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KERR RESERVOIR LANDSAT EXPERIMENT ANALYSIS

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ABS: 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 complete mix of different types of algorithms using the LANDSAT bands was generated to provide a thorough understanding of the relationships among the data involved. The study demonstrated that for the ranges measured, the algorithms that

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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 complete mix of different types of algorithms using the Landsat bands was generated to provide a thorough understanding of the relationships among the data involved. The study demonstrated that for the ranges measured, the algorithms that satisfactorily represented the data are mostly linear and only require a maximum of one or two Landsat bands. Ratioing techniques did not improve the results since the initial design of the experiment minimized the errors that this procedure is effective against. Good correlations were established for inorganic suspended solids, iron, turbidity, and secchi depth. Marginal correlations were discovered for total suspended solids, chlorophyll _a_, tannin + lignin, and particulate organic carbon. Low variability of the data resulted in poor correlation for nitrate, total organic carbon, and dissolved organic carbon. Quantification maps of Kerr Reservoir are presented for several 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 on board 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 stripped 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 November 19, 1980. 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. Sample times were spaced about the Landsat overpass time and minimized as much as possible to lessen the effects of hydraulic, atmospheric, and solar changes.

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 lake itself. Numbers shown on the plots correspond to the sample sites as given in figure 1. Inorganic suspended solids (ISS), iron, turbidity, and tannin + lignin reveal highs at the entrance of Dan River into Kerr Reservoir and gradually decrease toward the dam. Total suspended solids (TSS), chlorophyll a, and particulate organic carbon (POC) display a maximum between the causeways at Clarksville, while ISS and tannin + lignin disclose a local maximum in this region. Nitrate shows a high at the Dan River entrance, but there is a sharp drop between there and Buffalo Creek, and then a gradual increase toward the dam. Total organic carbon (TOC) exhibits a high at the Buffalo Creek sample site, yet it is nearly constant everywhere else. Also, dissolved organic carbon (DOC) displays little change except near Bluestone Creek and in Nutbush Creek. Inspecting the data in Nutbush Creek reveals that concentrations of TSS, chlorophyll a, TOC, POC, and DOC have larger values than in the main lake near the dam, while values of ISS, iron, tannin + lignin, and nitrate are lesser. In fact, DOC has greater concentrations in Nutbush Creek than any other place in the lake. The water in Nutbush Creek is also very clear as disclosed by the high secchi depth numbers.

To show the relationships 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. Scanning the data shows that there are high correlations among TSS, ISS, iron, turbidity, tannin + lignin, and secchi depth while chlorophyll a, nitrate, TOC, POC, and DOC correlate weakly with the other constituents. The table also reveals an inverse relationship between DOC and 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 located at the mouth of Dan River to be two kilometers off the edge 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 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 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 above 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 there was hardly any wind on this date. Ratioing techniques will be used in a later section of this report in an effort to reduce the effects of solar and atmospheric variations in the data. The smooth surface conditions of the water and a solar zenith angle of 68 degrees resulted in no sunglint problems. The corrected radiance data for both Kerr Reservoir and Nutbush Creek is shown in figure 3 as a function of distance from the dam. The data reveals a high in the vicinity of Buffalo Creek and gradually decreases toward the dam. Nutbush Creek radiance values are lower than in the main part of the reservoir and the band 7 data is nearly constant for all the sample stations.

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 upon 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 results of the best nonlinear algorithm of all that were tried are displayed in this table. 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 discloses that 59 percent of the variation in TSS can be accounted for by using the band 5 algorithm, 89 percent by using the algorithm for bands 4 and 5, and 91 percent by using the algorithm for all four bands. The combination of bands 4 and 5 gives the best mix of all the regression coefficients, although a larger value of $(F/F_{cr})_{0.95}$ would be preferred. The ratio combinations reveal lower coefficients for all possibilities. Because of the small geographical variation between station locations (35 km maximum) and 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 the solar position. The best nonlinear algorithm for all bands turns out to have a quadratic form. There is no improvement in the coefficients using nonlinear algorithms, therefore, the data is probably linear for the range of the variables measured. A contour map displaying levels of TSS using the derived algorithm for bands 4 and 5 was generated for Landsat data near Monteparro Peninsula on Kerr Reservoir. This area is particularly susceptible to siltation problems since the flow is forced to go through several ninety degree turns. The quantification map for this region is shown in figure 4. Higher levels of TSS are revealed on the south side of the lake before the first ninety degree turn. In addition, higher sediment patterns are shown on the west side of Monteparro Peninsula and near the south shore of the lake between Grassy Creek and Island

Creek. These types of maps using radiance data are probably not accurate near the shore because of the radiance effect of the bottom and the nearby land.

The regression coefficients for ISS are presented in table 2b and generally show good correlation for all bands. The best linear results are either bands 5 or 6 since their $(F/F_{cr})_{0.95}$ values are greater than 4. Good results are also evident for the 4/5 and 4/6 ratios. No improvement in the outcome was achieved by fitting the data to the nonlinear forms. The quantification map of ISS, shown in figure 5, was produced using the outcome of the band 5 algorithm for the Buffalo and Bluestone Creek section of the lake. Although the regression coefficients were slightly better for band 6, the band 5 algorithm was used because its equation coefficients are smaller and therefore less sensitive to noise. Larger concentrations of ISS are shown on the upstream or western portion of the area, with a gradual decrease to the east. Local highs are disclosed on the western side of Buffalo Creek and at the mouth of Bluestone Creek. The region on the dam side of Bluestone Creek displays little change in levels of concentration of ISS.

Chlorophyll a coefficients exhibited in table 2c disclose low values for most combinations. However, the combination of bands 4 and 5 display adequate coefficients for all the statistical parameters, although $(F/F_{cr})_{0.95}$ is a little low. Nothing is gained by ratioing the bands and the different nonlinear forms do not improve the results. A contour map using the algorithm for bands 4 and 5 is illustrated in figure 6 for the Bluestone Creek and Clarksville area of Kerr Reservoir. There are a lot of highs and lows on the map, but generally higher levels are seen near the shorelines and in the vicinity of Clarksville.

Table 2d reveals that iron correlates well with most of the band combinations. The coefficients display values that are good independently, but that are not adequate taken together. Band 6 discloses sufficient values for the coefficients except for Cp/p, which indicates that using this algorithm would produce biased results. The combination of bands 6 and 7 gives better coefficients, except that band 7 is constant and any algorithm using band 7 would give numbers that are suspicious. The first two ratios, 4/5 and 4/6, also yield good results, but the inverse quadratic fit using band 6 provides coefficients that are a lot better than all the rest, proving the data is nonlinear. The nonlinearity of the data is probably the reason Cp/p is so large.

Turbidity exhibits a good relationship with nearly all the band combinations as shown in table 2c. The ratios also demonstrate a good correlation between the variables, although not as good as the single bands. The best association, however, is produced by using a quadratic algorithm for band 5. This algorithm accounts for 100 percent of the variances (two decimal place accuracy), has a SE of 0.19, and a very large $(F/F_{cr})_{0.95}$.

The nitrate precision coefficients displayed in table 2f show that for this data set there is not a good correlation between it and the Landsat bands. While the bands 4 and 6 combination produces a coefficient of determination of 0.77, $(F/F_{cr})_{0.95}$ is only 0.98. The ratios display even less correlation and the nonlinear algorithms did not significantly improve the results.

The values of the tannin + lignin coefficients presented in table 2g are marginal in that they are not in the range needed for a confident relationship. The best correlation obtained is using band 5, since any results using band 7 is suspicious. Higher values of R^2 and $(F/F_{cr})_{0.95}$ are to be preferred for confidence in the algorithm's ability to predict tannin + lignin. Approximately the same values are obtained from the 4/5 ratio and the quadratic algorithm for band 5. For modeling purposes, the simpler algorithm is always used in that this minimizes the effects of unwanted variations in the data. Figure 7 illustrates a contour plot of tannin + lignin using the band 5 algorithm on Landsat data near the mouth of Nutbush Creek. Inasmuch as there is a lot of mixing in this area near the dam, the algorithm seems to do a reasonable job in describing tannin + lignin despite the not quite adequate regression coefficients. The quantification map shows a gradual decrease in concentration toward the southern part of Nutbush Creek.

The set of data for the organic carbons seen in tables 2h through 2j, do not exhibit a good correlation with Landsat data. The precision correlation coefficients for TOC and DOC are very low and no linear or nonlinear relationship can be inferred. Figures 2h and 2j of TOC and DOC, respectively, establish that there is not enough variability in the data to be represented by any Landsat bands. Noisy data has caused some of the Cp/p values to go below zero. Table 2i indicates that the bands 4 and 6 combination could be useful in predicting POC, since it has a R^2 of 0.90. But the value of $(F/F_{cr})_{0.95}$ of 2.68 is low and Cp/p of 3.58 is high. The three band combination of bands 4, 6, and 7 gives good results to all the coefficients, but band 7 results are suspect and experience has shown that three bands and above quantification results are extremely noisy. The ratios and the nonlinear efforts did not significantly improve the outcomes.

Table 2k indicates that secchi depth can be represented adequately by band 5 of Landsat. The ratio of 4/5 improves the coefficients slightly and the band 5 quadratic algorithm gives a little better fit than the ratios.

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.

This experiment has shown that a good correlation exists between ISS, iron, turbidity, and secchi depth and the remotely sensed data of Landsat. Only a marginal correlation was shown between TSS, chlorophyll a, tannin + lignin, and POC and the Landsat bands. Nitrate, TOC, and DOC displayed poor correlation with the bands of Landsat. The relationship between the water quality parameters and the Landsat bands are largely linear for the ranges of the variables measured in this study. 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 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. 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 necessary 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.

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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	.61	.89	.83	.48	.87	.02	.78	-.50	-.81
ISS	.88	1.00	.21	.96	.91	.74	.95	.07	.60	-.60	-.89
Chlor a	.61	.21	1.00	.33	.28	-.26	.19	.03	.65	.04	-.36
Iron	.89	.96	.33	1.00	.98	.61	.92	.23	.72	-.52	-.94
Turbidity	.83	.91	.28	.98	1.00	.59	.88	.37	.67	-.57	-.94
Nitrate	.48	.74	-.26	.61	.59	1.00	.79	-.22	-.04	-.69	-.65
Tann + Lign	.87	.95	.19	.92	.88	.79	1.00	.03	.56	-.70	-.84
TOC	.02	.07	.03	.23	.37	-.22	.03	1.00	.39	-.31	-.26
POC	.78	.60	.65	.72	.67	-.04	.56	.39	1.00	-.21	-.58
DOC	-.50	-.60	.04	-.52	-.57	-.69	-.70	-.31	-.21	1.00	.57
Secchi D.	-.81	-.89	-.36	-.94	-.94	-.65	-.84	-.26	-.58	.57	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	0.21	4.41	0.20	7.60
5	0.59	3.19	1.07	3.25
6	0.56	3.28	0.96	3.55
7	0.03	4.88	0.02	9.67
4,5	0.89	1.67	2.26	0.53
4,6	0.71	2.67	0.70	1.89
4,7	0.24	4.32	0.09	5.50
5,6	0.59	3.19	0.41	2.83
5,7	0.70	2.69	0.69	1.93
6,7	0.68	2.81	0.60	2.14
4,5,6	0.89	1.64	0.88	0.88
4,5,7	0.91	1.47	1.11	0.76
4,6,7	0.76	2.43	0.34	1.63
5,6,7	0.71	2.68	0.26	1.93
4,5,6,7	0.91	1.46	0.27	1.00
4/5	0.68	2.78	1.65	1.00
4/6	0.58	3.20	1.05	1.00
4/7	0.16	4.54	0.14	1.00
5/6	0.23	4.36	0.22	1.00
5/7	0.54	3.36	0.89	1.00
6/7	0.53	3.41	0.84	1.00
$5^2/4 \times 6$	0.57	3.25	1.00	1.00
$6^2/5 \times 7$	0.50	3.51	0.74	1.00
4*	0.22	4.36	0.21	1.00
5*	0.59	3.16	1.10	1.00
6*	0.58	3.21	1.03	1.00
7*	0.05	4.83	0.04	1.00

*Quadratic fit

TABLE 2. - CONTINUED

(b) Inorganic Suspended Solids

Bands Used	R^2	SE (mg/ℓ)	$(F/F_{CR})_{0.95}$	Cp/p
4	0.51	2.04	0.79	8.40
5	0.85	1.14	4.23	1.58
6	0.87	1.06	5.06	1.14
7	0.14	2.71	0.13	15.88
4,5	0.92	0.82	3.34	0.74
4,6	0.90	0.91	2.71	0.97
4,7	0.52	2.02	0.32	6.10
5,6	0.87	1.04	1.98	1.38
5,7	0.88	1.00	2.19	1.24
6,7	0.91	0.86	3.02	0.85
4,5,6	0.94	0.74	1.56	0.90
4,5,7	0.93	0.77	1.44	0.96
4,6,7	0.93	0.79	1.38	0.99
5,6,7	0.92	0.84	1.19	1.09
4,5,6,7	0.95	0.65	0.50	1.00
4/5	0.90	0.94	6.57	1.00
4/6	0.89	0.98	5.96	1.00
4/7	0.44	2.18	0.61	1.00
5/6	0.50	2.06	0.76	1.00
5/7	0.81	1.26	3.30	1.00
6/7	0.84	1.17	3.99	1.00
$5^2/4x6$	0.57	1.92	1.00	1.00
$6^2/5x7$	0.82	1.24	3.42	1.00
4*	0.52	2.02	0.83	1.00
5*	0.85	1.13	1.97	1.00
6*	0.87	1.06	5.08	1.00
7*	0.26	2.52	0.27	1.00

