Evaluation of Landsat-Based Area Measurement Accuracies for Surface Water Area in New Mexico

Principal Investigators:

Mike E. White
Technology Application Center
University of New Mexico

and

Dr. Stanley A. Morain
Geography Department
University of New Mexico

Technical Completion Report Project Nos. 3109216, 1345631

University of New Mexico, Department of Geography in cooperation with the Technology Application Center, University of New Mexico and with the New Mexico Water Resources Research Institute, New Mexico State University.

The work upon which this publication is based was supported in part by funds through the New Mexico Water Resources Research Institute by the State of New Mexico through state appropriations and by the United States Department of the Interior, Office of Water Research and Technology as authorized under the Water Resources Research Act of 1964, Public Law 88-379, under project numbers 3109216, 1345631.

The authors would also like to thank Mr. Dale Gehring of the U.S.G.S. EROS Data Center for his help in performing the automated image classification.

ABSTRACT

An effort to refine the techniques and methodology used in a previous WRRI project and to establish a better understanding of the data accuracy requirements of water resource management agencies are described. The objectives of this research were: 1) to identify the data accuracy requirements of resource management agencies who create or utilize reservoir volume statistics, and 2) to compare those requirements against measurements of surface water area taken from Landsat reflective infrared (band 7) imagery and digital data tapes by digital and areal measuring methods. Project results show that the maximum amount of tolerance acceptable would be ±20%. However, it was suggested that in all cases a ±10% accuracy range would be more useful.

The results for objective number two indicate that consistent and reliable measurements of reservoir surface areas from Landsat satellite data are possible. It appears that a computerized digital measuring technique such as the *Image 100* can be used now to make reservoir surface area estimations. It is also possible that measurements from the planimeter and image scales of 1:250,000 can be improved to meet the desired accuracy levels. Further work needs to be done to improve on the measuring techniques and procedures to provide data with a known variance and reliability. There is also room for newer and more advanced classification and measuring techniques to be evaluated. One such technique would be automated

image classification using unsupervised statistical classifiers. Other image processing systems which are more economic to run and easier to operate than the *Image 100* should also be investigated.

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I. PROBLEM DEFINITION

A. Introduction

The amount of fresh water available for consumption in New Mexico is severely limited. Except for small amounts of surface water, all of New Mexico's potable water supplies are allocated and in beneficial use as defined by the New Mexico State Engineer's Office.

Because of New Mexico's arid and semi-arid climate, little additional water is added to the state's resources through precipitation. Evaporation and evapotranspiration within the state are very high. Of the approximately 85 million acre-feet supplied each year from precipitation, an estimated 82 million are returned to the atmosphere or enter ground water aquifers prior to any designated beneficial use. The remaining 3 million acre-feet contribute to surface stream runoff and about 1 million acre-feet of this are returned to the atmosphere.

Numerous reservoirs have been developed on the major drainages in New Mexico to control sedimentation and flooding, and to act as major recreational and water storage facilities. This study investigated six of these reservoirs: Navajo, Heron, Conchas, Elephant Butte, Caballo and Abiquiu. These reservoirs were primarily constructed for irrigation water storage, flood control, and as desilting pools. They are all used for recreational purposes, and the associated economic impact of these on the surrounding local economy is significant (Coppedge and Gray, 1968).

Few recreational activities have any effect on the major uses of these reservoirs. However, the reverse is not true. Primary uses, such as irrigation water storage and river regulation, require given amounts of outflow from each reservoir to meet established needs. Outflow is at its peak during the spring and summer growing period, whereas inflow is highest during early spring and diminishes during the summer and autumn months. Lake level fluctuations associated with each reservoir's water budget directly impact on the aesthetic and physical value of the recreation obtainable at the reservoir.

Each reservoir has minimum pool levels established for secondary uses. For example, a minimum pool may be established to ensure survival of fish, or to serve as a "dead" pool for desilting. Each beneficial use of a reservoir's water has an economic value attached to it. As the water level fluctuates, economic values adjust accordingly. The multiple use of water constitutes a set of dependent variables, dependent not only on water level, but also on each other. New Mexico's rapidly expanding population and the resulting increased demand on the state's water resources is another factor affecting the interrelationships of the economic values attached to beneficial water uses.

The increased demand for water in New Mexico will require new management decisions to be made. Improved resource data collection methods might aid significantly in making these decisions. Past research at the University of New Mexico's

Geography Department and the Technology Application Center has established promising procedures that could lead to routine, practical and cost effective approaches for measuring the surface water area of New Mexico's reservoirs (Morain and White, 1976; White 1977). This report presents results of a research project based on these past efforts. The objectives of this project were to: 1) compare the required accuracies with measurements obtained from Landsat imagery; and 2) identify the surface area measurement accuracies needed by resource managers.

B. Literature Review

Several investigators have shown that remote sensing provides a useful methodology for mapping the spatial distribution of standing surface water (Brown, et.al., 1975; Work and Gilmer, 1976). Stoertz and Carter (1973), Salomonson and Rango (1973), and Brown, et.al, (1975), have used Landsat imagery to make regional inventories of impounded surface water. The use of Landsat imagery for detecting and measuring seasonal lake level fluctuations has been fairly successful (Burgy, 1973; Lind, 1973; and Reeves, 1973). A logical extension of these applications lies in measuring reservoir volumes through the measurement of reservoir surface areas.

Few published reports address this facet of the water resource management picture. Inglis (1975), Colcord (1975) and White (1977), have looked at measuring water surface area from Landsat imagery as a means of estimating reservoir volume. To varying degree, their results indicate good potential, but all show a need for further refinement. The relationship between reservoir basin morphology and water surface area has been referred to by Lind (1973), Burgy (1973), Reeves (1973) and White (1977). Each author has noted that the steepness of the basin profile directly affects the area of exposed surface water and, therefore, the detectability of temporal surface area changes.

C. Background and Objectives

White (1977) discusses a methodology and results of a prior effort upon which this project is based. The objectives of the earlier project were to examine a variety of techniques for measuring reservoir surface areas and to compare their accuracy with data reported by cognizant agencies. Related research questions included: (a) which measuring techniques provide surface area measurements that best meet the U.S.G.S. and Corps of Engineers' required ±10% accuracy?; (b) which image scales are most accurately measured?; and, (c) does reservoir basin morphology affect the accuracy of area measurements?

The results of White's study show that, although several of the techniques studied provided acreage estimates which approached the actual field data*, none was able to measure all of the reservoirs with consistent accuracy. Several explanations for the poor data accuracies, along with some

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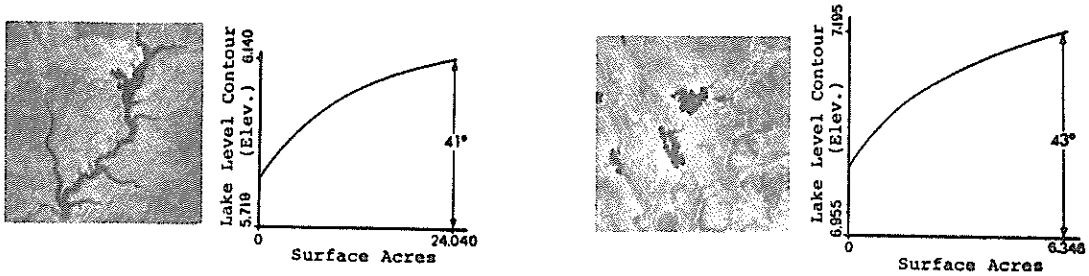
* field data were derived by interpolation, for a detail description of the interpolation procedure see White (1977), pages 18-21.

suggestions for further research, were presented. The present project is a direct extension of the conclusions and suggestions outlined in that earlier work.

For consistency between the studies, the same six New Mexico reservoirs studied by White (1977) were selected. These were: Navajo, Heron, Abiquiu, Conchas, Elephant Butte, and Caballo. The heterogeneity of these reservoirs allows comparisons to be made between measurement accuracies achieved from simple versus complex shorelines and steep versus gently sloping basin profiles. Figure 1 shows the geometric configurations and the basin gradients for each of the six reservoirs. Table 1, gives the dates for which Landsat images were obtained and the associated seasonal surface area fluctuations for the reservoirs studied. Where possible, Landsat band 7 infrared images were obtained for each reservoir during each season.

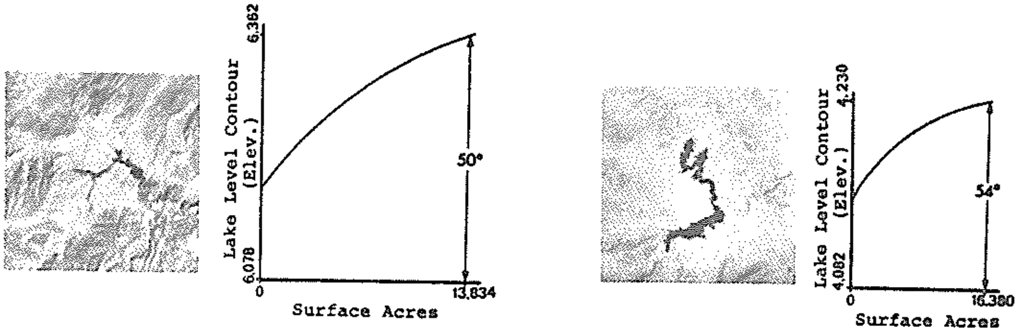
Four measuring techniques were used by White (1977) to measure surface water acreages from the Landsat images. They ranged in sophistication from: 1) a dot grid with 64 dots per square inch to, 2) an electronic 16-level density slicer. The other two instruments were: 3) electronic digital planimeter with a plotting accuracy of .01 inches; and 4) a 32-level density slicer.

