APPLICATION OF A SYSTEM FOR AUTOMATED MULTIDATE LANDSAT MEASUREMENT OF SUSPENDED SEDIMENT

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INTRODUCTION

Appropriate data reduction techniques for Landsat measurement of suspended sediment have been sought by many authors since the advent of Landsat in 1972. One very recent study aimed at universal methods appropriate for multispectral scanner data is that by Holyer (1979). Other studies have been referenced in our earlier papers. In this paper we describe a system implemented for Landsat suspended sediment measurement in relation to surface data from the Bay of Fundy, Nova Scotia. The system is available for testing on surface data from other sites around the world. The method of data reduction is chromaticity analysis (Munday 1974a,b) which permits adjustment of atmospheric variations between dates of Landsat over-passes.

The system has been used to study the distribution, transport, and disposition of suspended sediment in the Bay of Fundy, the site for a proposed tidal barrage designed to generate electric power. The distribution of suspended sediment mapped by Landsat, was used to calibrate and initialize a numerical model of post-barrage siltation. Also, the transport paths of suspended sediment and the general hydrodynamic character of the flow were determined by visual interpretation of mapped suspended sediment patterns.

The bulk of our work has been with suspended sediment measurement (Amos, 1976; Amos and Alfoldi, 1979; Munday and Alfoldi, 1979); equally satisfactory results are expected for measurement of Secchi disk depth or turbidity. Some preliminary results for the latter variables as well as chlorophyll are given below.

COLLECTION OF SURFACE DATA

The calibration and subsequent discrimination of suspended sediment concentration “S” using the chromaticity technique was initially undertaken in the Avon River Estuary, located in the Minas Basin System, Bay of Fundy (Fig 1), (Amos and Alfoldi, 1979). The calibration was thereafter extended to Chignecto Bay (Fig. 2), Bay of Fundy and Baie Verte, Gulf of St.

Lawrence. Nine data sets with a total of 108 surface samples have been obtained from 7 overpasses from Landsat 2 and 3.

Sample sites were marked by styrene floats, anchored approximately 1 km apart and at least 0.5 km from the shore (at low water). The floats were surveyed into position by sextant fixing on prominent coastal features, and resurveyed periodically to assess drift. The abundance of coastal features around the calibration site helped locate the sampling sites on the Landsat imagery to within one 57 x 79 pixel (Bernstein, 1978).

Samples were collected from a Bell Jet Ranger which hovered over each marked site at a height of 6 m. One litre surface water samples were collected using either Knudsen bottles or wide-neck Nalgene bottles lowered from the helicopter. In practice, one sample per minute could be collected using this technique.

The sampling time window was computed as: $T = \check{T} \pm L/\bar{U}$ where $\check{T}$ is the time of overpass on the previous satellite cycle, L is the Landsat sampling (spatial) resolution, and $\bar{U}$ is the mean tidal current speed at time $\check{T}$. The time window varied from 20 minutes to 6 minutes, decreasing as the tidal currents increased in speed. Within hours of collection, the samples were analyzed for:

1. Suspended sediment concentration (mg/l) determined by filtration through 0.45 μm Nuclipore filters (MacIntosh *et al*, 1976),
2. Chlorophyll a (mg/m^3), determined by fluorometry (Strickland and Parsons, 1972),
3. Grain size (microns), grain composition (elemental) and grain shape (Folk, 1968) measured directly from scanning electron micrographs, and
4. Selective absorbance of filtered and unfiltered water, using a Beckman 5 200 spectrophotometer.

The laboratory analyses of sediment concentrations have an accuracy of 1 mg/l. Twelve of the 108 samples have concentrations of sediment greater than 1 000 mg/l.

EFFECTS OF SEDIMENT SIZE AND COMPOSITION

Detailed results of the effects of sediment size and composition are available from the Minas Basin where S values ranged from 1.97 mg/l to 79.48 mg/l. From (SEM) microscopic examination, under rough conditions, sand size material up to 800 μm in diameter was found in suspension together with benthonic foraminifera and large diameter floccules of clay material. The following year (June 24, 1976), in contrast, conditions were calm, and small diatoms, clay particles and 30 μm floccules predominated. Chromaticity showed significant variation between differing dates of sampling, corresponding to differing S levels only. The percentage clay for a constant chromaticity X' value varied from 32 to 60. Samples containing 49% clay, on the other hand, show chromaticity X' variations from .434 to .556, which represents most of the calibration range. The percentage silt varied from 25.8% to 66.6% and sand varied up to 7.1%. Yet, as was the case for the clay content, little or no relationship could be found with the chromaticity coordinates. It appears, therefore, that within confines of the present work, grain size does not affect the chromaticity calibration to S.

