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DETERMINATION OF CIRCULATION AND TURBIDITY PATTERNS IN KERR LAKE FROM LANDSAT MSS IMAGERY

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

1.0 INTRODUCTION

Many of our inland bodies of water are faced with the problem of an increasing build-up of pollution and siltation. It is difficult to assess the overall magnitude and future impact of the problem without some effective monitoring tool. The launch of the Landsat satellites and their regular overpass over a given area afford a valuable reconnaissance tool in obtaining synoptic information from affected areas. The upwelled radiance data measured by the MSS (multispectral scanner) Landsat system can furnish seasonal and regional circulation and turbidity patterns which can be related to when and where the problems are occurring. By examining past Landsat scenes, a historical record of sediment transport and possible disposition can be obtained.

Turbidity patterns can be readily observed in Landsat's imagery scenes. Since an increase in the suspended and certain dissolved materials in the water increases the backscatter of light, many researchers have used Landsat data to statistically correlate its spectral intensity with water quality parameters in the form of transmittance, secchi depth, turbidity, and suspended solids. By using a minimum number of field samples, algorithms were developed by which many large inland bodies of water were quantified corresponding to their pollutants. Using in situ transmittance measurements (ref. 1), high correlations were found with Landsat spectral data for waters in Gunston Grove, Virginia, a branch of the Potomac River. Studies conducted on Kansas lakes (ref. 2 and 3) were able to correlate secchi depth and suspended solids with the Landsat bands for concentrations of suspended solids less than 80 ppm. Many lakes in Wisconsin were used to correlate Landsat's MSS data with secchi depth (ref. 4) and turbidity (ref. 5) for concentrations of suspended solids less than 40 ppm. Investigations conducted on South Dakota lakes (ref. 6 and 7) were able to relate secchi depth and turbidity with the output of Landsat for low levels of suspended solids. Minnesota lakes (ref. 8) were used to obtain high correlations of turbidity with the radiances measured by Landsat for suspended loads less than 3 ppm. The Great Lakes were the object of several intense studies. Lake Ontario's waters were used to correlate secchi depth, turbidity, and suspended solids (ref. 9) to Landsat's radiances for concentrations of suspended solids less than 95 ppm. Turbidity was related to Landsat's MSS data in Lake Superior (ref. 10) for suspended solids less than 20 ppm. Lake Erie (ref. 11) was used to connect turbidity and suspended solids to the bands of Landsat for suspended solids less than 80 ppm. Examination of the waters in Virginia lakes (ref. 12) found that Landsat data could be associated with suspended solids for concentrations less than 92 ppm. Studies conducted on Nebraska lakes (ref. 13) correlated turbidity and suspended solids with Landsat's radiances for suspended solids less than 184 ppm, although the fitted regressions were subjected to large levels of uncertainty.

Most of the previous investigations were carried out with levels of suspended solids less than 100 ppm which resulted in either band 5 or band 6 of Landsat given the best correlations. Generally, when levels of suspended solids were greater than 100 ppm, the data became nonlinear and the resulting regression efforts exhibited high levels of uncertainty. This effect is demonstrated in references 3 and 4, where the Landsat radiance data rapidly increased with concentrations of suspended solids less than 100 ppm, and then changed very little for levels greater than 100 ppm. In effect, the radiance signal saturates, that is, the upwelled signal for low wavelengths remain the same no matter how high the sediment loads.

A model of the Landsat's bands as a function of concentrations of suspended sediment is displayed in reference 14 that shows the exponential nature of their signal. This model shows that band 4 reaches a plateau at 10 ppm, band 5 reaches another plateau at 50 ppm, and band 6 reaches yet another plateau at about 150 ppm. Band 7 never reached an upper limit for the model shown which had a boundary of 1000 ppm. Studies were conducted on suspended solids from Lake Chicot in Arkansas and Kerr Lake in Virginia (ref. 15) as a function of wavelength. Results of the studies show the exponential nature of the upwelled radiance signal and demonstrate that larger wavelengths are needed to investigate higher concentrations of suspended solids. Investigations conducted on lakes in Mississippi (refs. 16 and 17), for suspended solids less than 350 ppm, and Lake Chicot in Arkansas (ref. 18), for suspended solids less than 550 ppm, illustrate that the best correlations between high levels of suspended solids and upwelled radiances are obtained for wavelengths between 700 and 900 nanometers.

2.0 LANDSAT'S SATELLITE AND MSS IMAGERY SYSTEM

The Landsat satellites are launched in a nearly circular sun-synchronous, north-south orbit with an inclination of 99° and a nominal altitude of 920 km. This permits the satellites to be over the same area at the same local time every 18 days. With a period of 103 minutes, Landsat makes approximately 14 revolutions of the Earth in a day and 251 revolutions in the 18 day cycle. The orbit progresses in the westwardly direction by 159 km per revolution at the equator. An overlap between adjacent ground scenes (14% at the equator) allows some areas to be seen 24 hours later.

The multispectral scanner system consists of 4 distinct ranges or bands as shown in figure 1. The gains on the sensors are set so that all possible ranges of the Earth's upwelled signal are bracketed, resulting in low sensitivities for the water areas. In order to achieve complete ground coverage with the given orbit, there are 6 rows of each of the scanners. This frequently leads to a noticeable difference in every sixth line of Landsat data (called banding) that is caused by different scanner drift rates. The on-board detectors scan in a west to east direction with an instantaneous field-of-view of 79 by 79 meters (because of overlap in the scan direction, there are only 56 meters of new information). A ground area of 185 km is swept by each cycle of the scanners, and a Landsat scene is formed when a ground track of 185 km is recorded.

3.0 RESULTS AND DISCUSSION

The Landsat scenes can be quantified for sediment in a limited way by noticing the difference in water patterns on separate bands of Landsat imagery. Patterns that appear in higher wavelength bands that do not appear in lower bands indicate higher loads of sediment. To maximize this difference, bands 5 and 7 of Landsat were chosen as the bands best suited to show a complete range of sediment transport patterns. The sensitivity curves for bands 5 and 7 are shown in figure 1. Close examination of the sensitivities reveals that band 7 has more response at the lower part of the band than the upper part. In fact, 51% of the response is between 0.8 and 0.9 micron and 89% is between 0.8 and 1.0 micron.

Two Landsat scenes of Kerr Lake, located on the Virginia-North Carolina border, were chosen to illustrate the effect of different sediment loads. Landsat's band 5, presented in figure 2 (October 11, 1972), shows high levels of brightness in the left part of the lake gradually tapering off toward the dam on the right. Band 7 has a uniform brightness over the length of the lake indicating that it is not sensitive to the low levels of sediment. The brightness levels displayed in band 5 can be directly related to different sediment loads, which are probably less than 100 ppm because of the absence of any signal in band 7. In figure 3 (April 29, 1978), band 5 again displays high levels of brightness in the left part of the lake and diminishes to the right. But this time band 7 shows a unique plume running partway down the middle of the lake, indicating levels of sediment larger than 100 ppm (this pattern may not show on some reproduced pictures, but will be repeated as a sketch in a later figure). Due to the large amounts of sediment present, some of the signal in the left part of the lake in band 5 has actually saturated, thus further information on the amount of sediment remaining is not measurable.

The Kerr Lake reservoir has been subjected to an increasing build-up of sediment, thus making it an ideal area to examine. In order to detect and delineate instantaneous and long term turbidity patterns of the area, Landsat scenes originating from the launch of the first satellite to present time had to be studied. Because of cloud cover or poor quality of the finished product, only a limited number of scenes were found to be beneficial to the investigation. Of all the imagery surveyed, 16 different dates were selected that cover a period from October 11, 1972 to March 26, 1981, and encompassed all seasons of the year, except the summer months. Several of the scenes were taken only a day apart, thus giving a good indication of velocity and dispersal patterns of sediment on a small time frame.

To properly display sediment patterns observed on the available Landsat scenes, the intensities observed on bands 5 and 7 were divided into 6 different ranges and transformed onto maps of Kerr Lake. This procedure permits an easier and quicker examination of the scenes than is afforded by the original imagery. On some of the scenes band 7 has a uniform pattern of brightness for the entire lake; in this case the sketch will show only one level of brightness. The presentation of the Landsat imagery data will proceed from the most recent to the oldest scene.

3.1 LANDSAT IMAGERY FOR MARCH 26, 1981

Observing band 5 in figure 4 shows that the flow emerging from the Dan River is more turbid and stronger than the flow in the Roanoke River. A small region of high turbidity occurs just up from the mouth of Buffalo Creek. Less turbid waters issue from Bluestone Creek and are forced to the south side by the bridge causeways located at Clarksville. Turbidity in the Grassy Creek area is as high as the turbidity in the Dan River. The intensity decreases from the Grassy Creek area up to the dam region, which has the same intensity as Nutbush Creek. Only 2 levels of turbidity could be detected on band 7, with the boundary of lesser intensity beginning at the Mill Creek area.

3.2 LANDSAT IMAGERY FOR NOVEMBER 19, 1980

Water streaming into Kerr Lake from the Dan River, as viewed on band 5 in figure 5, is several levels of magnitude more turbid than the water in the Roanoke River, and also appears to have a higher volume of flow. There is a change in turbidity level at Buffalo Creek and again on the east side of the US 58 bridge, where the more turbid water stays on the north side. A temporary increase in intensity occurs in the Eastland Creek zone. The Nutbush Creek water has the lowest level of turbidity in the lake. A change of intensity below Bluestone Creek is the only difference observed in band 7.

3.3 LANDAT IMAGERY FOR APRIL 5, 1979

Once again, the water moving into Kerr Lake from Dan River has a higher turbidity than the waters in the Roanoke River, as indicated on the band 5 sketch shown in figure 6. However, the region of the highest turbidity is from the US 58 bridge at Clarksville to the Island Creek area, and also the lower part of Grassy Creek. The causeway at the highway bridge again restricts the water to the south shore. A decrease in the turbidity levels is observed above Island Creek and below Mill Creek. Several levels of different turbidity are seen in Nutbush Creek, with the lowest level being in a lower branch leading into Nutbush Creek from the east. No changes in turbidity were detected in band 7.

3.4 LANDSAT IMAGERY FOR FEBRUARY 19, 1979

Examining the band 5 scene in figure 7 disclosed that both the Dan and Roanoke rivers have the same level of intensity, which indicates very little flow coming into Kerr Lake. Also, no separation of flow is seen at the bridge, which is another indicator of low flow velocity of water in Kerr Lake. The turbidity levels actually increase above the mouth of Grassy Creek and again below the mouth of Mill Creek, where the highest level of turbidity exists. An interesting pattern of lower turbidity water is seen flowing from Nutbush Creek into the main part of Kerr Lake. Nutbush and all the other creeks connected to the main part of the lake display lower levels of turbidity. Again the response of band 7 is uniform for the entire lake.

3.5 LANDSAT IMAGERY FOR APRIL 29, 1978

The band 5 sketch in figure 8 discloses turbid water entering from the Dan River and continuing until the Island Creek region is reached. The land topology in the Grassy Creek and Island Creek area results in local eddies and flow impingements, giving rise to siltation build-up. A change of turbidity level occurs in the Butchers Creek area and the lowest turbidity occurs in a zone in front of Nutbush Creek. The region just up from the dam generally displays some interesting eddies because of the flow stoppage. Band 7 also reveals a flow of higher turbidity water moving into the lake from Dan River. Several levels of turbidity are observed in Grassy Creek and Island Creek area, where a curious narrow plume of highly turbid water is shown in the middle of the lake running to the dam side of Butchers Creek. The rest of the lake from Butchers Creek displays the same level of intensity. The unique pattern of lower turbidity water that appears to be emerging from the creek at Occoneechee State Park is probably caused by eddy currents due to the flow restriction of the bridge. Since turbidity patterns appear in band 7, the water most probably has suspended sediments greater than 100 ppm. Also, the signal from the water in the most turbid zone of band 5 has saturated, not capable of revealing higher levels of turbidity.

3.6 LANDSAT IMAGERY FOR APRIL 28, 1978

The scene displayed in figure 9 was taken one day earlier than the previous imagery, thus, revealing some indication of transitory effects of flow within the lake. Higher turbidity water flows out of the Dan River and is constrained and forced to the south side by the bridge causeway at Clarksville. A plume appears in the Island Creek area and another plume of lesser turbidity originates in the Butchers Creek area and continues on toward the dam. The appearance of the plumes and the flow channeling at the bridges implied a high volume and velocity of flow. The lowest turbidity is found in the lower part of Nutbush Creek. Band 7 discloses about the same types of flow pattern until the Island Creek area is reached. Thereafter, there is no difference in turbidity for the rest of the lake. The shape of the land between Grassy and Island creeks produces some interesting circulation patterns and also gives rise to flow impingement on the southern land area and the tip of land directly opposite on the north shore.

3.7 LANDSAT IMAGERY FOR MARCH 23, 1978

The highest turbidity level, as seen in the band 5 sketch of figure 10, occurs in the middle of the lake, extending from above Grassy Creek to the dam area.

Distinct circulation patterns are noticed in the area at the mouth of Nutbush Creek. Several levels of lesser intensity are observed in Nutbush Creek, where the lower part of the creek has the lowest turbidity in the lake. Only 2 levels of intensity could be visually determined from the band 7 imagery.

3.8 LANDSAT IMAGERY FOR JANUARY 11, 1978

Band 5 data viewed in figure 11 disclosed several distinct plumes. The most turbid water flows out of the Dan River and retains its intensity until it reaches the bend at the Grassy-Island Creek section. This bend causes a short plume to be formed, which dissipates on the downstream side of Island Creek. The other distinct plume occurs in the dam area just off the mouth of Nutbush Creek. Nutbush Creek again has the lowest level of turbidity in the lake. Two distinct plumes of different intensities are exhibited on the band 7 image in the region of Grassy Creek. Only one other level of lesser turbidity is discernible in the region from Island Creek to the dam. A flow of low turbidity is observed emerging from the Hyco River into the Dan River, staying on the east shore, and dissipating at the juncture with the Roanoke River. The appearances of plumes in band 5 and turbidity patterns in band 7 indicate levels of suspended solids greater than 100 ppm. The absence of any flow patterns through the bridge in band 5 indicates the signal has saturated.

3.9 LANDSAT IMAGERY FOR JANUARY 10, 1978

This image, displayed in figure 12, was taken 24 hours earlier than the previous scene. From viewing band 5, higher turbidity waters issue out of the Dan River, are constricted by the bridge causeway, and forced to the north side of the lake further downstream. A plume of lower turbidity is formed on the west side of the bend and vanishes on the east side. Another plume forms in the region of

Nutbush Creek and the dam. Nutbush Creek has the lowest turbidity in the lake, but its small tributaries in the lower region have water as turbid as the Dan River. Band 7 exhibits flow constriction as well as several different levels of turbidity at the bridges. The rest of the lake toward the dam is of uniform intensity. Again the low turbidity water flowing out of the Hyco River into the Dan River is noticeable. The higher turbidity waters of this date are further up the lake than the waters of the January 11 date.

3.10 LANDSAT IMAGERY FOR APRIL 8, 1975

Band 5 of figure 13 indicates a strong flow of water is emerging into Kerr Lake from Dan River. A high uniform level of turbidity runs the length of the lake and into the upper part of Nutbush Creek. There are sharp divisions of flow between the main lake and the creeks leading into it, implying a high rate of flow in the lake. The waters in Nutbush Creek also display sharp boundaries at levels of different intensity, revealing that flow from the main lake is backing up into Nutbush. A similar type of flow is also shown in band 7, implying a high sediment load. A plume is shown starting at the Grassy Creek region and finally disappearing just up from the dam. Signal saturation is indicated in band 5 from the lack of appearances of any flow eddies at the bridges at Clarksville.

3.11 LANDSAT IMAGERY FOR MARCH 21, 1975

A high volume of very turbid water from the Dan River is flowing into the upper part of the lake as revealed on band 5 of figure 14. The water showing the constriction at the Clarksville bridges, keeps the same intensity until it reaches the dam where it forms a hook like plume. Several different levels of turbidity are observed in the dam area and also in Nutbush Creek, which again displays sharp boundaries between levels of turbidity. Nearly the same pattern occurs in band 7, but the intensity changes at the bend above Grassy Creek. About the same circulation pattern is seen in the dam area, however, a bigger hook plume is evident. Nutbush Creek is of constant intensity. The appearances of patterns in band 7 indicate a suspended solid load greater than 100 ppm.

