

LANDSAT-1 DATA AS IT HAS BEEN APPLIED FOR
LAND USE AND WATER QUALITY DATA BY THE
VIRGINIA STATE WATER CONTROL BOARD

E-10

I. - THE STATE PROJECT

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ABSTRACT

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In March, 1974, the Virginia State Water Control Board embarked on a program with the National Aeronautics and Space Administration (NASA) User Demonstration Group, LANDSAT Resources Branch of the Applications Directorate. The program first centered on a proposed development approximately ten miles west of Richmond, Virginia, which involved land use monitoring as well as water quality monitoring of the Swift Creek Reservoir and the Brandermill development which was to be built around the Reservoir. After several months of both water quality and LANDSAT-1 monitoring, it was decided that the water was high quality and homogenous throughout the Reservoir. At this time a decision was made to continue Reservoir monitoring on days of LANDSAT-1 passovers and also to monitor another nearby reservoir, Lake Chesdin, which was of generally poorer water quality and not homogenous. Concentration on land use, however, was to remain in the Swift Creek Reservoir area. After only nine months of work with LANDSAT-1 imagery, we have found data to be very helpful in both water quality monitoring and land use monitoring.

Water quality monitoring in Swift Creek and Lake Chesdin Reservoirs by LANDSAT-1 has proved useful in the following ways:

1. It has helped determine valid reservoir sampling stations.
2. It monitors areas of the Reservoirs which are not accessible by land or water.
3. It gives the State a viable means of measuring Secchi depth readings in these inaccessible areas.
4. It gives an overview of trends in changing sedimentation loadings during a specific period of time and will class these waters into various categories.
5. It enables the State to inventory all major lakes and reservoirs and gives accurate acreage estimations of lakes and reservoirs in each region.

Land use monitoring by LANDSAT-1 in the area around the Swift Creek Reservoir has been extremely useful in the following ways:

1. It has been found that LANDSAT-1 is exceedingly accurate in monitoring land use changes in any specific area (Example: Swift Creek Reservoir-Brandermill area).

2. LANDSAT-1 monitoring can evaluate possible long-term environmental effects of the Brandermill development on the Reservoir as applied to completing environmental impact statements.
3. LANDSAT-1 data will aid in monitoring and predicting population shifts which will key future water quality problems.

Problems which exist for the present and the future with organizations such as ours using available LANDSAT-1 or LANDSAT-2 are as follows:

1. Because of 18-day lapses between passovers and the limitation of cloud cover at passover times, areas cannot be monitored with any type of consistency.
2. NASA, by design, is not user oriented, therefore, any sort of permanent user program must either be taken on by the agency or contracted with a company such as Bendix or General Electric. In each case, considerable expense would be involved thereby making such a program unfeasible for small state agencies.
3. LANDSAT-1 and -2 are both devoid of sensors which would prove to be very valuable in the work in which this agency is involved, the most notable being a thermo sensor.

In conclusion, the State Water Control Board has found LANDSAT-1 imagery to be valuable in both land use and water quality monitoring. This agency also feels there is great potential in satellite monitoring for the future as the science comes of age and various sensors are added to future vehicles. We do feel that cost is probably the major problem with the program at this time, but solutions are not impossible and will be forthcoming.

INTRODUCTION

In February of 1974 personnel from the Virginia State Water Control Board (VSWCB) office were attracted by an article in a magazine that dealt briefly with the potential of LANDSAT satellite monitoring as applied to water quality studies and land use. After writing the National Aeronautics and Space Administration (NASA) at the Goddard Space Flight Center, Greenbelt, Maryland, it was learned that we could visit the complex to learn more about the potential use of LANDSAT. In March, 1974, a visit was made by me and two other members of the VSWCB staff. We were very impressed with satellite monitoring system and felt that it held great potential for our organization; this we related to NASA personnel.

In January, 1974, the VSWCB began a water quality study on the Swift Creek Reservoir, a 1700 acre impoundment, which supplies drinking water to some 30,000 people. The reason for such a study was a proposed development to be built around the Reservoir by Sea Pines, Inc. The development was to be called Brandermill, Inc. It would encompass approximately 3,000 acres, take five years to complete, and house some 70,000 people (Reference: Figure A). The VSWCB felt that reservoir monitoring would serve two purposes:

1. It would be an opportunity to monitor the water quality during the five year period of construction to ensure that it would not suffer due to this development.
2. It gave the VSWCB an opportunity to work directly with a private firm (Sea Pines, Inc.) to further ensure non-degradation of the water quality in the Reservoir.

After further discussion of LANDSAT use with NASA personnel, it was decided that the Swift Creek Reservoir held potential as a study area for LANDSAT monitoring. The Reservoir was large enough to be monitored accurately, and the greatest problem we anticipated with the construction, namely siltation runoff, could be measured by satellite reflectance. It was at this time that Dr. John Barker of the NASA Earth Resources Branch at Goddard Space Flight Center contacted my office.

After several months of both VSWCB and LANDSAT-1 monitoring, it was decided by the two groups involved that Swift Creek Reservoir was homogenous throughout and water quality variation would have to be found in another body of water, preferably within the same satellite image. After some field examination, it was decided that Lake Chesdin, a 3,060 acre lake south of Swift Creek Reservoir, would be chosen. This decision was made on the basis of a preliminary investigation that indicated serious siltation problems on the Lake. Lake Chesdin supplies drinking water for areas in Chesterfield County, Virginia.

NOMENCLATURE

Secchi disk. - Black and white circular disk which is lowered into the water until it just disappears from view. The distance between the disk and the surface of the water is the Secchi reading in inches.

Turbidity meter. - An instrument which is used to measure the transmittance of light through that water as measured in Jackson Turbidity Units (JTU).

Total solids. - Total solids is defined as the sum total of the dissolved solids (those solids which are in true solution) and total suspended solids (includes settleable solids). Consists of both organic and inorganic solids and is expressed in mg/l.

Total volatile solids. - That portion of total solids which can be ignited at a constant temperature of 600°C thereby classing such material as organic. Expressed in mg/l.

Total fixed solids. - That portion of total solids which will not oxidize at 600°C thereby classing such materials as inorganic. Expressed in mg/l.

Total suspended solids. - The total amount of residue which is filterable with a Reeve Angel grade 934AH fiberglass filter. Consists of both organic and inorganic material. Expressed in mg/l.

Volatile suspended solids. - That portion of total suspended residue which can be ignited at 550°C thereby classing such material as organic. Expressed in mg/l.

Fixed suspended solids. - That portion of the total suspended residue which will not oxidize at 550°C thereby classing such material as inorganic. Expressed in mg/l.

Tri-depth sampling. - Method of sampling by which three samples are taken from each point or station. These samples are taken at surface, 60% from surface, and 95% from surface of water.

Mid-depth sampling. - Method of sampling by which a single sample is taken from each point or station at 60% from water surface.

Stratification. - Vertical temperature layers in water usually associated with deep lakes and reservoirs.

APPROACH

Sampling began on the Reservoir in January, 1974. Originally, there were five sampling stations around the main Reservoir body (Reference: Figure B). These stations were sampled monthly at tri-depth for the first two months. Upon review of the satellite imagery and ground observation, it was decided that the impoundment was shallow enough (average depth nine feet) so that stratification was not occurring; therefore, mid-depth sampling replaced the tri-depth sampling.

In April, 1974, when NASA began to work with the VSWCB, it was recognized that an increase in sampling stations would be beneficial. None of the original stations were deleted and five new stations were added (Reference: Figure C). Also, at this time Secchi disk readings were initiated at each station as well as lab and field turbidity readings. Other parameters to be examined were total solids, volatile and fixed, and suspended solids, volatile and fixed. All of these parameters were to be used to relate to reflectance of LANDSAT imagery. Sampling runs were to coincide directly with the time of satellite overpass schedules. Construction at Brandermill began in the later part of June, 1974.

Certain difficulties occurred during the nine months of sampling on overpass days. These involved equipment and procedural malfunctions, weather conditions, and in two cases an incorrect overpass schedule. As with all new programs in which new sampling techniques are involved, members of the VSWCB staff incurred certain problems with the equipment and with the procedure used in handling this equipment. When there were no field problems, cloud cover interfered; and when neither of these occurred, it was discovered that in October and November of 1974 the overpass schedule was in error. In summary, out of the nine months of sampling and overpass days only two months of images were analyzed, June 15 and September 13.

During the summer and early fall, NASA and the VSWCB worked closely to coordinate efforts including visits to Richmond and Goddard Space Flight Center. During the trips to Swift Creek and Lake Chesdin Reservoir, photographs were taken for ground truth purposes. On the September visit Secchi depth readings were taken during satellite overpass. Large variations were found throughout the Lake, especially in one area which was protected by a causeway and a bridge. Here Secchi readings were twice as great as in other parts of the Lake. Other VSWCB field personnel were simultaneously sampling on Swift Creek Reservoir. Cloud cover was at a minimum and all equipment functioned properly.

From this data and the June data, Dr. Barker and I were able to gather a great deal of information relating to the project. By comparing the differences in the June and September images, the Brandermill construction area was pinpointed and its acreage measured. Airplane flights were made by VSWCB personnel to produce photographs for this land use classification.

Visits to NASA, Goddard Space Flight Center, included working sessions on both the General Electric Image 100 and the IDAMS computer systems. These sessions proved beneficial; NASA personnel obtained information on ground truth and VSWCB personnel became more familiar with the classification techniques involved in digital image processing. Seeing the projects produced was essential in supplying the appropriate ground observations.

CONCLUSION

With field work completed, the VSWCB began to receive from NASA satellite imagery and plots which demonstrated a considerable amount of usefulness in our assessment of the entire program. Water quality monitoring on Swift Creek Reservoir and Lake Chesdin by LANDSAT-1 was demonstrated useful in the following ways:

1. Sampling and Overview. - Instead of a hit-and-miss system of determining sampling stations, satellite classification products have guided our personnel in choosing stations that are more representative of the total picture. Two areas on Lake Chesdin show much higher quality of water than the main body, Namozine Creek and Whipponock Creek (Reference: Figure D). On Swift Creek Reservoir water does appear homogenous, yet, any future problems that may occur will be noted much earlier because of the rearrangement of sampling stations due to LANDSAT. Imagery gives an overview of trends in changing sedimentation loadings during a specific period of time and then these waters may be arranged into various categories of loadings.
2. Inaccessible Areas. - Imagery can be useful in monitoring areas not accessible by land or boat or at least not easily accessible by land or boat. Examples of this are seen in the Goose Island portion of Lake Chesdin (Reference: Figure D) and the upper reaches around station #5 on Swift Creek Reservoir (Reference: Figure C). With satellite monitoring of these stations, the VSWCB can save 40 man-hours per year and laboratory cost in sampling programs; and annual or semiannual review should reveal problems which may occur in the inaccessible areas.
3. Reduced Manpower and Increased Coverage. - A regular program of water quality monitoring via satellite should reduce manpower requirements and substantially extend the coverage of the state lake monitoring programs as they pertain to siltation problems. If a problem area is discovered by imagery, action can be initiated thereby eliminating useless trips.
4. Acreage. - LANDSAT imagery enables the State to inventory major lakes and reservoirs and establish accurate acreage estimations of these lakes and reservoirs. This phase of monitoring is not only important in that it can measure acreage sizes, which can be done as accurately by other methods: its importance lies in the potential of measuring changes in acreage. By normal methods, acreage changes in lakes and reservoirs are only measured every ten years by the United States Geological Survey (USGS). Satellite imagery can update changes as needed. Although this phase of the program has not gone beyond two major lakes in the Richmond area, it is certainly safe to assume that it holds potential throughout the State of Virginia.
5. Watershed Land Use. - In addition to measuring the size accurately for each major lake or reservoir, NASA has demonstrated that

watershed boundaries can be plotted thereby giving users such as the VSWCB an overall view of each watershed. With this knowledge, agencies will be able to assess water quality problems as they pertain to land use in the watershed. If any type of accurate assessments are to be made in the future, information of this type will be necessary.

Each of these five major categories from LANDSAT-1 form a picture of the two lakes studied that has not been surpassed by any other method of evaluating siltation problems.

Changes in use directly impact water quality studies. If a population shift is experienced in any specific area, it can be anticipated that several things will happen to the water quality in that area. Unless the people involved in the actual construction are careful to limit to a minimum any disruption of underbrush and trees, it is certain that there will be siltation runoff from cleared areas. After construction is over and the area established, the presence of populace will contribute to further degradation of water quality. Complications such as the above serve to point out the value of land use monitoring via satellite.

LANDSAT-1 land use monitoring in the area around Swift Creek Reservoir proved helpful in monitoring land use changes. Using two images, one on June 15, 1974, (before actual construction had begun) and the other September 13, 1974, (after the major part of clearing had been completed) NASA personnel were able to plot construction areas to such a fine degree as to pinpoint small waterholes on the fairways of the golf course. With this type of accuracy, the VSWCB can get an overall view of any existing or potential problems as they pertain to the construction project. Current spatial resolution appears adequate for monitoring change in land use. It is reasonable to assume that a man preparing an environmental impact statement can use LANDSAT data to evaluate land use and its effects on watersheds as was done by our office with the Brandermill project.

The VSWCB can foresee other State agencies using the same data that we receive and applying it in various ways, such as forestry classification, population studies, and many others. An effort has been made to expand interest for LANDSAT use among other State agencies. Contacts have been made and response has generally been positive. As new awareness generates response, we at the VSWCB foresee an increase in use within the State government.

As with all projects of this type, problems were encountered. It should be understood that some of the difficulties listed below are inherent as a part of the nature of environmental satellite monitoring; however, many of these difficulties can be corrected or improved with future satellites and with a broadening of techniques and increase in use.

