ABSTRACT Suspended sediment is a visible indicator of water quality in lakes and reservoirs and a potential indicator of soil erosion on the drainage basin. An economical method is needed for surveying the landscape to locate water bodies with significant suspended sediment concentrations. This paper discusses remote sensing studies using multispectral scanner (MSS) digital data from the Landsat satellite to estimate the concentration of surface suspended sediment in two oxbow lakes in the lower Mississippi River valley. These studies show that MSS data can be used to estimate the concentration of suspended sediment. Using this remote sensing technology, it would be possible to survey large segments of the landscape economically and efficiently to locate water bodies with significant suspended sediment concentrations.

INTRODUCTION

Water quality is a problem in lakes and reservoirs around the world. While many factors (i.e. sediments, nutrients, salts) contribute to water quality problems, the most visible indicator of
these problems is sediments suspended in surface waters. A method to rapidly and economically survey and estimate suspended sediment in water bodies across the landscape would provide valuable information about water quality and help locate basins with soil erosion problems. Traditional technology for measuring surface suspended sediment requires making in situ measurements or collecting water samples for laboratory analyses. These methods are expensive and time-consuming and do not give a synoptic view of a water body. More importantly, a simultaneous synoptic view of the landscape is necessary if lakes and reservoirs with water quality problems are to be located and associated with basins with potential soil erosion problems.

Satellite remote sensing has been used for monitoring vast areas of the landscape, effectively, efficiently and repeatedly (Tucker et al., 1985). Techniques using satellite sensors have been used to estimate suspended sediments in surface waters (Lathrop & Lillesand, 1986; Lindell et al., 1986; Ritchie et al., 1987; Ritchie & Cooper, 1988; Schiebe et al., 1988; Verdin, 1985). The purpose of this paper is to describe three analytical models developed to use Landsat multispectral scanner (MSS) data to estimate suspended sediment concentrations in two oxbow lakes in the lower Mississippi River valley.

Using this technique, the landscape can be rapidly surveyed to locate lakes and reservoirs with high suspended sediment concentrations. Soil conservation specialists could use this information to identify basins with the most serious water quality problems.

METHODS

Two oxbow lakes in the lower Mississippi River valley were used in this study. Lake Chicot is an oxbow lake adjacent to the Mississippi River in southeastern Arkansas. It is approximately 20 km long and 1 km wide. The basin is approximately 900 km² and is extensively cropped with soybeans and cotton. The soils are developed on Mississippi alluvial flood plain deposits of clays and silts. Erosion on the basin caused chronic sediment problems in the lake and led the U.S. Army Corps of Engineers to develop a management plan to reduce sediment delivery to the lake. The plan, which included construction and management of several structures, was placed in operation in the Spring of 1985 and has significantly reduced suspended sediment concentrations in the lake (Schiebe et al., 1988).

Moon Lake is an oxbow lake adjacent to the Mississippi River in northwestern Mississippi. Moon Lake is approximately 140 km north of Lake Chicot and is approximately 12 km long and 1 km wide. The basin is approximately 166 km² and is also extensively cropped with soybeans and cotton. Soils are developed on Mississippi alluvial flood plain deposits.

Water quality measurements have been made at four sample sites on Lake Chicot since 1976 (Schiebe et al., 1988) and at five sample sites on Moon Lake between June 1982 and June 1985 (Cooper, 1985). Water quality measurements included suspended sediments, total solids, chlorophylls, nutrients, pH, conductivity, dissolved oxygen, and temperature. These water quality measurements were usually made in conjunction with the date of an overpass of Landsat.
Geometrically corrected (Verdin, 1983) digital Landsat data for the four MSS spectral bands were purchased for an area surrounding Lake Chicot (Path 23 Row 37) and Moon Lake (Path 23 Row 36). Data extraction and analyses were made using a microcomputer based image processing system. A total of 76 Landsat MSS scenes for the 1976 to 1986 time period for Lake Chicot have been analyzed. For Moon Lake, 27 Landsat MSS scenes were analyzed for the June 1982 to June 1985 period.

Digital pixel data for each Landsat MSS band were extracted for a 5x5 pixel area surrounding each sample site on Lake Chicot and Moon Lake. The average of these 25 pixels was calculated (Ritchie & Cooper, 1987) and used for the analyses in this paper. The pixel data were converted to physical values of radiance and exoatmospheric reflectance for comparison between satellites (Landsat 1 through 5), scenes, and locations (Price, 1987; Robinove, 1982).

