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DISTRICT-WIDE WATER RESOURCES INVESTIGATION
AND MANAGEMENT USING LANDSAT DATA

PHASE 1: LAKE VOLUME - DSR#81006cg-1

Final Report

by

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15. Abstract

The severe drought experienced in Central Florida throughout most of 1981 brought increased attention to the long recognized problem of fresh water availability across the State.

During drought conditions, a close watch is maintained over all water supplies. This is most commonly done through monitoring water stage, the water height above sea level. Although water stage is an important indicator, water storage volume is a more critical paramter. Volume can only be obtained if accurate data exists as to the lake contours in conjunction with water stage.

The University of Florida, in cooperation with the St. Johns River Water Management District, and Kennedy Space Center developed a technique using Landsat data for estimating available water storage volume and applied it successfully to Lake Washington and Lake Harris in central Florida.

The technique is discussed in this study and can be applied two ways. First, where the historical stage records are available, the historical Landsat data can be used to establish the relationship between lake volume and lake stage. In the second case, where the historical stage records are not available, the historical

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VOLUME DETERMINATION OF THE LAKE WASHINGTON AND LAKE HARRIS.

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EXECUTIVE SUMMARY

The severe drought experienced in Central Florida throughout most of 1981 brought increased attention to the long recognized problem of fresh water availability across the State. Much of the state's fresh water supply is obtained from groundwater storage and natural lakes. Many of these lakes reached record and near-record low levels during late summer of 1981 and forced the imposition of the restricted water use practice for individual households and municipal supplies as well as agricultural irrigation.

Management of water resources in Florida is the responsibility of Florida's five Water Management Districts. Especially during drought conditions, a close watch is maintained over all water supplies. This is most commonly done through monitoring water stage, the water height above sea level. Although water stage is an important indicator, water storage volume is a more critical parameter. Volume can only be obtained if accurate data exists as to the lake contours in conjunction with water stage. Such data rarely exists because of the extensive time and cost associated with conventional transect survey methods of collecting such data and the fact that they are subject to change over extended periods of time.

The University of Florida, in cooperation with the St. Johns River Water Management District, and Kennedy Space Center developed a technique using Landsat data for estimating available water storage volume and applied it successfully to Lake Washington and Lake Harris in central Florida. A number of Landsat scenes including the lakes of interest were selected to correspond with a wide range of lake stages as measured over the past nine years. Lake surface area was then measured from the Landsat data, and when properly averaged, was used with the change in lake level to estimate the change in lake volume. Thus, a change in lake stage can be directly correlated with available water volume.

Eight cloud free dates were chosen for Lake Washington, Florida. The lake stages on those dates were recorded. The dates were rearranged in order of increasing lake stage. The water surface was measured from Landsat along with the lake stage that ranged from 10.60 to 15.85 ft. (msl). The results indicated that the water surface varied from 2,537 acres at the stage 10.60 ft. to 2,850 acres at the stage 15.85 ft. The ground truth measurement of water surface around the stage 15.85 ft was 2848 acres which was very close to 2850 acres, the area estimated by the Landsat system at the stage 15.85 ft. The difference was negligible. This implies that the technique developed in this study is quite applicable to measure the water surface area of the lake. The lake volume between two stages was computed from the average area between the stages multiplied by the stage increment. The lake volume between the stages 10.60 and 15.85 ft is about 14,352 acre-ft. The lake volume ranged from 26 to 28 acre-ft. for each 0.01 ft. increment in lake stage.

Four cloud free dates were chosen for Lake Harris, Florida. The similar techniques as used in Lake Washington were applied to Lake Harris for measuring the lake water surface area. The results indicated that the water surface varied from 17,430 acres at the stage 62.38 ft (msl) to 18,657 acres at the stage 63.30 ft. The lake volume between the stages 62.38 ft. and 63.30 ft. was about 16,682 acre-ft. The lake volume ranged from 176 to 183 acre-ft. for each 0.01 ft. change in lake stage.

The rates of change in lake volumes in relation to lake stage increments are quite stabilized in both lakes. This implies that the lake volume at other stages could be roughly estimated based on the lake volume increment relation obtained in this study.

The key element in this approach, i.e. the lake surface measurement from Landsat was accomplished by density slicing in the near infrared-band 7. For lakes having shallow depths and marshy shores as represented here, such measurements are highly sensitive to the upper limits chosen for band 7. The upper limit of 25 was selected in this study.

The technique developed in this study can be applied two ways. First, where the historical stage records are available, the historical Landsat data can be used to establish the relationship between lake volume and lake stage. In the second case, where the historical stage records are not available, the historical Landsat data can be used to estimate the historical lake stage after the lake volume and lake stage information becomes available in the future.

General information on Landsat remote sensing system is presented in Appendix A in this report. Computerized methods used for bounded area and weighted sub-area computation are presented in Appendix B.

INTRODUCTION

Florida Legislature passed the Florida Water Resources Act of 1972, which established five Water Management Districts in the state of Florida and required that each district should develop a Water Use and Supply Development Plan that would take into account all factors involved up through the year 2020. To meet the mandate of this legislation the districts have to use every available technology and are looking toward National Aeronautics and Space Administration (NASA) remote sensing and Automatic Data Process (ADP) techniques for major help in solving the complex problems. Even though NASA is presently involved in considerable research in the area of water resources, much of this work cannot be directly applied to the problems of the area. For instance, the geology of the district with its sandy soil, shallow lakes, and large flat marshland areas make the storage of adequate surface water difficult. These water conditions not only can produce severe water shortages during the winter dry season which coincides with a period of high agricultural water demand, but also can cause an acute problem of flooding during wet season. For instance, the severe drought experienced in Central Florida throughout most of 1981 and the beginning of 1982 brought increased attention to the long recognized problem of fresh water availability across the State. Much of the state's fresh water supply is obtained from groundwater storage and natural lakes. Many of these lakes reached record and near-record low levels during late summer of 1981 and forced the imposition of the restricted water use practice for individual households and municipal supplies as well as agricultural irrigation.

A typical basin in central Florida is the St. Johns River basin (as shown in Figure 1) which encompasses approximately 11,430 square miles. The river rises in poorly defined marshland west of Fort Pierce and Vero Beach in east central Florida. It flows northward, roughly parallel to Florida's east coast for 285 miles before merging into the Atlantic Ocean just north of Jacksonville. Management of water resources in St. Johns River basin is the responsibility of St. Johns River Water Management District (SJRWMD). A close watch is maintained over all water supplies, especially during drought conditions. This is most commonly done through monitoring water stage, the water height above sea level. Although water stage is an important indicator, however, water storage volume is a more critical parameter for precise assessment of available water. Volume can only be obtained if accurate data exists as to the lake contours in conjunction with water stage. Such data rarely exists because of the extensive time and cost associated with conventional transect survey methods of collecting such data and the fact that they are subject to change over extended periods of time. Therefore, the management of water within the basin poses many unique and difficult problems that warrant the use of recently developed Landsat remote sensing techniques to help the district make realistic decisions concerning water resources planning and management.

The University of Florida, in cooperation with the St. Johns River Water Management District, and NASA, Kennedy Space Center initiated a joint project to deal with the district-wide Water Resources Investigations and Management using Landsat Data. The Phase I of this study includes the lake volume determination. Recently, applications of Landsat data to determine the lake volume in Lake Okeechobee have been done by Shih (1980), and Gervin and Shih (1981). The basic technique used in their study was to analyze the digital data from the Landsat earth-orbiting satellite by using the General Electric's multispectral image analyzer, the Image 100. In typical classification analysis, an area where land cover is known from ground observations is located as a training site on the image and its spectral characteristics are measured. Then all areas which have similar spectral characteristics are identified and assigned a color and a number code. The similar spectral characteristics are referred to as the signature for that land cover type and the location of the color-coded pixels possessing that signature is displayed on the CRT screen as a theme. Once the signature is finalized, the pixels (picture elements) in the satellite scene which posses that signature (theme) can be counted. Thus, the area of that signature is obtained. A more detailed description of the Landsat data analysis was presented by Gervin and Shih (1981). The general information on Landsat remote sensing systems is presented as Appendix A in this report. However, the previous studies required some ground truths of the vegetation classification before a proper area could be estimated from each signature. In other words, the sole band which can be used to identify the land-water boundaries directly without the ground truth information was not emphasized well previously. Therefore, in this study, the image enhancement of sole band with density slicing technique was used to determine the lake water surface area.

In developing a new technique to be used for Landsat remote sensing application, a groundtruth calibration is an important procedure to demonstrate the applicability of the new technique. Thus, computerized methods [illegible] area and weighted sub-area computation were also presented in this study.

The general objective of this study was to demonstrate the application of Landsat remote sensing techniques for determining the lake volume of Lake Washington (Figure 2), and Lake Harris (Figure 3). The specific objectives were:

1) to introduce the general information on Landsat remote sensing systems;
2) to introduce computerized methods used for surface area and sub-area computation;
3) to develop a new method used to compute water surface area from the Landsat data; and
4) to discuss the applicability of the new developed method for lake volume determination using Landsat data.

MATERIALS AND METHODS

Two aspects are involved in this section: remote sensing techniques and groundtruth calibration.

Remote Sensing Techniques

Landsat Remote Sensing Systems: The general information on Landsat remote sensing system is presented as an Appendix A in this report. Nine sections comprise Appendix A: 1) introduction to Landsat Remote Sensing System; 2) Sensor, Band Designation, Wavelength, and Resolution which include the Return-Beam Vidicon (RBV) Camera, Multispectral Scanner System (MSS), and Thematic Mapper (TM); 3) Ground Receiving Stations; 4) General Electric "Image 100" System; 5) United States Distribution Center; 6) The Northeast Regional Data Center, Florida; 7) University of Florida, IFAS Remote Sensing Facilities; 8) Landsat Newsletters; and 9) Landsat Update Information.

As mentioned in Appendix A, Landsat passed over the same swath (185 km wide) of the ground every 18 days during the period from January 23, 1972 to January 22, 1975, after that the coverage period was 9 days except during the period between January 6 and March 5, 1978 when the operation of Landsat 1 was ended and the Landsat 3 was not launched as yet. Among the sensors of Landsats 1, 2, and 3, Multispectral Scanner Systems (MSS) have provided the remote sensing community with a preview of what to expect from an operational remote sensing satellite. Certainly, the MSS system is going to be replaced by the Thematic Mapper system on Landsat 4 system. The MSS systems on Landsats 1, 2, and 3 are operated on bands 4, 5, 6, and 7 and another band 8 is also operated in Landsat 3. The Thematic Mapper systems on Landsat 4 are operated on bands 1, 2, 3, 4, 5, 6, and 7. The Landsat 4 is planned to be launched during the summer of 1982.

Before 1979, the Landsat data was stored on computer compatible tape (CCT) which was produced at the Goddard Space Flight Center Image Processing Facility from wideband videotape recordings received by stations of the Satellite Tracking and Data Network. The image data are reformated on high density digital tape. Since 1979, a new system has been operated to shorten the processing time. The user can have the tapes from the User Services Section, U.S. Geological Survey, Earth Resource Observation System Data Center, Sioux Falls, South Dakota, 57198 and the organizations mentioned in the Appendix A.

As the Landsats have been in operation for more than nine years, a large amount of data has been accumulated on the Lake Washington and Lake Harris. In order to save image analyzing time, selection of useful tapes is necessary. The procedure to pick up useful tapes can be summarized as follows:

1. Calculate the date of which Landsats flew over the Lake Washington. and Lake Harris.
2. Pick up the cloud free days from the dates obtained in the previous step by consulting meteorology.
3. Pick up the various dates, when the water level is distributed from low to high levels. In this step, for a given observation date the lake water stage is required.

Using Landsat Data for Water Surface Area Measurements. As mentioned in the Appendix A, the characteristics of band 7 provide best penetration through haze and light clouds and it also emphasizes live vegetation and land-water boundaries. For these reasons, band 7 was chosen in this study for the lake water surface area measurement.

The Landsat high density digital tapes of the chosen dates for the Lake Washington and Lake Harris were analyzed on General Electric's multispectral image analyzer, the Image 100. The Image 100 consists of two tape drives, for inputting and outputting data; a color CRT screen which displays $(512)^2$ pixels of digital data; a memory for storing and refreshing the displayed image, and a battery of programs capable of measuring, manipulating and highlighting the satellite data. Because the spectral characteristics of a water body, vegetations and ground are different, each characteristic can be identifiea and assigned a color and a number code. The spectral characteristics are referred to as the signature for the land cover type and the location of those color-coded pixels possessing that signature is displayed on the CRT screen (or mapped on paper) as a theme. Once the signature is finalized, the pixels in the satellite scene which possess that signature (theme) can be counted. In this way, maps and tabulations of areas that have similar spectral properties can be obtained.

The key element in this approach, lake surface measurement from Landsat was accomplished by density slicing in the near infrared band 7. The density slicing is a procedure used to carry out the enhancement of the remote sening data. The density slicing is a digital approach which has the advantage of flexibility. Any level or levels of grey may be selected on a photographic or electrical imprint, with output via a line printer, on a flat-bed or drum plotter, or directly onto a photographic film writer, CRT screen. Quantization noise or spurious contouring may result if the slices are not chosen carefully. For lakes having shallow depths and marshy shores as represented here, such measurements are highly sensitive to the upper limits chosen for band 7. The upper limit of 25 was selected in this study.

Lake Volume Computation: After lake water surface area was estimated by Landsat data, the following equation was used to calculate the increase in lake volume associated with a small increase in lake stage:

$$V_{s+1} = V_s + \Delta h \, [(A_s + A_{s+1})/2] \qquad (1)$$

where V_{s+1} = lake storage volume at lake stage s + 1 in acre ft;

V_s = lake storage volume at lake stage s, in acre-ft;

A_{s+1} = lake surface area at lake stage s + 1 in acres as measured by Landsat data;

A_s = lake surface area at lake stage s as measured by Landsat data, in acres; and

Δh = the range between lake stages.

Because of the initial lake volume at s=1 is unknown, the V_1=C is used, where C is a constant.

Ground Truth Measurement

A contour map provided by the St. Johns River Water Management District was used to compute the surface area. A computerized method as presented in Appendix B was used to compute the ground truth area measurement. In order to explore further potential applications of computerized methods for bounded area and weighted sub-area computations the detailed computer programs for each method are also presented as an Appendix B in this report.

RESULTS AND DISCUSSION

Dates Selection

As presented in the previous section, three step procedures were used to select cloud free dates associated with a wide range of lake stage fluctuations for areas of Lake Washington and Lake Harris, Florida. The results for selected eight cloud free dates of 9/6/72, 11/29/73, 2/27/74, 3/17/74, 6/15/74, 10/19/74, 2/9/76 and 4/11/76 were used for Lake Washington and those used for Lake Harris were taken from four cloud free dates of 9/6/72, 8/31/75, 2/14/75 and 1/22/76. The lake stages on those dates were also recorded.

Area Measurement

Lake Washington: The dates were rearranged as shown in Table 1 in the increasing order of the lake stage. The Lake Washington water surface area at those eight dates was estimated from the Image 100 after density slicing of the band 7 was done and a theme for the lake water surface was assigned. A typical color-coded classification result of water surface area for the Lake Washington on date 10/19/74 is shown in Figure 4. The results of water surface area estimated by Landsat data on those eight dates are shown in Table 1. The surface area varied from 2,537 acres at the stage of 10.60 ft above mean sea level to 2,850 acres at the stage 15.85 ft. The stages are plotted against the water surface area as shown on Figure 5 which can be used to estimate the surface area associated with any stage between the measurements. For instance, the surface area is 2816 acres when the stage is 14.6 ft.

The ground truth measurement was made from the contour map provided by the District using the computerized method as given in the attached Appendix B. The computed value was 2,848 acres around the stage 15.85 ft. This is slightly lower than 2,850 acres as estimated from the Landsat data. The difference seems to be negligible in practical application. Furthermore, Connor and Belanger (1981) reported that the Lake Washington water surface area was 2,851 acres at the stage 14.6 ft. But, the surface area estimated from the Figure 5 is 2816 acres at the same stage of 14.6 ft. The difference is about 1.2%. This difference is hard to explain due to the lack of details associated with the area computation method used by Connor and Belanger (1981). However, this 1.2% difference is considered within limits of an acceptable deviation from the standpoint of practical application.

