QUANTITATIVE WATER QUALITY WITH LANDSAT AND SKYLAB* E-9

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ABSTRACT

LANDSAT Multispectral Scanner (MSS) reflectance levels are useful for quantitive measurement of suspended solids up to at least 900 ppm. MSS band ratios derived from computer compatible tape (CCT) can measure suspended solids with 67% confidence level accuracy of 12 ppm over the range 0-80 ppm and 35 ppm over the range 0-900 ppm. Suspended solids contour maps can be easily constructed from CCT's for water bodies larger than approximately 100 acres. Ratioing suppresses MSS reflectance level dependence on seasonal sun angle variation and permits measurement of suspended load the year round in the middle latitudes. These LANDSAT results are based on correlation studies between MSS CCT's and 170 water samples taken from three large Kansas reservoirs coincident with 16 different LANDSAT passes over a period of 13 months. SKYLAB imagery, S190A and S192, from a single pass over three reservoirs compares favorably to LANDSAT results up to 100 ppm. No samples were obtained with suspended solids greater than 100 ppm during the SKYLAB overpass. Typical mid-continent values for variables such as sun angle, wind speed and temperature do not significantly affect the correlation between satellite band ratios and suspended solids. The relatively high inorganic suspended solids, characteristic of mid-continent reservoirs, dominates the reflected energy present in the satellite spectral bands. Dissolved solids concentrations up to 500 ppm and algal nutrients up to 20 ppm are not detectable. The RED/GREEN ratio may have a weak negative correlation with total chlorophyll above $\sim 8 \mu g/l$.

INTRODUCTION

In the North American Great Plains, where natural permanent lakes are a rarity, the dominant limnological feature today takes the form of manmade reservoirs. The major reservoirs in Kansas, as well as in other Great Plains states, are playing increasingly important roles in flood control, recreation, agricultural and urban water supply and wildlife management. The primary influence on the reservoir ecosystem is the suspended load and chemicals carried in by streams and rivers. The reservoirs are typically shallow and thus are susceptible to mixing by strong winds which are a characteristic climatic feature of this region. Wind generated currents are of sufficiently high velocity to maintain a sizable fraction of the silts and clays in suspension and the result is turbid water (mean light extinction coefficient = 2.45 meter^{-1}). A method for acquiring timely low cost water quality data is needed to achieve optimum management of these fresh water resources.

A number of state and federal agencies in Kansas have expressed the need for repetitive water quality data such as suspended solids, dissolved solids, chlorophyll, and the algal nutrients. Some specific problems this data would apply to are discussed in the next several paragraphs.

The Forestry, Fish and Game Commission (FFGC) estimates that at least $18 million is spent annually by sport fisherman in Kansas. To help insure

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continued growth and good health for the sport fishing industry, the FFGC is interested in determining the effect of water environment on fish spawning and subsequent fish population. It is felt that the level of suspended solids significantly affects spawning and subsequent fish population. A knowledge of suspended load distribution in the lake would allow better fish management. Suspended load maps over a period of time would help to identify the best spawning areas within a reservoir and also would identify source points of undesirable high suspended load.

The Kansas State Health Department (KSHD) is concerned about the unpredictable occurrences of feedlot waste coming in contact with some of the city lakes used for drinking water. Feedlot waste usually contributes to the suspended load which is detectable by satellite. The KSHD is also concerned with chlorophyll and dissolved solids in the city lakes. The federal guideline of 500 PPM maximum allowable dissolved solids is often exceeded in the state of Kansas.

Temporal data on sediment load and source point location would allow better estimates of reservoir lifetime. Unusually high increases in sediment load/algal nutrients might permit timely identification of poor cultivation/fertilization practices upstream.

The goal of this study is to test the feasibility of using satellite imagery to monitor suspended load and chemical concentrations in Kansas reservoirs, which should be representative of most Great Plains reservoirs. This paper summarizes the contents of LANDSAT and SKYLAB contract final reports recently submitted to NASA (ref. 1,2). As work progressed on this project, a number of papers were presented at various symposia and subsequently published in proceedings (ref. 3-7). Figure 1 shows the distribution of the nineteen federal reservoirs in Kansas and the satellite ground traces used in this study. These reservoirs were built by the U.S. Army Corps of Engineers and the U.S. Bureau of Reclamation within the last 35 years. At normal pool elevation these water bodies have large surface areas relative to LANDSAT/SKYLAB resolution. The surface areas vary from about 3 square miles at Lovewell to about 25 square miles at Tuttle Creek. The shortest dimension of the main part of any of the reservoirs is approximately 1/2 mile. The largest dimension is about 20 miles. Depths vary from 40 to 50 feet at the dam to 1 to 2 feet at the upper end. Normal pool capacities vary from 10,000 to 500,000 acre-feet of water. In addition to the 19 major reservoirs there are approximately 100 smaller lakes in the state of Kansas with surface area greater than 20 acres as well as numerous stock ponds and ephemeral lakes which are detectable on LANDSAT and SKYLAB imagery.

The nineteen major reservoirs of Kansas are well distributed throughout the state occurring in a number of physiographic and land use regions that adequately represent much of the Great Plains environment. Lakes in extreme eastern Kansas lie within the humid portion of the state that is dominated by corn belt type agriculture. Lakes in central Kansas located within the Flint Hills and Smoky Hills escarpments collect drainage from important livestock grazing regions. Those reservoirs farther west in the semi-arid High Plains are in an important wheat and cattle producing area. Most of these lakes are operated by the Bureau of Reclamation and some are used for irrigation. Lakes in eastern Kansas are operated by the Corps of Engineers.

Two reservoirs, Perry and Tuttle Creek, were singled out for close study. Approximately ten water samples from each reservoir were collected during each cloud-free LANDSAT overpass for a 13 month period and analyzed for concentrations of inorganic suspended and dissolved solids, organic suspended and dissolved solids, chlorophyll, potassium, phosphate, and nitrate ions. In addition, secchi disc and temperature measurements were taken at each sampling station. Wind velocity and lake level were also recorded. These two reservoirs are distinct in terms of the geology and land-use of their watersheds. Perry lies in the Corn Belt of Eastern Kansas in an area that was glaciated during the Kansas stage of Pleistocene glaciation. Tuttle Creek lies farther west in the northern portion of the Flint Hills and has a watershed underlain by Permian and Cretaceous rocks where livestock grazing and small grains production are important. Occasionally samples were collected from Milford Reservoir which lies 20 miles southwest of Tuttle Creek.

In addition to the relatively large amount of LANDSAT data, SKYLAB data from one pass (SL-3 September 18, 1973) was studied for correlation with water quality in three reservoirs in southeastern Kansas (see Figure 1 for location and size of reservoirs). S190A and B imagery was obtained for Toronto, Fall River and Elk City reservoirs. S192 CCT's were obtained for Elk City reservoir (the narrower S192 field of view missed the other two reservoirs). Water samples were collected from ten stations on each reservoir the same day as the SL-3 overpass.

LANDSAT DATA ACQUISITION AND REDUCTION

Ground truth and imagery were accumulated during the first 23 LANDSAT cycles over the state of Kansas. Of the 46 combined cycles over Perry and Tuttle Creek Reservoirs, 25 were cloud-free. Water samples (grab samples from first 30 cm. of water) were collected for 18 of the 25 cloud-free reservoir cycles. Conditions such as ice cover, high wind and mechanical failure prevented sample collection for the remaining 7 cloud-free cycles.

Four bands of MSS imagery in the form of 9-inch black-and-white positive transparencies were acquired for 15 of the 18 cloud-free cycles with ground truth. MSS computer compatible tapes (CCT's) were acquired for 16 of the 18 cloud-free cycles with ground truth.

The suspended and dissolved solids were determined using normal evaporation plus gravimetric procedures. Dissolved solids are defined as material surviving a 0.45 micron filter. The inorganic fraction of suspended and dissolved solids is defined as material that survived 1 hour at 600°C. Chlorophyll a, b and c concentrations were determined by acetonic extraction (ref. 8) and subsequent spectrophotometric measurement (ref. 9). Nitrate, phosphate and potassium concentrations were determined spectrophotometrically (ref. 10) on a Beckman DU Spectrophotometer.

Digital levels for each water sample were extracted from the CCT by locating the sample station coordinates on a CCT generated computer printout gray level map, then averaging 9 pixels centered around the coordinate which corresponds to a 240 x 240 meter square area on the water surface.

The water quality data along with secchi depth, temperature, lake level, wind speed and CCT digital levels were entered onto a disc file accessible by a time-sharing terminal. This data was used to search for quantitative correlation between MSS imagery and water quality parameters. The 9" positive transparencies for each MSS band were electronically sliced and displayed on our IDECS (Image Discrimination, Enhancement, and Combination System) system. The color coded displays were recorded on 35 mm film for permanent storage and further analysis. The level slicing was done on the basis of equal vidicon output voltage intervals which is equivalent to equal log density intervals. The maximum number of levels/ image was determined by the dynamic range of the particular band over the reservoir surface and varied from 2 to 8 levels. The equal gray levels selected by IDECS correspond to nearly equal reflected energy intervals as defined on the NASA 15 step gray tablet. Maximum density variation (∿0.6 to 1.7) is usually found on the red band (MSS5) and corresponds to a power return range of 0 to ∿ 25%. The IDECS data was used as a qualitative guide in the study of quantitative correlation between water quality parameters and MSS CCT's.

SUN ANGLE EFFECTS

The multispectral scanner (MSS) in LANDSAT records light reflected from a scene illuminated by an admixture of sunlight and skylight (Figure 2). On relatively clear days the spectral shape of the illumination remains fairly constant throughout the year. However, the intensity, angle of incidence, and path length through the atmosphere depend on sun angle (angle above horizon). The reflectance levels from the concrete dam at Tuttle Creek Reservoir, a target with constant spectral reflectance, demonstrate a strong sun angle dependence in all MSS bands (Figure 3). As has been suggested by Vincent (ref. 11), the sun angle dependence is suppressed by plotting band ratios instead of absolute levels (Figure 4). The three other possible ratios, not plotted in Figure 4, also show a flat response to change in sun angle. Ratioing essentially removes the effect of unequal illuminating intensities caused by the continuously changing sun angle from one LANDSAT pass to the next. Since the ratio curves for the dam are flat, the angle of incidence and atmospheric scattering of reflected light are not important factors, at least for a concrete target.

Water reflectance levels do not exhibit as strong a dependence on sun angle, but there is a significant measureable effect (see Figure 5 for band 5 example). As for concrete, the absolute, reflectance levels for water decrease with lower sun angle. After ratioing (Figure 6) the three passes appear to be statistically similar. Dark object subtraction on each band before ratioing, as suggested by Vincent (ref. 11), does not significantly change the ratio curves in Figure 6. Dark object subtraction, which is the absolute level detected by LANDSAT minus level of darkest object in scene, should suppress atmospheric scattering effects present in the ratios.