*Quadratic fit

TABLE 2. - CONTINUED

(c) Chlorophyll a

Bands Used	R^2	SE (μg/ℓ)	$(F/F_{CR})_{0.95}$	Cp/p
4	0.05	2.70	0.04	9.10
5	0.35	2.23	0.41	5.73
6	0.32	2.29	0.36	6.10
7	0.03	2.73	0.02	9.36
4,5	0.88	0.96	2.11	0.56
4,6	0.60	1.75	0.44	2.62
4,7	0.05	2.70	0.02	6.73
5,6	0.36	2.22	0.16	4.46
5,7	0.40	2.15	0.19	4.13
6,7	0.36	2.21	0.16	4.41
4,5,6	0.90	0.86	1.02	0.78
4,5,7	0.88	0.95	0.81	0.91
4,6,7	0.60	1.74	0.16	2.46
5,6,7	0.40	2.14	0.07	3.59
4,5,6,7	0.91	0.83	0.26	1.00
4/5	0.47	2.02	0.66	1.00
4/6	0.36	2.21	0.43	1.00
4/7	0.05	2.70	0.04	1.00
5/6	0.10	2.62	0.09	1.00
5/7	0.33	2.27	0.37	1.00
6/7	0.30	2.32	0.33	1.00
$5^2/4 \times 6$	0.46	2.04	0.63	1.00
$6^2/5 \times 7$	0.27	2.36	0.29	1.00
4#	0.06	3.08	0.04	1.00
5*	0.36	2.22	0.42	1.00
6*	0.33	2.27	0.37	1.00
7#	0.04	3.03	0.03	1.00

*Quadratic fit
#Inverse linear fit

TABLE 2. - CONTINUED

(d) Iron

Bands Used	R^2	SE (mg/ℓ)	$(F/F_{CR})_{0.95}$	Cp/p
4	0.56	0.10	0.97	186.07
5	0.89	0.05	6.44	43.40
6	0.92	0.04	8.99	31.64
7	0.14	0.14	0.13	364.11
4,5	0.95	0.03	5.99	12.73
4,6	0.95	0.03	5.46	13.95
4,7	0.58	0.10	0.40	119.30
5,6	0.92	0.04	3.53	21.15
5,7	0.94	0.04	4.24	17.78
6,7	0.97	0.02	10.48	7.28
4,5,6	0.97	0.02	4.03	5.81
4,5,7	0.97	0.03	3.44	6.73
4,6,7	0.98	0.02	5.87	4.10
5,6,7	0.98	0.02	4.42	5.33
4,5,6,7	1.00	0.01	11.07	1.00
4/5	0.92	0.04	8.44	1.00
4/6	0.92	0.04	8.23	1.00
4/7	0.48	0.11	0.70	1.00
5/6	0.53	0.10	0.87	1.00
5/7	0.86	0.06	4.62	1.00
6/7	0.89	0.05	6.31	1.00
$5^2/4 \times 6$	0.58	0.10	1.04	1.00
$6^2/5 \times 7$	0.87	0.05	5.17	1.00
4*	0.56	0.10	0.98	1.00
5*	0.93	0.04	10.55	1.00
6$	0.97	0.02	28.51	1.00
7*	0.24	0.13	0.24	1.00

*Quadratic fit
$Inverse quadratic fit

TABLE 2. - CONTINUED

(e) Turbidity

Bands Used	R^2	SE (FTU)	$(F/F_{CR})_{0.95}$	Cp/p
4	0.64	2.67	1.31	9.35
5	0.93	1.19	9.68	0.65
6	0.93	1.18	9.79	0.63
7	0.23	3.87	0.23	21.27
4,5	0.96	0.93	6.23	0.54
4,6	0.93	1.14	4.07	0.98
4,7	0.64	2.67	0.50	6.86
5,6	0.94	1.08	4.52	0.85
5,7	0.94	1.12	4.18	0.94
6,7	0.94	1.10	4.38	0.89
4,5,6	0.96	0.84	2.88	0.78
4,5,7	0.96	0.92	2.38	0.89
4,6,7	0.94	1.08	1.69	1.14
5,6,7	0.95	0.98	2.09	0.98
4,5,6,7	0.97	0.81	0.74	1.00
4/5	0.92	1.24	8.89	1.00
4/6	0.88	1.52	5.64	1.00
4/7	0.59	2.84	1.07	1.00
5/6	0.47	3.22	0.67	1.00
5/7	0.91	1.31	7.84	1.00
6/7	0.92	1.27	8.44	1.00
$5^2/4x6$	0.63	2.69	1.29	1.00
$6^2/5x7$	0.88	1.53	5.54	1.00
4*	0.68	2.51	1.59	1.00
5*	1.00	0.19	377.43	1.00
6*	0.97	0.76	24.63	1.00
7*	0.25	3.83	0.25	1.00

*Quadratic fit

TABLE 2. - CONTINUED

(f) Nitrate

Bands Used	R^2	SE (mg/ℓ)	$(F/F_{CR})_{0.95}$	Cp/p
4	0.58	0.16	1.06	0.87
5	0.31	0.20	0.34	2.41
6	0.20	0.22	0.19	3.07
7	0.12	0.23	0.11	3.48
4,5	0.67	0.14	0.60	0.90
4,6	0.77	0.12	0.98	0.53
4,7	0.62	0.15	0.46	1.12
5,6	0.51	0.17	0.30	1.53
5,7	0.31	0.20	0.13	2.27
6,7	0.21	0.22	0.08	2.66
4,5,6	0.81	0.11	0.46	0.79
4,5,7	0.71	0.13	0.27	1.07
4,6,7	0.80	0.11	0.42	0.83
5,6,7	0.52	0.17	0.12	1.62
4,5,6,7	0.82	0.10	0.12	1.00
4/5	0.27	0.21	0.28	1.00
4/6	0.17	0.22	0.15	1.00
4/7	0.48	0.18	0.70	1.00
5/6	0.01	0.24	0.01	1.00
5/7	0.31	0.20	0.34	1.00
6/7	0.20	0.22	0.19	1.00
$5^2/4\times6$	0.35	0.20	0.40	1.00
$6^2/5\times7$	0.13	0.23	0.11	1.00
4+	0.59	0.16	1.08	1.00
5+	0.34	0.20	0.40	1.00
6+	0.23	0.22	0.22	1.00
7$	0.16	0.22	0.15	1.00

+Log fit
$Inverse quadratic fit

TABLE 2. - CONTINUED

(g) Tannin and Lignin

Bands Used	R^2	SE (mg/ℓ)	$(F/F_{CR})_{0.95}$	Cp/p
4	0.53	0.04	0.86	4.04
5	0.76	0.02	2.39	1.35
6	0.69	0.03	1.65	2.22
7	0.03	0.05	0.03	9.95
4,5	0.78	0.02	1.00	1.43
4,6	0.69	0.03	0.63	2.14
4,7	0.68	0.03	0.60	2.22
5,6	0.77	0.02	0.95	1.50
5,7	0.91	0.01	3.05	0.35
6,7	0.82	0.02	1.36	1.05
4,5,6	0.79	0.02	0.40	1.50
4,5,7	0.91	0.01	1.14	0.76
4,6,7	0.85	0.02	0.62	1.13
5,6,7	0.92	0.01	1.17	0.75
4,5,6,7	0.92	0.01	0.28	1.00
4/5	0.78	0.02	2.68	1.00
4/6	0.64	0.03	1.32	1.00
4/7	0.38	0.04	0.47	1.00
5/6	0.22	0.05	0.21	1.00
5/7	0.70	0.03	1.78	1.00
6/7	0.65	0.03	1.38	1.00
5^2/4x6	0.67	0.03	1.55	1.00
6^2/5x7	0.58	0.03	1.07	1.00
4*	0.53	0.04	0.87	1.00
5*	0.76	0.03	2.40	1.00
6*	0.70	0.03	1.73	1.00
7+	0.03	0.05	0.03	1.00

*Quadratic fit
+Log fit

TABLE 2. - CONTINUED

(h) Total Organic Carbon

Bands Used	R^2	SE (mg/1)	$(F/F_{CR})_{0.95}$	Cp/p
4	0.18	0.47	0.16	0.15
5	0.19	0.47	0.18	0.13
6	0.28	0.44	0.30	-0.06
7	0.29	0.44	0.31	-0.06
4,5	0.19	0.46	0.07	0.75
4,6	0.29	0.44	0.12	0.62
4,7	0.30	0.43	0.12	0.61
5,6	0.42	0.40	0.21	0.45
5,7	0.31	0.43	0.13	0.59
6,7	0.36	0.41	0.16	0.52
4,5,6	0.43	0.39	0.08	0.82
4,5,7	0.32	0.43	0.05	0.94
4,6,7	0.39	0.40	0.07	0.86
5,6,7	0.50	0.36	0.11	0.75
4,5,6,7	0.50	0.36	0.03	1.00
4/5	0.15	0.48	0.13	1.00
4/6	0.23	0.45	0.23	1.00
4/7	0.25	0.45	0.25	1.00
5/6	0.33	0.42	0.37	1.00
5/7	0.22	0.46	0.21	1.00
6/7	0.31	0.43	0.34	1.00
$5^2/4x6$	0.02	0.51	0.01	1.00
$6^2/5x7$	0.36	0.41	0.24	1.00
4†	0.18	0.47	0.17	1.00
5†	0.19	0.47	0.18	1.00
6†	0.29	0.44	0.31	1.00
7*	0.36	0.41	0.43	1.00

†Exponential fit
*Quadratic fit

TABLE 2. - CONTINUED

(i) Particulate Organic Carbon

Bands Used	R^2	SE (mg/1)	$(F/F_{CR})_{0.95}$	Cp/p
4	0.10	0.21	0.08	53.27
5	0.40	0.17	0.51	34.77
6	0.51	0.15	0.80	27.94
7	0.00	0.22	0.00	59.00
4,5	0.77	0.12	0.98	8.83
4,6	0.90	0.08	2.68	3.58
4,7	0.14	0.23	0.05	34.16
5,6	0.60	0.16	0.43	19.96
5,7	0.57	0.16	0.38	17.00
6,7	0.75	0.12	0.85	9.92
4,5,6	0.90	0.09	1.03	3.13
4,5,7	0.82	0.12	0.48	5.84
4,6,7	0.98	0.04	6.40	0.75
5,6,7	0.82	0.12	0.49	5.74
4,5,6,7	0.98	0.04	1.55	1.00
4/5	0.45	0.16	0.62	1.00
4/6	0.53	0.15	0.86	1.00
4/7	0.06	0.21	0.05	1.00
5/6	0.47	0.16	0.66	1.00
5/7	0.36	0.18	0.43	1.00
6/7	0.47	0.16	0.68	1.00
$5^2/4\times6$	0.19	0.20	0.17	1.00
$6^2/5\times7$	0.53	0.15	0.87	1.00
4+	0.09	0.21	0.08	1.00
5†	0.42	0.17	0.55	1.00
6†	0.55	0.15	0.92	1.00
7#	0.02	0.23	0.01	1.00

+Log fit
†Exponential fit
#Inverse linear fit

TABLE 2. - CONTINUED

(j) Dissolved Organic Carbon

Bands Used	R^2	SE (mg/ℓ)	$(F/F_{CR})_{0.95}$	Cp/p
4	0.35	0.13	0.41	-0.48
5	0.28	0.14	0.30	-0.37
6	0.24	0.15	0.24	-0.30
7	0.19	0.15	0.18	-0.23
4,5	0.35	0.13	0.16	0.35
4,6	0.35	0.13	0.16	0.35
4,7	0.36	0.13	0.16	0.34
5,6	0.30	0.14	0.12	0.41
5,7	0.31	0.14	0.13	0.39
6,7	0.28	0.14	0.11	0.43
4,5,6	0.36	0.13	0.06	0.76
4,5,7	0.36	0.13	0.06	0.76
4,6,7	0.36	0.13	0.06	0.76
5,6,7	0.33	0.14	0.53	0.78
4,5,6,7	0.37	0.13	0.02	1.00
4/5	0.26	0.14	0.27	1.00
4/6	0.18	0.15	0.17	1.00
4/7	0.36	0.13	0.42	1.00
5/6	0.04	0.16	0.03	1.00
5/7	0.30	0.14	0.32	1.00
6/7	0.26	0.14	0.26	1.00
$5^2/4\times6$	0.23	0.15	0.23	1.00
$6^2/5\times7$	0.22	0.15	0.22	1.00
4+	0.35	0.13	0.41	1.00
5+	0.29	0.14	0.31	1.00
6*	0.26	0.14	0.27	1.00
7*	0.24	0.14	0.24	1.00

