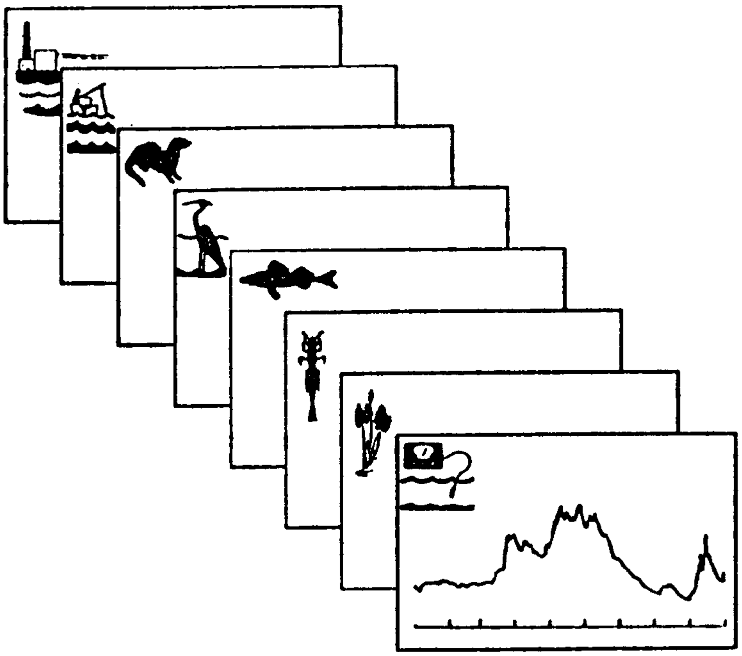
ENVIRONMENTAL MANAGEMENT PROGRAM

LONG TERM RESOURCE MONITORING PROGRAM
UPPER MISSISSIPPI RIVER SYSTEM



RECOMMENDATIONS FOR ESTIMATING SUSPENDED SOLIDS IN THE UPPER MISSISSIPPI RIVER SYSTEM USING REMOTE SENSING

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PREFACE

This report was prepared as part of the Long Term Resource Monitoring Program for the Upper Mississippi River System. The Upper Mississippi River System is composed of the navigable reaches of the Upper Mississippi, Illinois, Kaskaskia, Black, St. Croix and Minnesota rivers. The Long Term Resource Monitoring Program is part of the Environmental Management Program which was authorized under the Water Resources Development Act of 1986 (Public Law 99-662).

The report was prepared by Sean C. Ahearn and Robert D. Martin of the Remote Sensing Laboratory, University of Minnesota and Joseph H. Wlosinski of the Environmental Management Technical Center, U.S. Fish and Wildlife Service. This report was performed as part of Problem Solving Task PA(S)4 "Determine areas in the Upper Mississippi River System and times of year when excessive suspended solids concentrations occur". Funding for the Remote Sensing Laboratory was provided through Cooperative Agreement No. 14-16-0003-88-951 with the Environmental Management Technical Center. The report was reviewed by Barry W. Drazkowski from the Environmental Management Technical Center, the Computerized River Information Center Analysis Team and the Ecological Analysis Team. Mary Mackrill performed editorial and administrative tasks.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

RECOMMENDATIONS FOR ESTIMATING SUSPENDED SOLIDS IN THE UPPER MISSISSIPPI RIVER SYSTEM USING REMOTE SENSING

INTRODUCTION

Sedimentation is considered the most significant factor limiting fish and wildlife resources in the Upper Mississippi River System (UMRS) (Great River Environmental Action Team, 1979). Between Guttenberg, Iowa and the head of navigation on the Mississippi River about one-fourth of the open water area has been converted to marshlands since the locks and dams were built (St. Paul District, 1981). According to the Great River Environmental Action Team (1980), most of the open water areas of backwater lakes will succeed to marshlands within the next century if reported rates of sedimentation are allowed to continue.

Sedimentation has been selected as one of five critical problems which are being addressed within the Long Term Resource Monitoring Program (LTRMP) for the UMRS (Rasmussen and Wlosinski, 1988). One of 19 tasks outlined to address the sedimentation problem is to "Determine areas in the Upper Mississippi River System and times of year when excessive suspended solids concentrations occur" (Rasmussen and Wlosinski, 1988). Remote sensing of water bodies for estimation of suspended solids has been shown to be an effective tool to this end (Kritikos and Yorinks, 1974; Johnson, 1977; LeCroy, 1982, Lathrop and Lillesand, 1986).