These results suggest that the point scatter present in Figure 6 is not due to atmospheric scattering. For the remaining discussion it is assumed that, after ratioing, sun angle dependence and atmospheric scattering are relatively unimportant.

SUSPENDED SOLIDS

In general, bands 4, 5 and 6 (green, red, and near IR) exhibit substantial gray level variation across a reservoir surface. This gray level variation which is related to reflected energy detected by LANDSAT is highly correlated to the suspended sediment pattern in the reservoir. Bottom reflection is not a factor, because the reservoir bottom was not visible at any sample station. The subsequent discussion relates CCT digital levels (which are linearly proportional to reflected energy) to suspended load.

Band 4 shows no correlation beyond ∿ 50 ppm and is useful only for relatively clear water. This band (green) penetrates the water column more than the other bands (Figure 2), but as a consequence encounters a large amount of scattering material which produces saturation or maximum scattering at suspended solids levels (∿80 ppm) but its response to suspended load is quite similar to band 4. Band 6 exhibits good correlation over the entire range 0 to 240 ppm. The band 7 reflection levels are very low, but still show some correlation with increasing suspended load.

As expected from the analysis in the previous section, band 5 ratioed with band 4 (Figure 7) improves suspended load correlation and is roughly linear in the range of 0 to 80 ppm with RMS residual of 12 ppm. All regression fits displayed in subsequent figures were done with horizontal axis as the dependent variable and vertical axis as the independent variable. The band 6 correlation is also improved by ratioing with band 4 (Figure 8). The MSS6/MSS4 ratio is linearly related to suspended solids in the region $\leq$ 100 ppm with an RMS residual of 19 ppm. The band 7 correlation, after ratioing with band 4, is not significantly improved.

Although the bulk of the suspended solids measurements were $\leq$240 ppm, there were a few (samples collected upstream in the reservoir after a recent rain) that extended as high as 900 ppm. The MSS5/MSS3 ratio rises sharply to $\sim$ 80 ppm then turns over and remains flat up to 900 ppm which is the limit of this investigation. The MSS6/MSS4 ratio (Figure 9) rises sharply to $\sim$ 120 ppm then turns over, but continues to correlate well with suspended solids up to 900 ppm. It appears that this correlation would continue well beyond 900 ppm. A smooth polynominal fit over the range 0-900 ppm yields an RMS residual of 35 ppm. Band 7/Band 4 (Figure 10) also shows correlation up to 900 ppm with an RMS residual of 44 ppm. The same third order fit to band 7 (not ratioed with another band) yielded an RMS residual of 46 ppm. Since band 7 is nowhere near maximum reflection at 900 ppm it is expected this band would continue to correlate up to extremely high suspended loads.

Table I summarizes the correlations between the three MSS ratios and suspended solids. The regression coefficients can be used to predict suspended load from CCT digital levels. MSS5/MSS4 is effective in the range 0-80 ppm with accuracy of 12 ppm. MSS6/MSS4 is effective in the range 0-120 or 0-900 ppm with accuracies of 19 and 35 ppm respectively. MSS7/ MSS4 is useful over the range 0-900 ppm with 44 ppm accuracy. It appears that the regression coefficients for MSS6/MSS4 and MSS7/MSS4 fits would be applicable substantially beyond 900 ppm, although this is not confirmed experimentally.

Figure 11 is an example of a suspended solids contour maps which was produced, in an earlier stage of this study, using regression coefficients that related band 5 to suspended solids. The coefficients were derived from four nearly equal high sun angle cycles which yielded an RMS residual of 5 ppm. In this particular case, ratioing was not required, since the correlation was based on nearly equal sun angle cycles.

SECCHI DEPTH

Analysis in the previous section establishes that suspended solids in water are strongly correlated with reflected energy present in the four MSS bands. Secchi depth (or water clarity) is inversely correlated with suspended solids measurements $\gtrsim$ 15 ppm which represents the bulk of the data in this study. Linear regression of suspended solids against inverse secchi depth yields an RMS residual of 18 ppm, so that a secchi depth measurement can be used to determine suspended load to this level of accuracy.

The MSS5/MSS4 ratio is linearly correlated with secchi depth $\lesssim$ 0.6 meters (Figure 12), with RMS residual of 0.11 meters, which is merely a reflection of the fact that secchi depth is correlated with suspended solids $\gtrsim$ 15 ppm. Beyond 0.6 meters ($\gtrsim$ 15 ppm), where this ratio is not well correlated with suspended solids, the ratio correlation with secchi depth is much weaker, but still appears to decline slightly for increasing depths. MSS correlation with sunlight penetration depth in relatively clear ocean water has been found by other workers (ref. 12) and used to map ocean bottom to depths of 10 meters.

MSS6/MSS4 correlates with secchi depth down to $\sim$ 0.4 meters with RMS residual 0.06 meters (Figure 13). The correlation at shallow depth $\lesssim$ 0.2 meters is improved over the MSS5/MSS4 correlation. This is expected since this secchi depth range corresponds to suspended solids $\gtrsim$ 80 ppm where MSS5/MSS4 is poorly correlated. MSS7/MSS4 correlates with secchi depth up to $\sim$ 0.3 meters with RMS residual of 0.05 meters (not shown).

In summary, secchi depth correlates well with MSS ratios in relatively turbid water (suspended solids $\geq$ 15 ppm), but is primarily a reflection of the fact that secchi depth is correlated with suspended solids. Nevertheless, MSS ratios are useful for direct prediction of water clarity (secchi depth). Table II summarizes the results of the regression analysis.

WIND AND TEMPERATURE EFFECTS

An average wind velocity for each LANDSAT reservoir cycle was recorded along with a temperature measurement t each sample station. The three MSS ratios show no systematic correlation with wind speed (see Figure 14 for MSS5/MSS4 example) up to 21 miles/hour. As expected from previous laboratory work on distilled water (ref. 13), the MSS ratios exhibit no correlation with water temperature (Figure 15).

ORGANIC AND DISSOLVED SOLIDS

The character of the sediment carried into Tuttle Creek and Perry reservoirs can be summarized as follows. The lower part of the Blue River basin, which drains into Tuttle Creek, consists mainly of residual and alluvial soils derived from shales and limestones. The upper portion has loessial soils underlain by glacial tills and alluvial sands. The average particle size of the bottom sediment is 2 microns (ref. 14). The suspended sediment consists mostly of the three clays vermiculite, illite and kaolinite. Perry reservoir drains a basin consisting mostly of loessial soils underlain by glacial tills. Perry is generally not as turbid as Tuttle Creek, but its suspended sediment is very similar in mineralogy and degree of aggregation.

The following characterizes the composite sample set collected over a 13 month period from three reservoirs. The bulk of the samples contain total solids in the range 200 to 500 ppm. The suspended sediment fraction of the total solids ranges from 2 to 50%. The organic fraction of the suspended sediment is almost constant at 14% and is thus highly correlated with total suspended solids. Consequently, the MSS ratio correlation with organic suspended load (not shown) is merely a reflection of the MSS ratio dependence on total suspended load.

The dissolved solids fraction of total solids ranges from 50 to 98% which is, of course, the compliment of the suspended solids fraction. The organic fractions of dissolved solids range from 10 to 50%. The dissolved solids appear to be uncorrelated with suspended solids so that this experiment should be able to detect any appreciable influence dissolved solids have on reflected energy levels in the MSS bands. However, MSS5/MSS4 does not show any obvious correlation with dissolved solids. The MSS6/MSS4 ratio also does not reveal any correlation with dissolved solids.

In summary, dissolved solids up to 500 ppm, whose mineralogic characteristics were discussed in the first part of this section, do not influence energy levels present in the four MSS bands.

CHLOROPHYLL AND ALGAL NUTRIENTS

Based on the anlysis presented earlier, it is obvious that MSS correlation with water quality parameters such as chlorophyll and the algal nutrients will be slight, if detectable at all.

The absorption peaks of chlorophyll a, b and c, which are 665mμ, 645mμ and 630mμ respectively, fall inside MSS band 5 (see Figure 2). The presence of chlorophyll, therefore, would cause an energy decrease in band 5. The characteristic green color of chlorophyll would cause an increase in band 4 energy which means the MSS5/MSS4 should be negatively correlated with chlorophyll.

Total chlorophyll appears to be largely uncorrelated with suspended sediment (plot now shown), so any appreciable effect concentrations up to 20μg/l have on MSS ratios should be detectable. The MSS5/MSS4 shows no obvious correlation with the composite 13 month sample collection. The subset of samples, whose suspended load (>80 ppm) causes no variation in the MSS5/MSS4 ratio, also does not show any significant negative correlation with chlorophyll.

The residual MSS5/MSS4 ratio, obtained by removing the linear ratio dependence on suspended solids for samples with <80 ppm suspended load, is shown in Figure 16. As can be seen, a slight negative correlation with total chlorophyll may be setting in for chlorophyll concentrations $\gtrsim$8μg/l. Chlorophyll a, b and c were studied individually with results consistent with those for total chlorophyll. In each case, the 3 to 6 samples with highest concentration appeared to have a slight negative correlation with MSS5/MSS4.

In summary, typical chlorophyll levels in Kansas reservoirs of 0 to 8μg/l are not detectable by LANDSAT. There does seem to be a slight negative correlation with MSS5/MSS4 beyond 8μg/l but there are not enough samples to determine a reliable quantitative correlation. Other workers (ref. 15) have found that LANDSAT is able to detect chlorophyll at ~10μg/l concentration in relatively clear seawater. In our case, the noise from the relatively high turbidity is probably masking the chlorophyll signal from Kansas reservoirs.

Concentrations of potassium, phosphate and nitrate were studied for possible influence on reflected energy levels present in the four MSS bands. The results were negative except for some MSS ratio correlation with phosphate. This is due, however, to the fact that phosphate is somewhat correlated with suspended solids. In summary, the algal nutrients potassium, phosphate and nitrate at concentration levels up to 20, 2 and 10 ppm respectively are not correlated with LANDSAT imagery.

CCT'S VS. POSITIVE TRANSPARENCIES

Densitometer measurements were made of reservoir images and the accompanying gray-step scale at the bottom of each image. The gray steps are linearly related to CCT levels so that density measurements can be directly converted to an equivalent CCT levels. An example is shown in Figure 17. CCT and density values compare quite favorably thus indicating that density measurements should produce quantitative results comparable to those obtained using CCT's.