3.12 LANDSAT IMAGERY FOR FEBRUARY 13, 1975

The highest turbidity for band 5 in figure 15 is observed in a region from Bluestone Creek to Island Creek, including the upper part of Grassy Creek. Several turbidity levels are displayed in the area of the dam. The intensity in Nutbush Creek decreases in several stages, until the lowest turbidity in the lake is reached at the lower end. Only two levels of turbidity are revealed in the band 7 data, with a boundary occurring in the Island Creek region.

3.13 LANDSAT IMAGERY FOR JANUARY 22, 1974

A decrease in intensity of the turbid water flowing from the Dan River occurs on the band 5 data of figure 16 at the entrance to Buffalo Creek. After a second decrease in intensity below the bridges, the turbidity remains constant all the way to the dam. Several decreases in turbidity occur in Nutbush Creek, which has the lowest values in the lake. Band 7 shows no changes in turbidity for the entire system.

3.14 LANDSAT IMAGERY FOR JANUARY 9, 1973

Except for the Nutbush Creek area, the imagery displayed on figure 17 divulges very little differences in intensity. The band 5 scene shows a small plume of lower turbidity entering the main part of the lake at the mouth of Nutbush Creek. Another different turbidity zone is observed in the lower part of Nutbush and also in Beaver Park Creek. No unique patterns are revealed in the band 7 scene.

3.15 LANDSAT IMAGERY FOR DECEMBER 4, 1972

The band 5 image in figure 18 displays a more turbid and weaker flow emerging out of the Dan River than in the Roanoke River, and remaining on the south side of the lake. This flow pattern disappears in the vicinity of Buffalo Creek. A uniform turbidity pattern occurs from the Roanoke River to just below the dam, where a lower turbidity pattern emerges and extends into Nutbush Creek. Again, Nutbush Creek has the lowest intensities in the lake. There are no noticeable changes in turbidity on the band 7 imagery.

3.16 LANDSAT IMAGERY FOR OCTOBER 11, 1972

There are several distinct turbidity patterns shown on the band 5 scene of figure 19. The water shifts to a lower turbidity level above Grassy Creek and shifts again to another lower level on the north side of Island Creek. The water in Grassy Creek and in front of Island Creek has the same intensity as the water in the Dan River. A shift to a lower turbidity level occurs at Mill Creek, where a channel of constant turbidity goes all the way to the dam. The water in the lower half of Nutbush Creek has a higher turbidity than the water at the mouth of the creek. Band 7 imagery exhibits no change in intensity for all of Kerr Lake.

4.0 CONCLUSIONS

A historical review of available Landsat imagery over Kerr Lake has provided an insight into the distribution of sediment loads, local circulation patterns, and the seasonal variations of turbidity in the lake. Differences in and between band 5 and band 7 of Landsat indicate different levels of sediment concentration which can be used to survey surface sediment distributions. Distinct sediment patterns only occur on band 7 when the suspended sediment loads are greater than 100 ppm. Most of the sediment in the lake originates from the Dan River and the highest levels normally occur in the spring of the year. All the other creeks leading into the lake exhibit lower turbidity levels, except Grassy Creek, which has on occasion displayed highly turbid water. Sometimes the highest intensities are observed in the middle of the lake. The water in Nutbush Creek always has the lowest turbidity levels in the lake. Primarily in the spring of the year turbidity patterns appear in band 7 that are different from the patterns in band 5. This is due to the fact that band 7 is more sensitive to higher levels of sediment and band 5 saturates at these higher levels. An indication of high volume of water flow is the appearances of plumes in both band 5 and band 7 and the turbidity change in band 5 as water is forced to go through a narrow channel at the Clarksville bridges. The peninsula across the lake from Grassy and Island Creeks takes the first impact of the flow in the lake, resulting in local eddies and many turbidity patterns. There is much impingement of flow onto all land areas in this region, probably resulting in a major siltation build-up. Water piles up in an area around the entrance to Nutbush Creek and the dam, producing many different types of circulation patterns. High volumes of flow will sometimes result in turbid water being forced into Nutbush Creek. In the winter months, flow of less turbid water has been observed entering the main lake from Nutbush and other smaller creeks.

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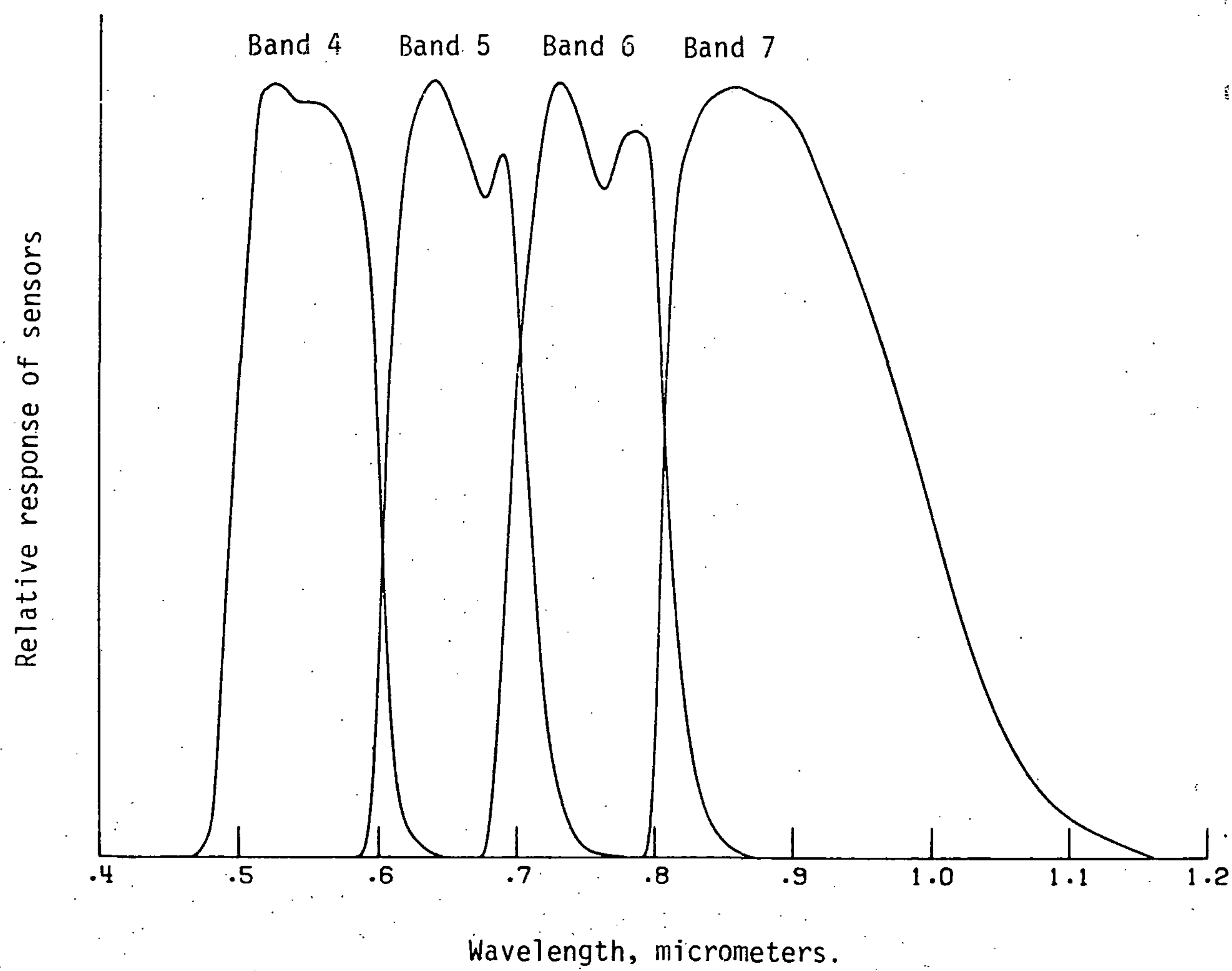
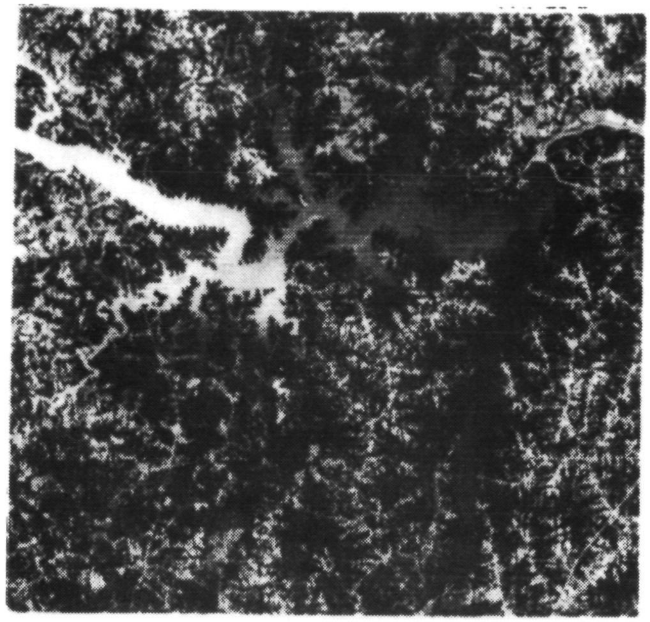
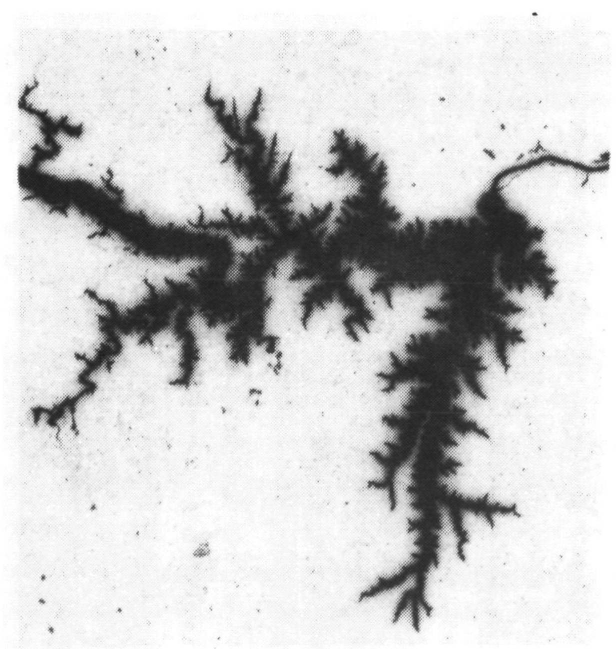


Figure 1. -Instrument sensitivity curves for Landsat's MSS sensors.



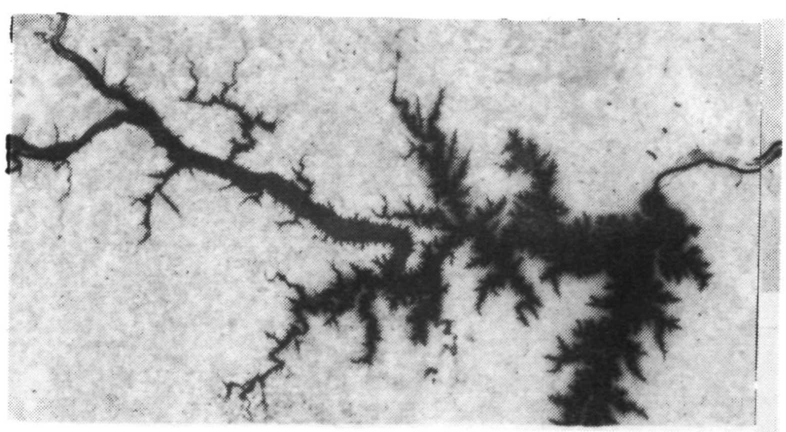
(a) Band 5



(b) Band 7

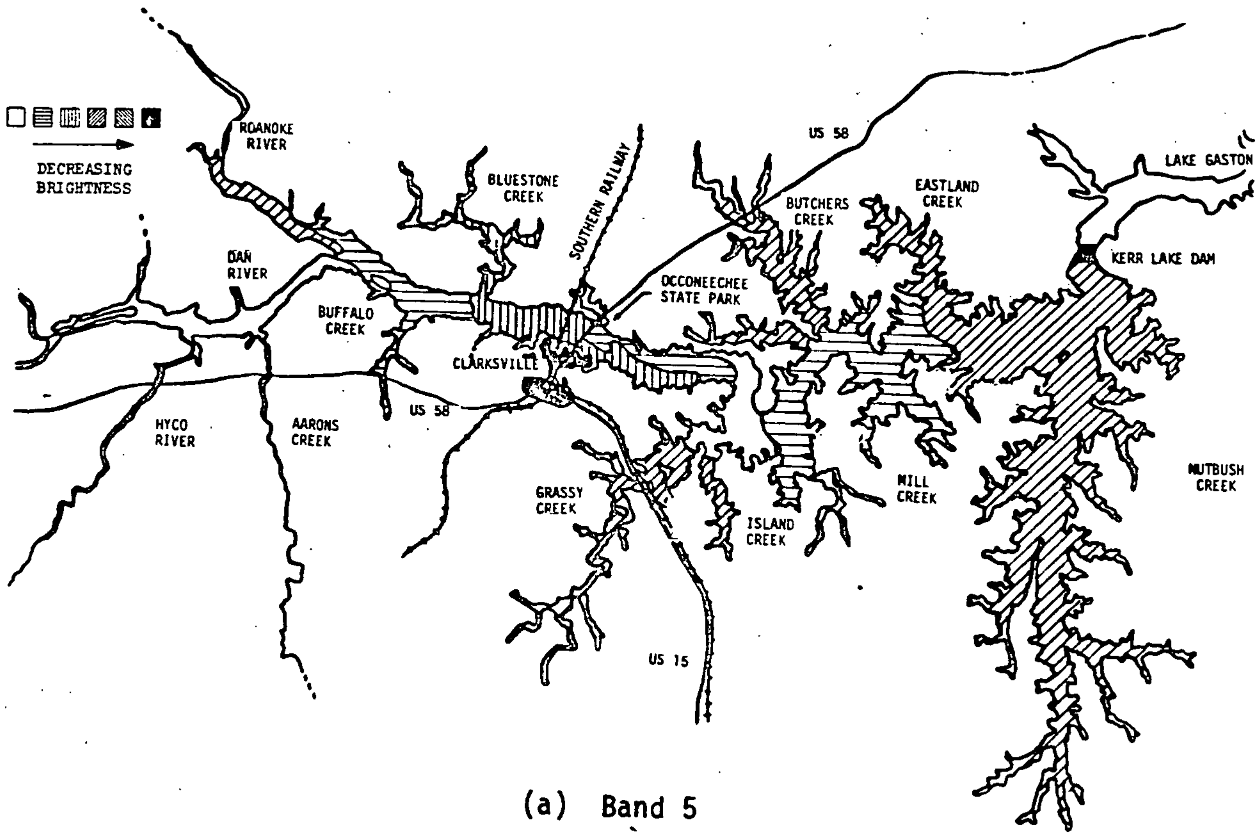
Figure 2. -Landsat images of Kerr Lake for October 11, 1972.

(a) Band 5



(b) Band 7

Figure 3. -Landsat images of Kerr Lake for April 29, 1978.