1. Frequency of Coverage. - Because of 18-day lapses between LANDSAT 1 overpasses and cloud cover in this region, areas cannot be monitored more frequently than once every two months. Consequently, the monitoring of water quality cannot be used as an instantaneous means of alert.
2. Cost. - The next and most significant problem a state agency faces is funding. NASA by design is not user oriented; therefore, anyone who finds the type of monitoring in which we have been involved to be of use must approach a private concern for a contractual agreement. This service appears to be too expensive. There are several solutions to this situation, the most notable in my opinion being the federal government's reevaluation of NASA to become user oriented. If this were a federal government

program, states would only have to share a small percentage of the cost. I can see many advantages to this including:

- a. NASA would receive additional funding to increase staff to support the program.
 - b. The program would be available to many agencies, such as ours, that are already aware of LANDSAT potential and also to untold numbers of agencies who are not aware of LANDSAT potential.
 - c. With increased use, the program should become more cost effective and usable in various applications.
 - d. Lastly, such a growth would serve to benefit the environment. With increased use, advancements in technology and new environmentally designed satellites, we could not help but receive a greater understanding of our environment, its problems, and solutions to these problems. This is the essence of the program.
3. Sensors. - The VSWCB would especially like to see additional sensors on satellites, the most notable of which would be a thermo sensor with resolution of better than one hundred meters on the side. An instrument such as this could prove invaluable to environmental work as related to thermo nuclear power plant discharges, sewage disposal diffusion patterns, air pollution problems, and many others. Certainly there are other sensors which would be of value, but it is our opinion that the thermo sensor with temperature sensitivity of at least 0.3°C should be one of the first to be considered for the future.

In summary, the VSWCB has found our program with NASA to be one of great value as applied to the Brandermill-Swift Creek Reservoir and Lake Chesdin projects. We have gained a great deal of knowledge about these particular impoundments and an acute insight into the nature of the problems.

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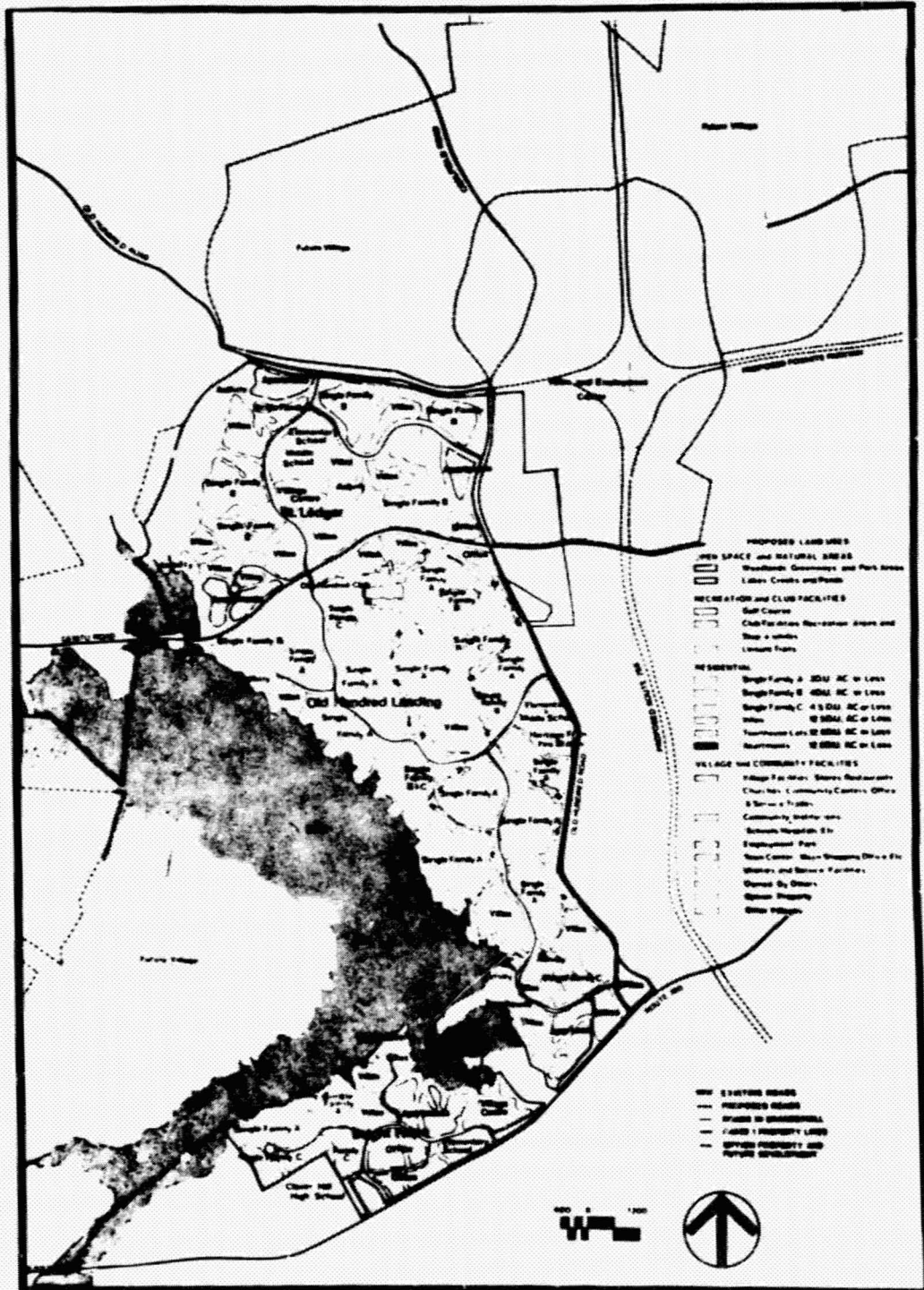
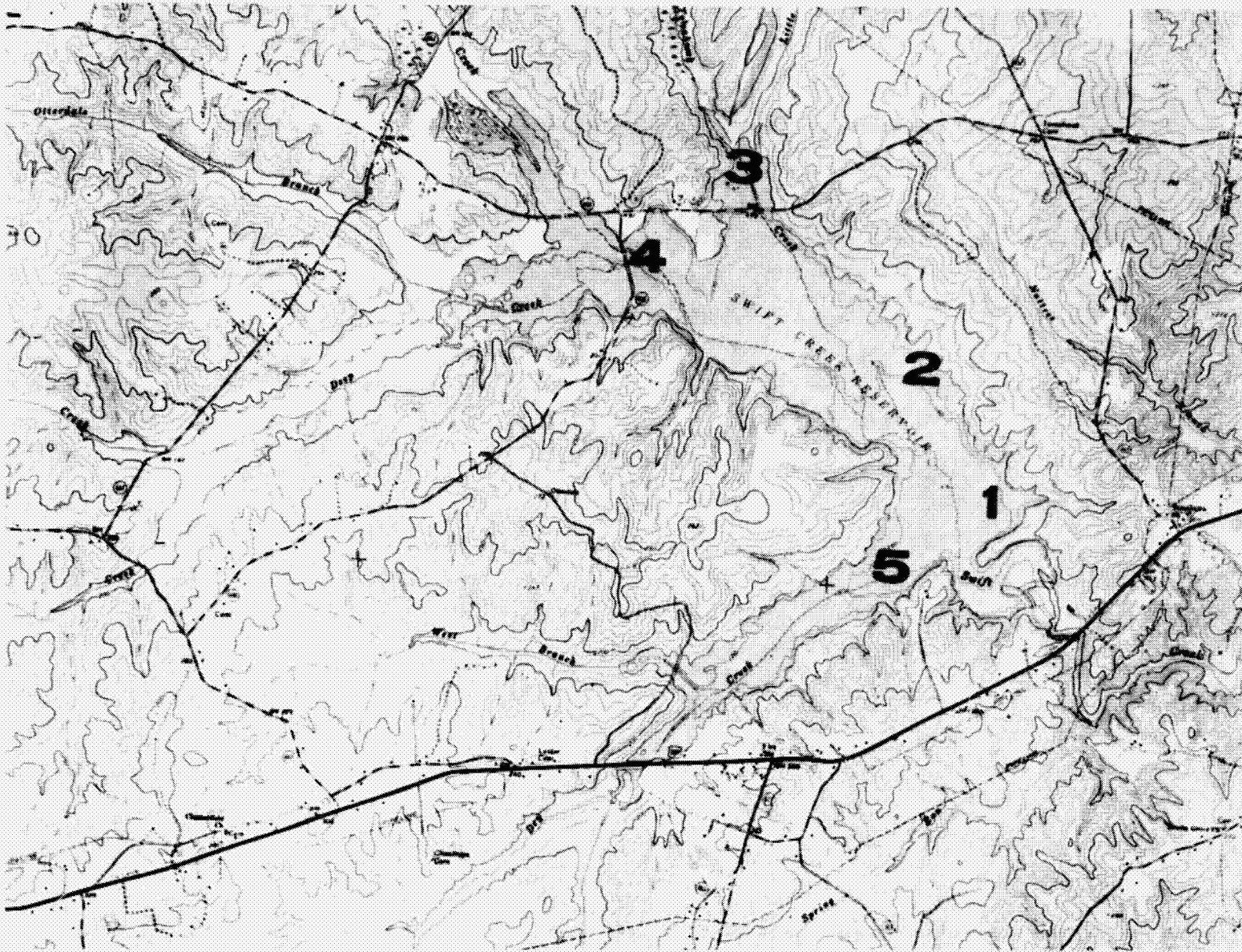


Figure A



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Figure B

Figure C

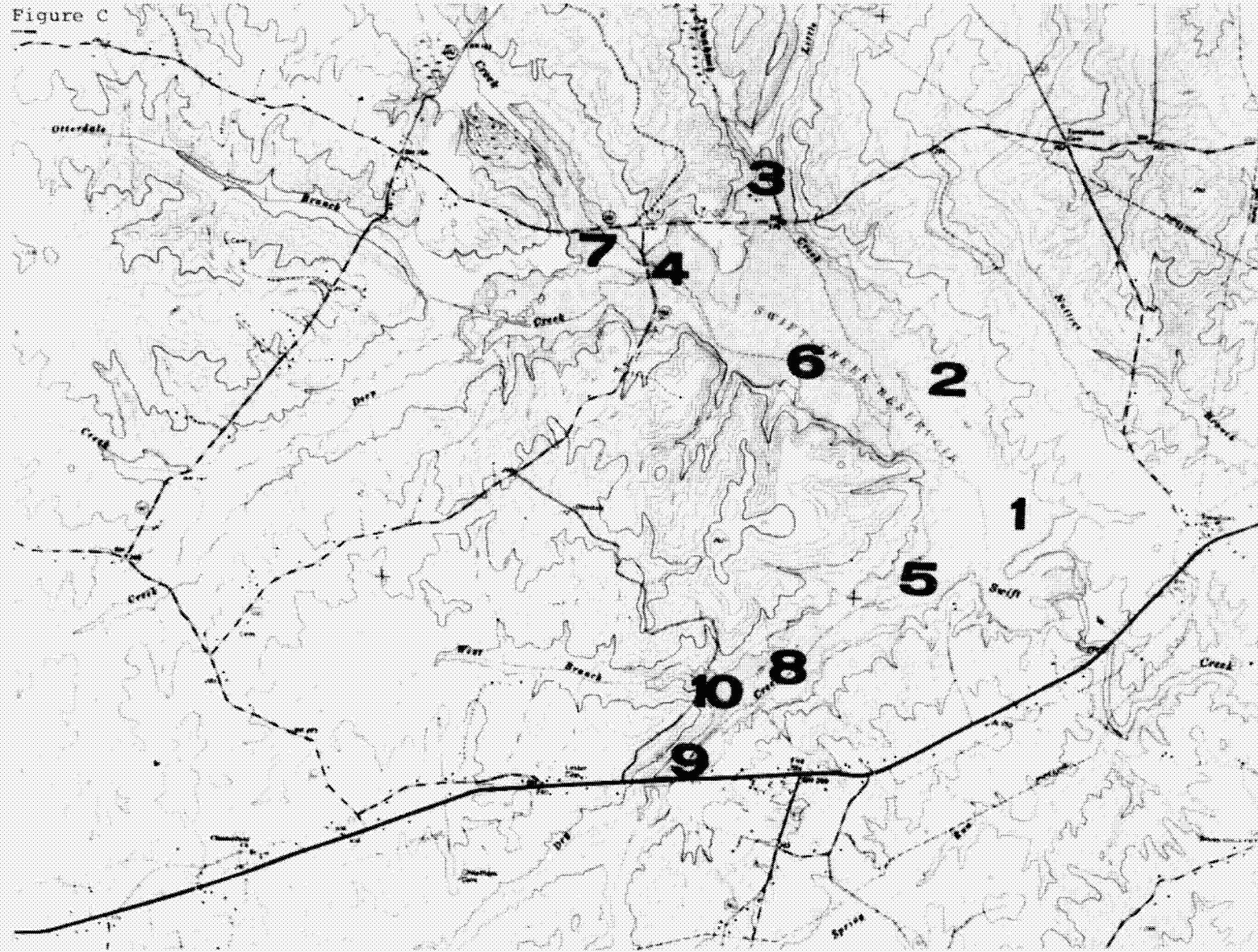
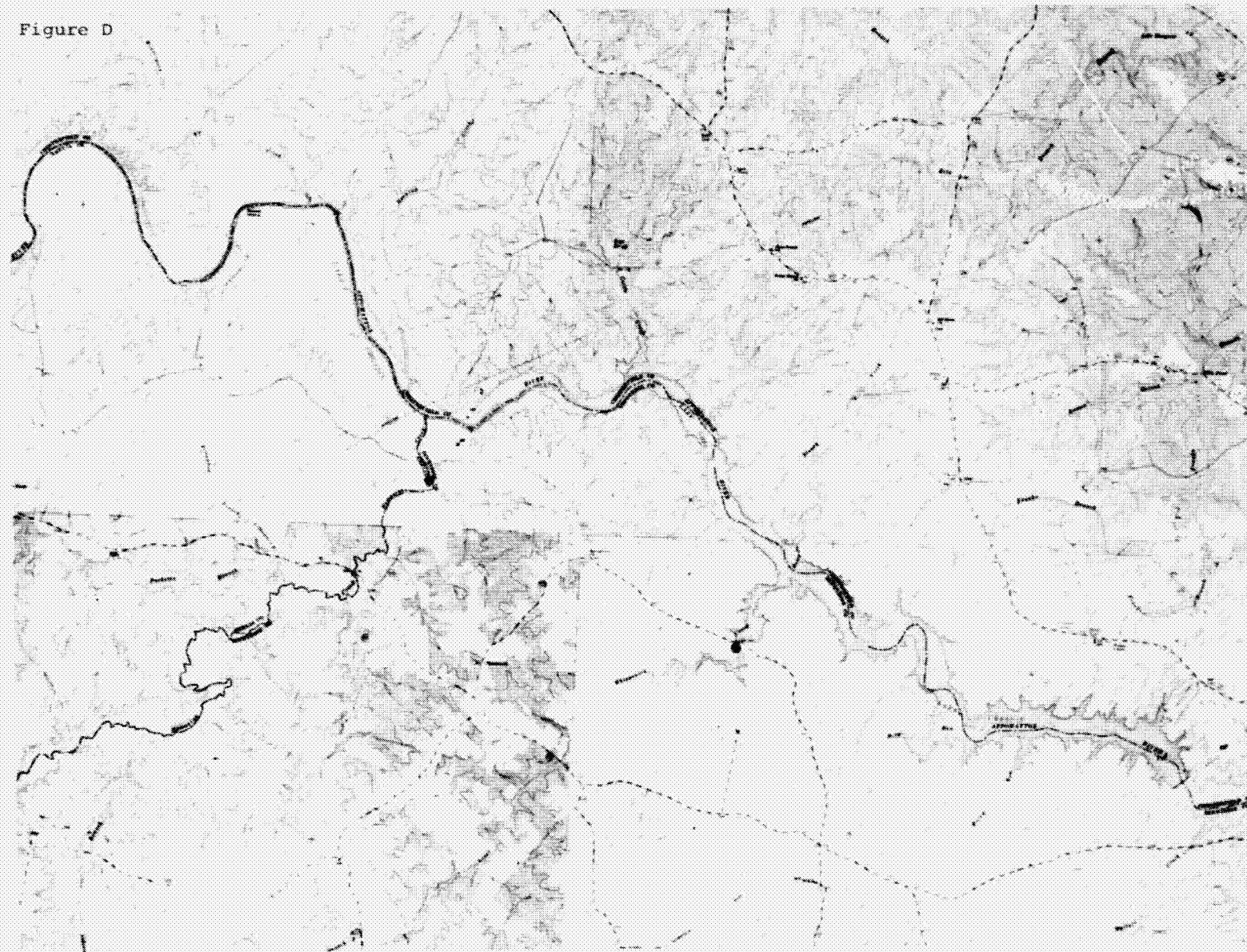