The purpose of this report is to determine the feasibility associated with obtaining estimates of suspended solids in the UMRS using remote sensing and to outline the steps necessary to initiate such a study. The report includes a review of the spectral characteristics of suspended solids in water bodies in the laboratory and field and the use of remote sensing for qualitative and quantitative estimation of suspended solids in water bodies. Questions to be addressed in the report include:

* What is the concentration range of suspended solids in the UMRS?

* Is remote sensing technology adequately proven to estimate the suspended solids concentration (SSC) in the entire UMRS over the range of historical values?

* Should Landsat Thematic Mapper (TM), SPOT HRV panchromatic, SPOT multispectral sensors, or aerial photography be used?

* What is the accuracy of the estimate using different sensors?

* Is ground truthing needed? If yes, how many samples? How should ground truth samples be measured? When and where should samples be collected?

* Can information be gained concerning bed load transport using this method?

* Can information be gained concerning other themes needed for the UMRS database?

* Can information be gained concerning past sedimentation problems using this method?

* Can information be gained concerning the components of suspended solids (algae, other organics, inorganics) using this method?

* Can information be gained concerning the causes of sedimentation (discharge, resuspension caused by wind or towboat) using this method?

* Can information from this method be used for other tasks concerning the sedimentation problem?

* What costs are associated with this method?

* At what resolution will the data be reported?

HISTORICAL VALUES

Historical values for suspended solids were obtained from the Environmental Protection Agency's STORET database. Only those stations that had at least 15 samples reported over a period of seven years, between 1977 and 1988, were used. Concentrations were reported as mg/l of total nonfilterable residue and include both organic and inorganic matter.

Nine stations on the Mississippi River and seven stations on the Illinois River met the criteria (Table 1). Mean concentrations on the Mississippi River ranged from 13 to 135 mg/l and on the Illinois River from 57 to 166 mg/l. The range of reported values was from 0 to 910 mg/l. Three tributaries also had stations which were near the Mississippi River: Black River (Wisconsin), Cannon River (Minnesota), and the Maquoketa River (Iowa). The Maquoketa had the highest reported values, with a mean of 276 mg/l and a maximum reading of 2991 mg/l.

LITERATURE REVIEW

The majority of the bibliographic references were obtained using a DIALOG search. The keyword string used was "remote or sensing or satellite or mapping or SPOT or LANDSAT and suspended or sediment or solid or bed load." Bibliographic data bases used Biosis Previews, Enviroline, Environmental Bibliography, Pollution Abstracts, Water Resources Abstracts, Georef, NTIS, Federal Research in Progress, and Aquatic Science Abstracts. All papers included in the review can be found in the references.

Table 1. Concentrations reported as nonfilterable residue in the Upper Mississippi River System and tributaries (from STORET).

LOCATION	**NUMBER OF SAMPLES**	**MEAN mg/l**	**STANDARD DEVIATION mg/l**	**MINIMUM mg/l**	**MAXIMUM mg/l**
Mississippi River					
Lock and Dam 3	136	28	21	0	122
Lake City MN	114	16	13	1	87
Lake Pepin	137	15	32	0	273
Lock and Dam 4	136	13	9	0	80
Lock and Dam 5	102	20	16	1	70
Lock and Dam 9	134	30	25	0	116
Davenport IA	27	65	71	1	290
Keokuk IA	21	93	94	8	320
Thebes IL	15	135	165	2	620
Illinois River					
Hennepin IL	97	57	66	1	440
Lacon IL	100	73	54	1	340
Peoria IL	109	72	59	0	427
Pekin IL	101	106	83	2	527
Havana IL	106	156	176	3	908
Valley City IL	103	158	159	0	910
Hardin IL	100	166	146	6	760
Tributaries					
Black River WI	123	24	32	0	250
Cannon River MN	93	43	77	1	580
Maquoketa IA	59	276	541	8	2991

LABORATORY AND FIELD MEASUREMENTS

The spectral property of pure water is characterized by low reflectance in the visible region of the spectrum and virtually no reflectance in the near- and middle-infrared wavelengths (Hoffer, et al. 1978). With the addition of sediments of increasing size, scattering becomes independent of wavelength. The result is a shift in the apparent color of the water from blue toward green. Increasing turbidity results in a shift of water color towards the color of the particle creating the turbidity (Salomonson, et al., 1983). The shift results in reflectance reaching a maximum in the visible red and very near infrared region of the spectrum (Ritchie et al., 1976; Schiebe and Ritchie, 1986; Topliss, 1986).

