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Multidate Landsat Lake Quality Monitoring Program

A statewide program, involving a unified package of files and programs, has been developed in Wisconsin.

ABSTRACT: *The University of Wisconsin-Madison and the Wisconsin Department of Natural Resources have developed multidate procedures using Landsat to operationally monitor water quality of about 3000 inland lakes throughout the state. With so large a collection of lakes and with the need for analysis of multiple dates, the data extraction process becomes very important. In order to cope with it, a unified package of files and programs has been developed which automates and systematizes procedure.*

Each lake is delimited by a latitude-longitude based polygon which is stored in a link listed filed whose structure allows considerable processing versatility. Another file allows storage of extracted data; it is built up gradually as many Landsat scenes are processed. A third file holds coordinates of control points distributed throughout the state. Three large programs comprise the main data extraction software. One locates all control points covered by a scene so that satellite coordinates can be measured for scene navigation. A second produces the navigation constants. The last program locates all lakes covered by a Landsat scene and extracts data from it, storing a statistical summary in the data file.

BACKGROUND

SINCE 1974, University of Wisconsin-Madison researchers have been working with Wisconsin Department of Natural Resources (DNR) personnel to apply remote sensing and, in particular, Landsat to help monitor and classify water quality of about 3,000 inland lakes larger than 20 acres. Fisher and Scarpace (1975), Scarpace *et al.* (1974), Scarpace *et al.* (1978), and Scherz *et al.* (1977) describe more of the background: The work done with photographic densitometry; early interactive computer analysis; and extensions and modifications which were required for a practical statewide monitoring program to be used in a production regimen. Scarpace *et al.* (1978) discuss classification processes, approaches to atmospheric correction, correlations with ground data, and status of the overall project.

This paper is directed toward the technical question of operational measures to obtain data for a large number of lakes at frequent intervals over a large area.

Briefly, requirements imposed on the data extraction process were—

- A need for multidate analysis: Comparing data for early summer, midsummer, and early autumn gives more dependable classifications than single dates.
- Consistent data set size: The lakes range in size from 20 acres to over 10,000 acres, but

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research indicated that, for our needs, multiband mean values and a variance-covariance matrix formed from all pixels within each lake would suffice.

- Automated techniques: The scale of the project required enough computation to warrant batch mode data processing with as little human intervention as possible. Since the procedure was to be delivered to an operational agency and was to be used by people whose background was not in computer operation, programs needed to be easy and simple to use.
- Existing hardware: The Madison Academic Computing Center's Univac 1110 machine was available to the University and the DNR, so programs were to be designed around it, using available facilities.

An integrated system of programs and files has been developed to meet these goals. Its major components include

- A master lakes file, ACCESS, which stores geographic information and other data for all the lakes of interest, with a linked list structure which allows its use in a variety of modes.
- A control point file, providing latitudes and longitudes of easily identifiable points throughout the state, for scene navigation.
- A data file, linked to ACCESS, to provide a storage place for extracted data. It is built up gradually, scene-by-scene, until sufficient data are present to run the classification programs.
- Programs to generate, test, and edit these files.
- A program, CONTROL, to estimate control point locations and produce microfiche character maps to allow manual determination of Landsat coordinates for scene navigation.
- A navigation program, SATNAV, to produce coefficients to convert Landsat coordinates to latitude-longitude, and vice versa.
- A data extraction program, EXTRACT, to locate and file data for all lakes covered by a single Landsat tape file.

A novel approach was taken to solve the problem of restricting very large Landsat data sets to much smaller subsets including only the lakes of interest, while simultaneously systematizing identification and data extraction from multiple Landsat scenes.