Only three of the twelve combinations (3 scales; 1:1,000,000; 1:500,000; and 1:250,000 x 4 measurement techniques) evaluated produced data with mean percentage errors



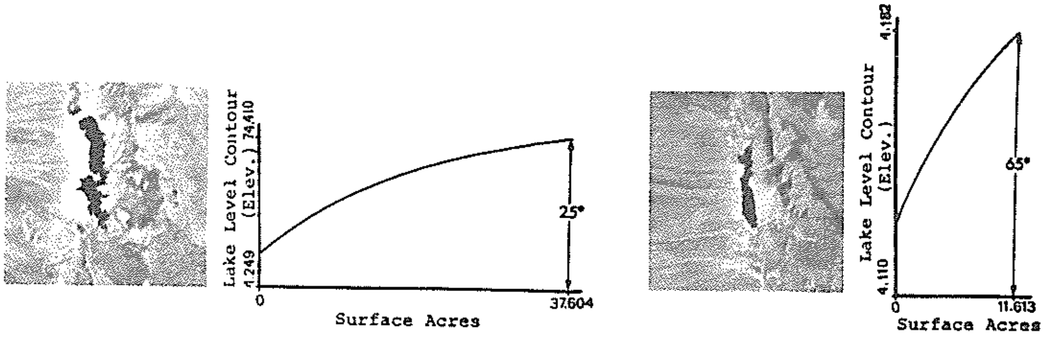
NAVAJO RESERVOIR
complex/gentle

HERON RESERVOIR
simple/gentle



ABIQUIU RESERVOIR
complex/steep

CONCHAS LAKE
complex/steep



ELEPHANT BUTTE RESERVOIR
complex/gentle

CABALLO RESERVOIR
simple/steep

Figure 1: Shoreline configurations and basin gradients of reservoirs studied (from White 1977).

RESERVOIR	IMAGE DATE	SURFACE AREA FLUCTUATION IN ACRES*
NAVAJO	Jan 30	
	May 18	+3122
	Jul 29	+2636
	Oct 27	-2832
HERON	No Useable Imagery	
	May 17	
	Aug 15	+1658
	Oct 27	+16
ABIQUIU	No Useable Imagery	
	May 17	
	Aug 15	+454
	Oct 26	-18
CONCHAS	Mar 4	
	Apr 27	+1380
	Aug 13	+611
	Oct 6	-850
ELEPHANT BUTTE	Mar 6	
	May 17	+827
	Aug 15	+4099
	Oct 26	-790
CABALLO	Mar 6	
	May 17	+1106
	Aug 15	-684
	Oct 26	-2178

TABLE 1: Dates for which Landsat images were selected to provide seasonal coverage (from White 1977).

* Figures represent the variation in reservoir surface area from the previous image date. Positive figures indicate an increase in area, negative figures show a decrease in area.

within the ±10% range.* They were:

1) the dot grid with 1:250,000 scale imagery;

2) the planimeter with 1:500,000 scale imagery; and,

3) the planimeter with 1:250,000 scale imagery.

None of the techniques employed could consistently measure reservoir surface areas within the required ±10% error range.

The current project is an effort to refine and extend the techniques used in the previous effort and to establish a better understanding of the data accuracy requirements of water resource management agencies. Specifically, the objectives were to: 1) identify the data accuracy requirements of resource management agencies who create or utilize reservoir volume statistics, and 2) compare those accuracy requirements against measurements of surface water area taken from Landsat data (both imagery and computer compatible tape) by digital and areal measuring methods. Extensions of this project to White's original effort include:

- Evaluation of a fine mesh dot grid to see what measurement improvement might be obtained over our previous use of 1 dot = 2500 ac. This would be the simplest and least costly technique available, but one which could be easily implemented, if desired accuracies can be achieved.

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* The ±10% accuracy range was suggested by the Corps of Engineers for use in the previous project as being the limit of accuracy of water resource data published by federal reporting agencies. We have used this number as a working number pending the results of the survey in the present project.

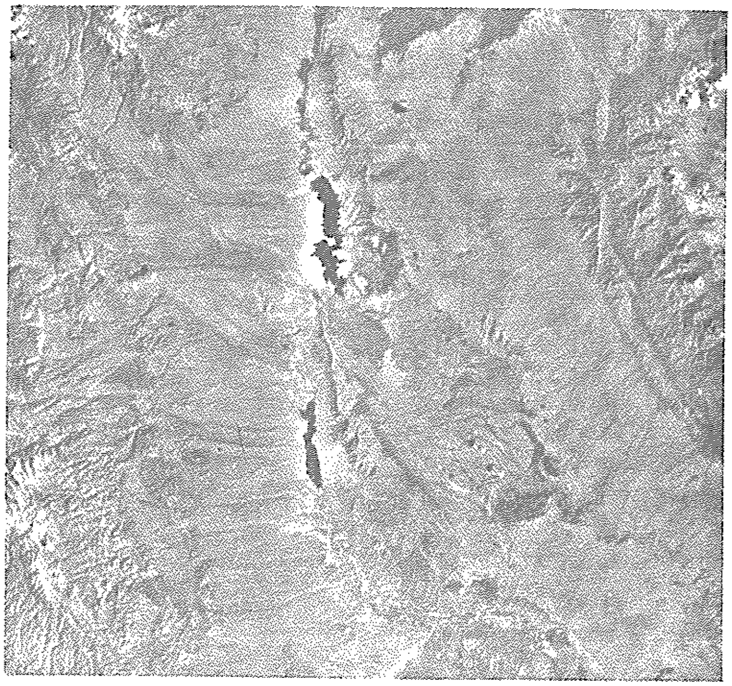
- An electronic planimeter - The effort here was to determine whether higher contrast images yield improved accuracy over those already investigated by White.
- Analysis of Landsat data tapes to see if pixel-by-pixel counts could provide sufficiently better acreage estimates than the above techniques.

Landsat Data Base

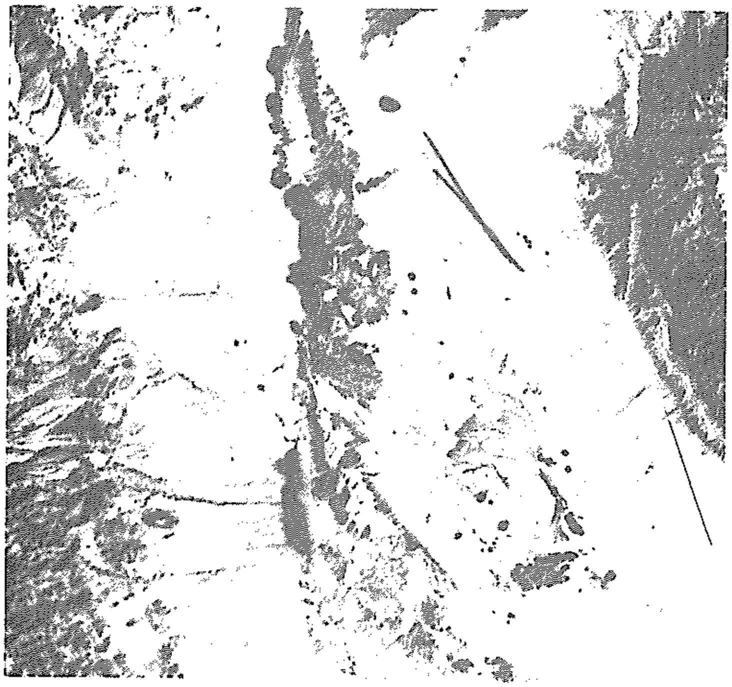
Only one significant difference exists in the Landsat data base used in the current project and that of the previous one. In the first project White utilized continuous tone negative images as a base for making his measurements. His reasons for using negatives were founded primarily in the data format needed by the density slicing techniques used. In his conclusions he has explained a number of problems related to the imagery format which he encountered and has described possible solutions. One idea was the production of the images on high contrast black and white film to help clarify the shoreline/water interface and eliminate the photographic "halo" around the reservoirs caused by the number of grey tones available in the continuous tone film. Figure 2 shows the difference between a continuous tone image and high contrast image. Table 2 provides the scene identification numbers, dates, percent cloud cover and scene quality for the images used in this project.

Scale

The same three image scales (1:1,000,000, 1:500,000, and 1:250,000) were used to evaluate the importance of this



Continuous Tone Landsat Image



High Contrast

Figure 2: Comparison of Continuous Tone and High Contrast Reproductions of Landsat Image over Elephant Butte and Caballo Reservoirs.

RESERVOIR	SCENE IDENTIFICATION NUMBER	DATE 1973	SCENE CLOUD COVER	SCENE QUALITY
NAVAJO	1191-17204	30 Jan	0%	Good
	1299-17205	18 May	5%	Good
	1371-17200	29 Jul	30%	Fair
	1461-171681	27 Oct	0%	Good
HERON	No Useable Imagery	------	---	----
	1298-17153	17 May	15%	Fair
	1388-17143	15 Aug	15%	Fair
	1461-17181	27 Oct	0%	Good
ABIQUIU	No Useable Imagery	------	---	----
	1298-17153	17 May	15%	Fair
	1388-17143	15 Aug	15%	Fair
	1460-17125	26 Oct	15%	Good
CONCHAS	1224-17042	4 Mar	30%	Poor
	1278-17044	27 Apr	0%	Good
	1386-17030	13 Aug	8%	Good
	1440-17015	6 Oct	0%	Good
ELEPHANT BUTTE	1226-17163	6 Mar	20%	Fair
	1298-17162	17 May	15%	Good
	1388-17152	15 Aug	15%	Fair
	1460-17134	26 Oct	0%	Good
CABALLO	1226-17163	6 Mar	20%	Fair
	1298-17162	17 May	15%	Good
	1388-17152	15 Aug	15%	Fair
	1460-17134	26 Oct	0%	Good

TABLE 2: Landsat image scene identification numbers and image quality data (from White 1977)

parameter on the accuracy of the measurements obtained from the dot grid and planimeter.

