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KERR RESERVOIR LANDSAT EXPERIMENT ANALYSIS

FOR MARCH 1981

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SUMMARY

An experiment was conducted on the waters of Kerr Reservoir to determine if reliable algorithms could be developed that relate water quality parameters to remotely sensed data. Landsat radiance data was used in the analysis since it is readily available and covers the area of interest on a regular basis. By properly designing the experiment, many of the unwanted variations due to atmosphere, solar, and hydraulic changes were minimized. The algorithms developed were constrained to satisfy rigorous statistical criteria before they could be considered dependable in predicting water quality parameters. A mix of different types of algorithms using the Landsat bands was generated to provide a thorough understanding of the relationships among the data involved. Except for secchi depth, the study demonstrated that for the ranges measured, the algorithms that satisfactorily represented the data encompass a mix of linear and nonlinear forms using only one Landsat band. Ratioing techniques did not improve the results since the initial design of the experiment minimized the errors against which this procedure is effective. Good correlations were found for total suspended solids, iron, turbidity, and secchi depth. Marginal correlations were discovered for nitrate and tannin + lignin. Quantification maps of Kerr Reservoir are presented for many of the water quality parameters using the developed algorithms.

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1.0 INTRODUCTION

The purpose of this report is to demonstrate a practical and economical approach for the quantification of inland bodies of water through the use of remotely sensed data. Classification procedures are needed to evaluate conservation practices, to measure sediments and pollutants, and to aid in verifying rainfall-runoff models of large drainage basins. This study was performed in support of the AgRISTARS (Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing) program which is a joint venture of NASA and USDA. The multispectral scanners onboard the Landsat satellites are ideally suited as a monitoring tool inasmuch as they furnish valuable synoptic information over most areas of the world on a regular schedule. Past studies, such as references 1 and 2, have shown that the radiance data measured by Landsat can be statistically related to water quality parameters and the algorithms developed can then be used to quantify the total water system under investigation. The advantage of statistical regression analysis is that a finite number of samples can be used to quantify the entire system. Hence, algorithms can be developed by which the dynamics of the total system can be understood. The source, movement, and fate of each pollutant can be traced and the characteristics of the system thus obtained can be used for future conservation measures and possible remedial actions. The regression techniques makes available an important tool in understanding environmental problems and providing inputs for management of these problems.

The use of regression analysis requires that careful attention be observed in data reduction, calibration, and the interpretation of the results. The sample sites need to be accurately located in order to match the Landsat coordinates with the ground truth coordinates, and to also ensure that all possible ranges of the water quality variables are covered. Delay times between the passing of the satellite and the taking of the water sample should be reduced to a minimum to reduce the effects of hydraulic, atmospheric, and solar variations. Due to noise and some uncertainties in location and time, smoothing is necessary, but it should be kept to a minimum to avoid losing the local character of the data and biasing the regression results. Observance of statistical criteria relating to goodness of fit, such as given in reference 3, should be closely followed if the results are to be meaningful. Several procedures have to be completed if the resulting algorithms are to be portable. First, the effects of the atmosphere have to be removed or

accounted for in the data reduction process. Second, the variations in the solar zenith angle should be normalized or accounted for in the data reduction process. Finally, the data should be referenced to some known level to minimize variations in sensors, electronics, and data reduction procedures that are carried out in converting the electronic signals to data tape products.

The experimental analysis are performed on data obtained from Kerr Reservoir, located on the Virginia-North Carolina border, and from Landsat data tapes for March 26, 1981. Data handling and calibration tactics are reviewed and the resulting data examined in some detail. The criteria for statistical significance are covered and applied to the data used in this report. Contour plots displaying the regression products are surveyed for different areas of Kerr Reservoir.

2.0 GROUND TRUTH MEASUREMENTS

Past Landsat scenes, visual observations, and the results of previous testing were used to establish the location of the sample stations. Results of studies given in reference 4 help pinpoint possible problem areas and sources of pollutants entering the lake. The sample sites were chosen to include these problem areas and also were selected in an effort to evenly space the data between the extremes for a more accurate statistical representation. Final corrections were then made to align the sites with prominent Landsat landmarks so that accurate determination of the sample stations could be carried out on the Landsat data scene. The location of the sample stations are shown in figure 1. Due to unavoidable delays, the actual water samples were not taken until four hours after the overpass of the Landsat satellite, however, since the flow in the reservoir was at a minimum, it is felt that the effects on most of the regression analysis would be negligible.

The water samples were analyzed for ten constituents plus turbidity and are presented in figure 2 as a function of distance from the dam. Secchi depth was obtained at the time of the original sample and is included with the rest of the data. The data is presented as occurring in either Nutbush Creek, a branch of the lake, or in the main reservoir itself. Numbers shown on the plots correspond to the sample sites as given in figure 1. Total suspended solids (TSS), nitrate, tannin + lignin, and turbidity follow the same pattern in Kerr Reservoir. These constituents show a high concentration at the mouth of Dan River, decrease to a low value at the bridges near Clarksville, increase to another high value near Monteparvo Peninsula, and then gradually decline in intensity toward the dam. Chlorophyll a has nearly the opposite pattern; it has a high value at the mouth of the Dan River, drops to a low concentration at the Buffalo Creek sample station, rises to a high level at the bridges at Clarksville, declines in value until the Monteparvo Peninsula sample station, and then gradually increases in magnitude toward the dam. Inorganic suspended solids (ISS) reveal a maximum value at the mouth of Dan River and then drop rapidly to a minimum quantity at the Bluestone Creek sample station, and thereafter increase slowly toward the dam. Iron displays a high concentration at the Dan River station, a relative high value at the Bluestone Creek station, and slowly decreases all the way to the dam. Total organic carbon (TOC) and dissolved organic carbon (DOC) disclose the same characteristics; these constituents have relative low values at the Dan River

Station, increase to a maximum level at the Buffalo Creek station, decline to a minimum level at either the Bluestone Creek or bridge stations, and then increase in value toward the dam. Particular organic carbon (POC) does not display much variation between the Dan River and Monteparvo Peninsula stations, but shows a sharp increase between Monteparvo Peninsula and the dam. Values for TSS, turbidity, tannin + lignin, iron, chlorophyll a, and DOC are less in Nutbush Creek than anywhere else in Kerr Reservoir. The magnitudes of ISS, TOC, and DOC in Nutbush Creek are less than the values near the dam but greater than values near the bridges at Clarksville or Bluestone Creek. The values for nitrate are higher in Nutbush Creek than at the dam station, and are also higher at the bridges at Clarksville. The water in Nutbush Creek is very clear as disclosed by the high secchi depth numbers.

To show the relationship between the samples taken, correlation coefficients were computed and are presented in table 1. The correlation matrix is symmetric with ones on the diagonal and has values ranging from minus one to plus one. The closer the values are to plus or minus one, the more the variables are related. The table reveals a high correlation among TSS, iron, turbidity, tannin + lignin and secchi depth while little correlation is revealed with chlorophyll a, nitrate, TOC, POC and DOC. There is a high correlation shown between TSS and ISS, and also between TOC and DOC. An inverse relationship is evident between secchi depth and the other parameters.

3.0 LANDSAT MEASUREMENTS

The Landsat radiance data is located on tapes in the form of counts and has to be extracted, smoothed, radiometrically calibrated, and adjusted to account for atmospheric and solar effects. By triangulating the water sample sites with recognizable Landsat landmarks, the stations were quickly and accurately located on the Landsat data tapes. Orbit eccentricities resulted in the sample station 8, located in the middle of Nutbush Creek, to be 1.3 kilometers off the bottom of the Landsat scene and, thus, no radiance data is available for this site. The radiance data for the other sample sites for all four Landsat bands were extracted from the tapes and hand smoothed to eliminate system noise. Smoothing also helps to minimize uncertainties due to inexact location of the sites and delay times in sampling. The data has to be smoothed by hand also to ensure that no hydraulic boundaries are crossed and, thus, giving erroneous results. Past studies have shown that between 9 to 16 pixels have to be averaged about the sample site to effectively eliminate the contributions due to noise. Correlation results were improved slightly by using 16 pixels in the average, so the final values will reflect this number.

Several calibration techniques have to be performed on the data to reduce the effects due to atmosphere, solar, and system variabilities. Using the constants given in reference 5, the data tape counts were first calibrated to radiance units. Dark object subtraction, division by the cosine of the solar zenith angle, and statistical normalization were used on the data to eliminate the atmospheric, solar, and system effects. However, these calibration methods did not improve the regression results of this study and were not incorporated in the final radiance data. Since the spatial and time variations in this data set were small, atmospheric and solar differences did not significantly influence the data. Also, the atmosphere was visually clear and the wind was minimal on this date. Ratioing techniques will be used in a later section of this report to reduce the effects of any solar and atmospheric variations in the data. The smooth surface conditions of the water and a solar zenith angle of 46 degrees resulted in no sunglint problems. The corrected radiance data for both Kerr Reservoir and Nutbush Creek are shown in figure 3 as a function of distance from the dam. The radiance data for bands 4 through 6 show a maximum value at the Dan River sample station, decrease to a low value at either Buffalo Creek or the bridges at Clarksville, increase to a high

value at Monteparvo Peninsula, and then decline to a low value at the dam. Except for a slight increase at the Bluestone Creek station, the radiance values of band 7 diminishes from the mouth of Dan River all the way to the dam. There is a slight increase in radiance value for the band 4 data in Nutbush Creek, but the other 3 Landsat bands display a slight decrease in their radiance values from the station located at the mouth of Nutbush Creek.

4.0 STATISTICAL ANALYSIS AND REGRESSION STRATEGY

Algorithms have to be found that reliably couple the water quality parameters to Landsat radiance data. These algorithms not only have to satisfy the least squares criteria, but certain statistical constraints as well. To determine the best relationship, both linear and nonlinear algorithms have to be investigated and the algorithm coefficients need to be specified by the least squares principle. To decide if the resulting equation is statistically significant, certain coefficients from the data are computed and compared against previously determined standards. Multiple linear correlating techniques are used not only to determine the best combination of bands, but to get a feel for the relationships among all the bands. It is often very informative to know which combinations of bands are good and bad in their comparison to the water quality parameters. Sometimes the connections between variables can better be described by a nonlinear algorithm. Nonlinearity is checked by using algorithms in the form of quadratics, exponentials, logs, inverse linear, and inverse quadratics. The effects of atmospheric and solar variations within the data can often be minimized by defining new pseudo bands composed of ratios of Landsat bands. References 1 and 6 found that forming new independent variables composed of simple ratios of Landsat bands improved the correlation of water quality parameters with Landsat bands. To reduce the atmospheric and solar interferences even further, references 7 and 8 formed new pseudo independent variables by ratioing the ratios themselves.

Various methods have been developed to determine whether an algorithm will be capable of predicting the independent variables. The coefficients described in reference 3 will be used in deciding the merits of the algorithms developed in the regression process. These coefficients are called regression precision coefficients and are briefly summarized as follows:

R^2 - This dimensionless number between zero and one is the regression coefficient squared and is known as the coefficient of determination. Multiplied by 100, it gives the percentage of the total variation explained or accounted for by the regression algorithm.

SE - This coefficient is known as the standard error and is one standard deviation of the water quality parameters about the fitted regression algorithm. It is given in units of the water quality parameter.

$(F/F_{cr})_{0.95}$ - This dimensionless coefficient determines the significance of the regression algorithm for the 95 percent confidence level. The algorithm is considered significant if the ratio is large, in particular, if the ratio is above 4.

(Cp/p) - This dimensionless coefficient is known as Mallows statistic (p equal to the number of unknowns in the algorithm) and is used to decide if certain combinations of bands bias the results. The coefficient was designed to equal one with all the bands in the regression, but noisy data can drive the values below one and even below zero.

If the developed algorithm simultaneously gives a high R^2, a low SE, a $(F/F_{cr})_{0.95}$ greater than 4, and a Cp/p near 1, then a high degree of confidence can be placed in the algorithm. These coefficients collectively determine whether the data is biased, noisy, or not significant. If one or more of the precision coefficients are not satisfied, then the algorithm should either be discarded or used very judiciously. Noisy data should be carefully checked out, since in a multiple band algorithm its effects are greatly exaggerated. Nonlinear algorithms should also be checked for local maximums or minimums that are not characteristic of the data but are a consequence of forcing the data to fit a certain style of algorithm.

5.0 RESULTS AND DISCUSSION

The results of the linear, nonlinear, and ratio regression procedures for each of the water quality parameters are shown in table 2 as a function of their regression precision coefficients. All the linear and simple ratio combinations are presented to show the influence of all the band combinations. Only the double ratios that were shown to be effective in references 7 and 8 are listed in this table, and these ratios are presented in their simplest form. Only the best result for each band of the nonlinear algorithms is displayed. Since the ratios and nonlinear algorithms only have one resultant band in the regression, their Cp/p will be equal to one. An algorithm that provides confidence in successfully relating the water quality parameters with Landsat data requires jointly a high value of R^2, a low value of SE, a value of $(F/F_{cr})_{0.95}$ greater than 4, and a Cp/p near 1.

Table 2a reveals that 76 percent of the variation in TSS can be accounted for by using the linear algorithm for band 7, 80 percent by using the linear algorithm for bands 4 and 7, and 81 percent by using the linear algorithm that involves all four bands. The values of $(F/F_{cr})_{0.95}$ are low for the all the linear cases and Cp/p does not offer any help since all the numbers are less than one. All the ratio combinations yield unacceptable coefficients. Because of the small geographical variation between station locations (35 km maximum), the small variations between sample times (1 hour maximum difference between the first and last sample time), and a visually clear sky, the solar and atmospheric variations in the radiance signals are probably negligible. Also, division of noisy data greatly amplifies the original errors so that the resultant error is greater than the bias errors caused by changes in the intervening atmosphere and solar position. Examining the nonlinear algorithms reveals that by using an inverse linear fit for band 6, 95 percent of the variation in TSS can be accounted for. This algorithm also gives a SE of only 1.15 mg/l and a $(F/F_{cr})_{0.95}$ of 13.44. A contour map displaying levels of TSS using the nonlinear (inverse linear) algorithm for band 6 is shown in figure 4 for the Dan River area of Kerr Reservoir. This map reveals an interesting fact about the reservoir in that the flow out of the Dan River has much higher sediment loads than the Roanoke River, in this case twice as much. The flow from the Dan River remains on the southwestern shore for a distance and dissipates by the time it reaches the Buffalo Creek region. These types of maps using

radiance data are probably not accurate near the shore because of the radiance effects of the bottom and the nearby land.

The precision coefficients for ISS are shown in table 2b and disclose low values for all combinations of bands. Using all four bands in a linear association produces a R^2 of 0.65, but results in a $(F/F_{cr})_{0.95}$ of only 0.05. The data in the table demonstrates that there is no apparent relationship between this particular constituent and the radiance values. Examination of the ISS curve in figure 2b confirms that it is unlike any of the radiance data shown in figure 3.

The values of the coefficients in table 2c for chlorophyll a are lower than the coefficients for ISS for most combinations of the Landsat bands. The all band linear combination accounts for 71 percent of the variation in the data, but it would not be a reliable algorithm since $(F/F_{cr})_{0.95}$ is only equal to 0.06. One of the double ratios has the best selection of coefficients of all the algorithms, but they are still too low for an adequate representation. Comparison of the chlorophyll a curve in figure 2c with the radiance curves in figure 3 does not uncover any types of relationships.