RESULTS AND DISCUSSION

Lake Chicot and Moon Lake have developed under similar environmental conditions. Both are oxbow lakes in old channels of the Mississippi River that have been isolated from direct influence from the River by levees. While Lake Chicot has a much larger basin, agricultural crops and practices are similar. Extensive channelization has occurred in the Lake Chicot basin while little channelization has occurred in the Moon Lake basin leaving areas of wetland adjacent to the streams. Since Lake Chicot (Path 23 Row 37) and Moon Lake (Path 23 Row 36) are located on different Landsat MSS scenes, these lakes are useful for comparative studies of information transfer between Landsat scenes.

The range of suspended sediment concentrations in Lake Chicot (1 to 970 mg l⁻¹) was greater than that measured in Moon Lake (1 to 410 mg l⁻¹). The average value (183 mg l⁻¹ for Lake Chicot and 110 mg l⁻¹ for Moon Lake) may indicate a difference in suspended sediment in the lakes. There are a number of possible explanations of the larger range and higher average of suspended sediment in Lake Chicot. First, the length of record from Lake Chicot is three times greater than Moon Lake giving a greater opportunity for inclusion of extreme climatic events. Second, a model comparison of expected suspended sediment concentrations to similar climatic events indicates that Lake Chicot should have a higher concentration because of its much larger basin. Third, there is a possible filtering effect at Moon Lake since its contributing tributaries flow through wetlands and small ponds while the flow into Lake Chicot has been channelized. Both lakes had similar seasonal patterns of suspended sediment with highest concentrations in late spring and lowest concentrations in late fall.

The exoatmospheric reflectance data for MSS band 3 (700-800 nm) was plotted (Figs. 1 & 2) for Lake Chicot and Moon Lake as a function of suspended sediment. In both lakes, reflectance in the four MSS bands increased with suspended sediment concentration until a reflectance saturation level was reached. This saturation is especially noticeable in the Lake Chicot data where suspended sediment concentration greater than 500 mg l⁻¹ were measured. The reflectance saturation level was different for each MSS band.
Fig. 1. Linear model comparison of Moon Lake and Lake Chicot. Data range $0 < C < 450 \text{ mg} \; \text{l}^{-1}$.

Fig. 2. Three parameter exponential model comparison of Moon Lake and Lake Chicot. Data range $C > 0 \text{ mg} \; \text{l}^{-1}$.
If suspended sediment was the only source of reflectance from water, then reflectance would be expected to approach zero at low concentrations of suspended sediment. In both Lake Chicot and Moon Lake data, reflectance remained above 3% even at the lowest suspended sediment concentrations. Cooper et al. (1984) have shown that phytoplankton production is primarily light limited by suspended sediments in these lakes. Thus as suspended sediment decreased, phytoplankton production increased and light interaction with phytoplankton caused the reflectance measured.

The scatter in the MSS data (Figs. 1 & 2) reflects both a natural scatter in the data and scatter due to the comparison of two Landsat scenes on many different dates. The differences in the atmosphere between different dates over the 11 year period most likely contribute much of the scatter in the data sets. No attempt has been made to correct for the different atmospheric conditions since no acceptable method is available.

Three analytical models were developed to analyze data sets from Moon Lake and Lake Chicot. First, a simple linear regression model was used for each lake. The model has the form

\[ R = L + Mc \]  

where \( R \) is exoatmospheric reflectance, \( c \) is suspended sediment concentration, and \( L \) and \( M \) are parameters for intercept and slope calculated by fitting the equation to field data. The values for \( L \), \( M \), and the correlation coefficient \((R^2)\) were compared for each MSS band (Table 1).

Table 1 Comparison of linear regression models for the relationship between suspended sediment and Landsat MSS exoatmospheric reflectance data for Lake Chicot and Moon Lake. \( n \) is number of samples.

<table>
<thead>
<tr>
<th>MSS band</th>
<th>Lake Chicot ((n = 310))</th>
<th>Moon Lake ((n = 135))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( L ) ( M ) ( R^2 )</td>
<td>( L ) ( M ) ( R^2 )</td>
</tr>
<tr>
<td>1</td>
<td>0.125 0.0001 0.29</td>
<td>0.148 0.0002 0.40</td>
</tr>
<tr>
<td>2</td>
<td>0.093 0.0002 0.50</td>
<td>0.117 0.0004 0.64</td>
</tr>
<tr>
<td>3</td>
<td>0.071 0.0002 0.62</td>
<td>0.079 0.0004 0.83</td>
</tr>
<tr>
<td>4</td>
<td>0.043 0.0001 0.47</td>
<td>0.052 0.0002 0.53</td>
</tr>
</tbody>
</table>