+Log fit
*Quadratic fit

TABLE 2. - CONCLUDED

(k) Secchi Depth

Bands Used	R^2	SE (mg/ℓ)	$(F/F_{CR})_{0.95}$	Cp/p
4	0.77	18.02	2.53	9.61
5	0.97	6.78	22.49	0.07
6	0.95	8.90	12.71	1.21
7	0.40	29.00	0.51	27.25
4,5	0.97	6.72	8.73	0.70
4,6	0.95	8.48	5.37	1.31
4,7	0.78	17.71	1.01	6.82
5,6	0.97	6.40	9.64	0.60
5,7	0.97	6.00	11.00	0.49
6,7	0.95	8.34	5.56	1.25
4,5,6	0.97	6.37	3.64	0.94
4,5,7	0.98	5.60	4.74	0.79
4,6,7	0.95	8.16	2.18	1.39
5,6,7	0.97	5.71	4.55	0.81
4,5,6,7	0.98	5.41	1.23	1.00
4/5	0.97	6.26	26.43	1.00
4/6	0.94	8.83	12.94	1.00
4/7	0.76	18.39	2.40	1.00
5/6	0.49	26.76	0.73	1.00
5/7	0.97	6.26	26.43	1.00
6/7	0.95	8.67	13.43	1.00
$5^2/4x6$	0.65	22.19	1.41	1.00
$6^2/5x7$	0.88	12.72	5.84	1.00
4*	0.79	17.25	2.82	1.00
5*	0.97	5.97	28.51	1.00
6*	0.97	6.96	21.67	1.00
7*	0.51	26.31	0.79	1.00

*Quadratic fit

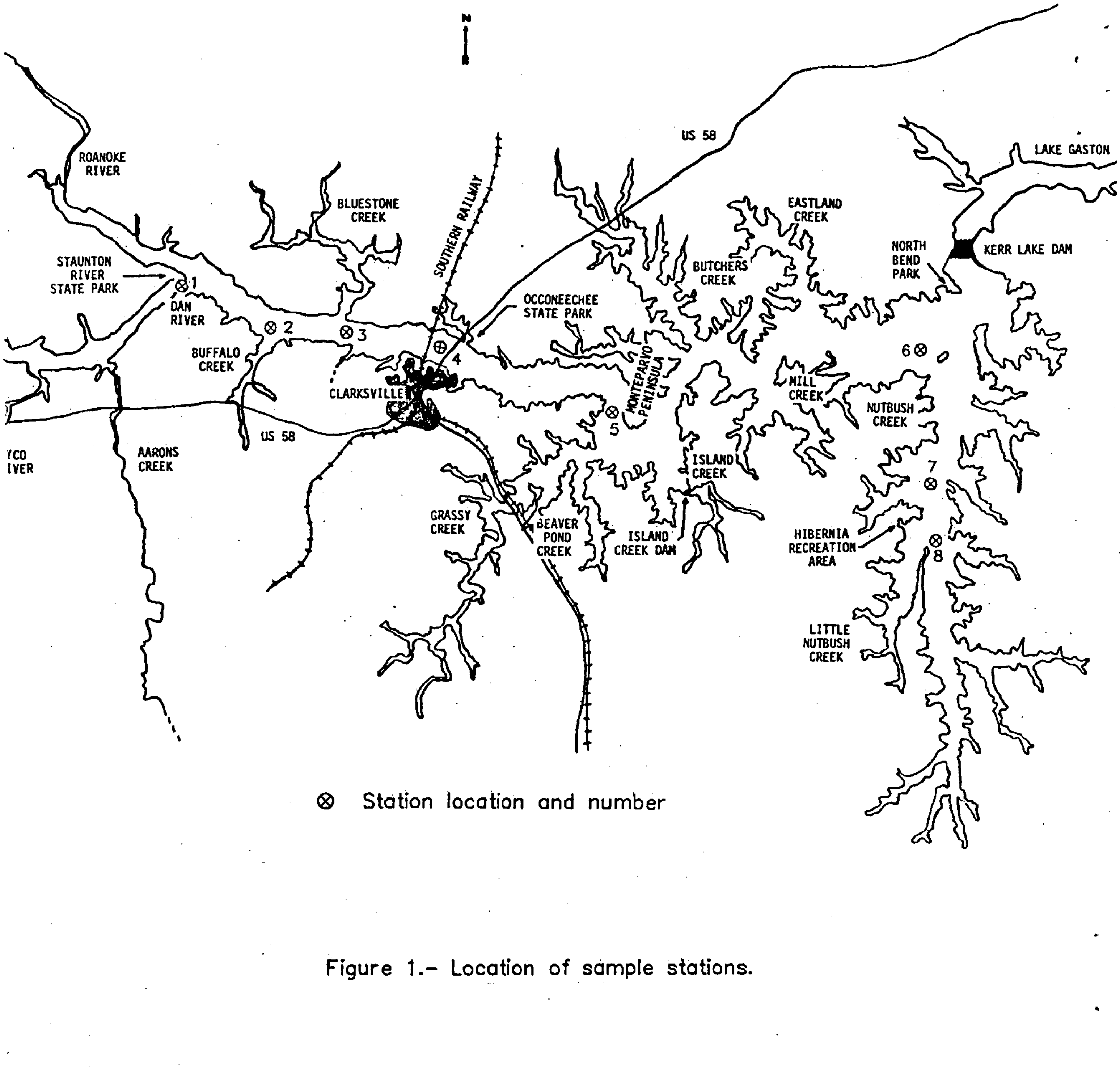
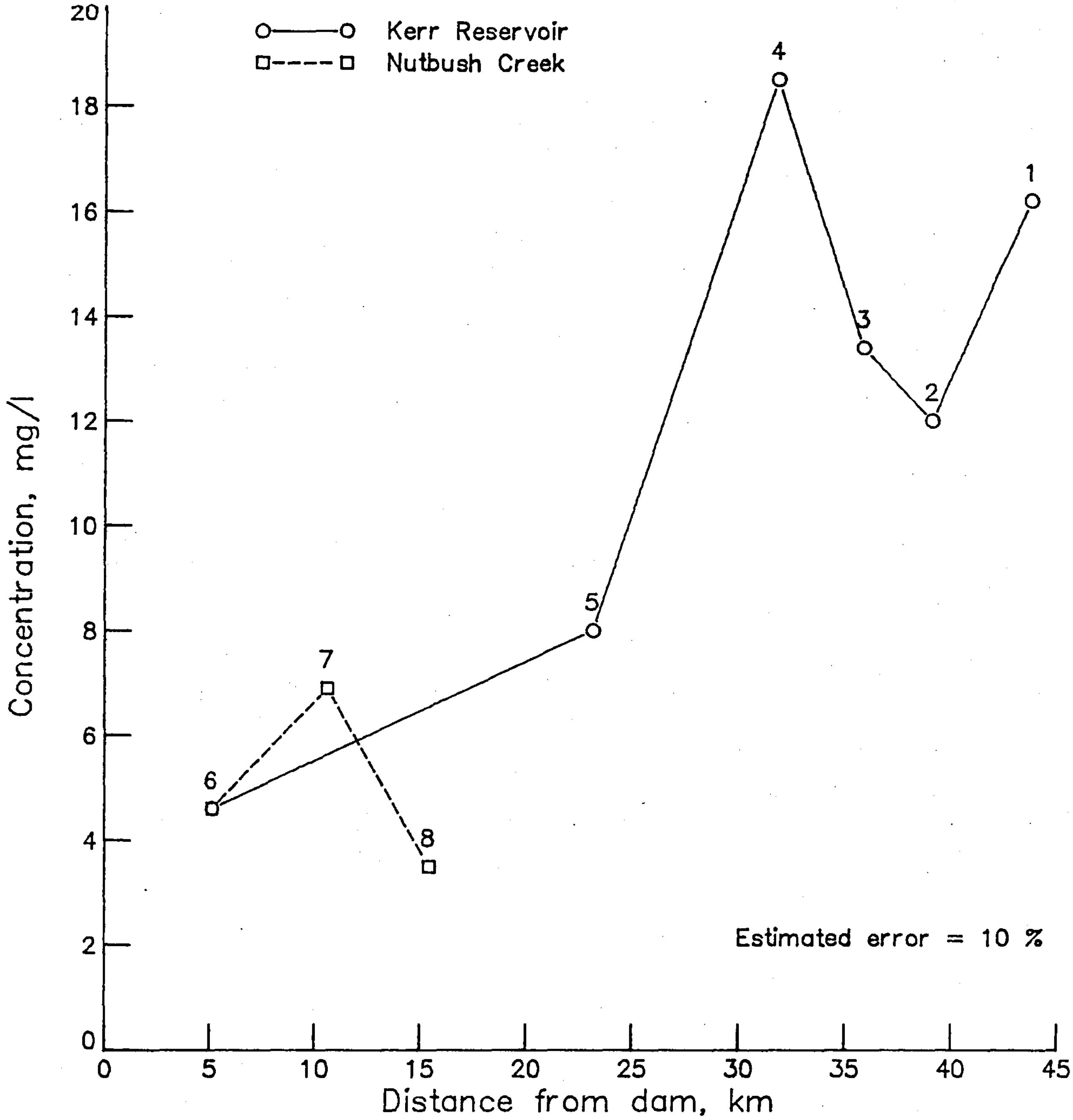
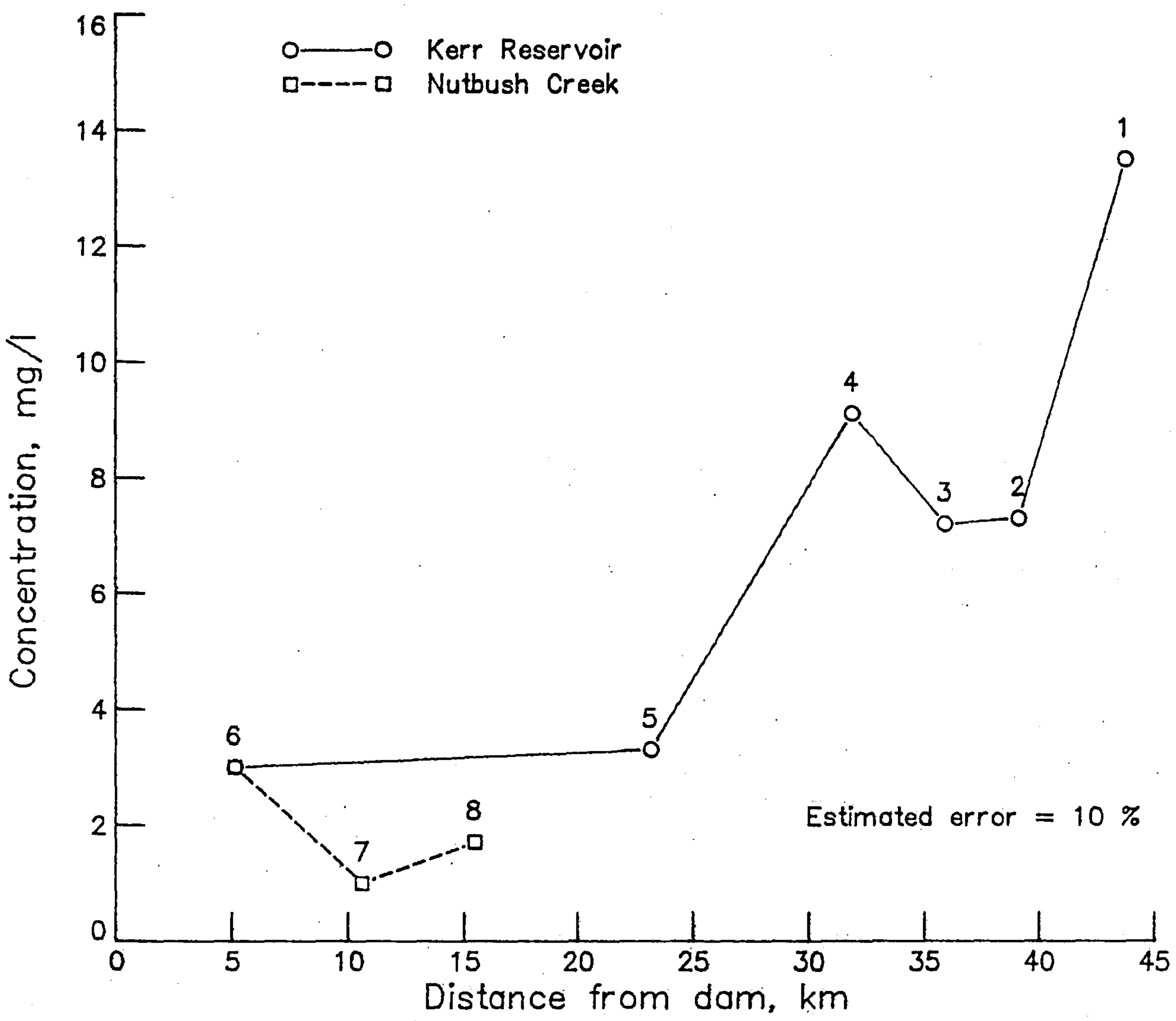


Figure 1.- Location of sample stations.



