Hydraulics Research
Wallingford

A Literature Review of Remote Sensing of Suspended Solids in Estuaries

A P Diserens BSc

E A Delo BSc PhD CEng MICE MIWEM

SR Report 177
May 1988

Registered Office: Hydraulics Research Limited,
Wallingford, Oxfordshire OX10 8BA.
Telephone: 0491 35381. Telex: 848552

This report describes work funded by the Department of the Environment under Research Contract PECD 7/6/59 for which the DoE nominated officer was Dr R P Thorogood. It is published on behalf of the Department of the Environment, but any opinions expressed in this report are not necessarily those of the funding Department. The work was carried out by A P Diserens under the direction of Dr E A Delo in Mr T N Burt's section in the Tidal Engineering Department of Hydraulics Research, Wallingford, under the management of Mr M F C Thorn.

ABSTRACT

The development of satellite remote sensing over the past twenty years has led to the availability of image data either by requesting archived information from previous satellite overpasses or by data retrieval on future overpasses. There have been a large number of feasibility studies investigating the possibility of using satellite remote sensing techniques, instead of high costs marine surveys, to determine the distribution and movement of suspended sediment.

The remotely sensed data can be used in three types of study;

i) qualitative studies which give information on the variation in position and extent of suspended sediment plumes
ii) quantitative studies using simultaneous field survey measurements to give calibration between sediment concentration and received light intensity at the satellite, and
iii) quantitative studies using universal algorithms to enable archive data for which simultaneous field measurements are not available to be used.

For the best calibration and verification of the remotely sensed data it is necessary to obtain a comprehensive set of suspended sediment concentrations concurrent with the satellite overpass. Information on the surface runoff, wind, tidal and other environmental factors are also required to put the survey results in context, for both qualitative and quantitative studies.

The use of remote sensing for both qualitative and quantitative studies has been shown to be potentially useful. However its use to determine the variation in distribution of sediments spatially and temporally is limited by the restriction of measurements to the top 2 metres of the water column.

The inflexibility of the timing of overpass is also a limitation to the use of satellites, since the overpass cannot necessarily be chosen to coincide with, for example, a high tide. The obstruction by clouds can also make it difficult to obtain data for high run-off periods, since peak run-off and cloudy periods are coincident.

CONTENTS

1 INTRODUCTION

1.1 Background

The development of satellite remote sensing over the past twenty years has led to the availability of image data, either by requesting data retrieval on future satellite overpasses or from archive data from previous overpasses. The use of remotely sensed information as an alternative to on-site marine surveys replaces the need for a large number of monitoring positions with a single satellite and a smaller number of calibration positions. Accordingly, the cost of a remote sensing exercise would typically be lower than that of a full on site marine survey.

The possibility of using satellite remote sensing techniques, instead of marine surveys, to determine the distribution and movement of suspended sediment has led to a large number of feasibility studies (Table 1). Traditional marine surveys involve monitoring of a large number of points over the survey area, the collected data is then used in one, two or three dimensional mathematical models. In one dimensional models the data is averaged both vertically through the water column and horizontally across the estuary. In two dimensional models the data is averaged either vertically or horizontally.

Satellite remote sensing, however, can not give information on the vertical distribution of sediment in the water column as only the surface two metres give reflected information. Hence, remotely sensed data is most useful in one or two dimensional studies where the data is vertically averaged. Remotely sensed data is of less use in three or two dimensional studies, where the data is not vertically averaged, since either an assumed vertical distribution must be used or a comprehensive series of samples from throughout the water column need to be obtained simultaneously with the overpass, to assess the vertical sediment distribution.

1.2 Principles of satellite remote sensing

A number of texts are available giving descriptions of the principles of satellite remote sensing and data processing techniques, for example Sabins (1978) and Cracknell (1980). The satellites used for oceanographic studies are: the ERTS (earth resources technology satellites) Landsat 1-4 launched in 1974 and the Nimbus-G with the CZCS (coastal zone colour scanner) launched in 1987. In addition a number of studies used data from the EREP (earth resource experimental package) on Skylab.

More recently the French SPOT spacecraft using HRV (high resolution visible and near infra red) sensors, has become available and the ERS 1 (european remote sensing satellite) will soon be available for studies.

