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# MONITORING WATER QUALITY FROM LANDSAT


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# 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 ±1% at 500 hectares to ±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 the water inventory maps from LANDSAT within a particular region can be accurate to ±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.

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## 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:

- Spatial and spectral resolution of LANDSAT film products as compared to digital LANDSAT data from Computer Compatible Tapes (CCT).
- A determination of the precision and accuracy of measuring surface areas of bodies of water from LANDSAT.
- 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.
- 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.

[1] One hectare is 0.01 $Km^2$ and equals 2.5 acres.

[2] "ERTS" has been renamed LANDSAT.

## 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 pixel[3] 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 7[4] 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 "pseudocolors" 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.

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

[3] A 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 0.45 hectares (1.1 acres).

[4] LANDSAT has four bands of light reflectance recorded with its Multi-Spectral Spectrometer. MSS-4 (0.5 to 0.6 microns) and MSS-5 (0.6 to 0.7 microns) are in the visible. MSS-6 (0.7 to 0.8) and MSS-7 (0.8 to 1.1) are in the near infrared.

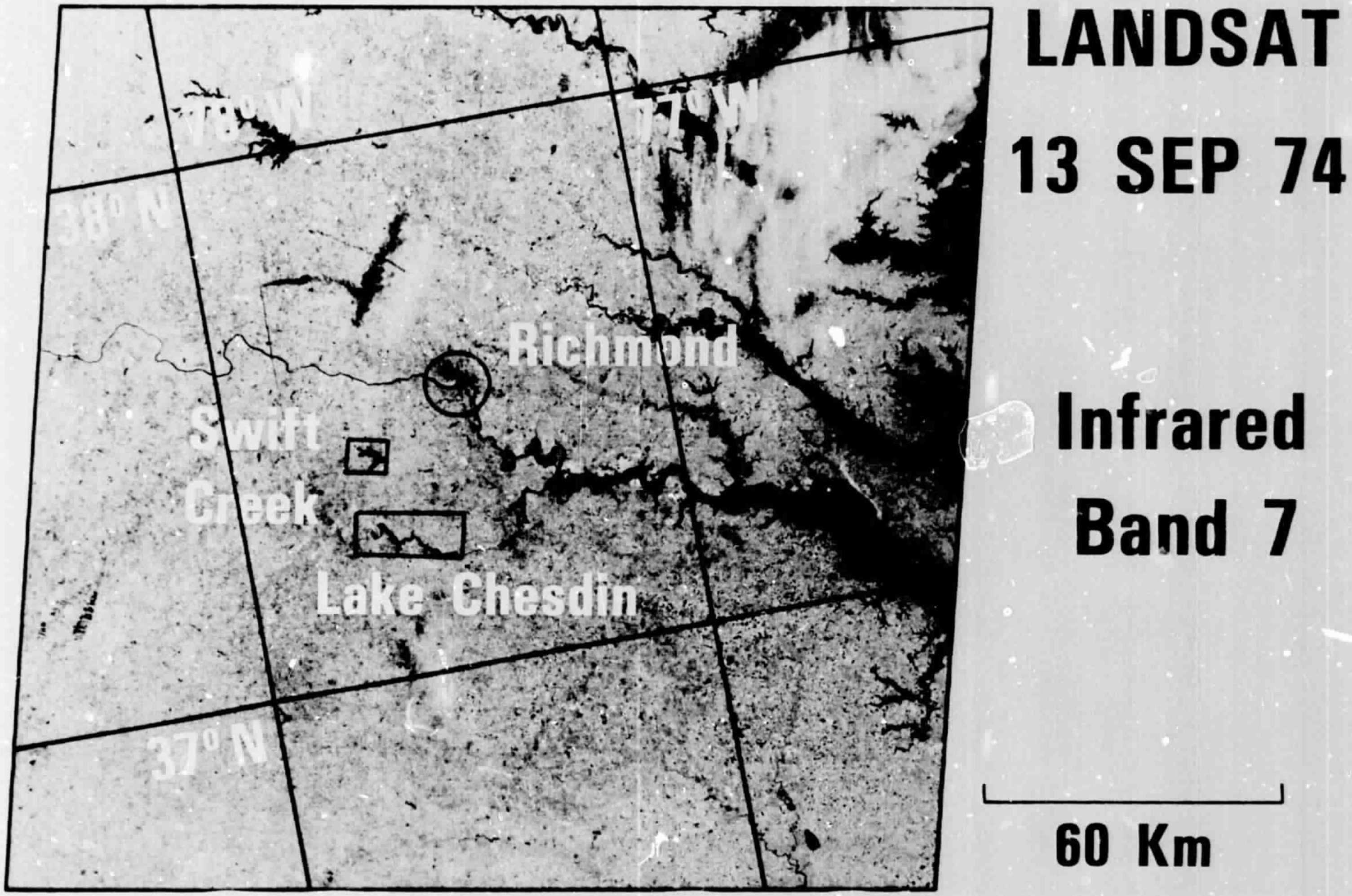


Figure 1. Annotated print of standard 8.5 cm x 8.5 cm NASA LANDSAT negative.