One of the principle extensions of White's previous work was the possible gain in measurement accuracy by using Landsat digital tapes. Each Landsat image is generated in four spectral channels and each channel is comprised of 2298 scan lines of 3240 radiance samples. Each sample in each scan line is referred to as a "pixel." For the infrared spectral channel, pixels recorded over water have very low radiance values; those recorded for land have higher values. Pixels that contain elements of both water and land (shoreline) have intermediate radiance values and these are the ones that cause ambiguity in lake area measurement accuracies.

All of the studies reviewed (including White's) have been based on image interpretation rather than pixel digital values. By convention, images produced from tapes utilize every 4th sample and every 4th scan line, or only 1/16th of the total data available. Further data degradations are suffered each time the images are processed by photographic or analog techniques. Measurement accuracies are therefore, greatly affected by poor resolution. By utilizing the data tapes, full resolution can be restored to the scene, thereby increasing measurement accuracy to the maximum obtainable. Each pixel is equivalent to about 1.1 acre, so the maximum error suffered depends on the number of pixels defining the shoreline. This number is, in turn, related to the intracacies of shoreline configuration.

II. TECHNIQUES AND METHODOLOGY

A. Survey of User Accuracy Needs

In the survey of water resource management and user agencies letters were sent requesting information on data accuracy needs. Appendix 1 provides a list of the agencies to whom letters were sent and also a copy of the solicitation letter. There were 25 responses to the 40 letters mailed.

Responses show that the maximum acceptable tolerance is ±20%. In all cases it was suggested that a ±10% accuracy would be more useful. In most instances the accuracy requirements vary according to reservoir use and season. Agencies such as the Bureau of Land Management, whose charters are to manage multiple resources other than just water, tend to have the wider tolerance ranges. On the other hand, agencies such as the River Forecast Center of the National Weather Service need at least ±10% surface area accuracy.

Requirements change with reservoir use. Reservoirs maintained for flood control, irrigation and multiple uses have the most stringent data requirements, at least ±10% accuracy. Impoundments used primarily for desilting and stock watering ponds have more relaxed requirements ranging between ±20 to 25% of the actual quantity. In the case of desiltation impoundments the need for accurate surface area data is somewhat higher, ±10 to 15%, than for volume data (±10 to 20%).

Accuracy needs also change with season. As would be expected, the greatest degree of accuracy required is during the peak use seasons of spring and summer. This appears to be especially true in areas outside the major river valleys or in rainfall-dependent areas. One would expect that as the overall accuracy of reported data improves, the variations in seasonal requirements would diminish.

Another factor influencing minimal acceptable accuracies is the associated data with which they are to be used. For example, the State Health and Social Services Department uses reservoir area and volume data in the development of nutrient loading models. Other data used in their models have relatively high degrees of accuracy (±2 to 3% in many cases). Thus, to utilize acreage or volume data of a much lower degree of accuracy might seriously diminish the validity of their model.

In our first study, the reservoir surface water records reported by the Corps of Engineers and the U.S.G.S. Water Resources Division were reported to be within ±10% of actual water quantities. During the completion of the first objective of this project however, communication with personnel at the Corps of Engineers indicated that the ±10% tolerance range is only approximate. A letter received from Mr. Jasper Coombs*, Chief of the Engineering Division, Albuquerque District Corps of Engineers, goes on to explain that..."Area capacity tables are periodically compiled from topographic data and hydrographic surveys for reservoirs under control of the Corps of Engineers, however their accuracy is not determined." Two of the six reservoirs in this study (Conchas and Abiquiu) are under Corps of Engineers control. Data for

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* personal communication

the other four are provided by the Bureau of Reclamation. Their data are collected and reported in the same manner as the Corps of Engineers. Apparently there are a number of reservoirs for which no error analyses have been performed. Thus, we can only assume that the reported surface areas are within the ±10% tolerance range prescribed by federal statute.

B. Area Measuring Techniques

Three measuring techniques were used to obtain acreage data from the Landsat imagery. They were: 1) a standard dot grid, 2) an electronic planimeter and 3) the *Image 100* digital image processing system at the U.S.G.S. EROS Data Center in Sioux Falls, South Dakota.

1. Dot Grids

Three different dot grid densities were used to take measurements from each of the three image scales. The coarsest dot grid had a density of 16 dots per square inch, the intermediate grid had 64 dots per square inch and the finest one had 256 dots per square inch. Figure 3 shows a sample portion of each dot grid and the acreage represented by each dot at the three image scales. The procedure used to measure the lake surface area was to count every dot in the water area and alternate dots which fell in the water/land interface around the lake. Three measurements were taken for each lake and season and were then averaged to produce one surface area value.

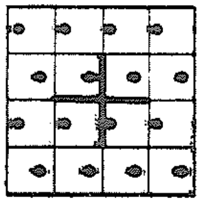
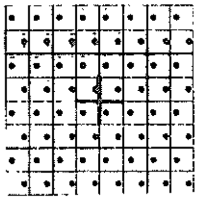
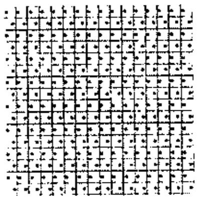
		At an Image Scale of:	1 dot	Acres
16 dots per sq in		1:1M ..	1 dot =	9963.91
		1:500K ..	1 dot =	2490.98
		1:250K ..	1 dot =	622.74
64 dots per sq in		1:1M ..	1 dot =	2490.98
		1:500K ..	1 dot =	622.74
		1:250K ..	1 dot =	155.69
256 dots per sq in		1:1M ..	1 dot =	622.74
		1:500K ..	1 dot =	155.69
		1:250K ..	1 dot =	38.92

Figure 3. Dot grid densities and acreage equivalents as a function of image scale (M = 1,000,000, K = 1,000)

2. Electronic Planimeter

The other measuring technique used to take acreage data from the imagery was an electronic digital planimeter, Figure 4. The planimeter tracing unit used to delineate the surface water area had a plotting accuracy of .01 inches. Measured areas were automatically converted into scaled acreages.

3. Image 100

The *Image 100* (Figure 5) is an interactive multispectral digital image analysis system which manipulates and classifies digital data using a series of "hardwired" programs.* The *Image 100* uses a PDP 11/35 computer linked to an image analysis console and maximum likelihood classification algorithms. In this project, data were entered into the analysis system via Landsat computer compatible tapes (CCT's). Reservoir surface area measurements were obtained by counting the number of pixel digital values classified as water.

The basic concept of image classification relies on the premise that earth terrain features having similar characteristics reflect equal amounts of electromagnetic energy. Therefore, when their spectral reflectances are recorded via a system such as the Landsat MSS, their radiant values can be used to segregate and group them apart from features having different responses, i.e., a unique signature is identified. The simplest electronic form of image classification is density slicing.

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* "hardwired" in this context means "unalterable." The software is not interactive but rather is "fixed." The operator can only choose whether or not to call a routine.

