees of freedom and confidence level.

6.) The confidence interval of the regression line slope is determined as followings:

$$b \pm tS_b$$

Results:

The slopes of the regression lines are significant at a 70% confidence level

Missouri River basin lakes: $0.832 < b < 1.048$

Mississippi River basin lakes: $0.669 < b < 0.827$

**No Classification of 40 Iowa Lakes Versus Classification According to Major River Basin**

Coefficients of correlation (R) from regression analysis:

No classification of lakes:

R = 0.91 (for all 40 Iowa lakes grouped together)

Classification of lakes according to major river basin:

R = 0.92 (for Missouri River basin lakes)

R = 0.91 (for Mississippi River basin lakes)

Table B-1. Watershed parameters measured for Iowa lakes

Missouri River basin lakes

| lake name | watershed shape ratio (1/km) | drainage density DD (km/sq.km) | basin relief ratio RR (%) | ruggedness number (RRxDD) |
|---|---|---|---|---|
| Allerton Reservoir | 0.239 | 0.88 | 0.35 | 9.1 |
| Centerville Res. #2 | 0.193 | 0.54 | 0.74 | 5.3 |
| Lake Icaria | 0.117 | 1.26 | 0.47 | 50.3 |
| Lake of Three Fires | 0.250 | 0.98 | 0.84 | 32.0 |
| Prairie Rose | 0.170 | 0.91 | 1.31 | 37.4 |

Mississippi River basin lakes

| lake name | watershed shape ratio (1/km) | drainage density DD (km/sq.km) | basin relief ratio RR (%) | ruggedness number (RRxDD) |
|---|---|---|---|---|
| Backbone Lake | 0.067 | 0.97 | 0.25 | 51.1 |
| Beeds Lake | 0.164 | 0.49 | 0.24 | 16.0 |
| Coralville Reservoir | ----- | ----- | 0.14 | ----- |
| Don Williams Lake | 0.146 | 0.30 | 0.18 | 6.4 |
| Lake Iowa | 0.283 | 0.67 | 1.38 | 14.1 |
| Lake John Deere | 0.428 | 0.45 | 0.94 | 6.2 |
| Lake Panorama | ----- | ----- | 0.13 | ----- |
| Lake Wapello | 0.157 | 1.01 | 0.97 | 31.1 |
| Lower Pine Lake | 0.280 | 1.22 | 0.39 | 51.7 |
| Springbrook Lake | 0.621 | 1.36 | 1.38 | 57.2 |
| Upper Pine Lake | 0.247 | 1.21 | 0.40 | 42.4 |
| Union Grove Lake | 0.167 | 0.89 | 0.59 | 24.7 |

Natural lakes (Mississippi River basin)

| lake name | watershed shape ratio (1/km) | drainage density DD (km/sq.km) | basin relief ratio RR (%) | ruggedness number (RRxDD) |
|---|---|---|---|---|
| Black Hawk Lake | 0.307 | 0.69 | 0.41 | 41.9 |
| Clear Lake | 0.056 | 0.16 | 0.34 | 1.1 |
| Five Island Lake | 0.067 | 0.17 | 1.04 | 4.0 |
| Silver Lake | 0.065 | 0.40 | 0.98 | 8.3 |
| Swan Lake | 0.445 | 0.78 | 1.26 | 13.8 |

## T-test for Watershed Shape Ratios

Watershed shape ratios for 5 Missouri River basin lakes and 10 artificial Mississippi River basin lakes are tested at a 70% confidence interval. The results are as follows:

Missouri River basin lakes:

$$0.165 < \text{watershed shape ratio} < 0.223$$

Mississippi River basin lakes:

$$0.199 < \text{watershed shape ratio} < 0.313$$

The watershed shape ratios are found not to be distinguished at a 70% confidence level by classifying lake watersheds according to major river basins.