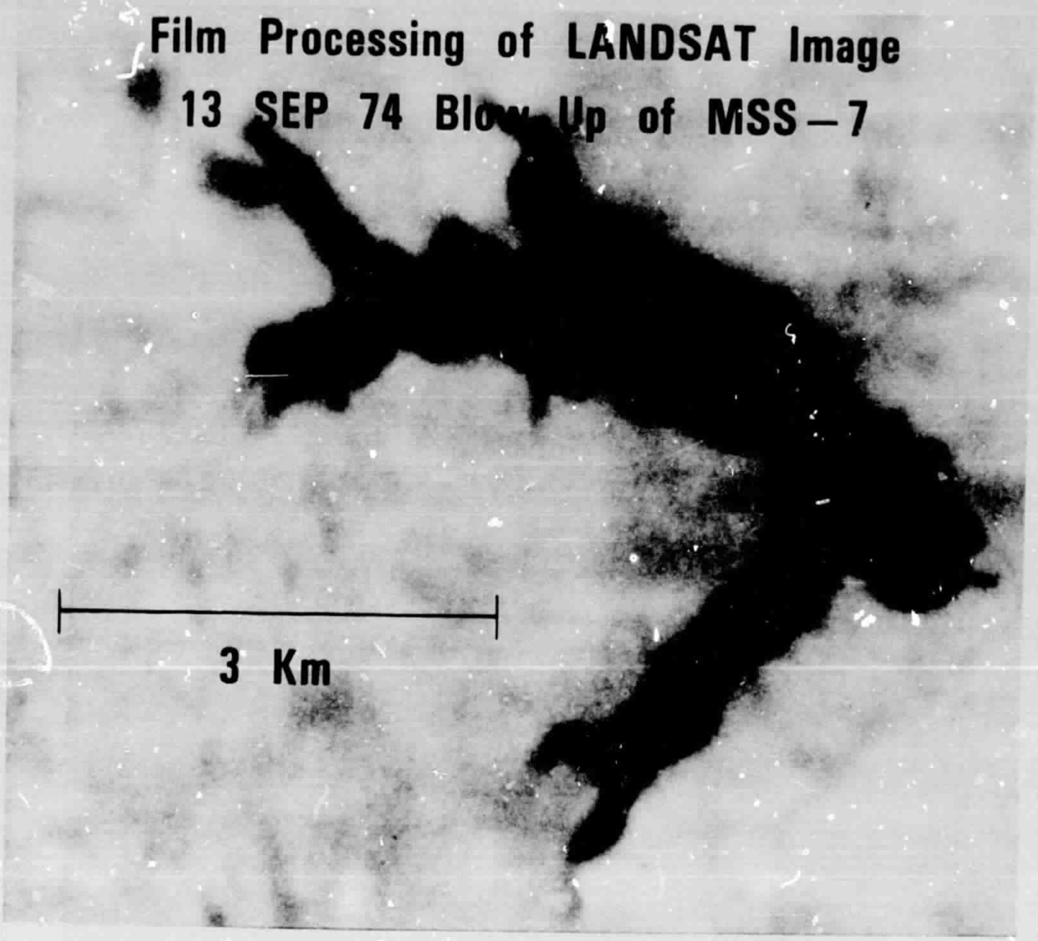


Figure 2. Photographic blow-up of Swift Creek Reservoir, Virginia from standard 8.5 cm x 8.5 cm LANDSAT negative.

**Digital Processing of LANDSAT Image**

**13 SEP 74 Pixel Print of MSS - 7**

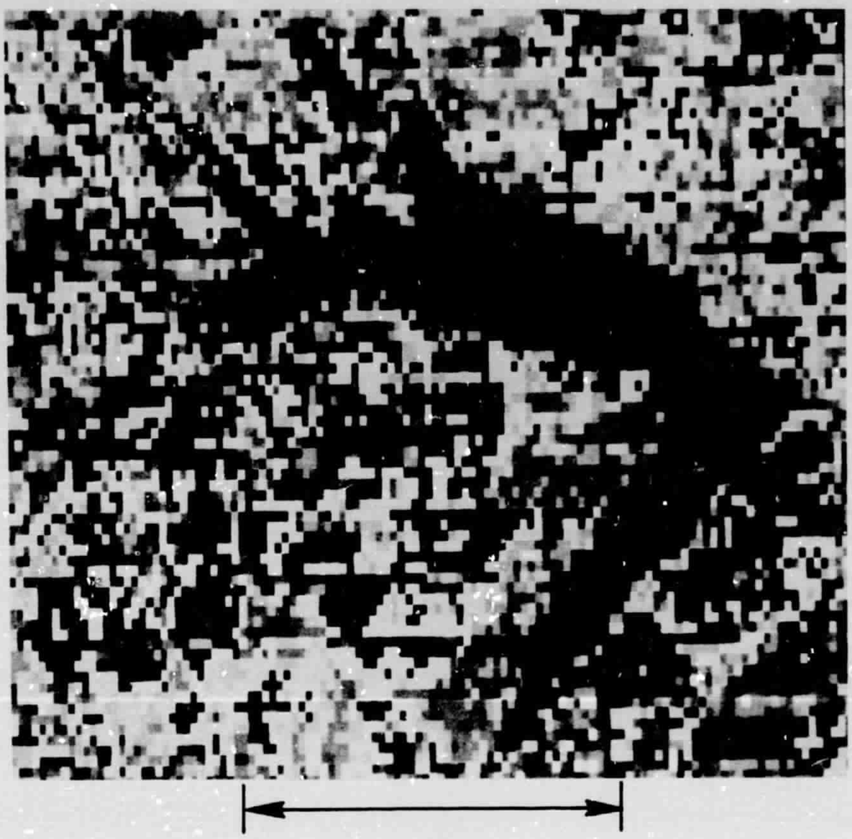


Figure 3. Pseudo-color pixel print of Swift Creek Reservoir, Virginia from LANDSAT CCT, illustrating potential for viewing every pixel and every reflectance value.

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, rather than for repeat measurements of the same water body in different images, 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).


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 Figures 5 and 6.

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 over-estimation 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:

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

## Locations for Area Measurements

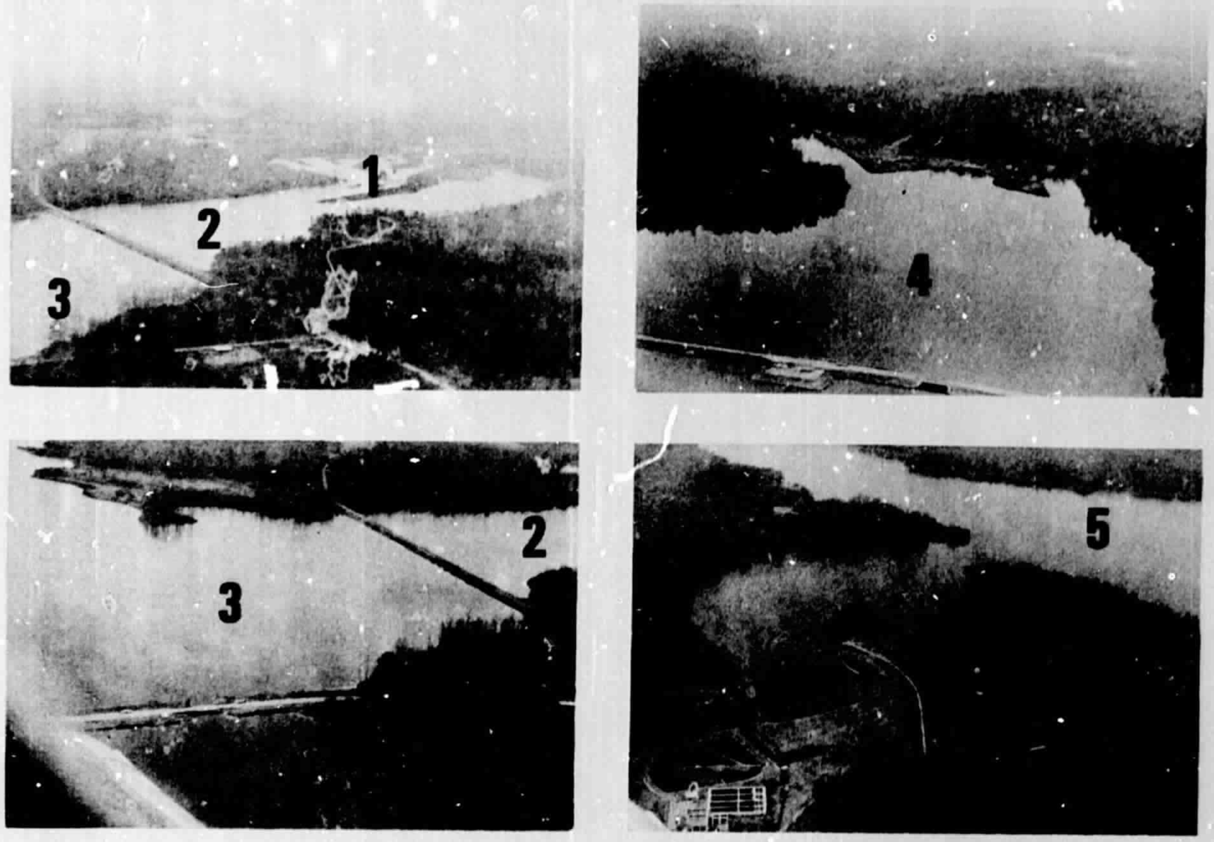


Figure 5. Low altitude Kodachrome prints of some of the 7 sections of Swift Creek Reservoir used for area measurements.