Pionke and Blanchard (1975) measured reflectance from impoundments with an airborne multispectral scanner (MSS). When these measurements were related to SSC, they found a curvilinear relationship between reflectance and SSC. The strongest correlations were found in bands defined by 0.59-0.64 Fm and 0.65 -0.69 Fm (note: these two bands coincide with MSS band 5). These bands exhibited the least curvilinearity in their relationship to SSC over a 13-232 mg/l range of concentrations. In comparing their work to that of previous authors, they concluded that differences in the relationship between SSC and reflectance were due to differences in sediment reflectance characteristics. This led them to speculate that estimates of SSC for different bodies of water might require different wavebands and different calibration equations depending on their individual sources of sediment. Additionally, they pointed out that since clay particles remain in suspension much longer than do larger particle sizes, reflectance measurements are more likely to be related to the concentration of clay-size particles than to the concentration of the larger particles.

Ritchie et al. (1976) were among the first to observe the shift in maximum reflectance toward longer wavelengths as SSC increased. They measured continuous spectra over the 0.4-1.1 Fm range using a field spectrometer and related reflectance to SSC over a range of 20-330 mg/l. In addition to observing a spectral shift with increasing SSC, they concluded that the MSS band 6 (0.7-0.8 Fm) wavelength region had the strongest correlation with SSC (i.e., r = 0.91) and showed that solar angle corrections should be incorporated in SSC estimates from reflectance data.

Rouse and Coleman (1976) developed a set of calibration equations for the Mississippi River with a laboratory experiment. SSC were varied over a range of 0-1500 mg/l in discrete steps. Measuring reflectance in the MSS band 5 region of the spectrum (0.6-0.7 Fm), they concluded that three separate equations (one for each of three ranges of SSC) were necessary for estimating SSC in the lower Mississippi River. The lower two concentration ranges (0-80 mg/l and 80-400 mg/l) were fit to linear equations with r = 0.96. They failed to report the equation fit to the upper range (400 mg/l and greater), but they indicated that reflectance had a nonlinear relationship to SSC in this range of concentrations. The calibration equations were later used to plot suspended sediment contours on LANDSAT images for the Louisiana Bight.

A field study by Bartolucci et al. (1977) using a field-portable spectrometer found the maximum difference between turbid (99 mg/l suspended solids) and clear (10 mg/l suspended solids) water reflectance to occur in the 0.6 to 0.9 Fm range of the spectrum. They concluded that MSS bands 5 (0.6-0.7 Fm), 6 (0.7-0.8 Fm), and 7 (0.8-1.1 Fm) would work well for discriminating between clear and turbid bodies of water and that band 5 was probably the best of the three. In addition, they found that bottom reflectance had no influence on the overall reflectance of a turbid water body when water was deeper than 30 cm.

Schiebe and Ritchie (1986), using laboratory and hand-held radiometers, found reflectance in the 0.7-0.95 Fm region of the spectrum to be linearly related to suspended inorganic sediment concentrations. By incrementally increasing the amount of suspended sediment in a tank of water and measuring the reflectance over the 0.4-1.0 Fm range, they found reflectance in the 0.65-0.9 Fm range to have good sensitivity to SSC up to 990 mg/l. At wavelengths less than 0.65 Fm they found that reflectance became insensitive to SSC greater than 100 mg/l. Their laboratory and field studies led them to conclude that MSS bands 6 and 7 would be best for estimating SSC over 100 mg/l. The 0.7-0.8 Fm (band 6) range did not become saturated until sediment exceeded 500 mg/l and were useful up to nearly 1000 mg/l levels.

Topliss (1986), measuring upwelling irradiance over the 0.4-0.73 Fm wavelength interval at a depth of 1 m in the Bay of Fundy, found that the wavelength of maximum irradiance increased as SSC increased. In other words, the subsurface irradiance spectra of the water shifted from a maximum in the 0.56-58 Fm (green) region at low concentrations (i.e., 1-5 mg/l) to 0.66-0.72 Fm (visible red) at higher concentrations (i.e., 50-150 mg/l). This shift in the spectral peak is similar to the one first described by Ritchie et al. (1976). The implication of this spectral shift is that "...different concentration ranges could best be monitored by different portions of the spectrum." However, it should be pointed out that Rimmer et al. (1987) observed no shift in the spectral peak towards red when working with Airborne TM data of the Swansea Bay in the United Kingdom. It may be that the spectral shift is a site specific phenomenon.

In summary, the laboratory and field experiments suggest that the best wavelengths to use for estimating SSC from reflectance fall in the 0.6-0.9 Fm range. The relationship between SSC and reflectance was generally found to be linear. Estimates of SSC from reflectance were reasonably accurate up to concentrations of almost 1000 mg/l, but sensitivity of reflectance to SSC was found to decrease beyond 400 mg/l.