FILES

ACCESS—THE PRIMARY LAKES FILE

A statewide random access file was generated, storing latitude-longitude coordinates of polygons surrounding each lake. Other information includes lake identification numbers and name, size of the lake in Landsat pixels, and a series of links to allow referencing lakes in a variety of ways. The file, and its associated calling subprograms, allows us to operate in the following modes:

- The first or next lake in alphabetical sequence within a county can be obtained. This is the way the file is physically organized, with counties also arranged in alphabetical order.
- The first, next, or previous lake on any 15 minute quadrangle can be found by specifying any latitude and longitude within the quadrangle. "First" in this sense means northwest-most, to facilitate Landsat tape handling, since the tape rec ords run generally north to south. Because many lakes cross quadrangle boundaries, dummy records are written into the file to provide entrances for any quadrangle involved with a lake.
- Lakes can be accessed by ID number or name.

Each lake has its own record in ACCESS, plus any needed dummy records. Table 1 shows the logical organization of a record. Latitudes and longitudes are in seconds north of 40° N and west of 85° W, which leaves all values in Wisconsin positive but small enough to fit in an 18 bit half-word.

GENERATION OF THE FILE

Generation of ACCESS began with a cooperative effort between DNR and the University to identify all lakes with sizes in excess of 20 acres (8.1 hectares) and depths of at least 8 feet (2.4 metres). Lake polygons were marked by hand on the largest-scale topographic maps available, chosen so that they had at most 10 apexes, and were located a modest distance—several hundred feet—from the lake itself, to allow reasonable errors in Landsat navigation. Several typical polygons are shown in Figure 1.

The maps were digitized by the University's Cartographic Laboratory, which provided punched card data reduced to latitude-longitude form.

DATA-FILE

This file serves as a repository for extracted statistical data. A record is provided for each lake, containing space for up to four data sets from different scenes, together with Landsat scene ID numbers and number of scenes filed. It is designed to be filled piecemeal as different scenes are processed, usually over a period of several weeks. It can then present its data to the classification programs.

CONTROL POINT FILE

Because lake information stored in ACCESS is in latitude-longitude form, it is necessary

TABLE 1. STRUCTURE OF ACCESS FILE

Word	Content		Form
1-4	NAME		24 character alphanumeric
5	COUNTY	LAKE ID	two half-word integers
6-7	SCENE I.D. for first scene done		two integers
8	PPTR	NPTR	two half-word integers
9	LKPTR	DPTR	"
10	NPTS	NPIXEL	"
11	MIN LAT	MIN LONG	"
12	MAX LAT	MAX LONG	"
13-22	LAT_i	$LONG_i$	"

PPTR, NPTR: Pointers to records for previous lake and next lake in quadrangle

LKPTR: Pointer to actual lake record if this is a dummy

DPTR: Point to record number in DATA-FILE

NPTS: Number of polygon apexes

NPIXEL: Number of expected Landsat pixels in the lake

MIN LAT, MIN LONG, MAX LAT, MAX LONG: Minimum and maximum latitude and longitude of the polygon