Since the range of the Lake Chicot data set is much greater than Moon Lake, the Lake Chicot data set was truncated at 450 mg l\(^{-1}\) to achieve similar ranges in the data sets and the parameter values for the linear regression and the resulting \( R^2 \) were calculated again with both data sets limited to a range from 0 to 450 mg l\(^{-1}\) for suspended sediment (Table 2) and the regression lines plotted for MSS band 3 (Fig. 1).
The second analytical model used is a nonlinear two parameter model (Schiebe et al., 1988). This model has the form

\[ R = B(1-e^{-c/S}) \]  

(2)

where \( R \) is exoatmospheric reflectance, \( c \) is suspended sediment, \( B \) is the apparent asymptotic value of the reflectance, and \( S \) is a concentration parameter when the average reflectance is 63% of the asymptotic value. This analytical model was developed from the physics of the underwater irradiance scattering. Parameter estimates of \( B \) and \( S \) were optimized to give a maximum value for \( R^2 \) (DeCoursey and Snyder, 1969) independently for each lake. Schiebe et al., (1988) have shown that reflectance data at concentrations less than 25 mg l\(^{-1}\) were due to factors other than suspended sediments such as chlorophyll. Thus for use with this two parameter model, the data sets were limited to suspended sediment concentrations greater than 25 mg l\(^{-1}\). The calculated parameters and \( R^2 \) for the two parameter models are compared in Table 3.

Table 3 Comparison of nonlinear two parameter models for the relationship between suspended sediment and Landsat MSS exoatmospheric reflectance data for Lake Chicot and Moon Lake with the data sets limited to suspended sediment concentrations greater than 25 mg l\(^{-1}\). n is number of samples.

<table>
<thead>
<tr>
<th>MSS band</th>
<th>Lake Chicot (n = 203)</th>
<th>Moon Lake (n = 109)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>S</td>
</tr>
<tr>
<td>1</td>
<td>0.168</td>
<td>26.1</td>
</tr>
<tr>
<td>2</td>
<td>0.187</td>
<td>56.7</td>
</tr>
<tr>
<td>3</td>
<td>0.176</td>
<td>88.2</td>
</tr>
<tr>
<td>4</td>
<td>0.102</td>
<td>91.7</td>
</tr>
</tbody>
</table>
To use the total data sets, a third analytical model was developed with a third parameter to account for reflectance at low suspended sediment concentrations. This exponential model had the form

\[ R = A e^{-cB/SA} + B(1-e^{-c/S}) \]  

(3)

where \( R \), \( B \), \( S \), and \( c \) are the same as equation 2, and \( A \) is the apparent intercept of the data on the ordinate. Again parameter estimates for \( A \), \( B \), and \( S \) were optimized to give a maximum value for \( R^2 \) (Table 4). The resulting models for MSS band 3 are plotted on Fig. 2.

Table 4 Comparison of nonlinear three parameter models for the relationship between suspended sediment and Landsat MSS exoatmospheric reflectance data for Lake Chicot and Moon Lake. \( n \) is number of samples.

<table>
<thead>
<tr>
<th>MSS band</th>
<th>Lake Chicot ( (n = 310) )</th>
<th>Moon Lake ( (n = 135) )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( A )</td>
<td>( B )</td>
</tr>
<tr>
<td>1</td>
<td>0.112</td>
<td>0.174</td>
</tr>
<tr>
<td>2</td>
<td>0.077</td>
<td>0.197</td>
</tr>
<tr>
<td>3</td>
<td>0.066</td>
<td>0.201</td>
</tr>
<tr>
<td>4</td>
<td>0.044</td>
<td>0.132</td>
</tr>
</tbody>
</table>

While the data from the two lakes appear to be from similar populations when plotted together (Figs. 1 & 2), the analytical models (i.e., Fig. 1) indicate that the reflectance from Moon Lake is about 20% higher than it is for Lake Chicot for the same suspended sediment concentration. Research continues on the properties of the suspended sediment particles in each lake to determine reflectance differences related to particle size or particle size distribution. Since inflow into Moon Lake is filtered through wetlands and small ponds, particles reaching Moon Lake may be smaller and thus have more reflecting surfaces. This is also supported by the nonlinear model which appears to reach a reflectance saturation level at lower suspended sediment concentration. Research continues to develop analytical models which will account for the differences between the lakes.

While the two lakes appear to have different reflectance properties, the high correlation coefficients, especially in MSS band 3 (700-800 nm), indicate that MSS digital data can be used to locate water bodies with high suspended sediment. This technique can be used to survey the landscape to locate water bodies with significant suspended sediment and to target conservation efforts to those basins with the most serious problems.
REFERENCES