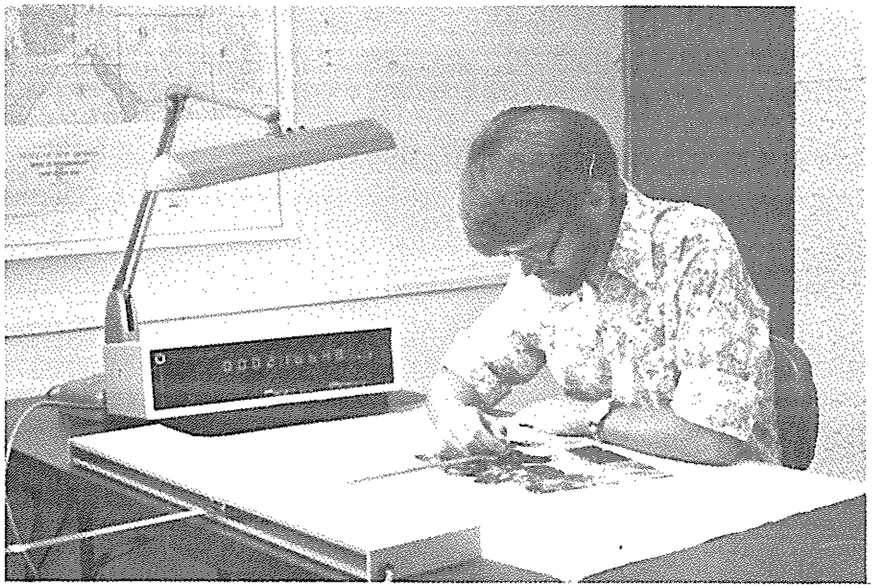


Figure 4: Numonics Electronic Planimeter

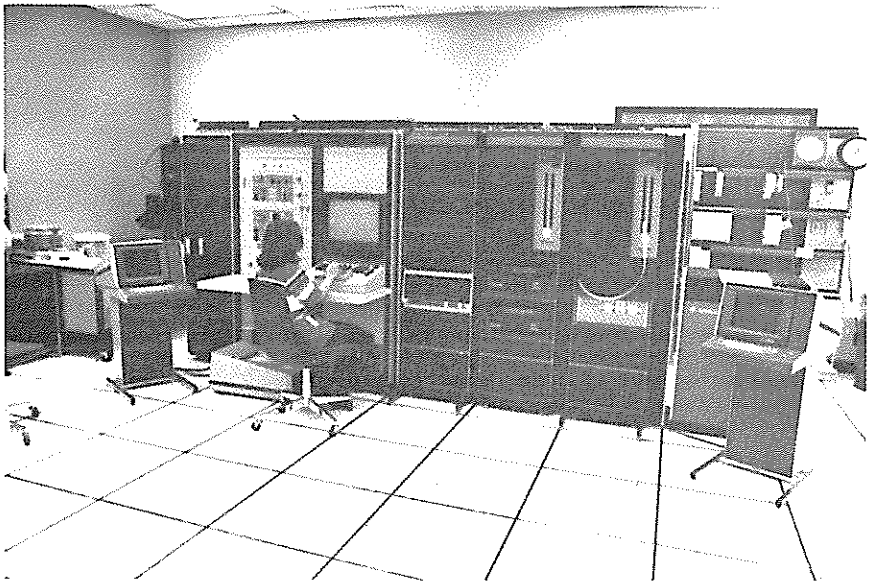
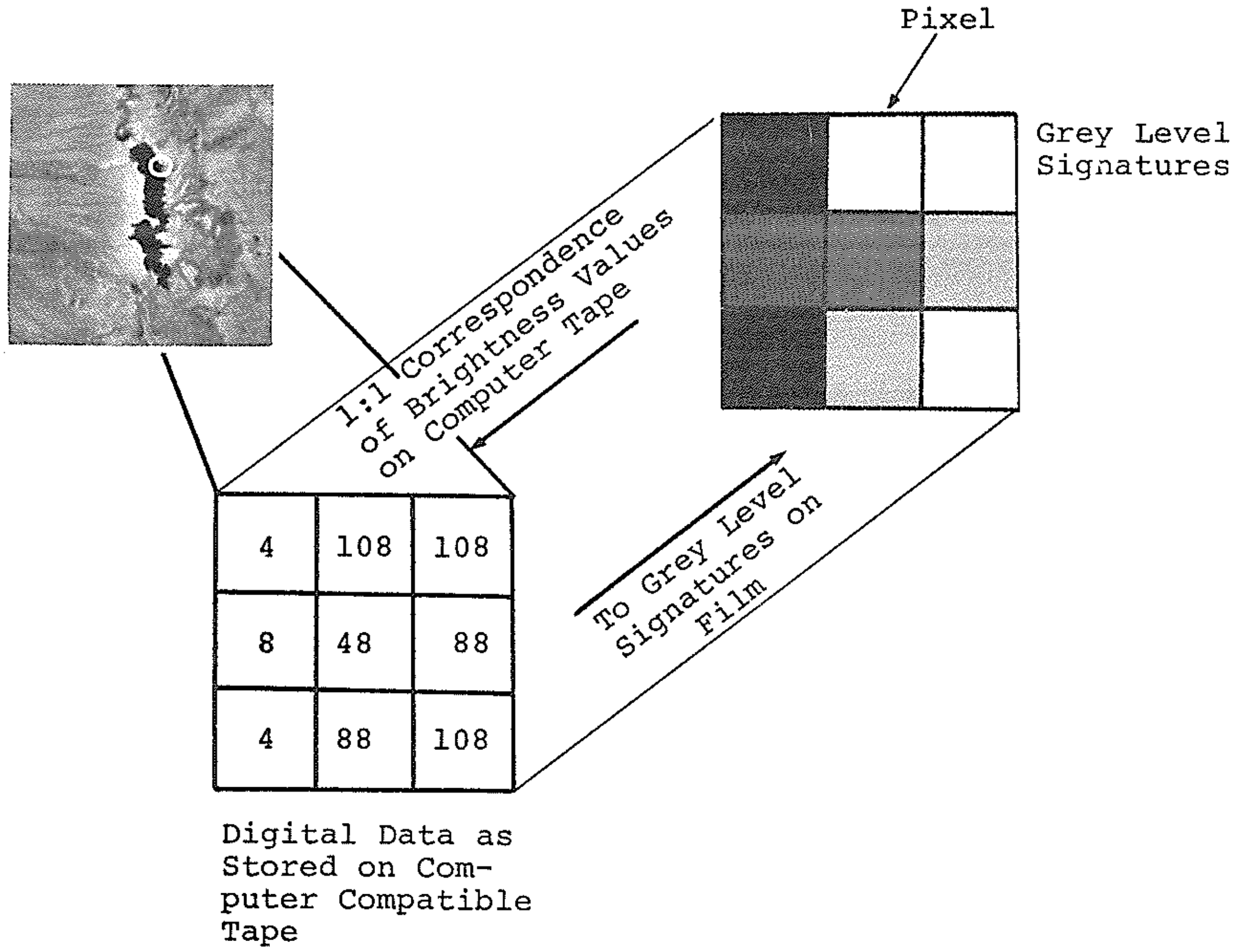


Figure 5: U.S.G.S. EROS Data Center Image 100 Digital Image Processing System

The *Image 100* has a density slicing function which utilizes the recorded digital values for each pixel as read from a CCT. The system scans the tape for all pixels having the same spectral signature. The system operator utilizes a cursor to delineate on a television screen the image area to be classified. The cursor is also used to identify, within the computer, which pixels are representative of the type to be classified. The computer scans the digital values for the image and classifies all pixels having the designated signature. These "classified" pixels can be assigned a color on the television screen to help the operator refine the classification. Several statistical algorithms are also available to operate on the digital image and refine the image classification.

A digital image is a two-dimensional matrix of integers corresponding to individual pixel digital values. When presented in film format these values form a checkerboard pattern. When recorded on magnetic tape, the same digital image can be expanded and separated into as many as 256 levels, thus the discrimination of earth terrain features is greatly enhanced. Figure 6, is an example of a reservoir shoreline with corresponding digital values and image grey levels. In a digital image, an integer value of 0 represents no detector response and a value of 255 indicates saturation of the detector. When observed on a black and white band 7 image, a 0 value could indicate either clear water or terrain shadows, among other phenomena; and a value of 255 could represent such features as snow cover or clouds.



4	108	108
8	48	88
4	88	108

Figure 6. Relationship between Landsat image, digital brightness values and single pixel grey level signatures (modified from: Condit, C.D. and Chavez, P.S., Jr., 1977).

If further discrimination is needed in the digital image, an image enhancement technique called "contrast stretching" can be employed. Contrast stretching is the expansion of a set of digital values to occupy the entire 0-255 range. This can be accomplished on the *Image 100* by displaying a histogram of the digital pixel values (Figure 7). The operator can then decide which radiance values to delete or expand on the image. By setting the upper bound of the histogram to a selected radiance value those pixels having a brighter signature can be eliminated. The upper bound can then be repositioned to include the entire 0-255 range. In this way values remaining in the histogram are reassigned to occupy the full range. Figure 7B shows the same histogram as in Figure 7A but the upper bound has been set to exclude all brightness values greater than 14. Figure 7C is the result when the remaining data from Figure 7B are reassigned and spread to occupy the full available range. The image classification strategy used in this project incorporated several levels of pixel signature discrimination.

A series of procedural steps was developed for measuring reservoir surface areas using the *Image 100*. Elephant Butte reservoir is presented here to illustrate the methodology used.

Elephant Butte reservoir is located on the Rio Grande river along the western slope of the Fra Cristobal Mountains (Figure 8). The steep slopes and cliff faces of the range form much of the eastern shoreline of the reservoir. Thus, at 9:30 in the morning when Landsat passes over, long shadows