The percentage organic matter, recognized as shell debris, sponge spicules, diatom frustules, egg sacks, foraminifera, radiolaria and lignaceous matter, varied from 30.9% to 54.2%. These materials show a wide variety of differing shapes, sizes and surface textures, quite different from the inorganic floccules of clay or the siliciclastic particles. Yet chromaticity appeared independent of such variations.

Backscatter, of which Landsat radiance is a measure, is indeed a function of grain size and shape (Jerlov, 1976). However, to the extent that grain size and shape cause radiance changes in all bands in the same proportion, the chromaticity transformation compensates for these effects. An initial examination of the sampled material from two other sites, Chignecto Bay and Baie Verte, shows that this material is quite different from that of the Minas Basin. Suspended particulate matter (SPM) from Chignecto Bay has a unimodal distribution of sizes, peaking in the 8-16 µm range. Flocculation, controlled by source material, is much less and siliciclastic material dominates (85.8% to 100%). In Baie Verte, S is typically below 2 mg/l, and the majority of the matter is organic (32.1% to 71.1%). The siliciclastic particle size distribution is unimodal, peaking in the 8-16 µm range. Despite obvious differences in the sample composition for the three calibration sites, the 45 data points from Chignecto Bay and Baie Verte do not appreciably alter the original Minas Basin calibration.

THE EFFECTS OF CHLOROPHYLL

Regressions between chlorophyll concentrations and Landsat MSS radiances have been examined by Bukata *et al* (1974), Bowker *et al* (1975), Rogers *et al* (1976) and Boland (1976). Obviously, chlorophyll can have an effect on Landsat measurements of S, but how this effect varies with S is uncertain. In the Avon River Estuary, the chlorophyll a concentration C is typically less than 0.5 mg/m^3, which according to Bukata et al (1974) is below the limits of detection by Landsat. In Baie Verte, C represented 0.4% to 0.7% of S (by weight), but the range of S in these samples is only 1.45 to 8.11 mg/l, and therefore the relative effects of sediment and chlorophyll cannot be assessed. In Chignecto Bay, C varied from 1.14 mg/m^3 to 11.6 mg/m^3. These chlorophyll values represent only 1 part in 5.4×10^3 to 1 part in 14×10^6 of the total S (by weight). Therefore, the direct effect of C relative to the remaining S is considered insignificant. Even the associated biomass contributes negligibly to S measurement. This can be verified by simple estimation of the dry weight associated with such values: in data reported by Scherz (1977, p. 150-158) laboratory algal cultures of three species had chlorophyll concentrations between 0.4% and 0.9% of dry cell weight. Taking chlorophyll as 1% of the dry cell weight, 15 mg/m^3 chlorophyll is associated with 1.5 mg/l dry cell weight, again an insignificant contribution to our results.

THE EFFECTS OF DISSOLVED ORGANIC MATTER

The effect of pigments dissolved in the sea water samples was assessed in an indirect manner by measuring the transmittance (t) of light between the wavelengths of 400-800 nm and along a 10 cm path length. The transmittances were normalized to a standard 30% NaCl solution in distilled water. Fresh water samples from river debouching into the Bay of Fundy were compared with filtered and unfiltered sea water samples.

The filtered sea water samples show light transmittances of 95% - 98%, similar to distilled water; attenuation results from colloidal matter not trapped by the filtering process. The unfiltered sea water samples show t less than 20% at 63 mg/l and less than 10% at 149 mg/l; here the effect of S dominates. The transmittance curve of the fresh water, on the other hand, shows the effect of pigmentation. The relative attenuation at 400-500 nm is significant and is probably the result of dissolved organic matter. This fresh water pigmentation is diluted by the enormous tidal prism into which it flows. The conclusion based on these observations is that our results are not affected by dissolved organic matter.

SECCHI DEPTH AND TURBIDITY

Some water quality monitoring agencies still find it convenient to characterize water bodies by Secchi disk depth and various other measures of "turbidity" or "water clarity", instead of by suspended sediment concentration in mg/l. Recently, the U.S. Geological Survey has recommended that the use of turbidity measures be discontinued altogether (see Pickering, 1976). However, the likelihood is that use of Secchi disk depth and other measures of turbidity will continue indefinitely. The question then arises whether the chromaticity system can be used to measure these variables.