Figure C

Figure D



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Figure D

II.- MONITORING WATER QUALITY FROM LANDSAT

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ABSTRACT

Water quality monitoring possibilities from LANDSAT were demonstrated both for direct readings of reflectances from the water and indirect monitoring of changes in use of land surrounding Swift Creek Reservoir in a joint project with the Virginia State Water Control Board and NASA. Film products were shown to have insufficient resolution and all work was done by digitally processing computer compatible tapes.

It was shown that areas of individual water bodies could be measured from LANDSAT with an accuracy that decreased from $\pm 1\%$ at 500 hectares to $\pm 8\%$ at 5 hectares. Mixed land and water pixels with more than 30% water were identified from low MSS-7 reflectance values. Since measurements of large bodies have relatively small errors, since random errors in the calculation of the area of small bodies will cancel out when several single body areas are summed, and since there were no observable systematic errors, it seems that water inventory maps from LANDSAT within a particular region can be accurate to $\pm 1\%$ in identifying the total area of water. Although mixed pixel methods were more accurate than pure 100% water pixel methods, for some applications pure pixel methods might be adequate for areas above 20 hectares as long as a theoretical correction for border pixels is made. For guaranteed repeat monitoring from LANDSAT, the homogenous body of water must be at least 160m by 160m or 2.5 hectares (6.2 acres) in size.

LANDSAT reflectances from water in the visible (MSS-4 and MSS-5) and near-infrared (MSS-6) spectral bands were shown to be nearly perfectly correlated and spatially coherent for both Swift Creek Reservoir and Lake Chesdin Reservoir, which has a ten times greater flow rate due to input from the Appomatox River. Maps of different reflectances in water were derived using only MSS-5 values for these two reservoirs. Secchi depth and MSS-5 reflectance values showed a 98% inverse correlation on one date in Lake Chesdin Reservoir which may be due to the mutual dependence on total solids content. It is expected that calibration equations of LANDSAT reflectance and a water quality parameter will be necessary for each region which supplies different types of organic and inorganic particles. For Lake Chesdin Reservoir it was possible to distinguish classes of water from LANDSAT imagery which differed by about 5cm at the most sediment-laden and reflective Secchi depths. Direct monitoring of water quality seems to be most useful for observing changes in water patterns and devising and verifying water sampling programs.

Perhaps the greatest potential contribution of LANDSAT is through indirect interpretation, by detecting changes in land cover in a watershed. Land cover maps of the 18,000 hectare Swift Creek Reservoir watershed were prepared for two dates in 1974. A significant decrease in the pine cover was observed in a 740 hectare construction site within the watershed. A measure of the accuracy of classification was obtained by comparing the LANDSAT results with visual classification at five sites on a U-2 photograph. Such changes in land cover can alert personnel to watch for potential changes in water quality.

INTRODUCTION

The Virginia State Water Control Board (VSWCB) has the responsibility for monitoring the water quality of all bodies of water in Virginia. The primary objective of this paper is to identify ways in which remotely sensed satellite data might help support this program, both qualitatively and quantitatively. Working with VSWCB, various products from image processing of LANDSAT data were prepared for evaluation by NASA/VSWCB personnel, as well as other potential users.

An object of immediate concern to VSWCB was the possible change in water quality due to the construction of a 1000 hectare (2500 acre)¹ residential community called Brandermill on land immediately adjacent to 600 hectare Swift Creek Reservoir (SCR). Therefore, the possibilities of using data from the Earth Resources Technology Satellite ² to monitor environmental impact on this water body were investigated both directly through readings of reflectances from the water, and indirectly by monitoring changes in reflectances from the land surrounding the reservoir.

For purposes of discussion, the evaluation has been divided into four sections:

- o Spatial and spectral resolution of LANDSAT film products as compared to digital LANDSAT data from Computer Compatible Tapes (CCT).
- o A determination of the precision and accuracy of measuring surface areas of bodies of water from LANDSAT.
- o LANDSAT monitoring of Secchi depths and total solids in Lake Chesdin Reservoir (LCR), and choice of water sampling sites at both LCR and SCR based on the synoptic overview of reflectances from LANDSAT.

¹One hectare is 0.01 Km² and equals 2.5 acres.

²"ERTS" has been renamed LANDSAT.

- o LANDSAT monitoring of changes in land cover in the SCR watershed, in the Brandermill construction site, and in the area of overlap between the construction site and the watershed.

DIGITAL VERSUS FILM PRODUCTS

Digital data are necessary for most water quality monitoring. This can be illustrated by comparing a standard black and white print of a LANDSAT image (Figure 1), and a photographic blow-up (Figure 2) from it, with a pseudo-color pixel³ print of the same area (Figure 3) prepared from a CCT.

The photographic blow-up in Figure 2 was prepared from a standard 70mm negative of MSS band 7⁴ for the LANDSAT image of 13 September 1974. It appears slightly out of focus because individual points of information can no longer be resolved at this scale. Photographic products have the inherent limitation that some information is lost in each successive generation of photographs. While some of the fuzziness of Figure 2 can theoretically be attributed to loss in printing from Figure 1, in this case the detail is not present in the original negative. Some of the information from the satellite has already been lost in the preparation of the second or third generation negatives used to prepare negatives for the user.

How does one extract the maximum amount of information from the satellite? Figure 3 is a pseudo-color pixel print prepared by computer assignment of different colors to every reflectance value in MSS-7. The choice of "pseudo-colors" is arbitrary and not necessarily optimum, but illustrates the ability to make each different reflectance value visible when one starts with the original digital data on the CCT's. Furthermore, every pixel can be seen as a distinct rectangle. One of the inherent advantages of digital image processing is that no information need be lost in computer processing.

³A pixel is a picture element. For LANDSAT, a typical pixel from the satellite corresponds to an area on the ground of about 57m by 79m, or .45 hectares (1.1 acres).

⁴LANDSAT has four bands of light reflectance recorded with its Multi-Spectral Spectrometer. MSS-4 (0.5 to .6 microns) and MSS-5 (0.6 to 0.7 microns) are in the visible. MSS-6 (.7 to .8) and MSS-7 (.8 to 1.1) are in the near infrared.

What is the ultimate LANDSAT resolution? Is it necessary to obtain this degree of precision when monitoring water quality? A theoretical estimate can be made of the smallest sized water area that can be reproducibly monitored from LANDSAT by knowing the size of a pixel and recognizing that the arbitrary starting point of the process of scanning on the satellite will result in pixel displacement from one date to another of up to plus or minus one column or one line, even after registration of the two images on top of each other. The nominal scan rate of the mirror in the satellite results in the storage of average reflectance values as individual pixels which are roughly centered in adjacent 57m by 79m areas on the ground. However, the Instantaneous Field Of View (IFOV) of the telescope on the satellite is about 79m by 79m. Since this area is greater than the area from the average scan rate, every pixel contains an overlap contribution to its reflectance from the two adjacent pixels on the same line. This larger 79m by 79m IFOV pixel area is the limiting size in resolving reflectance values from the ground. Given the arbitrary starting point of the scan of each image, the homogeneous water area on the ground would have to be at least twice as wide and twice as long as the IFOV to ensure that on every pass of the satellite at least one pixel contained nothing but reflectance from the homogeneous water area. Therefore, for guaranteed repeat monitoring from LANDSAT, the homogeneous area must be at least 158m by 158m or 2.5 hectares (6.2 acres) in size. In 50% of the images, a homogeneous area would be visible as a pixel containing 100% water if its dimensions were a factor of a square root of 2 less, namely 112m by 112m or 1.25 hectares (3.1 acres). If 2.5 hectare bodies of water, or bodies with lateral dimensions of down to 158m, are viewed as significant for purposes of repeatedly monitoring water quality from LANDSAT, then digital processing is required in order to retain all of the spatial resolution present in the data coming from the satellite.

In summary, all the spectral and spatial resolution is available from digital image processing of the CCT's, whereas film processing results in loss of information in both domains. Most potential applications for monitoring of water quality from LANDSAT seem to require digital image processing.

SURFACE AREA OF WATER

VSWCB needs to monitor the water quality of all bodies of water in the state. In order to accomplish this, they would like a periodically up-dated water inventory map which identifies the locations and surface areas of these water bodies. By monitoring changes in surface area and the creation of new bodies, the relatively understaffed field units within each region of the VSWCB can set up efficient and comprehensive water sampling programs.

LANDSAT's MSS band 7 is ideally suited for spectrally identifying water pixels because water absorbs so completely in the near infrared, relative to absorption by non-water areas. Since the question of identifying water by satellite was not in doubt, the objective of this phase of the demonstration project was to evaluate how precisely, and how accurately, surface areas of water could be measured. Sub-pixel spatial resolution is possible for determining water area because pixels containing as little as 30% water in them can be spectrally distinguished in MSS-7 from pixels containing less than 30% water. For measuring the area of water on any specific LANDSAT image, the spatial resolution is more than an order of magnitude better, i.e. of the order of 30% of a pixel which is about 0.2 hectare (0.4 acre).

Swift Creek Reservoir was chosen as the site for this evaluation of precision and accuracy because the water is maintained at the same level throughout the year. Furthermore, there is a steep shoreline and intense forest cover extends to the edge of the water. There is essentially no shore. Therefore, small changes in water level would result in even smaller percent changes in the total surface area. Seven sub-sections of the reservoir were used, ranging in size from about 500 hectares down to 5 hectares of water. They can be seen in a blow-up of a photograph from a U-2 aircraft flown at 60,000 feet (Figure 4) and in photographs taken from a light plane at an altitude of 300 feet (Figure 5).

Several methods of calculating areas were evaluated using these 7 sections, after converting pixel-by-pixel lists of MSS-7 into lists of per cent water (Figure 6). Lists of this type were prepared in 2 or 3 parts on three different images from 1974. One reason for this partitioning was because certain columns had been repeated in the original CCT's to fill out the overall image to 3240 columns; these repeated columns had to be removed to prevent overestimation of the area by as much as 15%. A second reason for partitioning was that a better estimate of the average reflectance of MSS-7 on land immediately adjacent to the water could be made by using the mean reflectances in separate parts. In each part, a "contrast stretch" program was used to convert reflectance values, R, into percent water, W, according to the formula:

$$W = 100 \left(\frac{RL-R}{RL-RW} \right) \quad \text{(Equation 1)}$$

Where RL is the mean reflectance of the land pixels (read from a histogram of number of pixels versus reflectance of the part) and RW is the mean reflectance of the water. The methods were divided into two types: pure pixel methods and mixed pixel methods.