The remote sensing of suspended sediments uses reflected electromagnetic radiation of wavelength between 0.5 and 0.8nm which corresponds to the visible, green, red and near infra red light. There are two distinct types of sensor used: multi spectral scanners which scan a complete series of wavelengths simultaneously; and Thematic mappers which have specially selected bands to cover items of interest, for example, to delineate water bodies, or green vegetation. A summary of the satellites and the band ranges available is given in Figure 1. The spectral response of each band is not evenly distributed but peaks around a centroid wavelength. The scanners provide data in digital or analogue form which is readily available for computer image processing techniques.

The light received by the satellite sensor is split into gray levels (levels of intensity of light). The Landsat bands have a maximum of 255 levels each having a digital value. Not all the 255 levels are utilized since reflection from the atmosphere and water will give a background reading of greater than zero. The maximum intensity measured is proportional to the intensity of the illuminating light, which varies with time of year and sun angle.

The intensity of the received radiation depends on
i) the sediment concentration in the upper two metres of the water column
ii) the chromatographic characteristics of the sediment, and
iii) interference from the water column, water surface and the atmosphere.

Only the upper 2 metres of the column can be sensed because of the rate of extinction by the water. In clear waters 99% of the incident light in band five is absorbed within the surface two metres. Dissolved substances, particularly some organic compounds, result in an increase in the adsorption coefficient of water. The amount of light remaining at any depth, in clear water is given by (Moore 1980)

$$I = I_s/e^{kz} \qquad (1)$$

where

I = Light remaining at a depth z from the surface
I_s = flux entering the water

k = coefficient of extinction

Quantitative information can be retrieved if the radiance received by the satellite is calibrated with suspended sediment concentration obtained simultaneously with an overpass.

Inaccuracies can occur because of spatial and temporal variations in atmospheric and sea surface interference and interference due to marine vegetation and sea bed reflections.

These relationships can be applied to data from other overpasses for which no calibration measurements are available provided corrections are made for variations in atmospheric and sea surface interference and intensity of incident light.

2 QUALITATIVE STUDIES

A number of studies have been carried out which look qualitatively at the tidal and seasonal variation in the position and extent of suspended sediment plumes (Klemas 1973, Rouse and Coleman 1976).

Qualitative studies are relatively simple in that they require no calibration measurements, this makes them potentially useful as a preliminary to sediment movement investigations. Archive satellite images can be used together with concurrent weather, tidal and freshwater runoff information to show variations in position and extent of sediment plumes with prevailing environmental conditions.

The image received by the satellite is processed to remove noise, to delineate the water masses and to divide the water masses into areas of equal intensity. The highest intensity having the highest concentration of suspended sediment.

The images can then be plotted up as contour maps of reflective intensity and compared and contrasted for different prevailing environmental conditions.

Rouse and Coleman (1976) used this procedure to investigate the position and shape of the Missisipi Delta sediment plume over a period of two years. A series of images showing the variation in the plume under a number of different river flows and weather conditions were obtained (Fig 2). It can be seen from the images that in January, May and November 1974 the plume intrudes into the Louisiana Bight and turns to the east. The presence of a clockwise circulation was evident from the images. The March and June 1974 images show spreading to the east caused by a southerly wind. The January and February 1973 images show the effect of wind, the wind in the February image was stronger than that in January and hence moved the plume further west.

The conclusions drawn from this study were that the size and shape of the plume was a function not only of the amount of freshwater discharge but also of the wind strength and direction. The intimation of a clockwise circulation in the Louisiana Bight also supports information previously found by field survey. The drawback with this study was the length of time between useful overpasses. A shorter time interval between images than was obtained from this survey is desirable.

3 QUANTITATIVE STUDIES USING SIMULTANEOUS FIELD MEASUREMENTS

Quantitative determination of suspended surface sediment distribution using a correlation between the radiance detected by the satellite sensor and similtaneous suspended sediment concentrations can yield useful information to marine scientists. Studies evaluating this technique include Klemas (1974 and 1975) and Collins (1983).

These studies involved taking a number of suspended solids concentration readings at the water surface simultaneously with the satellite overpass. The radiance received at the satellite may then be calibrated with the known suspended solids concentration readings. A contour map of the distribution of suspended solids in the surface water can then be plotted.

A study by Klemas (1974) of Delaware Bay used field data collected from boats and helicopters, on three transects across the bay, simultaneously with Landsat-1 overpasses. The field survey data included Secchi disc depth, suspended sediment concentration, optical transmissivity, temperature, salinity and water colour. The received radiance in Landsat wave band 5 was correlated with the field measurements of suspended sediment concentrations.