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:

$$A1 = C\,P \qquad (2)$$

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:

$$A2 = C\,(P + S\sqrt{P}\,) \qquad (3)$$

where S is a function of the shape of the body and can be shown to have a value between 2 (for a square[5]) 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.

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[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.

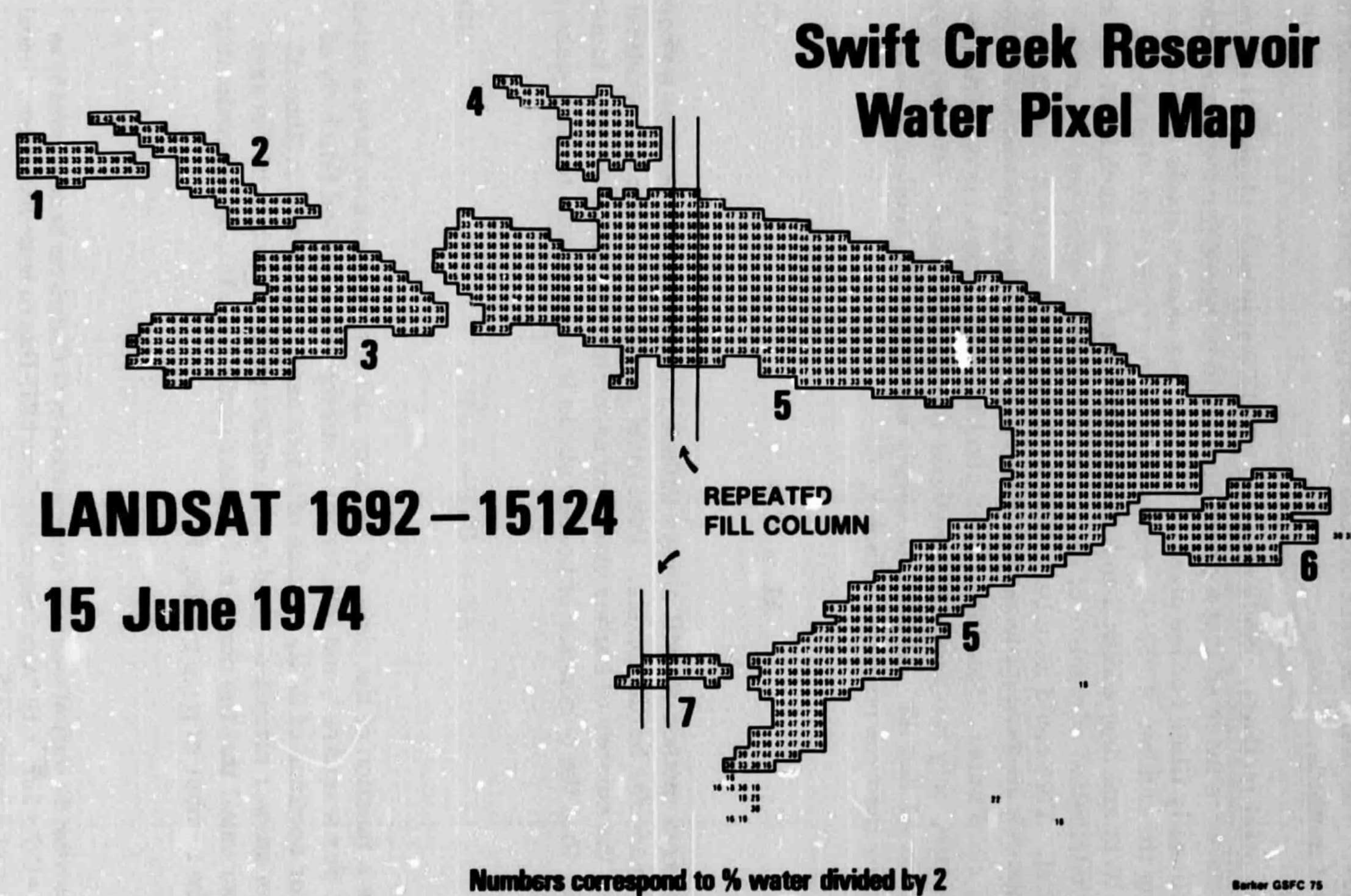


Figure 6. Computer list of MSS-7 reflectance values of Swift Creek Reservoir converted to percentage of water divided by 2 showing 7 sections used for area measurements.

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:

$$A3 = C\,(P + B50) \tag{4}$$

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 planimetering 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 1[6]. 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. One 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.

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.e three LANDSAT images used for this area study were: 1692-15124 (15 June (1974), 1710-1512( (3 July 1974) and 1782-15092 (13 September 1974).

Table 1

**Reproducibility of measurements of area from LANDSAT in 7 sections of Swift Creek Reservoir on three dates in 1974.**

| Areas of Water (in Hectares) | | | | |
|---|---|---|---|---|
| Location | USGS Map | LANDSAT | | |
| | | Jun. '74 | Jul. '74 | Sep. '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 | 11.0 | 9.4 | 10.2 |
| 7 | 5.5 | 5.0 | 5.5 | 5.9 |

Table 2

Accuracy of average area measurements of three dates on 7 sections Swift Creek Reservoir; percentage errors are given as the higher of either the precision or the deviation of the average from the area derived by planimetering a 1:24,000 scale USGS map.

| 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 |

R. Peterson[7] calculated the values of C for SCR for the three dates used in this study; they were 0.459, 0.459, and 0.463 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 estimated area could be reduced further by taking the mean of several measurements.