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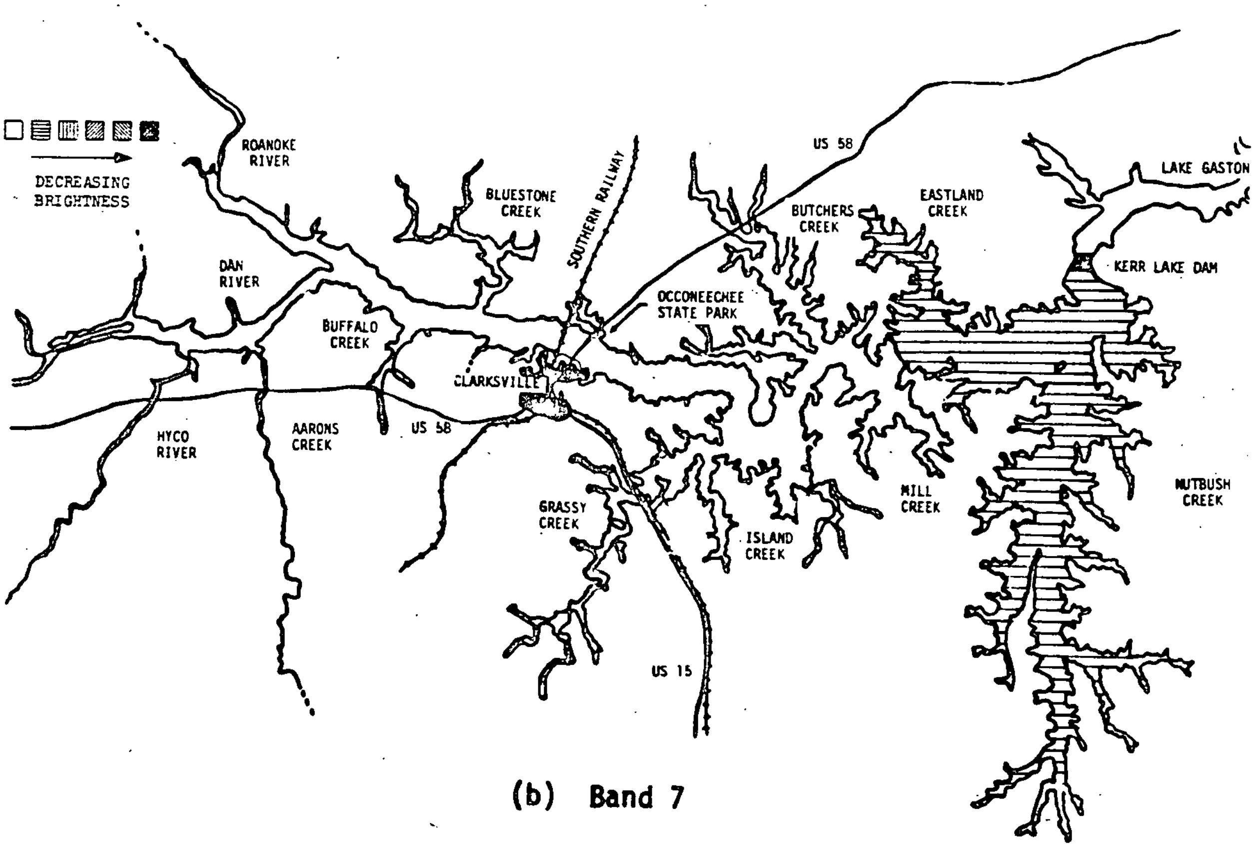
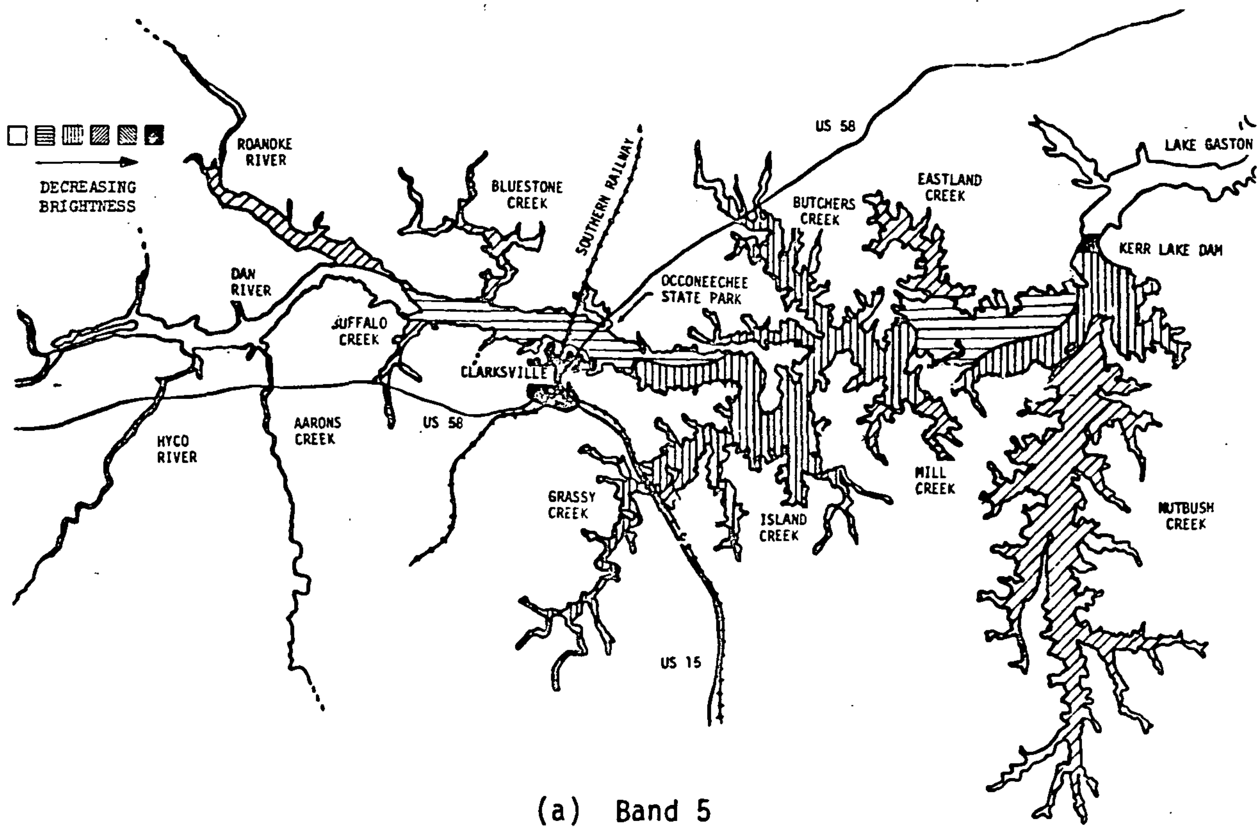


(b) Band 7

Figure 4. -Sketch of Landsat images of Kerr Lake for March 26, 1981.



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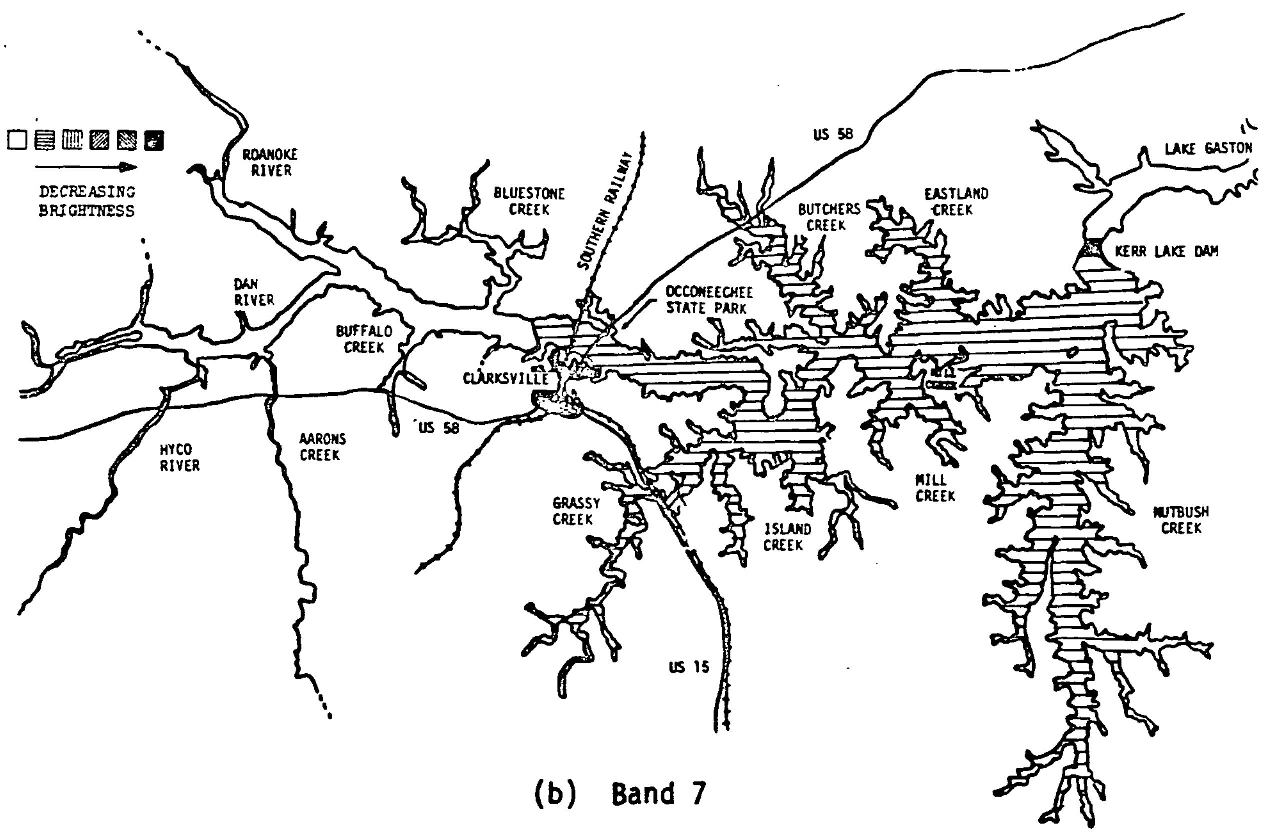
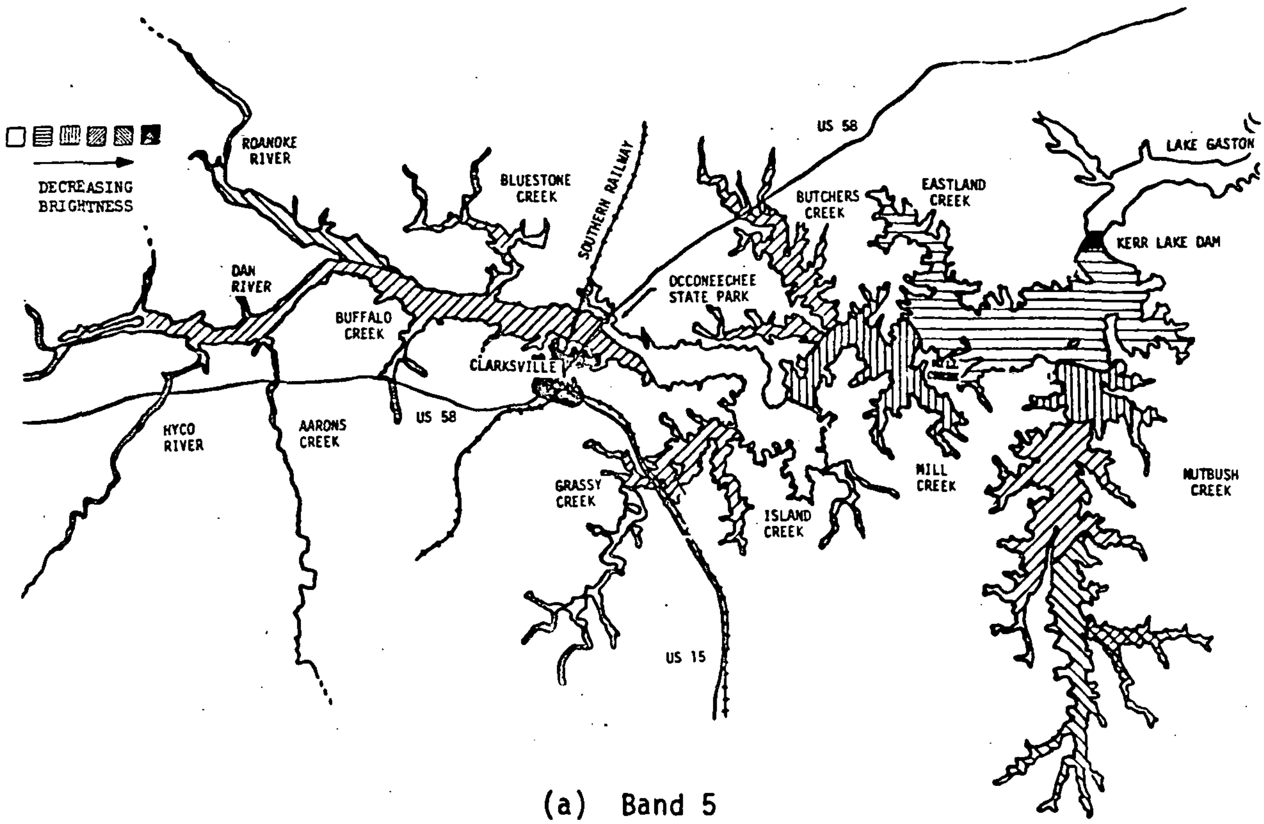


(b) Band 7

Figure 5. -Sketch of Landsat images of Kerr Lake for November 19, 1980.



