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USING LANDSAT DATA TO ESTIMATE RESERVOIR STORAGE

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I. ABSTRACT

A technique using Landsat data was developed to estimate the lake storage volume and was applied 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, the uses can directly correlate change in lake stage with available water volume. For instance, eight cloud free dates were chosen for Lake Washington. The water surface was measured from Landsat along with the lake stage that ranged from 3.23 to 4.83 m. The results indicated that the water surface varied from 1,027 hectares at the stage 3.23 m to 1,153 hectares at the stage 4.83 m. The ground truth measurement of water surface was 1,152 hectares around the stage 4.83 m. This is slightly lower than 1,153 hectares as estimated from Landsat data. The difference seems to be negligible in practical application. Thus, the techniques developed in this study are quite applicable to solve the problem of lake storage volume.

II. 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 Florida 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 a high agricultural water demand, but also can cause an acute problem of flooding during wet season. For instance, the severe drought experienced in 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 for individual households and municipal supplies as well as agricultural irrigation.

A typical basin in central Florida is the St. Johns River basin which encompasses approximately 29,600 km^2. 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 460 km 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 mean sea level (msl). 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 lake volume determination using Landsat Data. Recently, applications of Landsat data to determine the lake volume in Lake Okeechobee in south Florida have been done by several researchers[2,4]. 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 the 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 possess that signature (theme) can be counted. Thus, the area of that signature is obtained. 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 on vegetation 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.

The general objective of this study was to demonstrate the application of Landsat remote sensing techniques for determining the lake volume of Lake Washington and Lake Harris in central Florida. The specific objectives were: 1) to develop a new method used to compute water surface area from the Landsat data; and 2) to discuss the applicability of the newly developed method for lake volume determination using Landsat data.

III. MATERIALS AND METHODS

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

A. REMOTE SENSING TECHNIQUES

Landsat Remote Sensing System. 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 d 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.

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 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.

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 central Florida. 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 on which of 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; and 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. 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 identified 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 sensing 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, or 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. A number of limits were investigated and the final selection was based on ground truth data that is the investigators knowledge of the character of the lake under the conditions investigated.

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 m^3;

V_s = lake storage volume at lake stage s, in m^3;

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

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

B. GROUND TRUTH MEASUREMENT

A contour map provided by St. Johns River Water Management District was used to compute the surface area. A computerized method as presented by Shih and Hamrick[3] was used to compute the ground truth area measurement.

IV. RESULTS AND DISCUSSION

A. DATE 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 in central 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.

B. 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. The results of water surface area estimated by Landsat data on those eight dates are shown in Table 1. The surface area varied from

1,027 hectares at the stage of 3.23 m above mean sea level to 1,153 hectares at the stage 4.83 m.

The ground truth measurement was made from the contour map provided by the SJRWMD using the computerized method as presented by Shih and Hamrick[3]. The computed value was 1,152 hectares around the stage 4.83 m. This is slightly lower than 1,153 hectares as estimated from the Landsat data. This difference seems to be negligible in practical application. Furthermore, Connor and Belanger[1] reported that the Lake Washington water surface area was 1,153 hectares at the stage 4.45 m. But, the surface area estimated from the Table 1 is 1,140 hectares at the same stage of 4.45 m. The difference is about 1%. This difference is hard to explain due to the lack of details associated with the area computation method used by Connor and Belanger[1]. However, this 1% 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. The results of water surface area estimated by Landsat data on those four dates are shown in Table 2. The surface area varied from 7,054 hectares at the stage of 19.01 m above the mean sea level to 7,550 hectares at the stage 19.29 m. The range of stage fluctuation during the study period was only about 30 m. This was mainly because the stages of Lake Harris are regulated well by the St. Johns River Water Management District.

C. 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 3.23 m was not available. A constant volume designated as "C" was used as a lake volume below the stage of 3.23 m. 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 3.23 and 4.83 m was about 17,704,000 m^3. The lake volumes associated with each centimeter of lake stage increment are also listed in Table 1. The lake volume changes ranged from 105,000 to 115,000 m^3 for each centimeter increment of lake stage. The rate of change in Lake Washington volume in relation to lake stage increments appears to be a stabilized condition. This implies that the lake volume at other stages including stages below 3.23 m, or above 4.83 m could be roughly estimated based on the lake volume stage increment relation obtained in this study.

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 19.01 m. 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 centimeter of lake stage change are also listed in Table 2. The lake volume increment ranged from 711,000 to 741,000 m^3 per centimeter 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 19.01 m, or above 19.29 m.

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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: 1 centimeter increment of stage
	--m--	---hectare---	---------1,000 m^3---------	
6/15/74	3.23	1,027	C*	
				105
4/11/76	3.60	1,081	C+3,900	
				108
2/9/76	3.68	1,086	C+4,767	
				109
3/17/74	3.79	1,095	C+5,967	
				110
2/27/74	3.89	1,104	C+7,067	
				112
9/6/72	4.51	1,141	C+14,030	
				114
11/29/73	4.52	1,144	C+14,144	
				115
10/19/74	4.83	1,153	C+17,704	

* C is a constant volume below the stage of 3.23 m.

Table 2. Lake Harris Volume Computation Based on the Water Surface Measured from Four Dates of Landsat Data.

Date	Water stage	Water Surface area	Lake Volume: Different stages	Lake Volume: 1 centimeter increment of stage
	--m--	---hectare---	---------1,000 m^3---------	
9/6/72	19.01	7,054	C*	
				711
8/31/75	19.05	7,173	C+2,845	
				722
2/14/75	19.10	7,270	C+6,456	
				741
1/22/76	19.29	7,550	C+20,535	

*C is constant volume below the stage of 19.01 m.

VII. BIOGRAPHICAL DATA

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