In the pure pixel methods, pixels containing 100% water were identified and then assumptions were made so that a correction could be added for the contribution from fractionally filled border pixels. The number of pure pixels was obtained by counting the number of "50's" in lists such as in Figure 6 (the list shows values of W/2) and then adding 1 to 3 of the next lower levels such as 47 and 44 until the distribution of number of pixels versus percent water was approximately level. This could have been done in the original contrast stretch program. Such an addition appears necessary to avoid underestimating the number of pixels containing 100% water. Since the mixed pixel method of area measurement is more accurate, only two pure pixel methods will be mentioned, referred to as area methods A1 and A2. Method A1 simply multiplies the number of pure pixels, P, by the area conversion factor, C:

$$A1 = C P \quad (\text{Equation 2})$$

Pure pixel area method A1 will always underestimate the area because no correction is made for border pixels. Pure pixel method A2 makes a theoretical estimate of the number of border pixels by assuming that since the area is proportional to P, then the perimeter of border pixels is proportional to the square root of P:

$$A2 = C (P + S\sqrt{P}) \quad (\text{Equation 3})$$

where S is a function of the shape of the body and can be shown to have a value between 2 (for a square⁵) and infinity for a sufficiently long and thin body of water. For sections of SCR, a value of 4 was used to show that method A2 can give an answer almost as good as the mixed pixel method until the area becomes so small that the number of border pixels, $S\sqrt{P}$, is approximately equal to the number of pure pixels, P.

In the mixed pixel methods, pixels containing some water and some land are empirically identified and their fraction of water estimated from their reflectance values, these fractions are added to the pure pixels. Only one of the many possible mixed pixel methods will be examined, the one which estimates the number of border pixels that contain at least 50% water. This area method, A3, is obtained by counting all border pixels in Figure 6 which have a value of W equal to or greater than 50, to be called border-50% pixels or B50, and adding them to P:

$$A3 = C (P + B50) \quad (\text{Equation 4})$$

5

It can be shown that the study of square area determinations by G. Chafaris can be summarized by an equation $A2 = C (P + 2\sqrt{P} + 1)$; "Area Computation From ERTS Data via Image-100" internal General Electric Co. report, 9 January 1975.

This method A3 is equivalent to a threshold classifier which adjusts the range of reflectance values such that exactly 50% of the border pixels are included as part of the pure class,

Results of mixed pixel area method A3 are summarized in Tables 1 and 2. Areas given for the USGS map were obtained by using a planimeter on each of the seven areas on a 1:24,000 scale map. The error in reproducibility for the planimetry was as small as 0.1% for the largest area and about 4% for the smallest area. These errors can all be considered negligible in comparison to the reproducibility obtained on the three different LANDSAT images given in Table 1⁶. Table 2 lists the number of pure water pixels, P; the number of border pixels, B50; the average area of the three dates, A3; and finally the percent error which was taken as the larger of either the precision or the accuracy of the mean of three measurements. Only in area 6, near the dam, is the apparent error of +10% significantly greater than expected error based on the progression from +1% at 500 hectares to ±5% at 5 hectares. The reason for this apparent error near the dam seems to be that the planimetered area on the USGS map did not include the settling ponds below the dam and these were not separated out in calculating areas from the lists of LANDSAT images.

An area conversion factor, C, which converts pixel counts into area is required in all methods. For LANDSAT, it has a nominal value of 0.451 hectare/pixel, or 1.12 acre/pixel. This assumes that every pixel in every image is exactly the same 57m by 79m nominal size. When the location of the water body in the image is known, corrections can be made for the uneven scan rate of the satellite mirror across the scene and for the height of the satellite on different dates. R. Peterson⁷ calculated the values of C for SCR for the three dates used in this study; they were 0.463, 0.459, and 0.459 hectare/pixel. In order to reduce these known systematic errors due to mirror velocity profile and different satellite heights, these values of C were used here even though there were not enough larger areas to determine the extent to which the conversion factors may have improved accuracy over the nominal value.

Reproducibility decreases with decreasing size, as illustrated by the percent standard deviations of a single measurement in Table 3. The comparison of pure and mixed pixel methods shows that the mixed method is always more precise. The random error in the

⁶The three LANDSAT images used for this area study were: 1692-15124 (25 June 1974), 1710-15120 (3 July 1974) and 1782-15092 (13 September 1974).

⁷R. Peterson, "Landsat Pixel Spacing-User Demonstration Projects Technique Report," preliminary General Electric Co. Report, 27 May 1975.

estimated area could be reduced further by taking the mean of several measurements.

Accuracy also decreases with decreasing size, although this is not so obvious in Table 4 because of the fortuitously close agreement of the mean of three dates for the smallest area when compared to the planimetered area from the 1:24,000 scale USGS map. The pure pixel method, A1, which makes no correction for border pixels, always underestimates the area. However, by estimating the border pixels from the number of pure pixels, pure pixel method A2 can be as accurate as the mixed pixel method for areas greater than about 20 hectares. If water areas smaller than this size are to be measured, then a mixed pixel method such as A3 must be used. Observed averages of the three dates and expected areas from the USGS map differed by less than the measured precision. There were no systematic deviations. Therefore it was concluded that the accuracy of a LANDSAT area measurement of water was limited solely by its precision.

The smallest area of water that can be measured by LANDSAT depends on the required precision. If one is talking about the ability to reproducibly identify the existence of a water body on every LANDSAT overpass, and if a pixel with about 30% water in it can be spectrally distinguished from land, then the minimum size for an identifiable body of water is approximately 0.5 hectare (1 acre). If one is comparing water areas for the same body on two different dates and looking for the smallest observable change at the 95% level of confidence (± 2 standard deviations), then the precision depends on the size of the body; e.g. two times $\pm 8\%$ at 5 hectares is ± 0.9 hectare (± 2 acres), whereas two times $\pm 1\%$ at 500 hectares is ± 10 hectares (± 25 acres). For some purposes the measurement of area might be useless unless it contained at least one "all water" pixel on every overpass, in which case the minimum sized area was shown to be about 2.5 hectares (6 acres). Above these lower limits, a user's required precision determines the smallest measurable body of water.

Since the mixed pixel method A3 was the most precise, two alternate techniques for calculating it were explored. One used a threshold classifier. The other used a contouring program. Both are theoretically identical to counting pixels from a computer list such as Figure 6, and therefore users can decide for themselves which technique is most convenient.

G.E.'s Image-100 was used to test the interactive threshold classifier. Two separate sets of threshold limits for MSS-7 were used as input to define the class bounds of pure water pixels and pixels with up to a certain percent water, taken as 50% in method A3. Then a polygon cursor was drawn around the area to be measured. Output was produced as an alphanumeric list of the two classes, similar to Figure 6, and two numbers were produced giving the total number of pixels in the two separate themes, pure and mixed pixels. A check of several areas on the alphanumeric list for a single date verified the agreement of this technique and the computer technique used for Figure 6.

Contouring was done with an IBM 360 Computer and a CALCOMP plotter. This technique requires that the final plot have the correct aspect ratio so that the area can be measured by planimetry the band 7 contour line corresponding to 50% water. Such a contour map of MSS-7 for SCR is shown in Figure 7. A contour map for water has several distinctive features. It requires no interaction with the user other than the choice of reflectance values for contour lines and therefore is relatively fast. Contouring programs are available on most general purpose computers as well as on several small stand-alone devices. Contour lines, like classifiers, emphasize certain

features and omit extraneous information. A contour map is an analog product which the knowledgeable user might be able to scan for subtle boundary changes without further processing; Figures 7 and 3 can be used to compare analog and digital presentations of band 7 reflectance values. The precision of calculating areas from contour maps was not evaluated here.

An example of a water inventory map is shown in Figure 8. It was prepared on an Image-100 classifier and printed as a black and white product on a DICOMED photographic recorder. One potential use of this map is to monitor the creation of new bodies of water; e.g. the three pronged lake in the center of the picture is a new feature that is not on existing maps of the area.

In summary, individual water areas can be measured from LANDSAT with an accuracy that decreases from $\pm 1\%$ at 500 hectares to $\pm 8\%$ at 5 hectares.

Assuming that pixels with more than 30% water can be identified from low MSS-7 reflectance values, total area measurements will be more accurate than single body measurements if most of the water is contained in a few large bodies which have relatively few border pixels. Furthermore, random errors in the calculation of the areas of each single body, caused by the inclusion of too many or too few mixed pixels, will cancel out when all single body areas are summed into one total area measurement. The absence of observable systematic errors suggest that water inventory maps from LANDSAT within some political or physical region might be accurate to $\pm 1\%$ in identifying the total area of open water. Although mixed pixel methods were more accurate than pure pixel methods, for some applications pure pixel methods might be adequate for areas above 20 hectares when a theoretical correction for border pixels is made.

DIRECT MONITORING OF WATER QUALITY

Ideally, VSWCB would like to monitor water quality directly with a sufficiently fast turn-around time to permit corrective action to be taken whenever possible. Detectors on LANDSAT were found to record reflectances which showed an inverse correlation with the depth one could see into the water (Secchi depth) and an apparent direct correlation with total solids. Since cloud-free LANDSAT coverage in Virginia occurred about once every 2 months, the utility of these correlations with turbidity appears to be primarily for monitoring changing water patterns and verifying the statistical appropriateness of ground-based sampling programs, rather than for monitoring water quality. This direct type of remote sensing information might permit more extensive monitoring of slowly changing water bodies than current limited budgets for field work permit.

Swift Creek Reservoir was the desired demonstration site for testing LANDSAT's capabilities because of forthcoming construction there. However, inspection of about 10 LANDSAT images taken over a two year period indicated relatively little within-image variation in reflectance values for any of the bands in the main portion of this reservoir. Therefore, Lake Chesain Reservoir was added to the project because it tended to show much greater changes in reflectance values along its length.

Initial attempts to identify different types of water by using all four bands proved unnecessary for these two reservoirs. Using values averaged over six lines to remove differences in reflectance due to unequal sensor calibration, locations in both SCR and LCR showed correlations among bands 4, 5, and 6 on all seven cloud free LANDSAT images that were analyzed in detail. For the 13 Sept 74 image, the range of MSS-5 reflectance was arbitrarily sliced into seven approximately equal sections and the limits of each of these were used as threshold inputs to form classes on G.E.'s Image-100. Then, the mean values of the other three bands were calculated for each of the 7 classes. The

resulting band correlations are shown in Figure 9. There was a 99% linear correlation among bands 4, 5, and 6. Only MSS-5, which showed the largest range of the three, was used in subsequent classification work on these two reservoirs.

It seems likely that only one water quality parameter, such as turbidity, is causing all the observed changes in reflectances. Reflectances from bands 4, 5, and 6 are nearly perfectly correlated in LCR. If reflectances were being increased or decreased by more than one agent, it is unlikely that the proportional changes would be the same in all three bands.

13 Sept 74 was the LANDSAT image date chosen for making a water classification map because it was the only cloud-free date available for which significant ground truth was collected in LCR. A map of the seven band-5 level-sliced classes for the region SW of Richmond is given in Figure 10. The water in SCR is essentially in one class, except for some striping due to unequal sensor calibration on the satellite. Figure 11 is a blown-up portion of Figure 10 showing only LCR. Water of the same low reflectance as SCR can be seen in the southwest part of LCR. This low reflectance region had been noted on many previous images and personnel at VSWCB were unaware that two types of water existed in this part of LCR. It turned out that this was the place where Namozine Creek entered LCR, as seen in a U-2 photograph (Figure 12). The narrow flow of water under a small bridge produced a dramatic low reflectance water class coming into the highly reflectant sediment-laden water of Lake Chesdin. Figure 13 shows what this interface looked like from a VSWCB boat on 13 Sept 74. Another small tributary of low reflecting water entering LCR can be seen in Figure 11 to the east. This is Whipponock Creek. As a result of these observations from LANDSAT, a water sampling program has been proposed for VSWCB based on the locations of different types of water. It is particularly valuable for VSWCB to have information on the far western end of LCR from LANDSAT since this area is almost inaccessible by boat.

Having established that different types of water could be directly observed from LANDSAT, the question became one of trying to identify the water quality parameter most likely responsible for the changes in reflectance. For more than a year, extensive water quality measurements were made on water samples from SCR. However, since differences in LANDSAT reflectances were not observed in the main portion of SCR, no conclusion could be drawn except that observed variations in water quality were small and below the limit of detection from LANDSAT.

Secchi depth measurements taken by NASA and VSWCB personnel in LCR on 13 Sept 74 provided the first and only set of data where there was significant variation in both the LANDSAT and ground data to check for a possible correlation. Figure 14 shows the 98% inverse correlation of:

$$\text{Reflectance} = 32.1 - 0.22 \text{ Secchi} \quad (\text{Equation 5})$$

If one thinks in terms of using this as a calibration curve for estimating Secchi depths in other parts of the map, then the equation can be rearranged to make reflectance in MSS-5 the independent variable:

$$\text{Secchi} = 143.5 - 4.41 \text{ reflectance} \quad (\text{Equation 6})$$

Sixteen individual Secchi measurements were made, but the average Secchi value was used in each class to calculate Equations 5 and 6, in order to give equal statistical weight to all reflectances and not to bias the equation in favor of the area in which most of the data was taken. Furthermore,

the use of only four numbers emphasizes the lack of data at low reflectances here and therefore the need to treat these equations as illustrative rather than definitive.