# APPENDIX C: SEDIMENT UNIT WEIGHT DATA

Table C-1. Sediment particle size data for Iowa lakes

| lake name | boring number | approx. age of sed. (years) | dist. from dam (m) | % sand | % silt | % clay | Lane & Koelzer unit weight (kN/m ^ 3) | measured unit weight (kN/m ^ 3) |
|---|---|---|---|---|---|---|---|---|
| Black Hawk Lake | B1R | 25 | ----- | 5 | 64 | 31 | 10.62 | 7.01 |
| Black Hawk Lake | B1A | 25 | 30 | 18 | 52 | 30 | 11.06 | 8.36 |
| Black Hawk Lake | B2 | 25 | 823 | 0 | 63 | 37 | 10.27 | 5.08 |
| Black Hawk Lake | B2L | 25 | ----- | 0 | 55 | 45 | 10.01 | 5.19 |
| Black Hawk Lake | B3 | 25 | 1615 | 0 | 60 | 40 | 10.17 | 5.20 |
| Black Hawk Lake | B4 | 25 | 2256 | 5 | 51 | 44 | 10.20 | 5.37 |
| Black Hawk Lake | B4R | 25 | ----- | 23 | 56 | 21 | 11.51 | 13.07 |
| Black Hawk Lake | B5A | 25 | 2957 | 26 | 46 | 28 | 11.38 | 7.54 |
| Black Hawk Lake | B6 | 25 | ----- | 17 | 53 | 30 | 11.03 | 5.80 |
| Black Hawk Lake | PS-1 | 25 | 3505 | 6 | 50 | 44 | 10.23 | 5.39 |
| Black Hawk Lake | PS-2 | 25 | 4023 | 3 | 51 | 46 | 10.07 | 7.09 |
| Black Hawk Lake | PS-3 | 25 | 4206 | 5 | 61 | 34 | 10.52 | 8.06 |
| | | | | | | | | |
| Union Grove Lake | U-2 | 13 | 137 | 0 | 36 | 64 | 8.85 | 7.32 |
| Union Grove Lake | U-3 | 13 | 366 | 0 | 37 | 63 | 8.88 | 5.88 |
| Union Grove Lake | U-4 | 13 | 701 | 0 | 45 | 55 | 9.18 | 4.60 |
| Union Grove Lake | U-4W | 13 | ----- | 0 | 57 | 43 | 9.62 | 6.77 |
| Union Grove Lake | U-5 | 13 | 1006 | 0 | 52 | 48 | 9.44 | 7.39 |
| Union Grove Lake | U-5E | 13 | ----- | 0 | 40 | 60 | 8.99 | 6.73 |
| Union Grove Lake | U-6 | 13 | 1219 | 0 | 40 | 60 | 8.99 | 7.56 |
| Union Grove Lake | U-7 | 13 | 1524 | 0 | 57 | 43 | 9.62 | 7.57 |

Table C-2. Sediment particle size data for Iowa lakes

| lake name and boring number | | approx. age of sed. (years) | % sand | % silt | % clay | Lane & Koelzer unit weight (kN/m^3) | measured unit weight (kN/m^3) |
|---|---|---|---|---|---|---|---|
| Lake Panorama | B-4 | 10 | 48 | 34 | 18 | 12.09 | 13.86 |
| Lake Panorama | B-3, S-2 | 10 | 0 | 45 | 55 | 8.98 | 7.01 |
| Lake Panorama | B-2, S-3 | 10 | 0 | 30 | 70 | 8.39 | 7.48 |
| Lake Panorama | B-2, S-2 | 10 | 0 | 56 | 44 | 9.40 | 8.85 |
| Lake Panorama | B-1 | 10 | 0 | 30 | 70 | 8.39 | 10.15 |
| Lake Panorama | B-6 | 10 | 10 | 59 | 31 | 10.26 | 7.06 |
| Lake Panorama | B-7 | 10 | 0 | 63 | 37 | 9.67 | 7.89 |
| Lake McBride | 55 | 4 | 1 | 72 | 27 | 9.57 | 9.27 |
| Lake McBride | 56 | 4 | 3 | 72 | 25 | 9.74 | 9.27 |
| Lake McBride | 57 | 4 | 2 | 77 | 21 | 9.88 | 9.74 |
| Lake McBride | 58 | 4 | 4 | 76 | 20 | 10.00 | 8.80 |
| Lake McBride | 59 | 4 | 1 | 82 | 17 | 10.02 | 9.43 |
| Lake Wapello | | 22 | 2 | 40 | 58 | 9.55 | 5.11 |
| Don Williams Lake | | 7 | 10 | 56 | 34 | 9.93 | 5.44 |
| Springbrook Lake | | 22 | 4 | 52 | 44 | 10.08 | 7.53 |
| Lower Pine Lake | #1 | 55 | 6.3 | 73. | 20. | 11.40 | 10.98 |
| Lower Pine Lake | #2 | 55 | 54.4 | 32. | 13 | 12.97 | 14.08 |
| Lower Pine Lake | #3 | 55 | 50.6 | 33. | 16 | 12.78 | 11.88 |