SATELLITE MONITORING OF SSC

There have been studies done that have used satellite imagery for estimating SSC either qualitatively or quantitatively.

Qualitative Studies

Nayak and Sahai (1985) interpreted color density slices of four MSS images to gain insight into the factors influencing sediment patterns (e.g. flood tide, ebb time, currents). Brakel (1984), manually traced turbidity plumes during various seasons and found that movement was affected by local wind, tidal conditions and seasonal rains. In another study Thornton (1981) visually examined Landsat MSS data to map sediment transport after a flood off the coast of Southern California.

Rouse and Coleman, 1976, correlated film densities from MSS imagery with SSC in the Mississippi River. One of their findings was that the two rivers they studied had different reflectance characteristics and it was necessary to obtain calibration information for each area of interest in order to provide accurate estimates of suspended solids.

Gatto (1978) found that variations in SSC from 9 to 22 mg/l were not significant enough to be observed using aerial photography at Grays Harbor, Washington.

While precise estimates of suspended solids were not obtained by any of these studies, in most of the applications discussed the investigators were interested in relative estimates of suspended sediments. These relative estimates revealed information on plume shapes, dispersion trends and seasonal trends. Thus, for many applications where precise estimates of SSC are not needed, a qualitative approach to using satellite imagery to estimate SSC is adequate.

Quantitative Studies

Two separate techniques were used for quantitative studies; calibration and deterministic.

Calibration Technique. A number of researchers have shown the importance of correcting digital number (DN) values (digital numbers recorded by the sensor) for variations due to sensor, target, sun relationships, atmospheric conditions and air pollution (Munday, et al., 1979; Amos and Alfoldi, 1979; MacFarlane and Robinson, 1984; Verdin, 1985), when estimating water quality parameters from satellite remote sensing data.

Verdin (1985) corrected for sun angle and atmospheric effects which "permits the application of resulting predictive equations to estimate reservoir water quality conditions with imagery obtained on dates when there were no surface sampling crews in the field." In his study he measured chlorophyll-a with a sigma of 2.0 mg/m^3. Location of samples was difficult so the average of a 3x3 block of pixels subsuming the most probable sampling spot was used in the regressions.

Amos and Alfoldi (1979) used chromaticity to correlate with water quality parameters in the Minas Basin and Avon River estuary. Their assumption was that "unwanted contributions to signal, sun angle, look angle, sea state, surface reflection, bottom reflection, atmospheric attenuation, atmospheric path radiance and air pollution are achromatic with respect to Landsat Bands 4, 5, 6." They removed the brightness vector from a hue, intensity, saturation transformation leaving hue and saturation for regressing against SSC. R^2 values less than 0.60 for any single band, and R^2 greater than 0. 9 using chromaticity indices regressed against SSC, were found. These correlations were high despite large variety of grain sizes, composition and grain shapes. The model used was the chromaticity versus log of SSC. Amos and Alfoldi found that the error limits for a seven date regression ranged from plus or minus 0.3 mg/l at 1 mg/l to plus or minus 65 mg/l at 148 mg/l. They reported nearly exponentially increasing errors for SSC above 200 mg/l. Lindell et al. (1986) showed that the chromaticity technique predicted suspended sediment values that were statistically the same as measured values using a paired t-test, but they mention that the method is limited by interference by some types of chlorophyll.

MacFarlane and Robinson (1984) made atmospheric corrections to Landsat MSS data for multidate SSC estimations. As they stated, there is a "need to develop a universal calibration technique which will unlock some of the information from the archives and render them useful.... major obstacles are the difference in optical properties of different types of sediment in different locations." Their solution to the problems associated with sediment type and sources, and corrections for atmospheric variability was to correlate chromaticity (with correction for aerosols, by using a convolution of band 7) with suspended solids. Dark pixel subtraction, one of the models tested, was found to be unsatisfactory for calibrating the Landsat MSS data.

Munday et al. (1979) stated that "chromaticity analysis provides automatic pixel-by-pixel adjustment of atmospheric variations permitting reference calibration data from one or several dates to be spatially and temporally extrapolated to other regions and to other dates." The steps used in their correction procedure were: 1) derive radiance values for pre-launch radiometric calibration constants for each Landsat scene; 2) generate chromaticity coordinates for total radiance normalization; 3) make atmospheric adjustments to chromaticity values; 4) employ regression using the model $SSC = e^{mx1+b}$.