The correlation coefficient was 0.995. The suspended sediment plumes detected were used to give information on surface currents which agreed well with predicted current maps produced using on site survey data. An example of a sediment distribution map from this study is presented in Figure 3.

Collins (1983) used this technique to study the near surface suspended sediment concentration in the Bristol Channel. The images produced were used to give information on the concentration patterns, the transport paths and the source areas of surface sediments. This information, together with previously observed data on surface to bed concentration ratios in the region, was used to give an estimate of total sediment in suspension. The predicted figure was similar to that produced previously from field survey results.

Lindel (1986) used a study of Lake Malern in Sweden to test a development of the 'chromaticity' technique, first proposed by Alfoldi (1978). In this technique the ratio of the radiance in each waveband to the total radiance, called the 'chromaticity ordinate' is correlated with field measurements of suspended sediment concentration. The results obtained gave no significant deviation between the observed and predicted values of suspended sediment concentration. There was however interference in some regions of the study area from the presence of coloured phytoplankton.

4 QUANTITATIVE STUDIES USING MULTIDATE ALGORITHMS

To enable marine surveyors to make use of archive information, a number of studies proposing and testing multidate algorithms have been undertaken, for example Holyer (1978) and MacFarlane (1984).

Multidate algorithms use a correlation between sediment concentration and radiance measured at the satellite. The algorithm however has to take into account the variation in intensity of incident radiation and the atmospheric and sea surface contribution to the radiance. The concentration of sediment is found using a correlation between the suspended sediment concentration and diffuse upwelling radiance (the amount of light reflected by suspended sediment).

The diffuse upwelling radiance is found from the radiance received at the satellite from the relationship

$$L_u = (L-L_s-L_a)\ K_s\ K_w \qquad (2)$$

where

L_u = Diffuse upwelling radiance
L = radiance received at the satellite
L_s = contribution to the radiance from sea surface effects
L_a = contribution from atmospheric effects
K_s = correction for variation of sun angle and intensity
K_w = correction for sub sea surface effects

Each sensor in the scanner has individual response characteristics which have to be taken into account when transforming the digital read out to radiance. The calibration method is given in the Landsat users guide (see MacFarlane 1984).

It is the ratio of the incident to reflected light which is comparable to sediment concentration, rather than the absolute amount of reflected light. Two factors influence the intensity of incident light: the angle of incident radiation; and the distance from the sun.

Both the angle (solar zenith angle) and distance from the sun can be found since the precise position of the earth and sun are known. The formula for the corrections is given by (MacFarlane 1984)

$$L_s(i) = J\ L\ (i)/\cos\Theta \qquad (3)$$

where

L_s = corrected radiance in band (i)
L = measured radiance in band (i)
J = correction for sun distance fluctuations
Θ = incident angle of sunlight

There are four atmospheric and sea surface effects which contribute to the measured radiance (MacFarlane 1984):

i) Rayleigh scattering of light by air molecules including ozone, carbon dioxide etc. The magnitude of this effect is dependent upon the quantity and characteristics of the molecules present, which may be assumed to be constant for a particular study area.

ii) aerosol scattering by fine water droplets - the size of which is again taken to be a constant for a particular study area.

iii) skyglitter - reflection of sunlight from atmospheric particles direct to the sensor.

iv) sunglitter - reflection of sunlight from the water surface to the sensor which is proportional to the sea surface roughness and sun angle.

The contribution from Rayleigh scattering, sunglitter and skyglitter are derived from Landsat data and standard functions (MacFarlane 1984, Sturm 1981, 1983).

The sub-sea-surface reflection in band 7 is negligible and can be assumed to be zero, hence the contribution to the radiance from aerosol scattering in band 7 can be found by subtracting the contribution from the atmosphere and sea surface effects. The aerosol scattering component of bands 4 and 5 can then be found, since they are assumed to be directly proportional to that in band 7 (MacFarlane 1984).

The influence from aerosol scattering for the CZCS can be found in a similar way (MacFarlane 1984). However, as the wavelength range of the CZCS is far less than that of Landsat, the value of aerosol scattering in band 7 is found using clear water pixels (ie areas of no suspended sediment). In many cases there are no clear water pixels available so a correction factor is found from the ratio of estimated aerosol scattering values (MacFarlane 1984, Strum 1981).