Lake Harris: The dates were rearranged as shown in Table 2 in the increasing order of the lake stage. The water surface area at those four dates was estimated from the Image 100 using the same procedure as used for Lake Washington. A typical color-coded classification result of water surface area for the Lake Harris on date 1/22/76 is shown in Figure 6. The results of water surface aréa estimated by Landsat data on those four dates are shown in Table 2. The surface area varied from 17,430 acres at the stage of 62.38 ft above the mean sea level to 18,657 acres at the stage 63.30 ft. The stages are plotted against the water surface area as shown in Figure 7. As Figure 7 shows, the range of stage fluctuation during the study period was only about 1 foot. This was mainly because the stages of Lake Harris are regulated well by the St. Johns River Water Management District.

Storage Volume Determination

Lake Washington: The volume of lake was computed based on the method given in equation 1. The initial volume of lake at the stage 10.60 ft was not available. A constant volume designated as "C" was used as a lake volume below the stage of 10.60 ft. The volume increments at each stage of measurement were estimated. The results of the computed volumes are also shown in Table 1. The volume between the stages 10.6 and 15.85 ft was about 14,352 acre-ft. The lake volumes associated with each 0.01 ft lake stage increment are also listed in Table 1. The lake volume changes ranged from 26 to 28 acre-ft for each 0.01 ft increment in lake stage. The rate of change in Lake Washington volume in relation to lake stage increments appears to be a stablized condition. This implies that the lake volume at other stages including stages below 10.60 ft, or above

15.85 ft could be roughly estimated based on the lake volume stage increment relation obtained in this study. The computed lake volumes are also plotted against the lake stages as shown in Figure 8. This figure can be used to estimate the surface area associated with any specified lake stage between the measurements.

Lake Harris: The same technique used in Lake Washington was also used in Lake Harris. A constant volume designated as "C" was used as a lake volume below the stage of 62.38 ft. The volume increments at each stage of measurement were computed based on the method given in equation 1. The results of the computed volume, and the lake volume associated with each 0.01 ft lake stage change are also listed in Table 2. The lake volume increment ranged from 176 to 183 acre-ft per 0.01 ft change in lake stage. This rate of change is considered to be quite a stablized condition and can be used to estimate the lake volumes for other stages including those below 62.38 ft, or above 63.30 ft. The computed lake volumes were also plotted against the lake stages as shown in Figure 9 which can be used to roughly estimate the lake volume associated with any specified lake stage between the measurements.

Further Applications

Based on the conclusions made from previous sections, the technique developed in this study can be further applied in the following two cases. First, when the historical stage records are available, the historical Landsat data can be used to measure the water surface area associated with a certain stage recorded. Consequently, the relationship between lake surface area and lake stage can be established. The lake volume as related to the lake stage can also be estimated. Thus the district can directly correlate change in lake stage with the available water volume. Second, the technique can be applied to the case where historical stage records are not available, but the current stage record is available or will be available in the future. The same technique as used in case 1 can be used to estimate both lake water surface area and lake volume as related to the lake stage based on the current and future Landsat data and stage records. Thus, the historical lake stage and lake volume can be predicted based on the historical lake water surface area which was estimated from the historical Landsat data.

Finally, an important action needs to be taken by the district is to establish a stage recorder for the lake that does not have any stage information. Thus, the application in above case 2 can be accomplished after the stage data is recorded.

REFERENCES

1. Connor, J.N. and T.V. Belanger. 1981. Groundwater seepage in Lake Washington and the Upper St. Johns River Basin, Florida. Water Resources Bulletin. Vol. 17(5):798-805.

2. Gervin, J.C. and S.F. Shih, 1981. Improvements in lake volume prediction using Landsat data. In:Satellite-Hydrology, Am. Water Resources Association.

3. Shih, S.F. 1980. Use of Landsat data to improve the water budget computation in Lake Okeechobee, Florida. Journal of Hydrology, Vol. 48:237-249.

Table 1. Lake Washington volume computation based on the water surface area measured from eight dates of Landsat data.

Date	Water stage	Water surface area	Lake Volume: Different stages	Lake Volume: 0.01 ft increment
	--ft--	----Acre----	-------Acre	ft-------
6/15/74	10.60	2,537	C*	
				26
4/11/76	11.81	2,670	C+3,150	
				27
2/9/76	12.06	2,683	C+3,819	
				27
3/17/74	12.45	2,705	C+4,870	
				27
2/27/74	12.75	2,729	C+5,685	
				28
9/6/72	14.80	2,819	C+11,372	
				28
11/29/73	14.84	2,827	C+11,482	
				28
10/19/74	15.85	2,850	C+14,352	

* C is a constant volume below the stage of 10.60 ft.

Table 2. Lake Harris volume computation based on the water surface measured by four dates of Landsat data.

Date	Water stage	Water surface area	Lake Volume: Different stages	Lake Volume: 0.01 ft increment
	--Ft--	---Acre---	-------Acre ft-------	
9/6/72	62.38	17,430	C*	
				176
8/31/75	62.50	17,724	C+2,109	
				178
2/14/75	62.66	17,963	C+4,964	
				183
1/22/76	63.30	18,657	C+16,682	

*C is a constant volume below the stage of 62.38 ft.

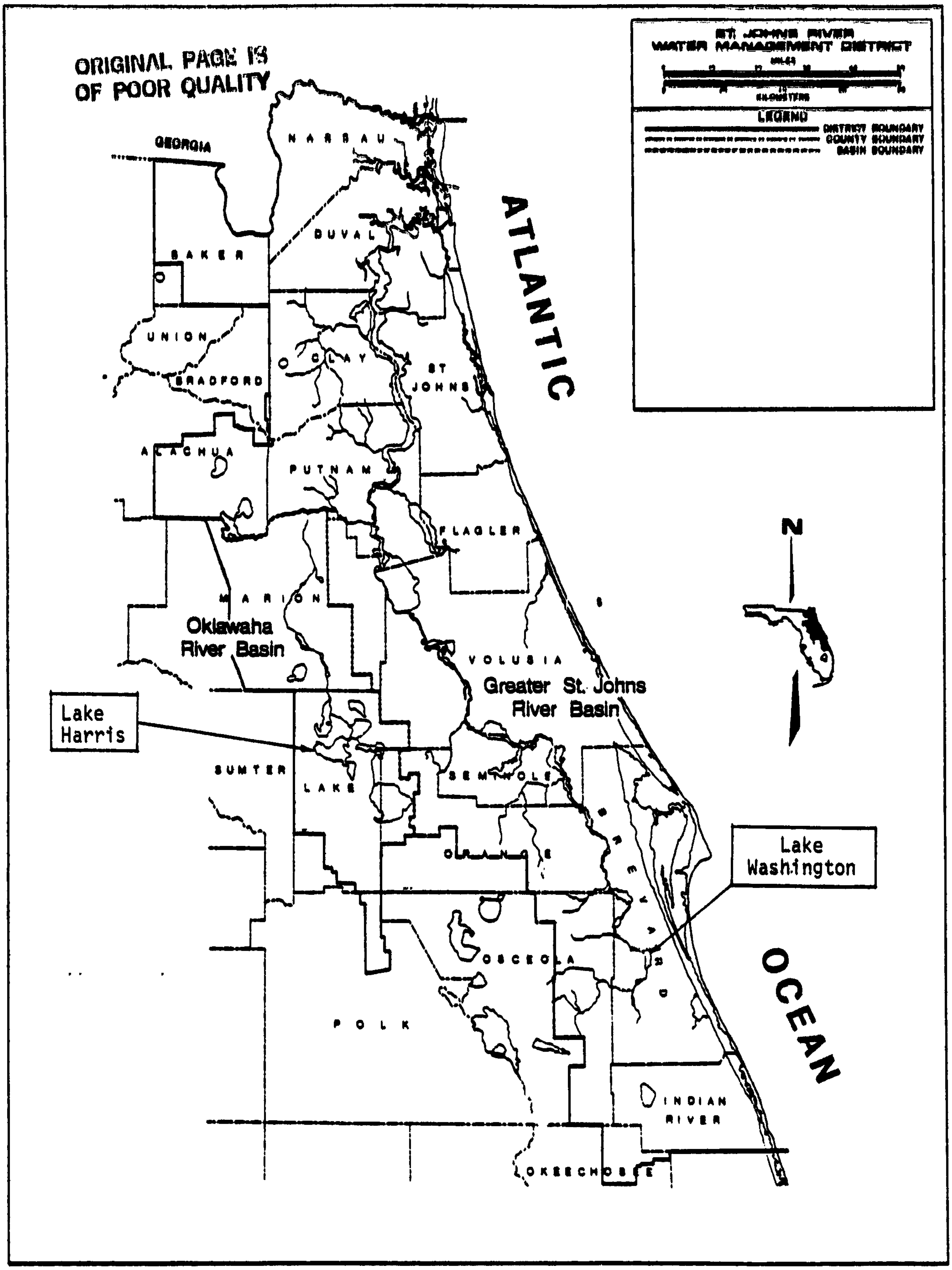

Figure 1. St. Johns River Water Management District

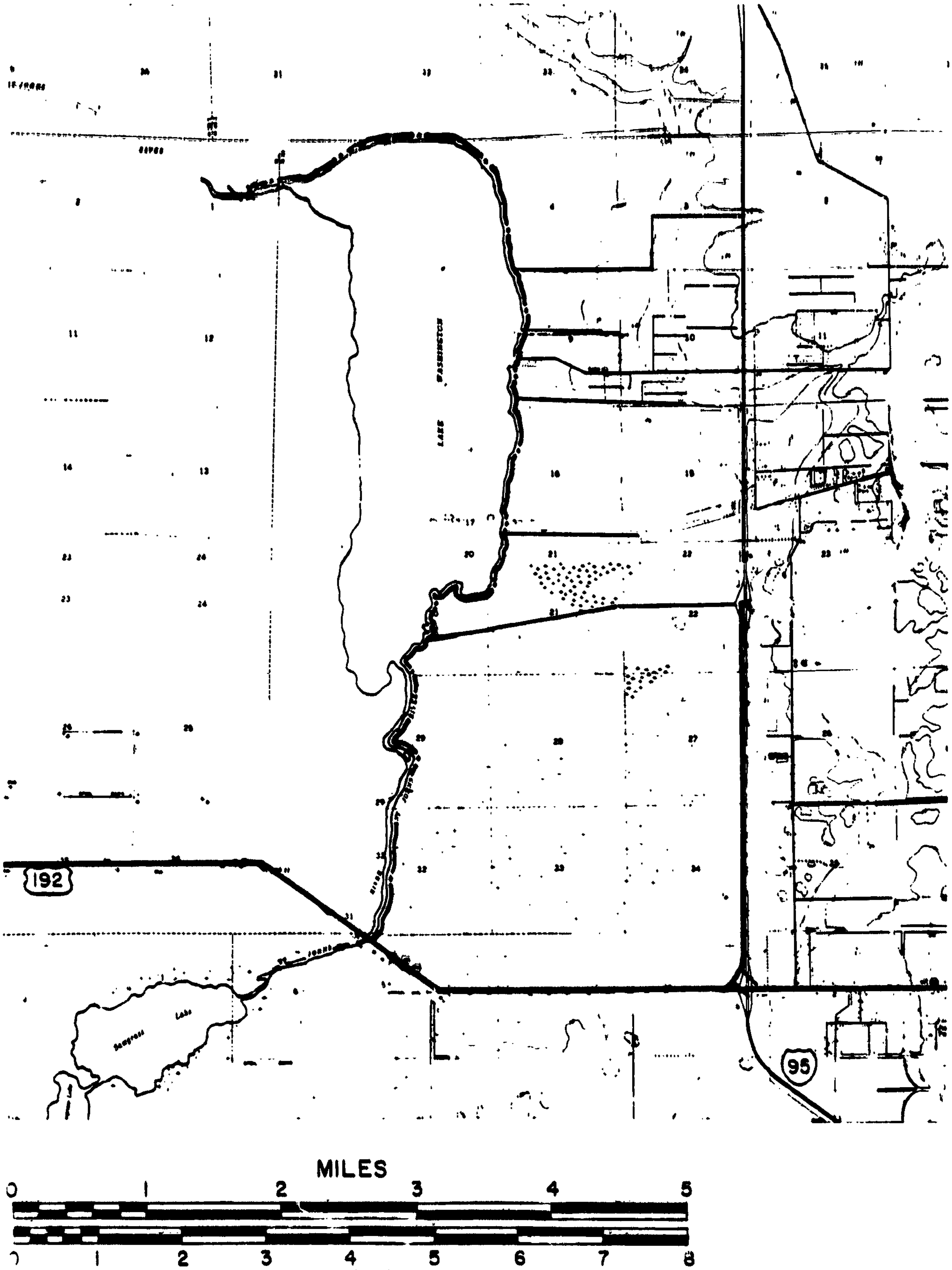

Figure 2. Map of Lake Washington Site.

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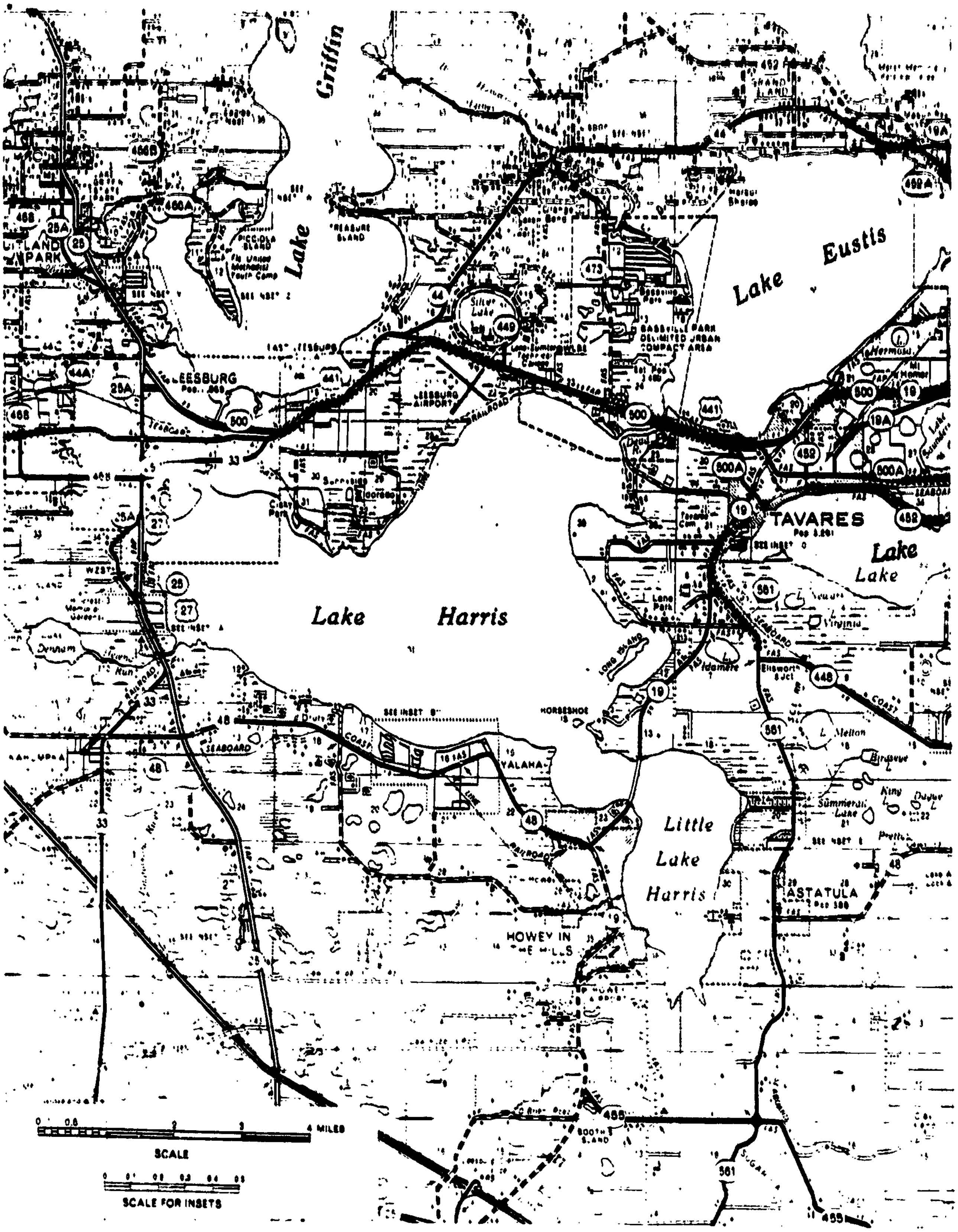

Figure 3. Map of Lake Harris site.