In summary, for multi-temporal analysis of satellite data for water quality estimation, some form of correction of the raw DN values should be made. Chromaticity transformation in conjunction with adjustments for atmospheric differences seemed to work well in several independent studies (MacFarlane and Robinson, 1984; Amos and

Alfoldi, 1979; Munday et al., 1979). This transformation appears to normalize the data with respect to differences in sun, sensor, target relationships as well as soil grain size, type and origin.

<u>Deterministic techniques.</u> Various techniques have been tested for relating SSC to remotely sensed satellite data (Horn and Morrissey, 1984; Ritchie et al., 1987; Shih and Gervin, 1980; Lathrop and Lillesand, 1986). Most have employed some form of linear regression.

Horn and Morrissey (1984) used multiple and stepwise regression to correlate Landsat TM bands with SSC. A 3x3 averaging filter for pixels corresponding to sample sites was used in the correlation. For SSC an $R^2 = 0.92$ with 7 bands was obtained for concentrations of 13-88 mg/l. The best single band for estimating SSC was TM 3 in which an R^2 of 0.71 was achieved.

Ritchie et al. (1987) used simple and multiple regression to estimate SSC greater than 50 mg/l. Fourteen dates, with five sample sites per date, using four transformation techniques were tested. The transformation techniques were to use raw counts, radiance, reflectance, minimum or dark pixel subtraction, and chromaticity. Linear relationships were found between pixel values and SSC for concentrations less than 200 mg/l. For concentrations greater than 200 mg/l the relationships were non linear. Least squares linear regression analysis using MSS Band 3 had the highest R^2. Dark pixel subtraction gave the best results of all of the transformations used to correct for atmospheric differences. This is in contrast to MacFarlane and Robinson's findings (1984).

Shih and Gervin (1980) compared the results from least squares and ridge regression. They reasoned that when "assessing causal models under conditions of multicollinearity, ordinary least square will frequently yield unreliable parameter estimates." They found that ridge regression reduced mean square error by 13-20%.

Lathrop and Lillesand (1986), used Landsat TM data to estimate various water quality parameters in Green Bay and Lake Michigan. The water masses in Green Bay and Lake Michigan had slightly different spectral characteristics, and so were treated separately in the regression analysis. The differences in spectral characteristics were attributed to differences in color attributed to the dissolved humic substances in Green Bay. Turbidity, not SSC, was tested for (although the two are highly correlated). There were not enough samples for correlating SSC. A simple one band power model was used. The band chosen was TM band 3 for turbidity and TM band 2 for chlorophyll and secchi disk depth.

Scherz et al. (1973) reported on a study concerning the correlation of satellite images and low altitude photography to turbidity and SSC in Lake Superior. They found that the relationship between turbidity and suspended solids changes as the character of suspended solids changes due to differential settling. In using an average curve obtained from values measured on three different days from aerial photography, suspended solids values would probably not be in error by more than 30%. In using earth resources technology satellite images they found expected errors of suspended solids values due to deviation from any point to the established curve for a particular day is no more than 10 to 20%.

Quarrar et al. (1987) found that turbidity correlations with simple spectral ratios were difficult because of high concentrations of chlorophyll in the presence of suspended sediment. They found improved correlations when the ratio of infrared spectral bands were included in the analysis. In summary, regression techniques are very useful for correlating satellite data with SSC. Findings of Shih and Gervin (1980) suggest that when using multiple linear regression techniques, adjustment should be made to compensate for the covariance among the spectral bands used in the model. Ridge regression was seen as one method for making this correction.

DISCUSSION AND RECOMMENDATIONS

Suspended sediment task PA(S)4 is to "Determine areas in the Upper Mississippi River System and times of year when excessive suspended solids concentrations occur" (Rasmussen and Wlosinski, 1988). Determining excessive SSC is not a part of this report. That information should be made available through task PA(S)2 "Determine concentrations of suspended sediment limiting aquatic plant growth on the Upper Mississippi River System" and task PA(S)3 "Determine problem concentrations, durations, and timing of suspended solids that adversely affect primary production, fish eggs and larvae and filter and sight feeding organisms." Discussion and recommendations here deal with estimating SSC in the UMRS using remote sensing.

The literature indicates that remote sensing can provide reasonably accurate estimates of SSC. However, no study was found which would suggest that the results from previous calibration or deterministic techniques could be used to accurately estimate SSC in the entire UMRS. Further, the results of studies by Lathrop and Lillesand (1986), MacFarlane and Robinson (1984), Ritchie et al. (1976), and Rouse and Coleman (1976) indicate that for an area as large and diverse as the UMRS it is probable that a number of different relationships would be needed to predict SSC with a high degree of accuracy. One relationship could be developed for the UMRS, but the accuracy would probably not be as high. In either case, a study which would include ground truthing at various points along the UMRS would be needed before estimates of accuracy could be obtained. Chromaticity transformations show promise for attenuating some of the differences due to sediment source, sun angle and various atmospheric effects. This transformation may permit more accurate estimates than if raw digital counts were used.