The correction for sub-sea-surface is dependant on the reflective and adsorbtion properties of both the water and the sediment, the most important of which is the refraction index of the water which is a constant.

The diffuse upwelling radiance, calculated using equation 2, is converted into a ratio value for correlation with suspended sediment concentration. This can be done either by calculating a chromaticity ordinate (Alfoldi 1978) or calculating a diffuse reflectance ratio (Gordon 1981).

A chromaticity ordinate is the ratio of the intensity of the upwelling radiance in band 4 or 5 to the sum of the upwelling radiance in wavebands 4 to 6. The diffuse subsurface reflection ratio (Gordon 1981) is the ratio of upwelling radiance to the estimated value of downwelling radiance.

MacFarlane (1984) used Landsat data of the Solent to compare calculation techniques. The correlation coefficients with suspended sediment concentration for each method were:

Chromaticity ordinate band 4;	-0.981
Chromaticity ordinate band 5;	0.792
Diffuse reflectance ratio band 4;	0.924
Diffuse reflectance ratio band 5;	0.977

The best correlation with suspended sediment concentration was found using the chromaticity ordinate for band 4. Figure 4 shows a plot of suspended sediment concentration against chromaticity ordinate.

5 DISCUSSION

The use of remote sensing for qualitative and quantitative studies has been shown to be potentially useful. However, its use to determine the variation in distribution of sediments spatially and temporally is limited by the restriction of measurements to the top 2 metres of the water column. In an estuarine system the surface to bed sediment concentration ratio can vary considerably, for example from 1:3 to 1:10 in the Severn Estuary (Collins 1983). The remotely sensed concentration can be depth averaged to give an estimate of total suspended sediment content of an estuary. However, a high proportion of estuarine studies require information on the vertical distribution of sediment, for use in two and three dimensional models. This cannot be found by remote sensing techniques.

In conjunction with the survey it is also necessary to obtain information on the surface runoff, wind, tidal and other relevant information to put the surveyed data in context, for both qualitative and quantitative studies.

The inflexibility of the timing of overpasses limits the use of remote sensing techniques, since an overpass cannot necessarily be chosen to coincide, with for example, a high tide. The obscuration by clouds can also make it difficult to obtain data for high run-off periods, since peak run-off and cloudy periods are often coincident.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

1. The capability of data retrieval of the suspended sediment concentration of only the upper 2 metres of the water column severely restricts the usefulness of satellite remote sensing for estuarine suspended sediment studies. In many studies information is required of the vertical distribution of sediment in the water column which cannot be obtained from remotely sensed data. In these cases a large quantity of on site field survey data is required thus limiting the benefits of using the remotely sensed information.

2. The inflexibility of the timing of overpasses and the vulnerability to the obscuration by cloud, results in restriction of the timing of data aquisition. Hence, it is impossible to acquire

data for a pre-alloted time sequence (for example every 20 minutes over a tidal cycle).

3. The technique can be used qualitatively to give prior information for field surveys, and also as a useful overview of the situation, supplementary to field surveys.

4. Studies using simultaneous field survey information will be the most accurate. However, extensive field surveys are required which incur high cost and are vulnerable to adverse weather conditions.

5. With the use of universal algorithms and only small amounts of field survey measurements, archive data can be used to give information on the surface concentration and transport of suspended sediments. This technique would probably be most useful for large scale investigations in remote areas where marine surveys prove difficult and expensive.

6.2 Recommendations

1. The use of archive data should be considered as a preliminary to large scale investigations. This can provide qualitative information on sediment plume shape and position.

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TABLE.