Three samples of water were also taken from LCR on 13 Sept 74. Laboratory measurements were made for the "volatile" (organic) and "fixed" (inorganic) fractions of both the "total solids" and the "suspended solids" content of samples. Reflectance is generally considered as being correlated with suspended solids; however, in LCR the particulate matter was nearly colloidal and 90% of total solids passed through the standard filter used for the suspended solids. There was an approximately equal contribution from the volatile and fixed fraction of the total solids and no correlation was found between the sum of the two fractions, namely the "total solids" and MSS-5.

The three values for total solids were 78, 82, and 92 mg/l, where the respective average gray level intensities for MSS-5 reflectance were 11.5, 21.5, and 25.8. This gives an 89% coefficient of correlation for:

$$\text{Total Solids} = 66.8 + .88 \text{ reflectance} \quad (\text{Equation 7})$$

It must be recognized that the total solids data, while perhaps more fundamental, is less statistically significant than the Secchi depth data because the former is based on only three water samples.

In summary, LANDSAT reflectances from water in the visible (MSS-4 and MSS-5) and near-infrared (MSS-6) spectral bands were shown to be spectrally and spatially coherent for both SCR and LCR, which is larger, narrower, and has a ten times greater flow rate than SCR, due to input from the Apponatox River. Maps of different reflectances in water could be derived using only MSS-5 values for these two reservoirs since it appeared that only total solids content was changing reflectances. The high correlation of Secchi depth and MSS-5 in LCR may be due to Secchi depth measurements being dependent on total solids. Since both the size and type of particle affects reflectance, it is expected that calibration equations of LANDSAT reflectance and a water quality parameter will be necessary for each region which supplies different organic and inorganic materials from its watershed. For LCR it was possible to distinguish classes of water from LANDSAT imagery which differed by about 5cm at the most sediment-laden and reflective Secchi depths. Direct monitoring of water quality from LANDSAT seems to be most useful for observing changes in water patterns and devising and verifying water sampling programs.

INDIRECT MONITORING - LAND COVER

Perhaps the greatest potential contribution of LANDSAT to a water quality monitoring program is through indirect interpretation, by detecting changes in land cover in a watershed. Surface alterations, such as deforestation or increase in agricultural use, may cause water quality changes due to increased runoff, pollutant input and other factors. The purpose of this section is to demonstrate both qualitative and quantitative means of monitoring land cover with LANDSAT.

One digital product that can be prepared from LANDSAT CCT's is a color composite of a subsection of the whole 185 km by 185 km image. Figure 15 is a picture of the 30 km by 30 km area surrounding SCR. It was prepared on a DICOMED printer. Geometric corrections were made to the picture on GE's Image-100 and an IBM 360 computer to correct for rotation of the Earth during satellite overpass (skew correction) and for the rectangular shape of pixels (aspect ratio correction). Without further processing, this picture can be scanned by people familiar with the area to see if there have been any major changes in land cover. For the knowledgeable expert, this picture provides more information than a classed image.

If it is necessary to quantify the extent of change in land cover, rather than simply identify that a change has occurred, then it is necessary to classify the image. This was done in several ways, one of which was using the normal threshold classifier on G.E.'s Image-100. One of the steps was to limit the area being classed on the LANDSAT image to the acreage inside the Swift Creek Reservoir watershed, shown in Figure 16. The resulting classification maps for 15 June 74 and 13 Sept 74 are given in Figures 17 and 18.

A check on the accuracy of the classification was made by visually classifying a U-2 photograph and checking the above classifications pixel-by-pixel with a zoom-transfer scope in 5 sites that were known to be unchanged. The results of these two checks are given in Tables 5 and 6. The thin cloud cover on 15 Jun resulted in 14% of the pixels being unclassified whereas only 5% were unclassified on the 13 Sept image. Clouds also interfered with the identification of all agricultural land on 15 June. This watershed is about 70% forest and it was impossible to find large homogeneous training sites for the non-forest classes on either date. Therefore these classes have a lower value in the accuracy table.

The overall results for the two dates have been summarized in Table 7. The "agriculture" class includes pixels which are mixtures of forest and open areas cleared for construction.

The area of the Brandemill construction site inside the watershed can be seen as the non-forest area north of the reservoir in the 13 Sept 74 classed image (Figure 18). One of the white "barren" class pixels near the water was identified in a low altitude aircraft photograph as containing several piles of white sand for a golf course.

In summary, changes in land cover classes can be monitored from LANDSAT. Useful integration of this information into predictions of changes in water quality is probably several years off and must await the development of quantitative models for the watershed. In the meantime, such maps and tables can alert personnel such as the VSWCB to possible changes in water quality. The observation of the Brandemill site before and after the start of construction illustrates the ability of LANDSAT to not only produce land

cover maps, but to monitor changes in land cover.

ACKNOWLEDGEMENT

This demonstration project could not have been completed without the scientific and technical assistance of Peter Trexler and Clark Thaler of the Division of Surveillance and Field Studies, Piedmont Regional Office of the Virginia State Water Control Board and Dorothy Schultz of General Electric's Beltsville, Maryland office.

TABLE 1 REPRODUCIBILITY OF MEASUREMENTS FROM LANDSAT

AREAS OF WATER (in Hectares)				
LOCATION	USGS MAP	LANDSAT		
		JUNE '74	JULY '74	SEPT '74
5	464.7	476.2	463.0	469.6
3	75.2	78.4	73.0	77.2
6	30.8	33.5	34.0	33.8
2	25.5	24.8	23.4	25.9
4	22.1	22.2	21.6	22.7
1	10.9	11.1	9.4	10.2
7	5.5	5.0	5.5	5.9

TABLE 2 ACCURACY OF AVERAGED AREA MEASUREMENTS FROM LANDSAT

AREAS OF WATER					
LOCATION	USGS MAP	LANDSAT			
	AREA Hectares	WATER Pixels	BORDER Pixels	AREA Hectares	ERROR %
5	464.7	902	118	469.6	± 1
3	75.2	117	49	76.2	± 2
6	(30.8)	53	20	33.8	±10
2	25.5	30	24	24.7	± 3
4	22.1	31	17	22.2	± 2
1	10.9	2	17	10.2	± 5
7	5.47	1	11	5.5	± 5

TABLE 3 REPRODUCIBILITY OF AREA MEASUREMENTS

Method	Percent Precision (by size)		
	at 500 hectares	at 25 hectares	at 5 hectares
Pure Pixel	$\pm 3\%$	$\pm 8\%$	---
Mixed Pixel	$\pm 1\%$	$\pm 4\%$	$\pm 8\%$

TABLE 4 ACCURACY OF AREA MEASUREMENTS

Method	Percent Deviation (by size)		
	at 500 hectares	at 25 hectares	at 5 hectares
Pure Pixel, A1	-10%	-40%	-90%
Pure Pixel, A2	+ 1%	+ 2%	-60%
Mixed Pixel, A3	+ 1%	- 2%	(+.1%)

TABLE 5 LANDSAT CLASSIFICATION COMPARED WITH KNOWN LAND COVER

PERCENT ACCURACY OF CLASSIFICATION									
	JUNE 74 LANDSAT-1								
U-2	WAT	W/L	PIN	HDW	AGR	BAR	RES	UNCL	MIS-CLSD
WATER	97	3	0	0	0	0	0	0	3
WATER/LAND	0	46	14	0	9	0	0	31	23
PINE	0	0	82	3	3	0	0	12	6
HARDWOOD	0	0	15	62	5	0	0	18	20
AGRICULTURE	0	0	4	1	54	2	4	35	11
BARREN	0	0	2	0	9	62	21	6	32
RESIDENTIAL	0	0	10	5	38	12	11	24	65

TABLE 6 CHANGED LANDSAT CLASSIFICATION AFTER 3 MONTHS

PERCENT ACCURACY OF CLASSIFICATION									
	SEPT 74 LANDSAT-1								
U-2	WAT	W/L	PIN	HDW	AGR	BAR	RES	UNCL	MIS-CLSD
WATER	97	3	0	0	0	0	0	0	3
WATER/LAND	0	46	17	1	1	0	0	35	19
PINE	0	0	80	9	4	0	0	7	13
HARDWOOD	0	0	30	61	6	0	1	2	37
AGRICULTURE	0	0	3	11	50	0	17	20	30
BARREN	0	0	0	0	11	34	39	16	49
RESIDENTIAL	0	0	2	1	50	1	36	10	54

TABLE 7 COMPARISON OF LAND COVER CLASSES FOR SWIFT CREEK RESERVOIR AND BRANDERMILL CONSTRUCTION SITE

LAND COVER CLASSES IN PERCENT				
	18,000 HECTARE BASIN		740 HECTARE CONSTRUCTION SITE	
	JUNE	SEPT	JUNE	SEPT
	PINE	38	38	65
HARDWOOD	33	35	16	17
AGRICULTURE	9	15	4	18
RESIDENTIAL	2	4	1	2
BARREN	1	0	0	1
UNCLASSSED	14	5	10	6
WATER	3	3	4	5

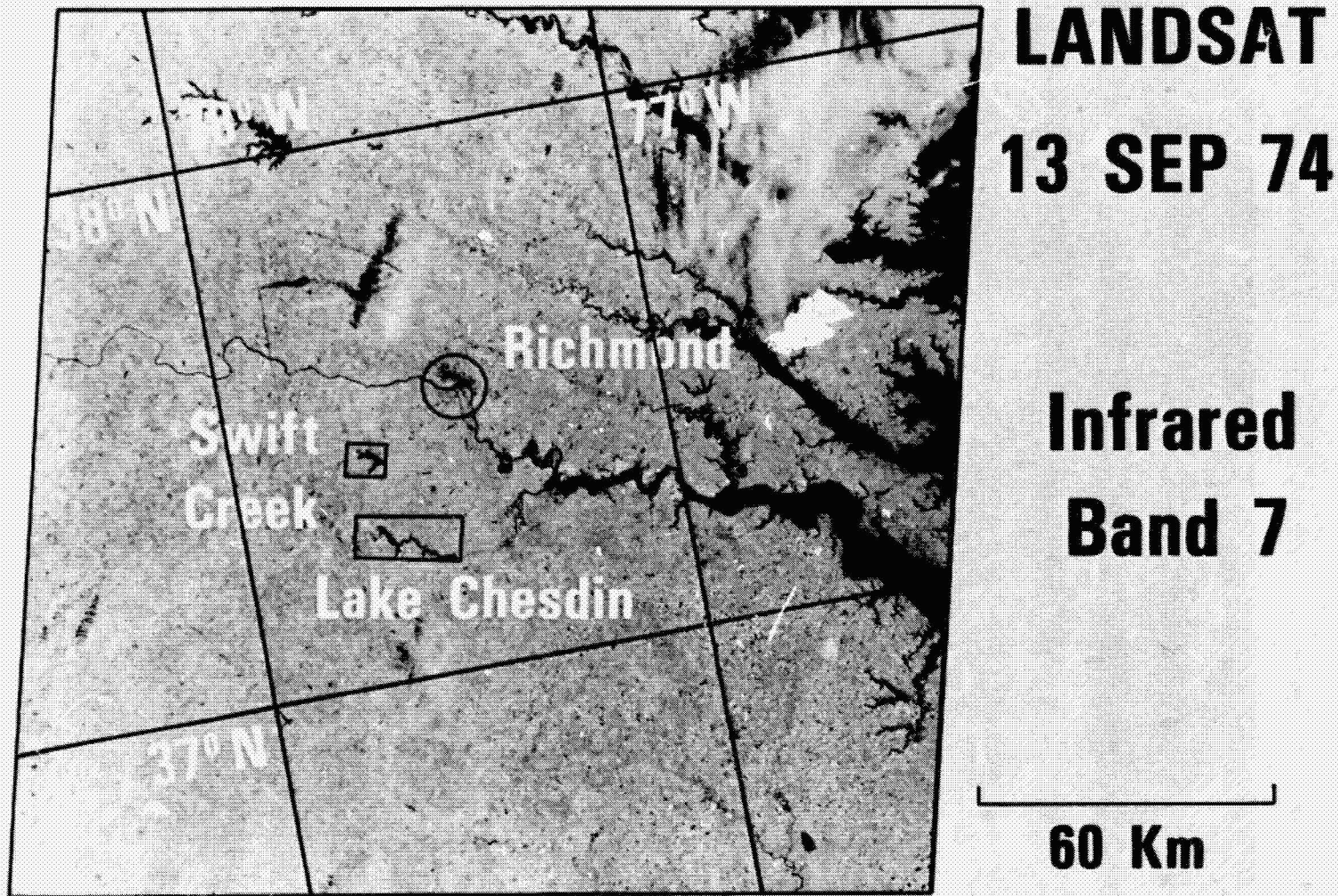


Figure 1.- Annotated print of standard 8.5 cm x 8.5 cm NASA LANDSAT negative.