Table 3

Reproducibility of Area Measurements

| Method | Percent Precision (by size) | | |
|---|---|---|---|
| | at 500 Hectares | at 25 Hectares | at 5 Hectares |
| Pure Pixel | ±3% | ±8% | — |
| Mixed Pixel | ±1% | ±4% | ±8% |

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 the 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

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

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%) |

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 ±8% at 5 hectares is ±0.9 hectare (±2 acres), whereas two times ±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 planimetering 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 ±1% at 500 hectares to ±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 a political or physical region might be accurate to ±1% in identifying the total area of open water. Although mixed pixel methods were more accurate than

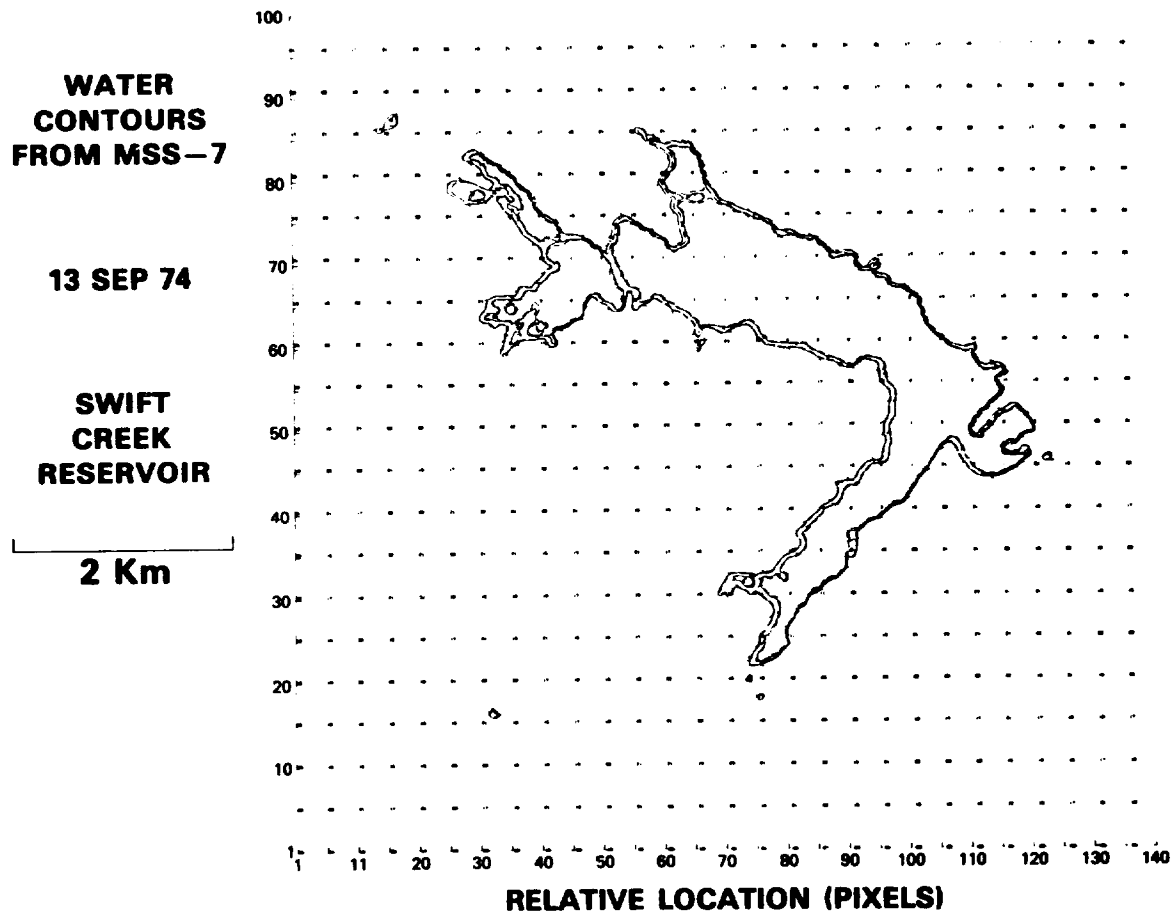


Figure 7. CALCOMP contour map of Swift Creek Reservoir for selected values of MSS-7 chosen to emphasize the boundary between land and water.

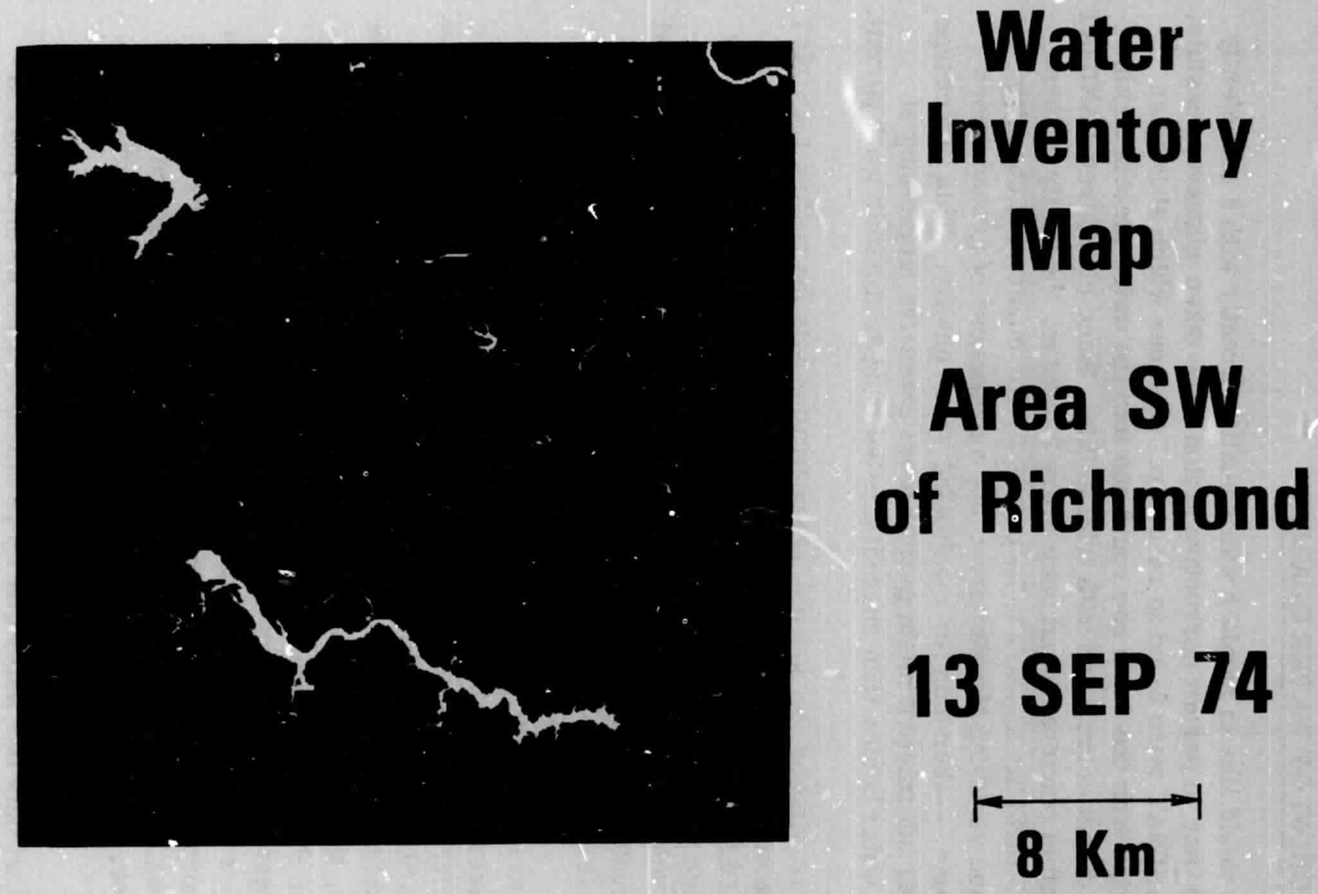


Figure 8. Water inventory map of a 30 Km by 30 Km region SW of Richmond derived from a LANDSAT image by identifying all pixels which contained more than approximately 60% water.