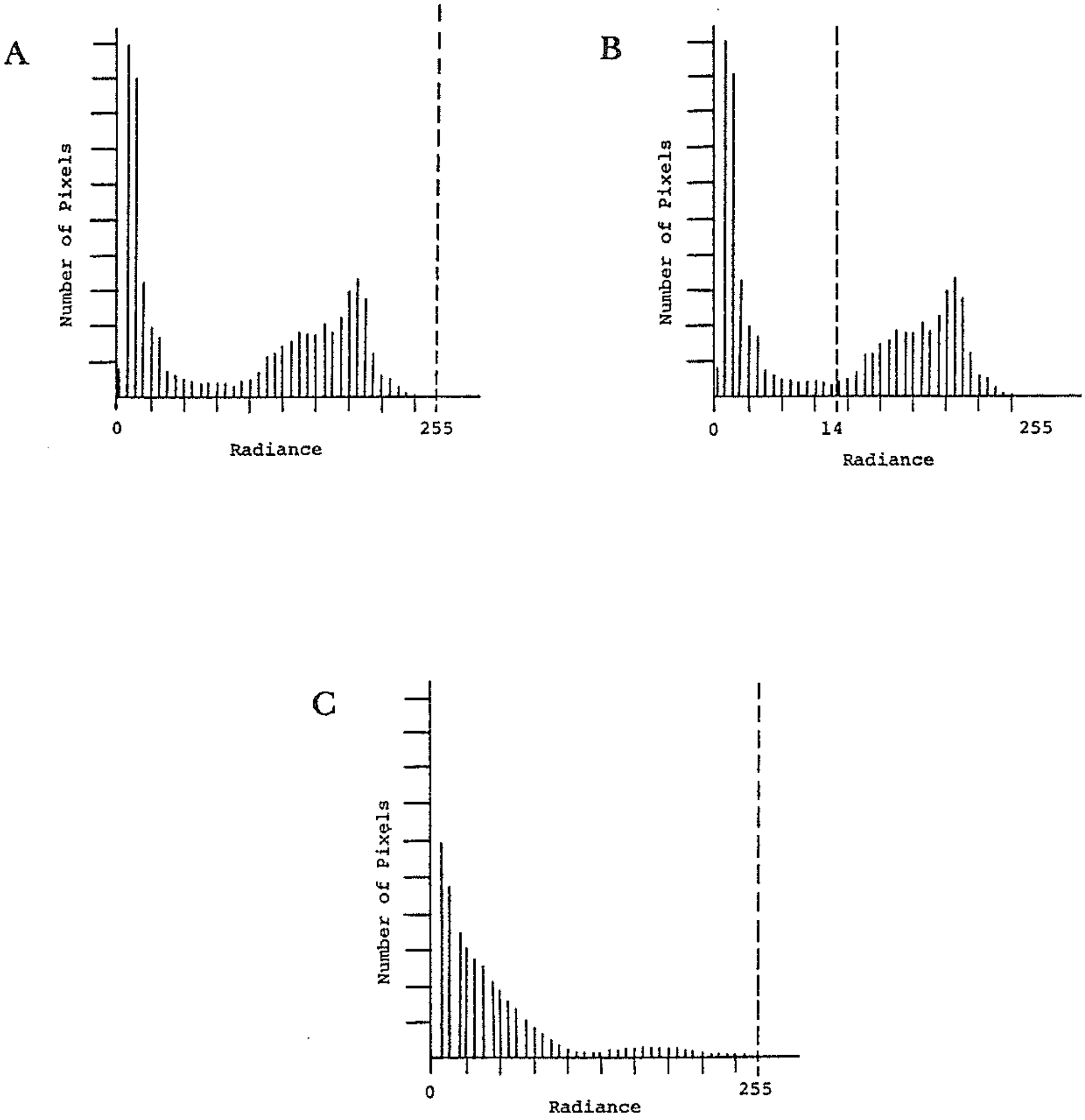


Figure 7: Radiance values for Band 7 (.8-1.1µm) of Elephant Butte Reservoir and the surrounding area (A). The upper bound of acceptable radiance is set at 14, thereby including all water, algae, and darker soils (B). In the final step (C), the remaining pixel values are reassigned to occupy the entire 0-255 radiance range.

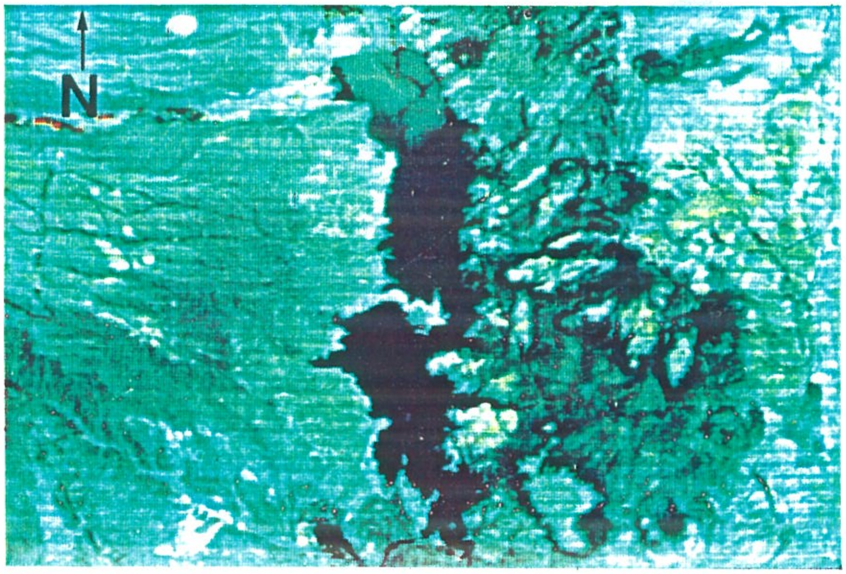


Figure 8: Physical setting of Elephant Butte Reservoir. The Fra Cristobal Mountains to the east cast long shadows over the eastern shoreline at 9:30 in the morning, while the saturated basin fill along the western shoreline presents another shoreline discrimination problem. Both environmental factors affect the accuracy with which reservoir surface area can be measured.

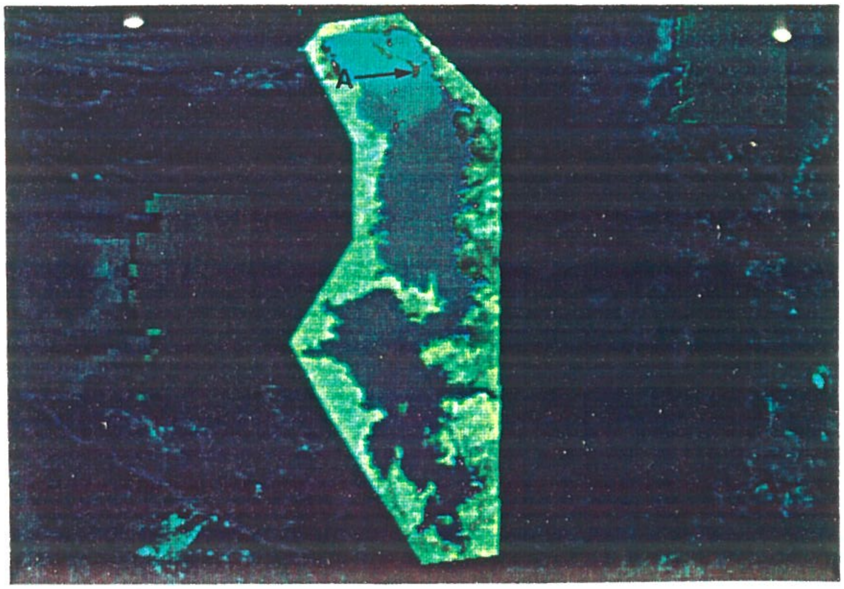


Figure 9: A Band 7 density slice of Elephant Butte provides a preliminary surface area measurement and identifies areas having shoreline discrimination problems. It also shows another classification problem; an algal bloom in the northern end of the reservoir(A). Shading in the reservoir shows different turbidity loads maximum sediment is in the northern end, gradually decreasing to relatively clear water at the southern end of the reservoir.

are still present along some areas of the eastern shore. The western shoreline is formed by low lying hills with gentle slopes extending into the reservoir. The physical setting of the reservoir therefore presents both a gentle shoreline with a saturated water/land interface (but without shadows), and a steep rocky shoreline with almost no horizontal extent of the water saturated zone (but with strong shadowing). These two attributes, shadowing and bank saturation, present problems when trying to precisely locate the water/land interface. In the case of shadows, the spectral signature is almost exactly that of water, but in the case of a water saturated shoreline, the spectral response can be similar to either water or land, depending on the amount of bank storage. The first case results in errors of commission when estimating area but the second can result in either errors of omission or commission.

The first step in our surface area measurements required a band 7 density slice which would serve two purposes: 1) it would provide a preliminary reservoir surface area measurement; and 2) it could be used to identify shoreline areas with either shadowing or bank storage problems. It also identified a third classification problem; namely, the discovery of an algal bloom in the northern end of the reservoir. During the initial surface area measurement by density slicing, the bloom was not included. Figure 9, shows the Elephant Butte reservoir and the bloom as highlighted by the band 7 density slice. The area to be digitally classified is outlined in yellow. The area measured by density slicing (shown as white in Figure 10) was 10,596 surface acres. Field data for the reservoir was 12,122 acres. The bloom area not included in the surface area measurement is shown in Figure 11.

The second step in our classification was to plot a histogram of pixel values. The upper bound was set to include water pixels along the shoreline. Figure 12 shows representative pixels along the shoreline which were not included in the first surface area measurement. Pixel values for the algae were so high that, to include them, we would have included much extraneous area peripheral to the reservoir. Therefore, its area was measured separately and added to the overall classified surface area. The acreage added by the algae and near shoreline pixels (displayed in white in Figure 13) was 293 acres. The total area classified as water was thereby increased to 10,889 acres, which is within 9% of the interpolated area for that date (Figure 14). In all, four reservoirs (Navajo, Heron, Elephant Butte and Caballo) were measured using the *Image 100* by the procedure just described. Because of cost restrictions, these lakes were measured for only one season each.

III. RESULTS

Table 3 shows the overall percentage errors for each measuring technique and scale combination investigated. Four of the combinations produced results with overall errors of less than 10%. The best result (.7%) was recorded for the electronic planimeter at a scale of 1:250,000. The planimeter

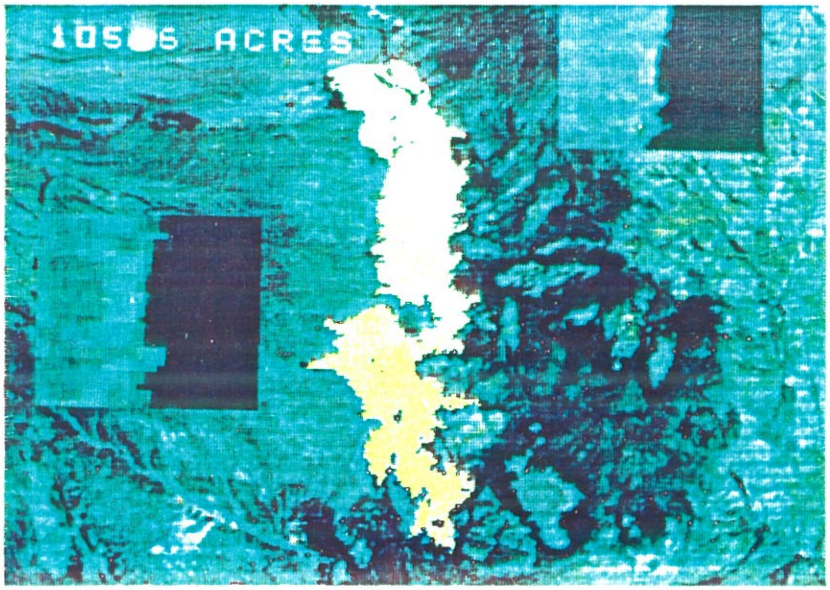


Figure 10. The initial surface area measurement obtained by the Band 7 density slice was 10,596 acres. The reported surface area by interpolation of published data was 12,122 acres. This represents a discrepancy of 13%.