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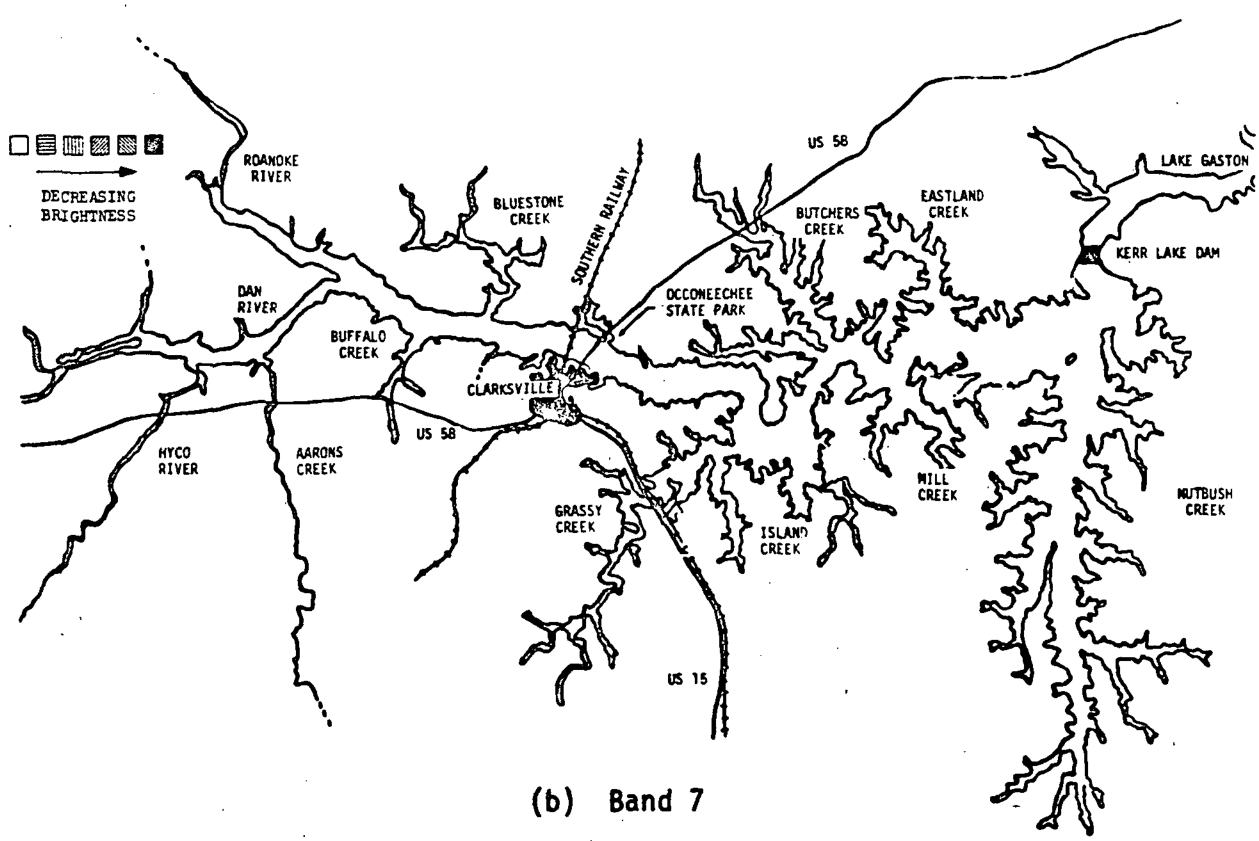
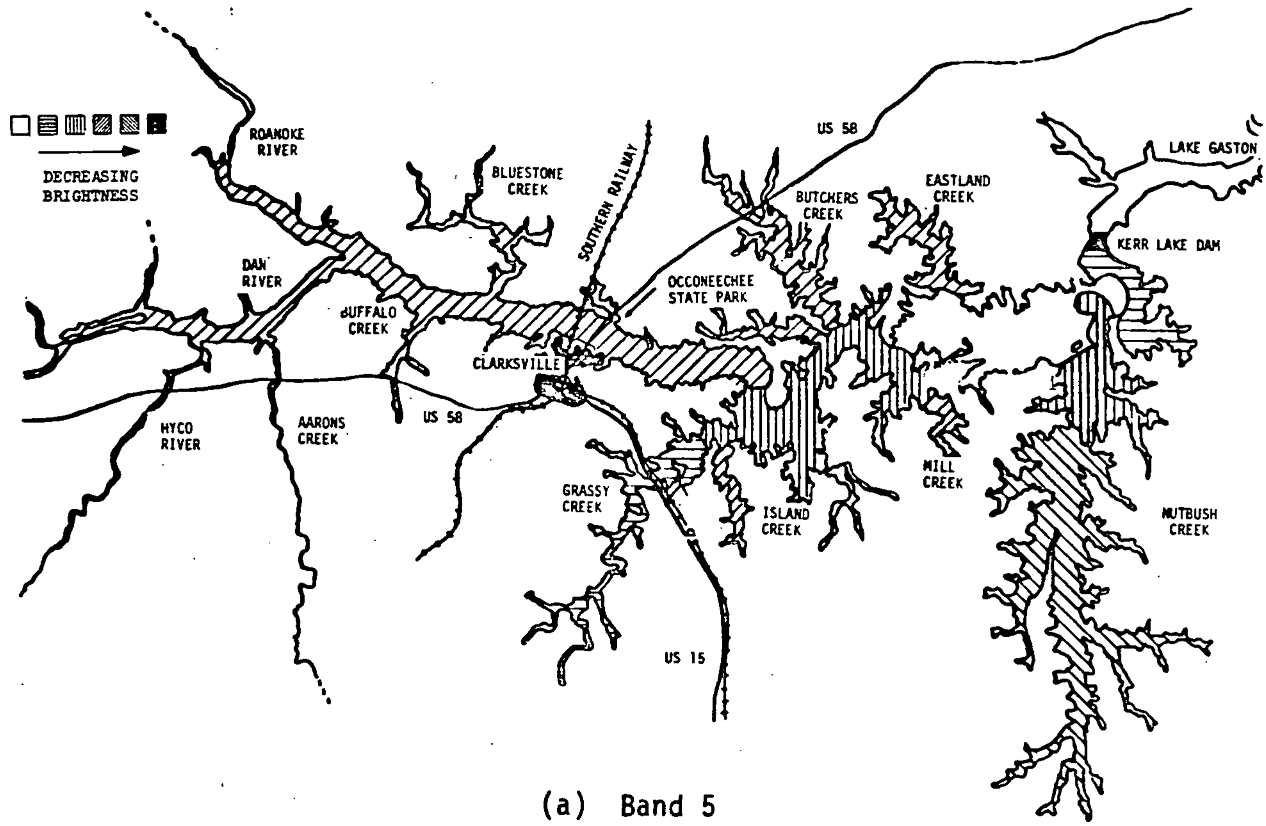
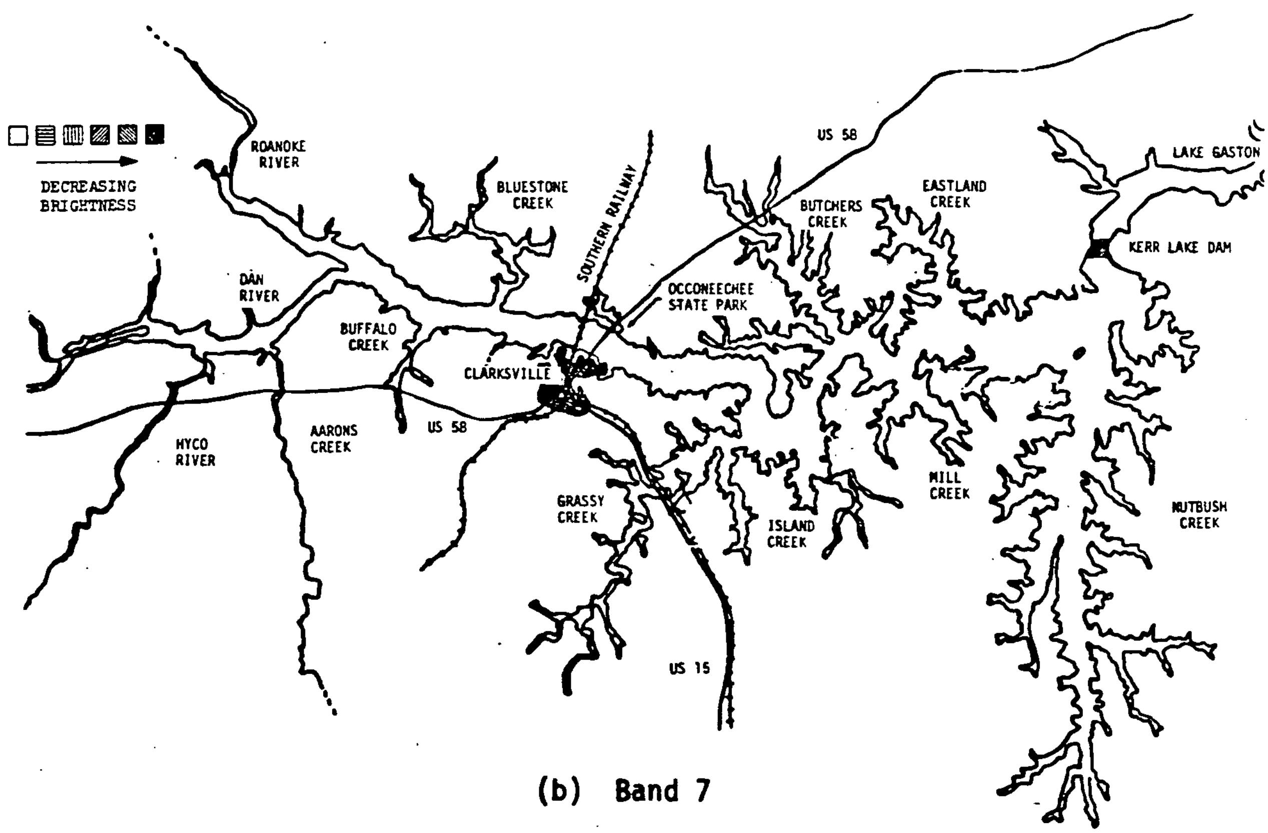


(b) Band 7

Figure 6. -Sketch of Landsat images of Kerr Lake for April 5, 1979.

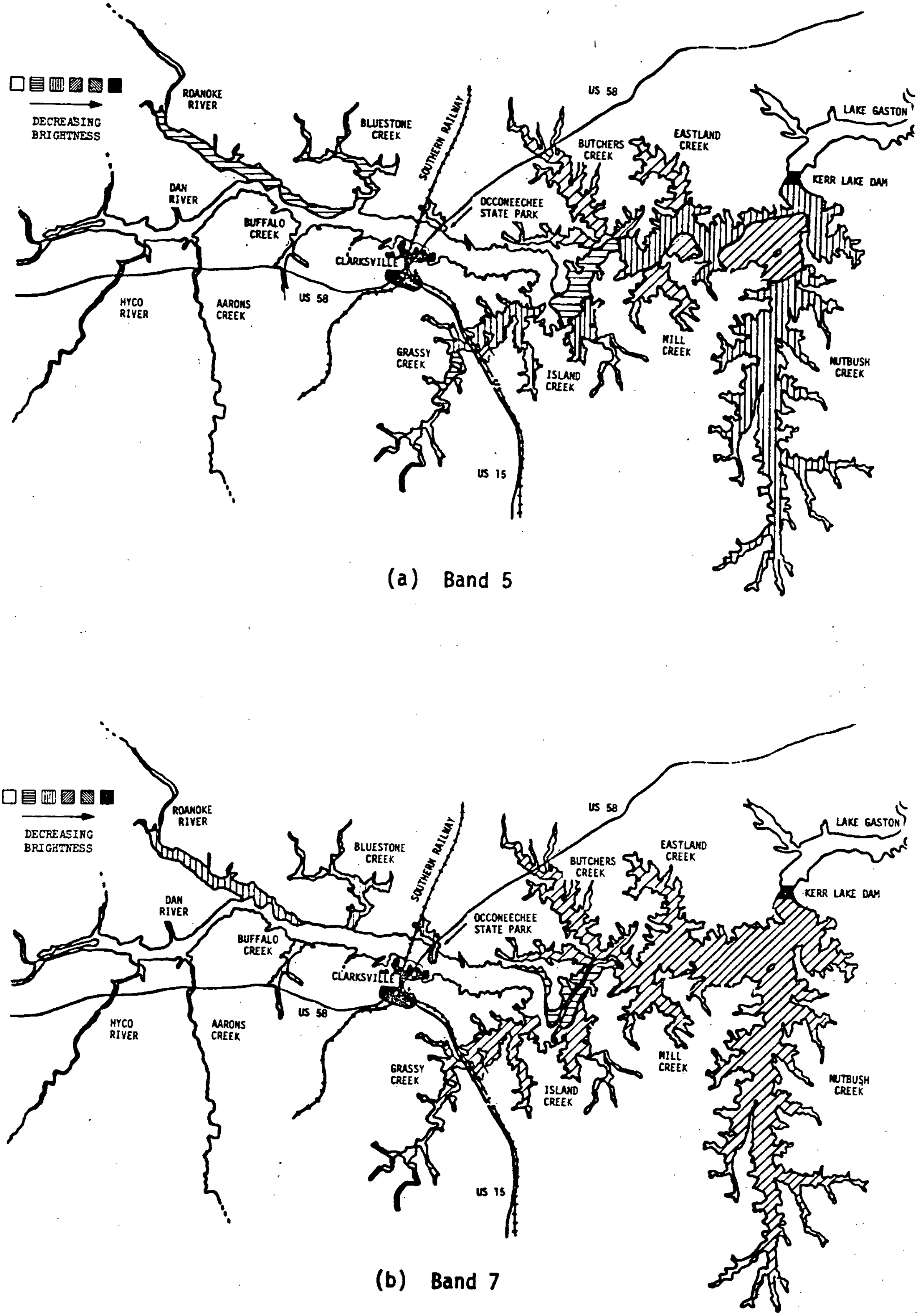


(a) Band 5



(b) Band 7

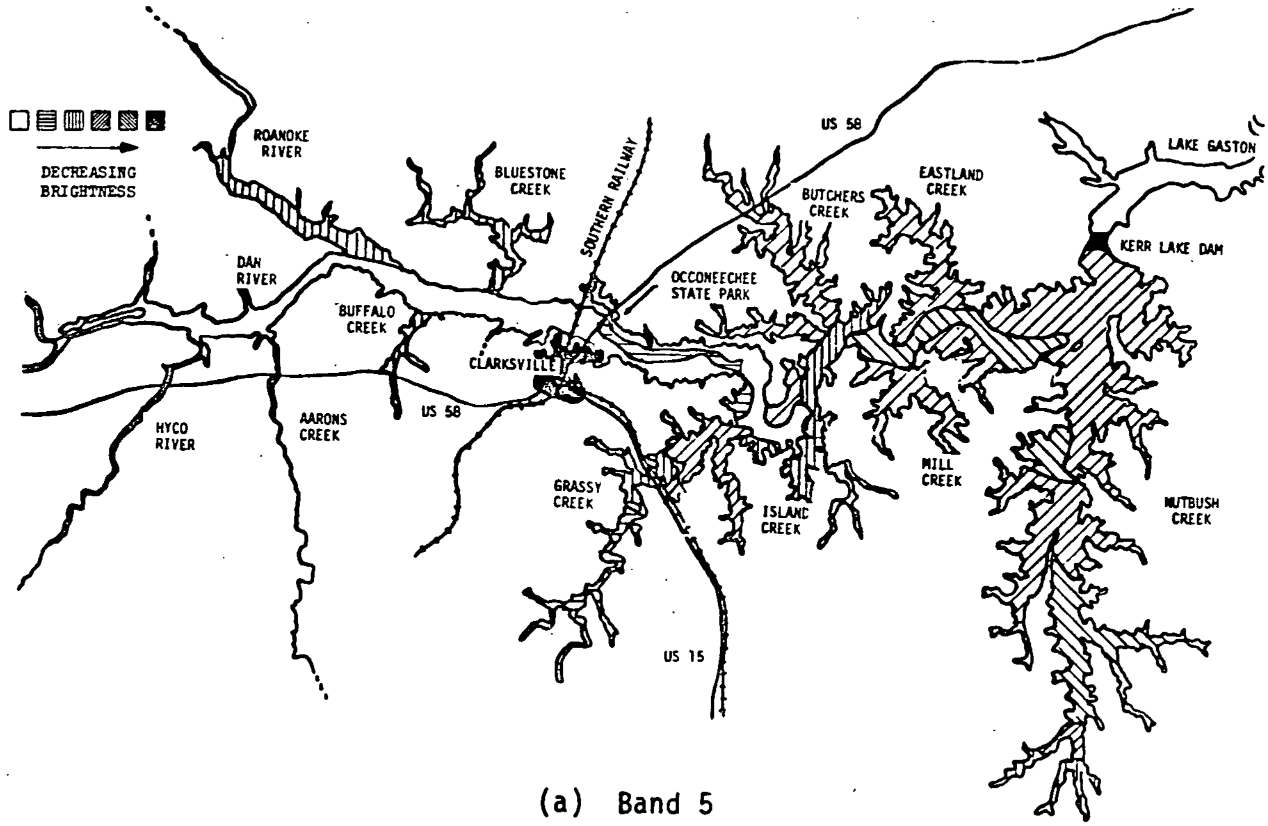
Figure 7. -Sketch of Landsat images of Kerr Lake for February 19, 1979.