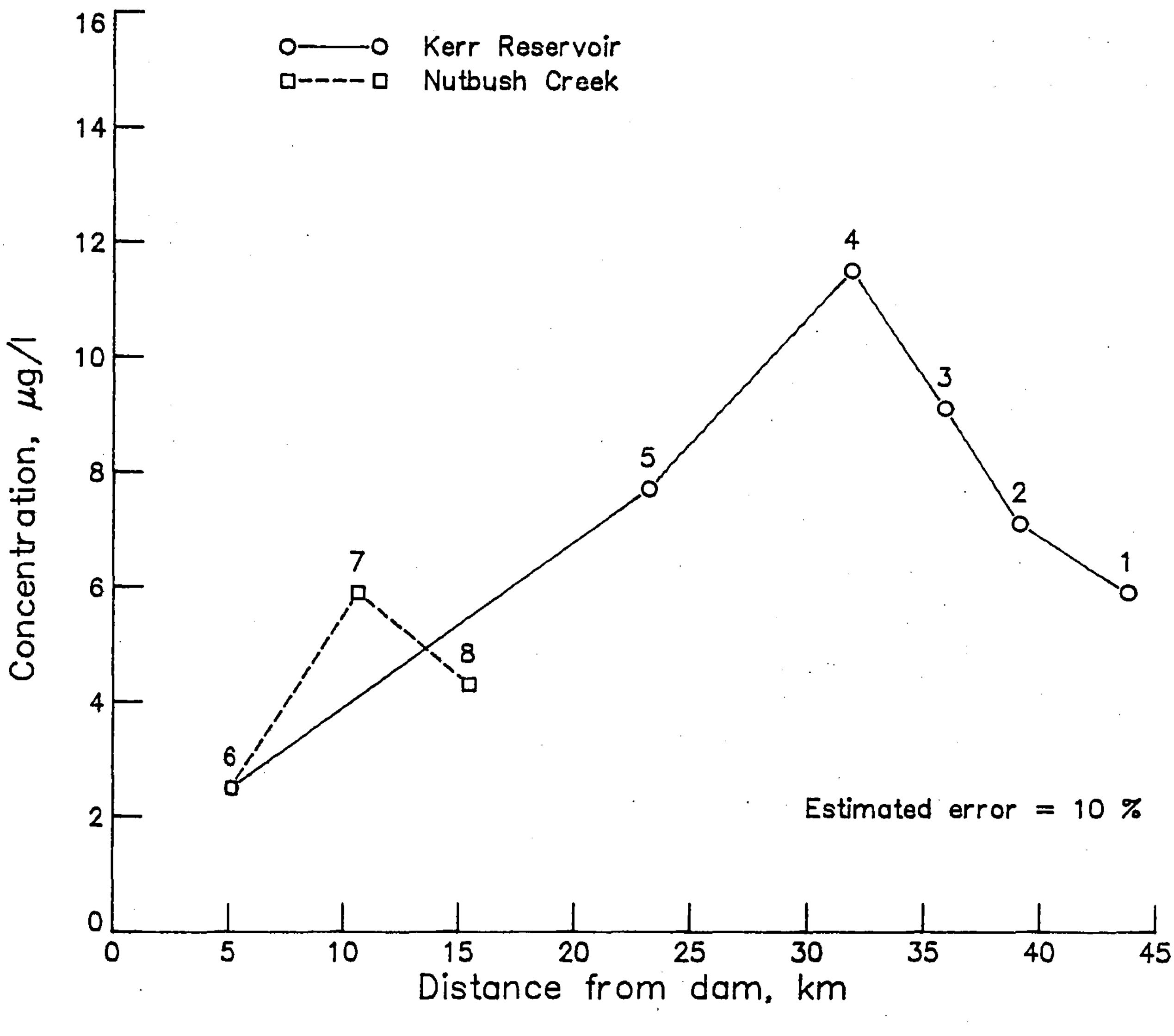
(a) Total suspended solids

Figure 2.- Water quality measurements taken from Kerr Reservoir on November 19, 1980.



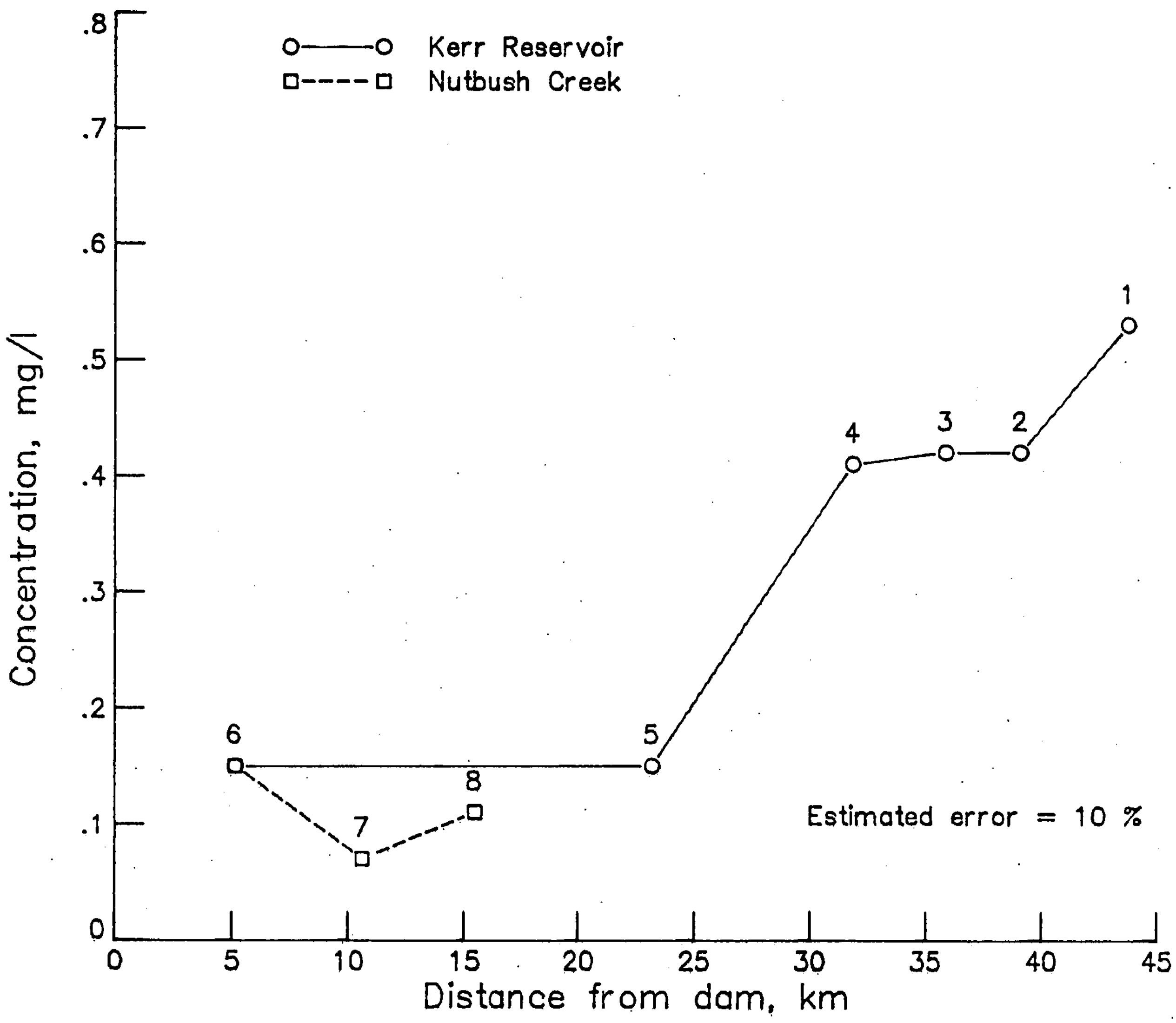
(b) Inorganic suspended solids

Figure 2.- Continued.



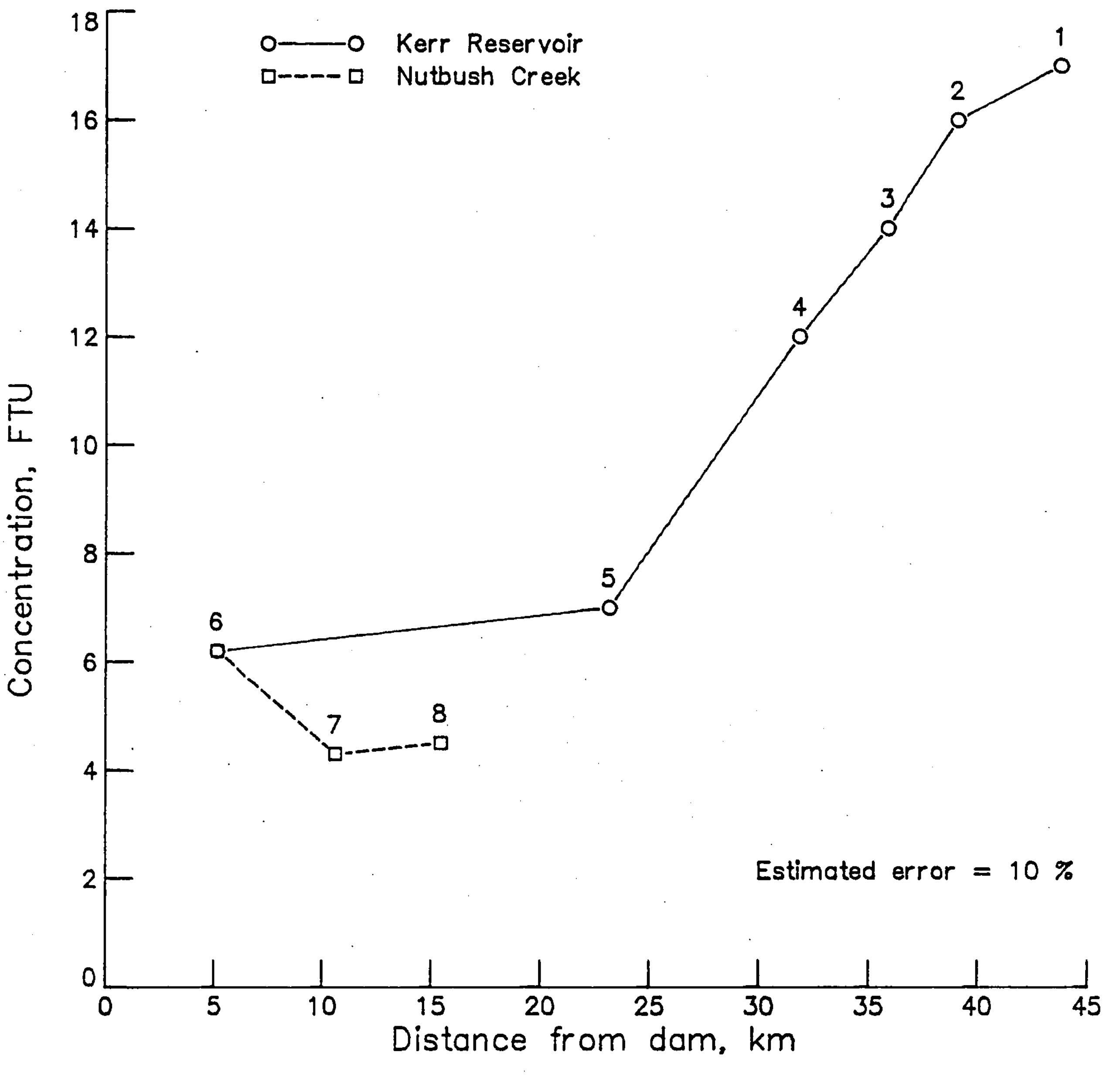
(c) Chlorophyll a

Figure 2.- Continued.