In Figure 18 IDECS levels are compared with digital tape levels for a cycle over Perry Reservoir. IDECS levels were normalized to the CCT levels by matching the lowest and highest IDECS levels to the lowest and highest CCT levels repsectively. As seen in Figure 18 the two methods of analysis compare favorably. Other cycles produced equally favorable results. In general, IDECS levels, once normalized to CCT levels agree well with CCT levels. However, IDECS levels, which are gray levels obtained from 9" transpar is are not useful in an absolute sense. IDECS levels are useful for qualitatively displaying relative suspended load distribution in a reservoir. IDECS levels are not related to a standard scale, as are the CCT levels, so are not as useful quantitatively.

SKYLAB IMAGERY

SKYLAB imagery was obtained for one SL-3 pass over southeastern Kansas. This imagery consists of S190A and B film and S192 CCT's. The S190A is in the form of 70 mm and 4X enlarged positive transparencies of the four bands green, red, IR_1 and IR_2 (see Figure 2 for band widths) and covers the three reservoirs Toronto, Elk City and Fall River (see Figure 1). The S190B is 5" aerial color over the same three reservoirs. The S192 CCT covers Elk City Reservoir only.

The superior resolution of S190B provides an excellent qualitative "first look" at turbidity patterns. This imagery will not, however, provide quantitative information on suspended solids. The S190A 70 mm transparencies were measured on a macrodensitometer with a 1 mm aperture. The small size of the reservoirs on 70 mm film permitted only one density measurement per reservoir. The densities were converted to absolute radiance levels using SL-3 sensitometric data (ref. 16) provided by NASA. The radiance levels are plotted against average suspended solids for each reservoir (Figure 19). The shaded areas in Figure 19 represent LANDSAT radiance levels for about 60 water samples from 7 passes with comparable sun angles. The agreement between S190A and LANDSAT in the three bands green, red and IR is quite good.

Digital level maps from S192 CCT's for Elk City reservoir were generated for the three bands shown in Figure 19. Nine pixels were averaged at each measurement station and converted to an absolute radiance level using the calibration coefficients on the CCT header record. The radiance levels for each station are shown as solid points in Figure 19. S192 green represents an average of band 3 and 4 (see Figure 2 for equivalent S192 green band width). The agreement between SKYLAB S192 and LANDSAT MSS is poor, fair and good respectively in the three bands green, red and IR. The poor agreement in the green band may be due to the fact that the band widths for S192 green and LANDSAT green are not an exact match.

SKYLAB band ratios vs. suspended solids are shown in Figure 20. All ratios, except perhaps S192 red/green, are consistent with linear fits to LANDSAT ratios.

The S190A 4X enlargements permitted density measurements of individual measurement stations on each reservoir. We have been unable to obtain the sensitometric data required to relate density on the enlargements to absolute radiance. However, if the reservoir densities are in the linear region of the density vs. log(exposure) curve for the film, then the radiance ratio can be written as

$$\frac{Ei}{Ej} = k \frac{10^{-Di}}{10^{-Dj}}$$

where Ei and Ej are band i and j radiances from the target and Di and Dj are corresponding film densities. K is a constant determined by the slope of the D vs. logE curve which relates the density of our film copy to the original exposure on SKYLAB. K also depends on filter and camera lense attenuation coefficients, shutter speed, etc. This constant has not yet been determined but is arbitrarily set = 1 in Figure 21. The absolute ratio values cannot be compared to S192 or LANDSAT because of the lack of sensitometric calibration data. The red to greed band ratio (Figure 21) exhibits a good linear correlation with suspended solids (RMS residual of 6 ppm). Beyond 80 ppm the LANDSAT MSS red/green ratio flattens out. We would expect the SKYLAB S190A red/green ratio to also flatten out, but the relatively clear water sampled does not permit confirmation of this.

In summary, the small amount of data available from the S190A and S192 is in general quantitatively consistent with water reflectance levels measured by the LANDSAT MSS sensor. It appears that S190A is superior to S192 for the purpose of predicting suspended solids in water. More data is needed to confirm this single pass result.

CONCLUSIONS

LANDSAT MSS ratios derived from CCT's are very effective for quantitative detection of suspended solids up to at least 900 ppm, which is the limit of this investigation. The actual upper limit on suspended solids LANDSAT can detect is probably substantially higher. Typical mid-continent values for variables such as sun angle, wind speed and temperature do not significantly affect MSS ratios.

Dissolved solids up to at least 500 ppm are not correlated with LANDSAT imagery. The algal nutrients potassium, phosphate and nitrate at concentration levels up to 20, 2 and 10 ppm respectively are not correlated with LANDSAT imagery. The MSS5/MSS4 ratio appears to be weakly correlated with total chlorophyll above concentration levels of $\sim 8 \mu g/l$, but more data are needed to confirm this.

Density measurements from the NASA 9" positive transparencies compare favorably with CCT levels. It would be relatively simple and inexpensive for interested agencies or groups to obtain suspended load information by using a macrodensitometer.

A small amount of data from the SKYLAB sensors S190A and S192 is consistent with LANDSAT results. S190A appears to do a superior job compared to S192 in measurement of suspended solids. Both sensors are probably as effective as the LANDSAT MSS for measuring suspended solids in water.

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TABLE 1. RESULTS OF FITTING SUSPENDED SOLIDS MEASUREMENTS TO CCT MSS BAND RATIOS. EQUATION USED IN FIT WAS $SS = a_0 + a_1 R_{ij} + a_2 R_{ij}^2 + a_3 R_{ij}^3$ WHERE SS = SUSPENDED SOLIDS (PPM) AND R_{ij} = (BAND$_i$ AVERAGE CCT LEVEL FOR 9 PIXELS)/(BAND$_j$ AVERAGE CCT LEVEL FOR 9 PIXELS).

MSS BAND RATIO	RANGE OF APPLICABILITY IN PPM	RMS RESIDUAL IN PPM	$a_0 \times 10^{-2}$	$a_1 \times 10^{-2}$	$a_2 \times 10^{-2}$	$a_3 \times 10^{-2}$
R_{54}	0-80	12	-0.793	1.387	-	-
R_{64}	0-120	19	-0.426	1.768	-	-
R_{64}	0-900	35	-6.403	42.598	-89.112	62.373
R_{74}	0-900	44	0.090	5.580	-43.879	254.654

TABLE 2. RESULTS OF FITTING SECCHI DEPTH MEASUREMENTS TO CCT MSS BAND RATIOS. EQUATION USED IN FIT WAS $SD = a_0 + a_1 R_{ij}$ WHERE SD = SECCHI DEPTH (METERS) AND R_{ij} = (BAND$_i$ AVERAGE CCT LEVEL FOR 9 PIXELS)/(BAND$_j$ AVERAGE CCT LEVEL FOR 9 PIXELS).

MSS BAND RATIO	RANGE OF APPLICABILITY IN METERS	RMS RESIDUAL IN METERS	a_0	a_1
R_{54}	0-0.70	0.11	1.210	-1.061
R_{64}	0-0.40	0.06	0.526	-0.529
R_{74}	0-0.30	0.05	0.278	-0.727

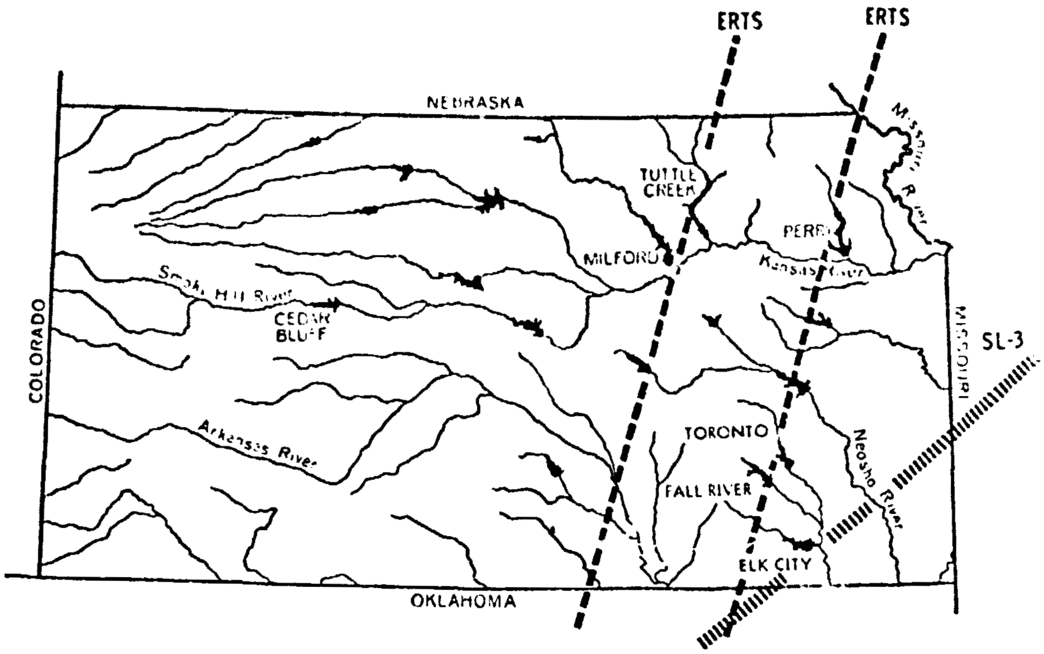

FIGURE 1. LANDSAT AND SKYLAB 3 GROUND TRACKS IN KANSAS.

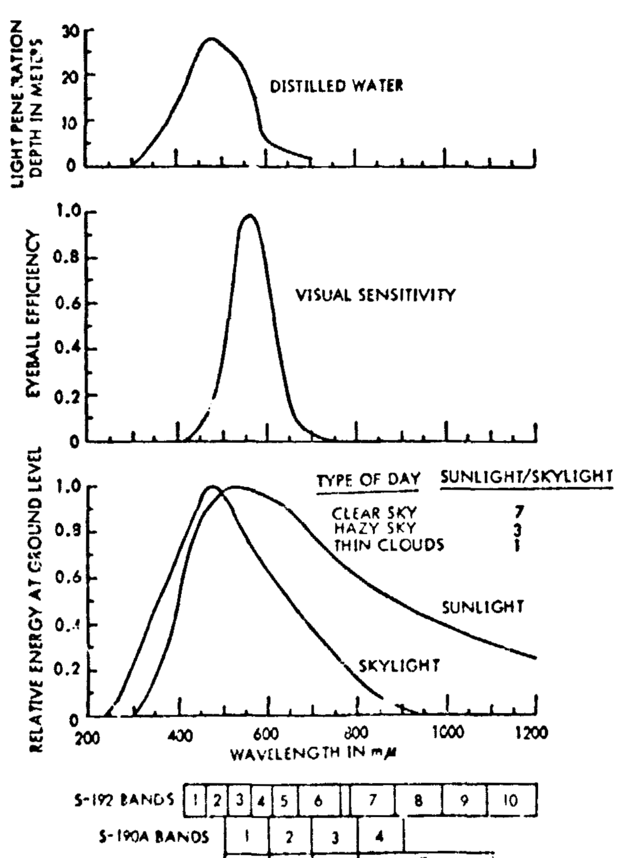

FIGURE 2. RADIANCE vs WAVELENGTH.