TABLE 1 SUMMARY OF REPORTS PUBLISED

INVETIGATORS	DATE	SATELLITE	AREA
Rochon*	1973	Landsat	St Lwrence River, Canada
Williamson	1973	Landsat	Chesapeake Bay, USA
Yarger	1973	Landsat	Kansas, USA
Klemas	1973	Landsat	Delaware Bay, USA
Kriticos	1974	Landsat	Potomac River, USA
Klemas	1974	Landsat/Skylab	Delaware Bay, USA
Maul	1975	Landsat	Gulf Stream, USA
Klemas	1975	Landsat/Skylab	Delaware Bay, USA
Bowker*	1975	Landsat	Chesapeake Bay, USA
Rouse	1976	Landsat	Louisiana Bight, USA
Ritchie	1976	Landsat	Mississippi, USA
Amos*	1979	Landsat	Minas Basin
Singh *	1979	Landsat	Southern North Sea, UK
Sydor*	1980	Landsat	Lake Superior, USA
Klemas*	1980	Landsat	Delaware Bay, USA
Thomas*	1980	Landsat	Patanatahui Inlet, New Zealand
Aranavachapu	1981	Landsat	River Fraser Estuary, Canada
Robinson	1981	Landsat	The Solent, UK
Khorram	1982	Landsat	San Fransisco Bay, California
Cracknell*	1982	Landsat	Tay Estuary, UK
Collins	1983	Landsat	Various
Collins	1983	Landsat	South China Sea
Lathrop	1986	Landsat	Lake Michigan, USA
Ritchie	1987	Landsat	Mississippi, USA
OTHER REFERENCES			
Holyer	1978	Multidate algorithms	
Munday	1979	General review of Models	
Moore	1980	General	
Whitlock	1981		
Witte	1982	Effect of dissolved materials	
Macfarlane	1984	Multidate algorithms	
Lindell	1986	Chromaticiy technique, further developments	

* Abstracted from Collins 1983

FIGURES.