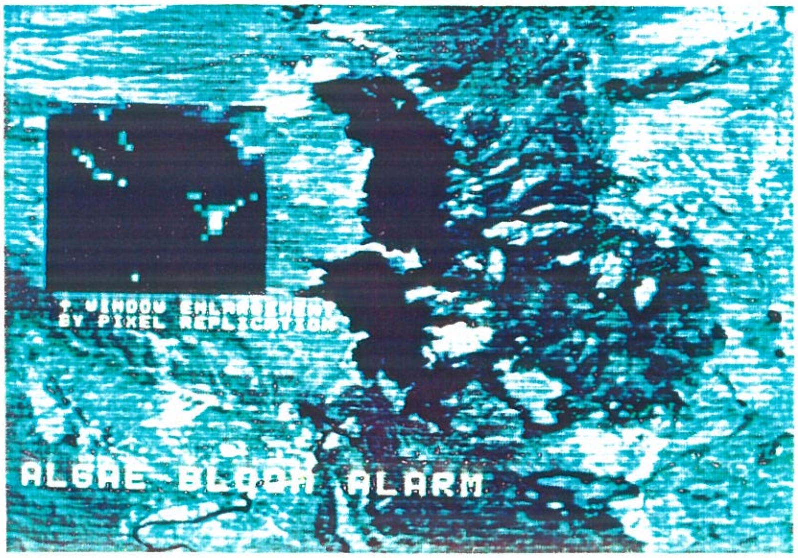


Figure 11. The algal bloom area as identified by the Band 7 density slice. This area had to be measured separately because even though it coincides with water surface, its spectral response is that of a vegetated surface.

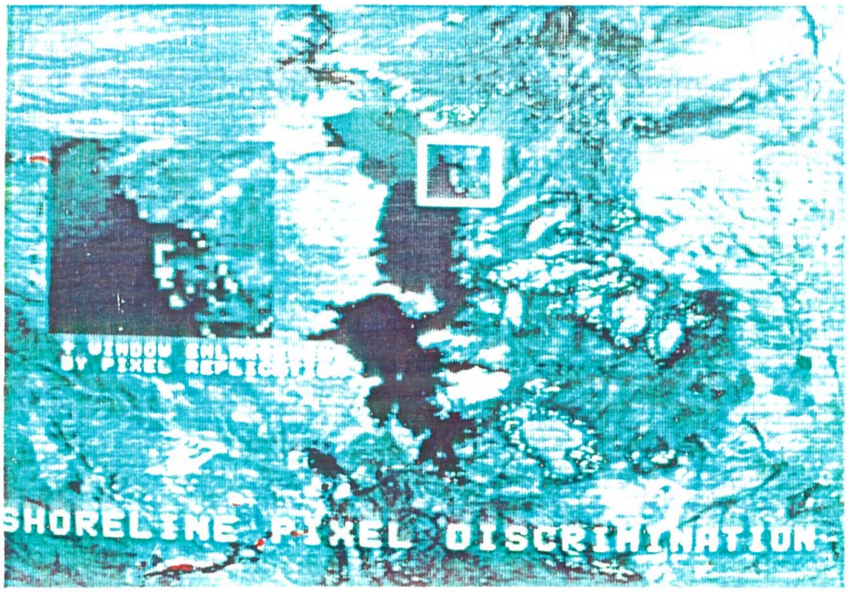


Figure 12. Typical area with shoreline pixel discrimination problem. Area at left is a 4x enlargement of the blocked area.

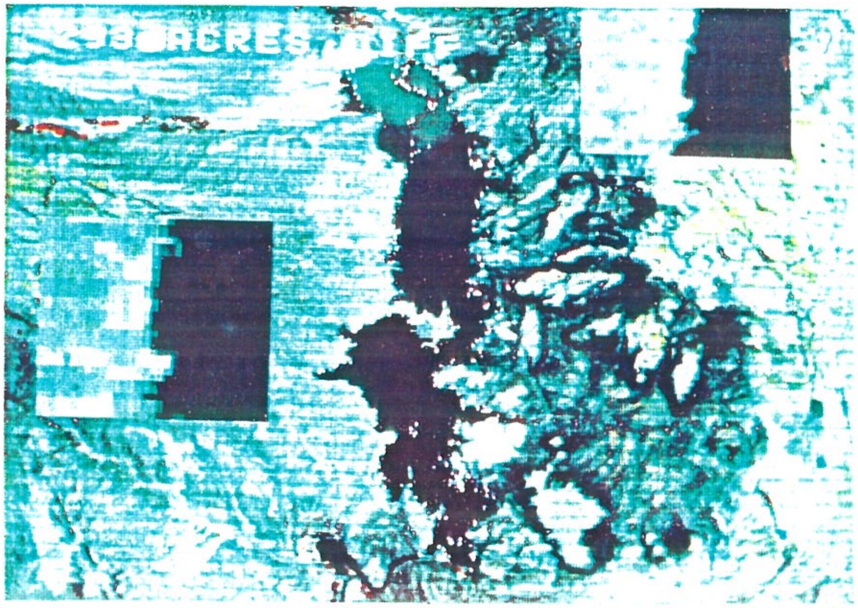


Figure 13. The area included after "stretching" the pixel values to help discriminate along the shoreline and after measuring the area of the algae bloom was 293 acres. Those areas included in this measurement are shown in white.

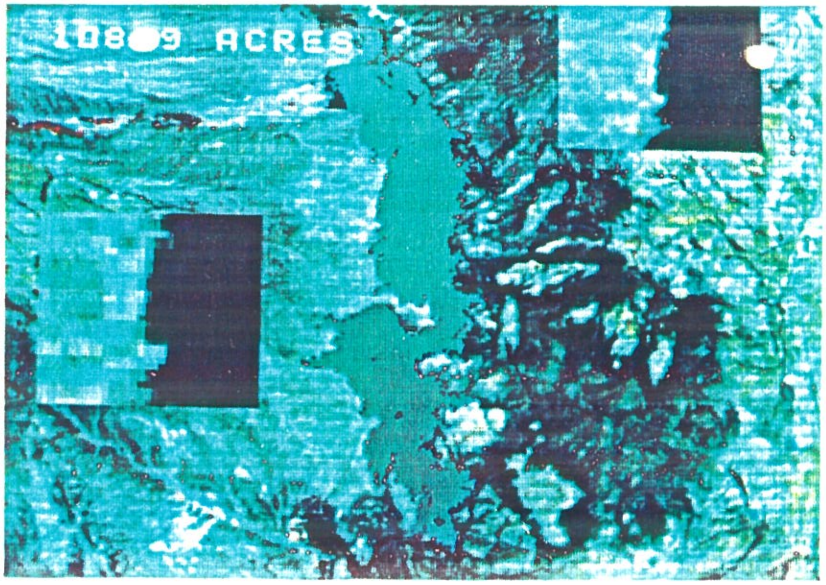


Figure 14. The measurement achieved by combining the density slice measurement and the area along the shoreline and in the algal bloom was 10,889 acres.

	DOT GRIDS				
Scale	16 Dots per Square Inch	64 Dots per Square Inch	256 Dots per Square Inch	Planimeter	*Image 100*
1:1,000,000	99.5%	47.4%	25.4%	69.8%	----
1:500,000	27.2%	22%	16%	*1.7%*	----
1:250,000	10.9%	*8.7%*	18.8%	*.7%*	----
Digital Data	----	----	----	----	*-7%*

TABLE 3: Overall percentage errors for each measuring technique/scale combination

Negative Percentages Indicate Underestimations
Positive Percentages Indicate Overestimations

(N=22 measurements, except for the *Image 100* in which case N=4) also produced the second best result, (1.7%), at a scale of 1:500,000. The *Image 100* produced data with an error of -7% and the dot grid with 64 dots per square inch produced data with an overall error of 8.7%. All of the acceptable errors were obtained for the larger scales.

The consistency of the data for each measuring technique, reservoir, season and scale can be seen in Tables 4 through 6. Table 4, presents the measurement errors obtained from 1:1,000,000 scale images. There were no measuring techniques which produced acceptable data using this small scale base. Table 5, shows the errors for the 1:500,000 scale estimates. At this scale the planimeter produced an overall percentage error of 1.7%; however, the data presented in Table 5 show that the planimeter did not produce consistently acceptable data for all reservoir types.

The percentage errors for the 1:250,000 scale estimates are presented in Table 6. Two techniques, the dot grid with 64 dots per square inch and the planimeter, had acceptable overall percentage errors at this scale. As in Table 5, however the errors show that neither technique produced consistently acceptable data. From the values obtained it would appear that with further refinement of the procedure, the planimeter could produce consistently acceptable data at a 1:250,000 scale.