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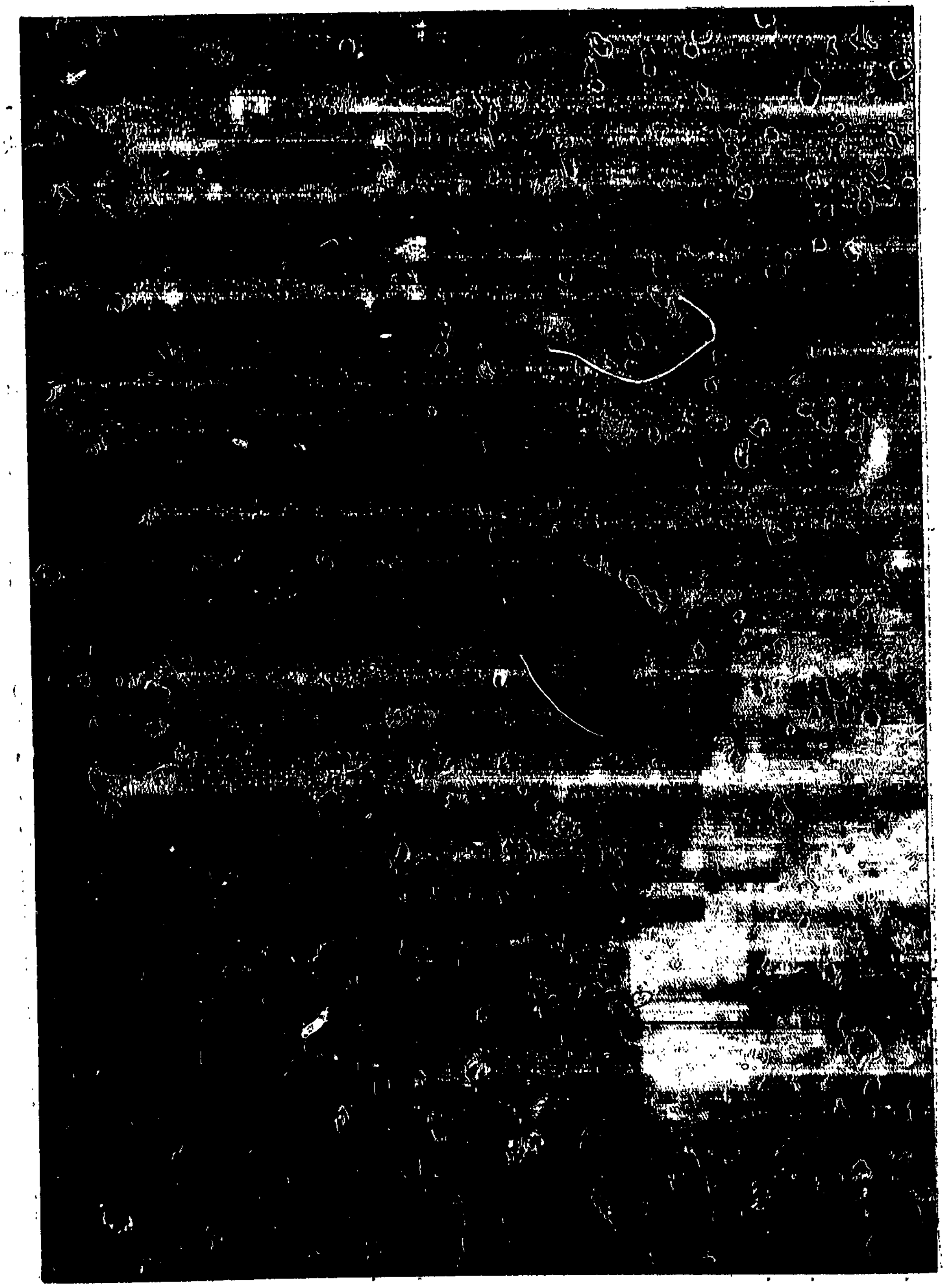

Figure 4. Color-coded classification result of water surface area for Lake Washington, Florida on October 19, 1974.

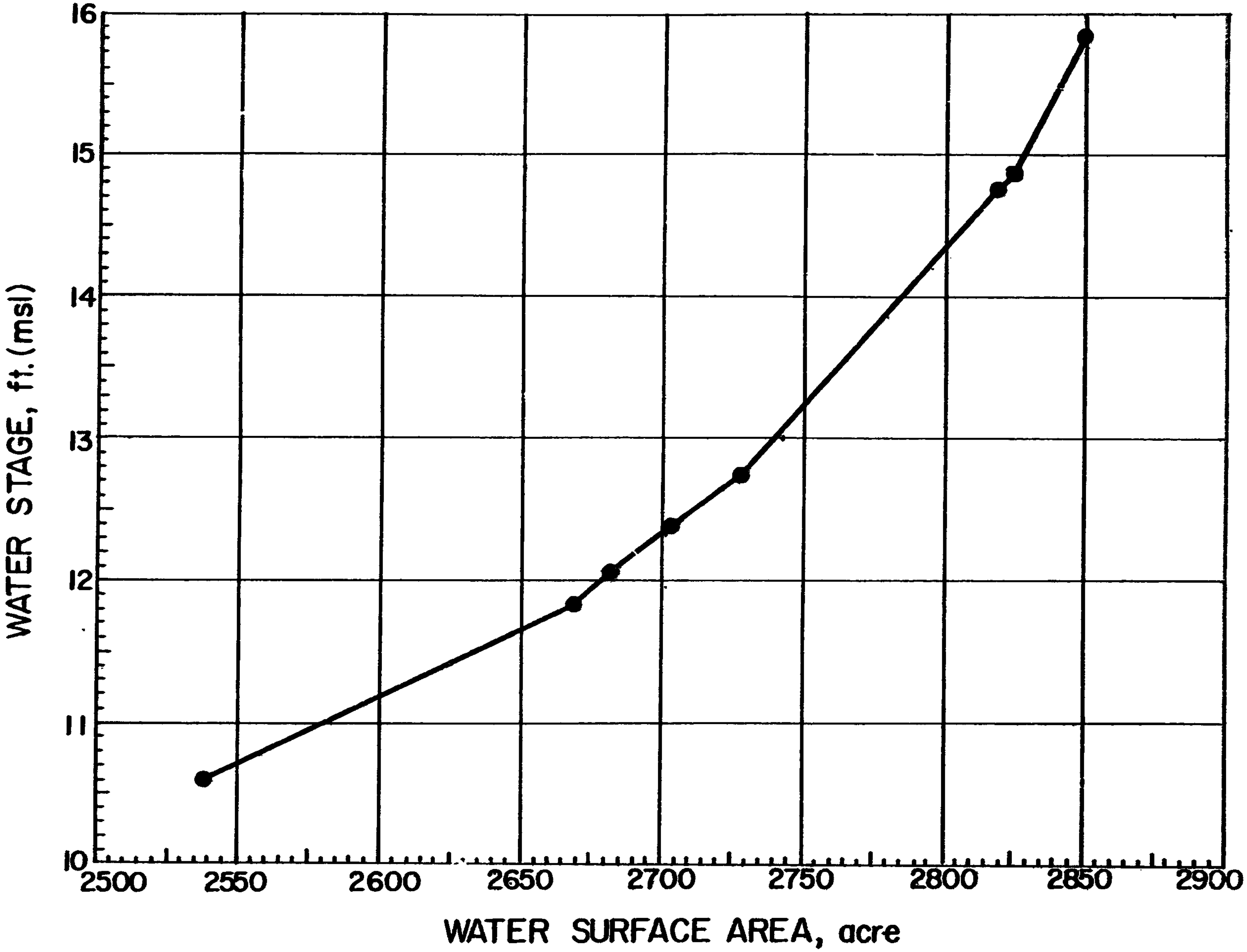

Figure 5. Relationship between water stage and water surface area for Lake Washington estimated from Landsat data.

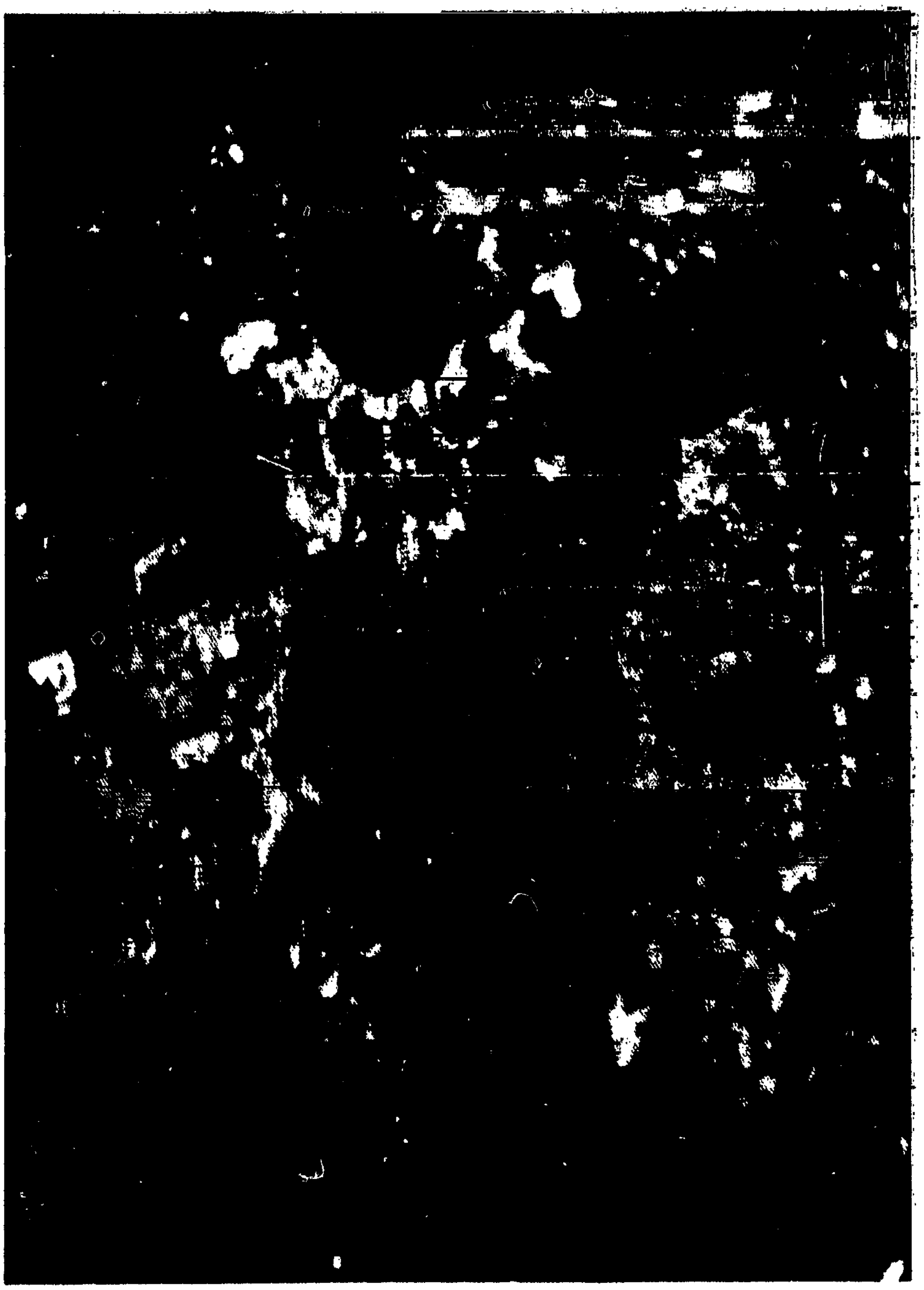

Figure 6. Color-coded classification result of water surface area for Lake Harris, Florida on January 22, 1976.

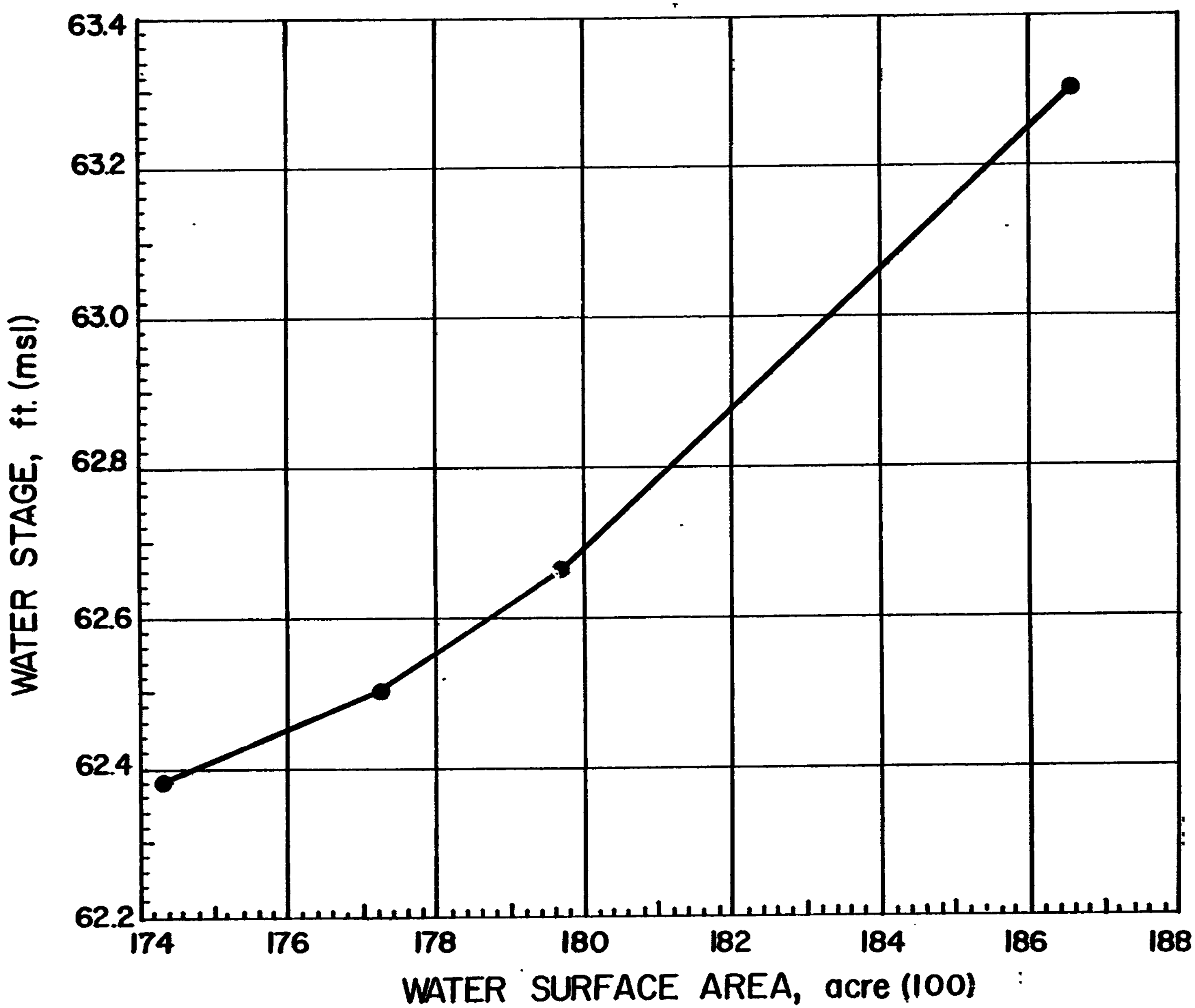

Figure 7. Relationship between water stage and water surface area for Lake Harris estimated from Landsat data.