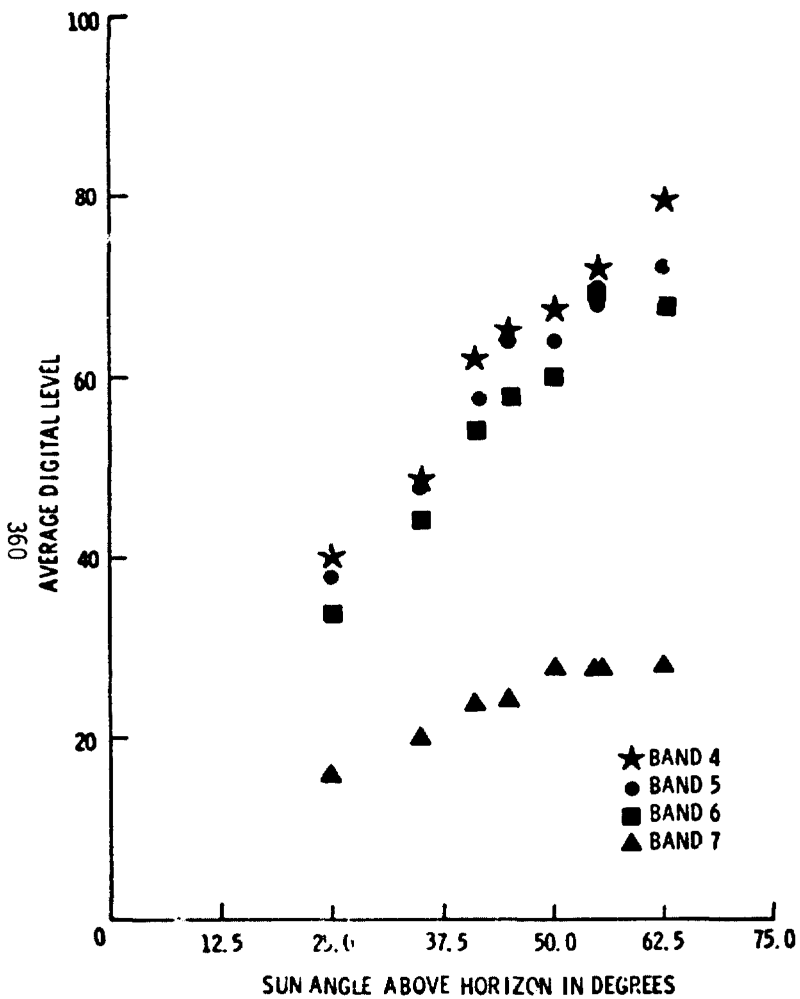

FIGURE 3. MSS DIGITAL LEVELS FROM CCT VS. SUN ANGLE FOR TUTTLE CREEK CONCRETE DAM.

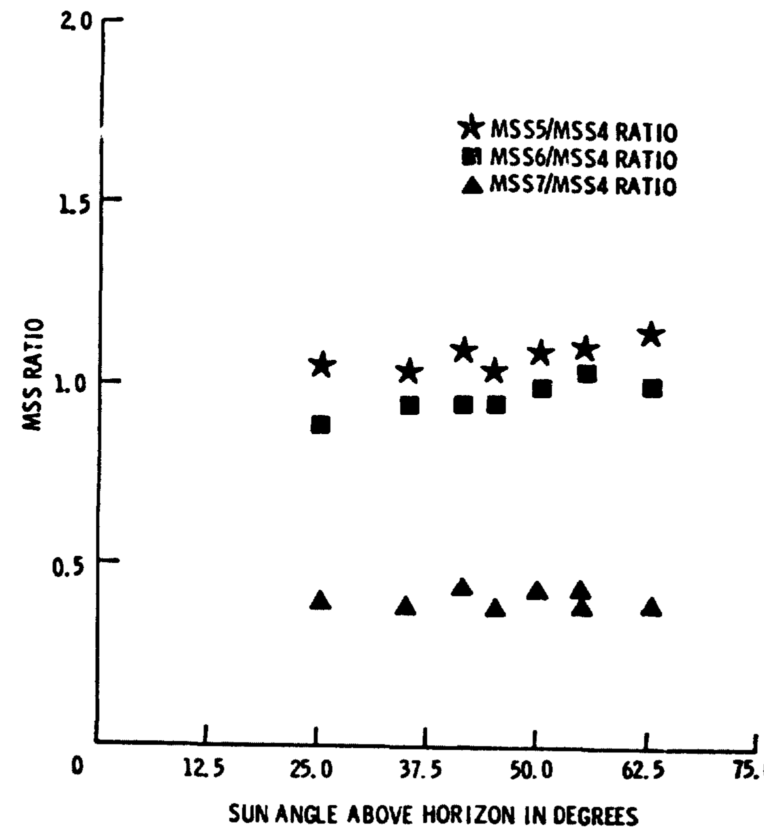

FIGURE 4. MSS BAND RATIOS FROM CCT VS. SUN ANGLE FOR TUTTLE CREEK CONCRETE DAM.

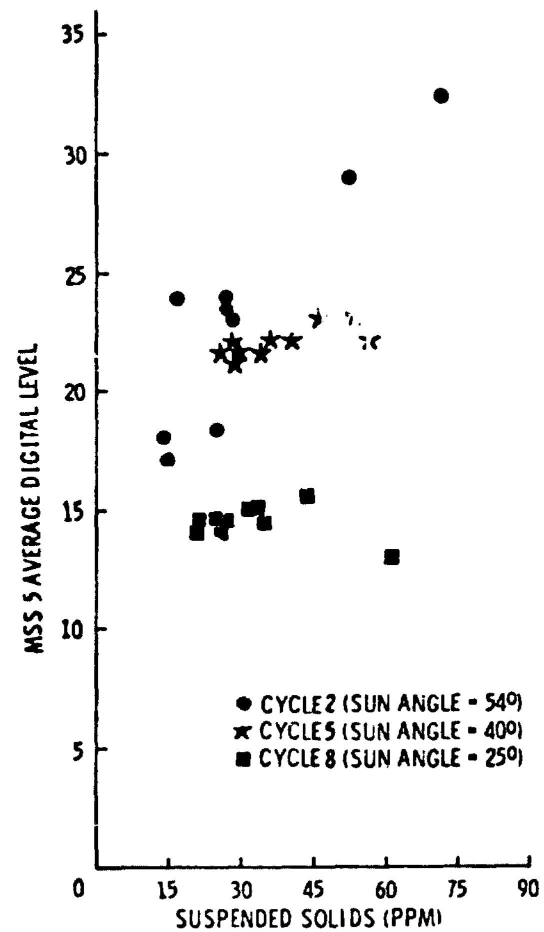

FIGURE 5. MSS5 DIGITAL LEVELS FROM CCT VS. SUSPENDED SOLIDS FOR 28 WATER SAMPLES FROM 3 LANDSAT-1 CYCLES.

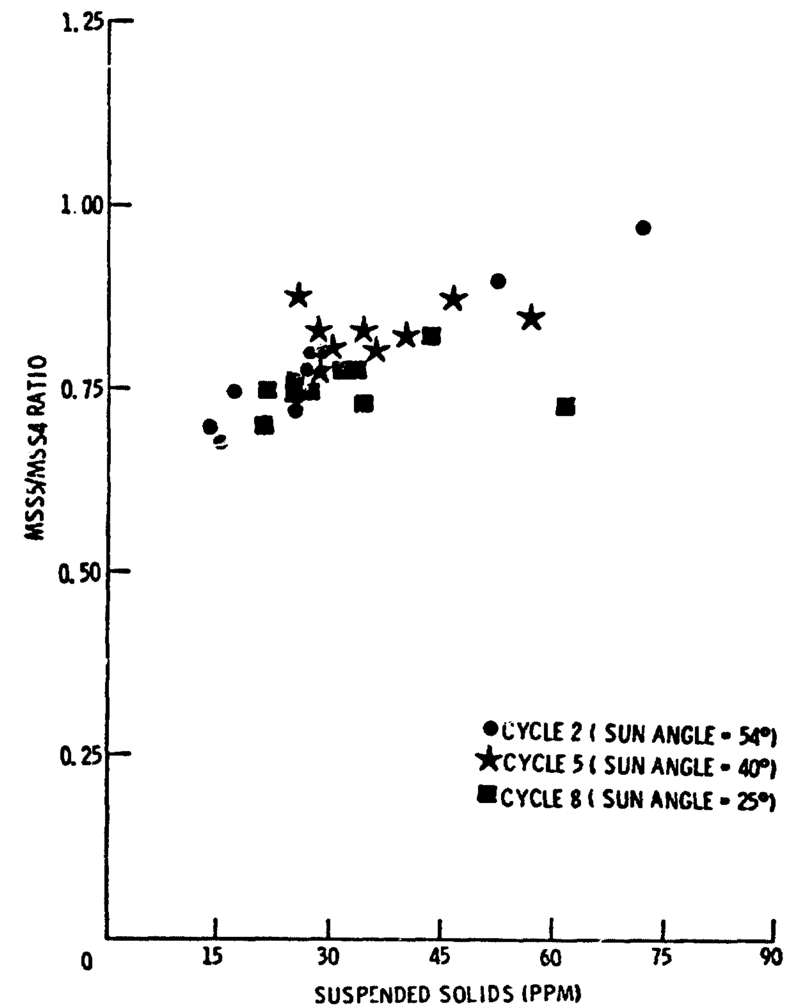

FIGURE 6. MSS5/MSS4 RATIO FROM CCT VS. SUSPENDED SOLIDS FOR 28 WATER SAMPLES FROM 3 LANDSAT-1 CYCLES.