The suspended solids task, PA(S)4, calls for both a temporal and a spatial analysis. For the spatial analysis, remote sensing using information gathered by Landsat TM is recommended. Landsat TM is the most economical means of collecting data on an area as large as the UMRS and it has a greater spectral resolution than SPOT HRV panchromatic or SPOT multispectral sensors. In addition, Landsat data is available for as far back as 1972, although it was not always collected with the TM. MSS data, which has been used in many reported studies for estimating SSC, is available from 1972; TM data is available since 1982. The resolution of Landsat TM is 30x3O m, although some previous studies have averaged over a number of pixels.

The use of Landsat for the temporal analysis would prove to be prohibitively expensive. A combination of Landsat imagery and in place sensors measuring light penetration would be the most economical way to analyze the SSC problem both temporally and spatially. In place sensors are already being planned for use in the LTRMP (Lubinski and Rasmussen, 1988). Sensors placed above and below the water surface could give an indication of the amount of suspended solids in the water column.

An initial study for estimating the accuracy of measuring SSC using satellite imagery should include at least three or four different areas in the UMRS. Each area should include a major incoming tributary which usually has higher SSC values than the river into which it flows. Examples include the areas where the Illinois, Maquoketa, and Missouri Rivers flow into the Mississippi. The Illinois River usually has higher values than the Mississippi (Table 1), the Maquoketa has historically been one of the tributaries with high SSC values, and the Missouri contributes 90% of the sediment at it's confluence with the Mississippi River (Jordan, 1968). Numerous samples should be taken in the Mississippi River at various locations including stations which are a number of miles above and below the confluence with the tributary, and far enough into the tributary so that the Mississippi River would not have an effect on SSC. Samples should be taken at or near the time the satellite passes by. At least 30 samples at each of the three or four different areas should be collected. This number of samples would be enough to establish relationships between SSC and spectral reflectance, and would also include a few samples which would be used to verify relationships. A few samples at locations other than those used in establishing the models would also help verify the models. If a specific confidence limit must be attained, an iterative design may be required because the number of samples needed is a function of the variance of the estimates. The exact location of each sampling site must be known. Each site should be in water that is at least 30 cm deep because that is the point which the literature indicates insignificant bottom reflectance. Each site should also be at least 60 m from the nearest shore or patch of aquatic vegetation. To be able to sample over a number of pixels, it would be preferred if each sampling site had an open water area of at least 90x90 m. Sampling sites should be selected to get the greatest range of SSC.

Standard methods and procedures should be used to collect and analyze samples for SSC. The National Fisheries Research Center in La Crosse has written guidelines for sample collection and preservation (standard operating procedures number 705 for collection and preservation) and for laboratory analysis (standard operating procedure number 714.0). Estimated cost to analyze one sample for SSC is $2 in lots of 10 or more samples. 200 ml is required for each sample.

Although this study would be used primarily to satisfy the spatial aspects of task PA(S)4, some degree of measurement over time may still be needed to calibrate the relationship between spectral reflectance and SSC. To assure that a broad range of values for SSC is included in the analysis it may be necessary to sample some of the same areas more than once in the same year. The best chance of obtaining high values would be in the spring during high flows. Low concentrations would most likely occur near the end of summer.

Even if satisfactory results were obtained from a ground truthing study and it was shown that the same relationship held for different times of the year, it would not be possible to obtain estimates for the entire UMRS in one day using LANDSAT data. In order to cover the entire UMRS, information from eight Landsat scenes is necessary (Figure 1), and the scenes require four satellite passes. Four passes for the entire UMRS require a minimum of eight days, assuming relatively cloud-free coverage for the entire area. Information for Landsat coverage for the UMRS, during late summer and early fall of 1987 and 1988, is included in Table 2. In 1987 relatively cloud-free imagery was available during an eight day period in August. Relatively cloud-free is defined here as reported cloud cover of 20% or less for an entire scene. Any reported cloud cover for a scene may be detrimental to the suspended solids study if the clouds obscured parts of the UMRS. During the same period in 1988, Landsat imagery collected over ten weeks was needed to obtain relatively cloud-free scenes. Landsat covers the same area once every 16 days.

Table 2. Date, path and row number, and percent cloud cover for coverage of the UMRS using data from Landsat TM.