The iron precision coefficients presented in table 2d display acceptable values for many of the band associations, in particular for the linear multiband combinations. The linear and the quadratic algorithms using band 7 have by far the best resultant mixture of all the coefficients. Use of the simpler linear band 7 algorithm is preferred since it is not as sensitive to unwanted variations in the data. The ratio coefficients indicate that the algorithms connected with these forms would not adequately describe the water constituent. Figure 5 shows a contour map using the linear band 7 algorithm displaying levels of iron concentrations near Monteparvo Peninsula in Kerr Reservoir. Although figure 2d shows that higher levels of iron are near the mouth of Dan River, the contour map reveals a high concentration of iron at the first 90° bend near the upstream side of Monteparvo Peninsula. This is one of the benefits of this type of analysis, in that sources and local concentrations are revealed which are not readily discovered by a sampling program.

Turbidity, whose coefficients are shown in table 2e, seems to correlate well with any combination of the Landsat bands, with the exception of the different

mixtures involving band ratios. The linear combination of bands 4 and 6 would be satisfactory as well as the quadratic algorithms for bands 5 or 6. It is always preferred to use single bands since multiband results tend to be noisier. In addition, the algorithm that produces the least standard error should be chosen when there are several possibilities. The classification of a section of Kerr Reservoir near Clarksville using the band 6 quadratic algorithm is displayed in figure 6. Turbidity is reasonably constant in this region except for two areas. High values are evident in the area near Bluestone Creek and at the bridge causeways near Clarksville.

Table 2f discloses the precision coefficients for nitrate and establishes that there are some high values for R^2 but insufficient values for $(F/F_{cr})_{0.95}$ and Cp/p. The table does not contain any values of $(F/F_{cr})_{0.95}$ greater than four and the Cp/p values are much greater than one. The ratio coefficients are much worse than the linear and nonlinear coefficients. The best of all the algorithms is probably the band 4 inverse linear form, since it involves only one band. Its value for $(F/F_{cr})_{0.95}$ of 3.01 is a little low and the resulting algorithm should be used with care. A contour map using this algorithm is shown in figure 7 for the region of Kerr Reservoir upstream of Monteparvo Peninsula. The quantification seems reasonable and corresponds with the history given in figure 2f. High values of nitrate are disclosed on the north shore on the upstream side of the Monteparvo Peninsula and at the mouth of Grassy Creek.

The best algorithm for tannin + lignin is either the band 6 linear or quadratic form as given in table 2g. Adding other bands or ratioing the bands did not improve the total precision coefficients. Negative values for Cp/p indicate that the data is slightly noisy which is probably caused by the large drop in magnitude at the Clarksville bridges, as shown in figure 2g. Although higher values of R^2 and $(F/F_{cr})_{0.95}$ are preferred for maximum confidence in the algorithm, a contour map of tannin + lignin was generated using the linear form. This map, shown in figure 8, illustrates the classification of tannin + lignin near Eastland Creek on Kerr Reservoir. The concentrations seem reasonable and agreed with the numbers given in figure 2g. A gradual decrease in concentration is evident as the flow travels east towards the dam.

The organic carbon results, shown in tables 2h though 2j, does not indicate any kind of correlation with the Landsat bands. All the coefficients for TOC, POC, and DOC are low, except the SE, which illustrates that the constituents could have been approximated just as well by their averages as with the Landsat radiance data. Comparing the organic carbon data in figures 2h through 2j with the radiance data in figure 3, it looks as though the data might be inversely related, but there are too many dissimilarities for any concrete relationships.

Secchi depth can be described adequately by many combinations of the Landsat bands as indicated in table 2k. The linear band 6 or the quadratic band 5 algorithms give good combinations of all the precision coefficients. However, the 4/5 ratio gives the best blend of all the coefficients presented in the table. Using the algorithm for the band 4 to band 5 ratio, a contour map was generated for secchi depth for the region of Kerr Reservoir near Nutbush Creek. This map, shown in figure 9, displays many different patterns on the right side of the scene, which are caused by the flow backing-up in front of the dam, located just off the scene on the right. Generally, the values of secchi depth increases toward the dam and into Nutbush Creek.

6.0 CONCLUSIONS

Water constituents can be related to remotely sensed data if proper preparation is given to choosing the sample site and the sample time, the data reduction and calibration procedures, and the results constrained to satisfy rigorous statistical criteria. Sample stations need to be selected so that all ranges of the water quality parameters are present and are evenly distributed throughout their ranges. The time differences between the taking of the sample and passing of the remote sensing vehicle needs to be reduced to a minimum to eliminate hydraulic, atmospheric, and solar variations. Data reduction and calibration techniques have to be universal so that consistent results are obtained. Proper interpolation of statistical parameters and their comparison with established statistical norms are necessary in order to place any reliance on the regression outcomes.

The experiment has proven that good correlation exists between TSS, iron, turbidity, and secchi depth and the remotely sensed data of Landsat. Only marginal correlations were shown between nitrate and tannin + lignin and the Landsat bands. No correlation could be found between ISS, chlorophyll a, TOC, POC, and DOC and the bands of Landsat. The best relationship between the water quality parameters and the Landsat bands represent a combination of linear and nonlinear algorithms. The simple and double ratioing techniques used to minimize the solar and atmospheric variations did not improve the results because of the small spatial and temporal variations in the data.

This experiment has also proven that the Landsat bands can be coupled to water constituents under rigid conditions. It has given an insight into the types of algorithms and wavelengths needed for correlating water constituents to remotely sensed data. It has demonstrated a method by which localized accumulations and sources of pollution can be detected that could be easily missed by conventional sampling techniques. The results of this experiment are only effective over the ranges of the data measured for this study. Other data ranges could produce different types of algorithms using different bands. Although portability was not found to be neessary for this investigation, the effects of solar angle and atmosphere have to be accounted for, and some reference has to be established for data calibration.

REFERENCES

1. Boland, D. H. P.; and Blackwell, Richard J.: The Landsat-1 Multispectral Scanner as a Tool in the Classification of Inland Lakes. NASA Earth Resources Survey Symposium. Volume I-A: Technical Session Presentations-Agriculture, Environment, pp. 419-442, June 1975.

2. Thoreson, Brian D.; Moore, Donald G.; and Haertel, Lois: Remote Sensing of Water Quality in Prairie Lakes. Remote Sensing Institute Report SDSU-RSI-75-12, South Dakota State Univ., 1975.

3. Whitlock, Charles H.; Kuo, Chin Y.; and LeCroy, Stuart R.: Criteria for the Use of Regression Analysis for Remote Sensing of Sediment and Pollutants. Remote Sensing of Environment, vol. 12, no. 2, pp. 151-168, 1982.

4. LeCroy, Stuart R.: Determination of Circulation and Turbidity Patterns in Kerr Lake from Landsat MSS Imagery. NASA CR 165830, 1981.

5. Landsat Newsletter. Missions Utilization Office, Goddard Space Flight Center, no. 15, June 1977.

6. Yarger, Harold L; and McCauley, James R.: Quantitative Water Quality with Landsat and Skylab. Proceedings of the NASA Earth Resources Survey Symposium. Volume I-A: Technical Session Presentations-Agriculture, Environment, pp. 347-370, June 1975.

7. Grew, G. W.: Real-Time Test of MOCS Algorithm During Superflux 1980. Chesapeake Bay Plume Study-Superflux 1980 Symposium. NASA Conference Publication 2188, January 1981.

8. Bowker, David E.; Hardesty, Charles A.; Jobson, Daniel J.; and Bahn, Gilbert S.: Analysis of Testbed Airborne Multispectral Scanner Data from Superflux II. Chesapeake Bay Plume Study-Superflux 1980 Symposium. NASA Conference Publication 2188, January 1981.

TABLE 1. - CORRELATION MATRIX FOR GROUND TRUTH MEASUREMENTS

Variable	TSS	ISS	Chlor *a*	Iron	Turbidity	Nitrate	Tann + Lign	TOC	POC	DOC	Secchi D.
TSS	1.00	.88	.04	.87	.92	.56	.79	.46	-.08	.11	-.81
ISS	.88	1.00	-.20	.64	.68	.43	.47	.54	-.12	.13	-.48
Chlor *a*	.04	-.20	1.00	.06	.10	-.01	.13	-.25	.40	-.33	-.20
Iron	.87	.64	.06	1.00	.89	.39	.80	.14	-.19	-.11	-.88
Turbidity	.92	.68	.10	.89	1.00	.71	.85	.26	-.23	.02	-.91
Nitrate	.56	.43	-.01	.39	.71	1.00	.44	.00	-.36	-.12	-.43
Tann + Lign	.79	.47	.13	.80	.85	.44	1.00	.45	.19	.35	-.89
TOC	.46	.54	-.25	.14	.26	.00	.45	1.00	.35	.89	-.29
POC	-.08	-.12	.40	-.19	-.23	-.36	.19	.35	1.00	.40	.14
DOC	.11	.13	-.33	-.11	-.02	-.12	.35	.89	.40	1.00	-.14
Secchi D.	-.81	-.48	-.20	-.88	-.91	-.43	-.89	-.29	.14	-.14	1.00

TABLE 2. - REGRESSION PRECISION COEFFICIENTS ASSOCIATED WITH CORRELATING GROUND TRUTH DATA WITH LANDSAT DATA

(a) Total Suspended Solids

Bands Used	R^2	SE (mg/l)	$(F/F_{CR})_{0.95}$	Cp/p
4	.64	3.03	1.34	.39
5	.69	2.80	1.68	.12
6	.71	2.69	1.88	.00
7	.76	2.49	2.33	-.22
4,5	.70	2.76	.67	.72
4,6	.74	2.57	.82	.58
4,7	.80	2.27	1.13	.37
5,6	.72	2.69	.72	.66
5,7	.79	2.31	1.09	.40
6,7	.77	2.41	.97	.46
4,5,6	.76	2.48	.34	.88
4,5,7	.80	2.26	.43	.78
4,6,7	.80	2.27	.42	.78
5,6,7	.81	2.21	.45	.75
4,5,6,7	.81	2.20	.11	1.00
4/5	.55	3.39	.92	1.00
4/6	.43	3.79	.58	1.00
4/7	.29	4.24	.31	1.00
5/6	.34	4.09	.39	1.00
5/7	.24	4.38	.24	1.00
6/7	.13	4.70	.11	1.00
$5^2/4x6$	.57	3.31	.99	1.00
$6^2/5x7$	.04	4.93	.03	1.00
4*	.67	2.89	1.55	1.00
5#	.85	1.96	4.22	1.00
6#	.95	1.15	13.44	1.00
7†	.80	2.24	3.08	1.00

*Quadratic fit
#Inverse linear fit
†Exponential fit

TABLE 2. - CONTINUED

(b) Inorganic Suspended Solids

Bands Used	R^2	SE (mg/l)	$(F/F_{CR})_{0.95}$	Cp/p
4	.37	2.13	.44	.30
5	.32	2.22	.35	.44
6	.31	2.22	.34	.45
7	.47	1.95	.67	.00
4,5	.37	2.13	.17	.86
4,6	.37	2.12	.17	.85
4,7	.48	1.92	.27	.64
5,6	.32	2.21	.14	.95
5,7	.47	1.95	.26	.67
6,7	.50	1.90	.28	.62
4,5,6	.41	2.06	.08	1.09
4,5,7	.52	1.86	.12	.93
4,6,7	.56	1.78	.14	.88
5,6,7	.62	1.65	.18	.79
4,5,6,7	.65	1.59	.05	1.00
4/5	.18	2.43	.17	1.00
4/6	.12	2.52	.10	1.00
4/7	.19	2.42	.17	1.00
5/6	.16	2.45	.15	1.00
5/7	.04	2.62	.04	1.00
6/7	.00	2.68	.00	1.00
5^2/4x6	.23	2.36	.22	1.00
6^2/5x7	.20	2.40	.19	1.00
4+	.36	2.15	.42	1.00
5+	.28	2.28	.29	1.00
6+	.28	2.28	.29	1.00
7+	.44	2.01	.59	1.00

+Log fit

TABLE 2. - CONTINUED

(c) Chlorophyll a

Bands Used	R^2	SE (μg/l)	$(F/F_{CR})_{0.95}$	Cp/p
4	.04	4.02	.03	1.81
5	.00	4.10	.00	1.94
6	.00	4.10	.00	1.94
7	.07	3.96	.05	1.72
4,5	.18	3.71	.06	1.55
4,6	.13	3.82	.04	1.66
4,7	.07	3.96	.02	1.81
5,6	.02	4.07	.01	1.93
5,7	.18	3.72	.06	1.56
6,7	.38	3.23	.17	1.10
4,5,6	.20	3.67	.03	1.63
4,5,7	.36	3.29	.06	1.36
4,6,7	.51	2.87	.11	1.09
5,6,7	.64	2.45	.20	.86
4,5,6,7	.71	2.21	.06	1.00
4/5	.01	4.07	.01	1.00
4/6	.04	4.01	.03	1.00
4/7	.03	4.04	.02	1.00
5/6	.01	4.08	.01	1.00
5/7	.05	3.99	.04	1.00
6/7	.23	3.59	.23	1.00
5^2/4x6	.00	4.10	.00	1.00
6^2/5x7	.63	2.51	1.26	1.00
4+	.04	4.01	.03	1.00
5#	.02	4.05	.02	1.00
6#	.02	4.05	.02	1.00
7+	.06	3.97	.05	1.00

+Log fit
#Inverse linear fit

TABLE 2. - CONTINUED

(d) Iron

Bands Used	R^2	SE (mg/l)	$(F/F_{CR})_{0.95}$	Cp/p
4	.49	.19	.72	29.61
5	.67	.15	1.54	18.57
6	.83	.11	3.81	8.58
7	.96	.05	19.33	.78
4,5	.69	.15	.63	12.35
4,6	.85	.10	1.66	5.66
4,7	.97	.05	9.28	.89
5,6	.92	.07	3.58	2.69
5,7	.96	.05	7.42	1.18
6,7	.96	.05	7.92	1.09
4,5,6	.95	.06	2.14	1.71
4,5,7	.98	.04	5.34	.85
4,6,7	.98	.04	6.07	.78
5,6,7	.98	.04	6.19	.77
4,5,6,7	.98	.03	1.55	1.00
4/5	.68	.15	1.59	1.00
4/6	.72	.14	1.95	1.00
4/7	.67	.15	1.54	1.00
5/6	.19	.24	.18	1.00
5/7	.15	.25	.13	1.00
6/7	.11	.25	.09	1.00
5^2/4x6	.53	.18	.87	1.00
6^2/5x7	.00	.27	.00	1.00
4+	.50	.19	.74	1.00
5*	.68	.15	1.64	1.00
6*	.86	.10	4.48	1.00
7*	.96	.05	20.43	1.00

+Log fit
*Quadratic fit

TABLE 2. - CONTINUED

(e) Turbidity

Bands Used	R^2	SE (FTU)	$(F/F_{CR})_{0.95}$	Cp/p
4	.90	1.52	7.20	4.20
5	.92	1.38	8.88	3.21
6	.89	1.59	6.48	4.77
7	.79	2.24	2.87	11.02
4,5	.95	1.07	5.83	1.55
4,6	.98	.76	11.99	.61
4,7	.97	.90	8.29	1.01
5,6	.92	1.36	3.52	2.69
5,7	.95	1.14	5.09	1.81
6,7	.90	1.55	2.59	3.67
4,5,6	.98	.62	6.36	.75
4,5,7	.98	.73	4.71	.92
4,6,7	.98	.69	5.58	.82
5,6,7	.96	1.03	2.42	1.53
4,5,6,7	.98	.62	1.53	1.00
4/5	.74	2.51	2.15	1.00
4/6	.51	3.46	.77	1.00
4/7	.19	4.43	.17	1.00
5/6	.59	3.16	1.07	1.00
5/7	.50	3.49	.75	1.00
6/7	.31	4.07	.35	1.00
5^2/4x6	.80	2.21	2.98	1.00
6^2/5x7	.03	4.86	.02	1.00
4*	.90	1.52	7.15	1.00
5*	.95	1.07	15.18	1.00
6*	.96	.93	20.43	1.00
7*	.80	2.20	3.01	1.00