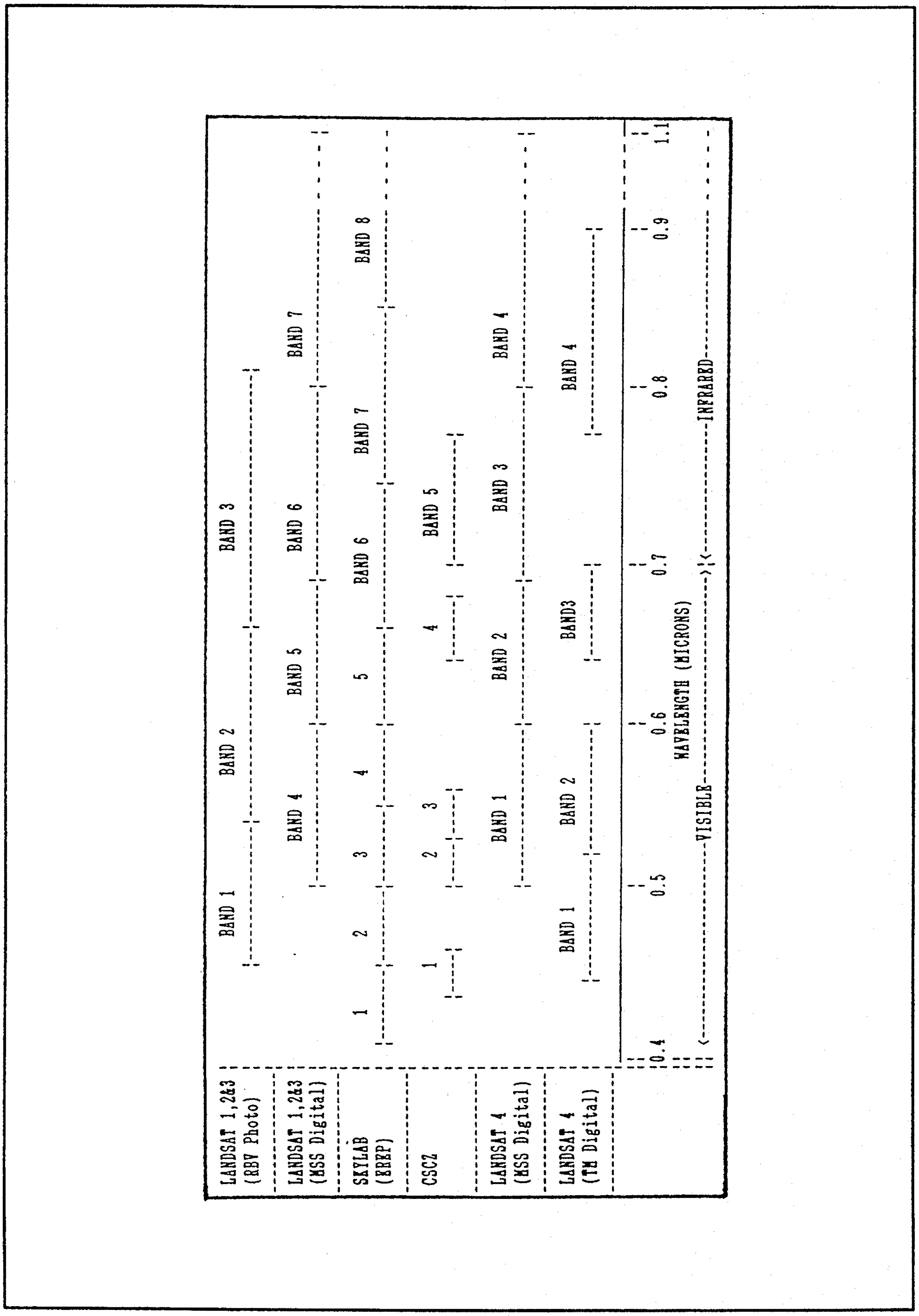

Fig 1 Wavelength ranges of satellite sensors

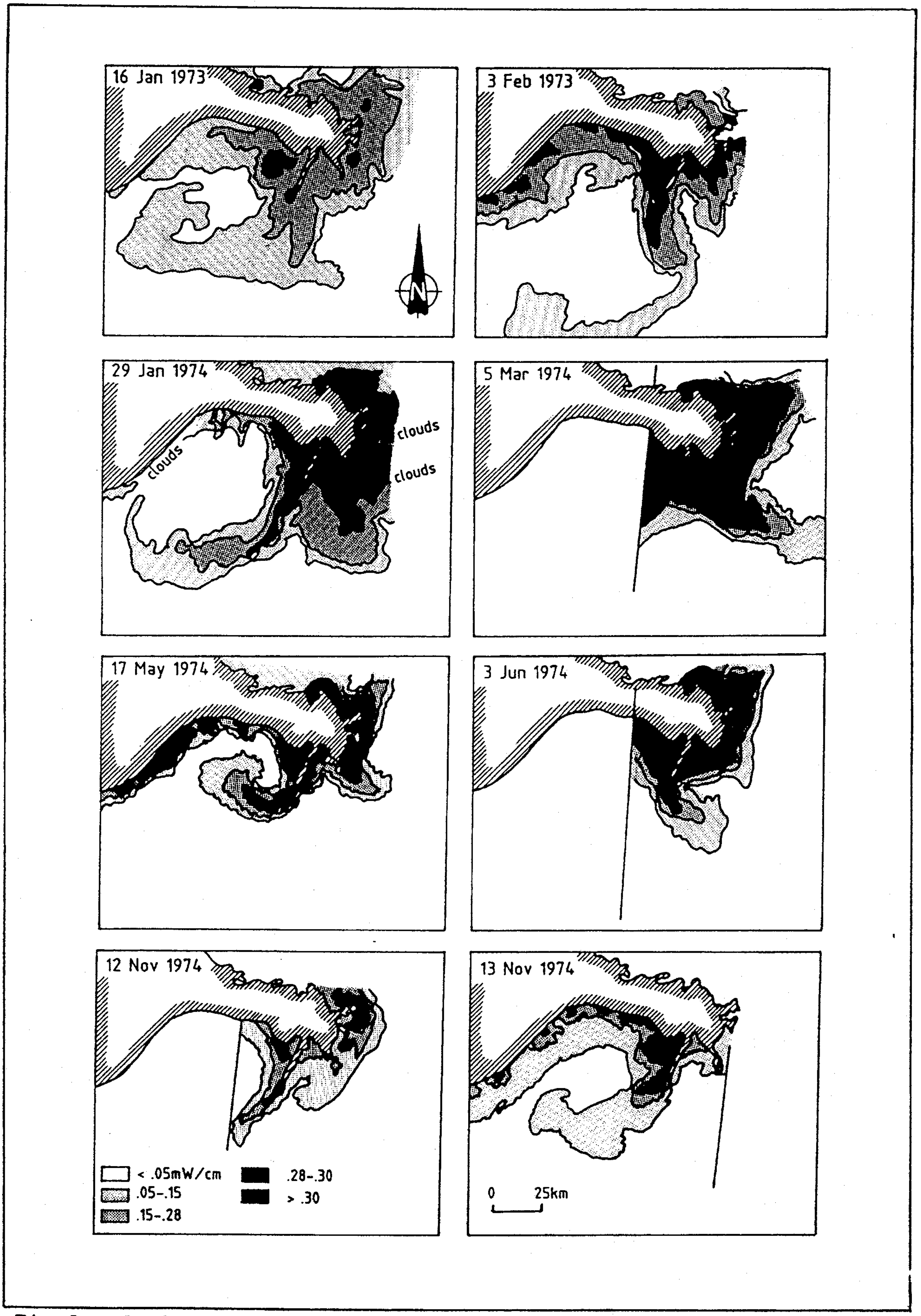

Fig 2 Contour plots of reflective intensity of the Louisiana Bight in landsat band 7 (From Rouse 1976)