Regression of chromaticity coordinates against Secchi disk depth for several sets of data in the literature produces high correlation coefficients. In these data sets, the correlations using chromaticity coordinates are as high or higher than those based on single MSS bands or on MSS band ratios. Also, a correlation will usually be found between suspended solids and some measure of turbidity. Hence, the indications at present are that the Landsat chromaticity system will be useful for multitemporal measurement of Secchi disk depth and turbidity.

SYSTEM APPLICATION IN THE BAY OF FUNDY TIDAL POWER PROJECT

The Nature of the Application

The Bay of Fundy, because of its large tidal range, is being considered for Tidal Power Development (Atlantic Tidal Power Programming Board, 1969; Bay of Fundy Tidal Power Review Board, 1977). This involves constructing a barrage across the tidal flow, thus creating a headpond, then generating energy of feeding water from the headpond to the sea during periods of low tide. The headpond is subsequently filled on the following high tide. Though simple in principle, the project is an enormous undertaking estimated to cost $4 billion.

Due to the asymmetric nature of tides and tidal currents in nearshore regions, suspended sediment is concentrated in the headward regions of estuaries (Postma, 1961). With constant supply, S is predominantly a function of current speed (A.S.C.E., 1975). If tidal currents are inhibited, or energy removed from the flow, the competency and capacity of the flow is reduced and siltation will occur. In the Wash, East England, rapid siltation has taken place immediately seawards of reclamation embankments and entraining walls constructed in the tidal flows (Kestner, 1975). The amount of siltation is proportional to the reduction in current speed. In the upper Bay of Fundy, dramatic accumulations of mud have developed to the seawards side of rock fill causeways built across tidal channel-ways (Amos, 1979). These causeways have completely altered the tidal flow and as a result, the original tidal channels have diminished to small creeks which are flushed by outflowing river water.

It appears reasonable to assume that siltation will result from Fundy Tidal Power development. The question is where and how much siltation will occur, and also, what will its impact be on the efficiency and lifetime of the power generation. Answers have been provided by a predictive numerical model of the Fundy system (Greenberg and Amos, in prep.; Greenberg, 1977) which has been initialized and calibrated from maps of suspended sediment concentration derived from chromaticity analysis of Landsat data.

Contour Maps of Suspended Sediment Concentration "S"

The Minas Basin region constitutes an area of 1 100 km^2 and is represented by 0.25×10^6 Landsat pixels. For several overpasses, contour maps were produced as shown in Figures 1 and 2.

A series of S contour maps were produced for differing weather conditions for each season and at various stages of the tide. Residual tidal circulation patterns were identified from the inflections of the contours, and verified by comparison to tidal flow models of Tee (1977) and Greenberg (1977). The contours in Figure 1 represent conditions during May 4, 1974, one half hour prior to high tide. The north shore of Minas Basin appears flood dominant and the south shore ebb dominant. The lobes and saddles of the contour lines show clearly the seaward transport of material along the south shore, a phenomenon which prior to this time had not been identified, and the movement of clearer offshore waters along the north shore. A total load of 0.25×10^6 m^3 of suspended particulate matter was estimated to be in suspension. Calculations were made by integrating the surface S distribution with depth, having previously determined the vertical distribution (Amos and Joice, 1977). During conditions of the highest S, 12×10^6 m^3 of material were in suspension.

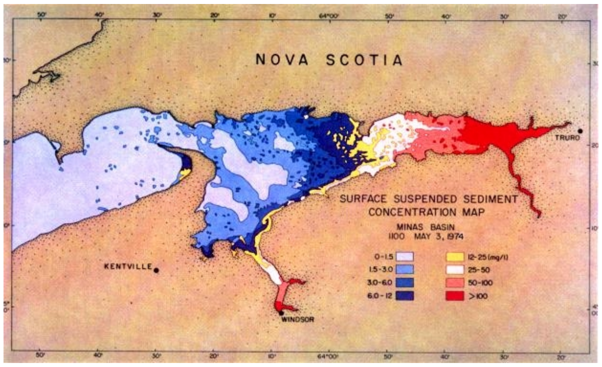

Figure 1: Thematic map of S derived from chromaticity analysis of Landsat digital data. The map is representative of conditions at 1430 (GMT), May 3, 1974, 0:30 mins after high water. The contours show the clearer water at the centre of a clockwise gyre in central Minas Basin, the general increase in S headwards through the system, and the seaward movement of sediment along the south shore of Minas Basin. The instantaneous volume of sediment was estimated to be 0.25×10^6 m^3 and was determined by integrating the S levels with depth.

The maps show that the highest S values occur during the spring. The average S in the central part of the basin in this season is approximately 60 mg/l.