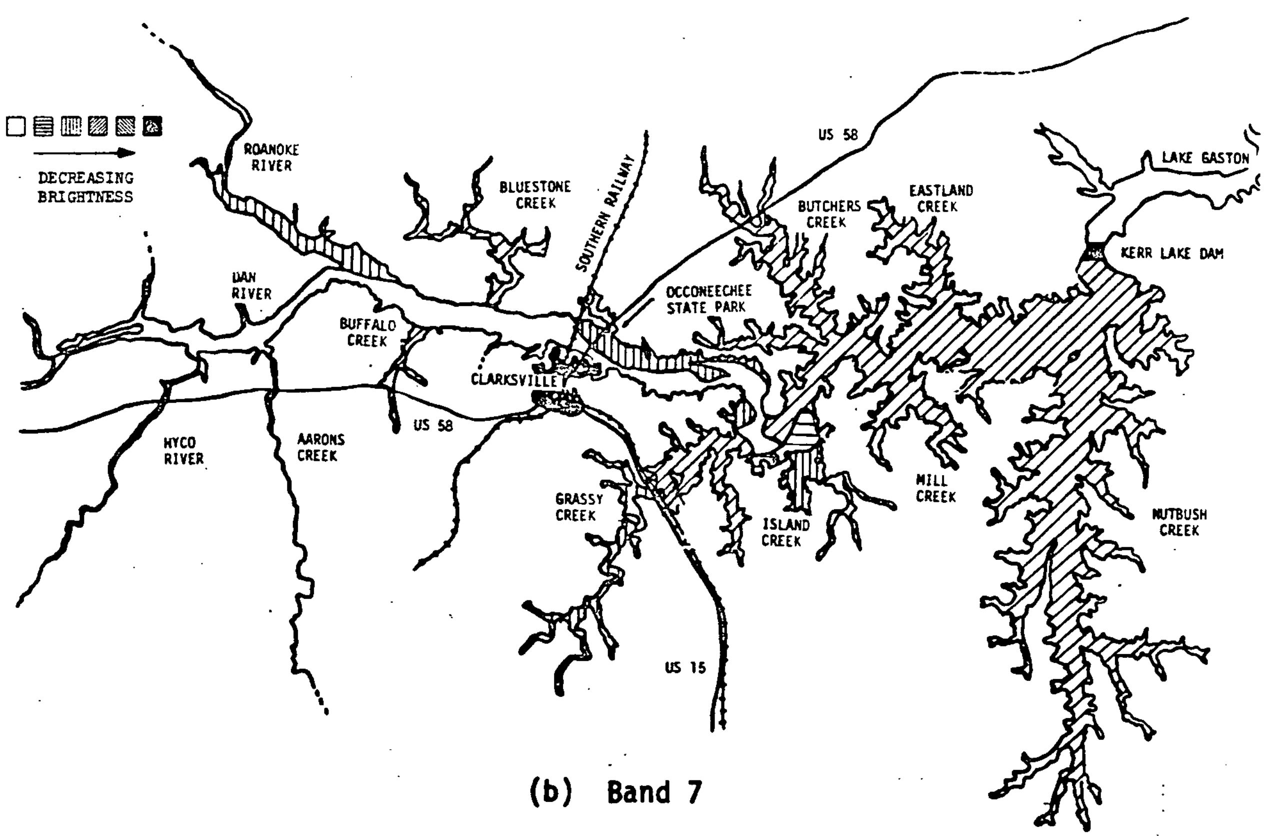
(a) Band 5

(b) Band 7

Figure 8. -Sketch of Landsat images of Kerr Lake for April 29, 1978

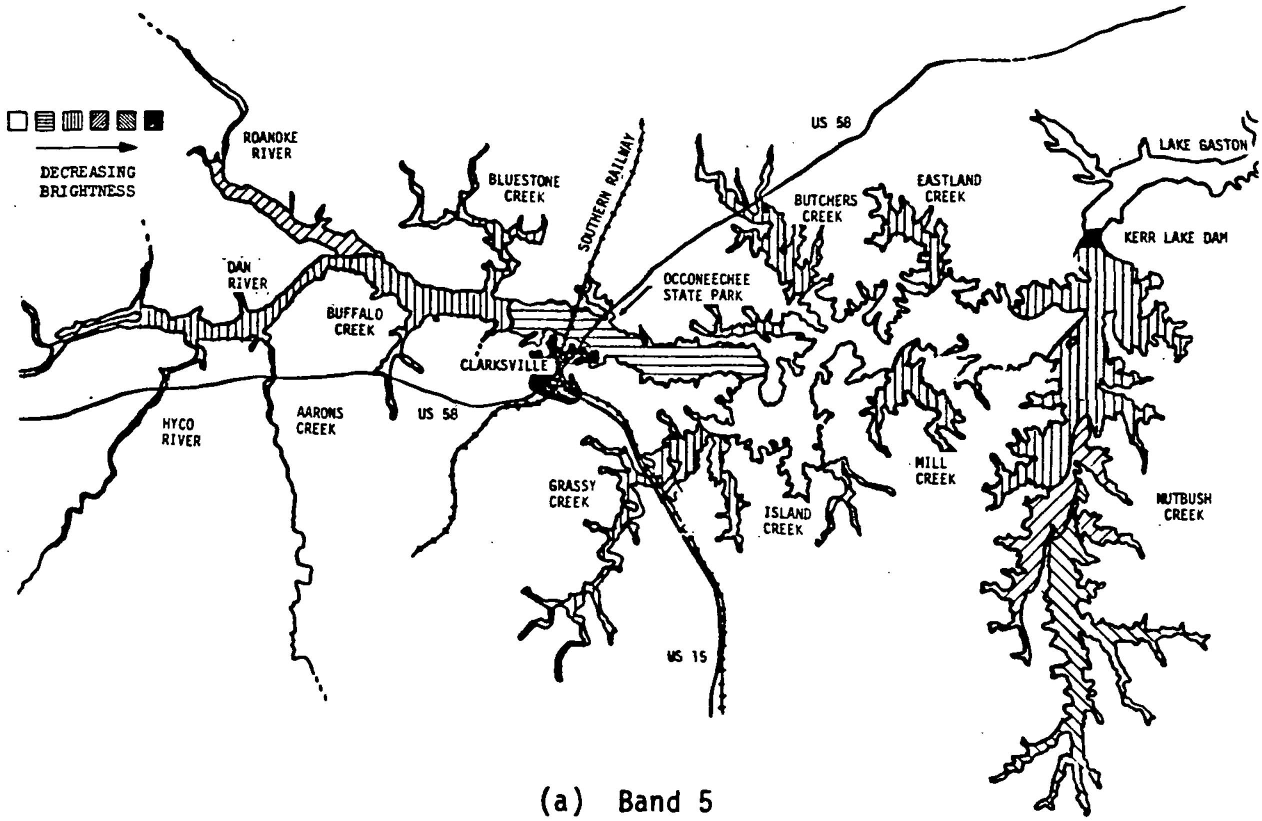


(a) Band 5

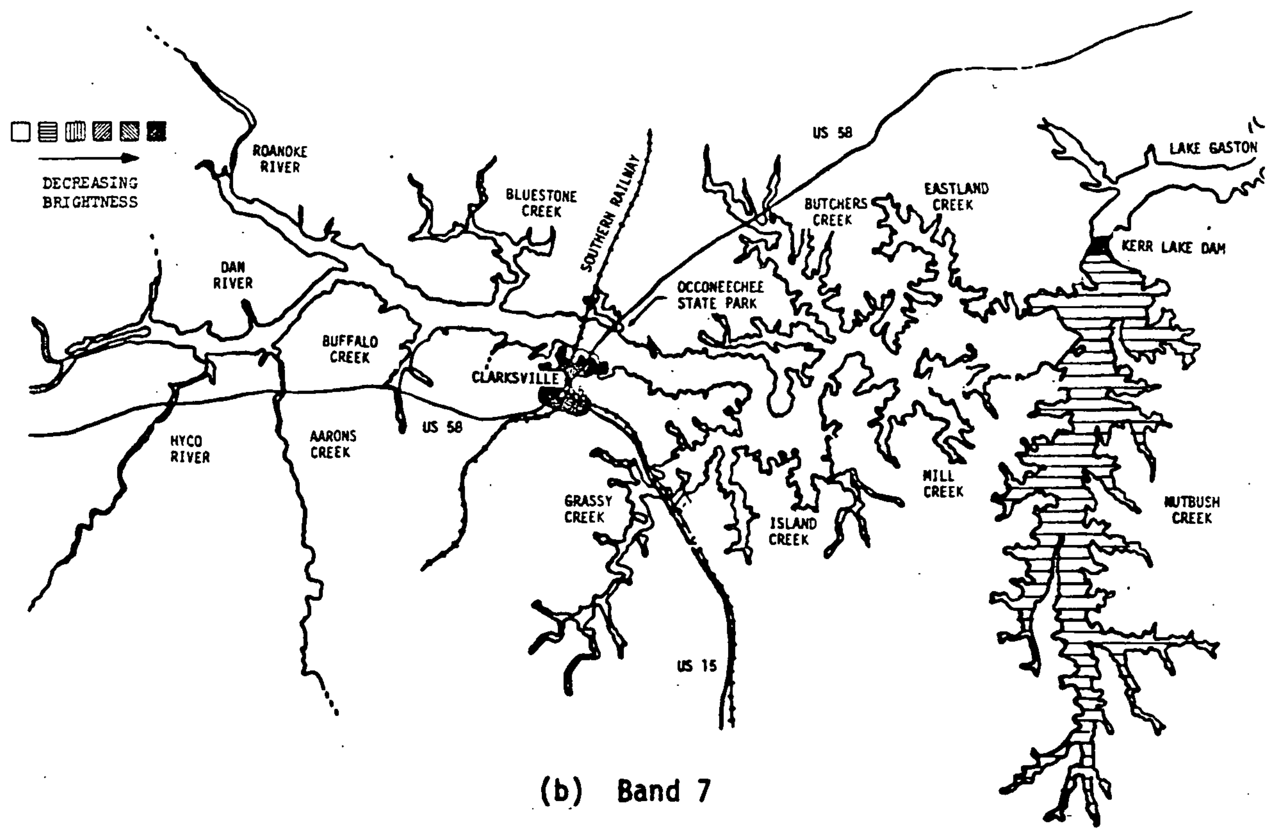


(b) Band 7

Figure 9. -Sketch of Landsat images of Kerr Lake for April 28, 1978



(a) Band 5



(b) Band 7

Figure 10. -Sketch of Landsat images of Kerr Lake for March 23, 1978.

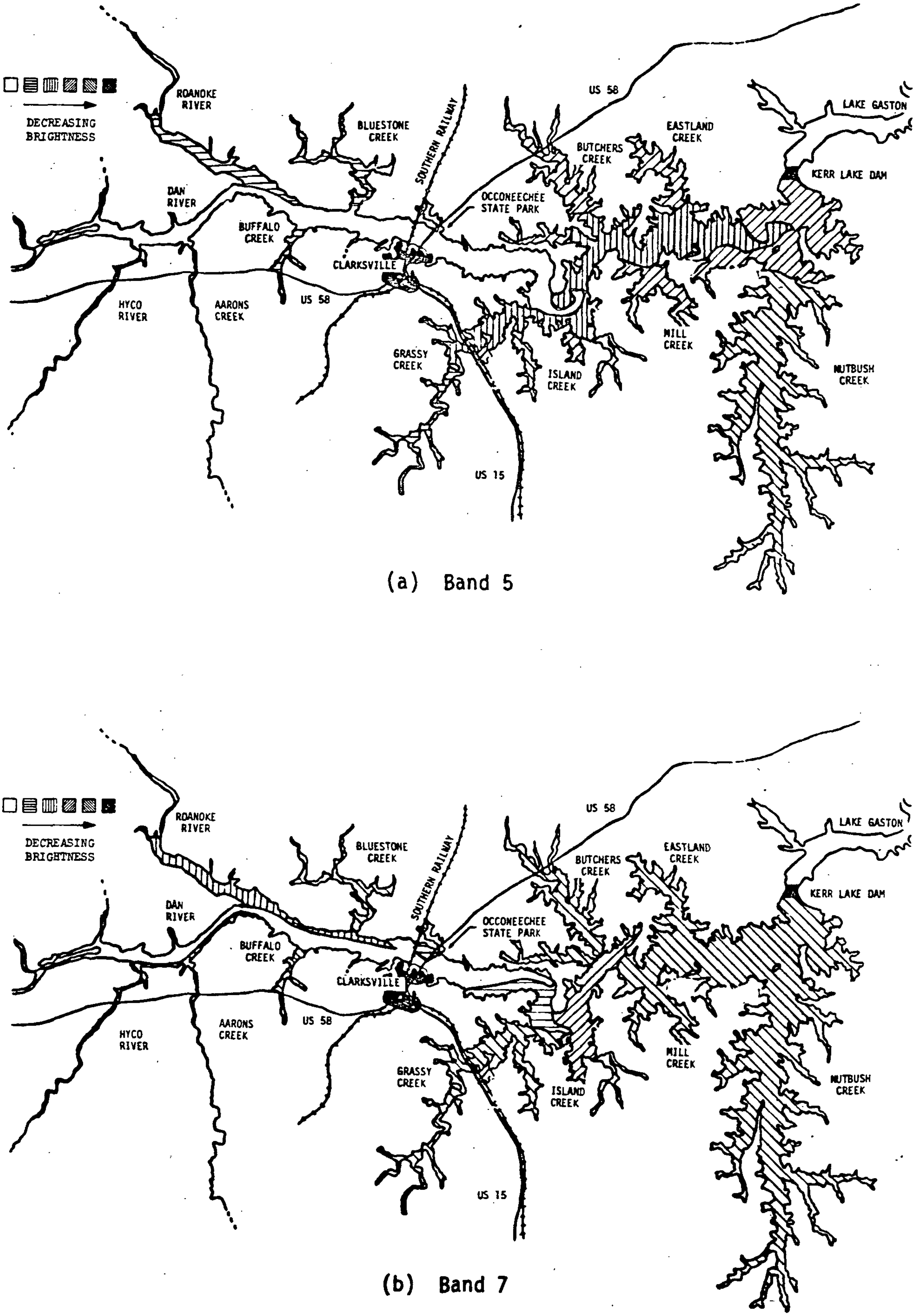
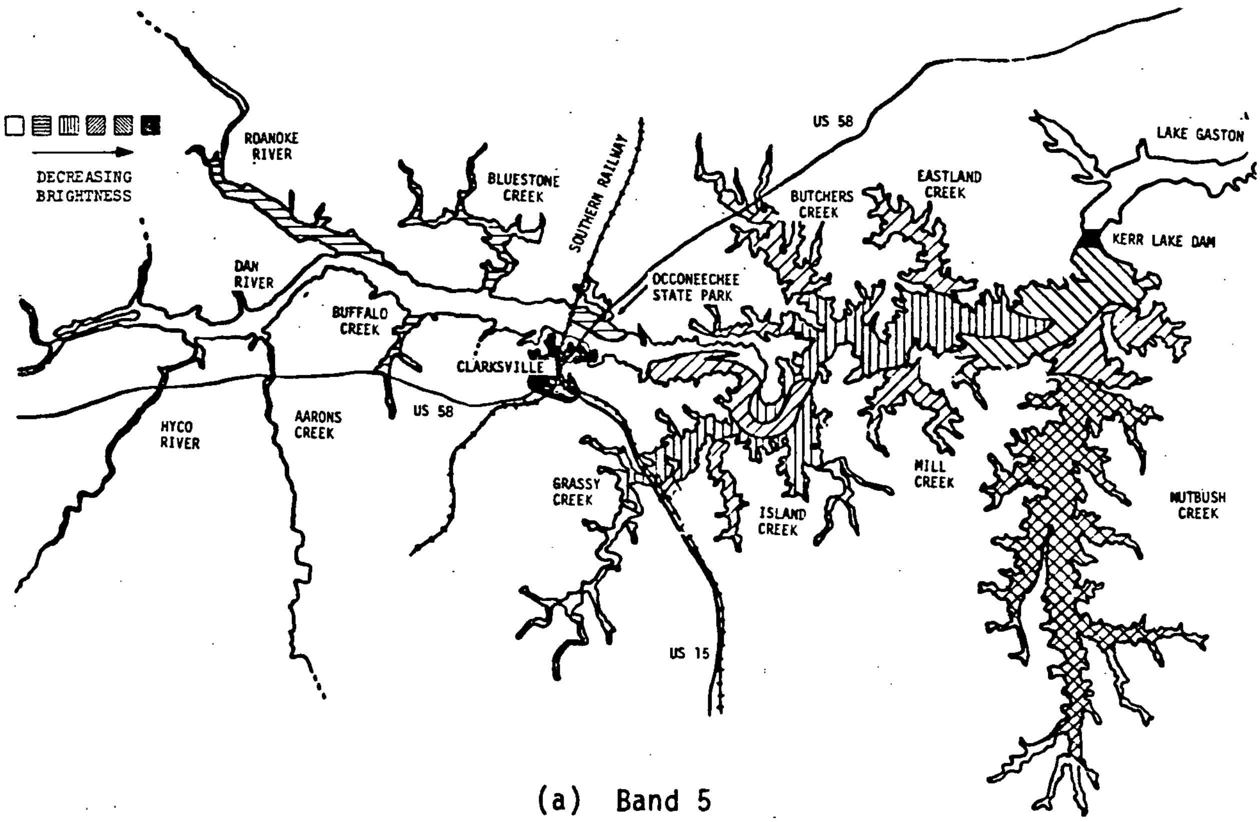
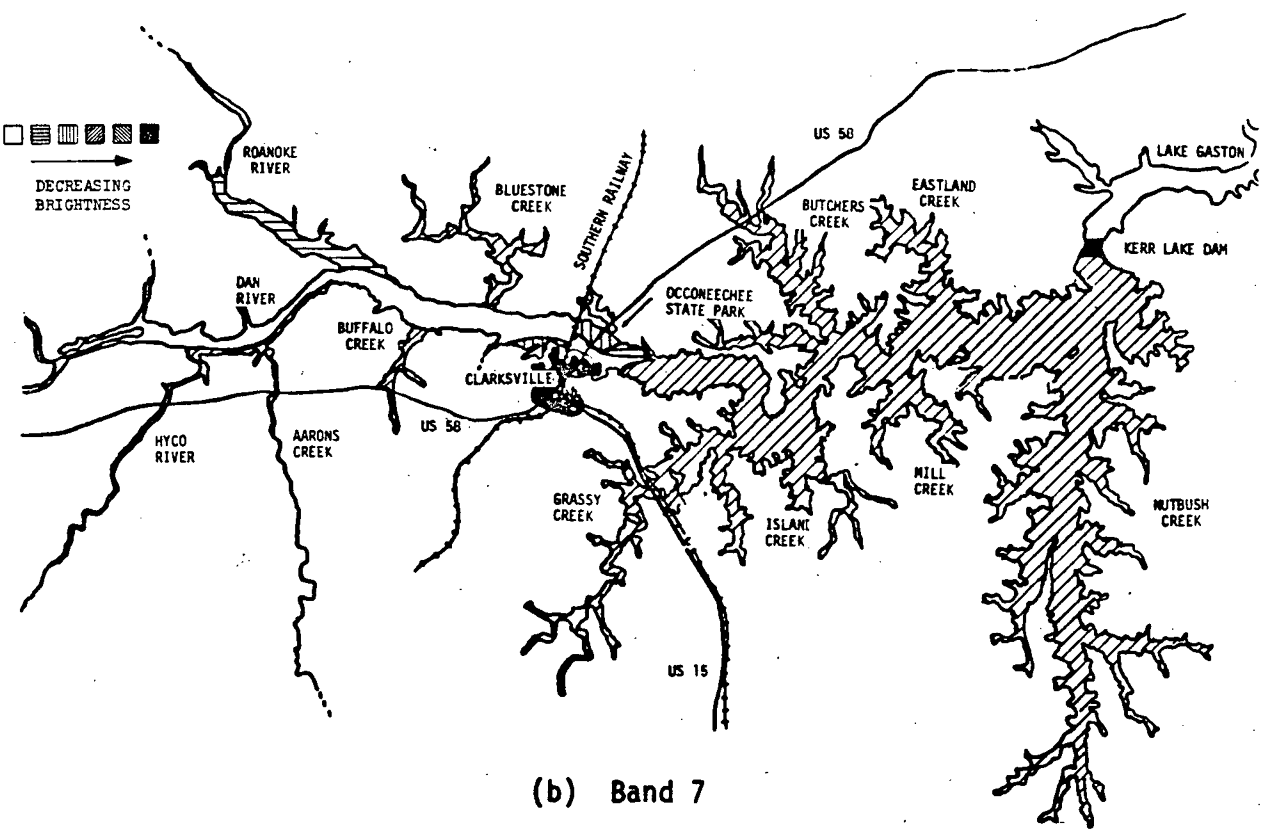