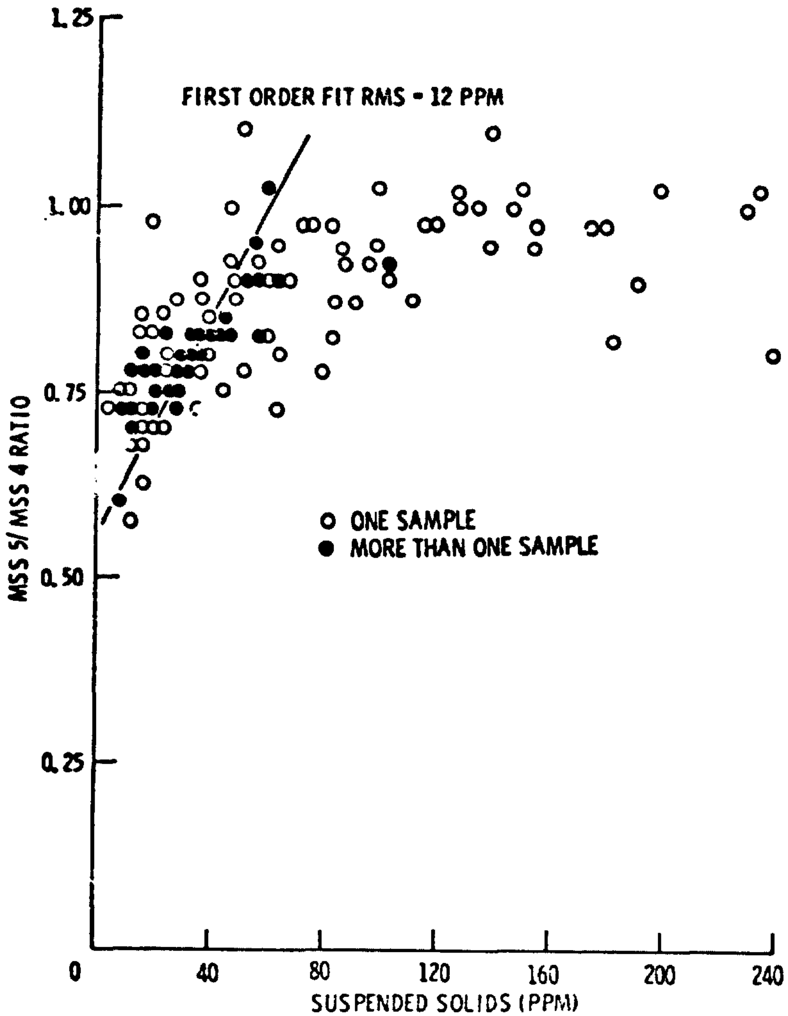

FIGURE 7. MSS 5/MSS 4 CCT RATIO VS. SUSPENDED SOLIDS FOR 167 WATER SAMPLES TAKEN FROM 3 KANSAS RESERVOIRS DURING 13 DIFFERENT LANDSAT-1 CYCLES.

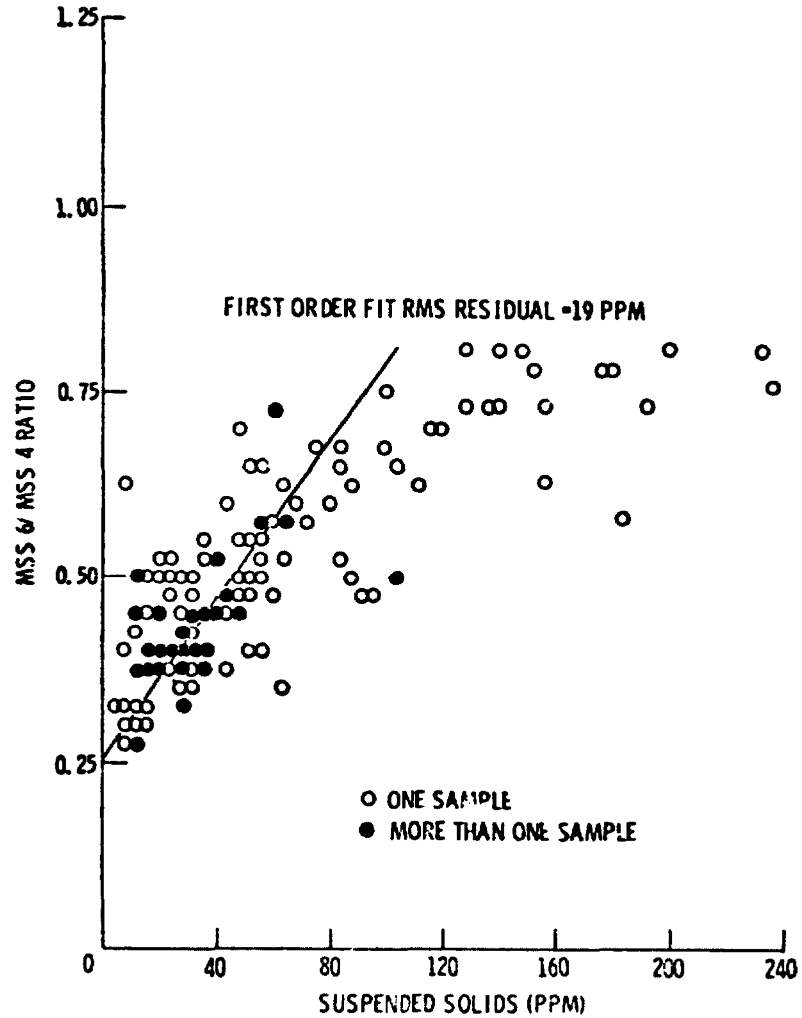

FIGURE 8. MSS6/MSS 4 CCT RATIO VS. SUSPENDED SOLIDS FOR 166 WATER SAMPLES TAKEN FROM 3 KANSAS RESERVOIRS DURING 13 DIFFERENT LANDSAT-1 CYCLES.

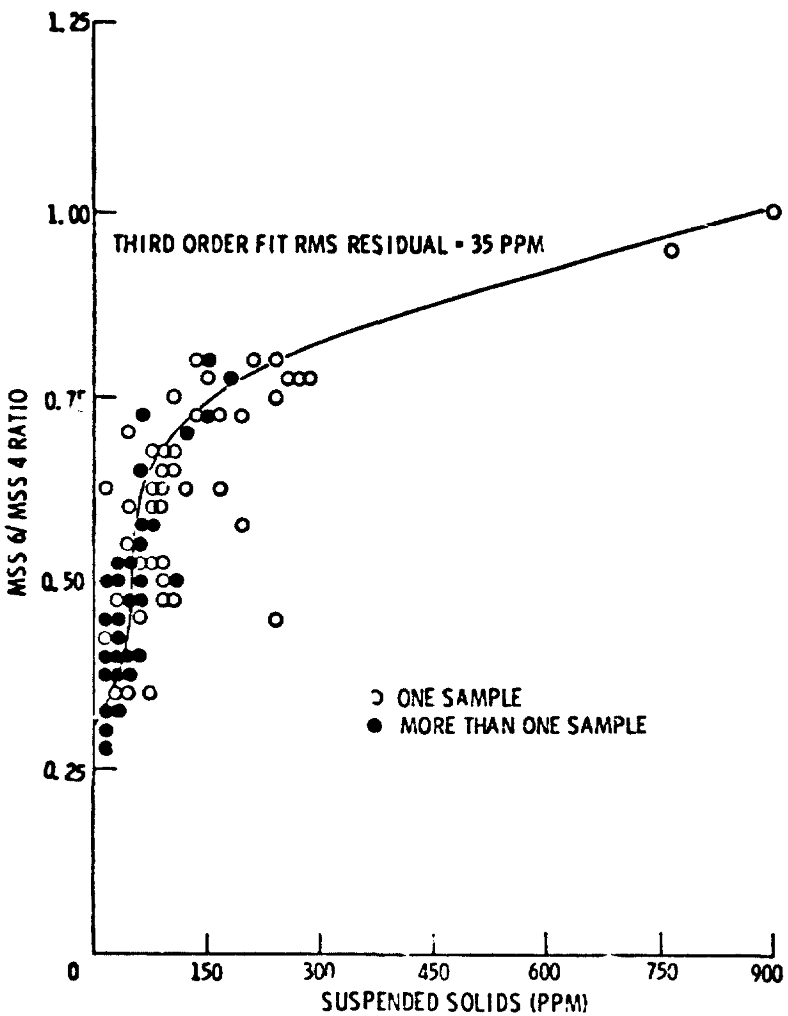

FIGURE 9. MSS 6/MSS 4 CCT RATIO VS. SUSPENDED SOLIDS FOR 170 WATER SAMPLES TAKEN FROM 3 KANSAS RESERVOIRS DURING 13 DIFFERENT LANDSAT-1 CYCLES.

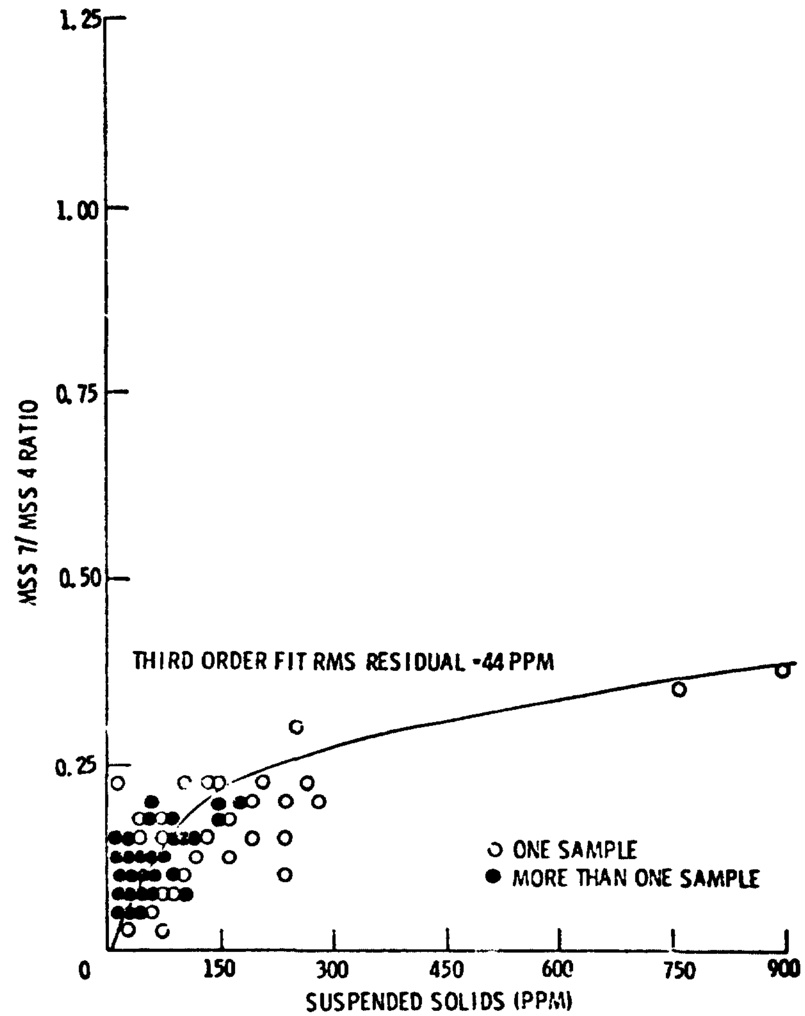

FIGURE 10. MSS 7/MSS 4 CCT RATIO VS. SUSPENDED SOLIDS FOR 171 WATER SAMPLES TAKEN FROM 3 KANSAS RESERVOIRS DURING 13 DIFFERENT LANDSAT-1 CYCLES.