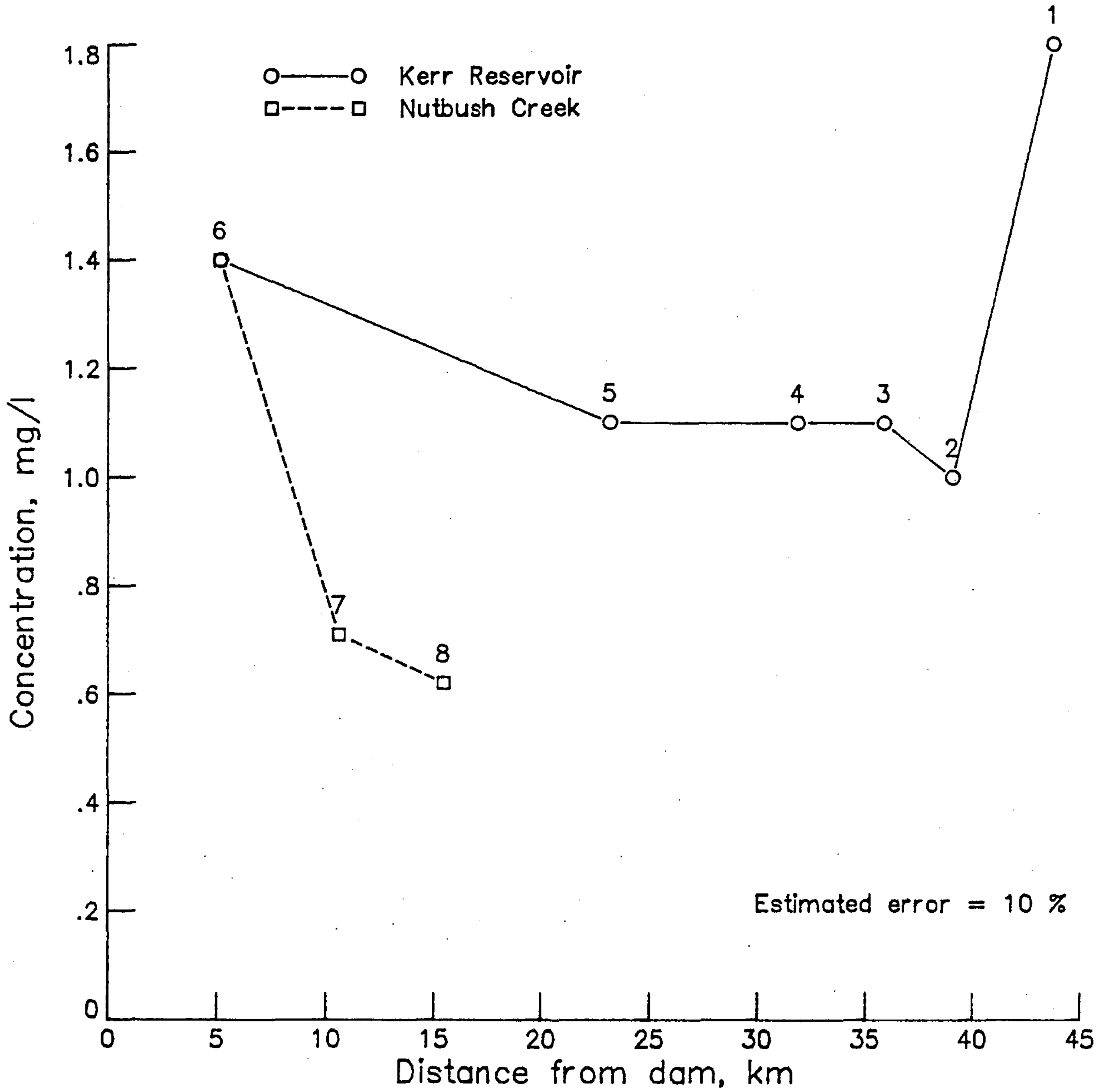
(d) Iron

Figure 2.- Continued.



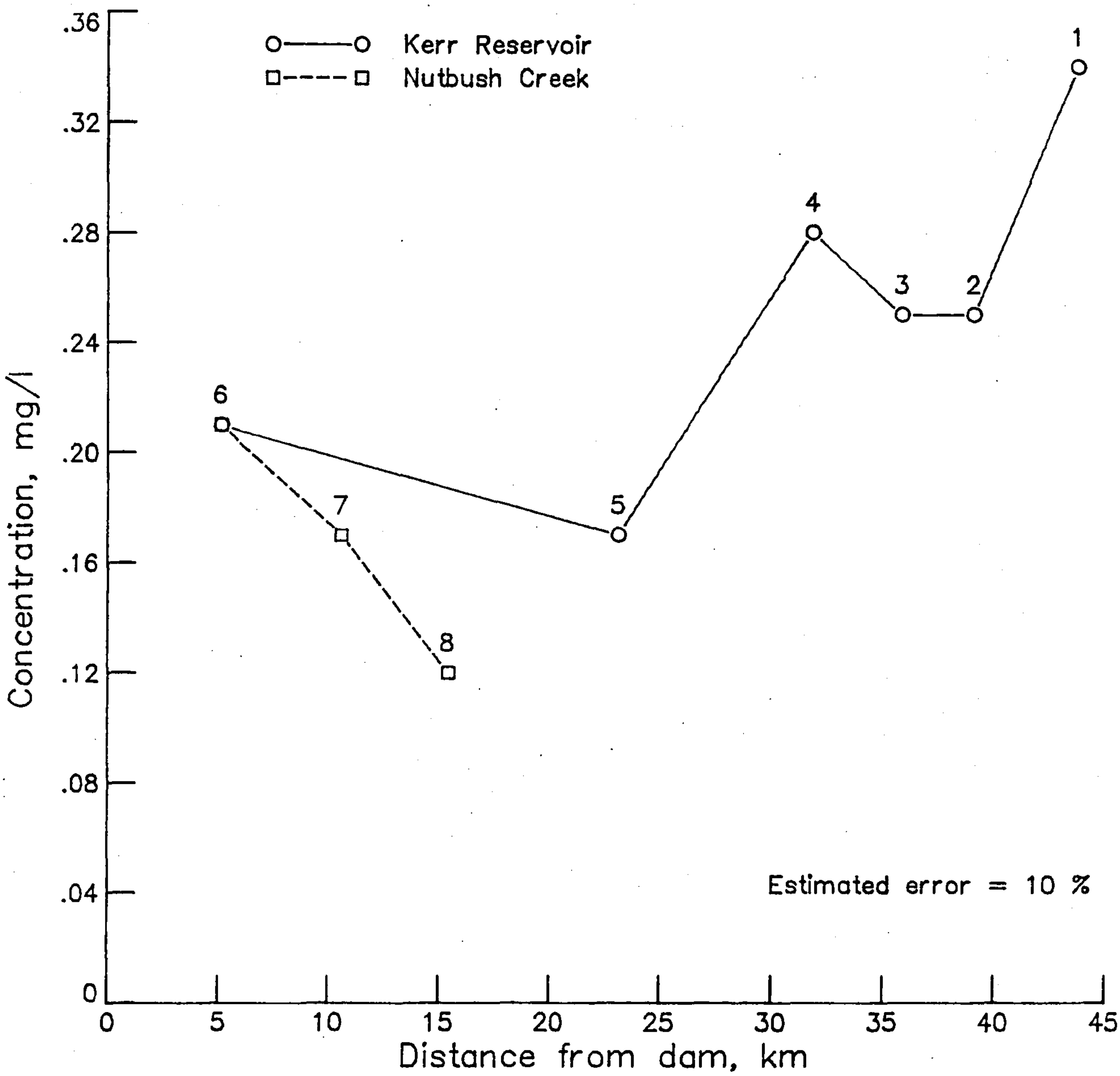
(e) Turbidity

Figure 2.- Continued.



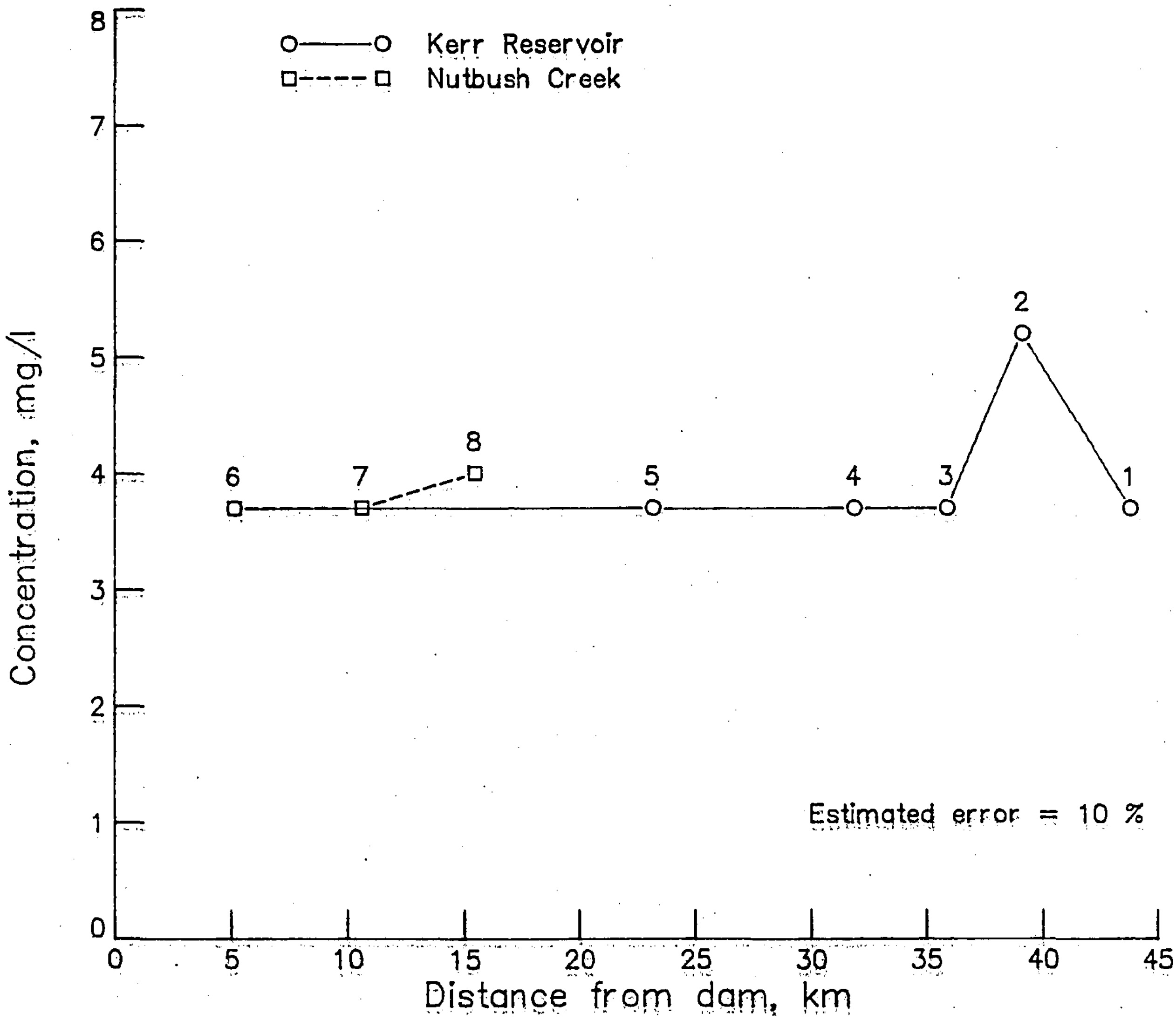
(f) Nitrate

Figure 2.- Continued.



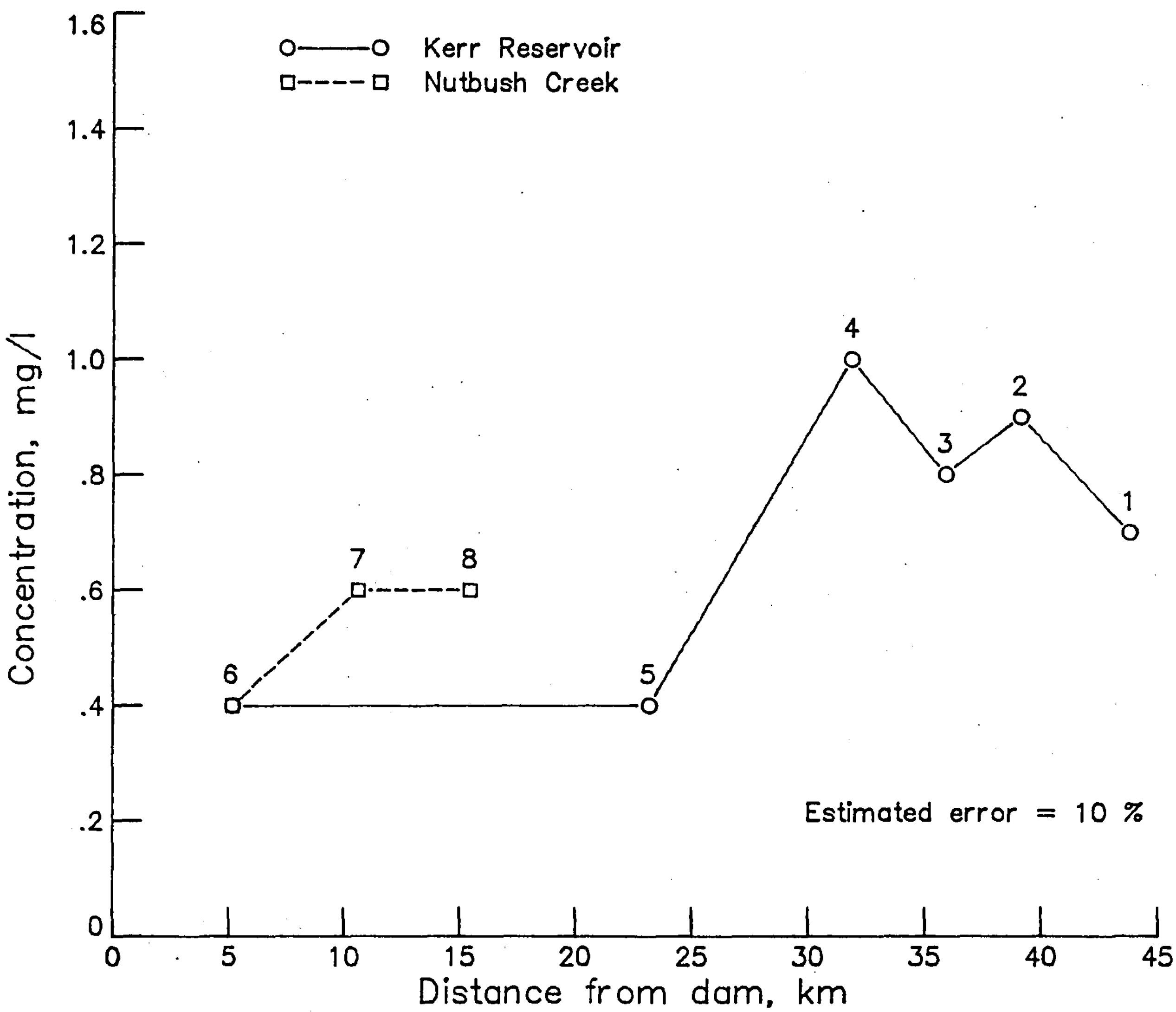
(g) Tannin + lignin

Figure 2.- Continued.