*Quadratic fit

TABLE 2. - CONTINUED

(f) Nitrate

Bands Used	R^2	SE (mg/l)	$(F/F_{CR})_{0.95}$	Cp/p
4	.75	.14	2.29	28.26
5	.41	.21	.53	69.28
6	.28	.23	.29	85.02
7	.20	.24	.19	94.39
4,5	.90	.08	2.75	7.25
4,6	.90	.09	2.49	7.98
4,7	.87	.10	1.90	10.21
5,6	.58	.18	.40	33.42
5,7	.44	.20	.22	44.81
6,7	.28	.23	.12	56.84
4,5,6	.91	.08	1.05	5.83
4,5,7	.93	.07	1.46	4.37
4,6,7	.90	.08	1.00	6.11
5,6,7	.64	.16	.19	22.16
4,5,6,7	.99	.02	3.09	1.00
4/5	.16	.25	.15	1.00
4/6	.02	.27	.01	1.00
4/7	.03	.27	.02	1.00
5/6	.55	.18	.93	1.00
5/7	.37	.22	.44	1.00
6/7	.15	.25	.13	1.00
$5^2/4x6$	.32	.22	.35	1.00
$6^2/5x7$	.14	.25	.13	1.00
4#	.89	.12	3.01	1.00
5†	.43	.21	.57	1.00
6†	.28	.23	.30	1.00
7*	.20	.24	.19	1.00

#Inverse linear fit
†Exponential fit
*Quadratic fit

TABLE 2. - CONTINUED

(g) Tannin and Lignin

Bands Used	R^2	SE (mg/l)	$(F/F_{CR})_{0.95}$	Cp/p
4	.50	.04	.75	.80
5	.68	.03	1.60	-.03
6	.76	.03	2.32	-.37
7	.62	.04	1.25	.23
4,5	.69	.03	.65	.60
4,6	.76	.03	.90	.41
4,7	.65	.04	.53	.75
5,6	.76	.03	.93	.39
5,7	.71	.03	.71	.55
6,7	.76	.03	.88	.42
4,5,6	.76	.03	.35	.79
4,5,7	.73	.03	.29	.88
4,6,7	.76	.03	.34	.81
5,6,7	.77	.03	.35	.78
4,5,6,7	.78	.03	.09	1.00
4/5	.69	.03	1.70	1.00
4/6	.67	.03	1.52	1.00
4/7	.29	.05	.31	1.00
5/6	.27	.05	.28	1.00
5/7	.35	.05	.41	1.00
6/7	.34	.05	.38	1.00
5^2/4x6	.60	.04	1.14	1.00
6^2/5x7	.03	.06	.02	1.00
4*	.52	.04	.81	1.00
5*	.69	.03	1.69	1.00
6*	.77	.03	2.57	1.00
7*	.73	.03	2.05	1.00

*Quadratic fit

TABLE 2. - CONTINUED

(h) Total Organic Carbon

Bands Used	R^2	SE (mg/l)	$(F/F_{CR})_{0.95}$	Cp/p
4	.03	1.11	.03	-.05
5	.06	1.09	.05	-.10
6	.04	1.11	.03	-.06
7	.03	1.11	.02	-.04
4,5	.08	1.09	.02	.59
4,6	.04	1.11	.01	.62
4,7	.03	1.11	.01	.63
5,6	.10	1.07	.03	.57
5,7	.07	1.09	.02	.60
6,7	.04	1.10	.01	.62
4,5,6	.16	1.03	.02	.88
4,5,7	.08	1.08	.01	.94
4,6,7	.04	1.10	.01	.97
5,6,7	.11	1.07	.01	.92
4,5,6,7	.33	.92	.01	1.00
4/5	.05	1.10	.04	1.00
4/6	.03	1.11	.02	1.00
4/7	.01	1.13	.00	1.00
5/6	.08	1.08	.06	1.00
5/7	.05	1.10	.04	1.00
6/7	.02	1.12	.02	1.00
5^2/4x6	.08	1.08	.07	1.00
6^2/5x7	.01	1.12	.01	1.00
4+	.03	1.10	.03	1.00
5+	.05	1.10	.04	1.00
6+	.04	1.10	.03	1.00
7+	.02	1.11	.02	1.00

+Log fit

TABLE 2. - CONTINUED

(i) Particulate Organic Carbon

Bands Used	R^2	SE (mg/l)	$(F/F_{CR})_{0.95}$	Cp/p
4	.37	.16	.45	-.27
5	.28	.17	.30	-.10
6	.21	.18	.20	.05
7	.20	.18	.19	.06
4,5	.37	.16	.17	.48
4,6	.38	.16	.18	.47
4,7	.37	.16	.17	.49
5,6	.36	.16	.16	.50
5,7	.28	.17	.12	.60
6,7	.22	.18	.08	.69
4,5,6	.39	.15	.07	.84
4,5,7	.37	.16	.06	.86
4,6,7	.39	.15	.07	.85
5,6,7	.48	.14	.10	.76
4,5,6,7	.49	.14	.02	1.00
4/5	.18	.18	.16	1.00
4/6	.03	.19	.03	1.00
4/7	.01	.20	.00	1.00
5/6	.40	.15	.51	1.00
5/7	.20	.18	.18	1.00
6/7	.04	.19	.04	1.00
$5^2/4x6$	.28	.17	.30	1.00
$6^2/5x7$	.25	.17	.26	1.00
4†	.39	.15	.48	1.00
5+	.28	.17	.30	1.00
6+	.19	.18	.18	1.00
7+	.21	.18	.20	1.00

†Exponential fit
+Log fit

TABLE 2. - CONTINUED

(j) Dissolved Organic Carbon

Bands Used	R^2	SE (mg/l)	$(F/F_{CR})_{0.95}$	Cp/p
4	.00	.89	.00	-.15
5	.00	.89	.00	-.15
6	.00	.89	.00	-.15
7	.01	.89	.01	-.16
4,5	.01	.89	.00	.56
4,6	.00	.89	.00	.57
4,7	.02	.88	.01	.55
5,6	.08	.86	.03	.50
5,7	.06	.88	.02	.52
6,7	.03	.88	.01	.54
4,5,6	.18	.81	.02	.81
4,5,7	.07	.86	.01	.88
4,6,7	.03	.88	.00	.90
5,6,7	.08	.86	.01	.87
4,5,6,7	.26	.77	.01	1.00
4/5	.00	.89	.00	1.00
4/6	.00	.89	.00	1.00
4/7	.02	.89	.01	1.00
5/6	.03	.88	.02	1.00
5/7	.02	.89	.01	1.00
6/7	.01	.89	.01	1.00
5^2/4x6	.01	.89	.01	1.00
6^2/5x7	.00	.89	.00	1.00
4#	.00	.89	.00	1.00
5#	.00	.89	.00	1.00
6#	.00	.89	.00	1.00
7+	.01	.89	.01	1.00

#Inverse linear fit
+Log fit

TABLE 2. - CONCLUDED

(k) Secchi Depth

Bands Used	R^2	SE (mg/l)	$(F/F_{CR})_{0.95}$	Cp/p
4	.61	23.30	1.20	77.66
5	.93	10.10	9.66	13.39
6	.96	7.46	17.91	6.81
7	.71	20.33	1.81	58.88
4,5	.99	3.35	32.13	.88
4,6	.97	6.88	8.17	4.32
4,7	.75	18.67	.87	33.55
5,6	.96	7.46	7.17	4.94
5,7	.93	9.82	3.91	9.06
6,7	.98	5.79	11.51	3.00
4,5,6	.99	2.90	19.88	.80
4,5,7	1.00	2.37	21.88	.75
4,6,7	.98	5.02	5.90	2.09
5,6,7	.98	5.79	4.43	2.68
4,5,6,7	1.00	2.37	5.30	1.00
4/5	.99	3.74	75.03	1.00
4/6	.83	15.53	3.64	1.00
4/7	.30	31.36	.32	1.00
5/6	.51	26.15	.80	1.00
5/7	.60	23.58	1.15	1.00
6/7	.54	25.28	.90	1.00
5^2/4x6	.92	10.23	9.38	1.00
6^2/5x7	.02	37.08	.02	1.00
4*	.73	19.37	2.07	1.00
5*	.98	5.01	41.43	1.00
6*	.97	6.02	28.51	1.00
7$	.93	9.69	10.55	1.00

*Quadratic fit
$Inverse quadratic fit

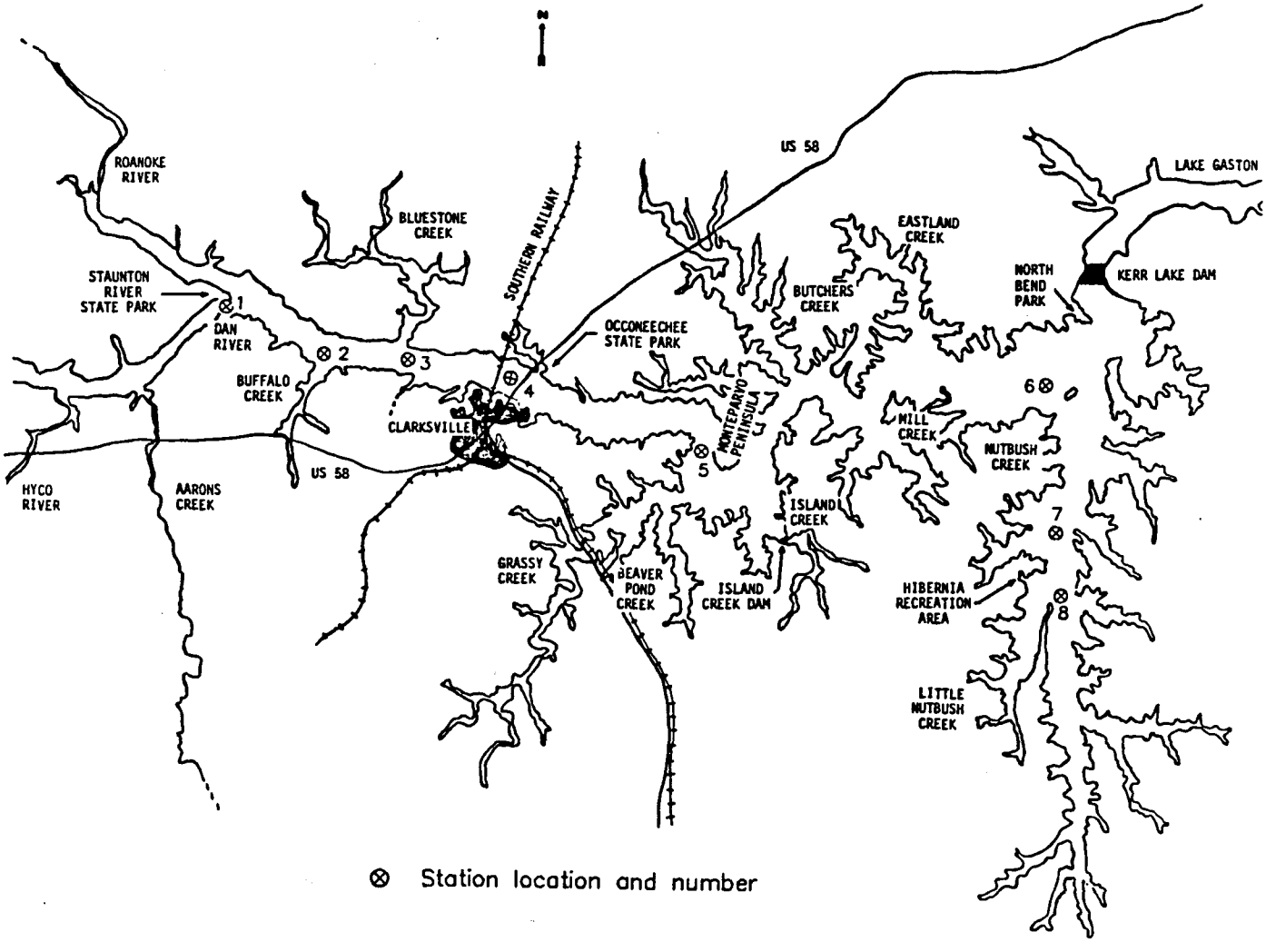
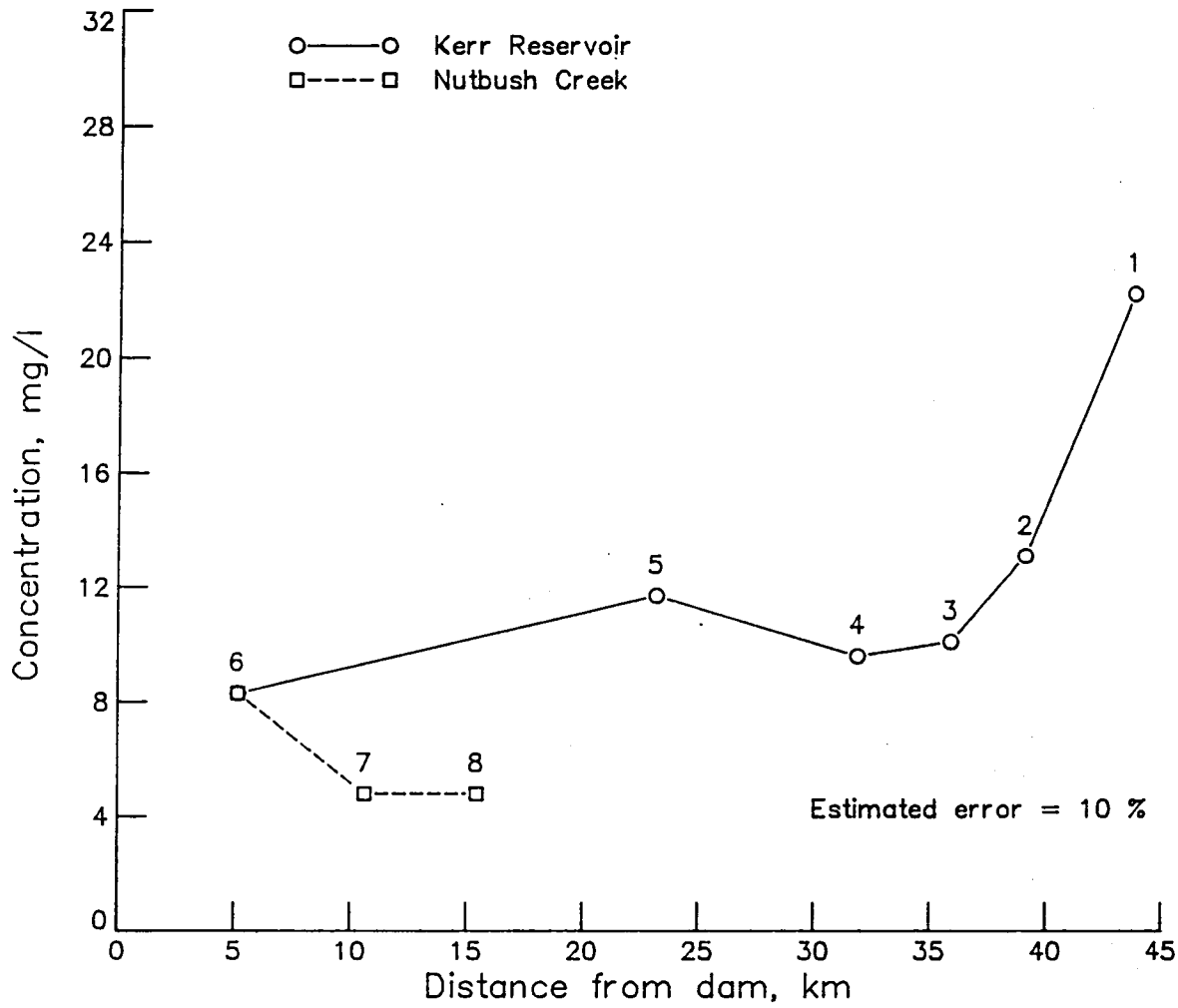
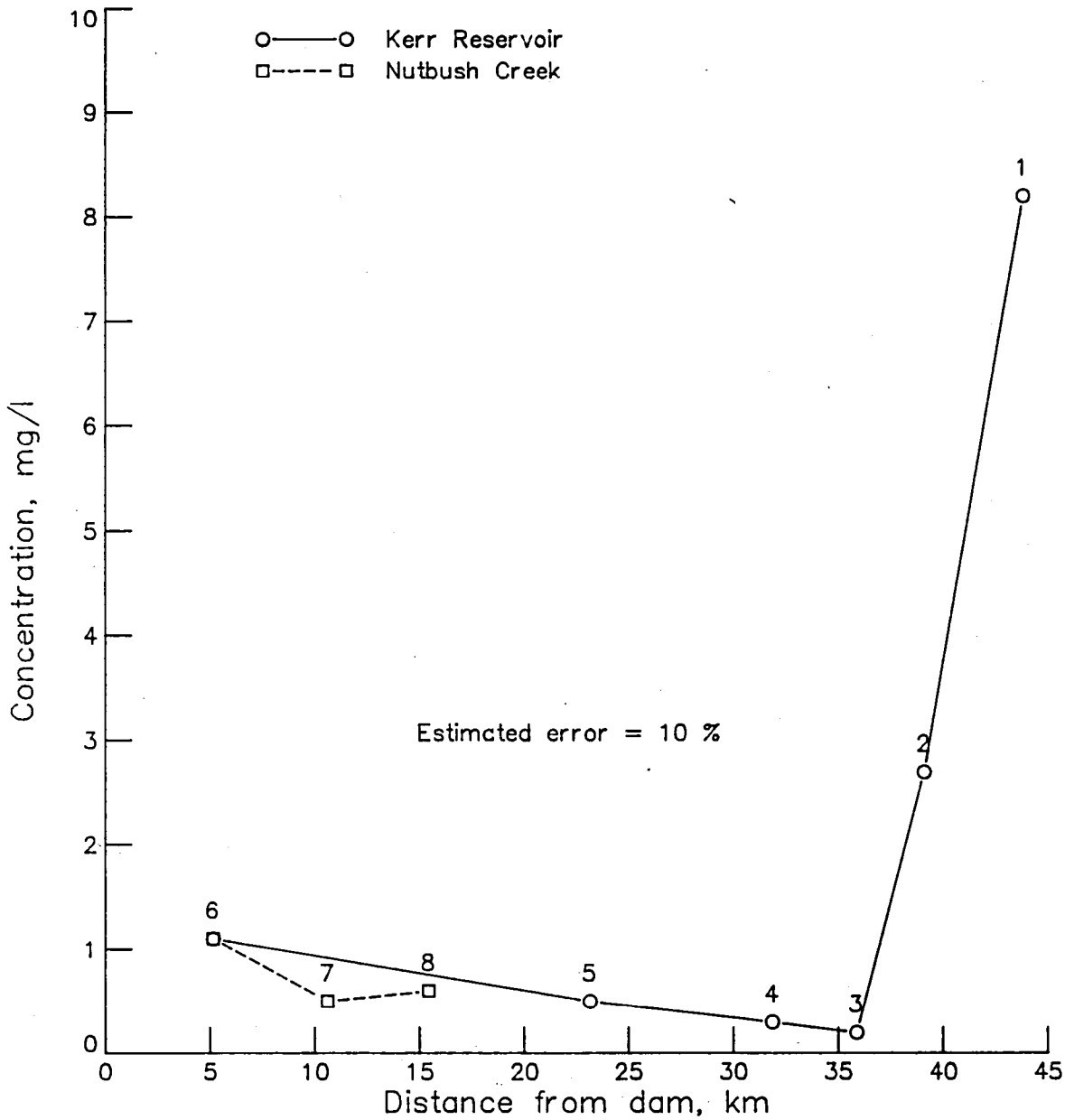