Date	Path	Row	% Cloud cover
1987			
August 17	26	29	20
August 10	25	30	20
August 19	24	31	10
August 12	23	31	0
August 19	24	32	0
August 19	24	33	10
August 12	23	34	0
1988			
October 6	26	29	20
August 28	25	30	0
September 6	24	31	0
July 29	23	31	10
September 6	24	32	0
September 6	24	33	10
August 30	23	34	0

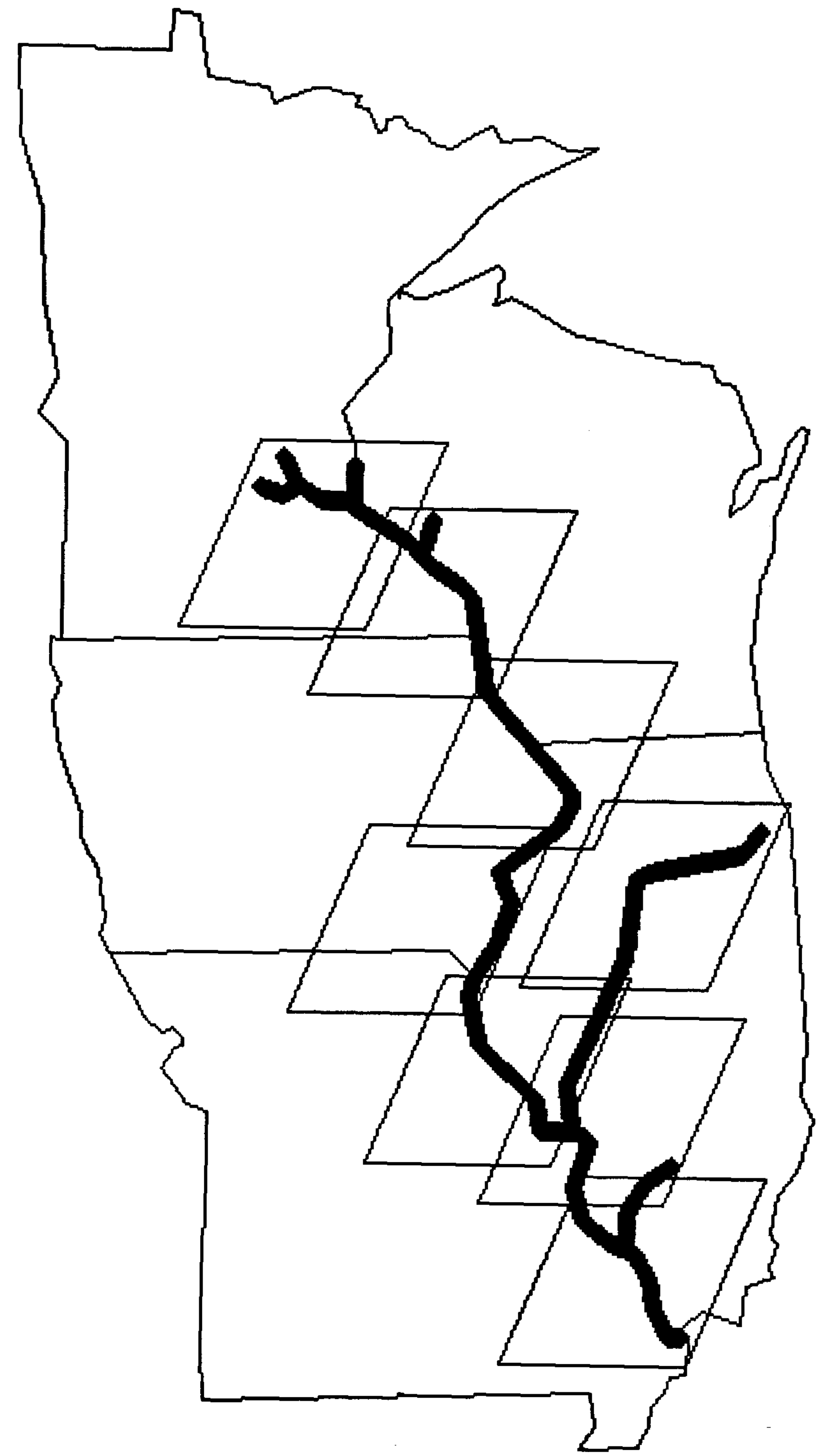
However, scenes from different satellite passes include approximately 10% overlap, so that for selected areas data may be available twice every 16 days. The cost for each Landsat TM scene is $3,600 as of January 1, 1989. The cost for a quarter scene is $1,800.