Film Processing of LANDSAT Image
13 SEP 74 Blow-Up of MSS-7



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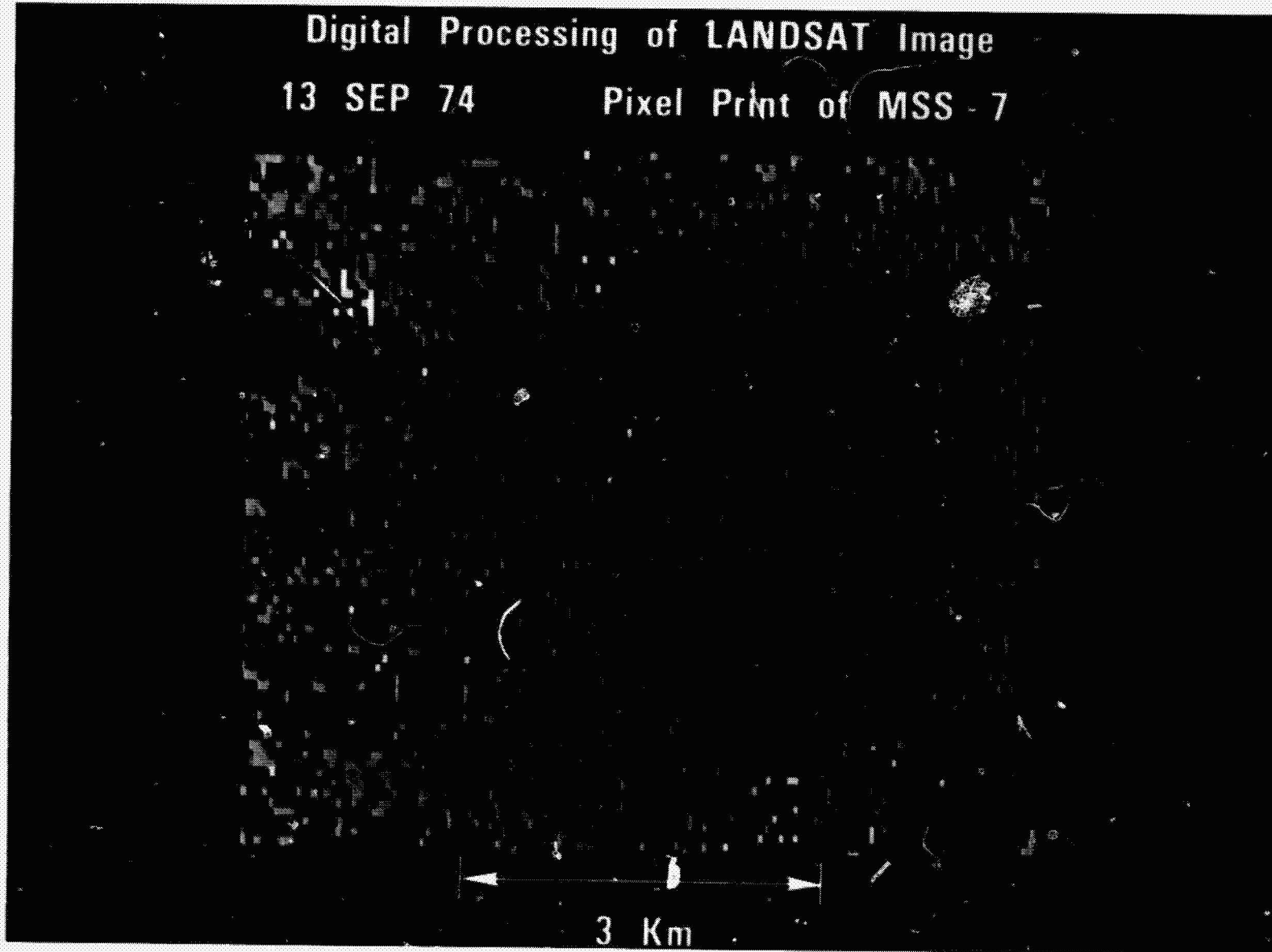
402

Figure 2.- Photographic blow-up of Swift Creek Reservoir, Virginia from standard
8.5 cm x 8.5 cm LANDSAT negative.

Digital Processing of LANDSAT Image

13 SEP 74

Pixel Print of MSS - 7



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Figure 3.- Pseudo-color pixel print of Swift Creek Reservoir, Virginia from LANDSAT CCT, illustrating potential for viewing every pixel and every reflectance value.

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Figure 4.- U-2 photograph taken at 60,000 feet. Locations of 7 sections of Swift Creek Reservoir, used in checking precision and accuracy of area measurements from LANDSAT, are shown in Figure 5 and 6.

Locations for Area Measurements

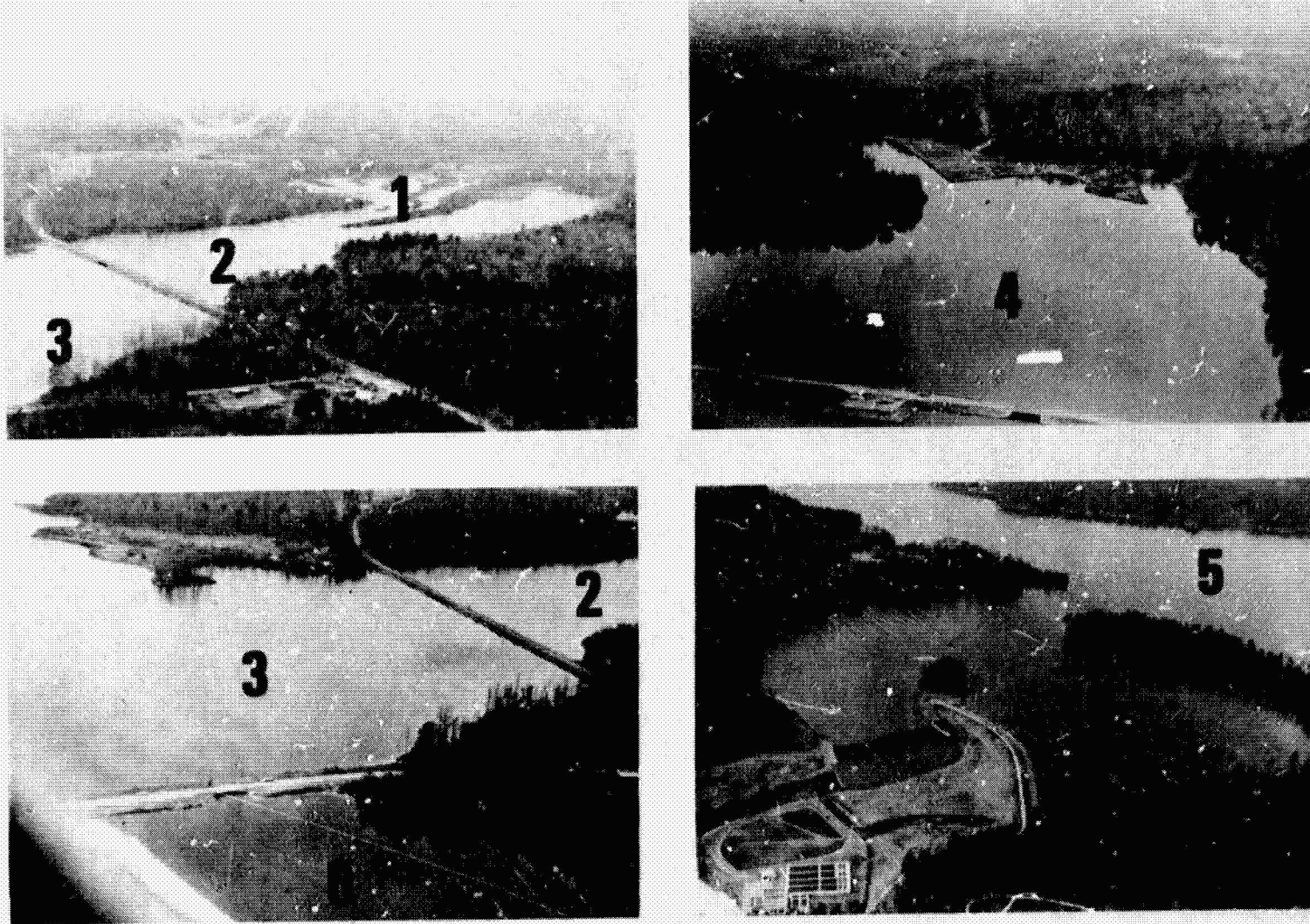
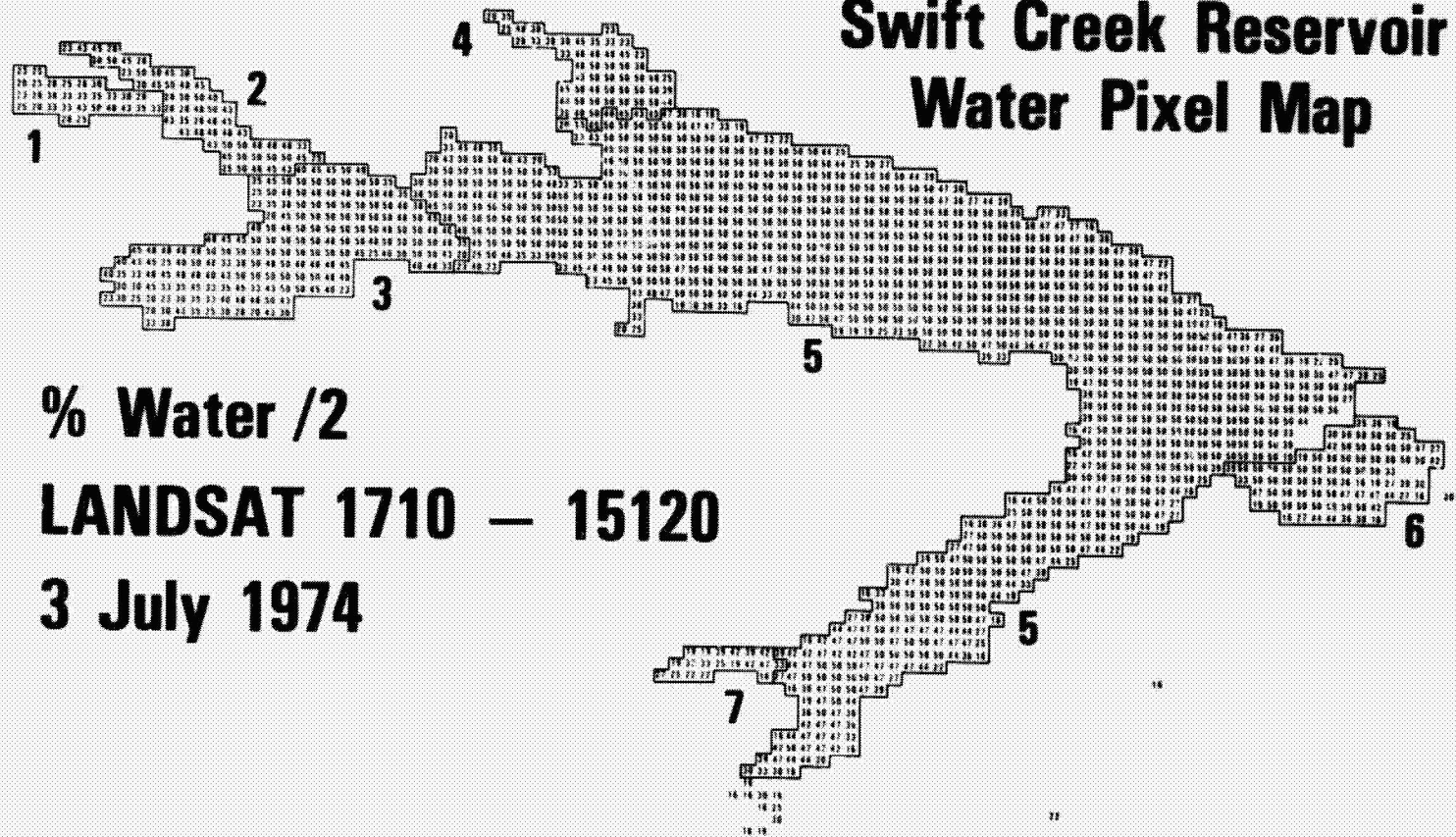


Figure 5.- Low altitude Kodachrome prints of some of the 7 sections of Swift Creek Reservoir used for area measurements.

Swift Creek Reservoir Water Pixel Map

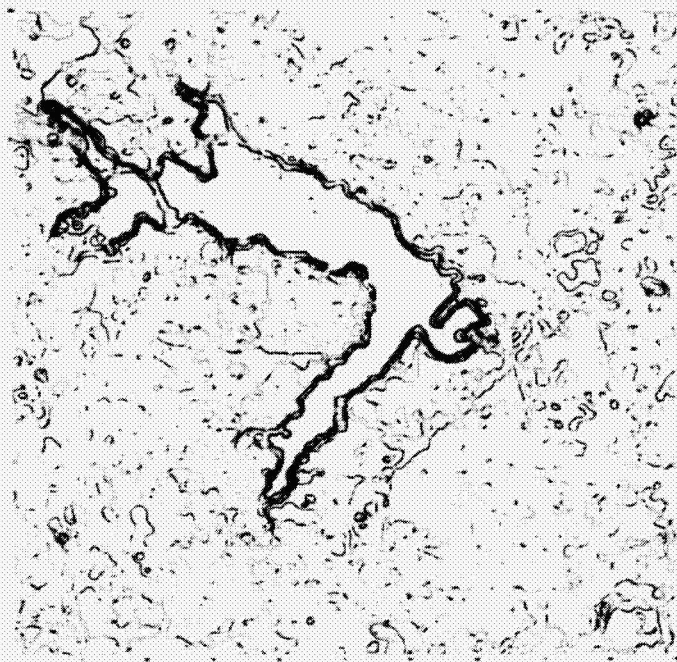


% Water /2

LANDSAT 1710 — 15120

3 July 1974

Figure 6.- Computer list of MSS-7 reflectance values of Swift Creek Reservoir converted to percentage of water divided by 2 showing 7 sections used for area measurements.



**MSS-7
CONTOUR MAP**

**13 SEP 74
1782 - 15092**

**SWIFT CREEK
RESERVOIR**

Figure 7.- CALCOMP contour map of Swift Creek Reservoir for selected values of MSS-7 chosen to emphasize the boundary between land and water.



**Water
Inventory
Map**

**Area SW
of Richmond**

13 SEP 74

8 Km

Figure 8.- Water inventory map of a 30 Km by 30 Km region SW of Richmond derived from a LANDSAT image by identifying all pixels which contained more than approximately 60% water.