Figure 1.- Location of sample stations



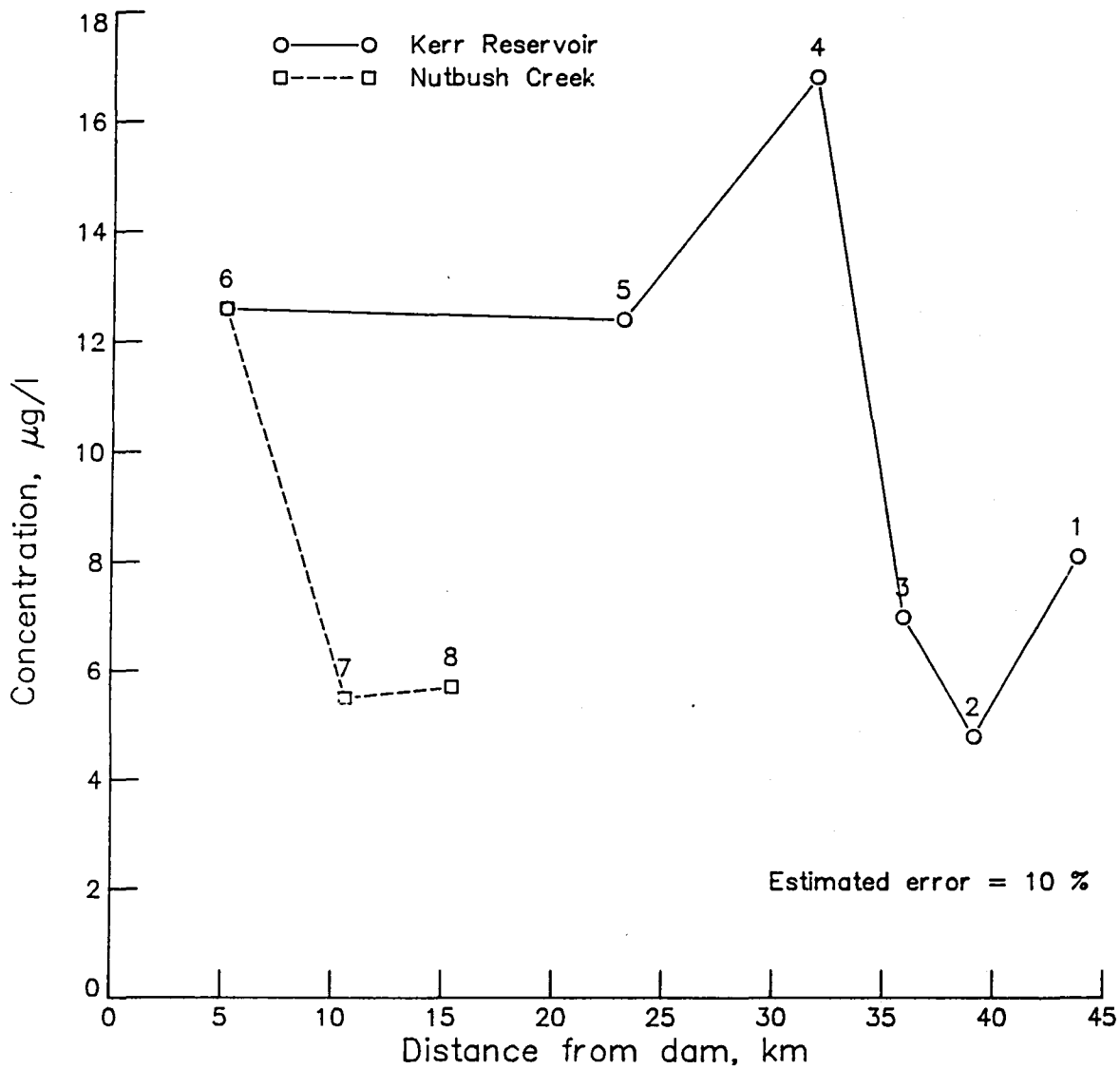
(a) Total suspended solids

Figure 2.- Water quality measurements taken from Kerr Reservoir on March 26, 1981.



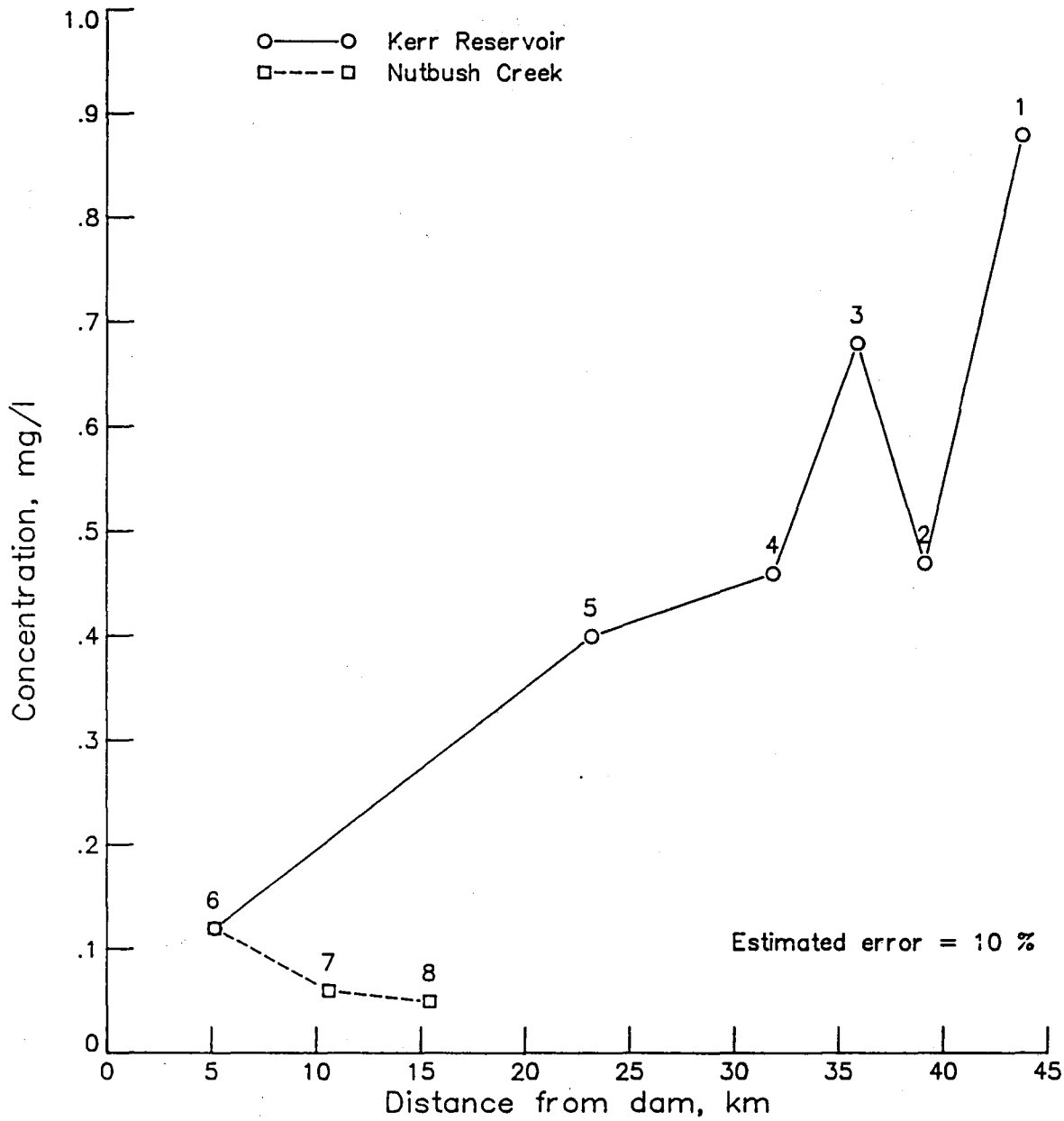
(b) Inorganic suspended solids

Figure 2.- Continued.



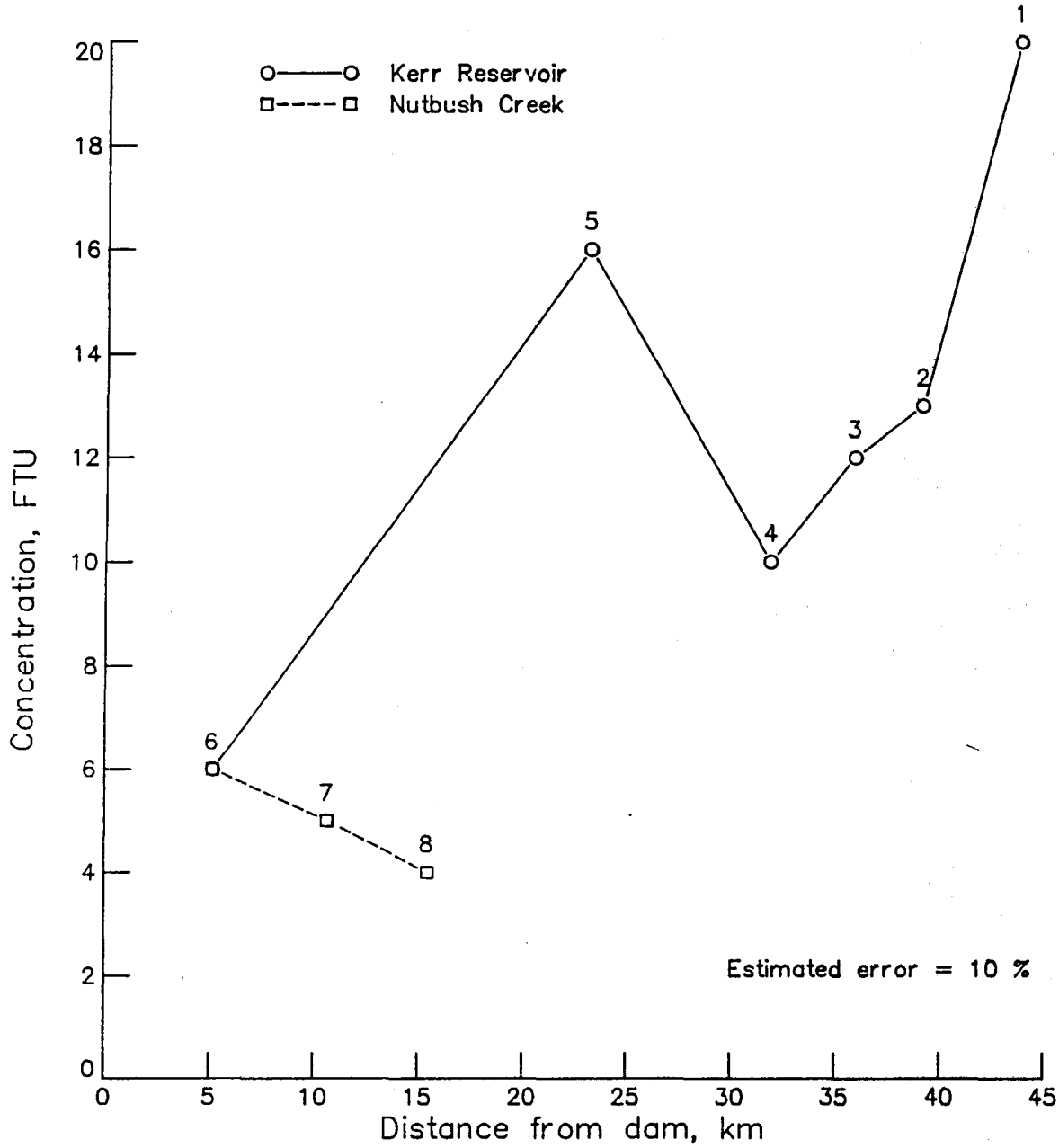
(c) Chlorophyll a

Figure 2.- Continued.