LAT_i, $LONG_i$: Latitude and Longitude of the "i'th" polygon apex

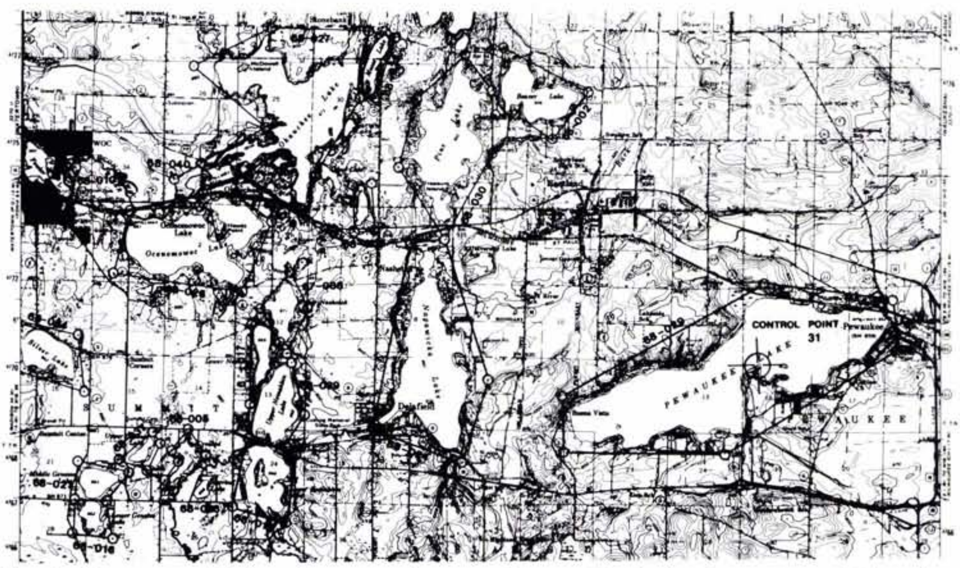

FIG. 1. Some typical lake polygons and a control point, Waukesha County, near Milwaukee (Hartland quadrangle).

to provide conversions to Landsat coordinates. The opposite conversion is also needed; for example, we must be able to accurately predict latitude and longitude of the extremes of a scene by using limiting rows and columns.

Landsat's geometry is relatively good and generally stable, but there are nonlinearities and perturbations. Precise estimates of attitude and position, if available at all, are difficult to obtain from information supplied to users. Other investigators (Bernstein, 1976; Van Wie and Stein, 1977) have concluded that accurate conversion between satellite and ground coordinates requires navigation using ground control points with regression procedures to establish good-quality models.

Using this approach, we have digitized latitudes and longitudes of 335 conspicuous points throughout the state (Figure 2). These are mostly peninsulas and islands in lakes, which makes them easy to identify from simple pictorial representations. An average of one point per topographic map quadrangle has been chosen, except in areas with

FIG. 2. Distribution of points in file CONTROL-PT.

no lakes of interest. These points, with descriptive records giving name, position, and quadrangle name and scale, are stored in a small file named CONTROL-PT. Figure 1 shows a representative control point in Pewaukee Lake near Milwaukee, marked by a circle and cross.

DATA EXTRACTION PROGRAMS

Three steps, each with its own large program, comprise the data extraction process for a single Landsat scene. First, a dozen or so well-distributed control points must be located and their Landsat coordinates found. Program CONTROL does this. Then navigation parameters must be determined for scene-to-ground and ground-to-scene coordinate transformations; this is the role of program SATNAV. Finally, program EXTRACT does the actual data extraction.

CONTROL

CONTROL uses nominal Landsat scene geometry to estimate Landsat coordinates of control points, and produces single page character maps of areas 55 rows long and 119 columns wide centered at these positions so that actual satellite coordinates can be measured.

In its normal or default mode, it operates file-by-file on all four files of a Landsat scene. (Landsat tapes supplied by the EROS Data Center divide scenes into four 25 nautical mile (NM) wide and 100 NM long strips, each forming a file on tape and following one another from west to east.) Scene-center coordinates provided by NASA to a precision of one minute are decoded from the Landsat tape annotation record, as is the actual scanner line length (usually 3240 pixels per scan for Landsat 1, or 3264 for Landsat 2). Nominal scene width and length of 100 NM each are assumed, and there are 2340 scan lines per scene. From these values, a number of constants can be found:

Distance down track per scan line: 79.1974 metres (m)
Distance across track per pixel: 57.1981 m (for 3240 pixels)
56.7775 m (for 3264 pixels)
Distance per second of latitude: 30.8807 m
Distance per second of longitude: (30.8807)·cos(latitude) m

Distances north (N) and west (W) of center are related to distances up track (U) and left of track (L) by the following linear transformations:

$$\begin{bmatrix} N \\ W \end{bmatrix} = \begin{bmatrix} \cos(A+B) & \sin(A) \\ -\sin(A+B) & \cos(A) \end{bmatrix} \cdot \begin{bmatrix} U \\ L \end{bmatrix}$$

and

$$\begin{bmatrix} U \\ L \end{bmatrix} = \frac{1}{\cos(B)} \begin{bmatrix} \cos(A) & -\sin(A) \\ -\sin(A+B) & \cos(A+B) \end{bmatrix} \cdot \begin{bmatrix} N \\ W \end{bmatrix}$$

where

A is the angle of a line normal to the scan line with respect to north, and
B is the angle between that normal line and the ground track; thus, the Earth's rotation skew angle.