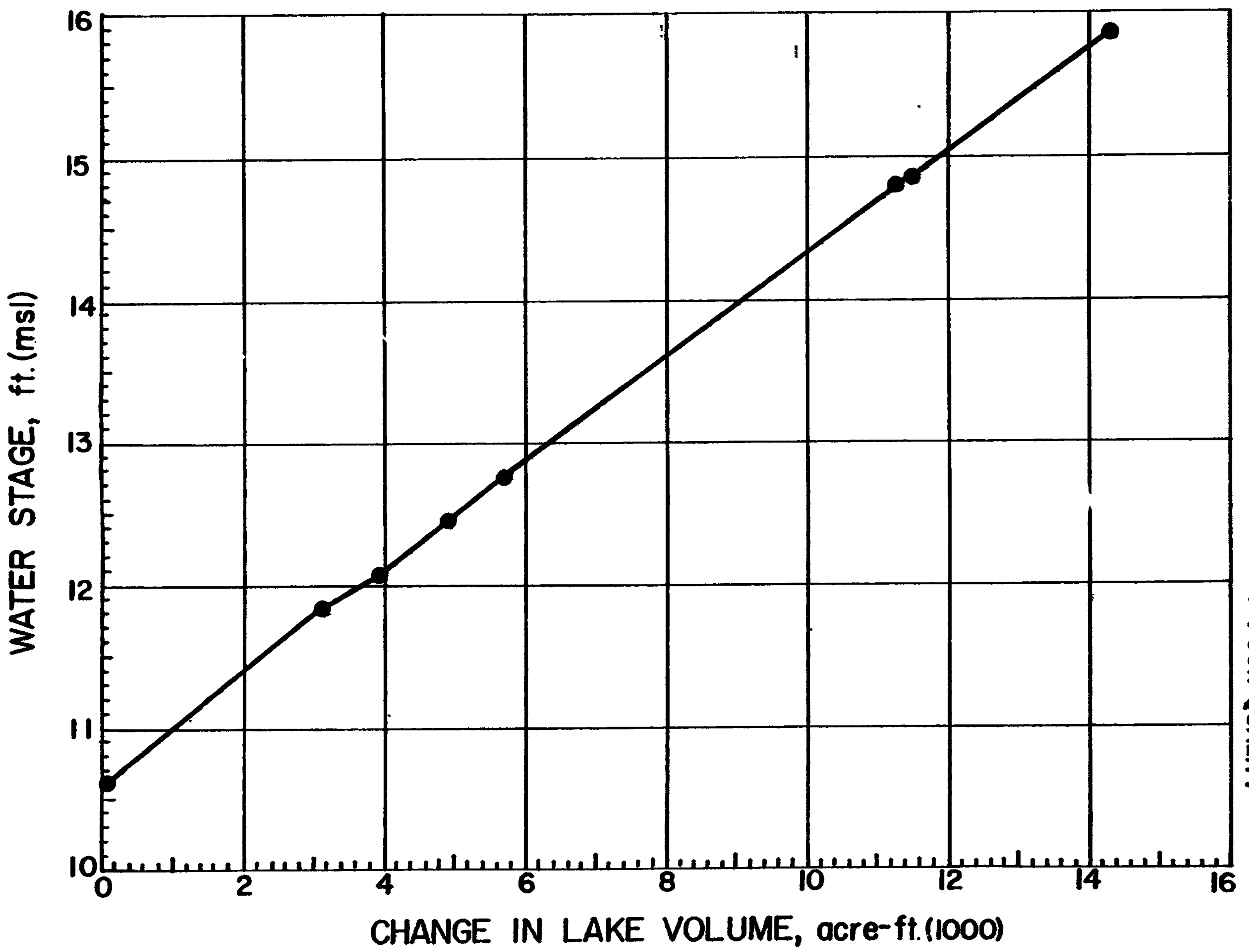

Figure 8. Relationship between water stage and lake volume changes for Lake Washington estimated from Landsat data.

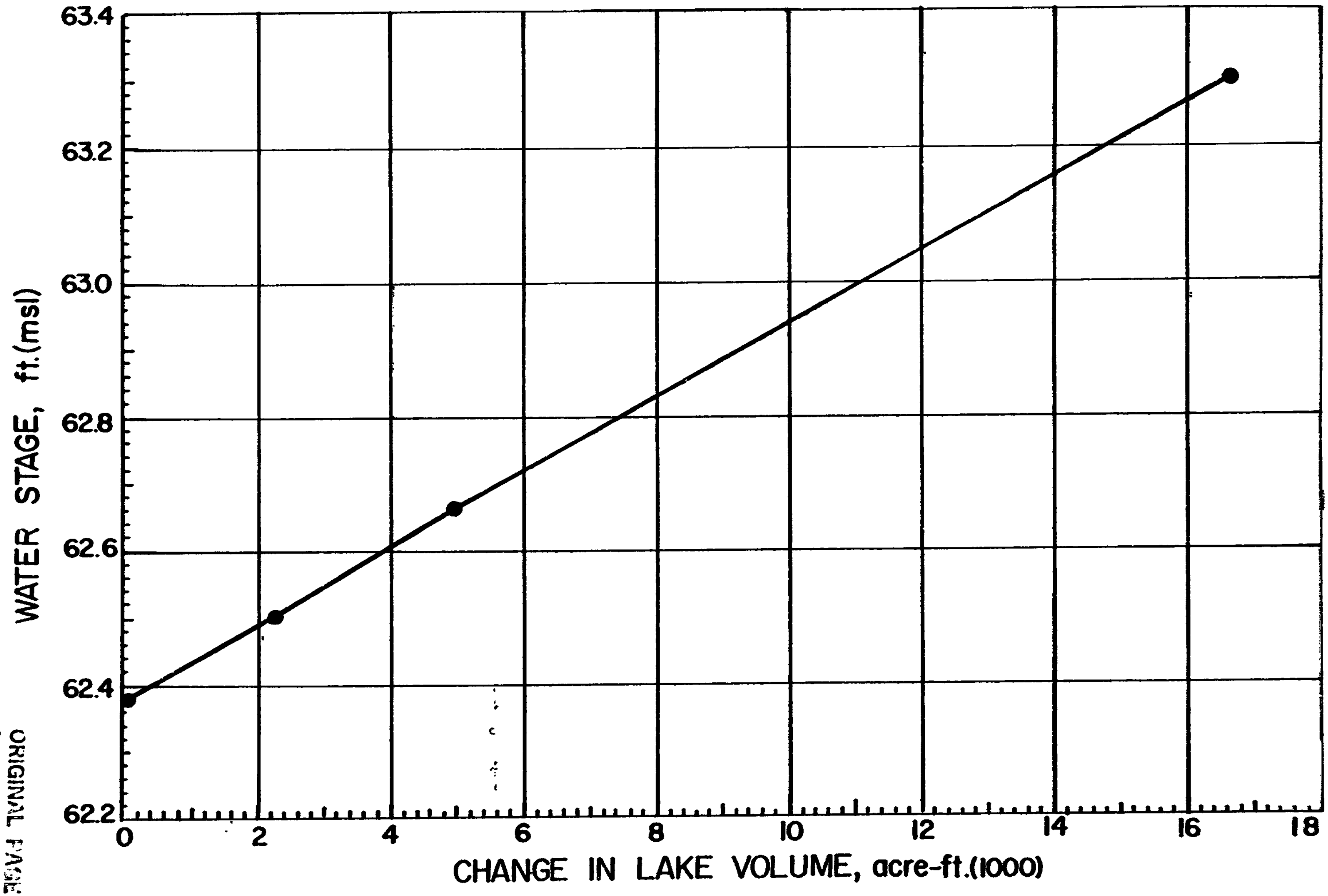

Figure 9. Relationship between water stage and lake volume changes for Lake Harris estimated from Landsat data.

APPENDIX A:

GENERAL INFORMATION ON LANDSAT REMOTE SENSING SYSTEMS

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I. Introduction to Landsat Remote Sensing System

Landsats 1, 2, and 3 were launched by National Aeronautics and Space Administration (NASA) on July 23, 1972, January 22, 1975, and March 5, 1978, respectively, to gather data about the earth's surface and telemeter those data to ground receiving stations. The operation of Landsat 1 was ended on January 6, 1978. The Landsat 3 follows the Landsat 2 by 9 days. Landsat 4 will be launched sometime during the summer of 1982.

Landsats 1, 2, and 3 were launched into a circular, near-polar orbit at an altitude of about 919 km. They circle the earth every 103.27 minutes, or roughly 14 times a day. Every 18 days the satellite passes over the same swath (185 km wide) of the ground. Landsat covers the earth's entire surface area except the northernmost 10% and southernmost 10% area. The orbital inclination angle of 99.11° was selected that provides a "sun-synchronous" orbit, so data collected are always at the same local time over the same region. At higher northern latitudes the local time will be a few minutes late as compared to the equatorial crossing time. Meanwhile, local time at lower southern latitudes will be a few minutes ahead. There is also a variation associated with the longitude, mainly because of the discrete time zones used. The average equatorial crossing time for Landsat 1 was 9:42 a.m. till March 1977, then it was changed to 8:30 a.m. Landsat 2 was initiated with an equatorial crossing time of about 9 a.m. and then was changed to 9:30 a.m. in December 1977.

Landsat 4 will be slightly different from the first three Landsats. For instance, the orbital altitude is 705 km and the earch coverage period is 16 days.

Landsat program is intended to establish the usefulness of relatively reflective multispectral imagery for earth resources study. The application to the following areas has been investigated:

(1) agricultural production;

(2) water resources planning and management;

(3) rangeland management;

(4) forestry management;

(5) land use and urban and regional planning and management;

(6) environmental conservation and management;

(7) geologic survey and mineral resource management;

(8) marine resource, oceanography, and coastal engineering;

(9) cartrographic and thematic mapping applications; and

(10) disaster warning and relief options.

II. Sensor, Band Designation, Wavelength, and Resolution:

The type of sensor, band designation, spectral sensitivity range, and spatial resolution used in Landsat are shown in Table 1. Three basic types of sensors are involved:

A. Return Beam Vidicon Camera: A multispectral return-beam vidicon (RBV) television system, that operates in three spectral pass bands designated as band 1, 2, and 3 is used on Landsats 1 and 2. The wavelengths associated with the bands 1, 2, and 3 are 0.475-0.575 μm (blue-green), 0.580-0.680 μm (yellow-red), and 0.690-0.830 μm (red-IR). The spatial resolution is 76 m.

Two panchromatic RBV cameras which replaced the three multispectral RBV cameras on Landsats 1 and 2, are being used on Landsat 3. The wavelength associated with this system ranges from 0.505 to 0.750 micrometer (μm), and the resolution is 40 m. This system has linear resolution which is twice as better and still provides approximately the same areal coverage as compared with the multispectral RBV cameras.

B. Multispectral Scanner System: A Multispectral Scanner System (MSS), that operates in four spectral passbands designated as bands 4, 5, 6, and 7, is used in Landsats 1, 2, and 3. Furthermore, band 8 is also used in Landsat 3 system. The wavelengths associated with the bands 4, 5, 6, 7 and 8 are 0.5-0.6 μm (green), 0.6-0.7 μm (red), 0.7-0.8 μm (near IR), 0.8-1.1 μm (near IR), and 10.4-12.6 μm (thermal IR), respectively. The resolutions for bands 4, 5, 6 and 7 are 76 m and for band 8 is 234 m. At the time of this writing (March, 1982), the band 8 is not operating satisfactorily.

Typical representations of the four bands of the Landsat Multispectral Scanner (MSS) are used in this study. The characteristics of each band are listed as follows:

Band 4: The band 4 emphasizes conditions of surface water bodies such as sediment loads, shallowness, directions and relative rates of flow.

Band 5: The band 5 emphasizes cultural features and exposed soil and rock surfaces and assists in the analysis of surface water conditions.

Band 6: The band 6 helps to distinguish between live vegetation and land-water boundaries.

Band 7: The band 7 penetrates best through haze and light clouds and also emphasizes live vegetation and land-water boundaries.

C. Thematic Mapper: A thematic mapper (TM), that operates in seven passbands designated as bands 1, 2, 3, 4, 5, 6, and 7 will be used on Landsat 4. The wavelength associated with the bands 1, 2, 3, 4, 5, 6, and 7 are 0.45-0.52 μm (blue), 0.52-0.60 μm (green), 0.63-0.69 μm (red), 0.76-0.90 μm (near infrared), 1.55-1.75 μm (intermediate infrared), 10.4-12.6 μm (thermal infrared), and 2.08-2.35 μm (intermediate infrared), respectively. The resolution is 30 m in all the bands except that the band 6 has a resolution of 120 m. Because of the resolution improvement and wider range of spectrum, the Landsat 4 is expected to be a powerful tool for a Landsat remote sensing application.

III. Ground Receiving Stations

The U. S. National Aeronautics and Space Administration (NASA) operates three Landsat tracking and ground receiving stations located at Greenbelt, Maryland; Goldstone, California; and Fairbands, Alaska. The ground area reception coverage for any receiving station is about 28×10^6 km^2. In addition to the U. S. receiving stations, existing foreign ground stations include two in Canada and one each in Brazil, Italy, and Iran. Besides, Landsat data outside the direct reception coverage areas of the existing ground stations can be acquired and recorded on the wide band video tape recorders and then subsequently transmitted to a ground receiving station when the satellite passes by within the range.

After the data have been received, either by real-time transmission or by tape recorder play-back, ground receiving stations record the data as wide band video recordings. These recordings are shipped to the NASA Image Processing Facility (IPF) at Goddard Space Flight Center (GSFC). Video tapes from the three U.S. stations are used to produce master 70 mm images from all Landsat data collected by the multispectral scanner (MSS) for Landsats 1, 2, and 3. Second generation negatives of all Landsat scenes are furnished routinely to three U.S. Government distribution centers. Computer compatible tapes are produced by the IPF only when user requests are received at the USGS EROS Data Center.

IV. General Electric's "Image 100" System

The General Electric "Image 100" is a system which incorporates both optical and electronic capabilities for enhancement purposes. This system is one of the most advanced in photoanalyzers. The system is designed to accept magnetic tapes with two tape drives and also contains a digitizer for use with films. A minicomputer associated with the system is used to gather spectral data from known local areas and then compare data from other areas to decide whether the latter area meets the criteria as shown in the known local area. Classifications appear graphically on the cathode ray tube display and outputs includes the digital tape, colored CRT display, line printer, and color film recorder.

Due to the very high price of this instrument, only the limited facilities are available within the United States. These facilities include such as USGS facility at Sixoux Falls, South Dakota; Jet Propulsion Laboratory in Pasadena, California; Johnson Manned Space Center, Huston, Texas; Goddard Space Flight Center facility in Beltsville, Maryland; and University of Florida, Gainesville, Florida.

V. U. S. Distribution Centers

Currently, Landsat images are reproduced and distributed to users by three Federal Data Centers operated separately by the U. S. Geological Survey (USGS), the U.S. Department of Agriculture (USDA), and the U.S. National Oceanic and Atmospheric Administration (NOAA). Tables 2 and 3 list the U.S. Data Centers and the sources of available image products. Image products provided by the data centers are similar in scale, format and type (Table 4). Interested users can request specific information on characteristics of image products available from the various data centers. USGS EROS Data Center does provide CCT's and various accession aids to users that are not available from the other Federal data centers.

VI. The Northeast Regional Data Center, Florida

The NERDC is currently in the process of setting up procedures to handle digital imagery facilities for its user community. As one part of this, we are intersted in increasing the facilities and services available to users of Landsat data bases.

LANDSAT DATA

If you are a current or future user of Landsat machine-readable data from either the Multispectral Scanner (MSS) or Return Beam Vidicon (RBV) systems, NERDC would like you to share your data with us.