Figure 11. -Sketch of Landsat images of Kerr Lake for January 11, 1978.

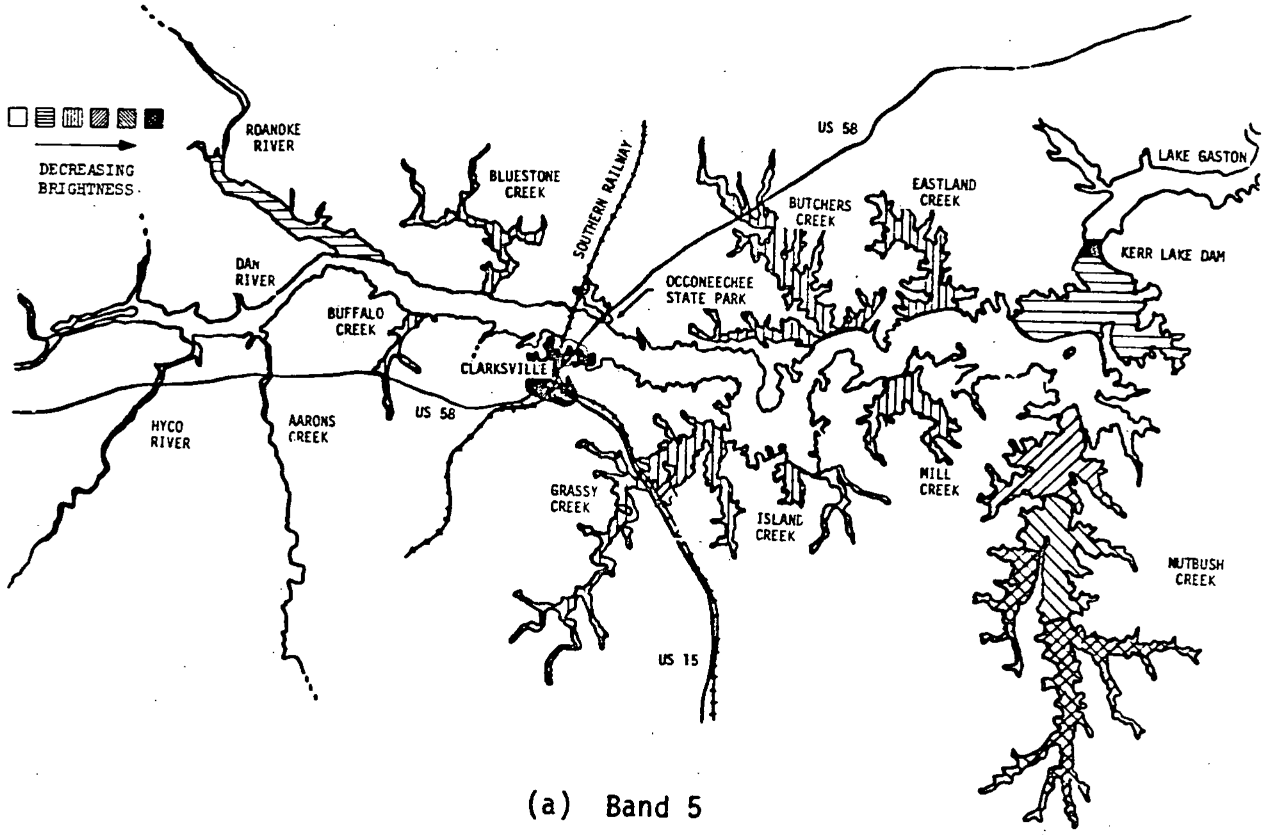


(a) Band 5

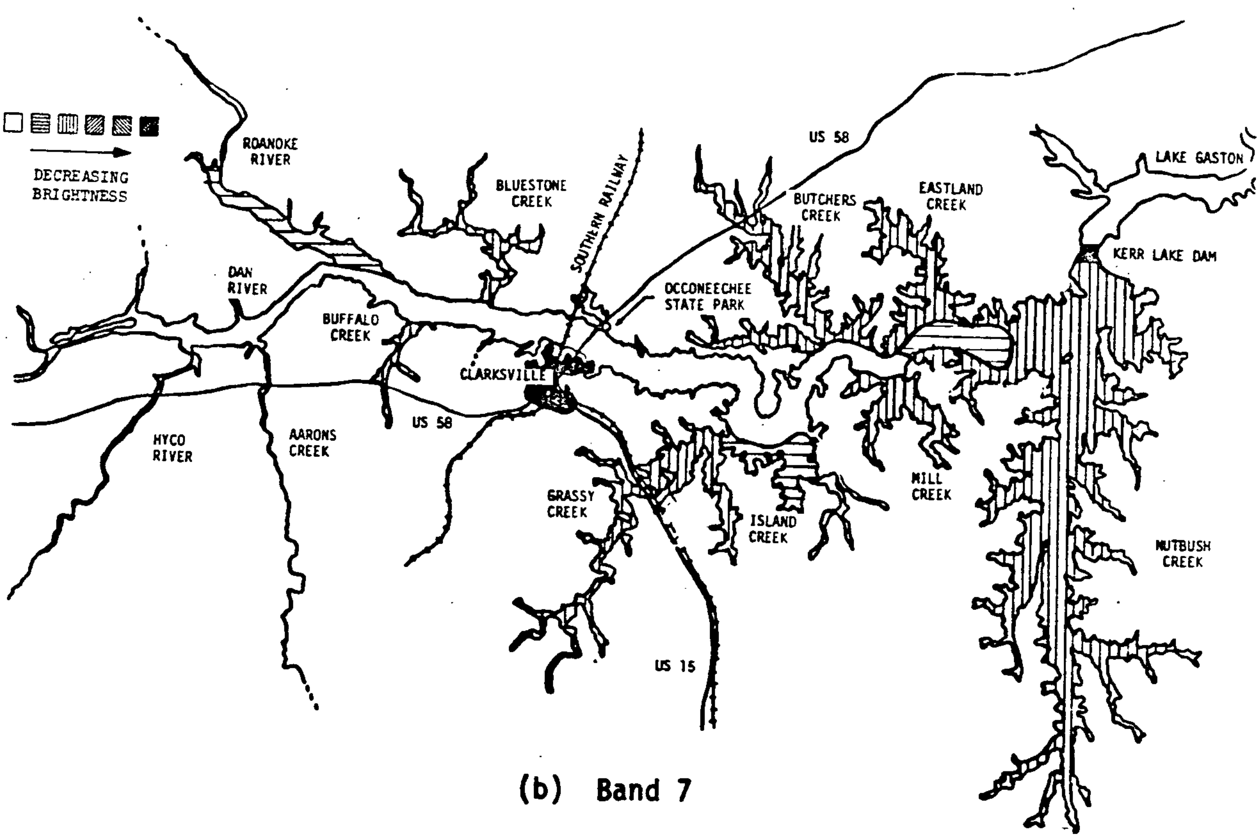


(b) Band 7

Figure 12. -Sketch of Landsat images of Kerr Lake for January 10, 1978.

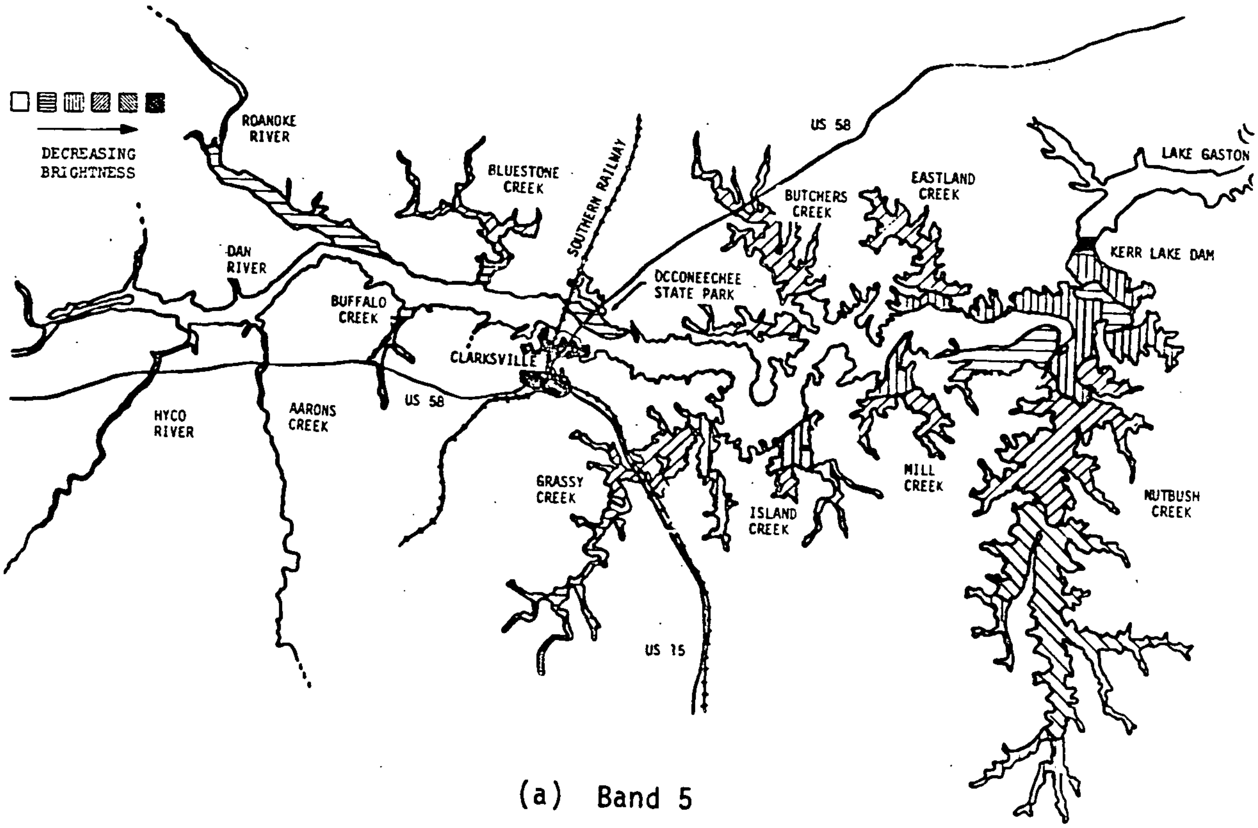


(a) Band 5

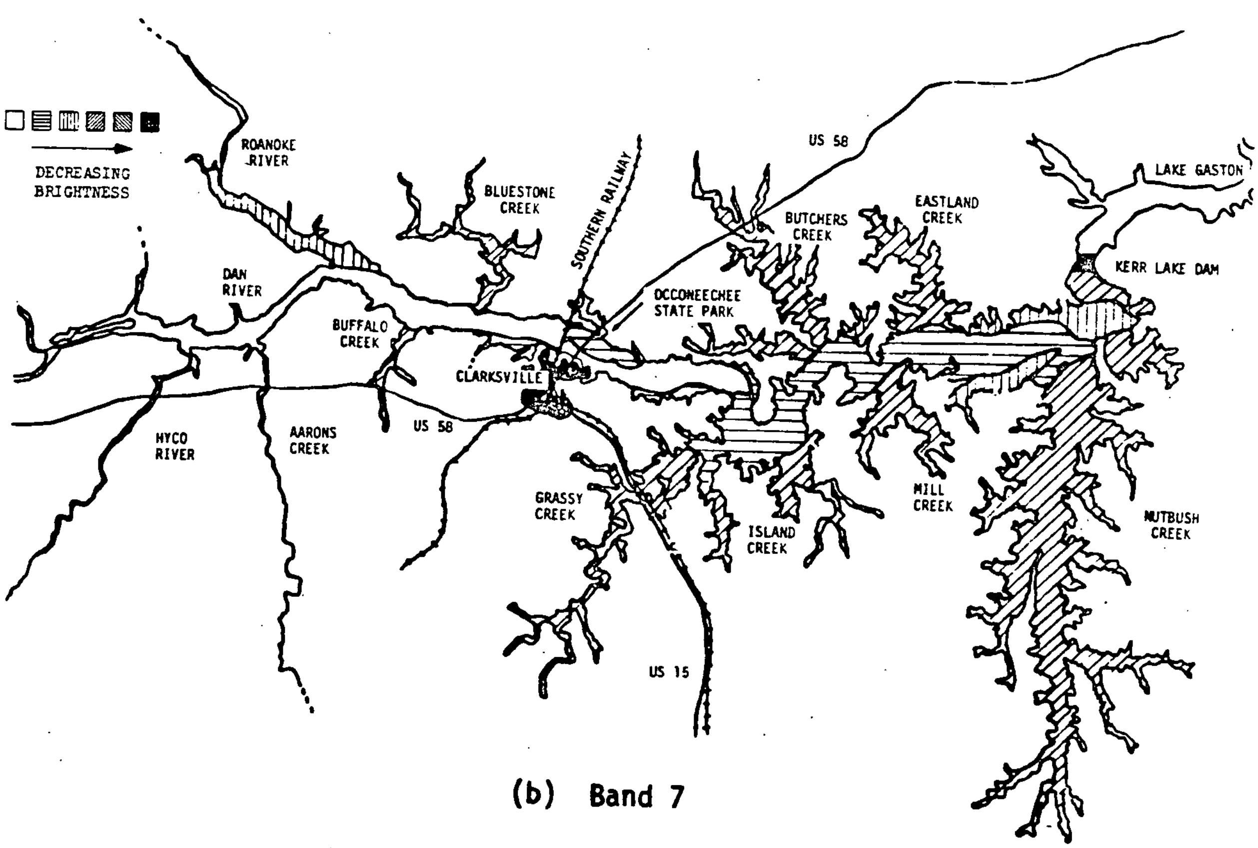


(b) Band 7

Figure 13. -Sketch of Landsat images of Kerr Lake for April 8, 1975.