From Heiber *et al* (1973),

$$A = \sin^{-1}[0.1583933/\mathrm{Cos(latitude)}]$$
$$B = \tan^{-1}[0.01135886/\mathrm{Tan}(A)].$$

If we were to plot the limits of a scene on a Mercator projection, the resulting shape would not be a true parallelepiped, but it can be closely approximated by one. With this assumption, define the four corners of the scene by the vectors

$$\{[p_i,q_i], i=0,\ldots,3\};\ p = \text{latitude and } q = \text{longitude}$$

which can be found by application of the linear transformation and scale factors above. The line joining point $[p_i,q_i]$ to point $[p_{i+1},q_{i+1}]$ can be expressed as the set

$$\{[x,y] \mid [x,y]\cdot[w_{i1},w_{i2}]^T = t_i\} \quad (1)$$

where

$w_{i1} = p_i - p_{i+1}$
$w_{i2} = q_{i+1} - q_i$
$t_i = q_i p_{i+1} - q_{i+1} p_i$ (The cross product of two consecutive lat/long vectors)

In these expressions, all subscript additions are modulo 4.

Points anywhere in 2-space can be considered above or below the line in Equation 1 if "=" is replaced with ">" or "<", but negating the w's and t_i changes the sense of above and below. If we do such negation whenever

$$[p_{i+1},q_{i+1}] \cdot [w_{i1},w_{i2}]^T < t_i,$$

then a point of latitude-longitude $[r,s]$ is interior to the scene if and only if

$$[r,s] \cdot [w_{i1},w_{i2}]^T \geq t_i \text{ for } i = 0, \ldots, 3 \; .$$

With this process, each control point can be quickly tested to see if its predicted position is covered by the scene and file in question.

Figure 3 shows a typical control point character map for the Pewaukee Lake control point shown in Figure 1. Blanks are shown for pixels with low Band 7 values. Other characters from the set { . , @ # = × + } are assigned using a histogram equalization procedure: A histogram of all Band 5 values is calculated, exempting those points with low Band 7 values. Characters are assigned to ranges of Band 5 values so as to approximately equalize their frequency of occurrence. Finally, "0's" are inserted for pixels with high Band 5 radiances, to attempt to highlight clouds.

Blanks and less-dense characters are generally water, wetlands, or cloud shadow; clouds themselves are so bright that they produce distinctive patterns of "0's". Other characters help interpretation by showing wetlands, rivers, and roads.

Usually, character maps produced by default position estimates actually show the control points about 75 percent of the time. An additional run, with specific row and column offsets, usually shows the others. Normally, interpreters have reasonable clues about which way and how much to introduce offsets. Subsequent runs to search for missed points are less expensive because only specified points are processed.

Precise control point interpretation is facilitated by 35 mm transparencies of all control points, photographed from the maps used to digitize them.

SATNAV

Program SATNAV accepts interpreted Landsat coordinates of control points and uses these, together with latitude-longitude coordinates of the points from CONTROL-PT, to perform a regression producing constants relating row and column to latitude and longitude. A simple affine model is used, providing coefficients of a 2 × 2 matrix $\boldsymbol{T}$ and a 2 × 1 vector $\boldsymbol{S}$ in the expression

$$\boldsymbol{L} = \boldsymbol{T}\boldsymbol{R} + \boldsymbol{S} \qquad (\text{or } \boldsymbol{R} = \boldsymbol{T}^{-1}[\boldsymbol{L} - \boldsymbol{S}])$$

where

$$\boldsymbol{L} = \begin{bmatrix} p \\ q \end{bmatrix} \text{and } \boldsymbol{R} = \begin{bmatrix} r \\ c \end{bmatrix}$$

p and q are latitude and longitude in seconds north of 40° N and west of 85° W

r and c are Landsat row and column

After performing the regression, SATNAV uses measured rows and columns to predict latitude and longitude, and measured latitude and longitude (from CONTROL-PT) to predict row and column. Resulting residuals are tabulated and plotted as in Figure 4, and the navigation parameters from matrix $\boldsymbol{T}$ and vector $\boldsymbol{S}$ are filed for reference by the data extraction program.