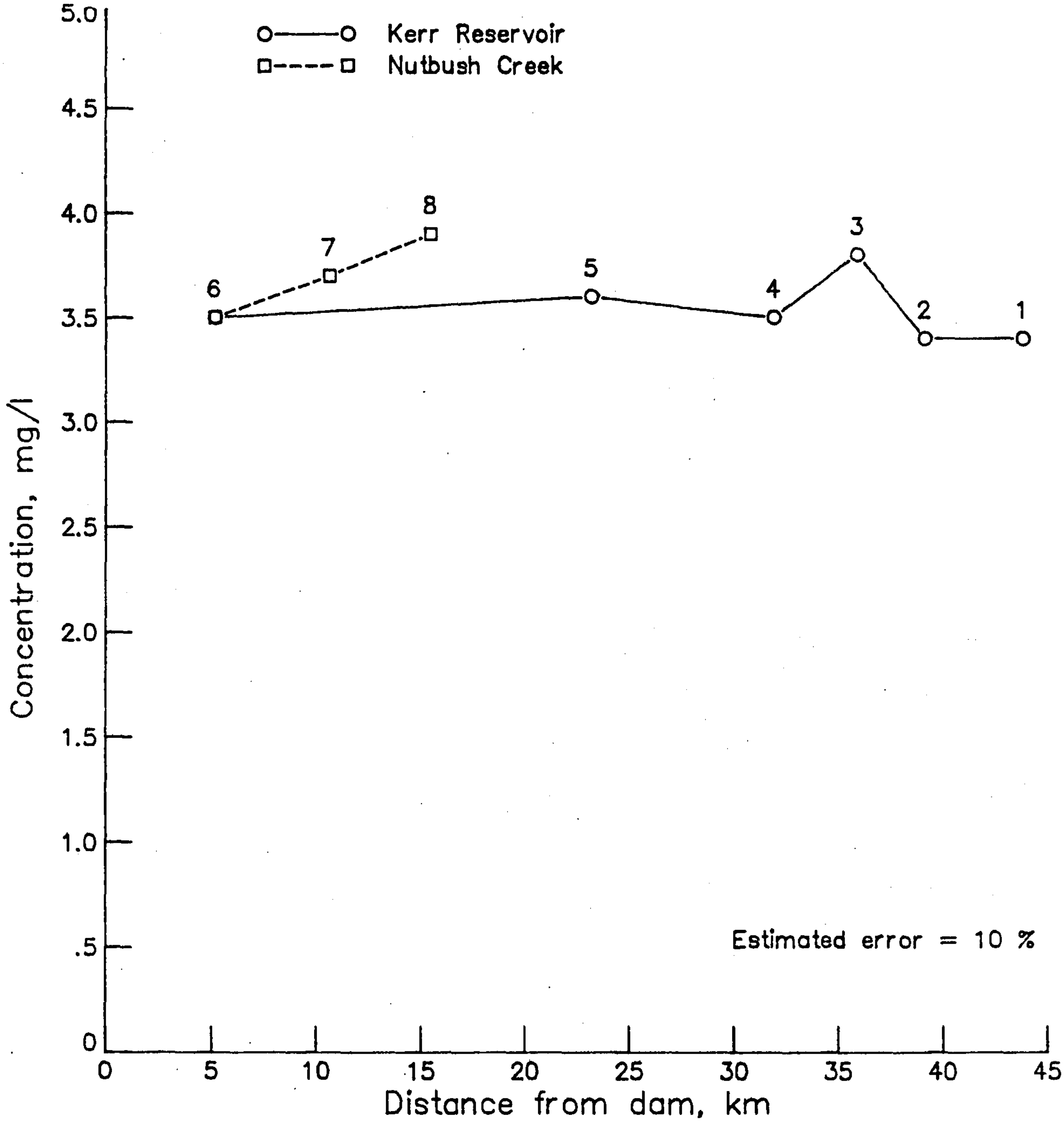
(h) Total organic carbon

Figure 2.- Continued.



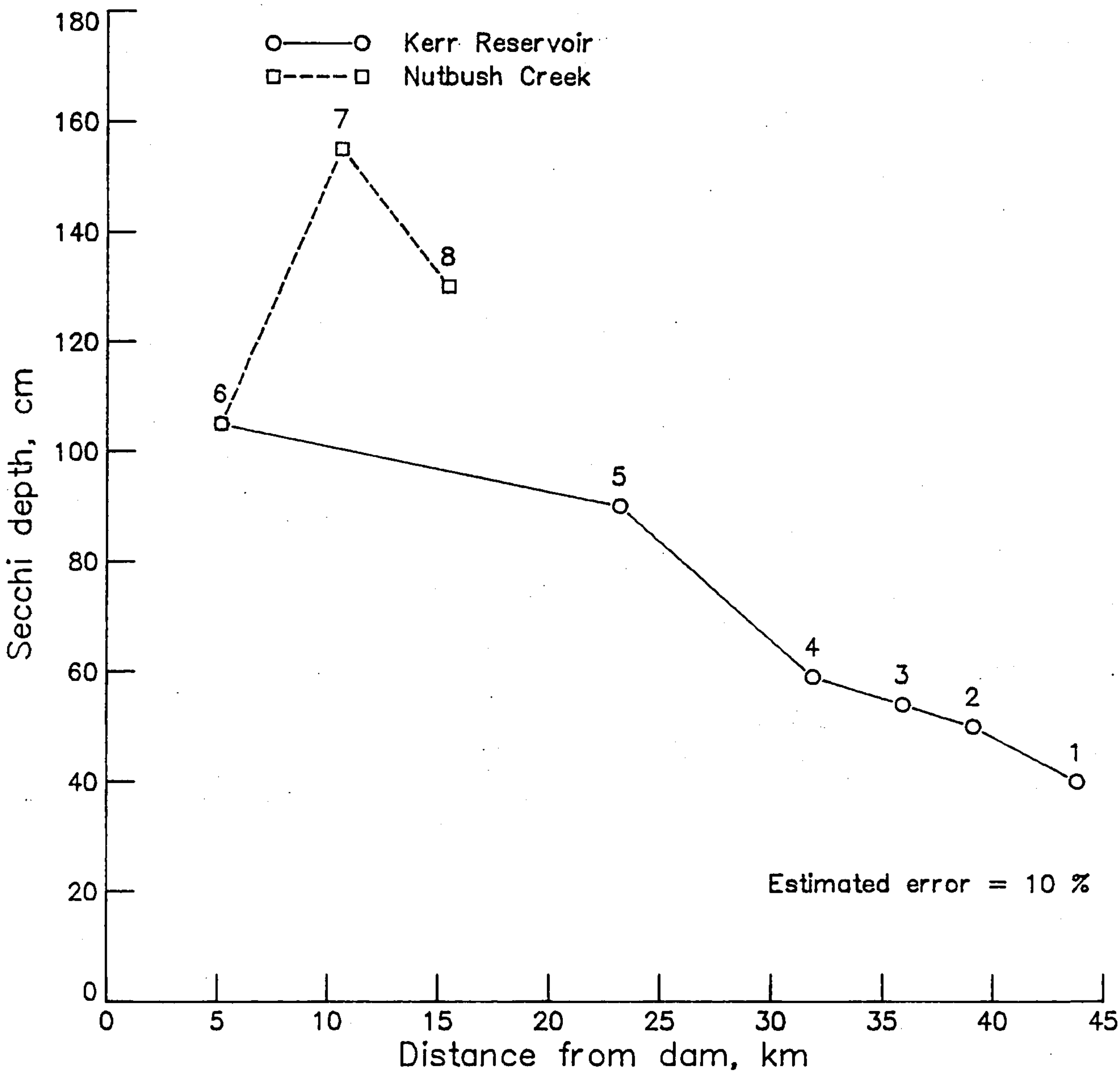
(i) Particulate organic carbon

Figure 2.- Continued.



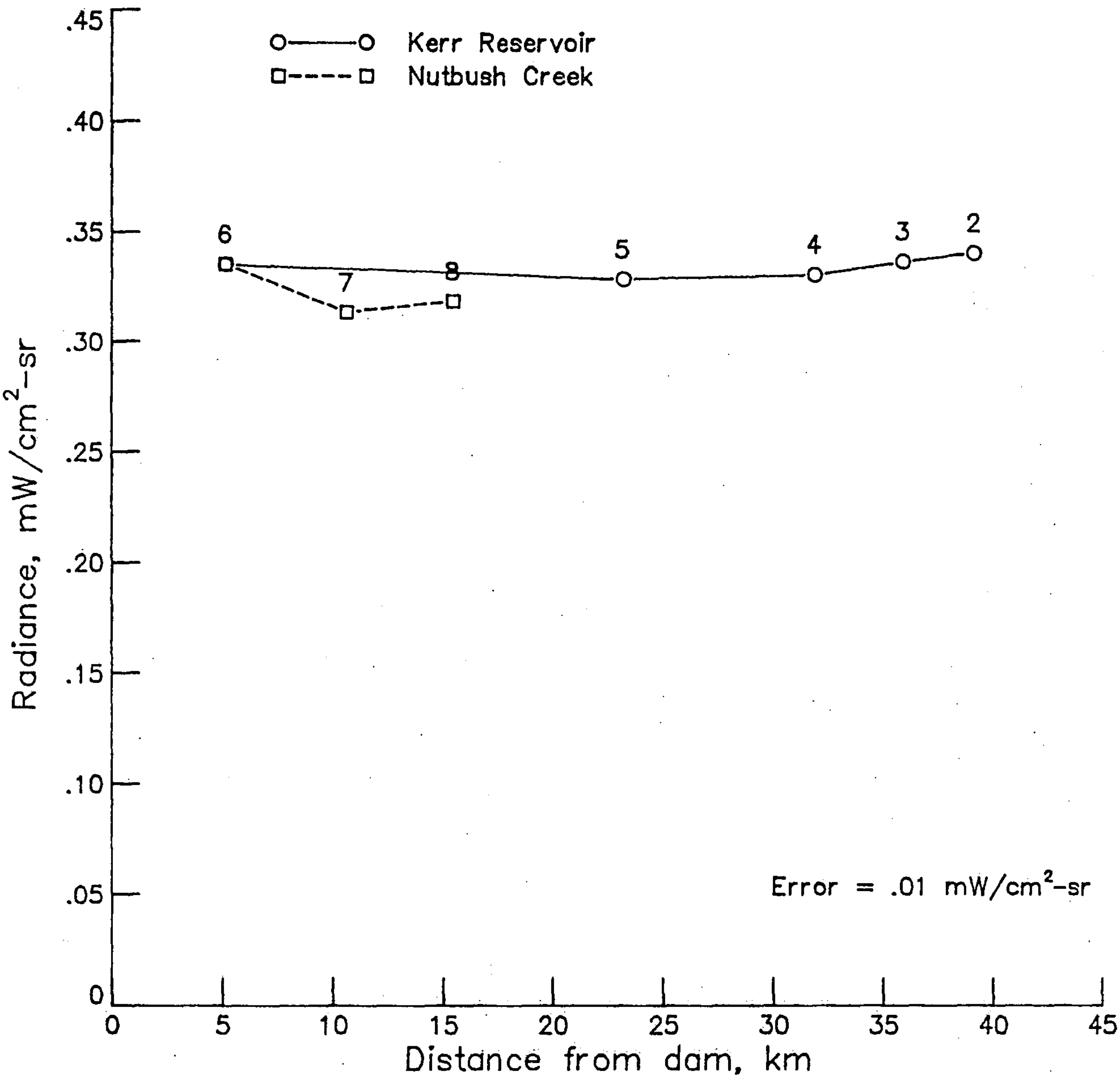
(j) Dissolved organic carbon

Figure 2.- Continued.