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 Chesdin 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 Sep 74 image, the range of MSS-5 reflectance was arbitrailiy 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

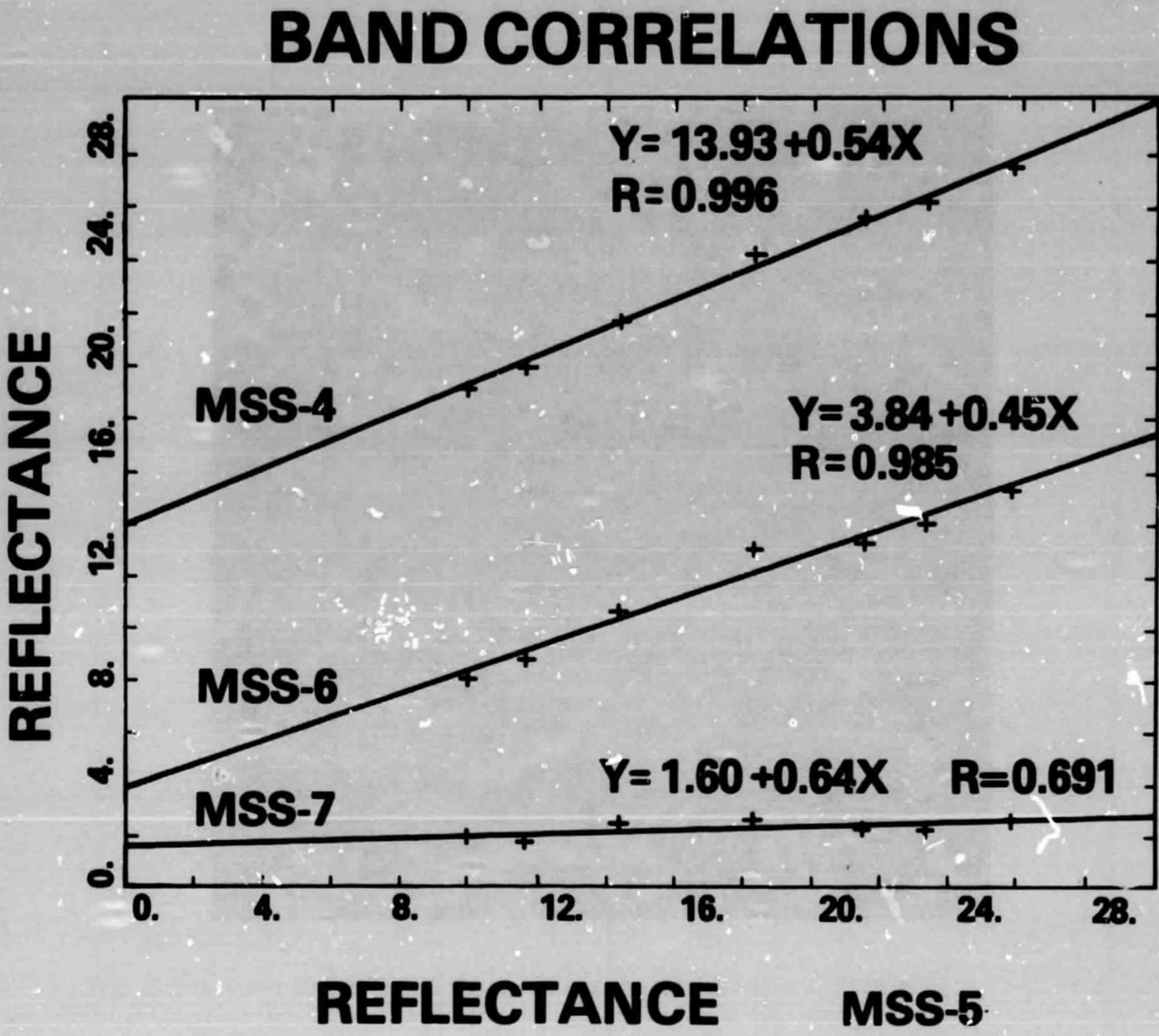


Figure 9. Correlation of LANDSAT reflectances from water in different MSS bands on 13 Sep 74 in Swift Creek and Lake Chesdin Reservoirs.

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

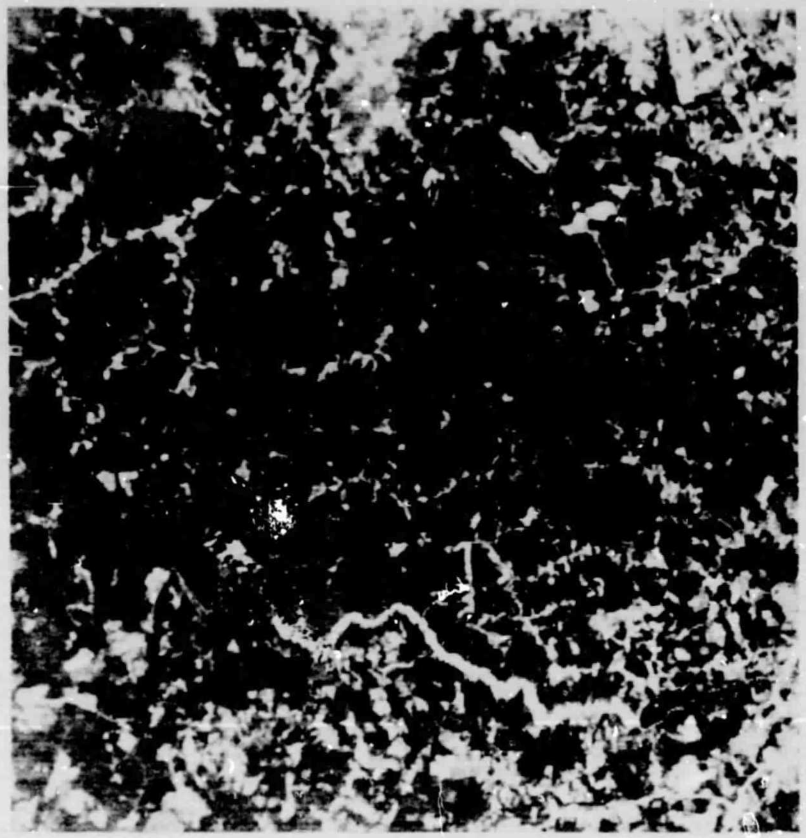

Figure 10. Map of seven MSS-5 level-sliced water classes for 30 Km by 30 Km region SW of Richmond on 13 Sep 74.