Usually, several runs of SATNAV are needed before all recording errors and poorly interpreted control points are corrected or eliminated. If residuals are high, the most successful strategy seems to be to discard the point with the highest residual, as long as this does not too severely limit control point distribution. Residuals can usually be brought down to acceptable levels while retaining adequate control after two or three such iterations.

Table 2 shows root mean square (RMS) row and column residuals for several typical scenes. Errors such as those of Table 2 are quite tolerable for data extraction, since the lake polygons in ACCESS usually are far enough from the actual lake edges to allow several rows or columns of navigation error.

Experience indicates that residuals are adequately low if there are control points within 5 to 10 kilometres of each lake. Since the control points themselves are in lakes, this needed proximity to lakes tends to occur without trouble.

EXTRACT

EXTRACT performs the actual data extraction process, working quadrangle-by-quadrangle to find all lake polygons covered by a single Landsat file, looking inside the polygons to find water-like pixels, extracting them, and finally calculating and filing statistics. Ordinarily, all four files of a scene are processed in a single run.

EXTRACT's operation is generally keyed to Figure 5. First, the navigation parameters are searched for the scene and file number of

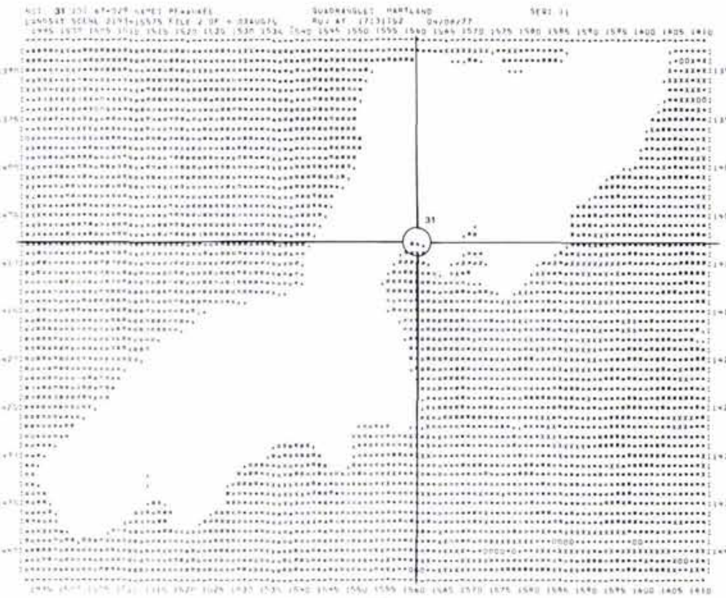

FIG. 3. Typical output from program CONTROL.