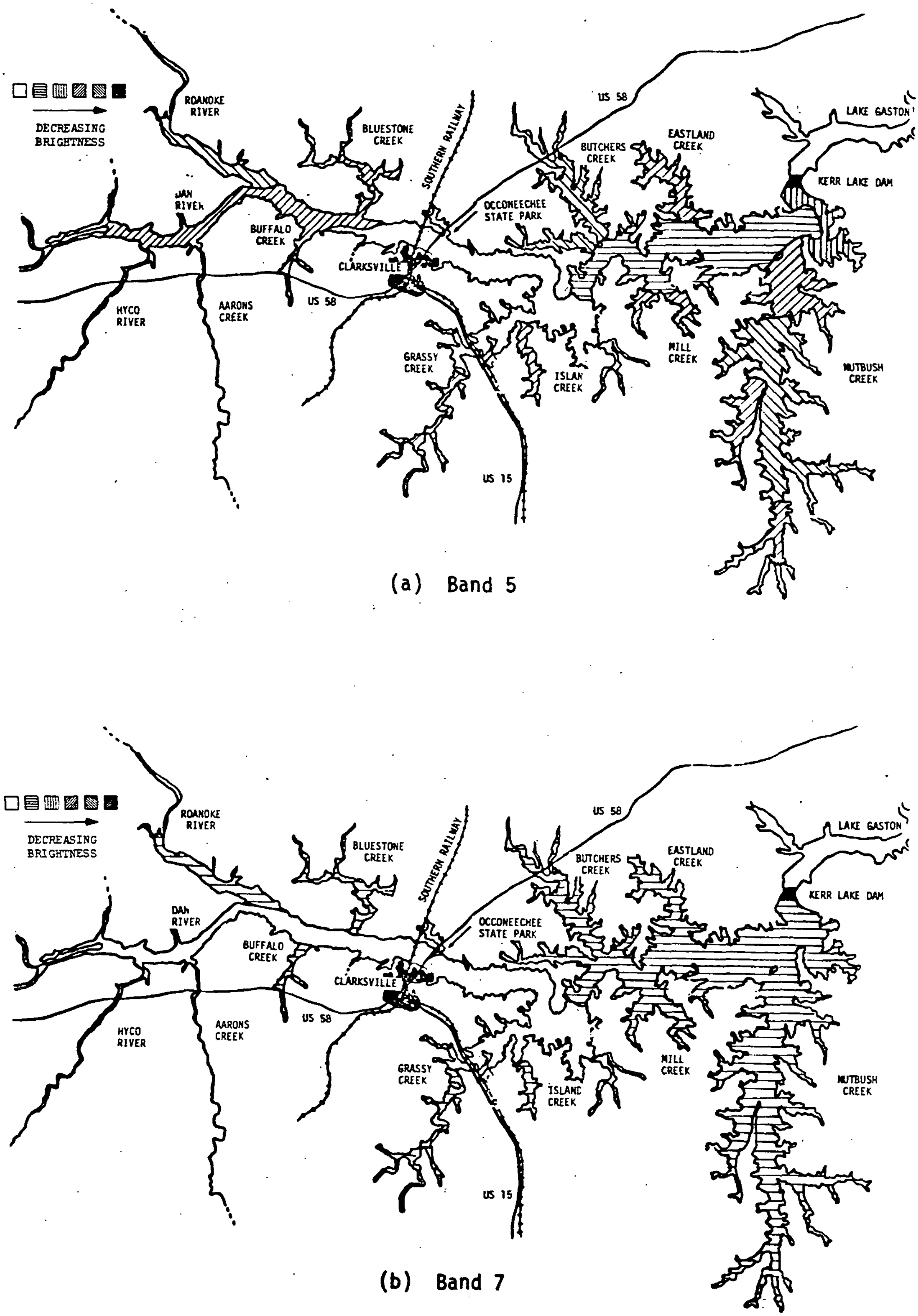


(a) Band 5



(b) Band 7

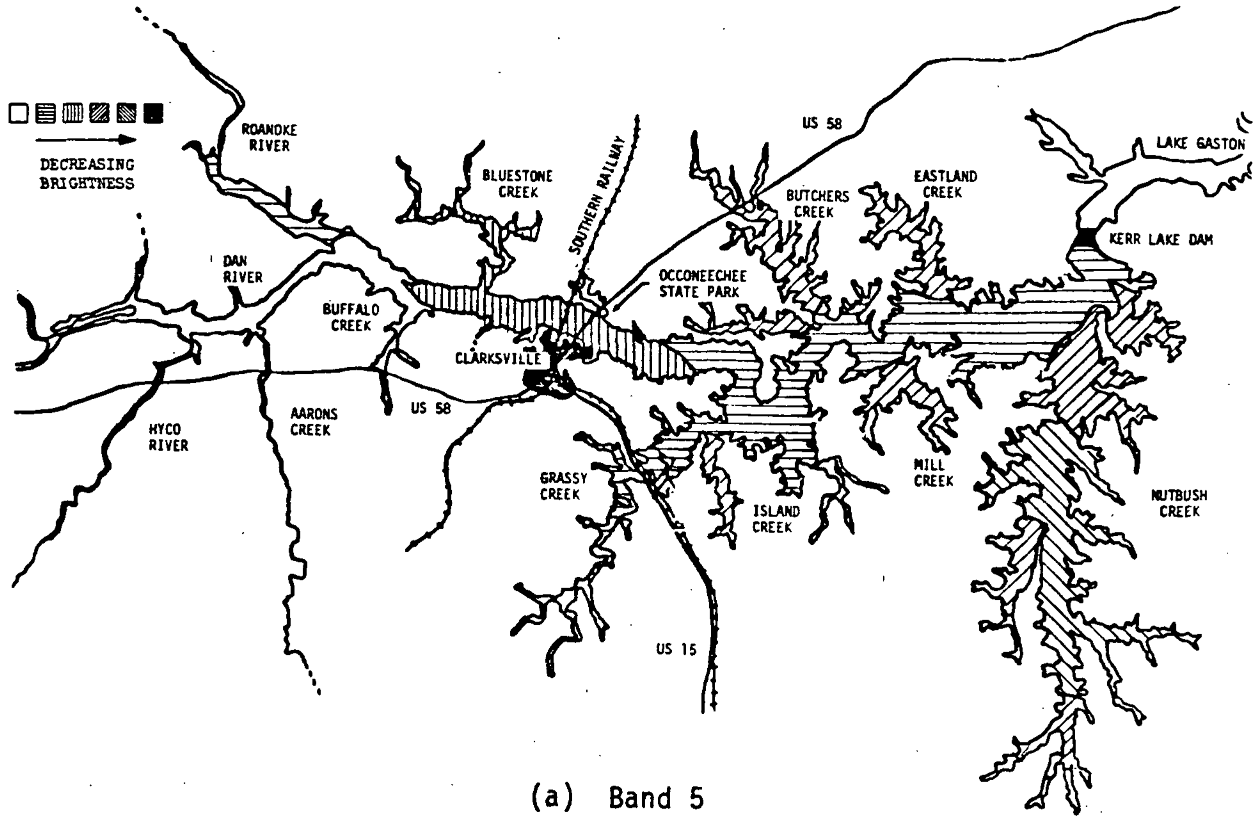
Figure 14. -Sketch of Landsat images of Kerr Lake for March 21, 1975.



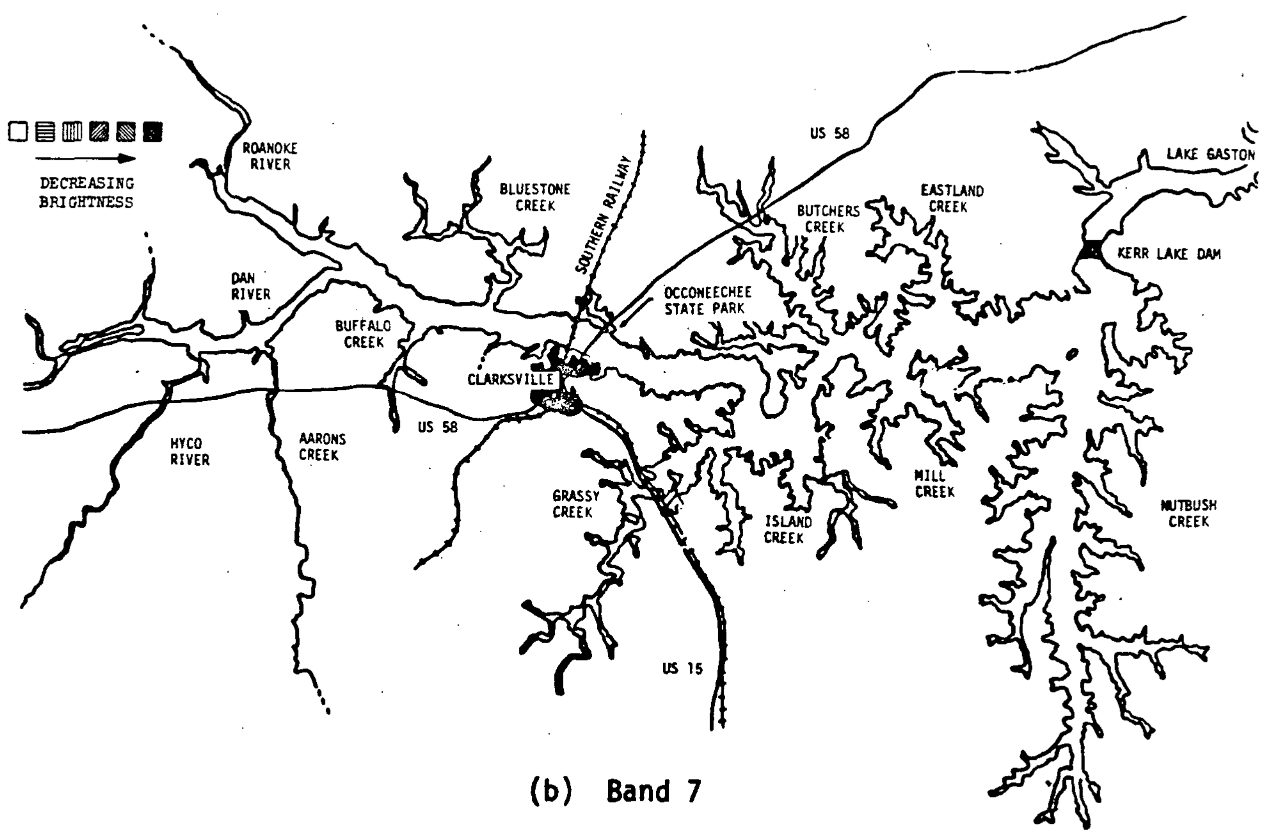
(a) Band 5

(b) Band 7

Figure 15. -Sketch of Landsat images of Kerr Lake for February 13, 1975.

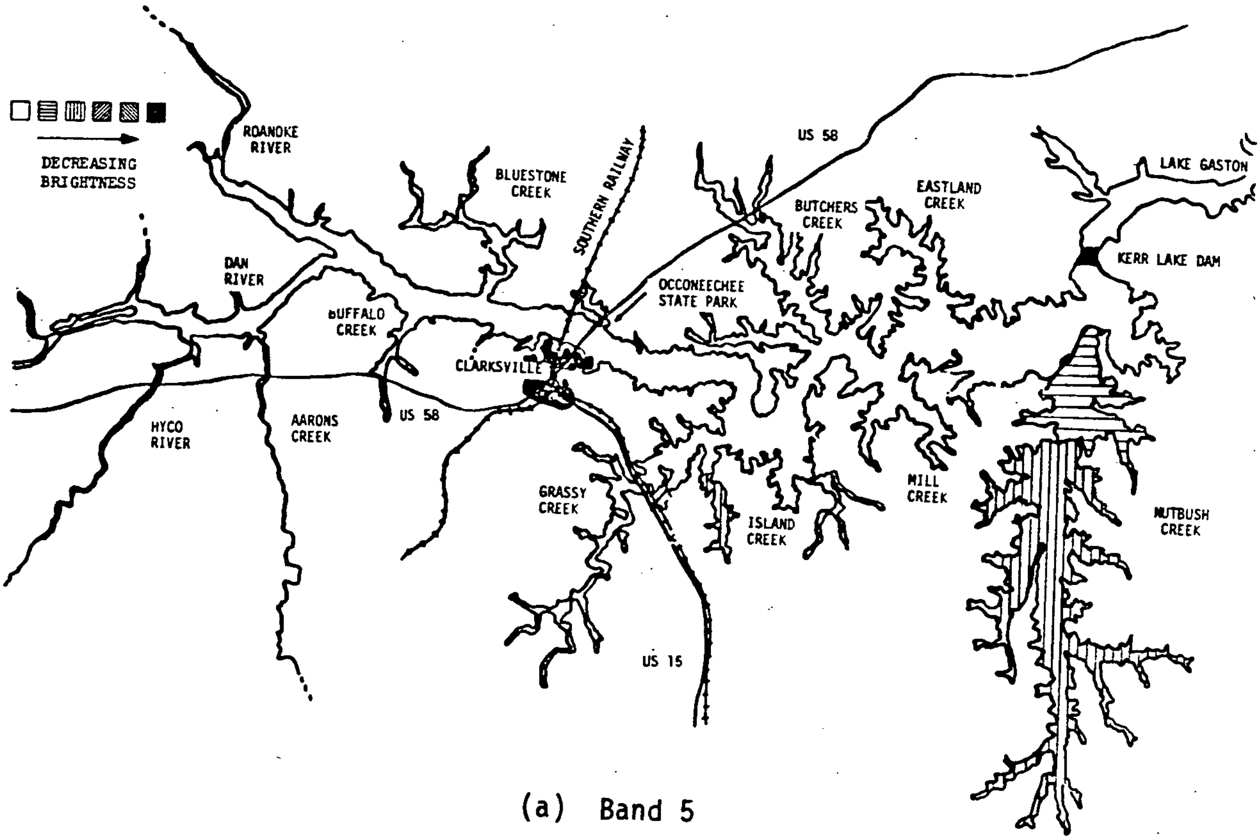


(a) Band 5

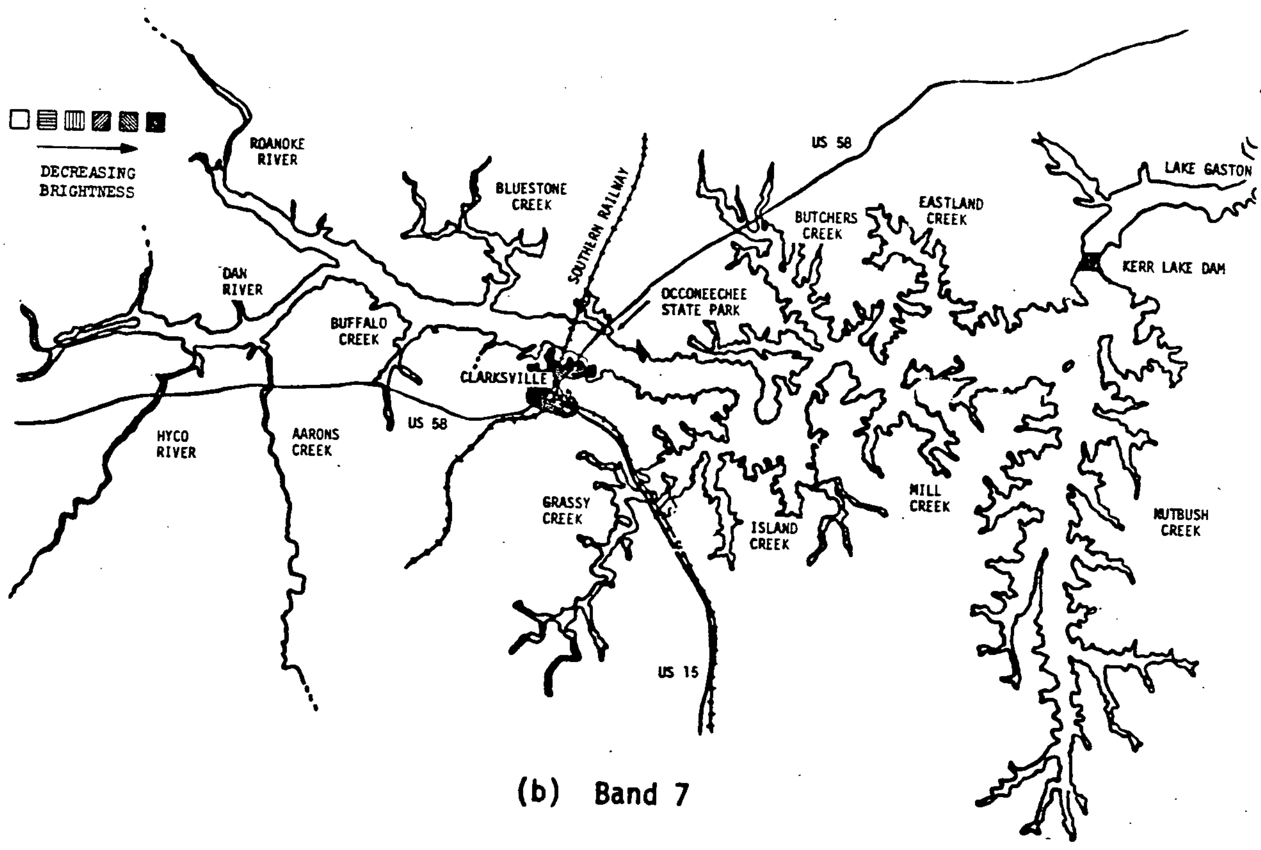


(b) Band 7

Figure 16. -Sketch of Landsat images of Kerr Lake for January 22, 1974.