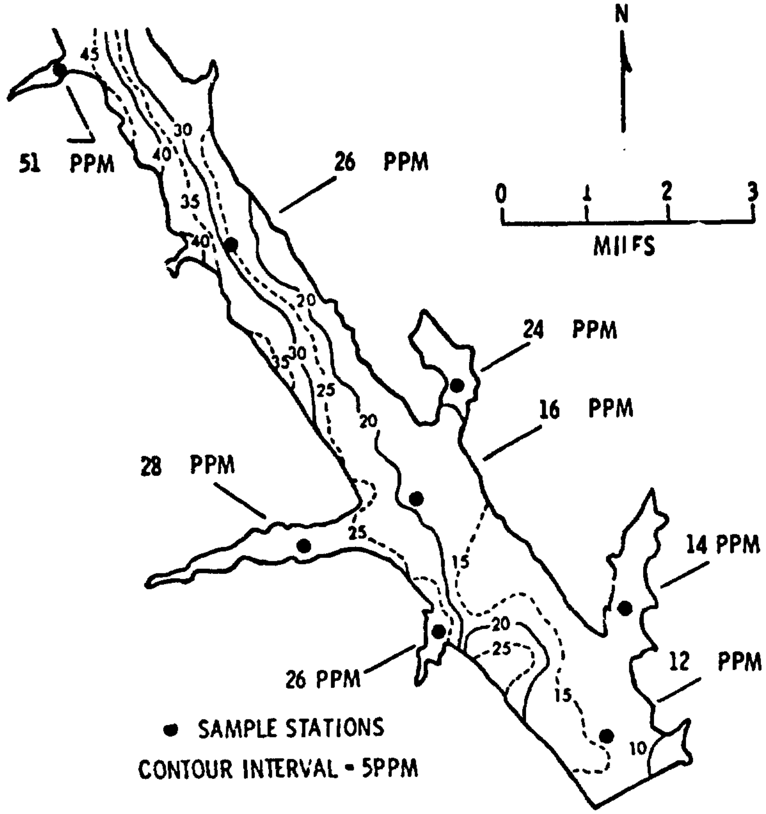

FIGURE 11. SUSPENDED SOLIDS CONTOUR MAP OF TUTTLE CREEK RESERVOIR (AUGUST 14, 1972 ERTS-1 ID NO. 1022-16391-5) DERIVED FROM CCTS (MSS 5) FOR 4 LANDSAT-1 PASSES.

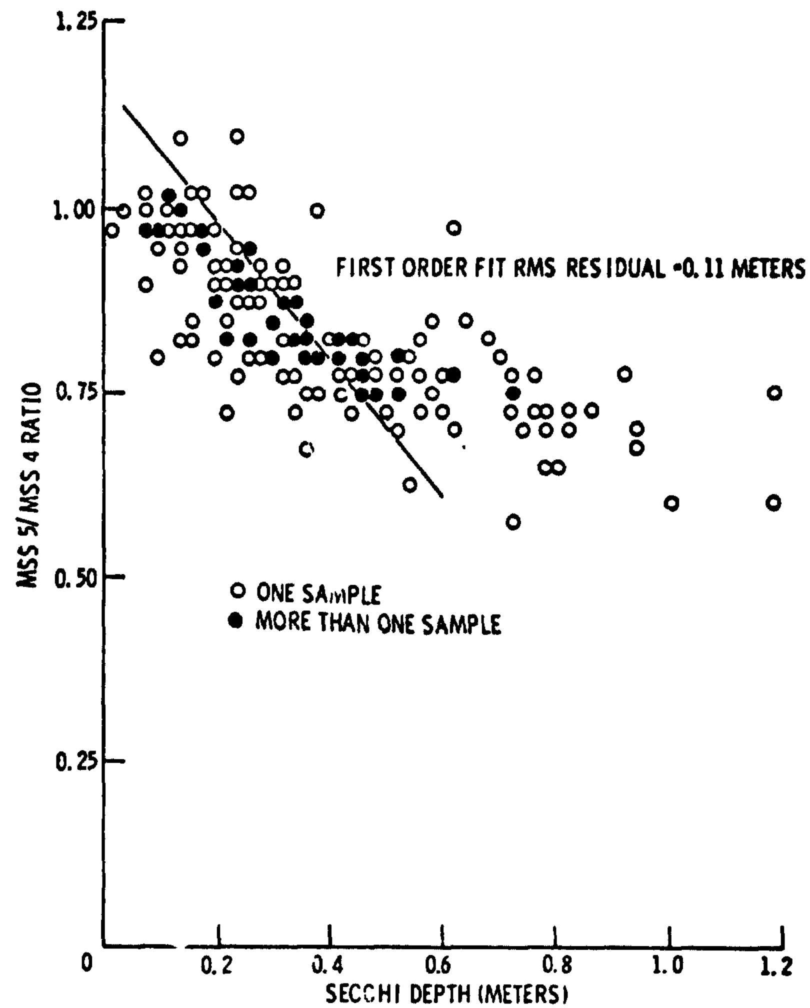

FIGURE 12. MSS 5/MSS 4 CCT RATIO VS. SECCHI DEPTH FOR 171 WATER SAMPLES TAKEN FROM 3 KANSAS RESERVOIRS DURING 13 DIFFERENT LANDSAT-1 CYCLES.

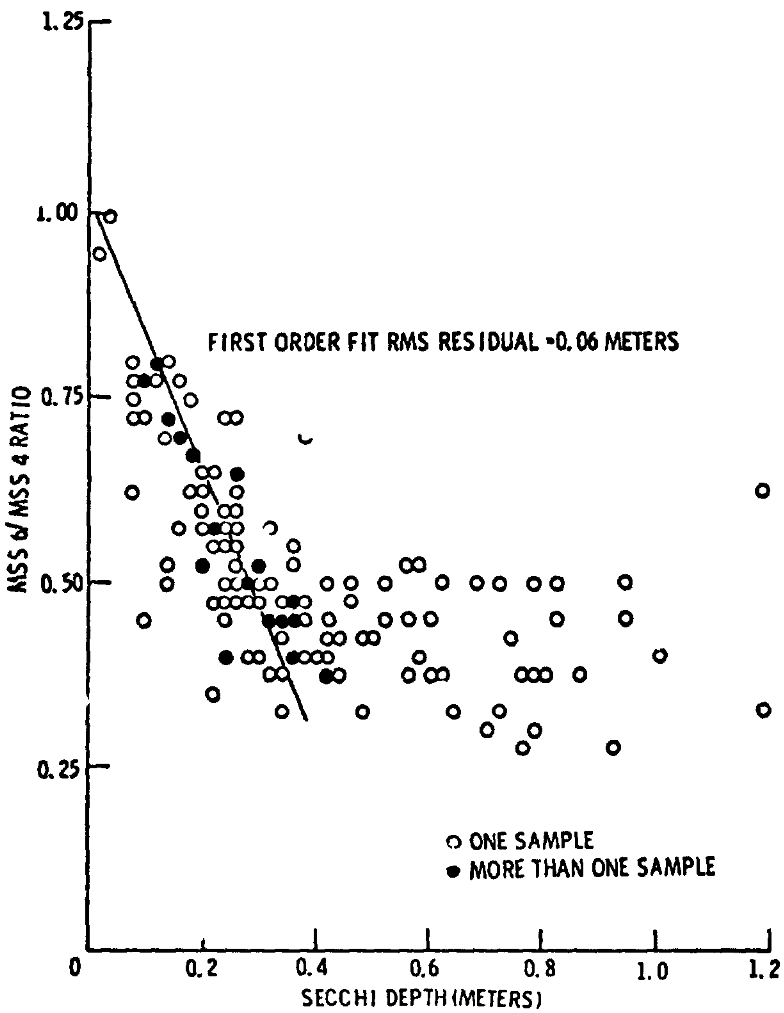

FIGURE 13. MSS 6/MSS 4 CCT RATIO VS. SECCHI DEPTH FOR 170 WATER SAMPLES TAKEN FROM 3 KANSAS RESERVOIRS DURING 13 DIFFERENT LANDSAT-1 CYCLES.

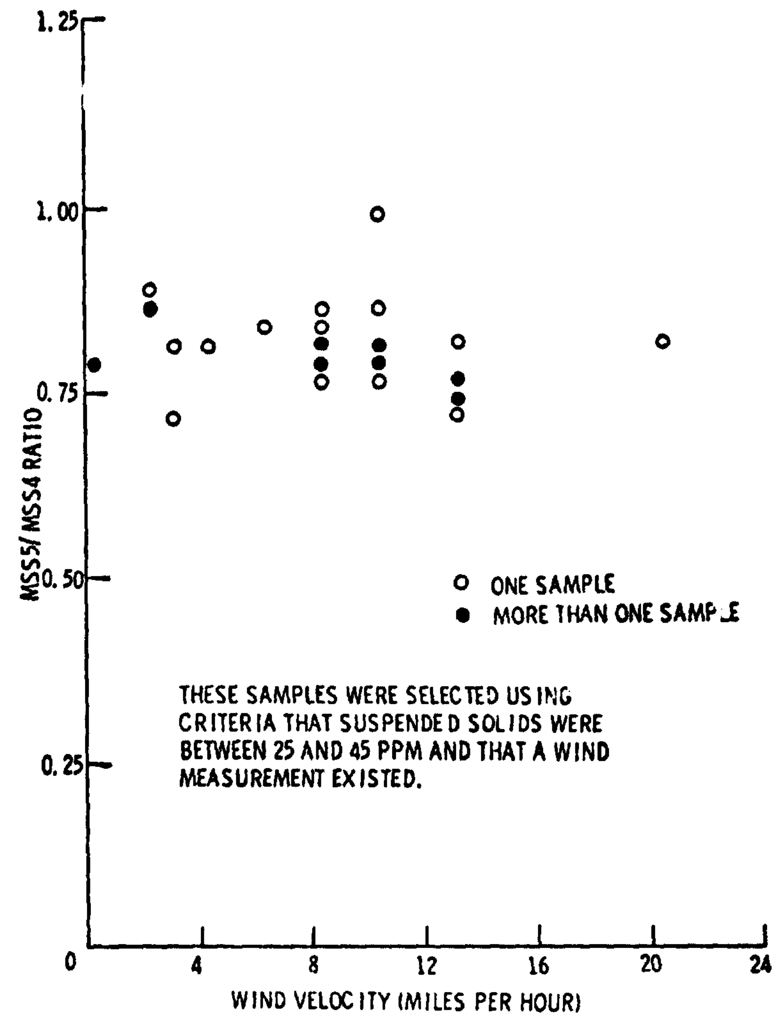

FIGURE 14. MSS 5/MSS 4 CCT RATIO VS. WIND VELOCITY FOR 35 SAMPLES TAKEN FROM 2 KANSAS RESERVOIRS OVER A 13 MONTH PERIOD.