The last measuring technique to produce an acceptable overall percentage error was the *Image 100*. Table 7 gives the individual errors and overall percentage error for the

	DOT GRIDS				
Reservoir	16 Dots per Square Inch	64 Dots per Square Inch	256 Dots per Square Inch	Planimeter	Image Date (1973)
Navajo	217%	85%	12%	-30%	Jan 30
	136%	57%	18%	27%	May 18
	31%	48%	31%	24%	Jul 29
	222%	122%	36%	27%	Oct 27
Heron	343%	122%	39%	16%	May 17
	155%	91%	44%	-.6%	Aug 15
	154%	27%	27%	-16%	Oct 27
Abiquiu	386%	265%	51%	81%	May 17
	298%	99%	24%	24%	Aug 15
	300%	100%	100%	10%	Oct 26
Conchas	46%	46%	46%	14%	Mar 4
	143%	52%	44%	13%	Apr 27
	126%	70%	55%	35%	Aug 13
	150%	56%	41%	18%	Oct 6
Elephant Butte	76%	10%	10%	.7%	Mar 6
	-18%	3%	-2%	-9%	May 17
	23%	7%	7%	3%	Aug 15
	-36%	29%	9%	10%	Oct 26
Caballo	111%	5%	19%	1%	Mar 6
	71%	-15%	-4%	-8%	May 17
	93%	45%	33%	17%	Aug 15
	68%	-16%	88%	14%	Oct 26

TABLE 4: Percentage errors at a scale of 1:1,000,000 for each machine, reservoir and season

	DOT GRIDS				
Reservoir	16 Dots per Square Inch	64 Dots per Square Inch	256 Dots per Square Inch	Planimeter	Image Date (1973)
Navajo	6%	-1%	-1%	-18%	Jan 30
	-2%	13%	8%	9%	May 18
	-1%	-1%	4%	11%	Jul 29
	21%	21%	18%	7%	Oct 27
Heron	11%	11%	-3%	7%	May 17
	28%	-4%	-.3%	-15%	Aug 15
	27%	27%	7%	8%	Oct 27
Abiquiu	22%	-39%	32%	-13%	May 17
	99%	-.5%	24%	3%	Aug 15
	100%	50%	44%	6%	Oct 26
Conchas	46%	10%	14%	6%	Mar 4
	21%	6%	6%	-31%	Apr 27
	98%	69%	41%	5%	Aug 13
	25%	48%	21%	13%	Oct 6
Elephant Butte	32%	21%	18%	3%	Mar 6
	3%	8%	4%	-3%	May 17
	38%	34%	24%	4%	Aug 15
	61%	49%	33%	2%	Oct 26
Caballo	5%	18%	19%	7%	Mar 6
	28%	7%	4%	-3%	May 17
	-3%	57%	48%	14%	Aug 15
	-16%	47%	20%	-5%	Oct 26

TABLE 5: Percentage errors at a scale of 1:500,000 for each machine, reservoir and season

Reservoir	DOT GRIDS 16 Dots per Square Inch	64 Dots per Square Inch	256 Dots per Square Inch	Planimeter	Image Date (1973)
Navajo	-41%	-34%	-40%	-29%	Jan 30
	13%	13%	11%	-2%	May 18
	3%	23%	22%	7%	Jul 29
	.7%	7%	13%	6%	Oct 27
Heron	39%	25%	49%	23%	May 17
	44%	44%	43%	2%	Aug 15
	-5%	-13%	-11%	-22%	Oct 27
Abiquiu	-9%	-1%	.6%	11%	May 17
	24%	24%	34%	12%	Aug 15
	-25%	.2%	5%	-4%	Oct 26
Conchas	37%	35%	36%	5%	Mar 4
	44%	27%	33%	6%	Apr 27
	55%	55%	59%	8%	Aug 13
	-6%	6%	10%	4%	Oct 6
Elephant Butte	16%	21%	24%	4%	Mar 6
	-2%	5%	9%	-.1%	May 17
	19%	30%	29%	1%	Aug 15
	5%	5%	17%	-4%	Oct 26
Caballo	19%	25%	26%	-.9%	Mar 6
	7%	1%	6%	-7%	May 17
	33%	45%	53%	8%	Aug 15
	-16%	5%	2%	-2%	Oct 26

TABLE 6: Percentage errors at a scale of 1:250,000 for each machine, reservoir and season

Reservoir	Percent Error
Navajo	-10%
Heron	-.4%
Elephant Butte	-9%
Caballo	-2%
	-7% overall percentage error

TABLE 7: Percentage errors and overall percentage error for *Image 100* surface area measurements for four reservoirs, one season each

measurements made by this technique. This procedure produced both an acceptable overall percentage error of -7%, and consistently acceptable percentage errors for each of the four reservoirs measured. The poorest results were obtained for Navajo, (-10%) and Elephant Butte reservoir, (-9%). Both reservoirs are affected by strong shadowing along portions of their shoreline. It is interesting to note that all of the surface area measurements made by the *Image 100* are underestimations. This could be the result of the operator being overly conservative in deciding exactly where the water/land interface was. Further refinement of the interpretive factor associated with using the *Image 100* may be able to improve these measurements still further.

Based on the data presented here it appears that a computerized digital measuring technique such as the *Image 100* can be used now to make reservoir surface area estimations. It is also possible that measurements from the planimeter at a scale of 1:250,000 can be improved to meet the data user's desired accuracy levels. The range of errors associated with the other measuring techniques tends to preclude them from all but the crudest of estimating efforts.

Table 8 presents the mean percentage errors for each measuring technique, image scale, season, and reservoir combination investigated in this project. A comparison between this table and Table 9 shows that the modified acreage dot grid used by White (1977) generally produced better results than either the 16 or 64 dots per square inch grids used in this project. The 255 dots per square inch grid used in this

	DOT GRIDS				
Reservoir	16 Dots per Square Inch	64 Dots per Square Inch	256 Dots per Square Inch	Planimeter	Scale
Navajo A.G.	141%	76%	26%	15%	1:1,000,000
	5%	8%	8%	4%	1:500,000
	-26%	6%	5%	-2%	1:250,000
Heron R.G.	197%	73%	36%	-3%	1:1,000,000
	24%	11%	2%	-1%	1:500,000
	24%	17%	23%	4%	1:250,000
Abiquiu A.S.	325%	148%	59%	36%	1:1,000,000
	77%	6%	15%	-.5%	1:500,000
	-17%	8%	14%	6%	1:250,000
Conchas A.G.	119%	57%	47%	21%	1:1,000,000
	49%	35%	21%	-2%	1:500,000
	33%	31%	35%	6%	1:250,000
Elephant Butte A.S.	9%	13%	6%	2%	1:1,000,000
	36%	30%	23%	2%	1:500,000
	10%	-7%	20%	1%	1:250,000
Caballo R.S.	86%	7%	27%	5%	1:1,000,000
	7%	30%	22%	4%	1:500,000
	13%	20%	23%	-.5%	1:250,000

TABLE 8: Mean percentage errors for acreage estimates for each manual measuring technique/image scale/season/reservoir combination investigated

R = rounded shoreline

A = angular shoreline

S = steep basin

G = gentle basin

Reservoir	Dot Grid	Planimeter	32-Level Color Density Slicer	16-Level Black and White Density Slicer	Scale
Navajo A.G.	107%	27%	-46%	61%	1:1,000,000
	-13%	10%	-35%	-76%	1:500,000
	36%	29%	-46%	122%	1:250,000
Heron R.G.	97%	7%	-26%	18%	1:1,000,000
	-2%	8%	-26%	-78%	1:500,000
	4%	6%	-58%	43%	1:250,000
Abiquiu A.S.	171%	27%	-35%	44%	1:1,000,000
	-19%	66%	-45%	-74%	1:500,000
	9%	15%	-66%	107%	1:250,000
Conchas A.G.	50%	17%	-39%	32%	1:1,000,000
	-11%	9%	-34%	-76%	1:500,000
	12%	8%	-60%	54%	1:250,000
Elephant Butte A.S.	14%	-1%	-40%	4%	1:1,000,000
	-13%	-4%	-36%	-80%	1:500,000
	-9%	-4%	-59%	20%	1:250,000
Caballo R.S.	54%	-4%	-16%	9%	1:1,000,000
	-11%	-1%	-31%	-79%	1:500,000
	2%	2%	-54%	26%	1:250,000

TABLE 9: Mean percentage errors for acreage estimates derived from each measuring device/image scale/season/reservoir combination investigated

R = rounded shoreline
A = angular shoreline
S = steep basin
G = gentle basin

project produced slightly better results than the modified dot grid. The planimeter also produced better results here than in the previous project. From this it appears that the high contrast negatives used here provided a better measurement base than the continuous tone negatives used in the previous effort. This improvement may be a result of less "halo" area (as described by White, 1977) around the reservoirs.

IV. CONCLUSIONS

These results indicate that consistent and reliable measurements of reservoir surface areas from Landsat satellite data are possible. These measurements have sufficient reliability to meet resource data user accuracy requirements. However, further work needs to be done to improve on the measuring techniques and procedures to provide data with a known variance and reliability. There is also room for newer and more advanced classification and measuring techniques to be evaluated. One such technique would be automated image classification using unsupervised statistical classifiers. Other image processing systems which are more economic to run and easier to operate than the *Image 100* should also be investigated.

As the measuring techniques are perfected, thought should be given to the idea of using surface area data to estimate reservoir volumes. Such a capability could provide data previously unavailable for many unsurveyed or unmonitored reservoirs. It is very possible that satellites can provide reservoir data of such high reliability that many of the water resource availability models presently in use can be enhanced. We can definitely meet the user requirements for surface area data. We must now work on improving these techniques and in estimating reservoir volume.