Since the acquisition charge for the computer-compatible tapes is $200 each, NERDC would like to make as many of these as possible available to all users. A copy of each tape that is made available will be placed in NERDC's tape library as a public reference volume available to all NERDC users. The advantages of sharing this data are that:

* It will make new data available to everyone;
* It will provide you with a working copy of your data maintained by the NERDC at no cost to you.

VII. University of Florida, IFAS Remote Sensing Facilities

The General Electric "Image 100" located at NASA, Kennedy Space Center was relocated at the Institute of Food and Agricultural Sciences (IFAS) remote sensing system, University of Florida, in January, 1982. About 1500 Landsat tapes came together with the Image 100 facility. This system will start operating sometime in the summer of 1982. The detailed information on operation and personnel involved will be given to all potential users around the state.

VIII. Landsat Newsletters

"Landsat Data User NOTES," a bi-monthly newsletter that presents information about Landsat products, systems, and related remote sensing developments, is available to subscribers free of charge. Anyone interested in receiving this publication should contact:

User Services Section
U.S. Geological Survey
EROS Data Center
Sioux Falls, South Dakota 57198

Another bi-monthly technical publication of interest to Landsat users is the "LANDSAT Newsletter," which provides both current statistics and historical data on satellite operations, as well as related information on other earth survey programs. This newsletter is available free of charge by contacting:

LANDSAT Newsletter
Missions Utilization Office
NASA/GSFC
Code 902.1
Greenbelt, Maryland 20771
(301) 344-8826

Users wishing to receive "Reflections," the quarterly newsletter of the Eastern Regional Remote Sensing Applications Center (ERRSAC) at NASA's Goddard Space Flight Center should write to:

Reflections
ERRSAC
NASA/GSFC
Code 902.1
Greenbelt, Maryland 20771
(800) 638-0748

Users with Landsat data to share or users desiring information about NERDC's Landsat computer support services should contact John Young at the NERDC or University of Florida, IFAS Remote Sensing Center.

IX. Landsat Update Information

According to the recent (March, 1982) information update for users of National Oceanic and Atmospheric Administration's National Earth Satellite Service (NOAA/NESS) satellite data, several subjects as related to Landsat are described as follows:

Landsat 2 problem: The Landsat 2 yaw axis momentum wheel has stopped. This spacecraft has been the prime Landsat data collection platform. A previous difficulty with this momentum wheel was overcome and it was restored to service in July, 1980. At the time of this writing (March, 1982), the satellite is not capable of collecting valid data. NASA is evaluating the problem and making efforts to restart the wheel, but without success so far. NASA regards the outlook for restoring the satellite to service as dim.

Landsat 3 problem: Variations in Landsat 3 multispectral scanner mirror scan motions have been detected. They result in data loss on the left one-third of the picture. NASA has developed a ground processing correlation scheme and implemented it from the Goddard Space Flight Center facility to preserve the right two-thirds of the picture. Poleward of 35°N or 35°S, provides contiguous coverage.

Landsat 4 system : So far no problems or delays have come up that would interfere with the launch of Landsat 4 in the summer of 1982 or with the initiation of NOAA's operational Landsat 4 program on January 31, 1983.

The multispectral scanner will be the operational sensor when NOAA first takes over the Landsat 4 system on January 31, 1983. It will take additional months to implement routine Thematic Mapper operations. Presently, NOAA is developing alternate Multispectral Scanner data acquisition schedules to find out which of them can be fitted to the engineering and cost constraints of the Landsat 4 system.

System output will be capped at 136 processed Multispectral Scanner scenes per day for the first year or two of operation. Disaster and emergency events will have first call on this capacity and special acquisitions, for which requestors pay the full cost. Remaining capacity will be used to collect the Multispectral Scanner Basic Data Set; scenes of general interest acquired, to the extent possible, according to a published plan. The MSS Basic Data Set will deal with the routine scene collection objective of the operational system.

Special Acquisition signifies Landsat 4 MSS scene data that are not scheduled for routine MSS Basic Data Set collection, but which are provided upon users' request according to the following five categories.

1. Delivery of preprocessed digital data, to the requestor's site via communication satellite; provided MSS scene collected at a time and place specified by the requestor is available.
2. Delivery to the requestor of a frame of standard MSS imagery (not a color composite); if MSS scene collected at a time and place specified by the requestor is available.
3. Delivery to the requestor of a computer compatible or high density digital tape; if MSS scene collected at a time and place specified by the requestor is available.
4. Surcharge for delivery of a color composite to the user originally requesting the special acquisition of an MSS scene.
5. Surcharge applied when the requestor establishes a maximum allowable cloud cover condition for the collection of an MSS scene.

Table 1. Comparisons of type of sensor, band designation, spectral sensitivity range, and spatial resolution used in different remote sensing systems.

Landsat	Type of sensor	Band (NASA designation)	Spectral sensitivity range	Spatial resolution
1,2	Return Beam Vidicon Camera (RBV)	Band 1	0.475-0.575 μm (blue-green)	76 m
		Band 2	0.580-0.680 μm (yellow-red)	76 m
		Band 3	0.690-0.830 μm (red-IR)	76 m
	Multispectral Scanner (MSS)	Band 4	0.5-0.6 μm (green)	76 m
		Band 5	0.6-0.7 μm (red)	76 m
		Band 6	0.7-0.8 μm (near IR)	76 m
		Band 7	0.8-1.1 μm (near IR)	76 m
3	RBV	two cameras	0.505-0.750 μm (Panchromatic)	40 m
	MSS	Band 4	0.5-0.6 μm (green)	76 m
		Band 5	0.6-0.7 μm (red)	76 m
		Band 6	0.7-0.8 μm (near IR)	76 m
		Band 7	0.8-1.1 μm (near IR)	76 m
		Band 8	10.4-12.6μm (thermal IR)	234 m
4	Thematic Mapper (TM)	Band 1	0.45-0.52 μm (blue)	30 m
		Band 2	0.52-0.60 μm (green)	30 m
		Band 3	0.63-0.69 μm (red)	30 m
		Band 4	0.76-0.90 μm (near IR)	30 m
		Band 5	1.55-1.75 μm (intermediate IR)	30 m
		Band 6	10.4-12.5 μm (thermal IR)	120 m
		Band 7	2.08-2.35 μm (intermediate IR)	30 m

[a]Launch Dates: Landsat 1, 7/23/72 Operation ended 1/6/78
Landsat 2, 1/22/75
Landsat 3, 3/5/78
Landsat 4, proposed Summer, 1982

Table 2. Landsat data availability from U.S. Federal Data Centers.

Agency	Source Materials
U.S. Department of Agriculture	Landsat Data USDA Aerial Photography Skylab Imagery
National Oceanic and Atmospheric Administration	Landsat Data NOAA Satellite Data Skylab Imagery
USGS EROS Data Center	Landsat Data NASA Research Photography USDA Aerial Mapping Photography Skylab, Apollo and Gemini Imagery

Table 3. EROS Data Center Imagery Holdings.

Data Types	Current Number of Frames
Landsat I & II (MSS & RBV)	1,067,000
Skylab, Apollo and Gemini Imagery	50,800
NASA Research Aircraft Imagery	1,420,000
USDI Aerial Mapping Photography	3,123,000
Total	5,660,800

Table 4. Summary of Landsat image products available at EROS Data Center (ED).

SIZE	FILM PRODUCTS
70 mm	Black & white; positive and negative products (scale 1:3,369,000)
9" x 9"	Black & white; positive and negative products (scale 1:1,000,000)
9" x 9"	False color composite: positive product only (scale 1:1,000,000)
	PAPER PRODUCTS
	(Positive only)
9" x 9"	Black & white and false color composite (1:1,000,000 scale)
20" x 20"	Black & white and false color composite (1:500,000 scale)
40" x 40"	Black & white and false color composite (1:250,000 scale)

APPENDIX B:

COMPUTERIZED METHODS FOR BOUNDED AREA AND WEIGHTED SUB-AREA COMPUTATIONS

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ABSTRACT

The methods of computing area from maps are classified under two categories: (1) bounded area, and (2) weighted sub-areas. Pioneering methods of planimeter, coordinate squares, triangular rule, trapezoidal rule, Simpson's rule, double-meridian-distance (DMD), coordinates, and digitizer are compared with the relatively easy methods of weighing technique and finite segments, and also with a recently developed Monte Carlo process.

The bounded area which is used extensively in computing area of land use can be obtained by any one of three methods: graphical, arithmetical and computer. The graphical method includes four techniques: weighing, planimeter, coordinates squares and digitizer. The accuracy of this graphical method is highly dependent upon the skill of the analyst and the correctness of instruments. The arithmetical method involves three rules: triangular, trapezoidal, and Simpson. The accuracy of this arithmetical technique is dependent upon the number of offsets used to divide the entire region. If a region is of very irregular shape and of large size, then this arithmetical method is very tedious and cumbersome to use. The techniques of double-meridian-distance, coordinates, finite segments and Monte Carlo are introduced by using a computerized procedure. The signs of latitudes, departures, and starting point are easily confused in the methods of DMD and coordinates. Finite segments can overcome some limitations such as a figure having some inactive areas within the figure, but it is also strongly dependent upon the direction used to select the boundary nodes. Monte Carlo is only a method which is independent of the direction and can be used in any complicated form of figure.

The weighted sub-area which is used widely in computing the areas weighted to a measurement station can be obtained by any one of the four techniques: simple arithmetic method, Thiessen method, stratified method and modified Monte Carlo method; however, the modified Monte Carlo method can be simulated directly by the computerized procedure and also has been applied successfully to compute the weighted area to each measured station.

Finally, from this study it can be concluded that the weighing technique is relatively easy to use in the laboratory; the finite segments method is a quick computerized procedure when the direction of selecting boundary points are correctly performed; and the Monte Carlo process is more applicable and powerful than other computerized methods because this method is not only independent of the direction used to select the boundary nodes but also applicable to any complicated form of figures with arbitrary signs of latitudes, departures and starting points.

INTRODUCTION

The computation of an area of land is most frequently used in several fields of water resource systems. Area calculations of interest to water resource workers include land use estimation, water quality, ecological systems, stratified sampling programs, etc. Pioneering methods used in computing area from maps, (hereafter the area computations are only referred to the area computed from the maps), are those of planimeter, coordinate squares, triangular rule, trapezoidal rule, Simpson's rule, double-meridian-distance (DMD), and coordinates (Brinker, 1969). Recently, a digitizer was also used (SAC, 1972). However, if an area is very irregular in shape and/or is of large size or has inactive areas within its boundaries, then the previous methods are very difficult to adapt to a computerized procedure. Hence, there is a need to introduce some other practical methods from which the area can be calculated directly, either by the computerized procedure or by a weighing machine.

OBJECTIVES

The purposes of this study are:

(1) To discuss the existing methods used in computing areas;

(2) To introduce two relatively easy methods of weighing techniques and finite segments, and a recently developed Monte Carlo process, together with their ranges of application, and

(3) To compare the advantages and disadvantages of each method.

DESCRIPTION OF METHODS

The methods of computing area from maps may be classified under two categories: (1) bounded area and (2) weighted to sub-areas.

BOUNDED AREA

The bounded area has been widely used in determining the area of land included within the boundaries. The area to be measured can be obtained by any one of the following methods:

I. Graphical Methods: The area is measured by using instruments such as: planimeter, coordinate squares counter, digitizer and weighing machine.

a. Weighing Method: A weighing machine used in a laboratory can be employed to obtain the area. Three procedures are involved: First, a ratio between a known area and weight must be procured from a control unit. Second, the weight of an unknown area is weighed. Third, multiplying the weight of an unknown area by the ratio which is obtained in the first procedure gives the area of an unknown figure. The nonuniform thickness of the paper and changing humidity can affect significantly the accuracy of measurement.

b. Planimeter: The planimeter is the commonest way of checking the area of a figure. It is a small instrument consisting of an arm, carrying a tracing point, which is moved over the outline of the figure to be computed. Poor setting of the planimeter scale bar, and failure to check the scale constant by tracing a known area, can cause an error of measurement.

c. Coordinate Squares: The figure is marked off in squares of unit area. The number of complete unit squares included is counted, and the sum of the partial units are also estimated. A transparent paper marked in squares to some scale is placed over the figure and the number of squares and partial units counted. The number of squares can also be counted by a mechanical dot counter or a transparent paper dotter.

Using coordinate squares which are too large makes it difficult to estimate the partial blocks and could cause an error in computation.

d. Digitizer: A digitizer is a device used to convert information in graphic form into numerical intelligence suitable for processing, recording, or transmission on a digital data system. After the (x, y) coordinates of each point on the outline of the figure is recorded, the size of the plane area also can be computed. This method is highly dependent upon the direction used to digitize the boundary coordinates.

II. Arithmetic Methods: A figure can be divided into geometrical shapes (triangles, trapezoids, and rectangles), and the following rules can be used to compute the area:

a. Triangular Rule: A figure may be divided into simple triangles. The area can be computed by the formula:

$$\text{Area} = \sqrt{S(S-a)(S-b)(S-c)} \qquad (1)$$

where

a, b, and c are the sides of the triangle

$$S = 0.5(a + b + c) \qquad (2)$$

Another formula is used when an angle between two sides is known,

$$\text{Area} = 0.5\ a\ b \sin C \qquad (3)$$

where C is the angle included between two sides a and b.

b. Trapezoidal Rule: If the figure is considered as made up of a series of trapezoids, all having the same base, the area can be determined based on the formula

$$\text{Area} = \frac{d}{2}(h_a + 2\ \Sigma\ h + h_b) \qquad (4)$$

where

d = common distance between offsets and

h_a, h_b, and h = first, last and intermediate offsets.

c. Simpson's Rule: For generally parabolic areas, Simpson's one-third rule as follows is applicable to obtain the size of the plane area.

$$\text{Area} = \frac{d}{3}\,(h_a + 2\,\Sigma\, h_{odd} + 4\,\Sigma\, h_{even} + h_b) \qquad (5)$$

where

d = common distance between offsets,

h_a,h_b,h_{odd} and h_{even} = first, last, odd and even offsets.

Furthermore, if the figure is very irregular in shape, then the arithmetical method is very difficult to adapt by a computerized procedure. Therefore, the following computerized methods are introduced:

III. Computer Methods: The following four methods can be performed by the computerized procedure.

a. Double-Meridian-Distance (DMD): The DMD of a traverse line is twice the distance from a meridian through the most westerly station to the middle point of the line. The double areas of all of the trapezoids may now be found by multiplying each DMD by the adjusted latitude of that side. The area obtained by plus latitudes and minus latitudes should be considered as a positive and negative area, respectively. The sum of these double areas will be double the area of the figures to be measured. The disadvantages of this DMD method is that the signs of DMD's, latitudes, departures, or areas are easily confused.

b. Coordinates: The area is equal to one-half the sum of the products obtained by each x-coordinate by the difference between the adjacent y-coordinate, taken in the same order around the figure. Similar to the DMD method, the signs of coordinates, latitudes, departures, or areas are easily confused.

If the signs and starting point are recorded carefully and without any inactive areas within the figure, the above two methods can be used quite satisfactorily by using a computerized procedure; however, in practical application the above methods can accrue difficulty such as an inactive area included within the figure. Therefore, the following two methods which can overcome the limitations are introduced.

c. Finite Segments: The boundary of a figure is defined by a series of linear segments between node points. The clockwise or counter-clockwise direction used to record (x, y) coordinates is dependent upon the figure either to be active or inactive, respectively. The area is obtained by the following formula:

$$\text{Area} = \sum_{i=1}^{M-1} (X_{i+1} - X_i) \frac{Y_{i+1} + Y_i}{2} + (X_1 - X_M) \frac{Y_1 + Y_M}{2} \qquad (6)$$

where X_i, Y_i = coordinates of boundary nodes;

i = boundary segment index; and

M = total number of segments.

d. Monte Carlo Method: The Monte Carlo method is a procedure which takes advantage of the high speed of an electronic computer in solving complex problems in physical and mathematical fields. Monte Carlo applications in the field of science and engineering are summarized in books by Hammersley and Handscombe (1964) and Shrieder (1967). This method involves enclosing the figure to be measured within a rectangular area and by generating random numbers choosing points randomly distributed throughout this rectangle. The proportion of these points falling within the figured area is, in the limit, the proportion of the rectangular area contained within the figure. But, in practical application, the previous method has some limitations which were removed by Shih and Hamrick (1974).

i. <u>To Determine Whether a Random Point is Within or Without the Watershed</u>:

Shih and Hamrick (1974) developed an alternative test based on the principle that for any completely bounded region, a radial line constructed in any direction from a given point must cross the boundary an odd number of times if the point is located within the region or an even number of times

if without (assuming zero to be an even number). This test is ambiguous only in the case of node points (the intersections of straight line segments representing the figure boundary). They also developed a second rule with a computerized technique for solving the ambiguity that exists when the radial line penetrates the boundary at the node point.

ii. <u>Procedure of Computation</u>:

Based on the technique described in the previous section, the following procedures are used to obtain an analog of any shape of figure.