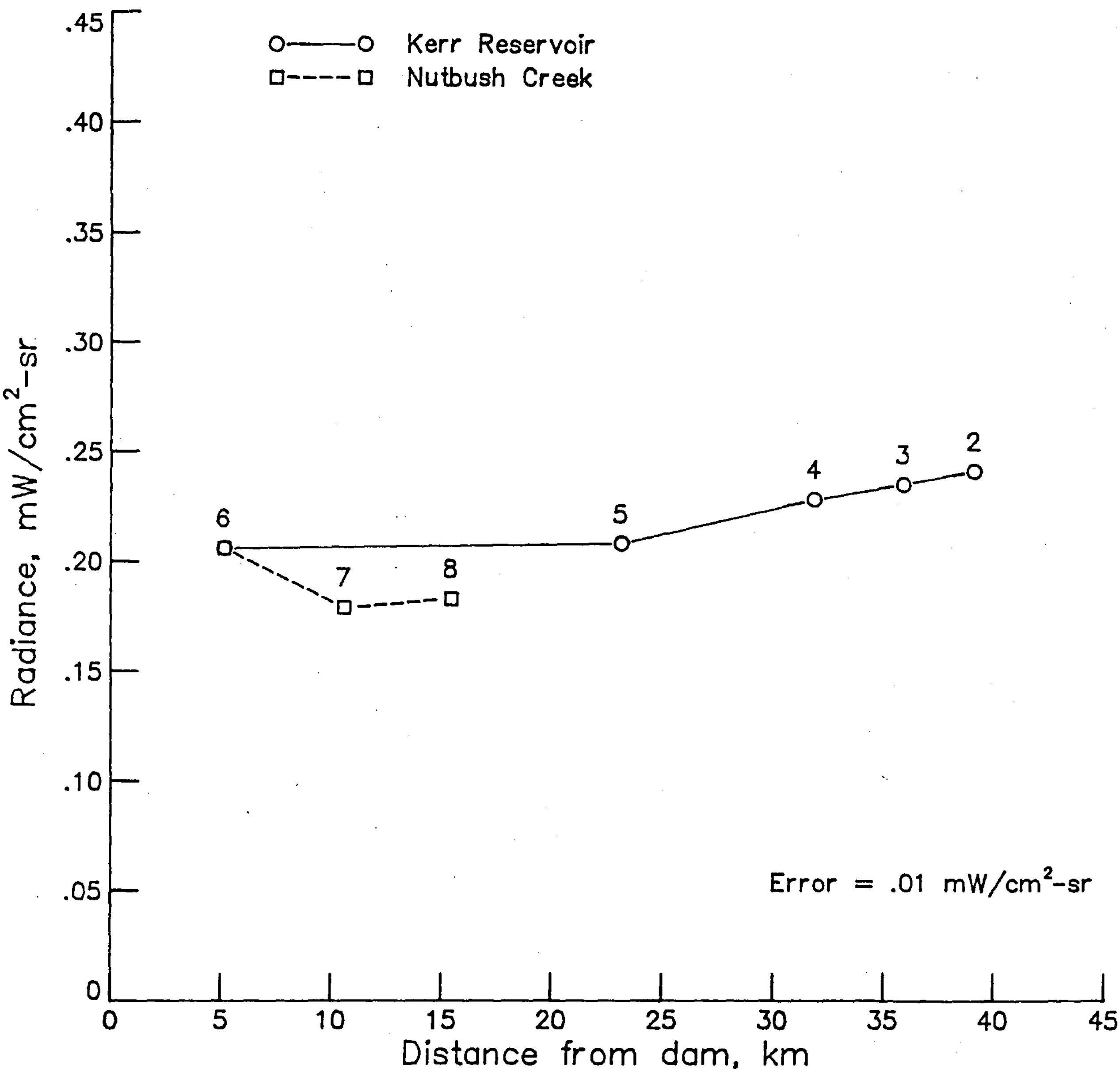
(k) Secchi depth

Figure 2.- Concluded.



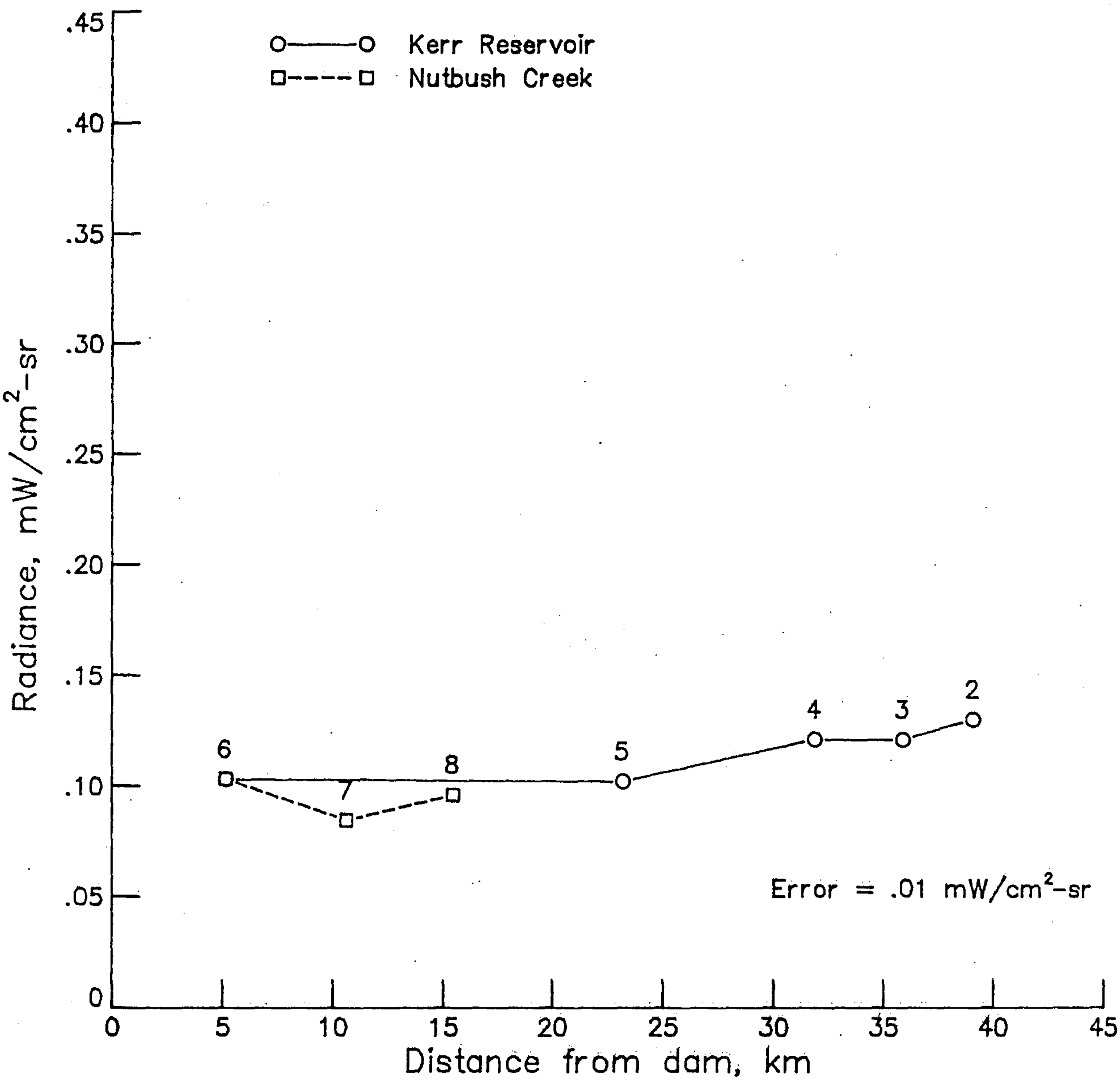
(a) Band 4

Figure 3.- Landsat radiances of Kerr Reservoir on November 19, 1980.



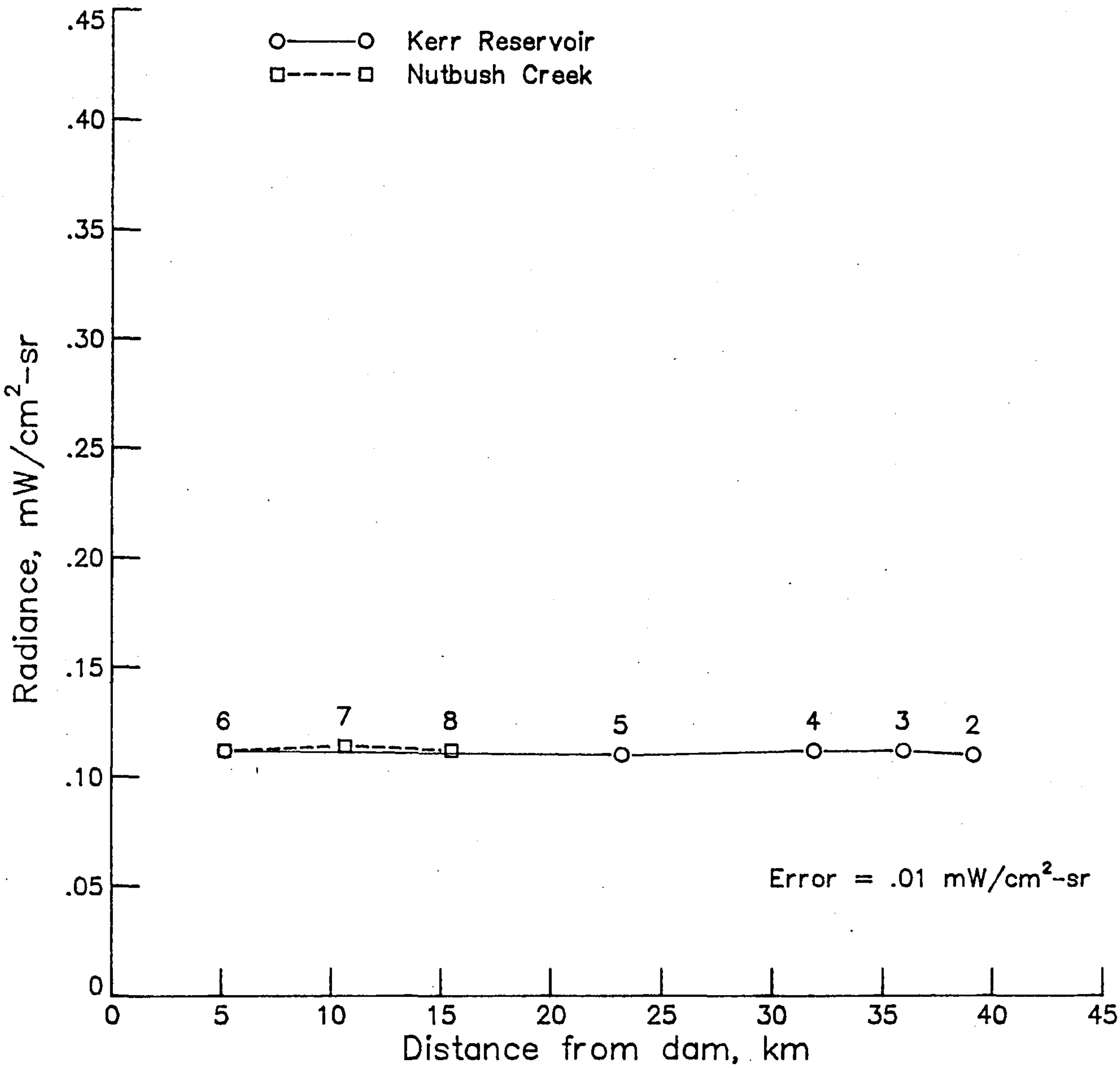
(b) Band 5

Figure 3.- Continued.



(c) Band 6

Figure 3.- Continued.



(d) Band 7

Figure 3.- Concluded.

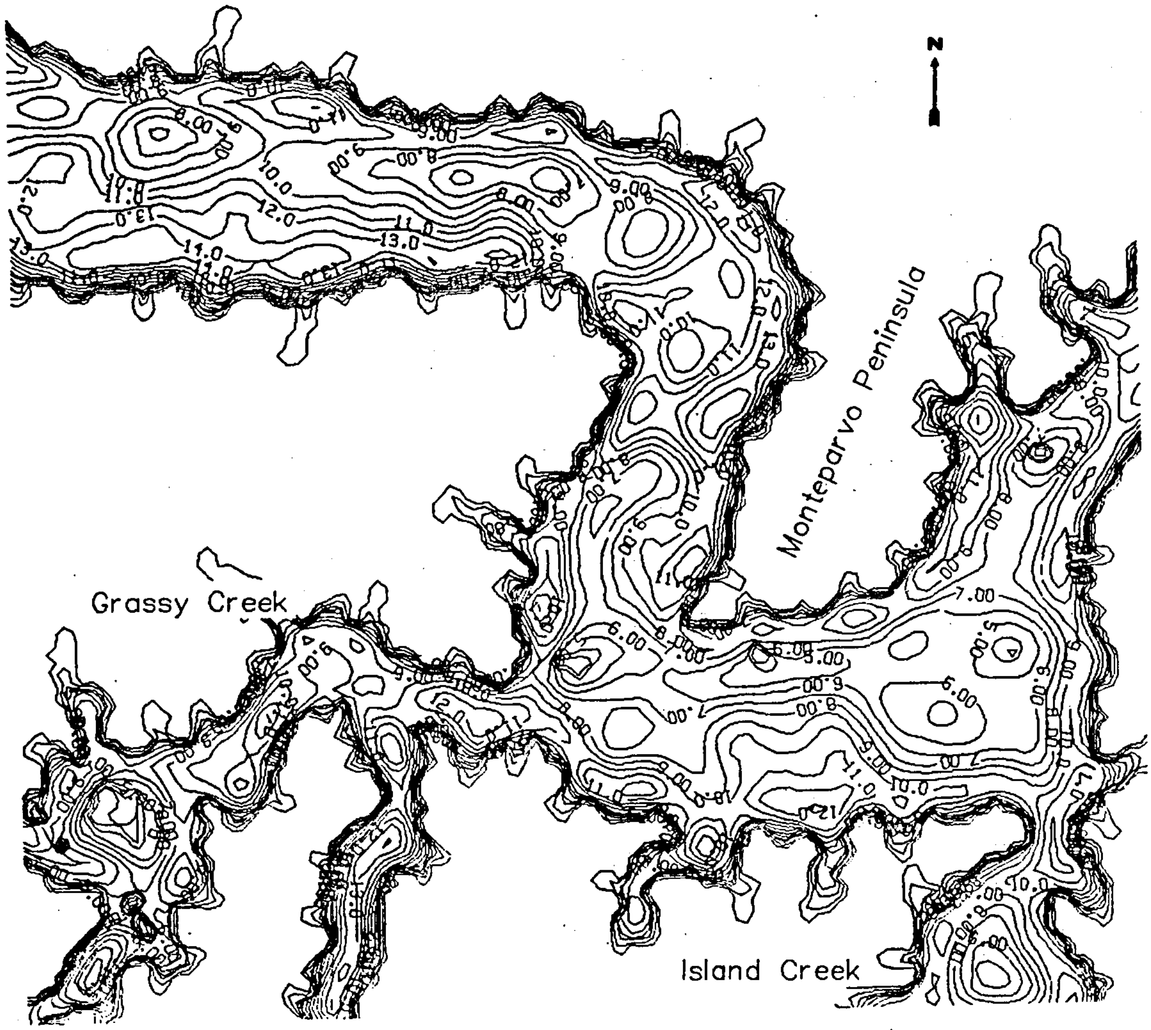


Figure 4.- Contour map for total suspended solids (mg/l) near Monteparvo Peninsula on Kerr Reservoir using Landsat's bands 4 and 5.