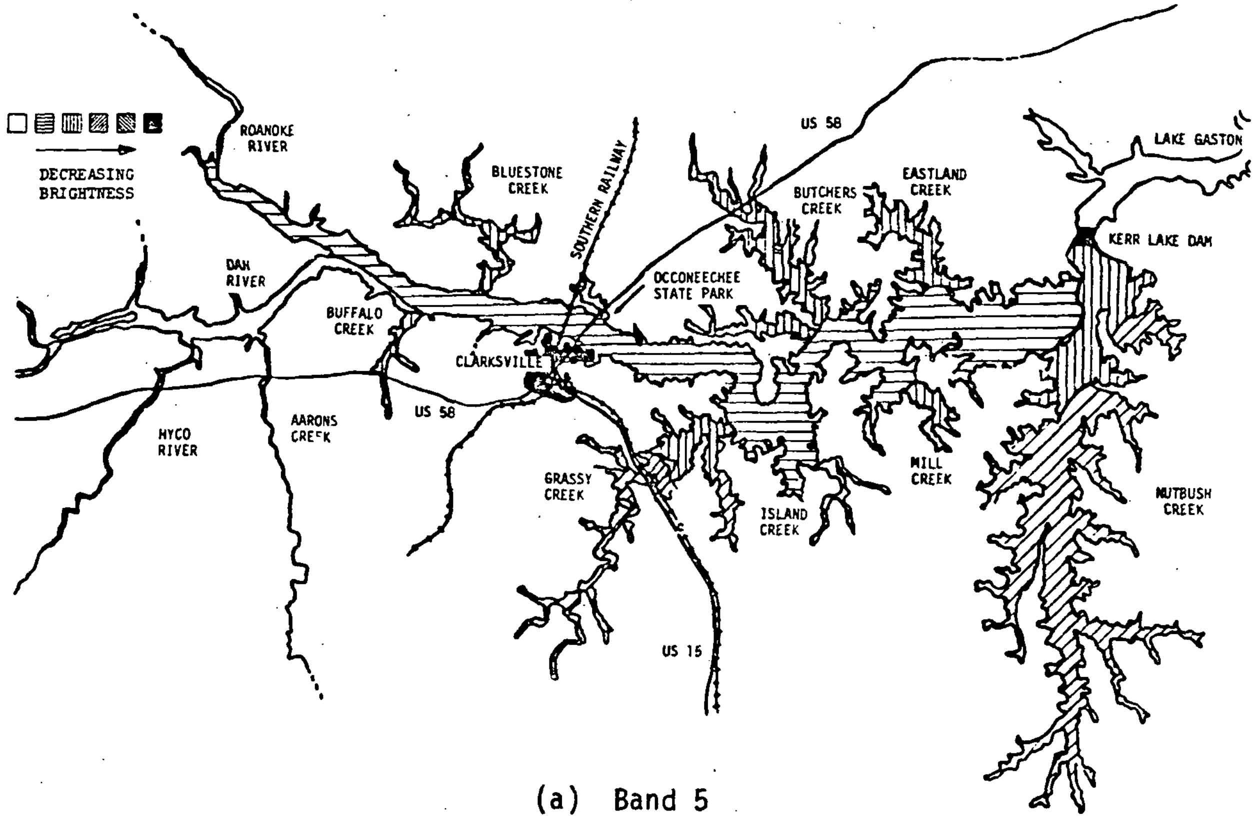


(a) Band 5

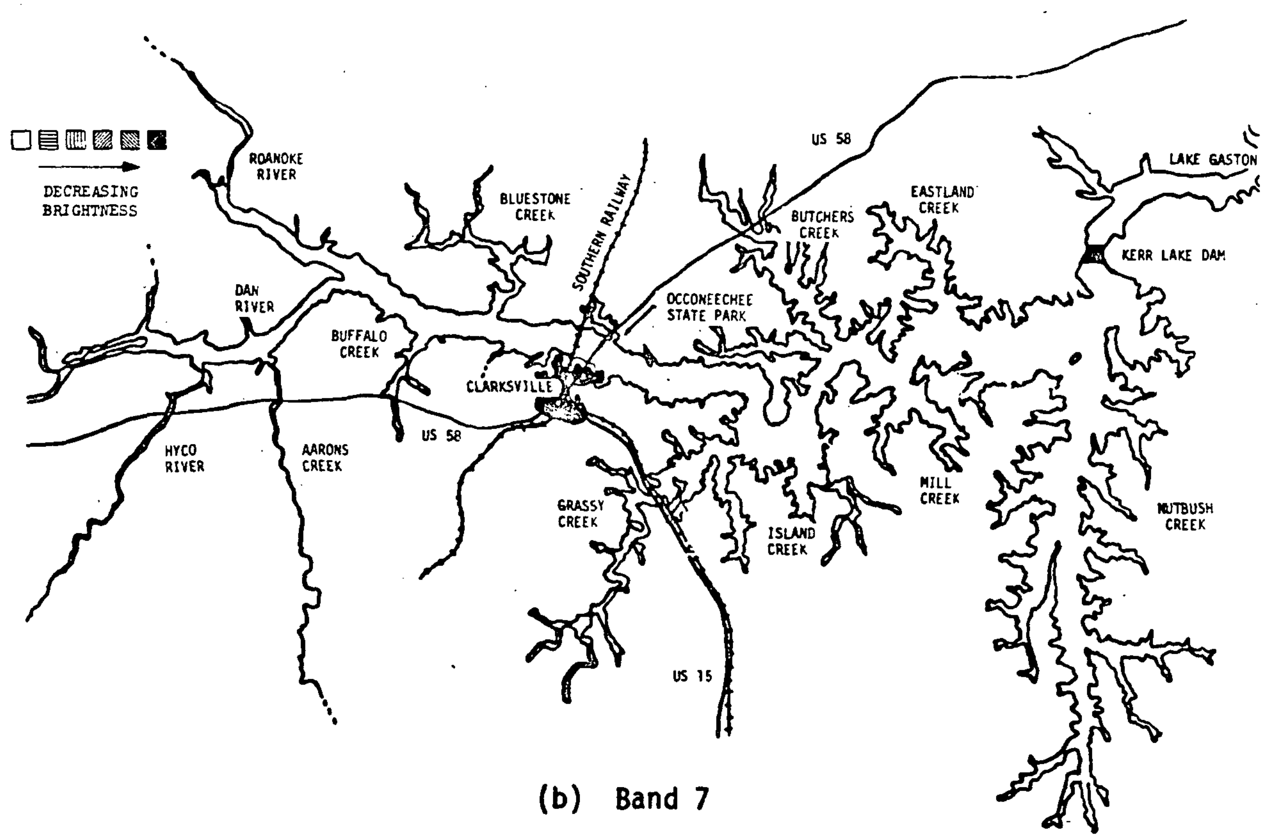


(b) Band 7

Figure 17. -Sketch of Landsat images of Kerr Lake for January 9, 1973.

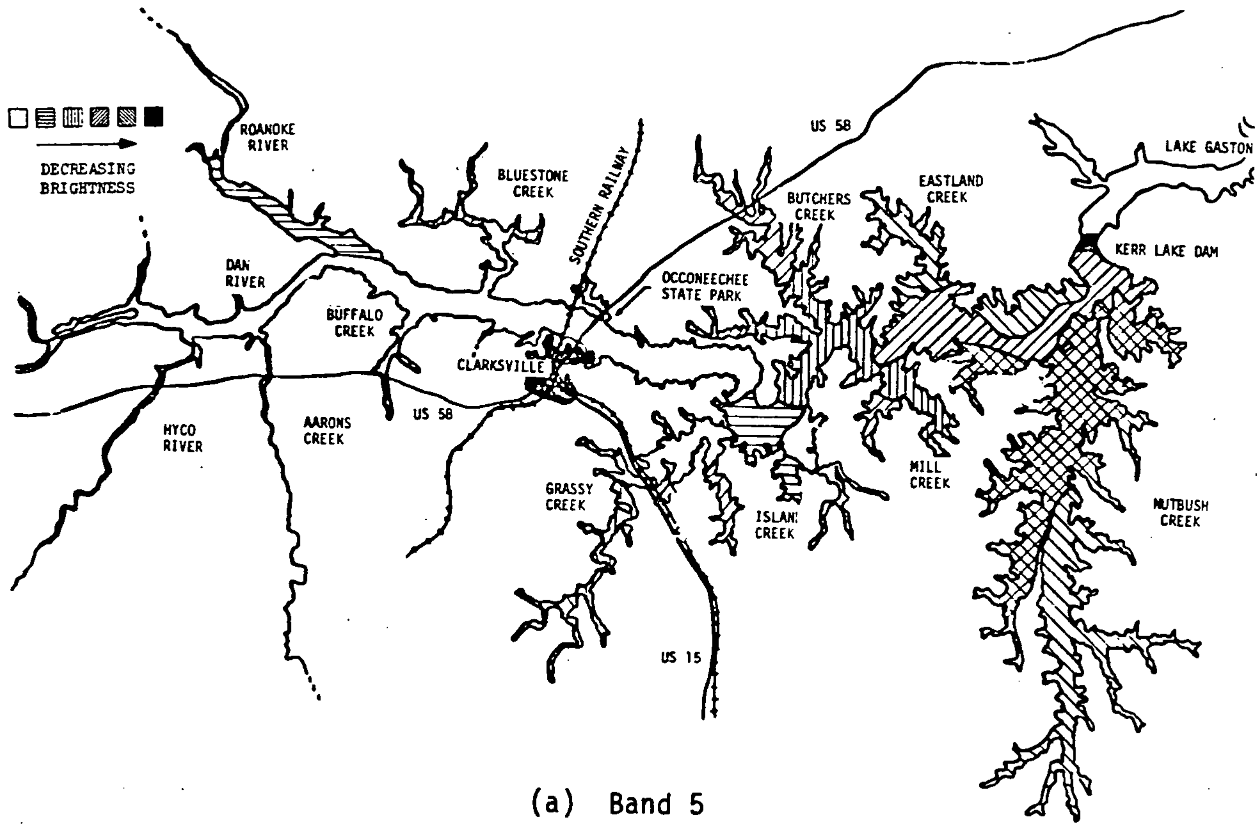


(a) Band 5

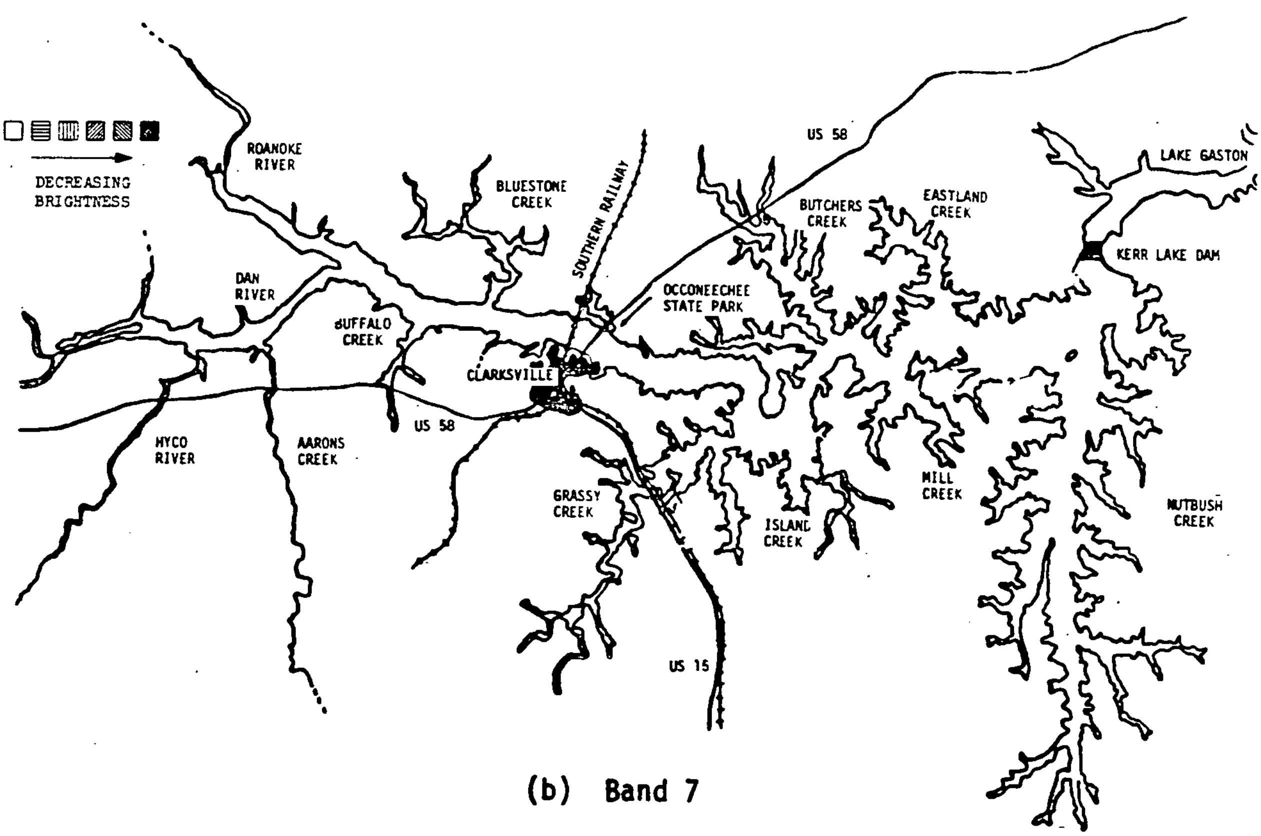


(b) Band 7

Figure 18. -Sketch of Landsat images of Kerr Lake for December 4, 1972.



(a) Band 5



(b) Band 7

Figure 19. -Sketch of Landsat images of Kerr Lake for October 11, 1972.

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16. Abstract
A historical analysis of the applicable Landsat imagery was conducted on the circulation and turbidity patterns of Kerr Lake, located on the Virginia-North Carolina border. By examining the seasonal and regional turbidity and circulation patterns, a record of sediment transport and possible disposition can be obtained. Sketches were generated from the suitable imagery, displaying different intensities of brightness observed in bands 5 and 7 of Landsat's multispectral scanner data. Differences in and between bands 5 and 7 indicate variances in the levels of surface sediment concentrations. High sediment loads are revealed when distinct patterns appear in the band 7 imagery. Additionally, the upwelled signal is exponential in nature and saturates in band 5 at low wavelengths for large concentrations of suspended solids.

17. Key Words (Suggested by Author(s))
Kerr Lake, Landsat, Multispectral Scanner, Turbidity, Sediment, Circulation

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