Lowest values occur during the summer (1-5 mg/l), and intermediate concentrations occur during the winter and autumn (40 mg/l). It is significant that the ice-free pattern of contours (at any particular stage of the tide) does not change. This indicates that the various sediment transport processes change only in magnitude and not in their spatial distribution.

The significance of these calculations is in the prediction of siltation associated with the Fundy Tidal Power Project. The masses of material determined from the maps of S clearly show the need for an analysis of post-barrage sedimentation patterns. Therefore, spring maps were used to initiate a numerical simulation model (Greenberg, 1977) and simulate the most intense conditions of sedimentation which could result. The model was then adjusted until, after a series of tidal cycles, it approached summer conditions of sediment transport, distribution and deposition.

The results from the Bay of Fundy model, run with a barrage term, show that only minor amounts of sedimentation within the headpond region will result; the lifetime expectancy (based purely on sediment deposition) will not be affected. This is a rather significant conclusion for the operation of the Tidal Power scheme, and is based in part on the information derived from the Landsat MSS.

S Patterns Derived from the Contour Maps

The spatial distribution of S at the head of the Bay of Fundy is often not regular, but shows a series of distinct patterns on the Landsat images and S contour maps (Fig. 2).

These patterns develop as a result of local irregularities in seabed morphology, channel shape and water depth, which in turn induce hydraulic irregularities on a local scale. Where such irregularities of flow do not exist, the simplest case of a regular headward increase in S is to be expected as illustrated in Figure 3(A). The S contours are then straight and normal to the direction of flow. Cobequid Bay in the Minas Basin demonstrates this pattern in general; however, irregularities of tidal flow have distorted the S contours into a series of saddles and lobes.

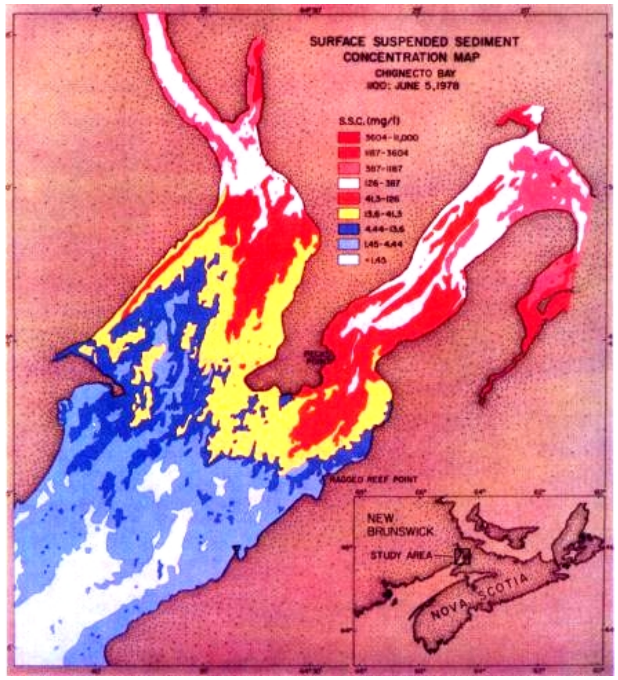

Figure 2: Thematic map of S in Chignecto Bay from a Landsat scene imaged at 1100 local time on June 5, 1978. The stage of the tide was 1-½ hours before high water. The tidal currents flowing at that time would be approximately 2 m/sec moving from the bottom to the top of the image.

In Chignecto Bay, lateral irregularities in bathymetry and inertial effects of flow cause the tidal water to shear into a number of water masses. These masses move parallel to one another but at different speeds. They are separated by narrow shear zones and are identified by markedly different concentrations of sediment. Figure 3(B) illustrates the S distributions developed under such conditions. The catenary pattern develops from a series of isolated S gradients within each of the "ribbons" of the tidal flow. This phenomenon demonstrates the problem of representative sampling in tidal regions, and the inherent errors involved in laterally extrapolating data from one point of a channel to define the total cross section. Mass transport calculations through channels subject to this type of flow cannot be made without representative sampling within each water mass.