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 Sep 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

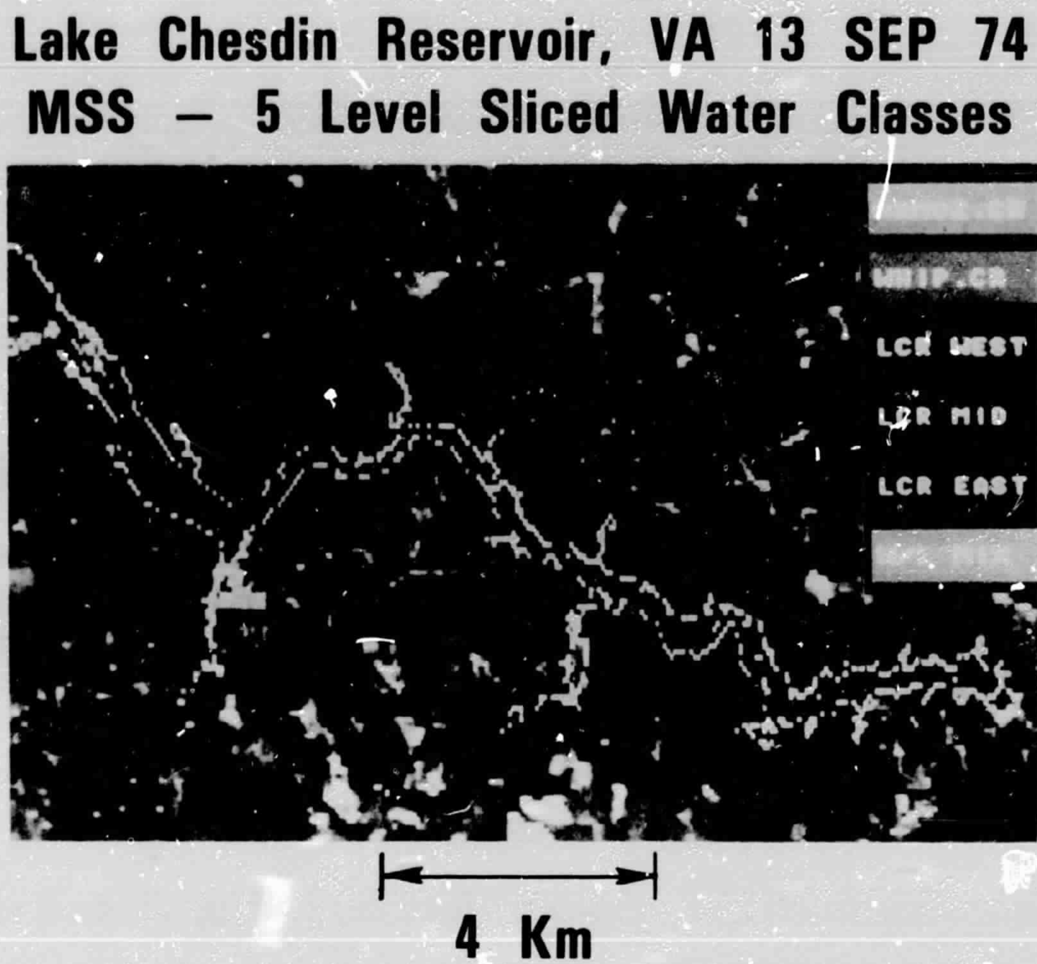


Figure 11. Map of seven MSS-5 level-sliced water classes in Lake Chesdin Reservoir on 13 Sep 74.

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.

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

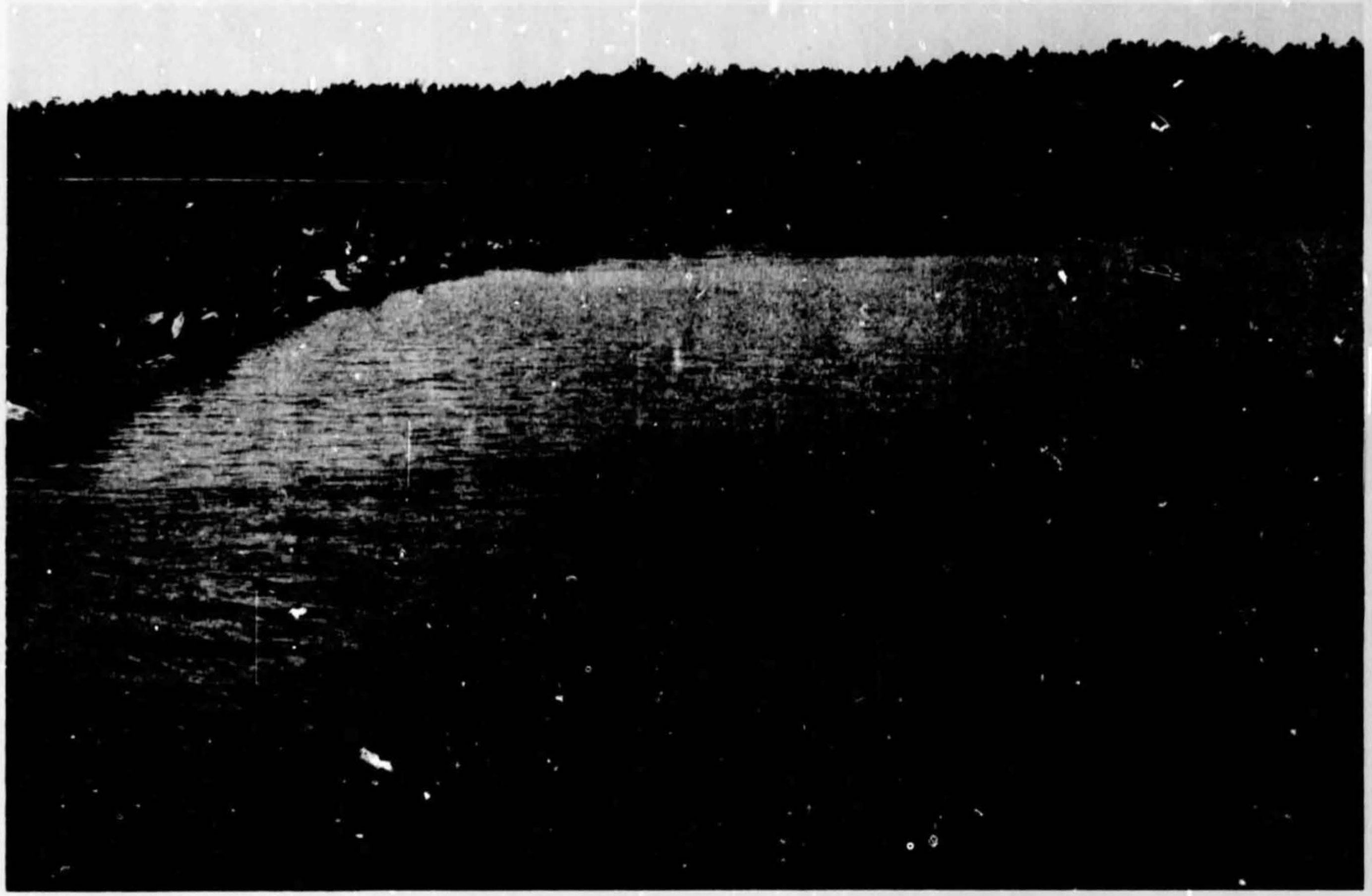

Figure 13. Ground level picture of interface boundary between clear water from Namozine Creek and sediment-laden water in Lake Chesdin on 13 Sep 74.