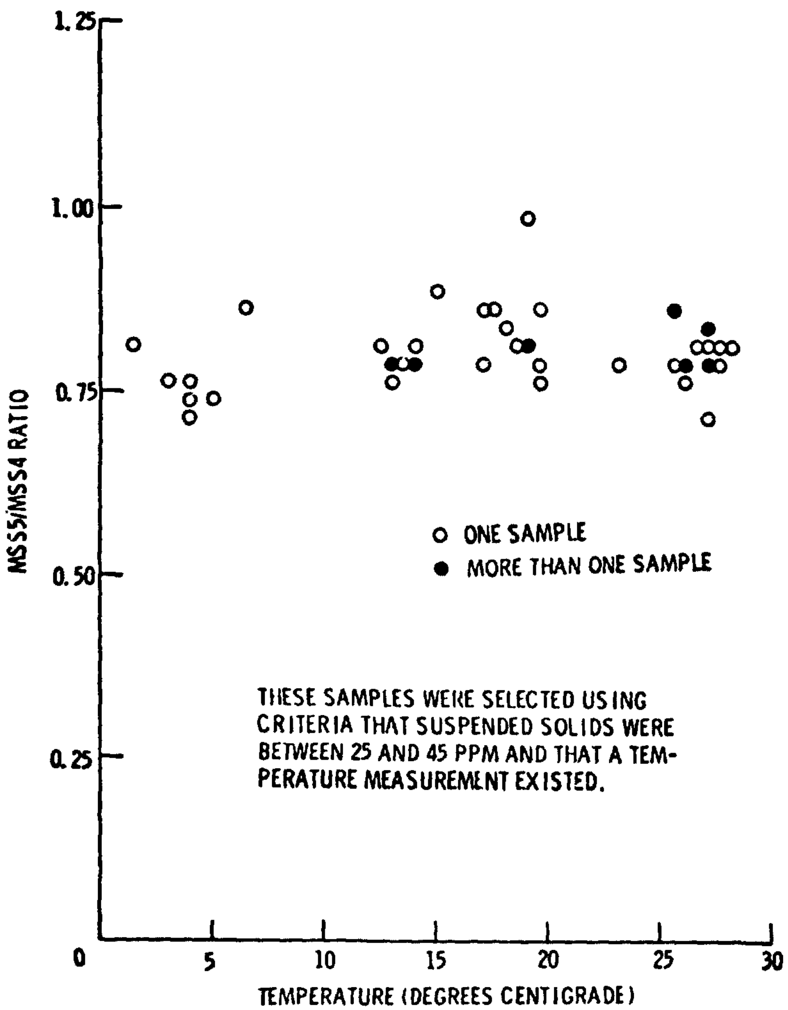

FIGURE 15. MSS 5/MSS 4 CCT RATIO VS. TEMPERATURE FOR 44 SAMPLES TAKEN FROM 2 KANSAS RESERVOIRS OVER A 13 MONTH PERIOD.

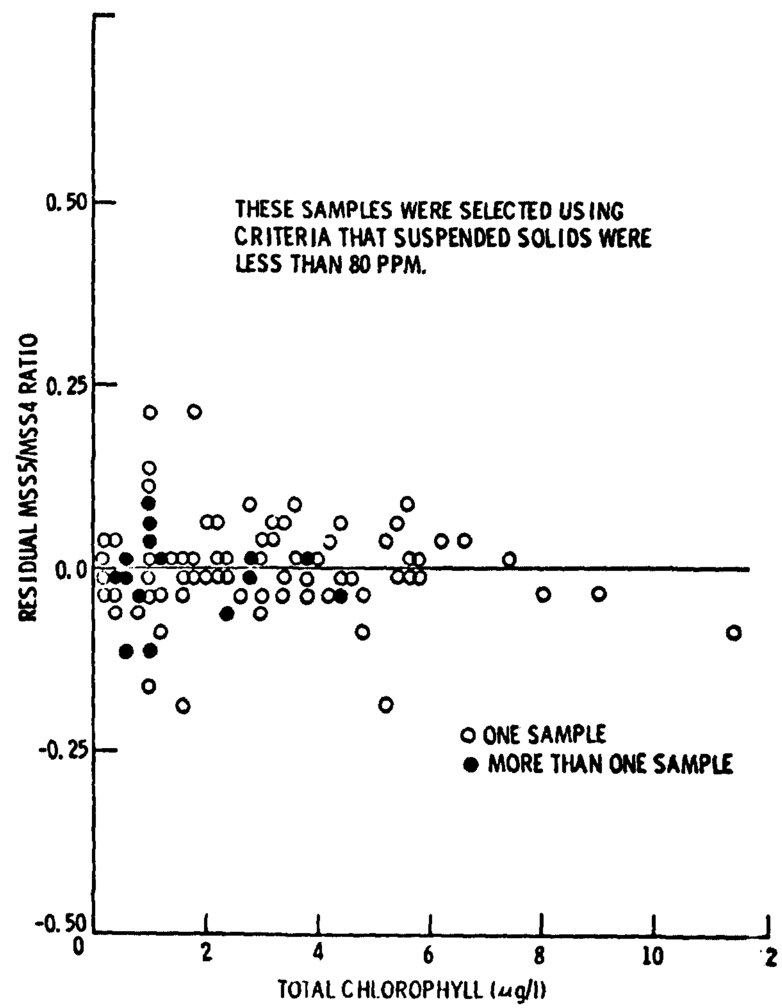

FIGURE 16. RESIDUAL MSS 5/MSS 4 CCT RATIO VS. TOTAL CHLOROPHYLL FOR 106 SAMPLES TAKEN FROM 2 KANSAS RESERVOIRS OVER A 13 MONTH PERIOD. RESIDUAL WAS OBTAINED BY SUBTRACTING LINEAR DEPENDENCE ON SUSPENDED SOLIDS.

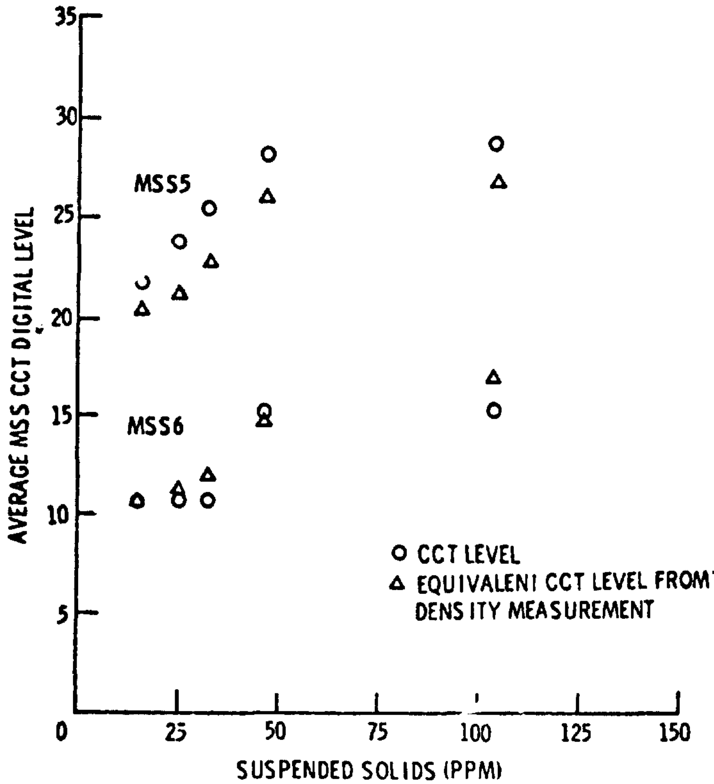

FIGURE 17. COMPARISON OF CCT DIGITAL LEVELS WITH IMAGE DENSITY MEASUREMENTS FOR TUTTLE CREEK RESERVIIR, LANDSAT CYCLE 4. DENSITY MEASUREMENTS WERE CONVERTED TO EQUIVALENT CCT LEVELS BY USING STEP WEDGE AT BOTTOM OF IMAGE.

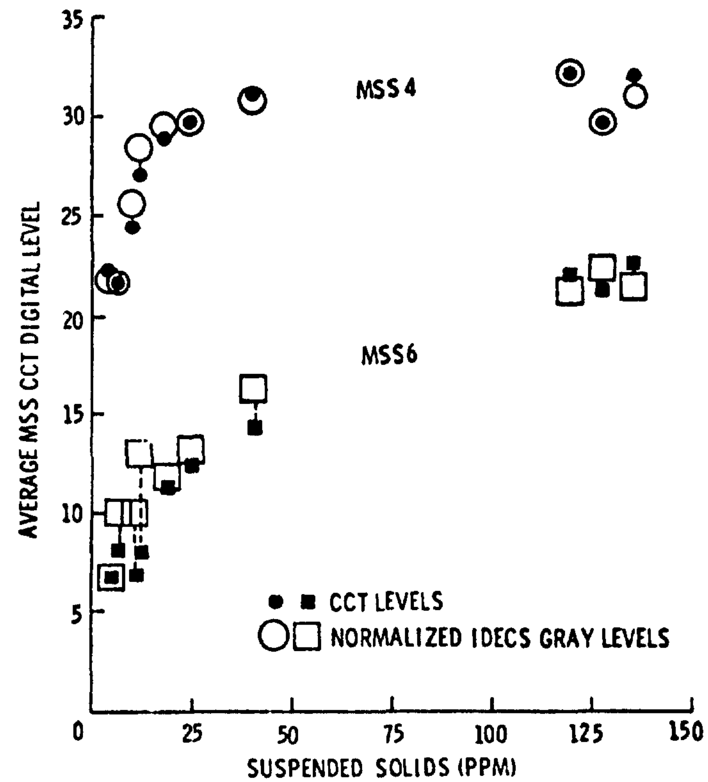

FIGURE 18. COMPARISON OF CCT LEVELS WITH IDECS LEVELS FOR PERRY, LANDSAT CYCLE 2.