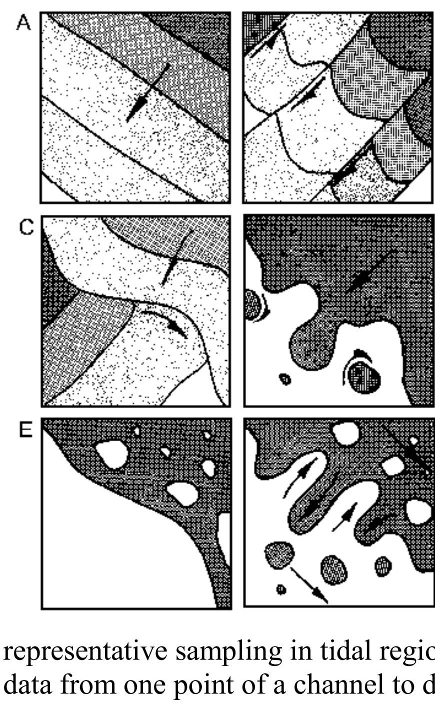

Figure 3: Schematic illustrations of the contour patterns of various S levels which occur in the Bay of Fundy system:

A. Demonstrates a regular gradation from high (darker) to low (lighter) S levels, contours are regular.
B. Lateral shearing causes tidal water to flow in parallel, distinct ribbons, each with an independent S, each ribbon of water moves at a different speed.
C. The boundary of two water masses moving at 90^0 to one another developed at the confluence of two tributaries. The flow of the lower water mass predominates.
D. The nature of an S contour under accelerating tidal currents. Turbulences "burst" to the surface in boils carrying sediments with them.
E. The nature of an S contour under dwindling tidal currents. Sediment settles out at higher levels causing the S gradient to disintegrate.
F. The nature of an S contour along the shear zone of two water masses moving in parallel. Lateral exchange of sea water and sediment occurs due to differential current speeds between the two water masses.

Waters ebbing through the confluence of two tidal estuaries, converging at a high angle, tend not to mix. Usually, the flow with the greatest momentum displaces that with the lesser to produce a situation illustrated in Figure 3(C). Here, the main flow is across the bottom of the diagram and the subsidiary flow is across the top. Two S gradients are developed oblique to one another and, an unconformity is developed at the junction of the two water masses. This is a short-lived phenomenon, occurring during an ebbing tide, and has been observed in the Petitcodiac River and Avon River estuaries.

The S levels are controlled principally by the magnitude of the tidal currents (A.S.C.E., 1975). These vary, accelerating and decelerating over a tidal cycle (Amos and Long, in press). During the phase of acceleration, material is swept into suspension by "boils" of turbulence. Such turbulent "boils" are illustrated in Figure 3(D). Zones of turbid boils are found intruding into the water masses generally characterized by lower S values. The S contours are convolute or often diffused and difficult to identify.

During phases of dwindling currents, when turbulence is low enough to allow sediment settling, the water begins to clear. The rate of clearing depends on the initial concentration, the particle settling rate, and the current shear velocity relative to the critical settling shear velocity (A.S.C.E., 1975). In the Bay of Fundy, settling varies on the pixel level, regions of clearer water appearing in more turbid zones in response to localized dynamic conditions. This phenomenon, illustrated in Figure 3(E), has been observed to take place after storms or periods of high wave activity at either high or low tide.

The final example, illustrated in figure 3(F), shows mass transport of water and sediment, either through a shear zone separating two water masses, or across contour levels. This mass exchange of water occurs typically at the pixel level. It can result from eddying of a shear zone separating two water masses, or through down current irregularities of flow. The resulting S pattern is typical in regions of strong currents. Examples can be seen in the colour map of Chignecto Bay, shown in Figure 2. The scene was recorded by Landsat on June 5, 1978, one and one half hours before high tide, during which time the currents were flowing at approximately 3 m/sec.

SYSTEM IMPLEMENTATION

A suite of computer programs has been developed for the quantitative mapping of S from Landsat CCTs using chromaticity analysis. The suite of programs is highly user-interactive, involving cued sequences and user queries, graphical and colour displays and hard copy output. The suite is implemented at the Canada Centre for Remote Sensing (CCRS) on the CCRS Image Analysis System (CIAS). The programs have recently been transferred under a Canada – U.S.A. software exchange agreement to the Eastern Region Remote Sensing Applications Center (ERRSAC) at NASA Goddard Space Flight Center.

CONCLUSIONS

A system for quantitative measurement of suspended sediment concentration from Landsat MSS is now operational. Based on chromaticity analysis, the system permits the surface calibration data of one satellite image to be applied to another, by an adjustment for variations in atmosphere, water surface geometry, and solar angle. The technique has been verified using nine data sets with a total of 108 points from the Bay of Fundy in Eastern Canada. Correlation between satellite and surface data for the combined data sets (after relative atmospheric adjustments) is 96% and the absolute error of the calibrated satellite measurements is approximately 44%.

The system has been applied to the Fundy Tidal Power Project, to initialize and calibrate a Bay of Fundy numerical model. This model indicates that no significant sedimentation is to be expected from the proposed tidal barrage during the design lifetime of the project, confirming the viability of the tidal power plan.

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