Secchi depth measurements taken by NASA and VSWCB personnel in LCR on 13 Sep 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:

$$\text{Reflectance} = 32.1 - 0.22 \text{ Secchi} \tag{5}$$

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:

$$\text{Secchi} = 143.5 - 4.41 \text{ reflectance} \tag{6}$$

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 Sep 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:

$$\text{Total Solids} = 66.8 + 0.88 \text{ reflectance} \tag{7}$$

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

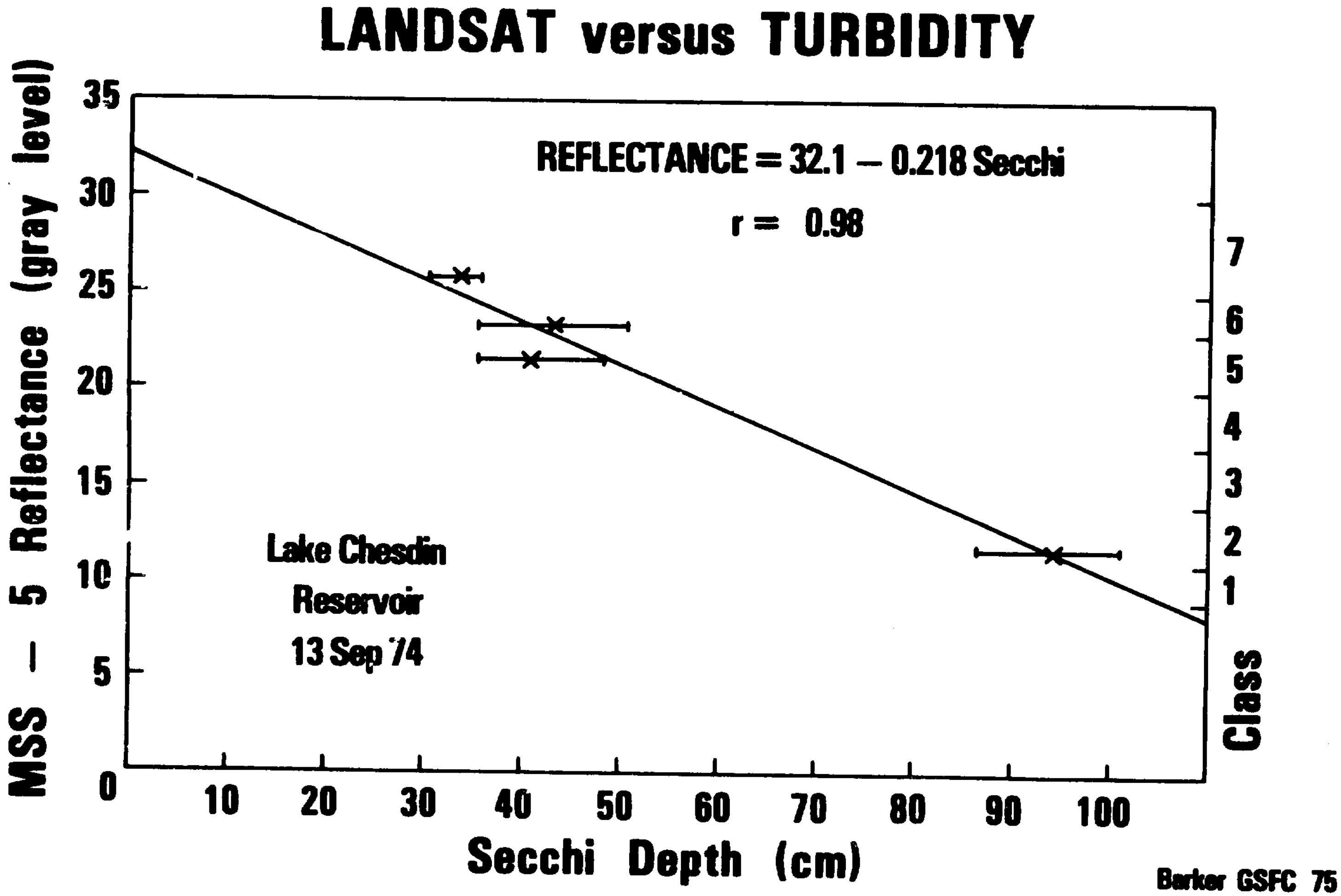


Figure 14. 98% correlation of LANDSAT MSS-5 reflectance with Secchi depth in Lake Chesdin Reservoir on 13 Sep 74.

has a ten times greater flow rate than SCR, due to input from the Appomatox 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 5 cm 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 or 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 Jun 74 and 13 Sep 74 are given in Figures 17 and 18.

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

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 unclassed whereas only 5% were unclassed on the 13 Sep image. Clouds also interfered with the identification of all agricultural land on 15 Jun. 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.