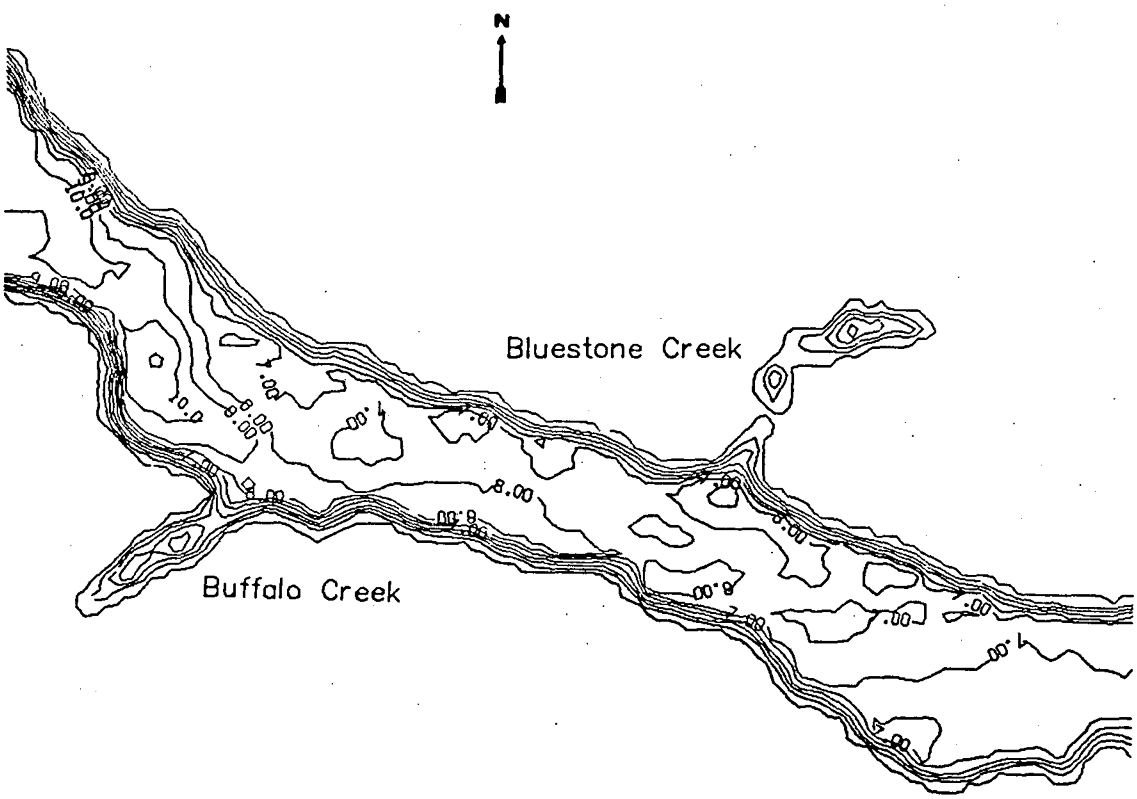


Figure 5.- Contour map for inorganic suspended solids (mg/l) near Buffalo Creek on Kerr Reservoir using Landsat's band 5.

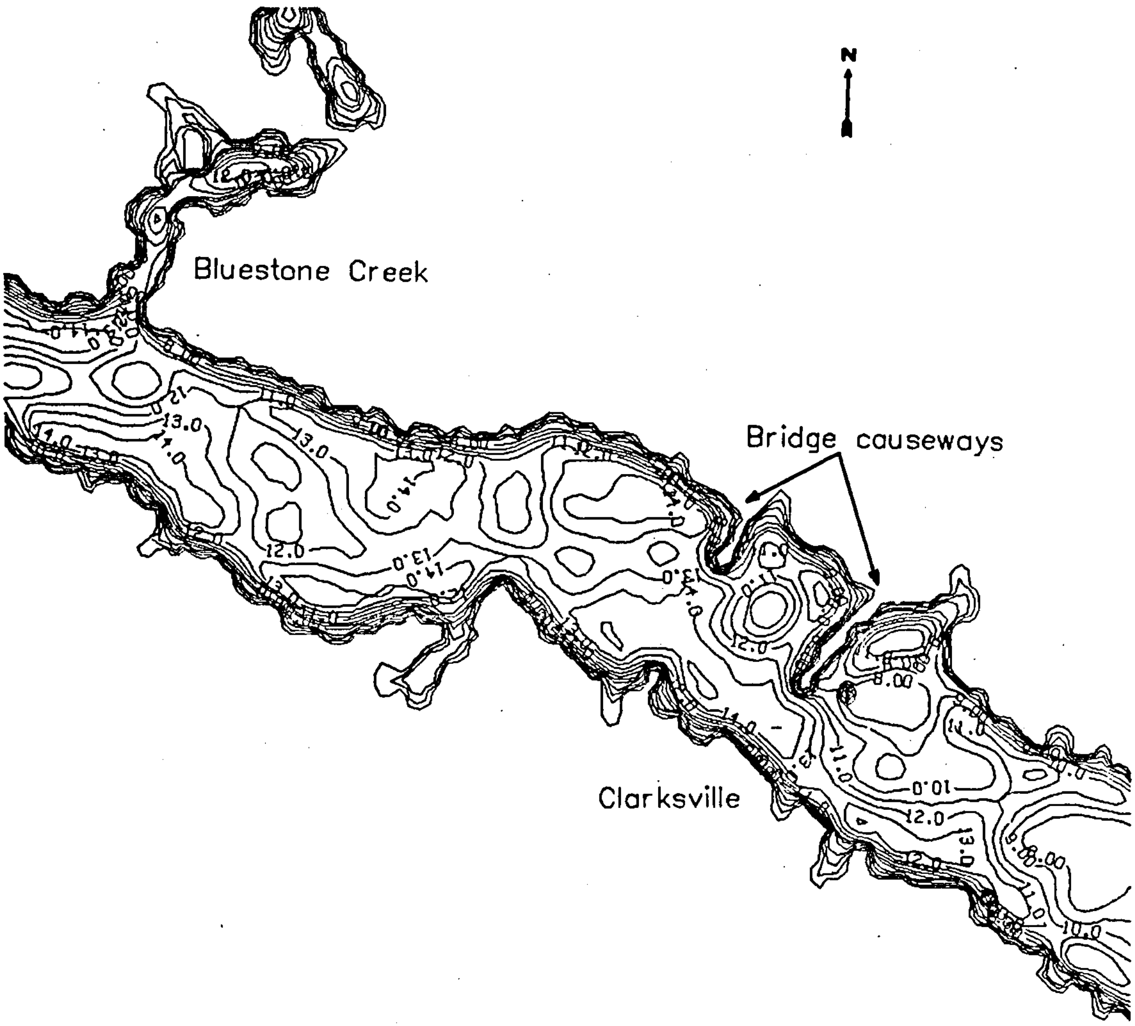


Figure 6.- Contour map for chlorophyll a ($\mu g/l$) near Clarksville on Kerr Reservoir using Landsat's bands 4 and 5.

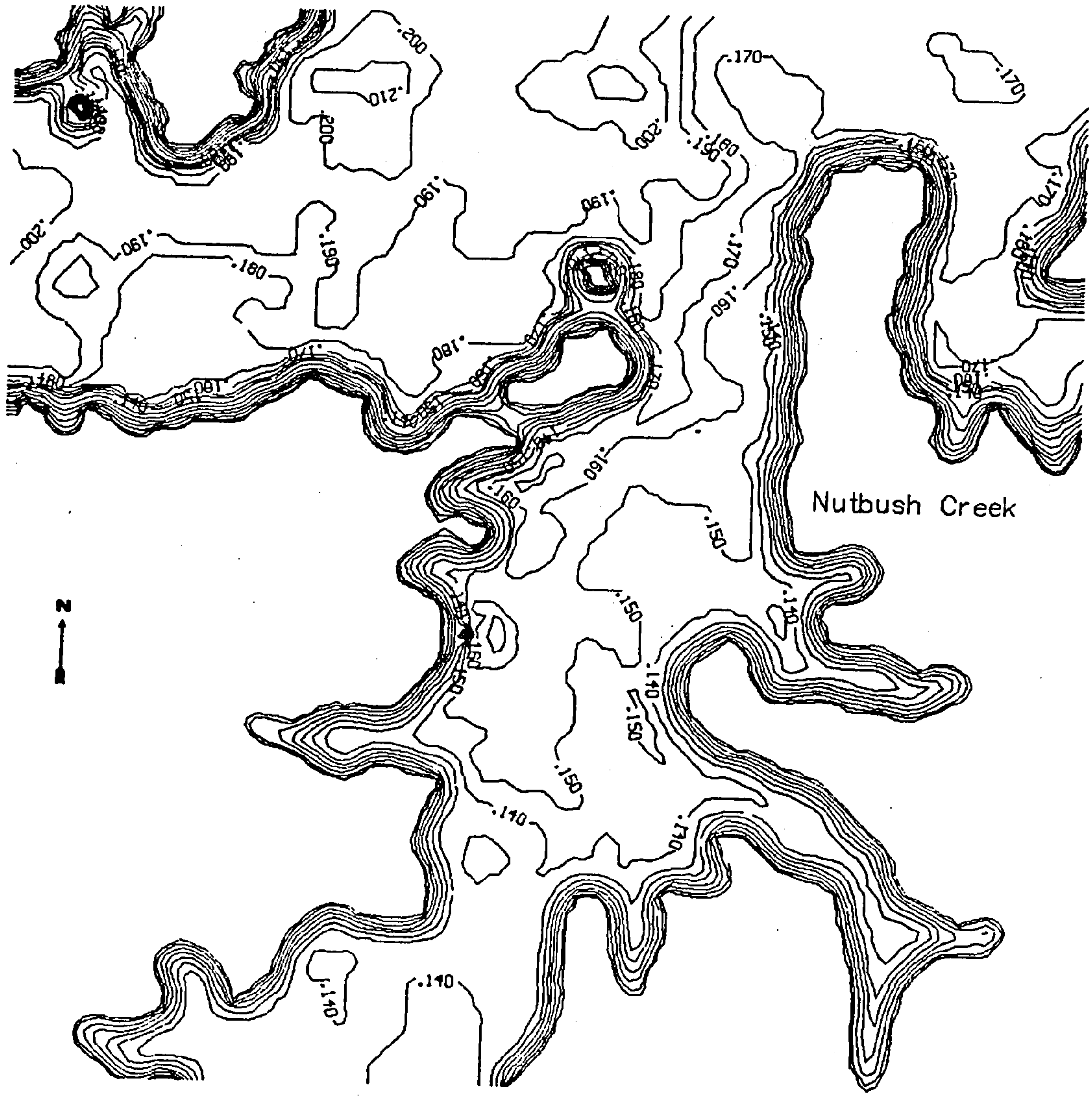


Figure 7.- Contour map for tannin and lignin (mg/l) near the mouth of Nutbush Creek on Kerr Resevoir using Landsat's band 5.

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15. Supplementary Notes

Langley Technical Monitor: Dr. Charles H. Whitlock

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 complete mix of different types of algorithms using the Landsat bands was generated to provide a thorough understanding of the relationships among the data involved. The study demonstrated that for the ranges measured, the algorithms that satisfactorily represented the data are mostly linear and only require a maximum of one or two Landsat bands. Ratioing techniques did not improve the results since the initial design of the experiment minimized the errors that this procedure is effective against. Good correlations were established for inorganic suspended solids, iron, turbidity, and secchi depth. Marginal correlations were discovered for total suspended solids, chlorophyll a, tannin + lignin, and particulate organic carbon. Low variability of the data resulted in poor correlation for nitrate, total organic carbon, and dissolved organic carbon. Quantification maps of Kerr Reservoir are presented for several 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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