# APPENDIX D: LAKE SURVEY DATA FOR FUTURE SEDIMENTATION STUDIES

Table D-1. Recent Iowa lake survey data

| lake name | date of most recent lake survey | surface area (hectares) | net drainage area (sq. km) | most recent volume (cubic meters) |
|---|---|---|---|---|
| Allerton Reservoir | 1939 | 41.4 | 12.5 | 494,830 |
| Backbone Lake | 1949 | 50.6 | 316.7 | 583,680 |
| Beeds Lake | 1979 | 42.9 | 81.8 | 1,066,180 |
| Black Hawk Lake | 1981 | 323.0 | 48.7 | 4,787,920 |
| Bloomfield | 1951 | 31.1 | 5.5 | 1,025,450 |
| Centerville Res. #2 | 1937 | 20.7 | 6.8 | 1,295,700 |
| Clear Lake | 1971 | 1,474.3 | 35.5 | 42,955,540 |
| Coralville Reservoir | 1975 | 1,983.0 | 7900.0 | 49,730,200 |
| Don Williams Lake | 1980 | 61.5 | 83.7 | 3,104,740 |
| Five Island Lake | 1970 | 401.1 | 34.1 | 4,221,510 |
| Honey Creek No. F-1 | 1961 | 3.4 | 3.1 | 220,890 |
| Jones Creek Reservoir | 1953 | 7.8 | 5.8 | 245,810 |
| Lake Iowa | 1988 | 34.0 | 5.4 | 1,187,110 |
| Lake John Deere | 1988 | 5.0 | 3.4 | 146,850 |
| Lake of Three Fires | 1950 | 39.3 | 15.5 | 1,061,240 |
| Lake Panorama | 1980 | 566.6 | 1139.6 | 17,299,450 |
| Lake Wapello | 1982 | 115.3 | 20.2 | 4,586,780 |
| Little Wall Lake (Hamilton Co.) | 1991 | 101.6 | 0.7 | 1,655,000 |
| McFarland (Story Co.) | 1975 | 2.7 | 1.7 | 68,000 |
| Prairie Rose Lake | 1985 | 88.2 | 18.5 | 1,890,490 |
| Red Rock Reservoir | 1984 | 4,208.9 | 15695.9 | 62,563,800 |
| Schley Park (Harrison Co.) | 1969 | 2.3 | 1.0 | 65,280 |
| Silver Lake | 1973 | 269.9 | 32.4 | 3,814,290 |
| Springbrook Lake | 1980 | 6.9 | 4.9 | 140,180 |
| Swan Lake | 1980 | 52.6 | 3.1 | 682,400 |
| Tuttle Lake | 1973 | 1,139.6 | 444.4 | 10,497,640 |
| Upper Pine Lake | 1990 | 23.9 | 35.7 | 673,150 |
| Volga Lake (Fayette Co.) | 1983 | 54.6 | 24.7 | 1,801,640 |