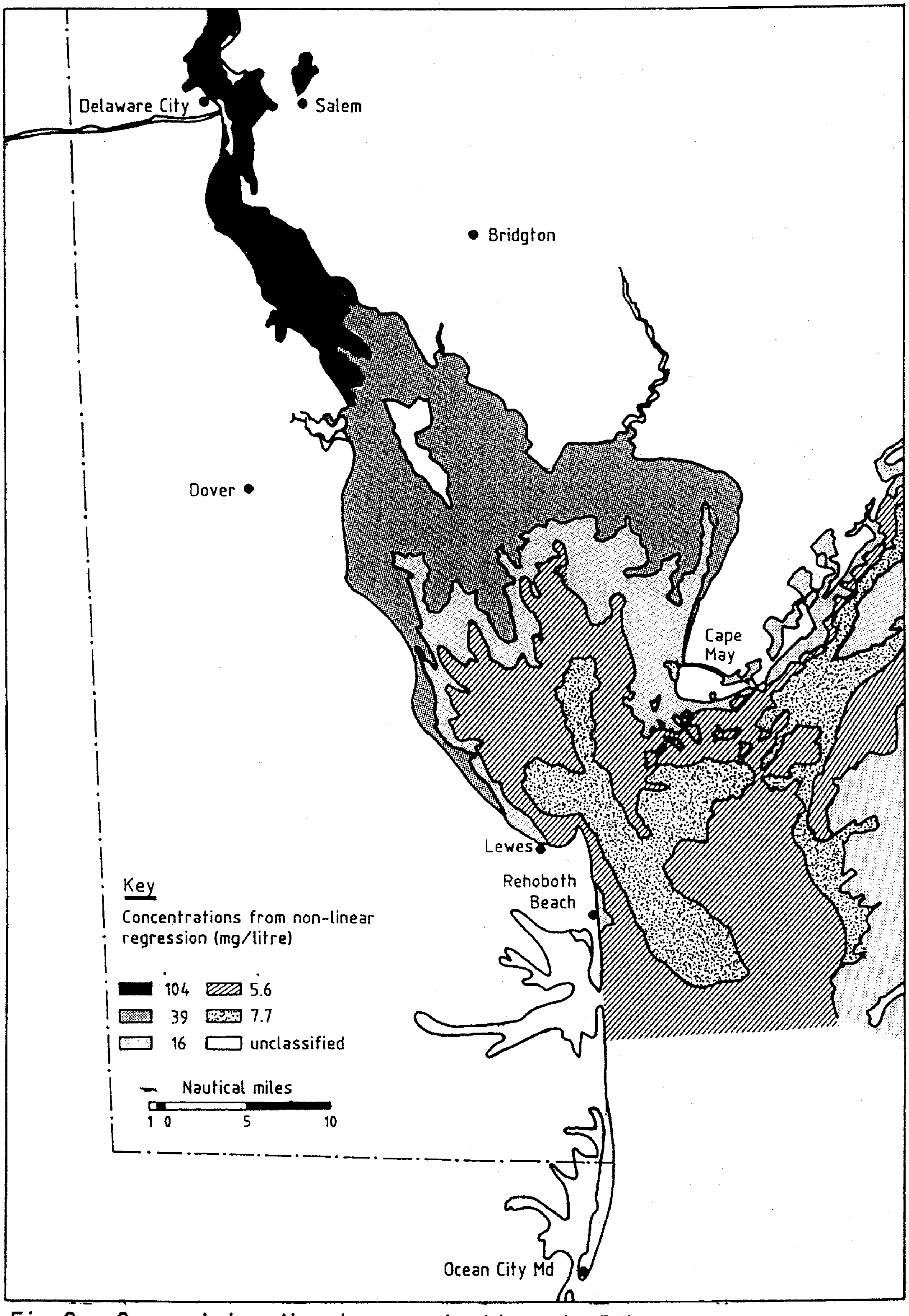

Fig 3 Suspended sediment concentrations in Delaware Bay derived from landsat data (From Klemas 1974)