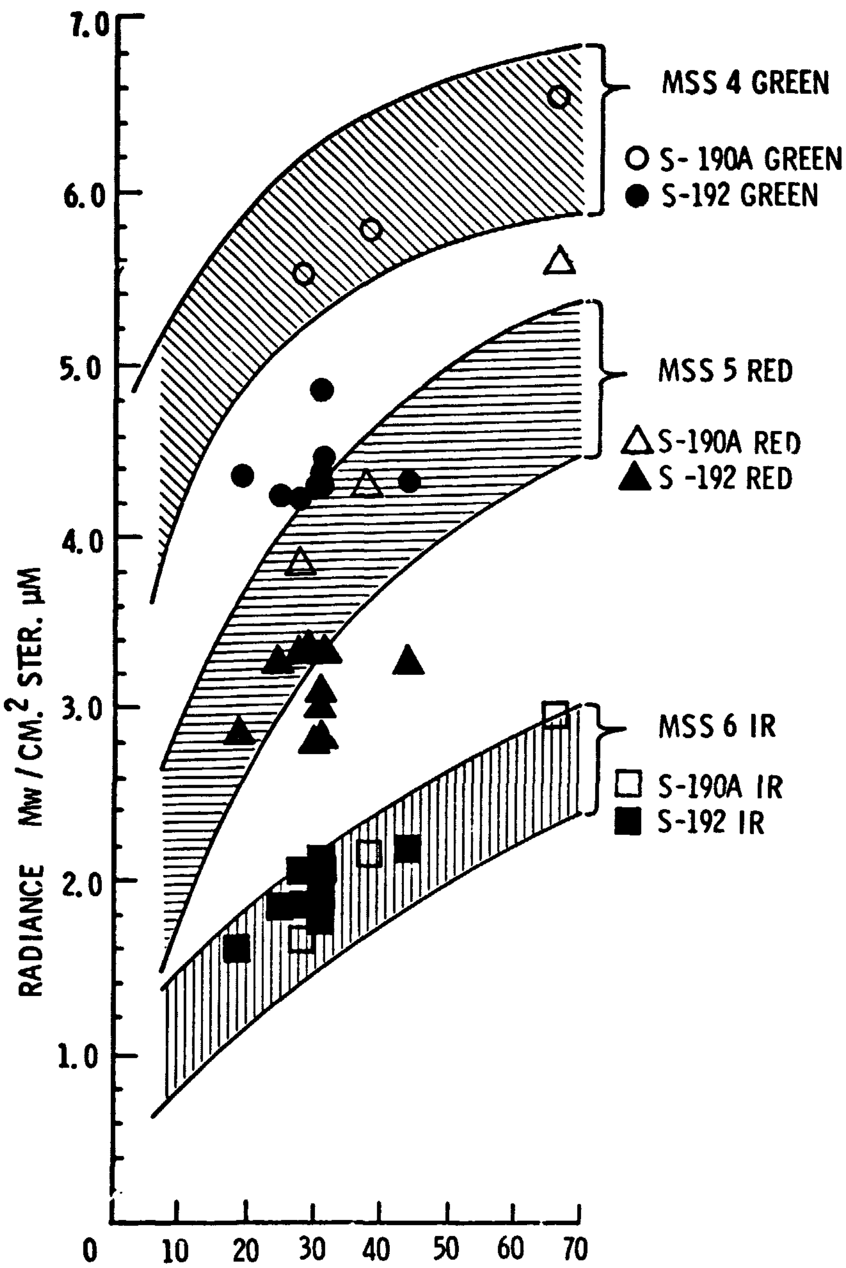

FIGURE 19. RADIANCE VS. SUSPENDED SOLIDS. ONE SL-3 PASS (SUN ANGLE = 44°) OVER 3 S.E. KANSAS RESERVOIRS AND 7 LANDSAT PASSES (SUN ANGLE = 40°- 54°) OVER 3 N.E. KANSAS RESERVOIRS.

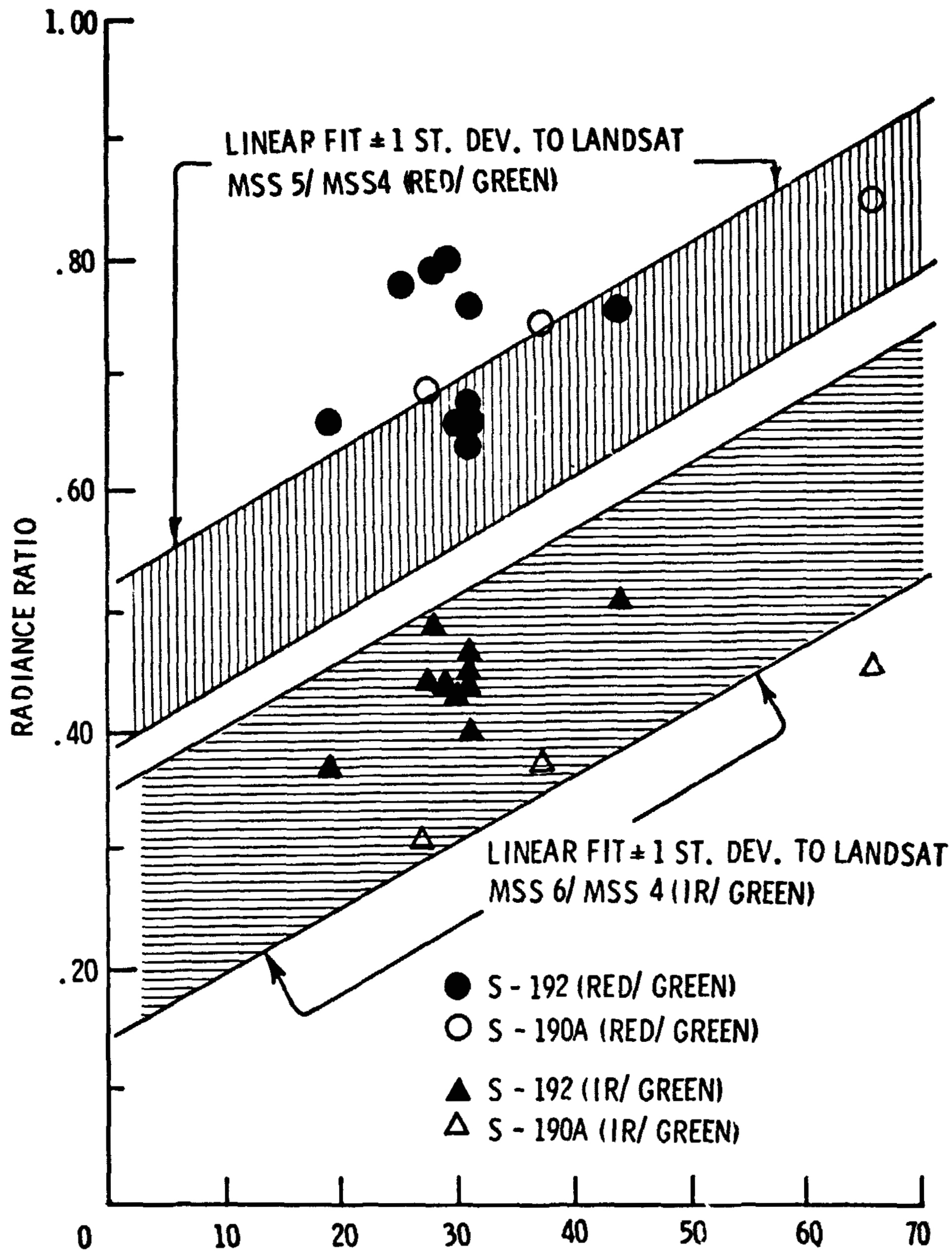

FIGURE 20. RADIANCE RATIOS VS. SUSPENDED SOLIDS. ONE SL-3 PASS (9/18/73) OVER 1 S.E. KANSAS RESERVOIR AND 13 LANDSAT CYCLES OVER 3 RESERVOIRS IN N.E. KANSAS OVER THE PERIOD JULY 25, 1972 TO AUG. 27, 1973.

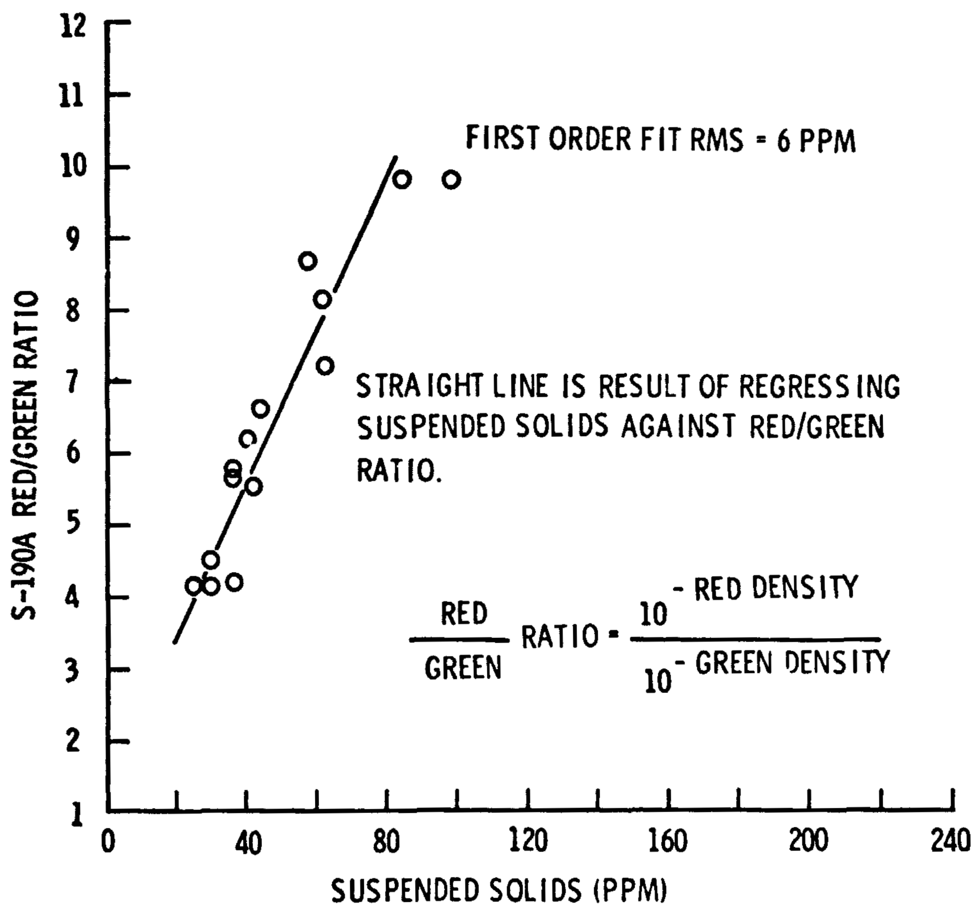

FIGURE 21. RED/ GREEN RATIO VS. SUSPENDED SOLIDS FOR WATER SAMPLES TAKEN FROM 3 S.E. KANSAS RESERVOIRS, SEPT. 18 1973.