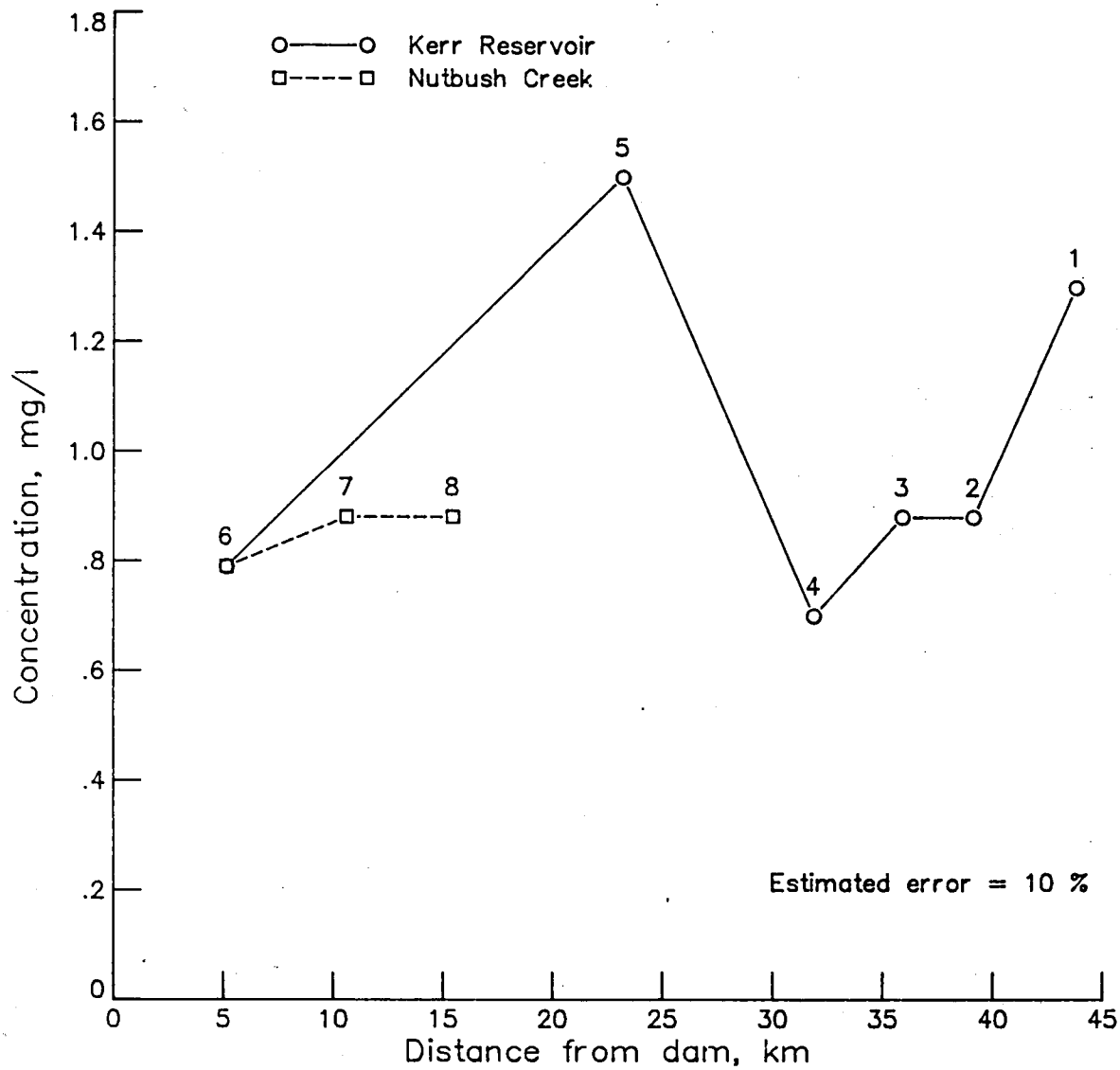
(d) Iron

Figure 2.- Continued.



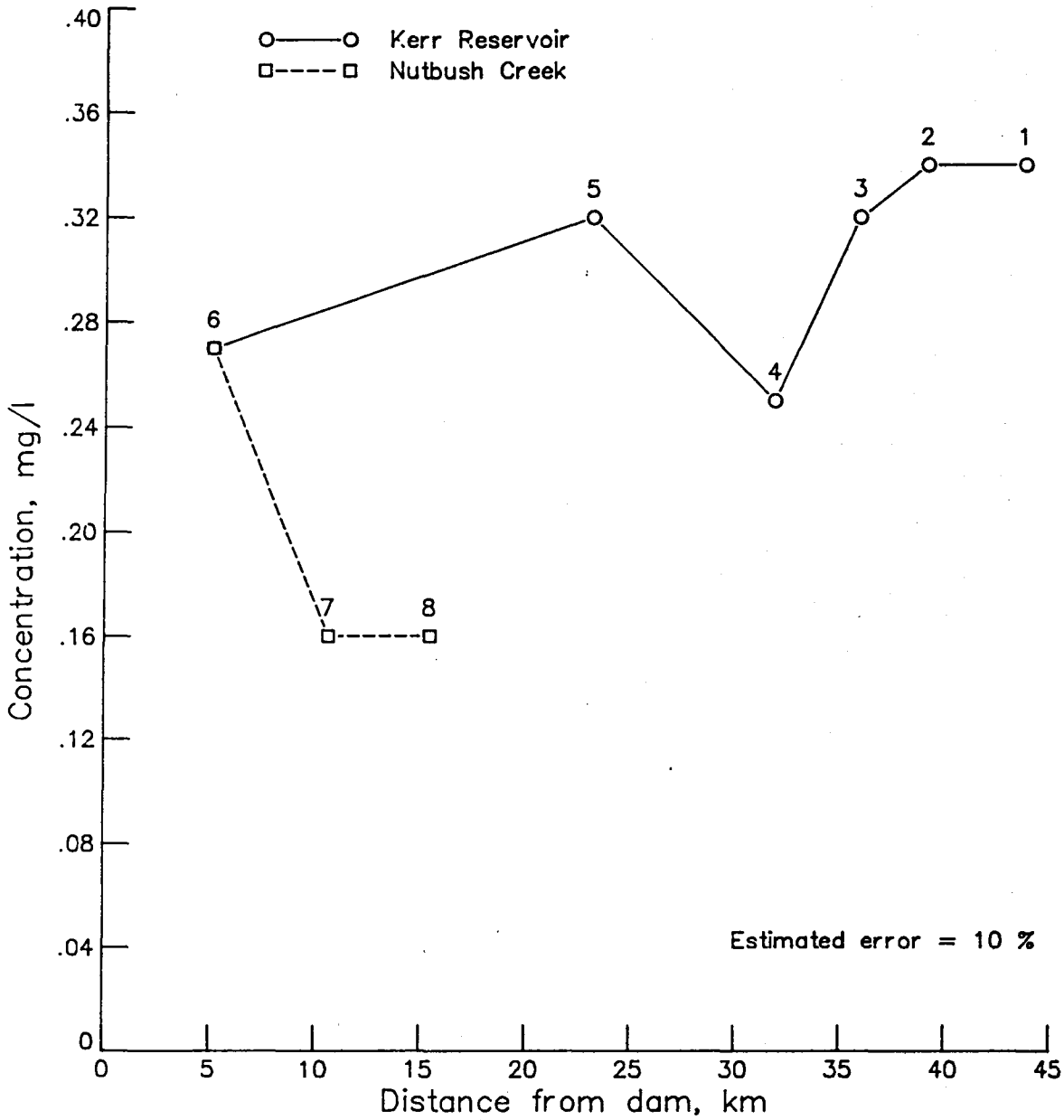
(e) Turbidity

Figure 2.- Continued.



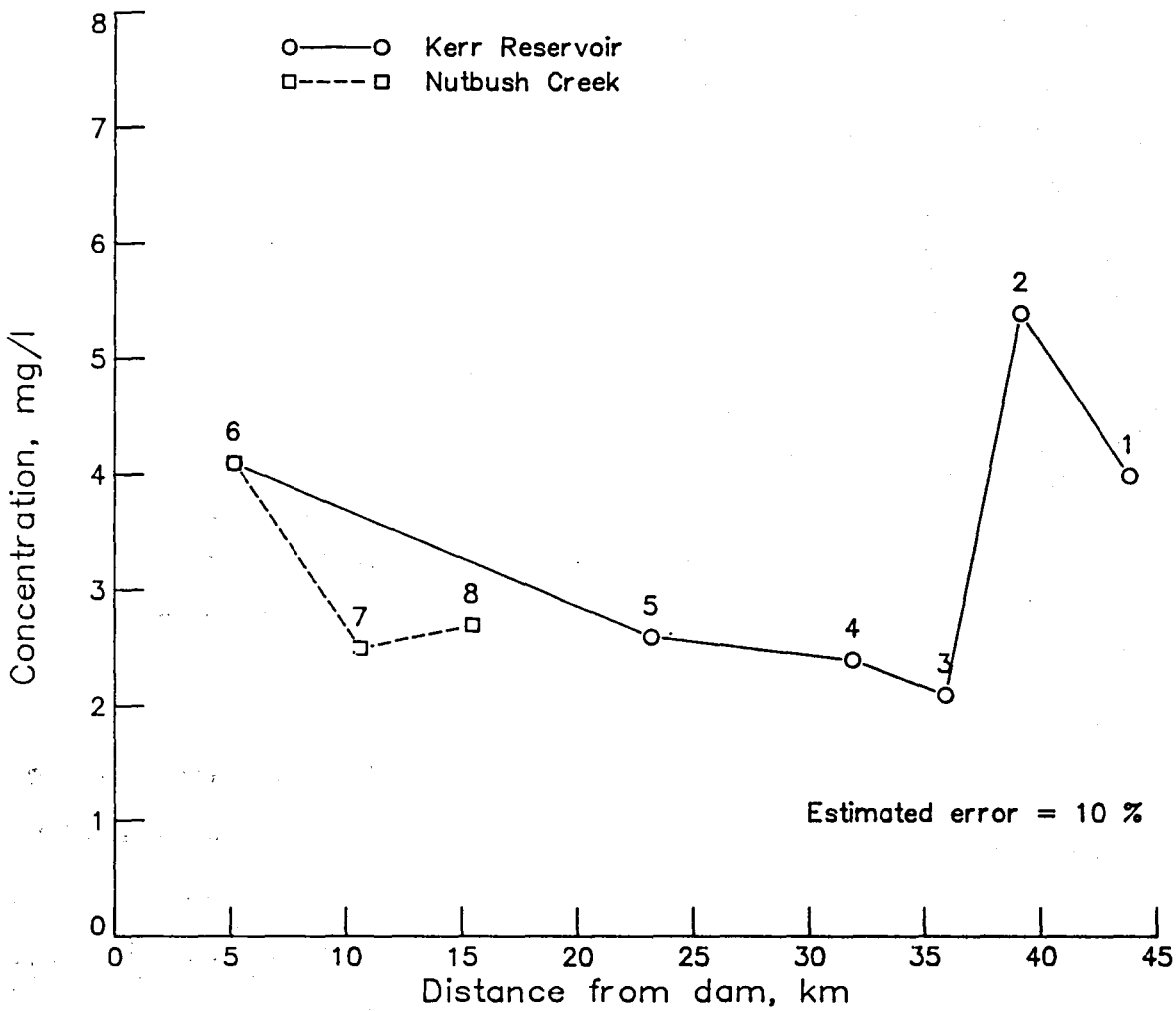
(f) Nitrate

Figure 2.- Continued.



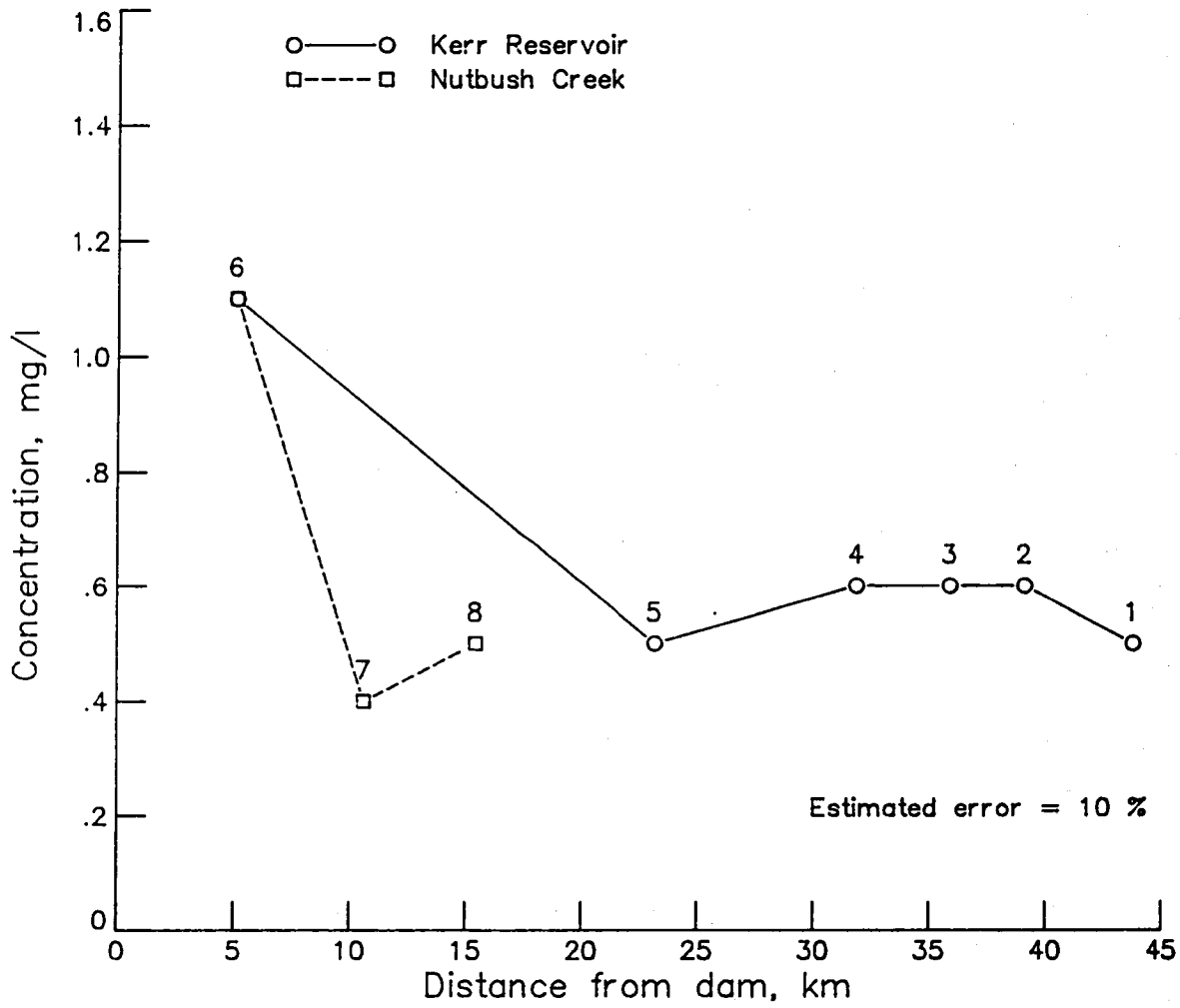
(g) Tannin + lignin

Figure 2.- Continued.