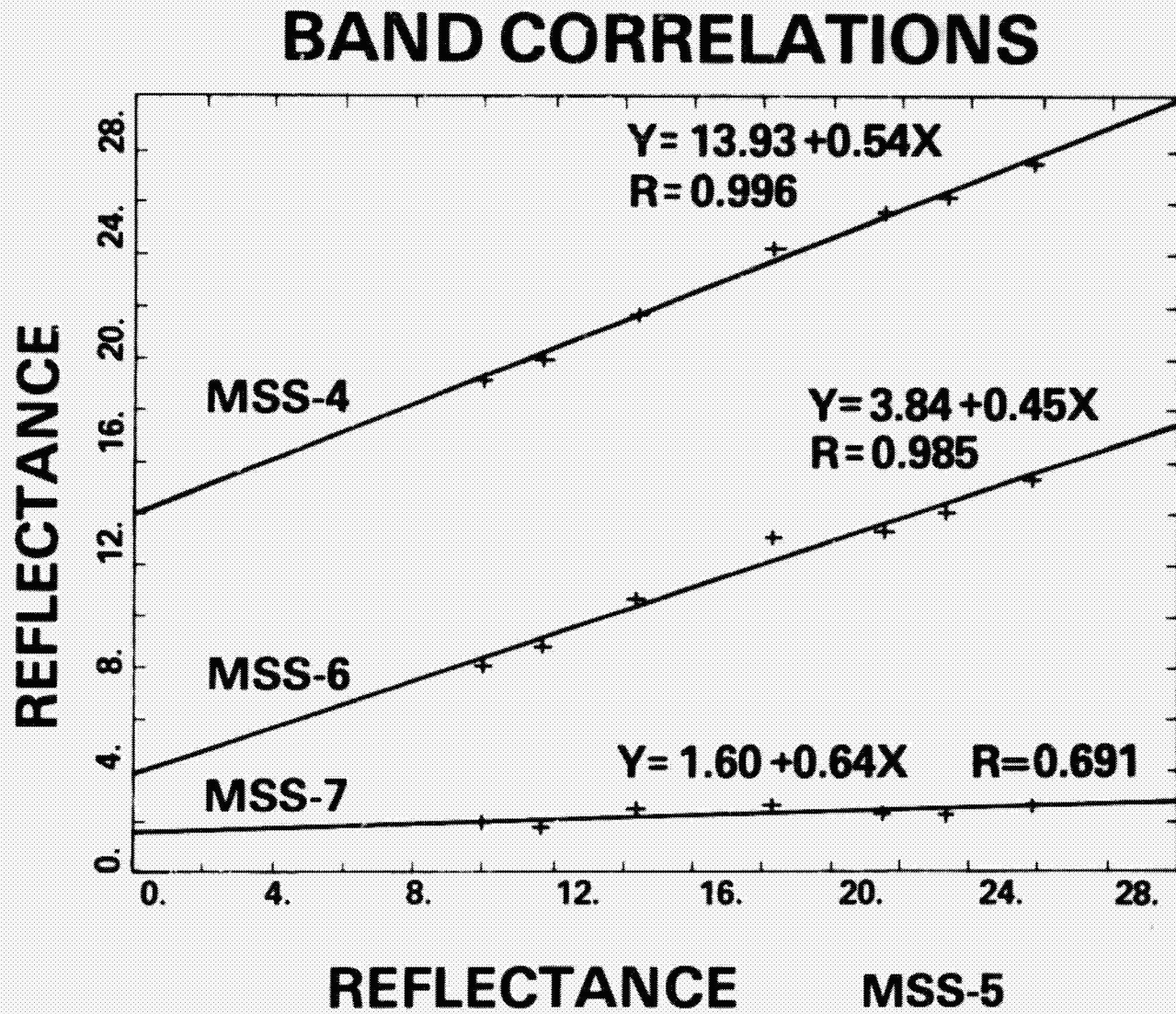
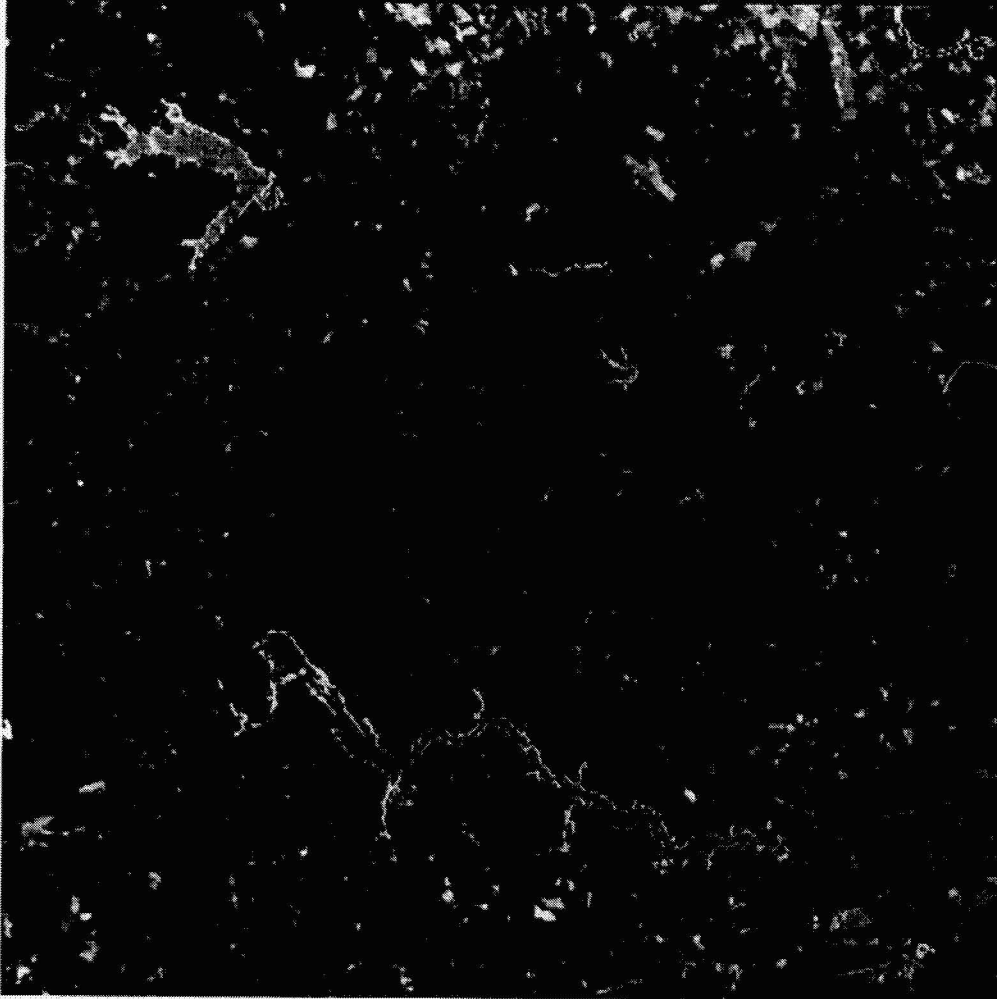


Figure 9.- Correlation of LANDSAT reflectances from water in different MSS bands on 13 Sept 74 in Swift Creek and Lake Chesdin Reservoirs.

13 SEP 74 LANDSAT I-100

SWIFT CREEK TAPE SP= 1 SL= 70 512 X 370 AREA EXPND BY 5X 7

B KM



- SCR 6
- SCR 8
- SCR TRIB 9
- WHIP.CR 12
- LCR WEST 5
- LCR MID 2
- LCR EAST 1
- W/L MIX 7

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Figure 10.- Map of seven MSS-5 level-sliced water classes for 30 Km by 30 Km region SW of Richmond on 13 Sept 74.

Lake Chesdin Reservoir, VA 13 SEP 74

MSS — 5 Level Sliced Water Classes

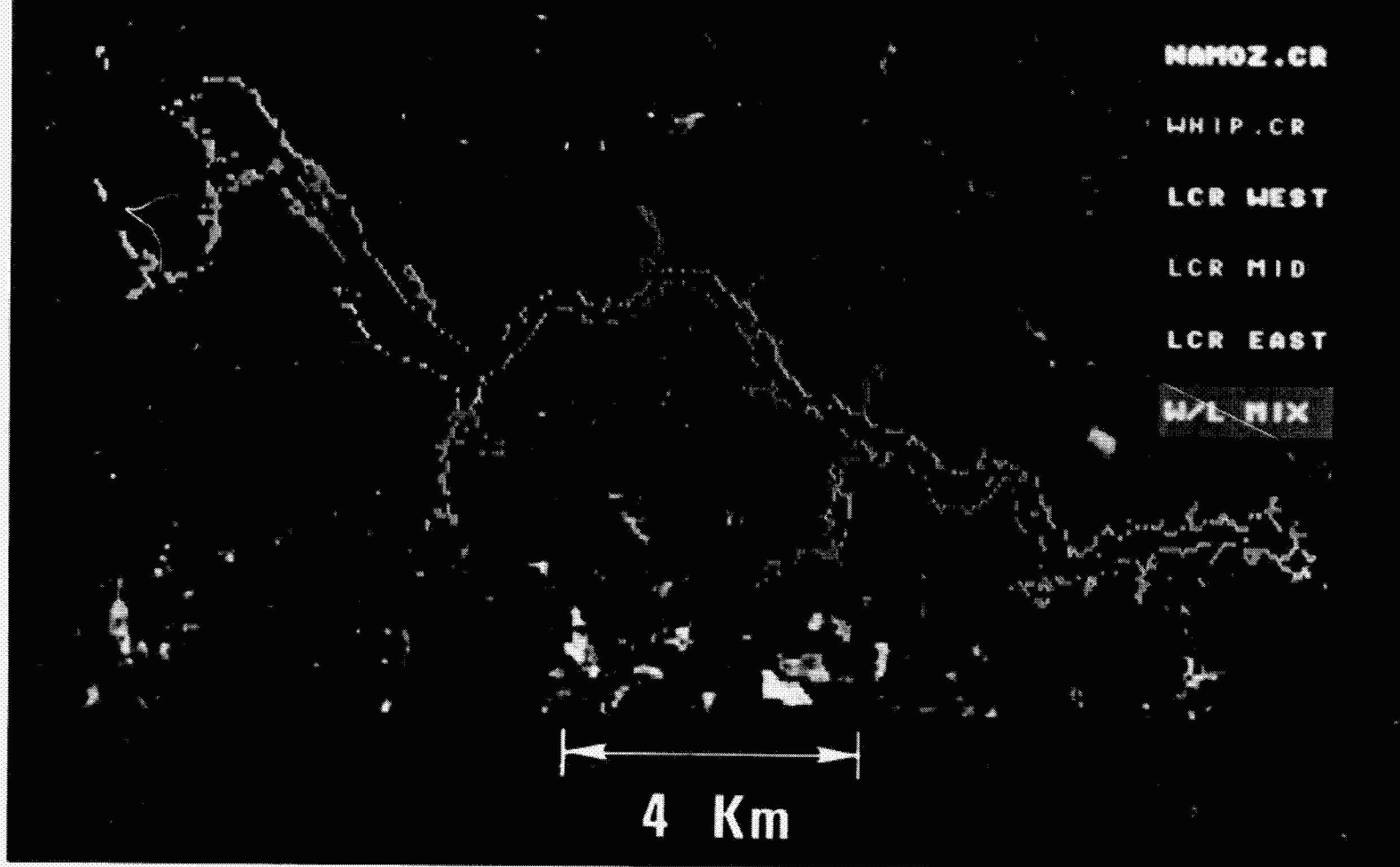


Figure 11.- Map of seven MSS-5 level-sliced water classes in Lake Chesdin Reservoir on 13 Sept 74.



Figure 12.- Blow-up of 2 Dec 72 U-2 photograph showing southwestern part of Lake Chesdin where Namozine Creek enters.