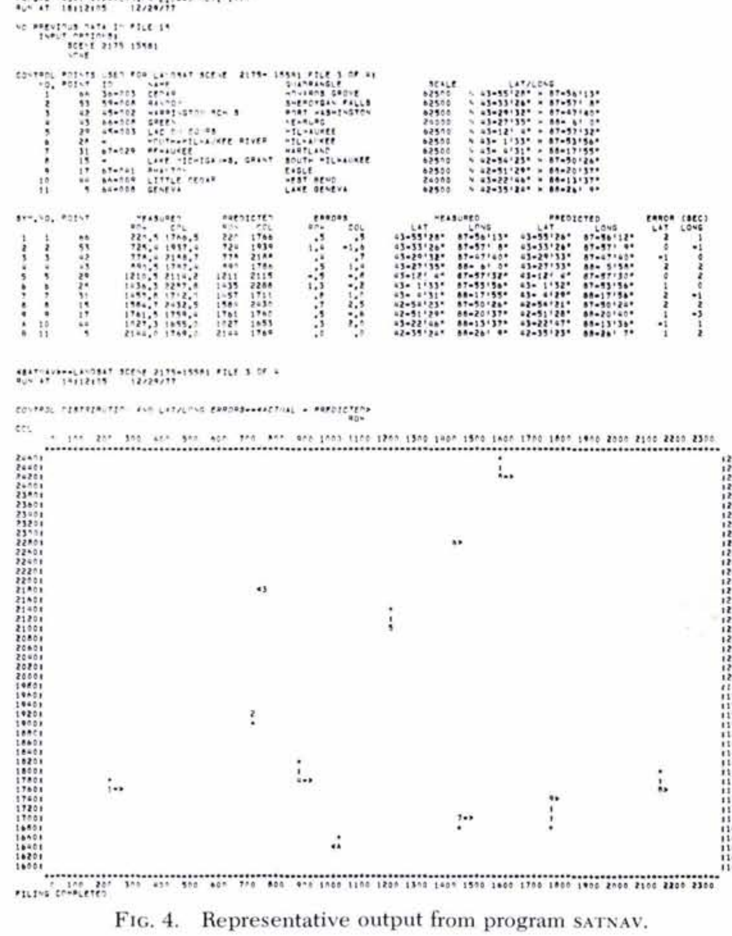

FIG. 4. Representative output from program SATNAV.

TABLE 2. ROW AND COLUMN RMS RESIDUALS FROM AFFINE MODEL FOR SEVERAL LANDSAT SCENES AND FILES

Scene	File	No. of Control Points	RMS Residuals Row	RMS Residuals Col
2644-15534	1	7	0.5	3.6
	2	7	0.4	1.9
	3	10	0.5	1.7
	4	9	0.9	0.9
5512-15230	1	8	1.6	0.9
	2	7	0.8	0.8
	3	7	0.6	0.8
	4	10	0.9	1.2
2482-15582	1	8	1.6	0.9
	2	7	0.7	3.2
	3	14	0.7	1.8
	4	7	0.9	1.5
2482-15573	1	14	0.7	1.0
	2	15	1.0	1.6
	4	7	0.0	0.2
5476-15251	2	13	0.6	0.4
	3	12	0.8	0.9
	4	9	0.7	1.3

interest, which is read from the tape annotation record. If this file were not navigated, processing moves to the next file. Otherwise, the navigation parameters are used to calculate latitudes and longitudes of the four corners of the file from which extremes of latitude and longitude are found. If necessary, a cloud-free portion of a scene may be selected by specifying any convex polygonal subset of a scene. With this option, the intersection of the total Landsat file and the specified polygon is used as the scene polygon. Then, starting at the northwest extremity, corner coordinates of 15 minute quadrangles are tested for intersection with the scene polygon. Quadrangles which do not intersect the scene or which are completely outside Wisconsin are skipped; in Figure 5 these are shaded. Processing continues with the next quadrangle east until the eastern extreme is reached; then the next row south is done. This strategy minimizes the amount of tape movement needed since it best follows the organization of the tape.

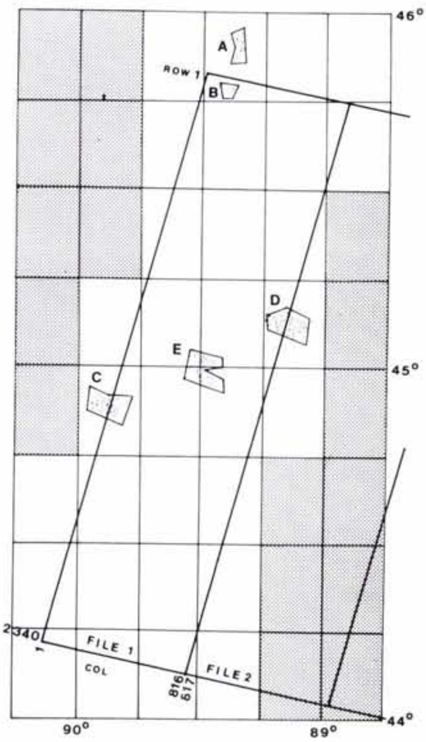

FIG. 5. Operation of program EXTRACT. Symbols are keyed to text.