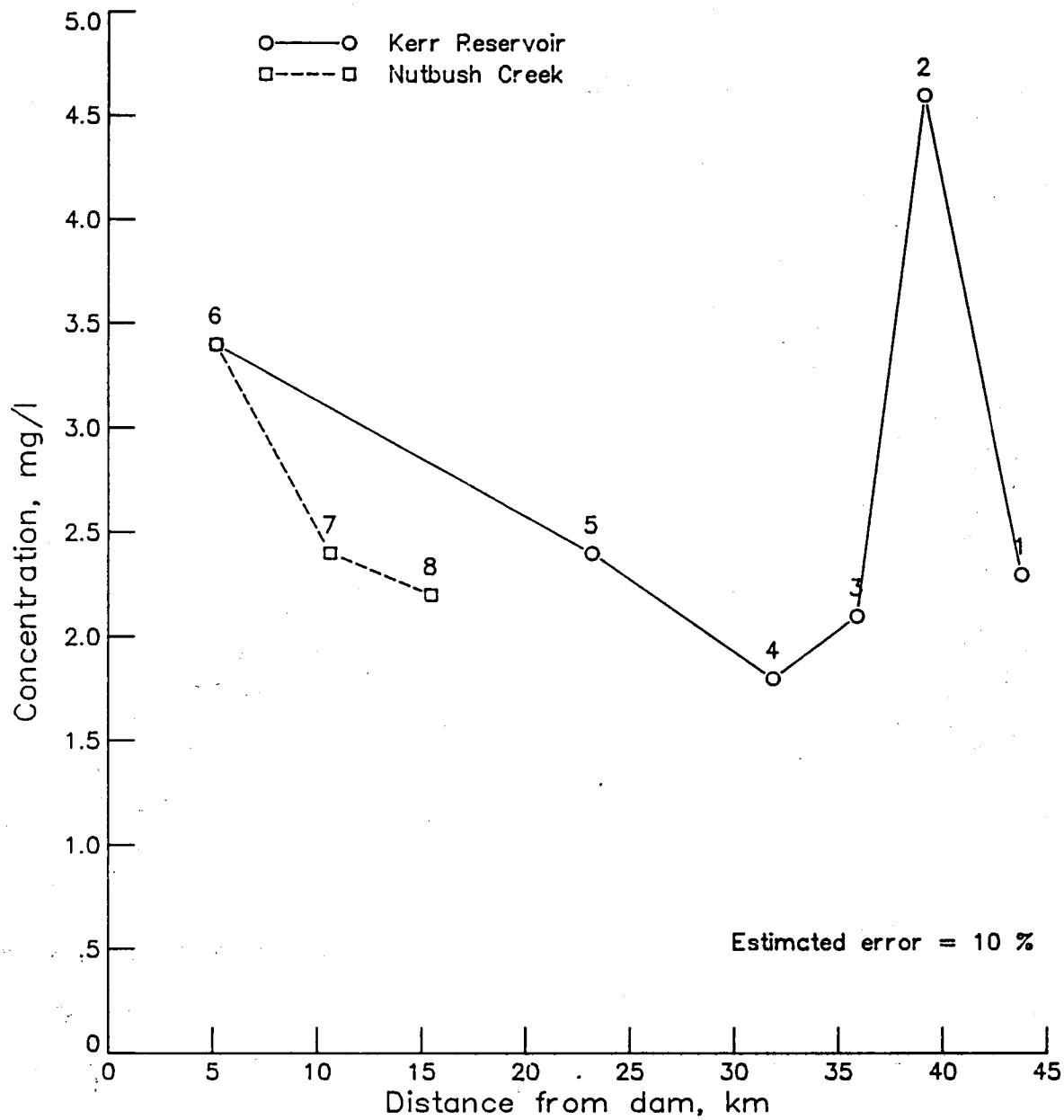
(h) Total organic carbon

Figure 2.- Continued.



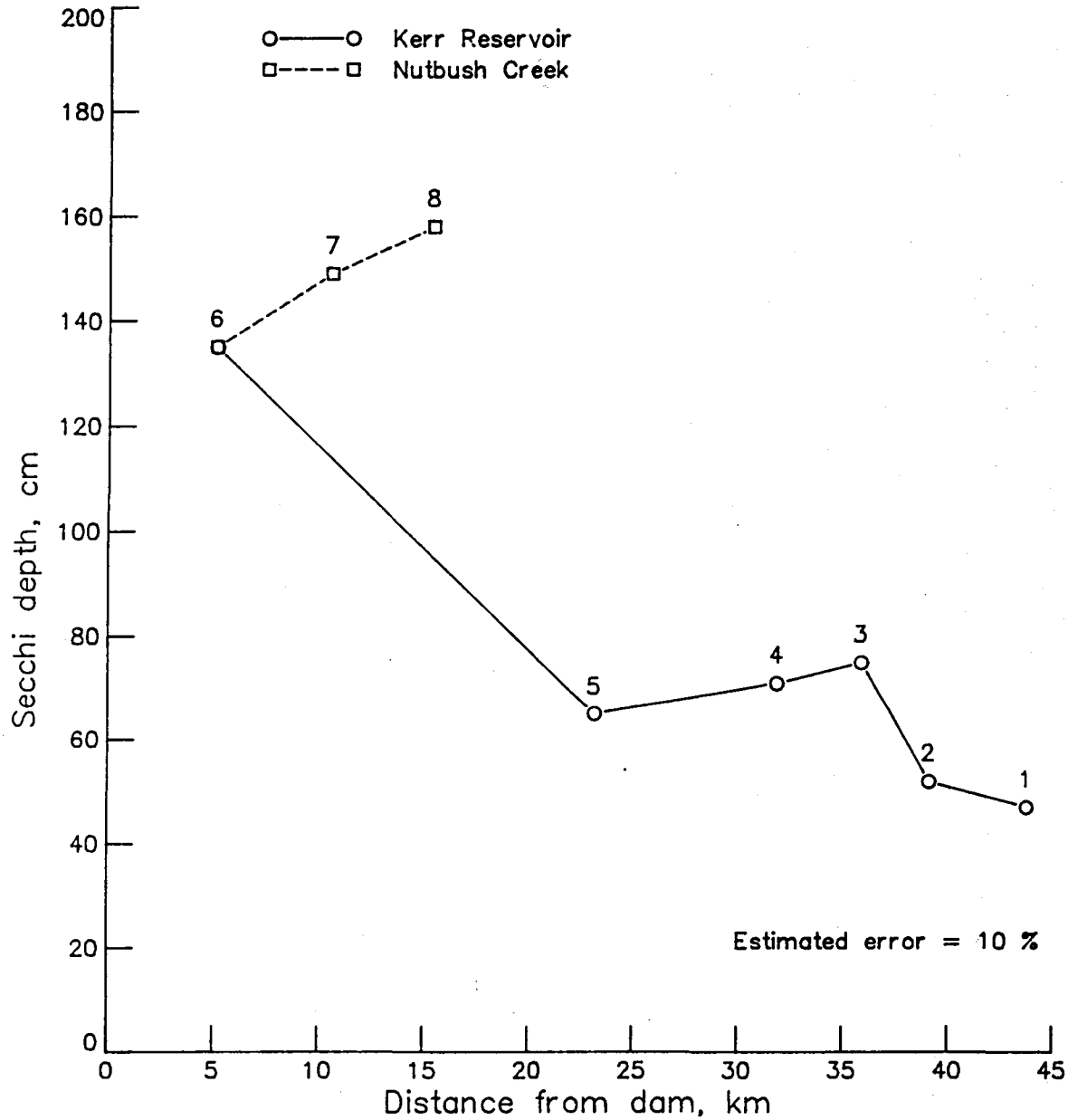
(i) Particulate organic carbon

Figure 2.- Continued.



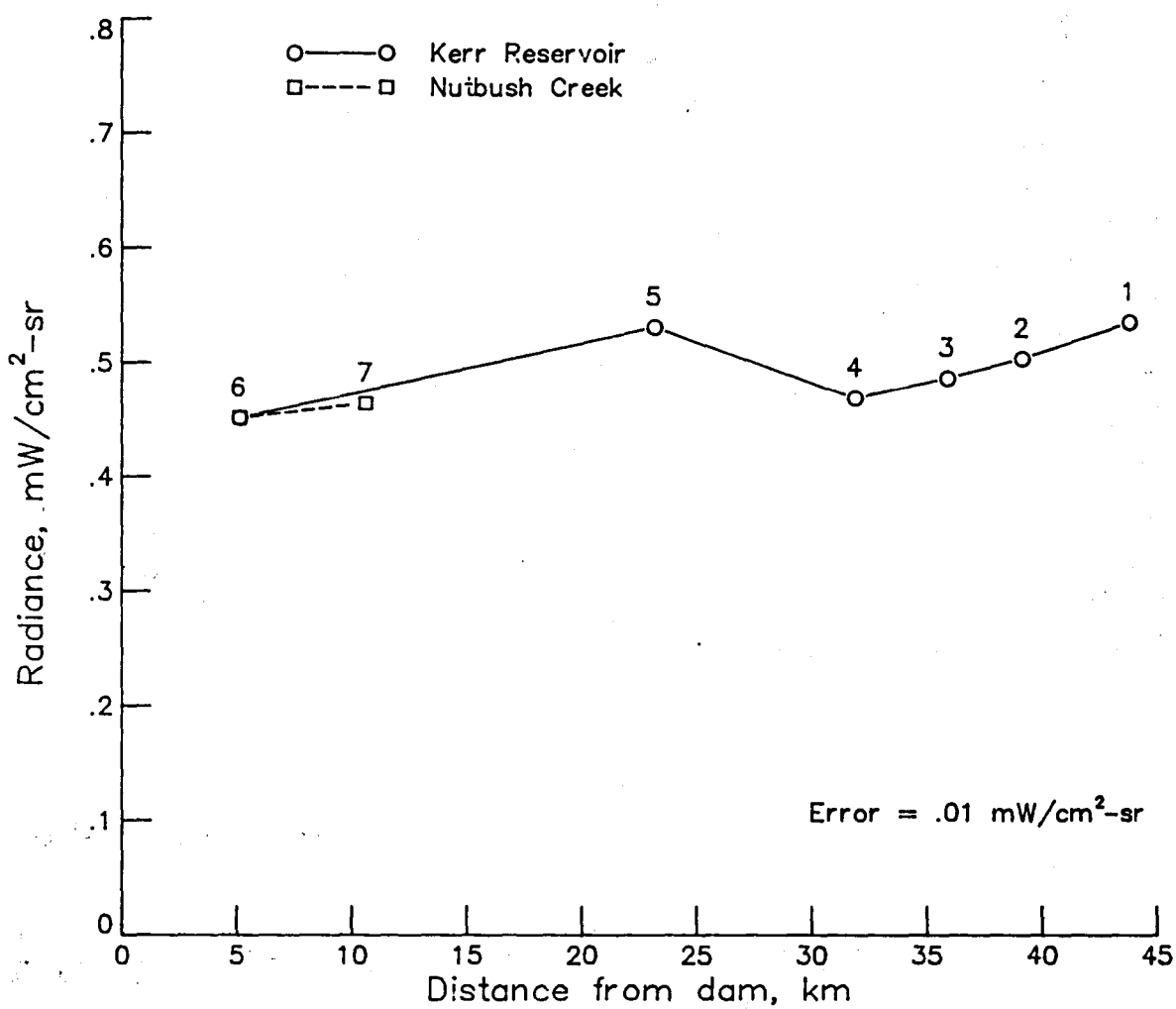
(j) Dissolved organic carbon

Figure 2.- Continued.



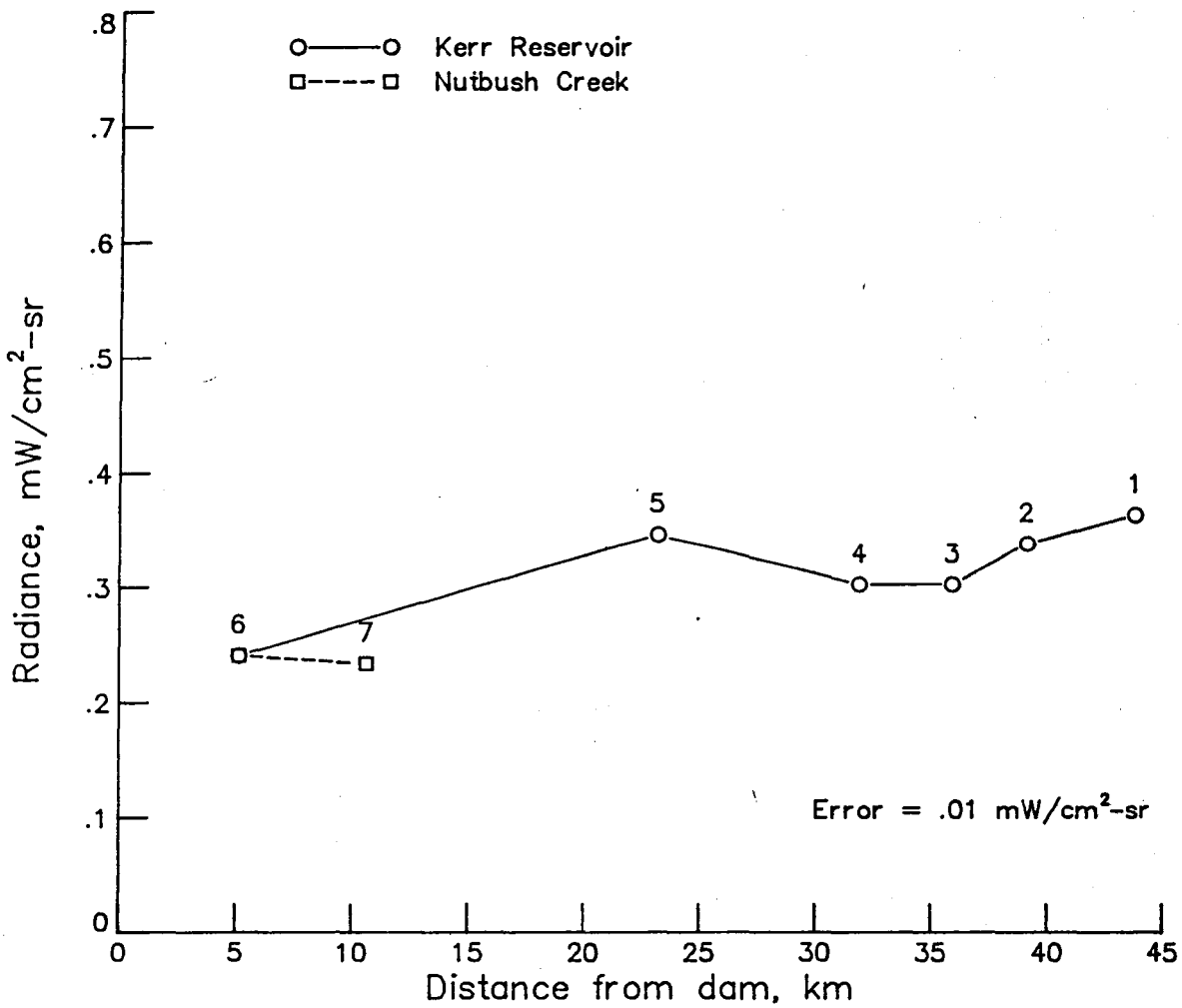
(k) Secchi depth

Figure 2.- Concluded.