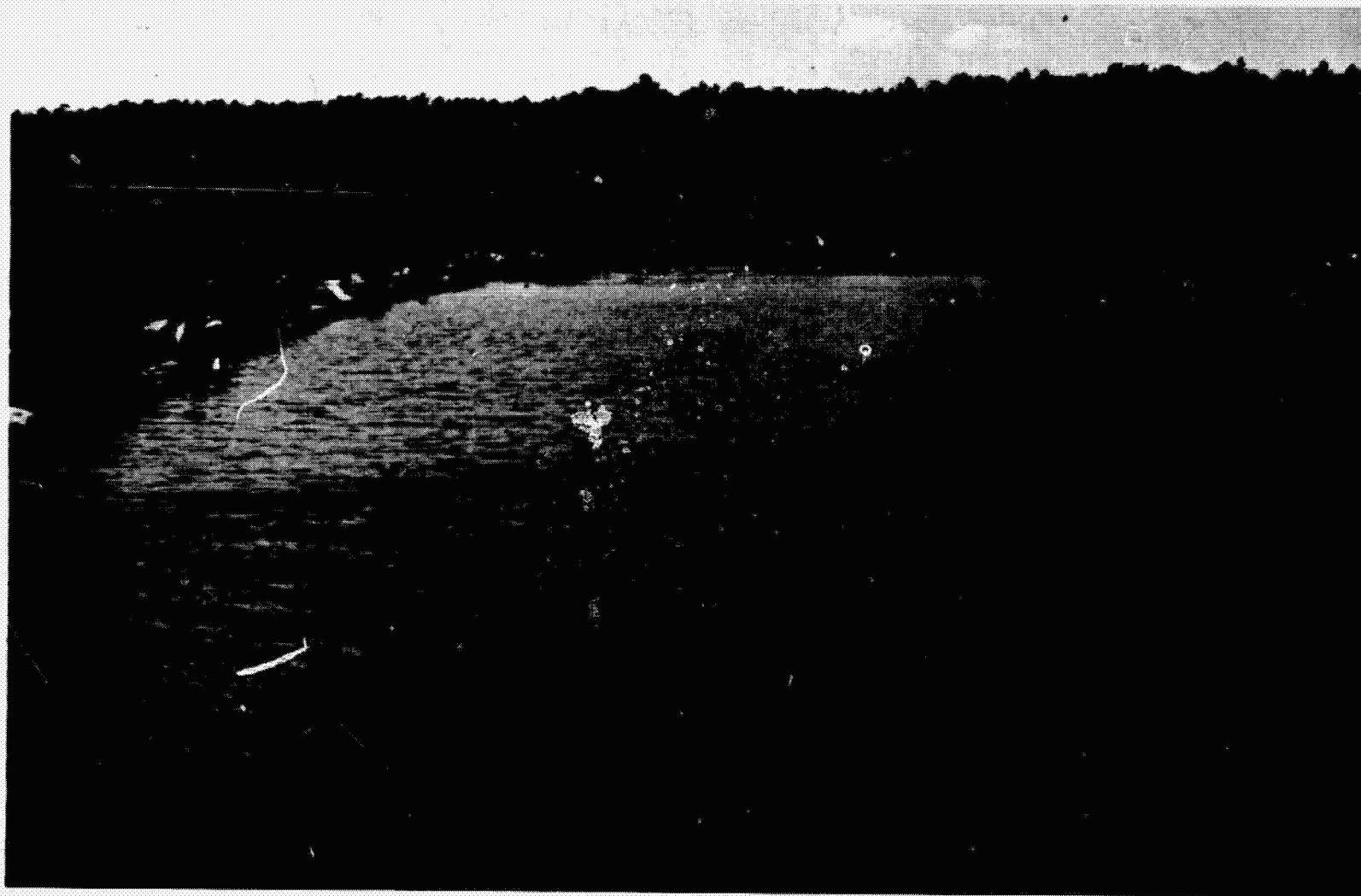
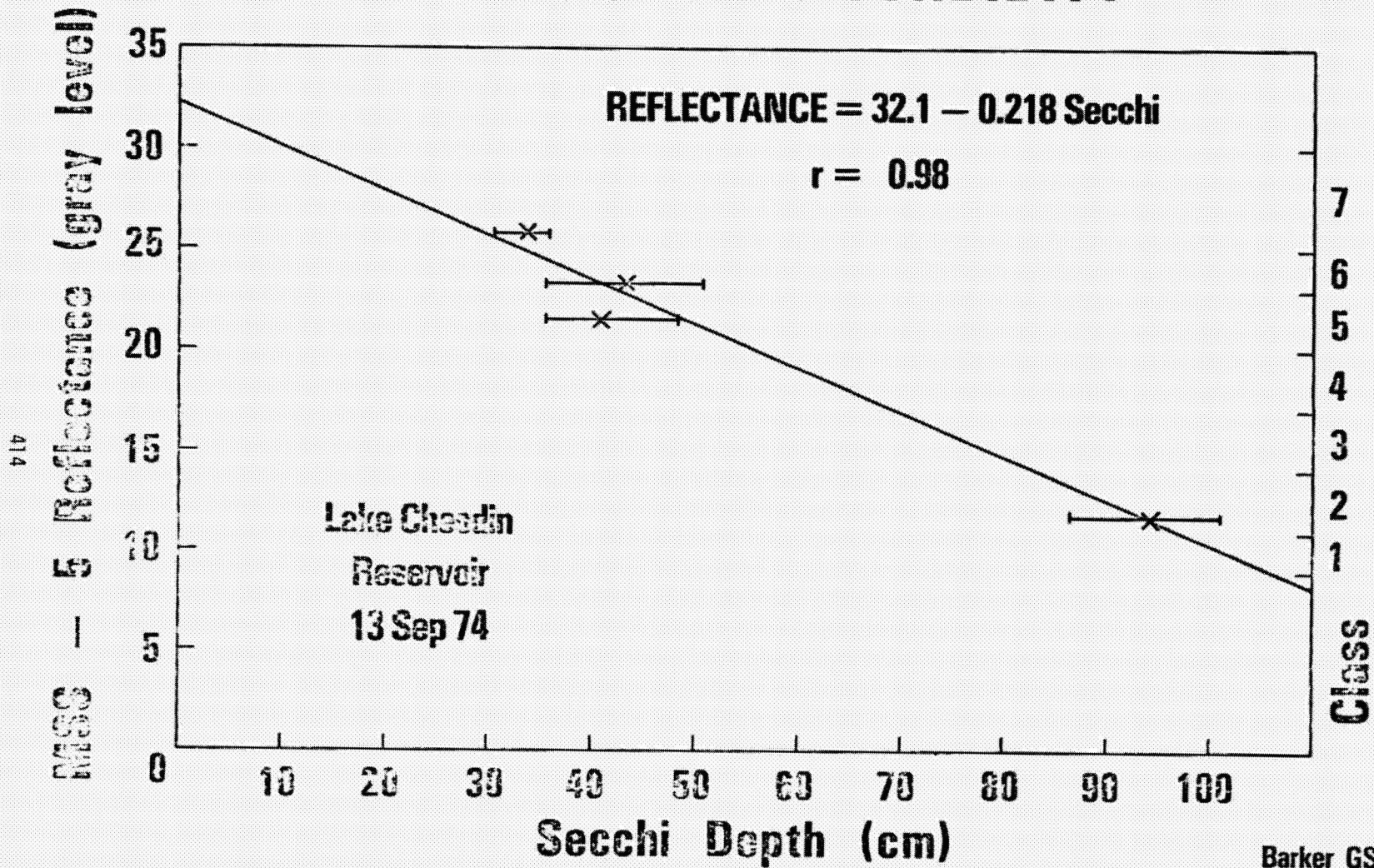


Figure 13.- Ground level picture of interface boundary between clear water from Namozine Creek and sediment-laden water in Lake Chesdin on 13 Sept 74.

LANDSAT versus TURBIDITY

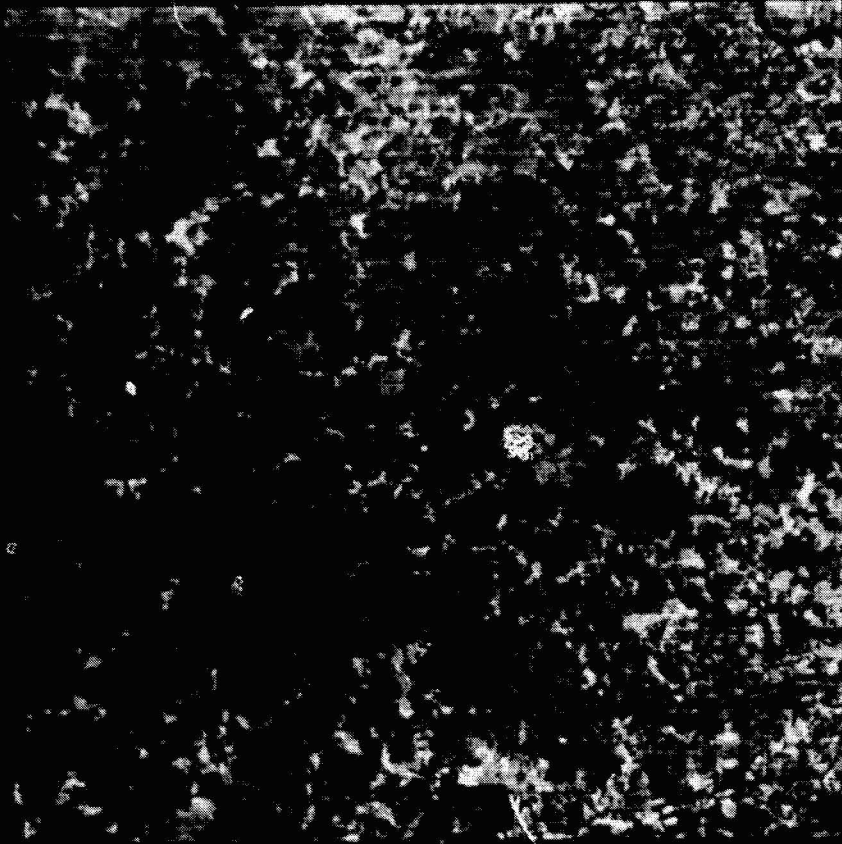


Barker GSFC 75

Figure 14.- 98% correlation of LANDSAT MSS-5 reflectance with Secchi depth in Lake Chesdin Reservoir on 13 Sept 74.

13 SEP 74 LANDSAT 1-100

VA RES"VOIR TAPE SP= 1 SL= 70 512 X 370 AREA EXPND BY ^{8 km} 5X 7



JLB 20 FEB 75

Figure 15.- Color composite of LANDSAT bands 4, 5, and 7 of 30 Km by 30 Km area around Swift Creek Reservoir on 13 Sept 74.

SWIFT CREEK RESERVOIR WATERSHED

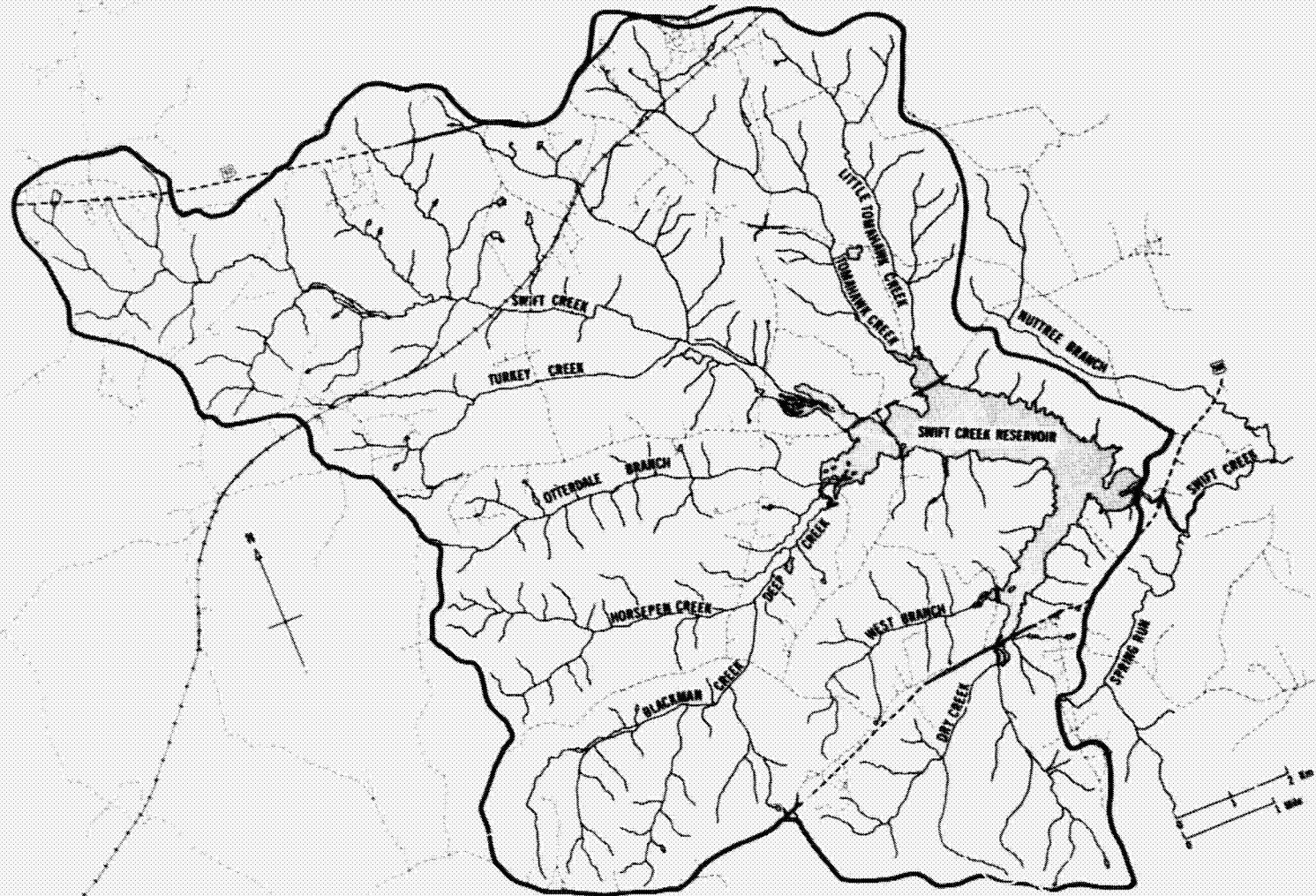


Figure 16.- Swift Creek Reservoir Watershed traced from contours on 1:24,000 scale USGS map.

15 JUN 74 LANDSAT I-100

SCR BASIN TAPE SP# 44 SL# 175 348 X 248 AREA EXPND BY 10X14



RESIDENT 4

PINE 6

WATER 10

HARDWOOD 8

WATER 10

W/L MIX 14

CONFLICT 17

923 13MAY 75

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

Figure 17.- Land cover classes from LANDSAT for Swift Creek Reservoir watershed on 15 June 74.

13 SEP 74 LANDSAT I-100
SCR BASIN TAPE SP= 44 SL= 175 348 X 248 AREA EXPND BY 10X14



RESIDENT	4
PINE	6
WATER	10
M/L MIX	14
COMPLEX	32

REPRODUCIBILITY OF THIS
ORIGINAL PAGE IS POOR

JLB 28 FEB 75

Figure 18.- Land cover classes from LANDSAT for Swift Creek Reservoir watershed on 13 Sept 74.