If a quadrangle and the scene do intersect, then ACCESS is instructed to return the lake polygon for the first lake on the quadrangle, and its apexes are converted to Landsat coordinates. This converted polygon is tested for intersection with the scene (working only in Landsat coordinates). If there is no intersection (such as **A** in Figure 5), then the next lake on the quadrangle is called out of ACCESS, with processing passing to the next quadrangle when the last lake is finished.

If the lake does intersect the scene (e.g., **B** in Figure 5), its minimum and maximum Landsat rows are found and the tape is positioned to the beginning row. Then, row by row, the tape is read and data for all columns which are inside the converted lake polygon are extracted and tested. If Band 7 values are below a certain threshold (presently 10), picture elements are assumed to be water-like and data for Bands 4, 5, and 6 are extracted and stored in main memory. Cloud shadows can defraud this test, so careful selection of cloud-free scenes or omission of cloudy areas is required.

When all data for a lake have been extracted, the total number of water-like pixels is compared to the number expected. This value, from ACCESS, is optionally loaded into the file as EXTRACT is executed, provided more water-like pixels were found than had previously been stored. If at least half as many pixels are found now as were expected, statistics are calculated and stored in DATA-FILE; these include mean values and a variance- covariance matrix for Bands 4, 5, and 6 for all water-like pixels.

If too few pixels are found, there could be several causes. First, a lake may be only partially covered by a scene (**C** in Figure 5). If so, it can best be neglected now and processed later in another scene. Second, it may lie on the boundary between two files, as in **D** in Figure 5. All data for the lake are present on the tape, but it is inconvenient to mosaic the two files together. Instead, data are taken only from the file which contains the most pixels. Third, the navigation parameters may have been so far in error that the converted polygon missed the lake. We can either rerun the program later, introducing an appropriate offset for specific missed lakes, or we can choose an option to expand the lake polygon to the rectangle bounded by minimum and maximum rows and columns and repeat the extraction. This runs the risk of expanding a polygon into a neighboring lake, but this can be checked and corrected later.

Lakes may appear on more than one quadrangle (**E** on Figure 5). ACCESS will return this lake for any of the quadrangles, so a flag is set as each lake is processed. If the lake is encountered again it is skipped.

A character map is printed for each lake, usually on microfiche, showing pixels within the polygon. Water-like points are marked by "0's", edge pixels by "×'s", and non-water like points by "+'s." Figure 6 shows such pictures for several lakes included in Figure 1. If necessary, only every second or third row and column is shown to fit available space.

Two polygon processing subprograms made construction of EXTRACT easier. One, INTSCT, tests an arbitrary polygon for intersection with a convex polygon. It returns logical variables indicating whether the two intersect and whether one is a subset of the other. If they do intersect, it also returns a new apex list describing the intersection polygon. The second, BDYHIT, is called row by row for an arbitrary polygon and returns columns at which the row crosses the polygon.