(1) Enclose the irregularly shaped boundary with a rectangle whose coordinates are also recorded.

(2) Read the X and Y coordinates of the boundary segments.

(3) Compute the weighting factor of each boundary node according to Rule 2 (Shih and Hamrick, 1974).

(4) Generate random points with uniform probability over the enclosing rectangle.

(5) Draw an imaginary line from the random point and parallel to the x-axis.

(6) Count the number of intersections of this line with the boundary

(7) Test whether the random point falls within the boundary according to Rule 1 (an odd or even number of intersections).

(8) If the above test succeeds, increase the counter of accepted points by one.

(9) Repeat the processes of 5, 6, 7 and 8 until the number of points assigned is reached.

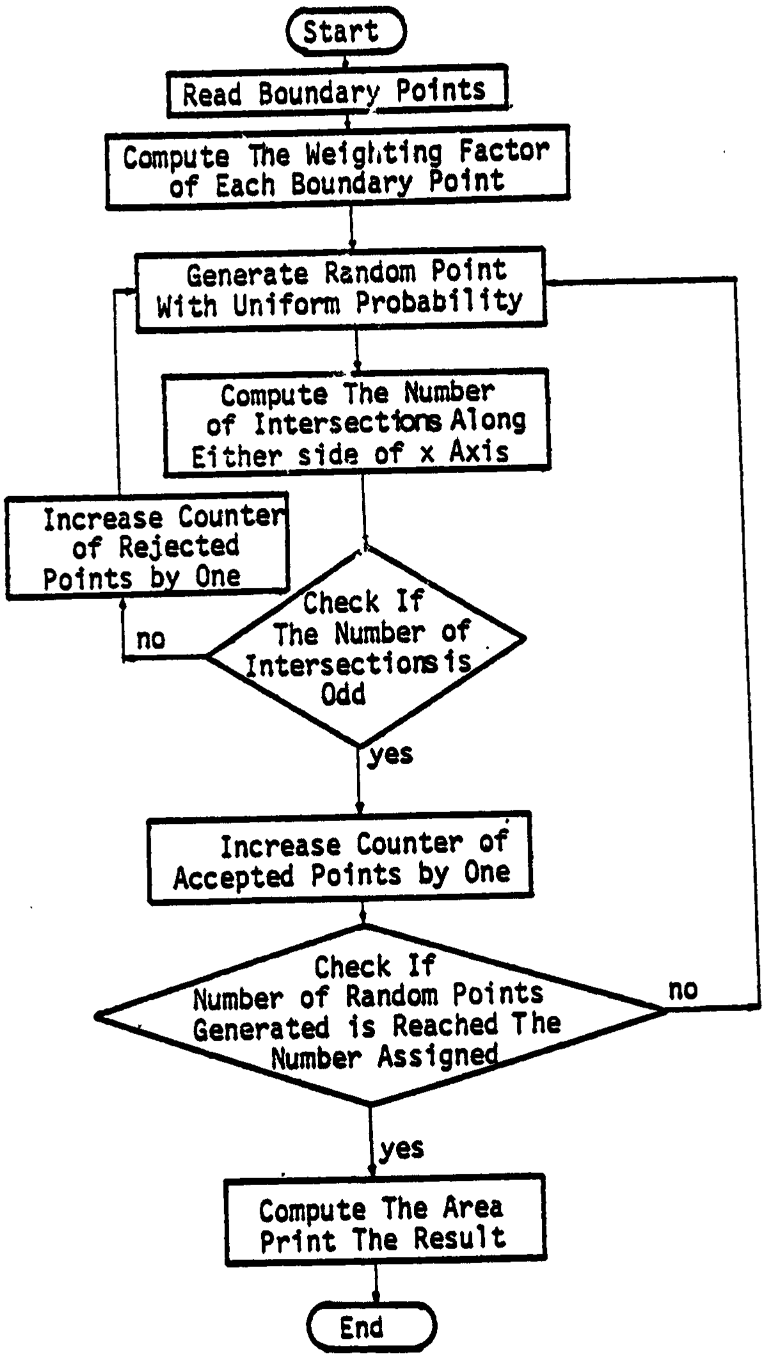
(10) Compute the area by dividing the accepted points by the total number of random points, and multiplying this ratio by the enclosing rectangular area.

The above procedure is simulated as a flow chart shown in Figure 1.

iii. Selecting Boundary Segments

The boundaries of a watershed can be defined by the given coordinates of successive points along the boundary (in a clockwise direction) and considering the boundary between each pair of successive points to be a straight-linear segment. The actual boundaries could be approximated as closely as desired by increasing the number of such segments; but, the user should note that the more segments chosen the more computing time and user's time are required. A later example will show the effects of many irregularities of natural boundaries such as lake shorelines and the watershed may be averaged by reducing the boundary planform to a simplified polygon. The general principle of this procedure is to represent the planform

Figure 1: Flowchart for Solving Integrated Area



with as few sides as possible without changing the basic shape of the boundary.

iv. Convergence of Weights

Because the Monte Carlo method relies on the laws of probability, a large number of random trials should be taken in the interest of precision. The method normally used to estimate the relationship of sample size and accuracy is the large-sample normal approximation. Using the Central-Limit Theorem, the binomial distribution can be approximated by a normal distribution for a large N, where N is the total number of trials. The sampling error of any statistic is proportional to $1/(N)^{1/2}$. The convergence of the Thiessen weights is a statistical convergence i.e., the probable error of estimation is proportional to $1/(N)^{1/2}$. A detailed discussion was given by Shih and Hamrick (1974).

WEIGHTED SUB-AREAS

The average amounts of environmental elements such as water quality, ecology system, and land use, etc. over a specific area is required in many water resource problems. Thus, mean value problems can be solved by sampling techniques. For convenience let variables $A_1, \ldots, A_k$, and $X_1, \ldots, X_k$ be the subareas and measured values of stations 1, ...k, respectively. Then the estimated weighted average amounts for the region are

$$X = W_1X_1 + \ldots + W_kX_k = \sum_{i=1}^{k} W_iX_i \qquad (7)$$

where $W_i = A_i/A$, weighted area; and

$A = A_1 + \ldots + A_k$, total area.

In most cases the values of X_i are obtained first by laboratory experiments or field measurements, and then the values of W_i are estimated based on the following four methods:

I. Simple Arithmetical Method: The values of A_i are assumed equal to one. Equation 6 can be rewritten as

$$\overline{X} = \sum_{i=1}^{k} X_i/k \tag{8}$$

Equation 8 is the simplest method which can give a good estimation of average value in a flat area under the condition of measurements that are uniformly distributed and the individual measurement does not vary widely from the true average. However, this method does not take into account the measurements outside, but near the boundaries of the area.

II. Thiessen Polygon Method: Thiessen (1911) developed a method which attempts to allow for nonuniform distribution of measurements by providing a weighting factor for each measurement. The measured points are plotted on a map, and connecting lines are drawn. Perpendicular bisectors of these connecting lines form polygons around each measured point. The sides of each polygon are the boundaries of the effective area assumed for the measured point. The values of A_i are determined by the methods indicated in the section of bounded area computation. However, the limitation of this method is its inflexibility; for instance, a new polygon being required every time there is a change in sampling location. Also, the method makes no attempt of overcome the orographic influences.

III. Stratified Method: This method is a plan by which the region is divided into homogeneous subregions or strata. In computing a strata the analyst can make full use of his knowledge of orographic effects or other influential factors. After constructing the strata, the following equation is used to calculate the mean values, $\overline{X}$,

$$\overline{X} = \sum_{i=1}^{M} \sum_{j=1}^{k_i} W_{ij} X_{ij} \tag{9}$$

where

M = total number of strata

k_i = total number of observed stations in the ith stratum

i, j = index of stratum and observed station, respectively; and

W_{ij} = observed value of the jth station in the ith stratum

The values of A_{ij} can be determined by either simple arithmetical method or the Thiessen method. If a simple arithmetical method is used, then equation 9 is reduced as

$$\overline{X} = \sum_{i=1}^{M} W_i \overline{X}_i \tag{10}$$

where

$W_i = A_i/A$, weighted area of the ith stratum; and

$\overline{X}_i = \sum_{j=1}^{k_i} X_{ij}/k_i$, average observed area of ith stratum.

If a Thiessen method is used to perform the subpolygon for each station X_{ij}, then equation 9 is used to calculate the weighted area. The greatest limitation of the stratified method is also its inflexibility.

IV. Modified Monte Carlo Method: As indicated in previous sections, the Thiessen polygon and stratified methods suffer from their inflexibility in that a new Thiessen diagram is required every time there is a change in the sampling location or a recorded station with missing data. This limitation can be overcome by the modified Monte Carlo method (Shih and Hamrick, 1975).

a. Procedures of Computation

The following procedures are used to compute an area weighted to each measured station:

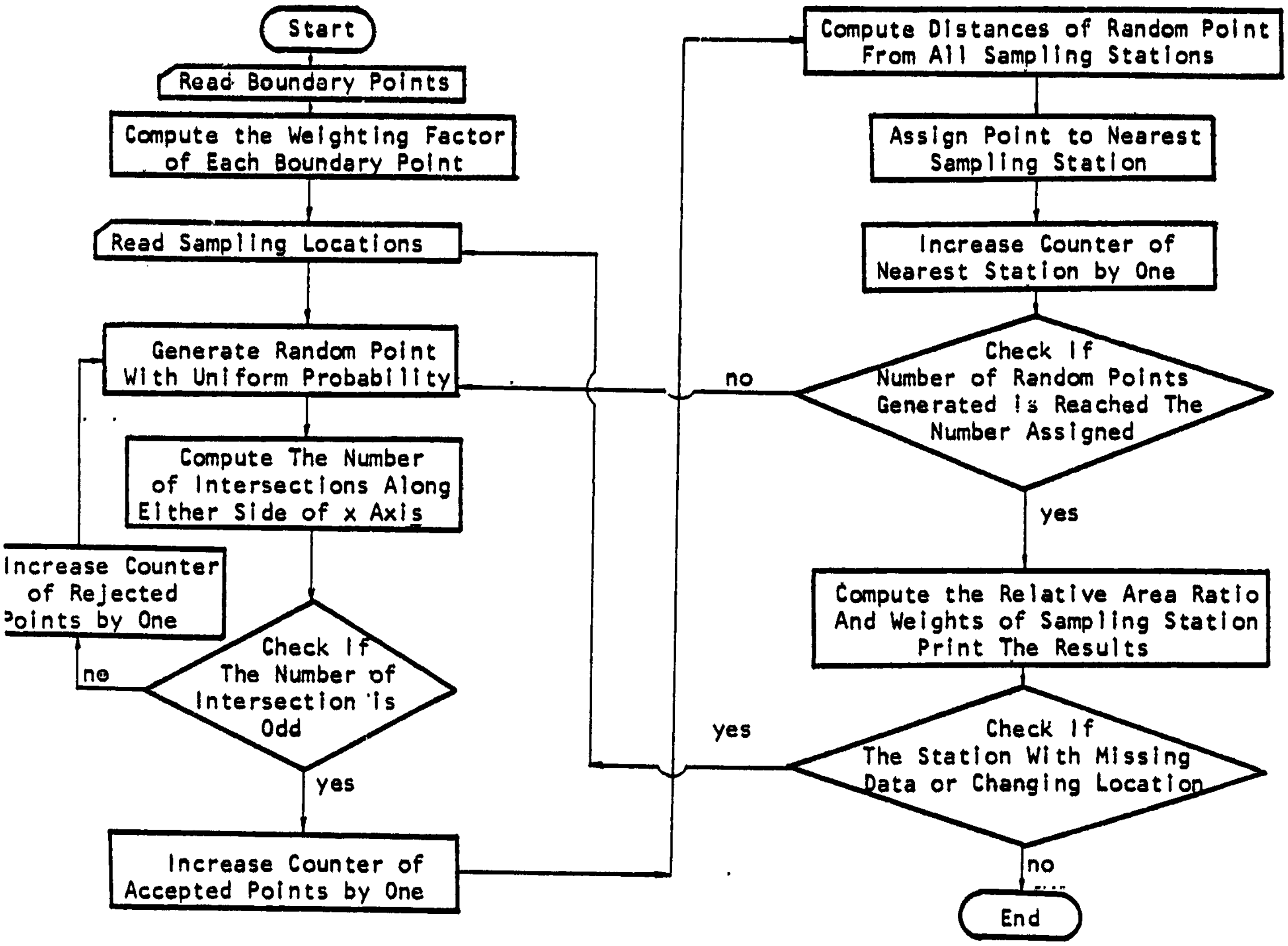
1. Compute the weighting factor of each boundary node which relies on the procedures 1, 2 and 3 as indicated in the previous section of the Monte Carlo method.
2. Determine whether a random point falls within any shape boundary which is based on the procedures 4, 5, 6, 7 and 8 as indicated in the previous section of Monte Carlo method.
3. Assign the random point which is falling within the boundary to the nearest measuring point.
4. Repeat processes 2 and 3 until a predetermined large number of points are reached.
5. Compute the relative area ratio of the bounded region to the enclosing rectangle by dividing the number of accepted points by the total number of random points.
6. Calculate the computed weights of each measuring point by dividing the number of points assigned to each measuring point by the total number of accepted points.
7. Check whether the sampling location is changing.
8. If the response to 7 is yes, the processes from 2 to 7 are repeated.

The above procedures are simulated in a flow chart in Figure 2.

b. An Irregular or L-Shaped Watershed

An expected accuracy of computation by this Monte Carlo method depends upon not only the number of random points, but also the shape of the watershed. The number of random points that affects the sample error has been discussed in a previous section. However, the

Figure 2: Flowchart for Computing the Weighted Sub-area.



efficiency of this Monte Carlo method affected by the shape formed by the watershed should also be discussed because a large number of random points fall off the outside boundaries of the watershed which differs greatly from that of the enclosing rectangle. This difficulty can be overcome by following three techniques:

i. Equal Rectangles: A watershed is enclosed by a number of smaller rectangles of equal area that have a common edge which cuts the watershed. In order for this method to be used more widely, the following relationship should be introduced. Let $A_1, \ldots, A_n$ be the relative area ratio falling within the boundaries of sub-watershed 1, ..., n. Then the new relative area ratio, $R_1, \ldots, R_n$, of sub-watershed 1, ..., n are equal to

$$\begin{aligned} R_1 &= A_1 / \sum_{i=1}^{n} A_i \\ &\vdots \\ R_n &= A_n / \sum_{i=1}^{n} A_i \end{aligned} \tag{11}$$

The final computed weights, $W_1, \ldots, W_m$, of rainfall stations 1, ..., m are equal to

$$\begin{aligned} W_1 &= \sum_{i=1}^{n} R_i E_{i1} \\ &\vdots \\ W_m &= \sum_{i=1}^{n} R_i E_{im} \end{aligned} \tag{12}$$

where E_{ij} is the computed weight of rainfall station j in subrectangle i; j includes the rainfall station from 1 to m and i includes the subrectangle from 1 to n. For example, m is the total number of rainfall stations and n is the total number of subrectangles.

ii. Unequal Rectangles: The technique of unequal rectangles is similar to the equal rectangles method except that the watershed is enclosed by a number of smaller unequal rectangles. Let $S_1, \ldots, S_n$ represent the area of enclosing rectangles $1, \ldots, n$; $A_1, \ldots A_n$ and $R_1, \ldots, R_n$ are defined in the case of equal rectangles. The value of R_i is

$$\begin{aligned} R_1 &= A_1 S_1 / \sum_{i=1}^{n} A_i S_i \\ &\vdots \\ R_n &= A_n S_n / \sum_{i=1}^{n} A_i S_i \end{aligned} \qquad (13)$$

The final computed weights, $W_1, \ldots, W_m$ of rainfall stations, $1, \ldots, m$, are similar to equation 12, except that the R_i values are replaced by equation 13.

iii. Single Rectangle: The more random points chosen, the greater the accuracy of the estimates obtained. Therefore, in a watershed which has a lower relative area ratio, the single-rectangle technique is still applicable by increasing the random trials. A detailed technique of application was given by Shih and Hamrick (1975).

c. New Thiessen Coefficients for Missing Data

As Linsley et al. (1958) indicated the greatest limitation of the Thiessen method is its inflexibility, because a new Thiessen polygon is required every time there is a change in the gage network. This modified Monte Carlo method can be used to overcome this limitation.