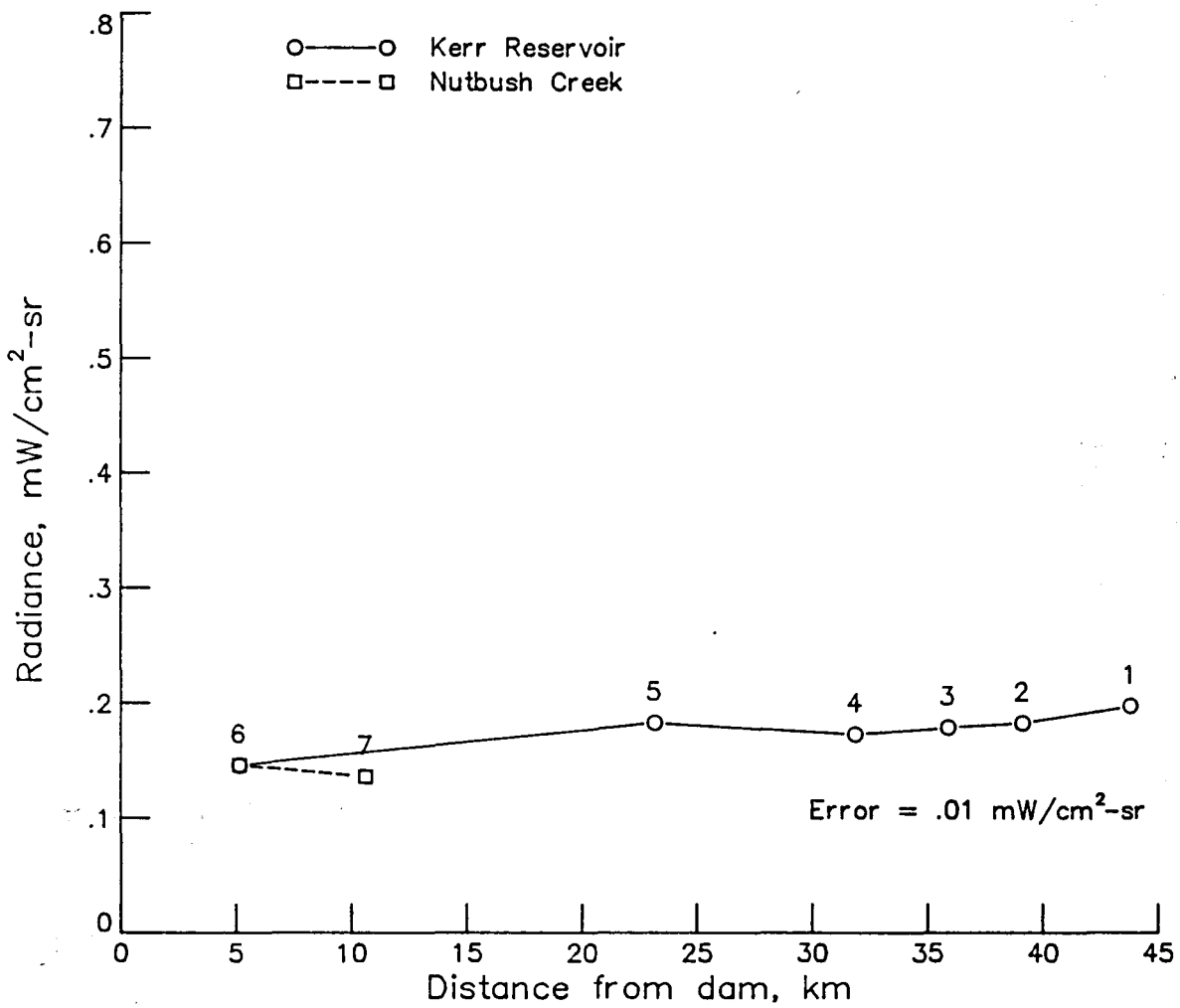
(a) Band 4

Figure 3.- Landsat radiances of Kerr Reservoir on March 26, 1981.



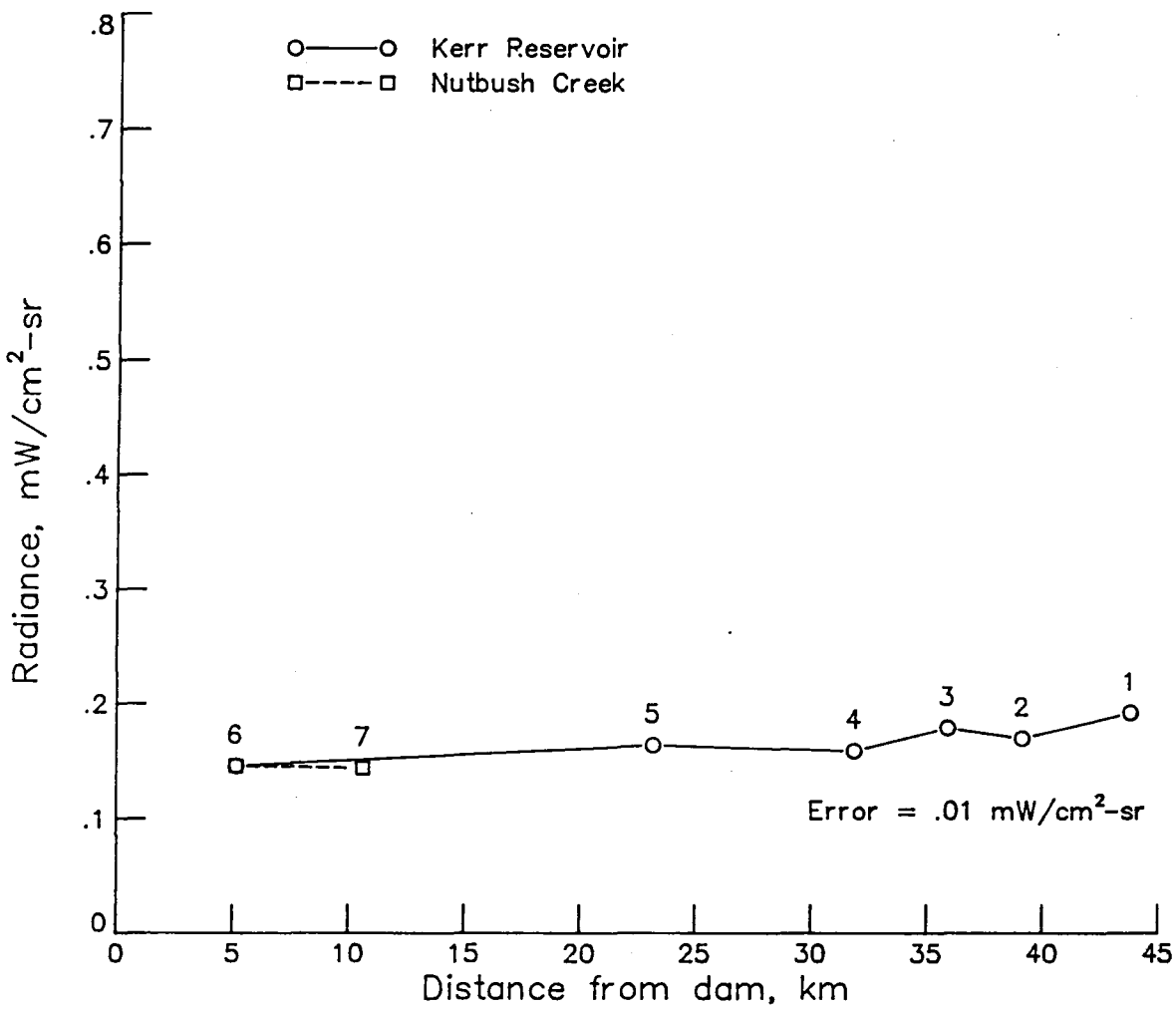
(b) Band 5

Figure 3. -Continued.



(c) Band 6

Figure 3. -Continued.



(d) Band 7

Figure 3. -Concluded.

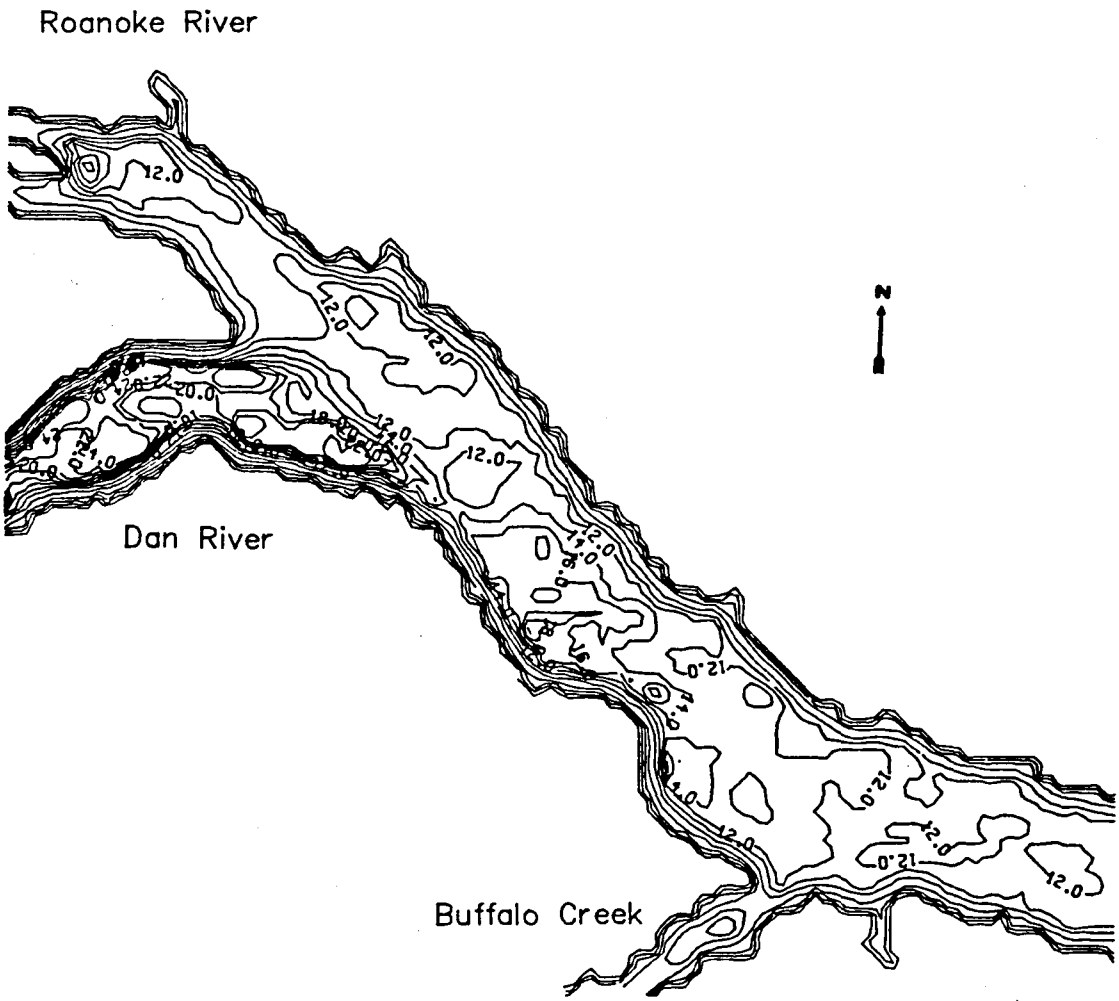


Figure 4.- Contour map for total suspended solids (mg/l) near the mouth of Dan River on Kerr Reservoir using Landsat's band 6.

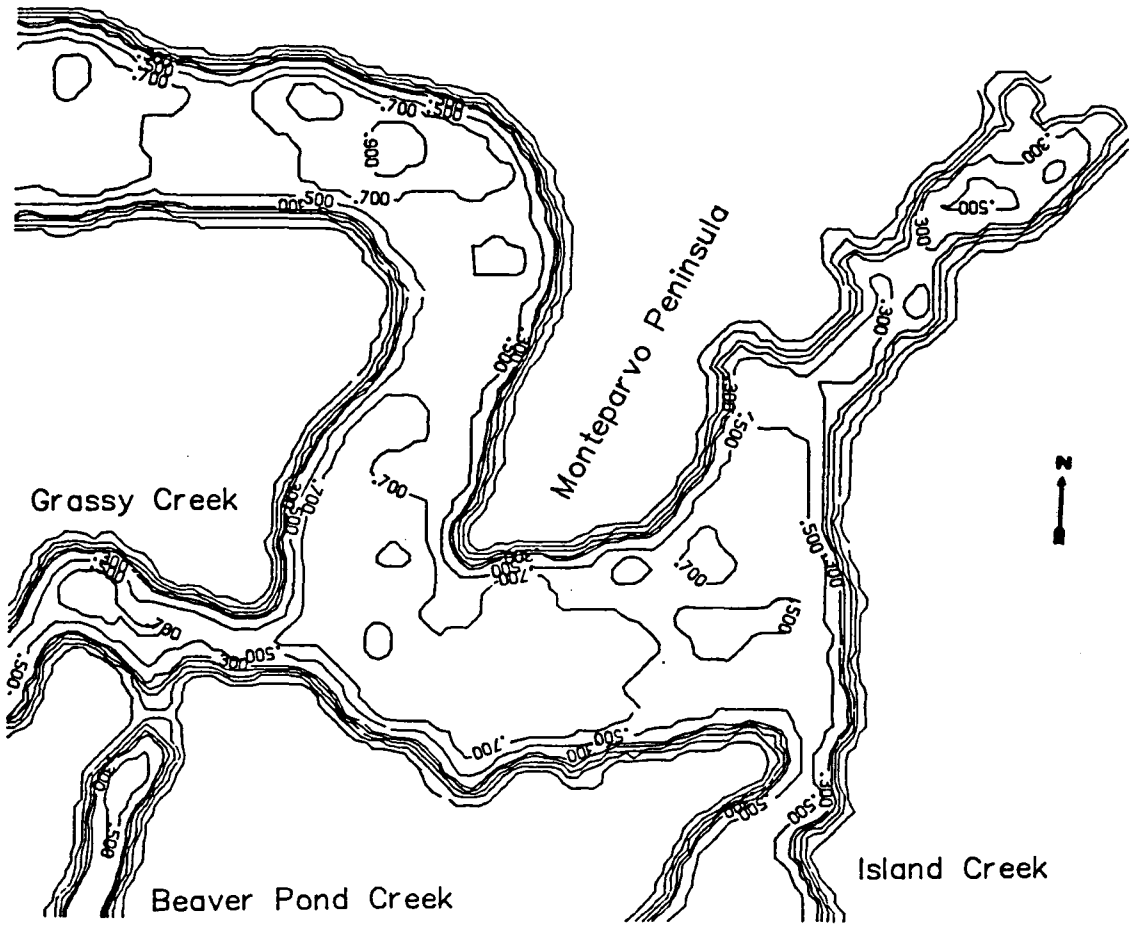


Figure 5.- Contour map for iron (mg/l) near Monteparvo Peninsula on Kerr Reservoir using Landsat's band 7.