Landsat TM data could be used for other purposes within the LTRMP besides estimating SSC. Examples include the preparation of themes for geographical information systems concerning: vegetative cover typing (current and historic); hydrology (water surface profile per discharge); transportation; hydrography (streams, marshes and lakes); dams, levees, dikes, and other structural features; habitat types (community definition); loosestrife distributions; floodplain zoning; and dredge cuts and dredge material placement sites.

Information on past SSC may be possible for those days which were cloud-free when the satellite passed over a specific area. An estimate of the accuracy on past SSC would be available from a properly planned ground truthing study. Using the chromaticity transformation would probably supply the best quantitative estimates.

No reported studies were found where remote sensing was used to accurately estimate bed load transport. The literature indicates that bottom reflectance is insignificant when water depths exceed 20 to 30 cm. With this being the case, it is not likely that any information can be gained directly from reflectance from the bed load. If bed load can be related to SSC in the upper 20 to 30 cm of water, it may

Figure 1. Approximate coverage of eight LANDSAT scenes for the Upper Mississippi River System.



be possible to indirectly obtain information about the bed load. Information on the relationship of bed load and suspended sediment for part of the UMRS was discussed by the Great River Environmental Action Team (1980). A qualitative analysis of areas of deposition and erosion over the years could be obtained from old Landsat imagery. It would probably not be possible to distinguish areas of deposition caused by settling of suspended solids versus bed load transport.

Information concerning the cause (discharge, resuspension caused by wind or tow-boat) of SSC may be gained from remote sensing, but it would require a carefully planned study. The study would probably occur in a relatively small, well defined area, with information needed on a more continuous basis than can be supplied by satellite imagery. Information for this study would be better supplied by low-level aerial photography or imagery and in-place sensors.

The literature suggests that multiple wavebands can be used to estimate the individual contributions of various components to the overall reflectance of water. Ritchie et al. (1987) correlated chlorophyll-a to Landsat MSS data and found correlation coefficients to -0.74. However, they mention that chlorophyll was strongly correlated to suspended sediment. Lindell et al. (1986) proposed that with the better radiometric resolution of Landsat TM that separation of organic and inorganic matter may be possible.

In general, total reflectance of SSC includes reflectance due to inorganic materials, algae and other organic matter. Estimates of inorganic suspended sediments can be affected by other materials, and this effect can change throughout the year as the ratio of these materials change.

A number of other tasks concerning the sedimentation problem (Rasmussen and Wlosinski, 1988) can be aided with the proposed method for estimating SSC in the UMRS including: TM data can be used to classify biotic characteristics of the UMRS; TM data can be used to help verify, on a system wide basis, SSC limiting aquatic plant growth, or adversely affecting organisms; TM data can help determine areas where SSC limit aquatic plant growth or production of aquatic organisms, and; TM data can be used in the design and verification of sediment control measures.

SUMMARY

Remote sensing can provide reasonably accurate spatial estimates of SSC. However, because of high costs and infrequent satellite passes, satellite imagery data is not recommended as a means of collecting accurate temporal differences of SSC, especially if the interest is over relatively short periods of time. We recommend using in-place sensors and aerial imagery if one is interested in temporal differences over relatively small areas.

For an area as large and diverse as the UMRS, a study, which must include ground truthing, would be needed to develop the best technique and estimates of error. Landsat TM data is recommended because it has higher spectral resolution. Such a study should be coordinated with other studies, such as landcover analysis, which would also use Landsat imagery. At least 30 samples from at least each of three different areas would be needed for a ground truthing study. Two boat crews would be needed to collect samples from each area. Minimum cost for Landsat data for three study areas is $5,400. Laboratory costs would be between $300 and $500. An estimated $15,000 would be needed to develop the technique to estimate suspended solids using satellite imagery. If the results were satisfactory, $28,800 would be needed to purchase satellite data for the entire UMRS for one period of time.

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ABSTRACT

The purpose of this report was to determine the feasibility of obtaining estimates of the concentrations of suspended solids in 1300 miles of the Upper Mississippi River System using remote sensing. The report includes 1) a review of measured concentrations of suspended solids in different portions of the system. 2) a literature search of the spectral characteristics of suspended solids in water bodies in the laboratory and field and the use of remote sensing for qualitative and quantitative estimation of suspended solids in water bodies; and 3) the steps necessary to initiate a study to obtain estimates of error which would be needed because of the length and diversity of the Upper Mississippi River System.

DOCUMENT ANALYSIS a. DESCRIPTORS

Suspended Solids, Remote Sensing

b. IDENTIFIERS/OPEN-ENDED TERMS

Mississippi River
Upper Mississippi River System
Long Term Resource Monitoring Program

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