In general, there are two cases of missing data. Case 1: The missing data of each rainfall station are priorly known, and any missing periods of record are assigned as a new station set. The distance of a random point from all rain measuring stations is calculated simultaneously in each station set, and the random point is assigned to the nearest rain measuring station in each set. Case 2: The missing data of each rainfall station is posteriorly known, i.e., how many stations with missing data are unknown. In this case, if a station with a missing record is found, then that station is omitted and a new gage network is considered. Based on this new gage network, a computed weight is performed by a repeating procedure. A detailed description of these procedures will be discussed in the section of computer program.

COMPUTER PROGRAM

Based on Equation 1 of finite segments, procedures for computation in Monte Carlo and modified Monte Carlo methods, a systematic flow chart for the computer program development is shown in Annex 1. Nomenclatures for the computer program are listed in Annex 2. The systematic flow chart was converted to a computer program for the CDC 3100 computer with Fortran IV language. The users manual for the CDC 3100 program is also presented in Annex 3. The computer programs are listed in Annex 4. If the other computer systems are used, some modifications of the computer program might be needed.

EXAMPLE OF APPLICATION

A example is used to illustrate the application of computing the bounded and weighted sub-areas.

In order to test the applicability of these newly developed techniques, an irregular area as shown in Figure 3 not only has inactive areas within the figure, but also can be calculated easily by the triangular rule. As mentioned in the previous sections, the direction used in setting boundary nodes is a very important feature in some methods, because an improper procedure can cause a serious error. In order to investigate this nature, as Figure 3 illustrates, four different sequences used to select the coordinates are demonstrated:

Case 1A: 1-2-3-4-5-6-7-8-9-10-6-11-12-13-14-11-5-1,

Case 2A: 1-2-3-4-5-6-10-9-8-7-6-11-12-13-14-11-5-1,

Case 1B: 1-2-3-4-5-6-7-8-9-10-11-12-13-10-9-14-6-5-1,

Case 2B: 1-2-3-4-5-6-14-9-10-13-12-11-10-9-8-7-6-5-1.

Based on these four cases, several methods are used to obtain the areas. The results are shown in Table 1. As can be seen from Table 1, the cases of 1A and 1B have a serious error by using the methods of finite segments and digitizer. The results of areas calculated by the Monte Carlo method with 2000 random walks are all the same values in four cases. This implies that the technique used to select the consecutive points along the boundary in either a clockwise or counterclockwise direction, or a combination of both directions, gives no difference in the results obtained by using the Monte Carlo method. This is a very useful tool when the directions used to select the boundary nodes are mixed up in both directions. The accuracy of Simpson's method is directly proportional to the number of divisions. For example, the number of eight and ten offsets as shown in Figure 3 are called Cases 1 and 2, respectively. The calculating results are also shown in Table 1. As Table 1 shows, Case 2 has a better solution than Case 1. The results obtained by the coordinates and weighed method give a good agreement with the results obtained by the triangular rule.

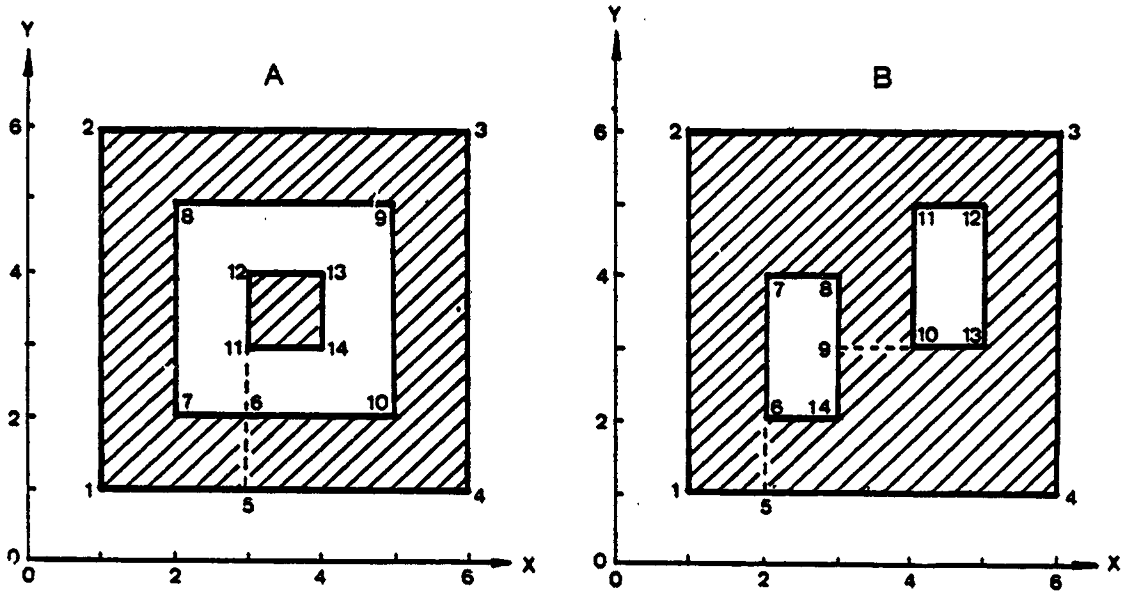


Fig. 3. Area Under an Irregularly Shaped Form.

Table 1. Comparison of the results of bounded area obtained by Monte Carlo method with other methods.

Diff. Cases	Graphical Method: Coordinate Squares	Graphical Method: Digitizer Method	Graphical Method: Weighed Method	Arithmetical Method: Triangular Rule	Arithmetical Method: Simp. Rule	Computerized Method: Monte Carlo	Computerized Method: Finite Segments
1A	16.97	34.03	17.18	17	18.3	17.06	35
2A	16.97	17.03	17.18	17	17	17.06	17
1B	20.84	29.82	19.98	21	20	20.81	29
2B	20.84	20.92	19.98	21	21	20.81	21

RESULTS AND DISCUSSION

After applying the techniques to several practical problems, the following conclusions were drawn:

1. The accuracy of the graphical method is highly dependent upon the skill of the analyst and the correctness of the instruments. Although the results obtained by the coordinate squares, planimeter and weighing technique are in good agreement with the results obtained by the triangular rule, some observations must be mentioned. For example, the nonuniform thickness of the paper and varying humidity can significantly affect the accuracy of weighing measurement. Poor setting of the planimeter scale bar, and failure to check for the scale constant by tracing a known area, can cause an error of planimeter measurement. Using coordinates which are too large make it difficult to estimate the partial blocks from which an error of computation can occur. The cases of 1A and 1B will have a serious error if the digitizer is used. These results show that the digitizer is highly dependent upon the direction used to digitize the boundary coordinates.

2. The accuracy of the arithmetical technique is dependent upon the number of offsets used to divide the entire region. Case 2 with ten offsets has a better solution than Case 1 with only eight offsets. If a region has a very irregular shape and large size, then this arithmetical method is very tedious and cumbersome to use.

3. The signs of latitudes, departures, and starting points are easily confused in the methods of DMD and coordinates. Although finite

segments can overcome some limitations such as a figure having some inactive areas within the figure, as Case 1A and 1B shows; it is strongly dependent upon the direction used to select the boundary nodes but also applicable to any complicated form of figures with arbitrary sign of latitudes, departures and starting points.

4. The modified Monte Carlo method has been successfully applied to compute the weighted sub-area. The result also indicated that only the modified Monte Carlo method can be simulated directly by a computerized procedure to compute the weighted sub-area to each measured station.

5. The modified Monte Carlo method can be applied to compute the weighted sub-area not only for rainfall stations but also for any type of estimating mean value over a specific area. For example, an average of nutrient concentration within the lake can also be computed based on the modified Monte Carlo method.

6. The modified Monte Carlo method has been extended to compute the new weighting factors when data are missing.

REFERENCES

1. Brinker, R. C., 1969, "Elementary Surveying", 5th Edition, International Textbook Company, Scranton, Pennsylvania, p.242-256.

2. Hammersley, J.M. and D.C. Handscombe, 1964. "Monte Carlo Methods," Meuthun, London178 p.p.

3. SAC, 1972, Graf/Pen GP3, Sonic Digitizer, Science Accessories Corporation, Southport, Connecticut.

4. Shih, S. F. and R. L. Hamrick, 1974, "A Technique Used to Determine Random Point Position", Water Resources Bulletin, 10(5): 884-898.

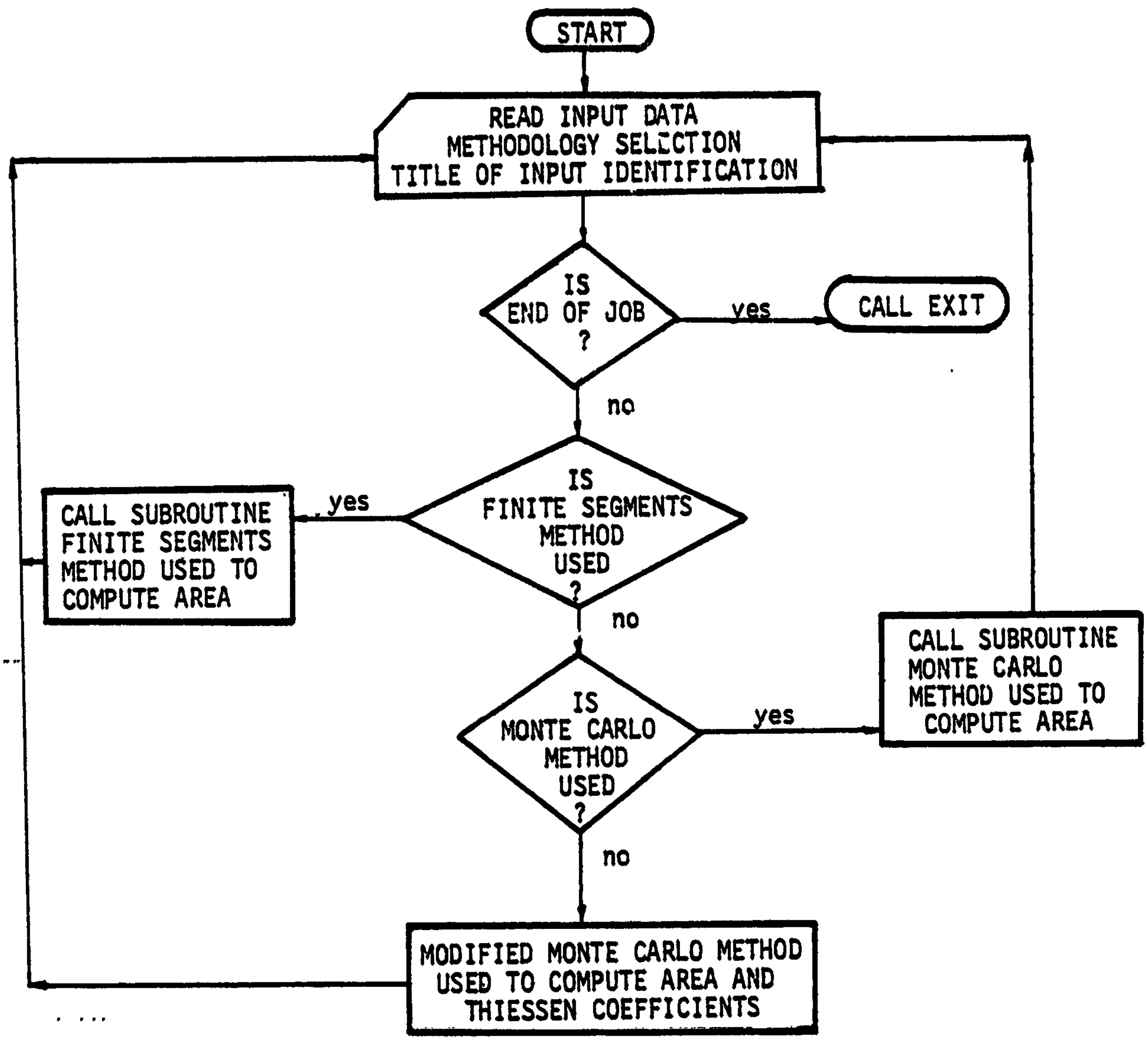
5. Shih, S. F. and R. L. Hamrick, 1975, "A Modified Monte Carlo Technique to Compute Thiessen Coefficients", Journal of Hydrology, 27: 339-356.

6. Shreider, Y. A. (ed), 1967, "The Monte Carlo Method", Second Impression, Pergamon, New York, 381 pp.

7. Thiessen, A. H., 1911, "Precipitation Averages for Large Areas", Monthly Weather Review, 39: 1082-1084.

ANNEXES

Annex 1. Systematic Flow Chart For Computer Program Development



Annex 2. Nomenclature For Computer Programs.

Variables of Input:

IN - Methodology indicator, the finite segments method used

1 = Finite Segments Method Used

2 = Monte Carlo Method Used

3 = Modified Monte Carlo Method Used

0 = End of Job

TITLE - Input data identification

N - The number of boundary points chosen

M - The number of measuring stations.

NSET - The number of Monte Carlo Points assigned

XMIN - Minimim range in X axis

XMAX - Maximum range in X axis

YMIN - Minimum range in Y axis

YMAX - Maximum range in Y axis

FAC - The scale of feet used in per unit of length, zero means the dimensionless of area

X - X coordinate of the boundary point

Y - Y coordinate of the boundary point

AX - X coordinate of the measuring station

AY - Y coordinate of the measuring station

Variables of Output:

AF - Relative area ratio

AREA - Total area in acres

I - Measuring station identification

WF(I) - Thiessen coefficient of station I

FACT - Area converting factor in unit of acres

SUM - Total area in acres computed by finite segments method.

Annex 3. Users Manual

For Program to Compute the Areas and Thiessen Coefficients Based on Finite Segments, Monte Carlo and Modified Monte Carlo Methods

Program Limitations

1. Limit of 400 boundary points per area
2. Limit of 500 measuring station per area

Requisition for Computer Work

Estimated Time - 5 seconds is needed in Finite Segment per area,

15 seconds is needed in Monte Carlo method per 1000 random points.

20 seconds is needed in Modified Monte Carlo Method per 1000 random points

Category - Production run

Disk - 6000

FORMAT INFORMATION

Symbols used to indicate the proper method for numbers or letters entered in card columns shown are :

RJ - indicates that a whole integel number must be right justified in card columns shown

DP - indicates that the number must have a decimal point indicated in one of the card columns.

A - any alpha-numeric character.

CARD FORMAT INFORMATION

First Card: Control and Parameters Card

C.C.	Symbol	Description
1-5	RJ	An integral value is required. 1, 2, and 3 indicate that the finite segments, Monte Carlo, and Modified Monte Carlo are used, respectively.
11-80	A	Title Input data identification.