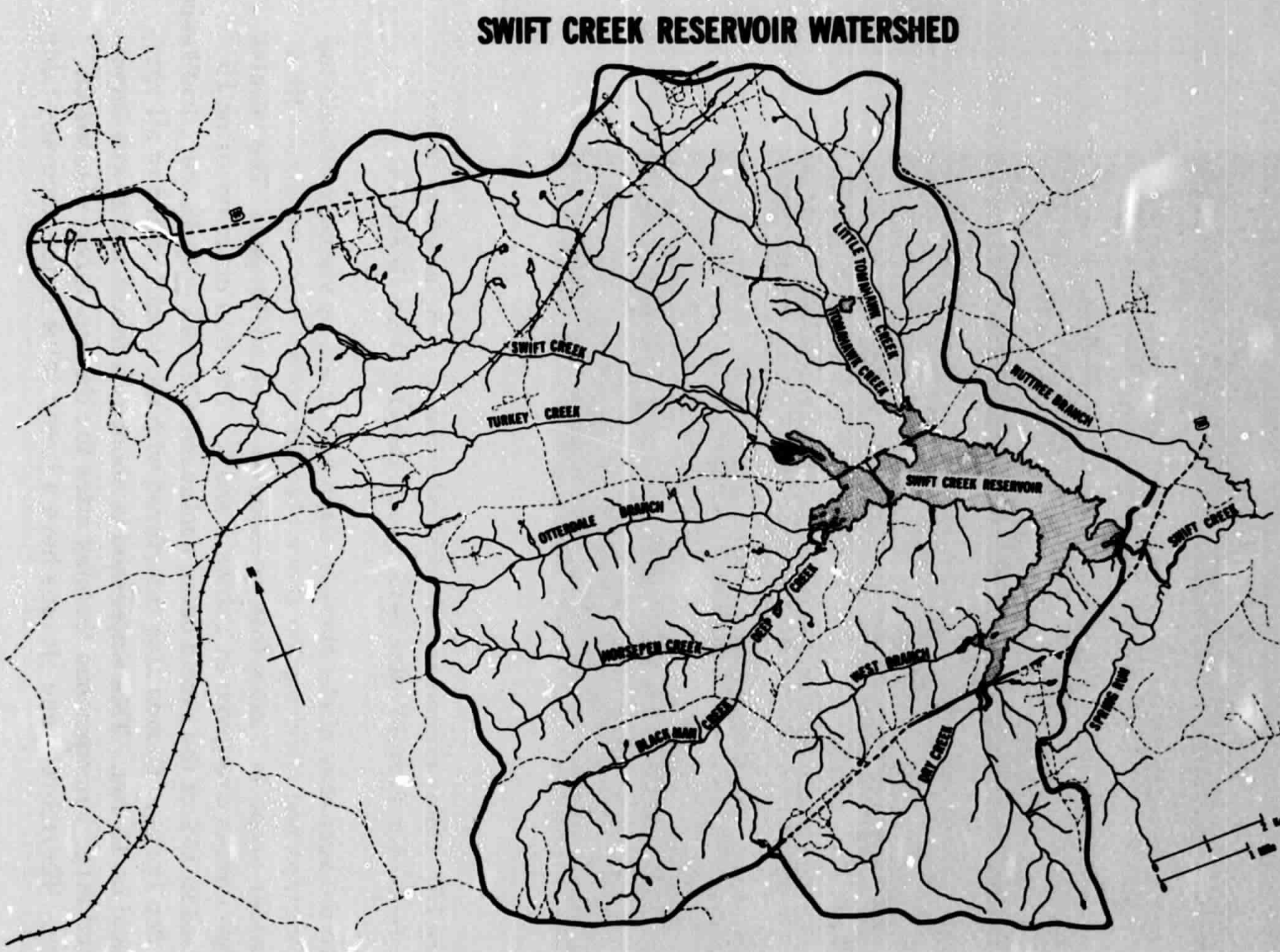


Figure 16. Swift Creek Reservoir Watershed traced from contours on 1:24,000 scale USGS map.

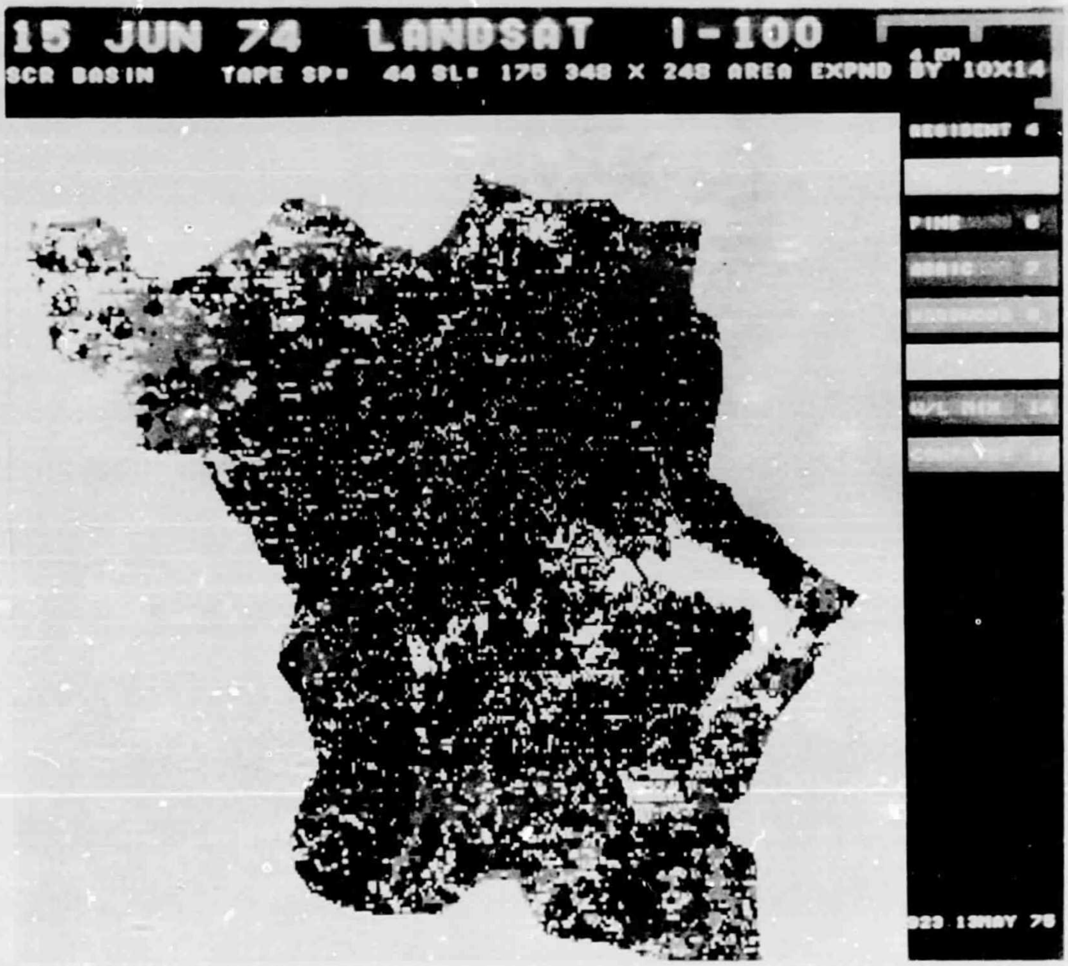


Figure 17. Land cover classes from LANDSAT for Swift Creek Reservoir watershed on 15 Jun 74.

The area of the Brandermill construction site inside the watershed can be seen as the non-forest area north of the reservoir in the 13 Sep 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


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

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 Brandermill 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

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Table 5.

Comparison of LANDSAT classification for 15 Jun 74 with known land cover classes from U-2 photography at 5 selected sites.

Percent Accuracy of Classification

| | Jun 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

Comparison of LANDSAT classification for 13 Sep 74 with known land cover classes from U-2 photography at 5 selected sites.

Percent Accuracy of Classification

| | Sep 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

Land Cover Classes In %

| | 18,000 Hectare Basin | | 740 Hectare Construction Site | |
|---|---|---|---|---|
| | Jun | Sep | Jun | Sep |
| Pine | 38 | 38 | 65 | 51 |
| Hardwood | 33 | 35 | 16 | 17 |
| Agriculture | 9 | 15 | 4 | 18 |
| Residential | 2 | 4 | 1 | 2 |
| Barren | 1 | 0 | 0 | 1 |
| Water | 3 | 3 | 4 | 5 |
| Unclassed | 14 | 5 | 10 | 6 |