V. SELECTED REFERENCES

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APPENDIX I

Survey Recipients and Letter of Solicitation

A)

List of Water Management and User Agencies

Responsible to:	Organization
private	Environmental Engineer Navajo Mine
private	National Water Well Association
private	Elephant Butte Irrigation District
federal	Department of the Army Albuquerque District, Corps of Engineers
federal	National Oceanic and Atmospheric Administration National Weather Service, River Forecast Center
federal	Bureau of Land Management New Mexico State Office
federal	U.S.D.A. Soil Conservation Service
federal	Bureau of Reclamation Upper Colorado Regional Office
federal	Bureau of Reclamation Southwest Region
federal	Bureau of Indian Affairs
federal	U.S. Geological Survey
federal	U.S. Forest Service
state	State of New Mexico Department of Game and Fish
state	New Mexico Department of State Forestry
state	State of New Mexico Health and Social Services Department
state	State of New Mexico State Planning Office
state	New Mexico State Parks and Recreation Commission
state	New Mexico State Engineers Office
state	New Mexico State Land Office
state	Interstate Stream Commission

state	New Mexico State Geologist
state	New Mexico Environmental Improvement Agency
state/ county	Four Corners Regional Commission
county	El Llano Estacado Resource Conservation and Development Area
county	North Central New Mexico Economic Development District
county	Eastern Plains Planning Council
county	Middle Rio Grande Council of Governments
county	McKinley Area Council of Governments
county	San Juan Council of Governments
county	Southeastern New Mexico Economic Development District
county	Southern Rio Grande Council of Governments
county	Southwest New Mexico Council of Governments

TECHNOLOGY APPLICATION CENTER
UNIVERSITY OF NEW MEXICO
ALBUQUERQUE, NEW MEXICO 87131
TELEPHONE: (505) 277-3622

The University of New Mexico Geography Department in cooperation with the Technology Application Center and the New Mexico Water Resources Research Institute are working on a water resources research project in which one of the objectives is: identify the data accuracies for lake area and reservoir volume presently required by cognizant state and federal agenices.

I would like to enlist your help and advice in accomplishing this objective. What degree of accuracy for lake area and volume does your agency require for their work? For example, could you use accuracies of ± 15%, ±20%, etc? (presently published data are reported to be within ± 10% accurate). Do your accuracy requirements vary from season to season? For example, do you need better accuracy during the early spring than in the fall?

I have enclosed several copies of this request, if you know of someone else that could also provide information, would you please pass one along to them. Your help in this matter would be greatly appreciated.

Sincerely,

Mike E. White
Project Scientist

MEW/jt
Enclosures

APPENDIX II

Cost Analysis

APPENDIX II

Cost Analysis

In reviewing the following cost analysis tables it must be kept in mind that the reported figures are estimates based on our experience through a *research* project. When the measurement techniques reach the applications mode they would most probably decline. This is especially true for the digital image processing technique, since, at this point, it is the most research oriented of the procedures studied.

Table 1, shows the estimated itemized costs for each machine/scale combination. The manpower cost estimates for performing reservoir measurements are based on a federal employee GS-3 rating, which is roughly equivalent to an hourly pay rate of $4.60 in 1978. Imagery costs were estimated from the U.S. Geological Surveys Price List (Table 2), plus a minimal effort for enlargements and reformatting in a commercial lab. Equipment costs are based on commercially available equipment. These costs have not been entered into the implementation costs given in Table 3, since they are one-time expenditures which must be amortized over an entire monitoring program.

Table 3 shows an estimated cost for implementing each measuring technique. Each figure is estimated on a per/lake basis. The high cost for the digital processing measurements represents rental time on an image processing system, plus computer data tape and interpreter costs. If one considers the data tape for application *only* in a reservoir monitoring

TABLE 1: Estimated Itemized Costs and Level of Effort for Implementing Measurement Techniques

	16 Dots			64 Dots			256 Dots		
Dot Grid	1:1 mil	1:500K	1:250K	1:1 mil	1:500K	1:250K	1:1 mil	1:500K	1:250K
Interpretation time - per lake 3 measurements (GS-3 rating- $4.60 per hr.)	1/4 hr. $1.15	1/2 hr. $2.30	1/2 hr. $2.30	1/2 hr. $2.30	3/4 hr. $3.45	3/4 hr. $3.45	3/4 hr. $3.45	1 hr. $4.60	1 hr. $4.60
Imagery Cost	$10.00	$10.00	$10.00	$18.00	$18.00	$18.00	$18.00	$18.00	$18.00
*Equipment Cost	$4.00	$4.00	$4.00	$10.00	$10.00	$10.00	$20.00	$20.00	$20.00

Planimeter	1:1,000,000	1:500,000	1:250,000
Interpretation time - per lake 3 measurements (GS-3 rating- $4.60 per hr.)	1/4 hr. $1.15 per lake	1/3 hr. $1.53 per lake	1/3 hr. $1.53 per lake
Imagery Cost	$10.00	$18.00	$18.00
*Equipment Cost	$3.500	$3,500	$3,500

(time and costs are independent of scale)

Digital Processing	
Interpretation time - per lake (GS-3 rating- $4.60 per hr.)	1/2 hr. $2.30
System Rental includes operator	$125.00 per hr.
**Computer Compatible Tapes	$200.00

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* Equipment costs should be amortized over a total project. It would be unrealistic to assess these costs on a per reservoir basis.

** The data availability on Landsat computer compatible tapes is such that the same tapes can be utilized for numerous natural resource assessment projects. The cost of these tapes in any applications role therefore, would most probably be cost shared by several resource management agencies.

TABLE 2

PRICE LIST

STANDARD REMOTE SENSING DATA

U. S. DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

JANUARY 1, 1977

SATELLITE DATA

STANDARD LANDSAT

			BLACK and WHITE		COLOR	
IMAGE SIZE	NOMINAL SCALE	PRODUCT FORMAT	UNIT PRICE	PRODUCT CODE	UNIT PRICE	PRODUCT CODE
55.8mm (2.2 in.)	1:3369000	Film Positive	$ 8.00	11		
55.8mm (2.2 in.)	1:3369000	Film Negative	10.00	01		
18.5cm (7.3 in.)	1:1000000	Paper	8.00	23	$12.00	63
18.5cm (7.3 in.)	1:1000000	Film Positive	10.00	13	15.00	53
18.5cm (7.3 in.)	1:1000000	Film Negative	10.00	03		
37.1cm (14.6 in.)	1:500000	Paper	12.00	24	25.00	64
74.2cm (29.2 in.)	1:250000	Paper	20.00	26	50.00	66

COLOR COMPOSITE GENERATION			$50.00	59

NOTE. 1) Portrayed in false color (infrared) and not true color
2) Cost of product from this composite must be added to total cost

COMPUTER COMPATIBLE TAPES (CCT)

TRACKS	b.p.i.	FORMAT	SET PRICE	PRODUCT CODE
7	800	Tape Set	$ 200.00	82
9	800	Tape Set	200.00	83
9	1600	Tape Set	200.00	84

SELECTED COVERAGE

		BLACK and WHITE			COLOR	
IMAGE SIZE	FORMAT	BAND(S)	UNIT PRICE	PRODUCT CODE	UNIT PRICE	PRODUCT CODE
18.5cm (7.3 in.)	Paper	5	$ 8.00	41	$12.00	46
18.5cm (7.3 in.)	Paper	4, 5, 6, 7	32.00	45		
37.1cm (14.6 in.)	Paper	5	12.00	42	25.00	47
74.2cm (29.2 in.)	Paper	5	20.00	43	50.00	48

TABLE 3: Estimated Costs* for Implementing Measurement Techniques

	Scale			
Dot Grids	1:1,000,000	1:500,000	1:250,000	Digital
16 Dots per sq. in.	$11.15	$12.30	$12.30	---
64 Dots per sq. in.	$20.30	$21.45	$21.45	---
256 Dots per sq. in.	$21.45	$22.60	$22.60	---
Planimeter	$11.15	$19.53	$19.53	---
Digital Processing	-----	-----	-----	$327.30

* Does not include equipment purchase cost. Digital processing cost reflects rented time on image processing system.

TABLE 4: Comparisons of machine/scale combination costs to observed accuracies

Machine/Scale Combination	Cost	Accuracy
Dot Grid - 65 dots per square inch/1:250,000	$21.45	8.7%
Planimeter/ 1:500,000	$19.53	1.7%
Planimeter/ 1:250,000	$19.53	.7%
Digital Processing	$327.30	-7%

negative percentages indicate underestimations
positive percentages indicate overestimations

program this cost, in relation to the others, is quite high. If the data tape can be used for other resource assessments, however, this cost can also be amortized.

Table 4 gives the implementation cost for the machine/scale combinations having satisfactory accuracies. The planimeter produces the best accuracy for the least cost. Future efforts may be able to: 1) improve accuracies, and 2) reduce application costs, for each technique.

There are very few data available on the present costs for monitoring reservoir surface areas. A comparison between present monitoring costs and the estimated costs arrived at here would be practically meaningless because of the diverse formats of the data. Presently in developed reservoirs, stage recorders provide hourly or daily data. The techniques discussed here could provide data every nine days at best (considering present system parameters). Thus, the systems discussed here will find the most application in monitoring reservoirs without stage recorders, and for controlling stage recorder accuracy degradation. For example, if a consistent accuracy can be achieved from one of the measuring techniques, its data can be compared to that of the stage recorder. When this comparison shows a variance of ±10% or greater, the recorder can be checked and appropriate maintenance procedures taken. Perhaps the most obvious applications for these techniques lies in monitoring temporal water bodies such as playa lakes and karst depressions.