Second Card: Parameters Card

C.C.	Symbol	Description
	Type I:	when the integer 1 is shown in first card on column 5
1-10	RJ	Total number of boundary points
11-20	DP	Scale of feet used in per unit of length
	Type II:	When the integer 2 is shown in first card on column 5
1-10	RJ	Total number of random points assigned
11-20	RJ	Total number of random points assigned
21-30	DP	Minimum value of enclosing rectangle coordinates along X-axis
31-40	DP	Maximum value of enclosing rectangle coordinates along X-axis
41-50	DP	Minimum value of enclosing rectangular coordinate along Y-axis
51-60	DP	Maximum value of enclosing rectangular coordinate along Y-axis
61-70	DP	Scale 4 feet used in per unit of length
	Type III:	When the integer 3 is shown in first card on column 5
1-10	RJ	Total number of boundary points
11-20	RJ	Total number of rain measuring stations. If a relative area ratio of study area to enclosing rectangle is expected,only the value of 1 should be used.
21-30	RJ	Total number of random points assigned.
31-40	DP	Minimum value of enclosing rectangular coordinate along X-axis
41-50	DP	Maximum value of enclosing rectangular coordinate along X-axis
51-60	DP	Minimum value of enclosing rectangular coordinate along Y-axis
61-70	DP	Maximum value of enclosing rectangular coordinate along Y-axis
71-80	DP	Scale of feet used in per unit of length

Third Card: Boundary Points Coordinates Card(s)

C.C.	Symbol	Description
1-5	DP	
11-15	DP	
31-35	DP	x coordinate value of boundary segments choosing in clockwise direction
41-45	DP	
51-55	DP	
61-65	DP	
71-75	DP	
6-10	DP	
16-20	DP	
26-30	DP	
36-40	DP	
46-50	DP	y coordinate value of boundary segments choosing in clockwise direction.
56-60	DP	
66-70	DP	
76-80	DP	

Note: The maximum boundary points included per card is only 8 points. Therefore, the card can be used as much as required in number of stations. For example, 7 cards are needed in 50 boundary points.

Measuring Stations Coordinate Card(s): This card is required only when the integer 3 is shown in the first card on column 5.

C.C.	Symbol	Description
1-5	DP	
11-15	DP	
21-25	DP	
31-35	DP	
41-45	DP	x coordinate of rain measuring station
51-55	DP	
61-65	DP	
71-75	DP	
6-10	DP	
16-20	DP	
26-30	DP	
36-40	DP	
46-50	DP	y coordinate of rainfall measuring station
56-60	DP	
66-70	DP	
76-80	DP	

Note 1: The maximum measuring stations involved per card is only 8 stations. Therefore, use as many new cards as necessary.

Note 2: Use as many new control and title cards with succeeding cards as necessary. The last card must be present as a blank form.

ANNEX 4. Computer Program with Fortran IV Language

ORIGINAL PAGE IS
OF POOR QUALITY

```
C     X IS THE X COORDINATE OF THE BOUNDARY
C     Y IS THE Y COORDINATE OF THE BOUNDARY
C     NN IS A WEIGHTING FACTOR FOR NODE POINT OF BOUNDARY
C     IA AND IX ARE INITIAL ODD INTEGER FOR USING IN  RANDU  SUBROUTINE
C     N IS THE NUMBER OF BOUNDARY POINTS CHOSEN
C     M IS THE NUMBER OF RAIN MEASURING STATION
C     NSET IS THE NUMBER OF RANDOM POINTS EXPECTED
C     XMIN AND XMAX ARE THE MINIMUM AND MAXIMUM RANGE IN X AXIS
C     YMIN AND YMAX ARE THE MINIMUM AND MAXIMUM RANGE IN Y AXIS
C     AX IS THE X COORDINATE OF THE RAIN MEASURING STATION
C     AY IS THE Y COORDINATE OF THE RAIN MEASURING STATION
C     FAC IS THE FEET USED IN PER UNIT ZERO MEANS DIMENSIONLESS OF AREA
      REAL L(500)
      DIMENSION X(400),Y(400),AX(500),AY(500),WF(500),NS(500),YY(400),
     1NN(400),TITLE(9)
      NR=60
      NW=61
C     READ INPUT DATA
   83 READ(NR,3) IW,TITLE
    3 FORMAT(I5,3X,9A8)
      IA=5
      IX=7
C     CHECK WHETHER THE END OF STATION SET
      IF(IW.EQ.0) GO TO 85
      WRITE(NW,5) TITLE
    5 FORMAT(1H1,//5X,9A8//)
      IF(IW.EQ.1) GO TO 119
      IF(IW.EQ.2) GO TO 110
      READ(NR,8) N,M,NSET,XMIN,XMAX,YMIN,YMAX,FAC
    8 FORMAT(3I10,5F10.3)
      IFAC=FAC+0.01
      FACT=FAC*FAC/43560.0
      IF(IFAC.EQ.0) FACT=1.0
      WRITE(NW,108) N,M,NSET,XMIN,XMAX,YMIN,YMAX,FACT
  108 FORMAT(//10X,29HNUMBER OF BOUNDARY SEGMENTS =,I4/10X,29HNUMBER OF
     1RAINFALL STATIONS =,I4/10X,25HNUMBER OF RANDOM POINTS =,I6/10X,16H
     2X-AXIS MINIMUM =,F8.4/10X,16HX-AXIS MAXIMUM =,F8.4/10X,16HY-AXIS M
     3INIMUM =,F8.4/10X,16HY-AXIS MAXIMUM =,F8.4/10X,24HAREA CONVERTING
     4FACTOR =,F15.5//)
      READ(NR,9) (X(I),Y(I),I=1,N)
    9 FORMAT(16F5.1)
      READ(NR,4) (AX(I),AY(I),I=1,M)
    4 FORMAT(16F5.1)
C     ADD A SMALL VALUE TO EACH NODE FOR OBTAING THE NN FACTOR
      DO 106 I=1,N
  106 YY(I)=Y(I)+0.00001
C     COMPUTE THE WEIGHTING FACTOR NN FOR EACH BOUNDARY NODE
      DO 101 I=1,N
      NN(I)=0
      IF(Y(I).EQ.Y(I+1)) GO TO 102
```

```
      IF(YY(I).LT.Y(I+1).AND.YY(I).GT.Y(I)) NN(I)=NN(I)+1
      IF(I.EQ.1) GO TO 103
      IF(YY(I).LT.Y(I-1).AND.YY(I).GT.Y(I)) NN(I)=NN(I)+1
      GO TO 101
  103 IF(YY(I).LT.Y(N).AND.YY(I).GT.Y(I)) NN(I)=NN(I)+1
      GO TO 101
  102 NN(I)=1
  101 CONTINUE
      DO 107 I=1,M
      NS(I) = 0
  107 CONTINUE
      NA=0
      NRR=0
      XMN=XMAX-XMIN
      YMN=YMAX-YMIN
      DO 500 IK=1,NSET
      IR=0
      IL=0
C     GENERATE THE RANDOM NUMBER
      CALL RANDD(IX,IY,RDM)
      IX=IY
      XT=XMIN + RDM*XMN
      CALL RANDD(IA,IB,RDN)
      IA=IB
      YT=YMIN + RDN*YMN
      X(N+1)=X(1)
      Y(N+1)=Y(1)
C     CALCULATE THE NUMBER OF INTERSECTION ALONG THE X AXIS IN EITHER SIDE
      DO 300 K=1,N
      IF(YT.EQ.Y(K).AND.XT.EQ.X(K)) GO TO 310
      IF(YT.EQ.Y(K).AND.YT.EQ.Y(K+1)) GO TO 10
      IF(YT.EQ.Y(K)) GO TO 20
      IF(Y(K).GT.YT.AND.YT.GT.Y(K+1)) GO TO 40
      IF(YT.GT.Y(K).AND.Y(K+1).GT.YT) GO TO 40
      GO TO 300
   10 IF(X(K).LT.XT.AND.X(K+1).GT.XT) GO TO 310
      IF(X(K).GT.XT.AND.X(K+1).LT.XT) GO TO 310
      IF(XT-X(K)) 11,310,12
   11 IR=IR+NN(K)
      GO TO 300
   12 IL=IL+NN(K)
      GO TO 300
   20 IF(X(K)-XT) 12,310,11
   40 XX=X(K)+ (YT-Y(K))*(X(K+1)-X(K))/(Y(K+1)-Y(K))
      IF(XX-XT) 42,310,41
   41 IR=IR+1
      GO TO 300
   42 IL=IL+1
  300 CONTINUE
C     CHECK WHETHER THE RANDOM POINT IS FALLING WITHIN THE BOUNDARY
      IF((IR-IR/2*2).EQ.0.OR.(IL-IL/2*2).EQ.0) GO TO 302
  310 NA=NA+1
C     ASSIGN THE FALLING WHITHIN BOUNDARY POINT TO THE NEAREST STATION
      L(1)=(XT-AX(1))**2 +(YT-AY(1))**2
```

```
      SAVE=L(1)
      ISUB =1
      DO 91 I =2,M
      L(I)=(XT-AX(I))**2 +(YT-AY(I))**2
      IF(L(I)-SAVE)13,91,91
13    SAVE=L(I)
      ISUB=I
   91 CONTINUE
      NS(ISUB)   =NS(ISUB)+1
      GO TO 500
  302 NPP=NPP+1
  500 CONTINUE
C   COMPUTE RELATIVE AREA RATIO AND WEIGHTING FACTOR OF EACH STATION
      AF= NA/(FLOAT(NA+NPP))
      AREA=AF*(XMAX-XMIN)*(YMAX-YMIN)*FACT
C   PRINT THE RESULTS
      WRITE(NW,7) AF,AREA
    7 FORMAT(10X,21HRELATIVE AREA RATIO =,F9.6,24H   TOTAL AREA IN ACRES
     1 =,F15.6//)
      DO  21 I=1,M
      WF(I) =NS(I)/FLOAT(NA)
   21 WRITE(NW,6) I,WF(I)
    6 FORMAT(10X,35HCOMPUTED WEIGHT OF RAINFALL STATION, I4,3H  =,F9.6/)
      GO TO 83
  109 CALL ARAA(X,Y,NR,NW)
      GO TO 83
  110 CALL MONTE(X,Y,YY,NN,NR,NW)
      GO TO 83
   85 CALL EXIT
      END


      SUBROUTINE ARAA(X,Y,NR,NW)
      DIMENSION X(1),Y(1)
C     READ INPUT DATA
      READ(NR,6) N,FAC
    6 FORMAT(I10,F10.3)
      READ(NR,4)  (X(I),Y(I),I=1,N)
    4 FORMAT(16F5.1)
      IFAC=FAC+0.01
      FACT=FAC*FAC/43560.0
      IF(IFAC.EQ.0) FACT=1.0
      WRITE(NW,108) N,FACT
  108 FORMAT(//10X,29HNUMBER OF BOUNDARY SEGMENTS =,I4/10X,24HAREA CONVE
     1RTING FACTOR =,F15.5//)
      SUM=0.0
      X(N+1)=X(1)
      Y(N+1)=Y(1)
      DO 7 K=1,N
      SUM1=(X(K+1)-X(K))*(Y(K+1)+Y(K))/2.0
    7 SUM=SUM+SUM1
      SUM=SUM*FACT
      WRITE(NW,8) SUM
```

```
    8 FORMAT(/2X,21HTOTAL AREA IN ACRES =,F15.6//)
      RETURN
      END



      SUBROUTINE MONTE(X,Y,YY,NN,NR,NW)
      DIMENSION X(1),Y(1),YY(1),NN(1)
      IA=5
      IX=7
C   READ INPUT DATA
      READ(NR,8) N,NSET,XMIN,XMAX,YMIN,YMAX,FAC
    8 FORMAT(2I10,5F10.3)
      IFAC=FAC+0.01
      FACT=FAC*FAC/43560.0
      IF(IFAC.EQ.0) FACT=1.0
      WRITE(NW,108) N,  NSET,XMIN,XMAX,YMIN,YMAX,FACT
  108 FORMAT(//10X,29HNUMBER OF BOUNDARY SEGMENTS =,I4/10X,25HNUMBER OF
     1RANDOM POINTS =,I6/10X,16HX-AXIS MINIMUM =,F8.4/10X,16HX-AXIS MAXI
     2MUM =,F8.4/10X,16HY-AXIS MINIMUM =,F8.4/10X,16HY-AXIS MAXIMUM =,F8
     3.4/10X,24HAREA CONVERTING FACTOR =,F15.5//)
      READ(NR,9) (X(I),Y(I),I=1,N)
    9 FORMAT(16F5.1)
C   ADD A SMALL VALUE TO EACH NODE FOR OBTAING THE NN FACTOR
      DO 106 I=1,N
  106 YY(I)=Y(I)+0.00001
C   COMPUTE THE WEIGHTING FACTOR NN FOR EACH BOUNDARY NODE
      DO 101 I=1,N
      NN(I)=0
      IF(Y(I).EQ.Y(I+1)) GO TO 102
      IF(YY(I).LT.Y(I+1).AND.YY(I).GT.Y(I)) NN(I)=NN(I)+1
      IF(I.EQ.1) GO TO 103
      IF(YY(I).LT.Y(I-1).AND.YY(I).GT.Y(I)) NN(I)=NN(I)+1
      GO TO 101
  103 IF(YY(I).LT.Y(N).AND.YY(I).GT.Y(I)) NN(I)=NN(I)+1
      GO TO 101
  102 NN(I)=1
  101 CONTINUE
C   GENERATE THE RANDOM POINT
      NA=0
      NBB=0
      XMN=XMAX-XMIN
      YMN=YMAX-YMIN
      DO 500 IK=1,NSET
      IR=0
      IL=0
      CALL RANDD(IX,IY,RDM)
      IX=IY
      XT=XMIN + RDM*XMN
      CALL RANDD(IA,IB,RDN)
      IA=IB
      YT=YMIN + RDN*YMN
      X(N+1)=X(1)
      Y(N+1)=Y(1)
```

```
C    CALCULATE THE NUMBER OF INTERSECTION ALONG THE X AXIS
      DO 300 K=1,N
      IF(YT.EQ.Y(K).AND.XT.EQ.X(K)) GO TO 310
      IF(YT.EQ.Y(K).AND.YT.EQ.Y(K+1)) GO TO 10
      IF(YT.EQ.Y(K)) GO TO 20
      IF(Y(K).GT.YT.AND.YT.GT.Y(K+1)) GO TO 40
      IF(YT.GT.Y(K).AND.Y(K+1).GT.YT) GO TO 40
      GO TO 300
   10 IF(X(K).LT.XT.AND.X(K+1).GT.XT) GO TO 310
      IF(X(K).GT.XT.AND.X(K+1).LT.XT) GO TO 310
      IF(XT-X(K)) 11,310,12
   11 IR=IR+NN(K)
      GO TO 300
   12 IL=IL+NN(K)
      GO TO 300
   20 IF(X(K)-XT) 12,310,11
   40 XX=X(K)+ (YT-Y(K))*(X(K+1)-X(K))/(Y(K+1)-Y(K))
      IF(XX-XT) 42,310,41
   41 IR=IR+1
      GO TO 300
   42 IL=IL+1
  300 CONTINUE
C    CHECK WHETHER THE RANDOM POINT IS FALLING WITHIN THE BOUNDARY
      IF((IR-IR/2*2).EQ.0.OR.(IL-IL/2*2).EQ.0) GO TO 302
  310 NA=NA+1
      GO TO 500
  302 NRR=NRR+1
  500 CONTINUE
      AF= NA/(FLOAT(NA+NRR))
      AREA=AF*(XMAX-XMIN)*(YMAX-YMIN)*FACT
      WRITE(NW,7) AF,AREA
    7 FORMAT(10X,21HRELATIVE AREA RATIO =,F9.6,24H   TOTAL AREA IN ACRES
     1 =,F15.6//)
      RETURN
      END



      SUBROUTINE RANDD(IX,IY,YFL)
C     GENERATE THE RANDOM NUMBER
      IY=IX*4099
      IF(IY)5,6,6
    5 IY=IY+8388607+1
    6 YFL=IY
      YFL=YFL/8388607.0
      RETURN
      END
```