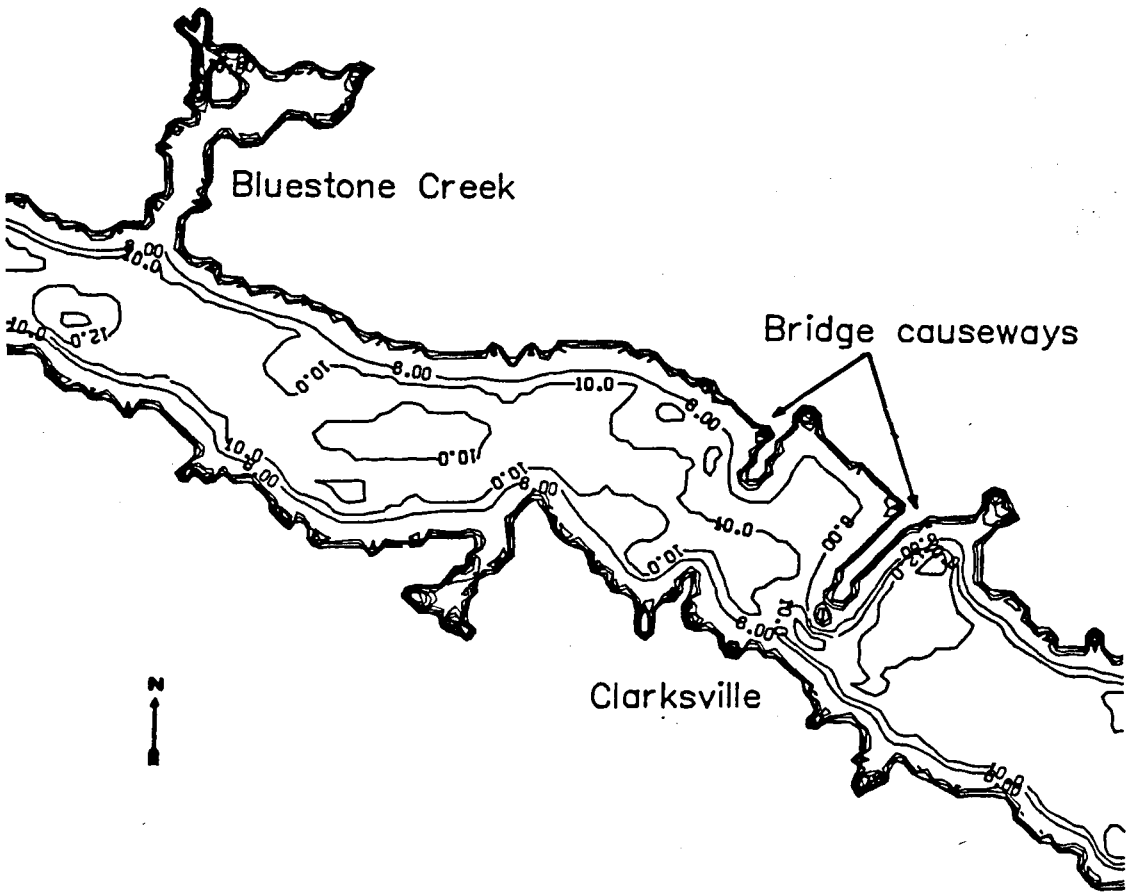


Figure 6.- Contour map for turbidity (FTU) near Clarksville on Kerr Reservoir using Landsat's band 6.

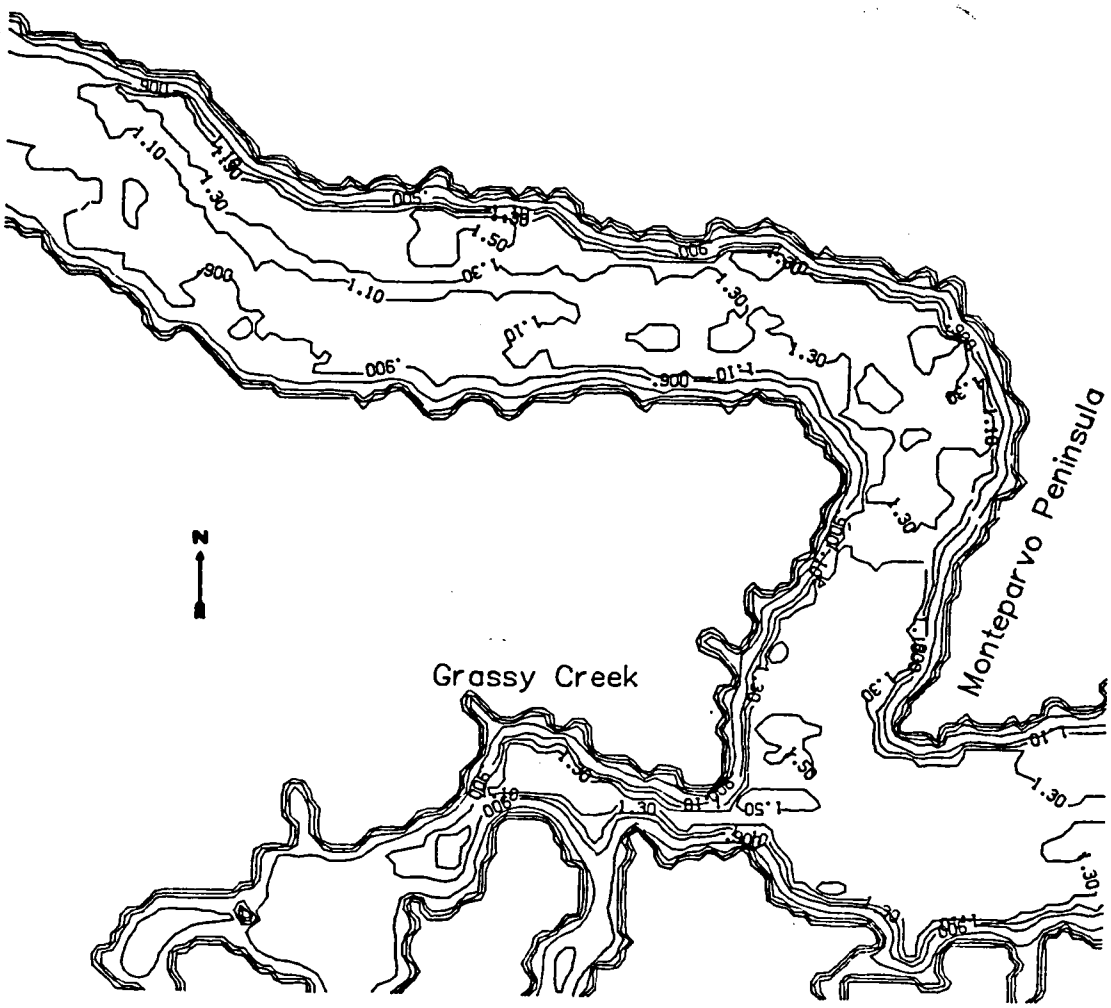


Figure 7.- Contour map for nitrate (mg/l) near Monteparvo Peninsula on Kerr Reservoir using Landsat's band 4.

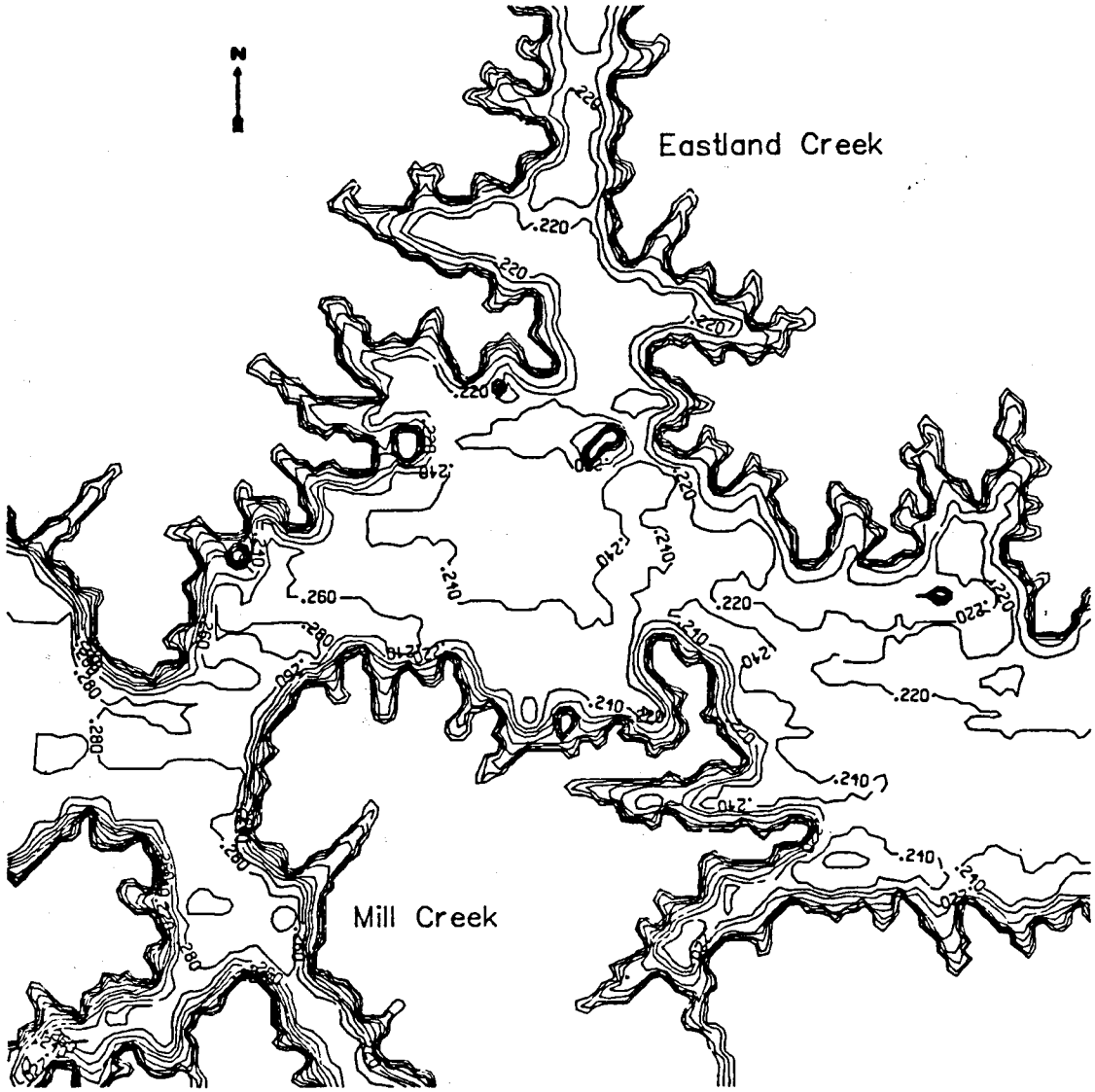


Figure 8.- Contour map for tannin and lignin (mg/l) near Eastland Creek on Kerr Reservoir using Landsat's band 6.

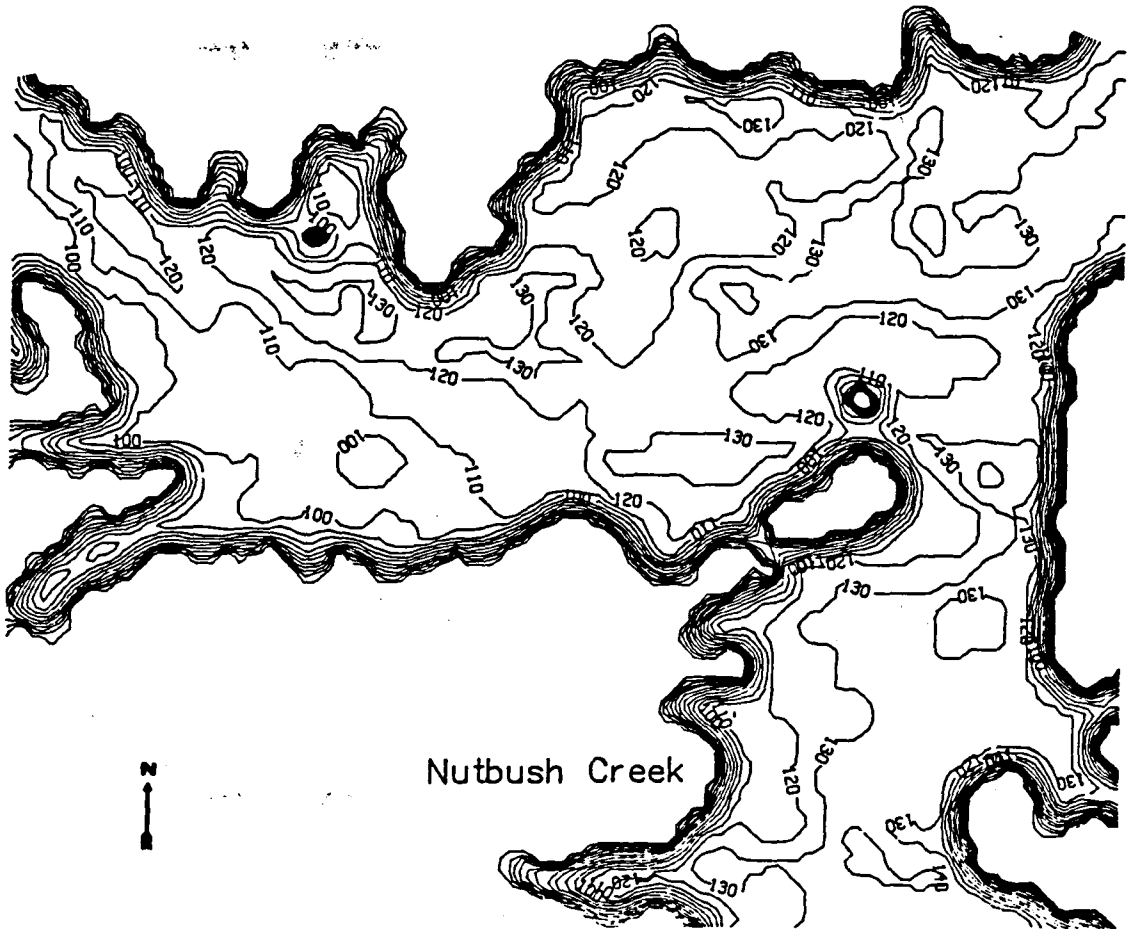


Figure 9.- Contour map for secchi depth (cm) near the mouth of Nutbush Creek on Kerr Reservoir using Landsat's bands 4 and 5.

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15. Supplementary Notes

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16. Abstract

An experiment was conducted on the waters of Kerr Reservoir to determine if reliable algorithms could be developed that relate water quality parameters to remotely sensed data. Landsat radiance data was used in the analysis since it is readily available and covers the area of interest on a regular basis. By properly designing the experiment, many of the unwanted variations due to atmosphere, solar, and hydraulic changes were minimized. The algorithms developed were constrained to satisfy rigorous statistical criteria before they could be considered dependable in predicting water quality parameters. A mix of different types of algorithms using the Landsat bands was generated to provide a thorough understanding of the relationships among the data involved. Except for secchi depth, the study demonstrated that for the ranges measured, the algorithms that satisfactorily represented the data encompass a mix of linear and nonlinear forms using only one Landsat band. Ratioing techniques did not improve the results since the initial design of the experiment minimized the errors against which this procedure is effective. Good correlations were found for total suspended solids, iron, turbidity, and secchi depth. Marginal correlations were discovered for nitrate and tannin + lignin. Quantification maps of Kerr Reservoir are presented for many of the water quality parameters using the developed algorithms.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Kerr Reservoir, Landsat, Multispectral Scanner, regression, algorithm, sediment pollution statistics	Unclassified-unlimited Subject Category 45

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