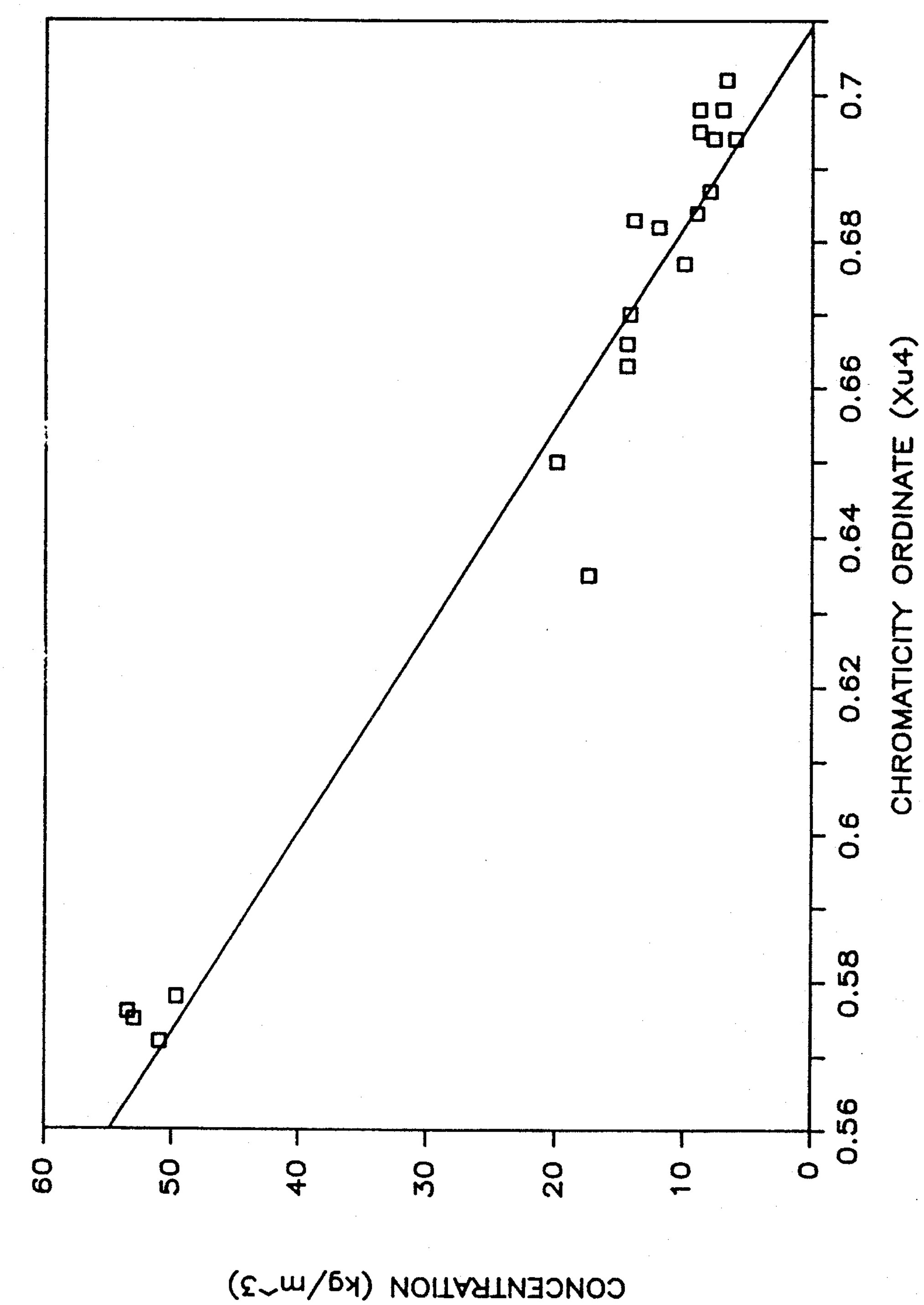

Fig 4 Sediment concentration against chromaticity ordinate (From MacFarlane 1981)