Cost Factors

Preparation of lake polygons from nearly 350 map sheets required about six man-

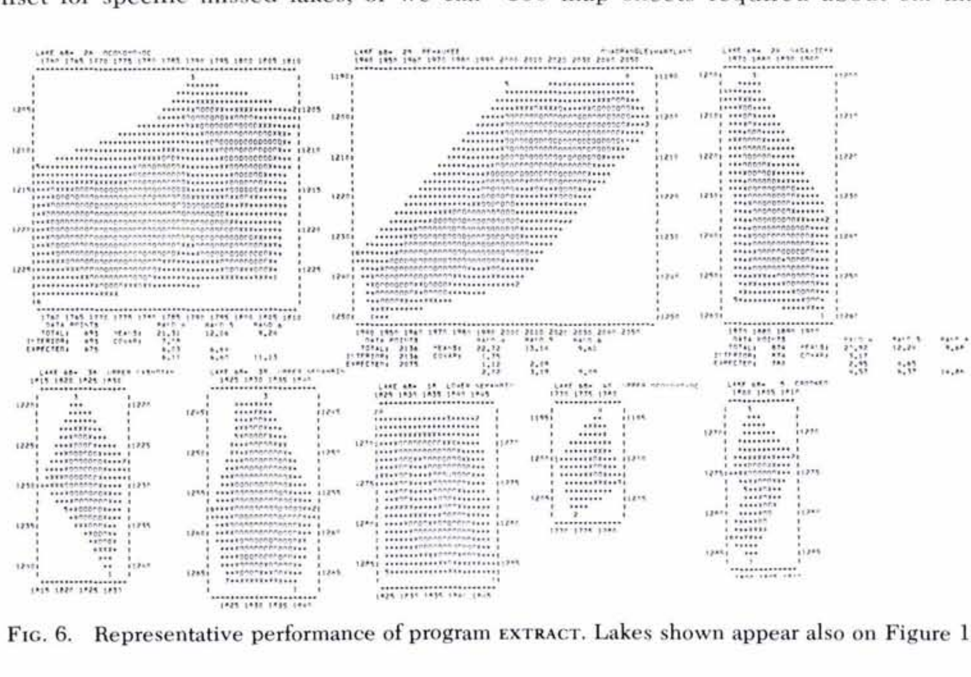

FIG. 6. Representative performance of program EXTRACT. Lakes shown appear also on Figure 1.

weeks. Digitization of 3,000 polygons and 335 control points cost $1,500. Creation and editing of ACCESS required perhaps $350 in computer charges.

Development of research computer prorams is hard to cost account. They required somewhere around one man-year; replicating them for another area would be much faster.

Files and programs have been evaluated by the DNR in a large-scale test project involving three dates each for two scenes in southern Wisconsin and one in the north central part of the state. Typical time requirements and charges will be about as follows for each Landsat scene:

- To extract and interpret about 50 control points:
  - One to two man-days
  - Computer charges—$30.00
- Scene navigation including error correction (three to four runs of SATNAV):
  - One man-day
  - Computer charges—$15.00
- Data extraction (two runs of EXTRACT, plus detailed examination of resulting output):
  - Two man-days
  - Computer charges: $120.00

Operational costs, and performance of the classification procedures described by Scarpace *et al.* (1978), appear quite promising. To classify all 3000 lakes in the system would require analysis of about 40 scenes to obtain the needed three lates per lake. We estimate that this would require a computer budget of about $5000, data costs of $8000 (at $200 per tape), and about 40 man-weeks.

Conclusions

An unusual approach to Landsat data extraction has been evolved and demonstrated. Use of ground coordinate systems to identify irregularly shaped areas which can be repeatedly accessed is a practical and economical method of restricting data set size. The method allows exploitation of Landsat's repeated coverage.

Inexpensive batch processing and simple geometric models can be used to navigate scenes without huge processing tasks to resample and remap data. For applications requiring statistical or aggregated information about areas, rather than precisely navigated pixel-by-pixel data, this approach should be considered.

Acknowledgments

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References

Bernstein, R. 1976. Digital Image Processing of Earth Observation Sensor Data, *IBM Jour. Res. Devel.*, Vol 20, No. 1.

Fisher, L. T., and F. L. Scarpace. 1975. Trophic Status of Inland Lakes from Landsat, Proc. NASA Earth Res. Survey Symp.

Heiber, R. H., W. Malila, and A. T. McClear. 1973. Correlation of ERTS MSS Data and Earth Coordinate Systems, Proc. Conf. Mach. Proc. Remotely Sensed Data, Purdue Univ.

Scarpace, F. L., L. T. Fisher, and R. Wade. 1974. Lake Classification Using ERTS Imagery, Proc. Symp. on Remote Sensing and Photo Interp., Comm. G, ISP, Banff, Alt.

Scarpace, F. L., K. Holmquist, and L. T. Fisher. 1978. Landsat Analysis of Lake Quality for Statewide Lake Classification, Proc. ASP.

Scherz, J. P., M. Adams, F. L. Scarpace, and W. J. Woelkerling. 1977. Assessment of Aquatic Environment by Remote Sensing, IES Report 84, Univ. Wis.-MSN.

Van Wie, P. and M. Stein, 1977. A Landsat Digital Image Rectification System, *IEEE Trans. Geoscience Electronics*, Vol. GE-15, No. 3.

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