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Monitoring the Water Bodies of the Mackenzie Delta by Remote Sensing Methods

MARIE-CATHERINE MOUCHOT,[1] THOMAS ALFÖLDI,[1]
DANIEL DE LISLE[2] and GREG McCULLOUGH[3]

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ABSTRACT. In the Mackenzie Delta, Northwest Territories, the thousands of lakes, ponds, channels and waterways, connected in an apparently chaotic manner, present a major logistical problem for collecting information regarding the nature of this complex hydrologic system. The use of satellite images gives an economical and synoptic view of this isolated region, while special analysis techniques simplify the environmental appraisal.

The use of (mathematical) morphological analysis of the surface waters imaged by the satellite allowed the authors to distinguish all water bodies, even when they were at the limit of the spatial resolution of the sensor. This technique further permitted the classification of these water bodies by their inter- and intra-connectivity.

Another technique, termed chromaticity analysis, allows for the removal of atmospheric differences among images, which in turn enables the use of surface calibration data from one date to be used on images of other dates. This method was also used to generate quantitative maps of suspended sediment concentration levels.

Together, these techniques permit the assessment of the hydrologic flow (or its hindrance) of sediment and nutrients for the sustenance of aquatic flora and fauna. They further supply a method for the mapping of access routes by water craft to all parts of the Delta.

Key words: mathematical morphology, chromaticity analysis, remote sensing, Landsat, Mackenzie Delta, suspended sediment, hydrologic network

RÉSUMÉ. Dans le Delta du Mackenzie, Territoires du Nord-ouest, le système hydrologique complexe que représentent les milliers de lacs, étangs, canaux et voies d'eau liés entre-eux d'une façon apparemment chaotique, pose un problème logistique majeur pour la collecte de l'information. L'utilisation d'images satellites permet d'obtenir une vision synoptique et économique de cette région isolée et d'extraire par certaines techniques d'analyse les paramètres nécessaires aux processus d'évaluation environnementale.

L'application des concepts de morphologie mathématique au réseau hydrologique a permis de distinguer les différentes masses d'eau du Delta, y compris celles dont la taille atteignait la limite de résolution du capteur. Cette technique a également permis la classification des masses d'eau par leur degré de connectivité.

Une autre technique, dénommée analyse chromatique, permet d'éliminer les écart relatifs d'effet atmosphérique entre images et, par là, d'utiliser les données de calibration acquises à une date pour l'analyse d'images de dates subséquentes. Cette méthode a été utilisée pour générer des cartes quantitatives représentant la concentration de sédiments en suspension.

Combinées, ces techniques permettent d'estimer l'importance de la contribution du flot de sédiments et d'éléments nutritifs pour le développement de la faune et de la flore. Elles fournissent également une méthode de cartographie des routes navigables à l'intérieur du Delta.

Mots clés: morphologie mathématique, analyse par chromaticité, télédétection, Landsat, Delta du Mackenzie, sediments en suspension, réseau hydrologique

INTRODUCTION

The Mackenzie Delta, at the mouth of the Mackenzie River in the Northwest Territories of Canada, is one of the largest in the world, with an area of about 12 000 km^2 and containing thousands of small lakes and hundreds of kilometres of river channels. The local hydrologic situation results in an ever-changing maze of very shallow lakes, meandering water courses and shifting vegetation. There are concerns regarding the existing use of the land and waters in the Delta and its vicinity by native peoples and others, wildlife preservation, the fishing industry, exploration activities and possible pipeline routings.

The subtle temporal changes in the water regime result in a sporadically reconfigured limnological network. As lakes and channels connect and disconnect from each other, the movement of sediment and nutrients has profound influence on water quality, water transportation, fishing and vegetation distribution. The interconnection of water bodies in the Delta dictates the method, and therefore the frequency, of resupply of nutrients within the water body matrix. Nutrient supply is primarily through the sediment transport of the Mackenzie River (Mouchot *et al.*, 1989). Connected lake systems enjoy continuous supply of nutrients, while unconnected bodies depend on flood episodes in the area and (weather-driven) level fluctuations of the Beaufort Sea. Thus, both water body connectivity and sediment loading within the water network are of prime importance to the development and sustenance of aquatic flora and fauna.

Due to the immense expanse of the Delta, an understanding of the synoptic limnology of the area is most practicable when viewing the Delta from above. Remote sensing methods (especially from satellite altitudes) offer a convenient and cost-efficient way of observing and monitoring the dynamic processes in this area.

We decided on the use of the Landsat Thematic Mapper (TM) data for studying the limnology of the Delta. The relatively high spatial resolution (30 m) of this instrument allowed us to study the fine topological features of the lake/channel network (Fig. 1). The spectral sensitivity of the TM, despite having been designed mainly for land applications, was proven to be very useful for studying the aquatic sediment patterns and levels.

METHODOLOGY

There are many ways to describe an object: by colour, shape, texture, etc. Usually, analyses of remotely sensed data employ the colour of an object, i.e., its spectral signature, to identify and/or characterize the object. In addition, other techniques can also be used to categorize/group objects by their shape.

[1]Canada Centre for Remote Sensing, Energy, Mines and Resources Canada, 2464 Sheffield Road, Ottawa, Ontario, Canada K1A 0Y7
[2]Intera Kenting, 1525 Carling Avenue, Suite 600, Ottawa, Ontario, Canada K1Z 8R9
[3]Freshwater Institute, Fisheries and Oceans Canada, 501 University Crescent, Winnipeg, Manitoba, Canada R3T 2N6

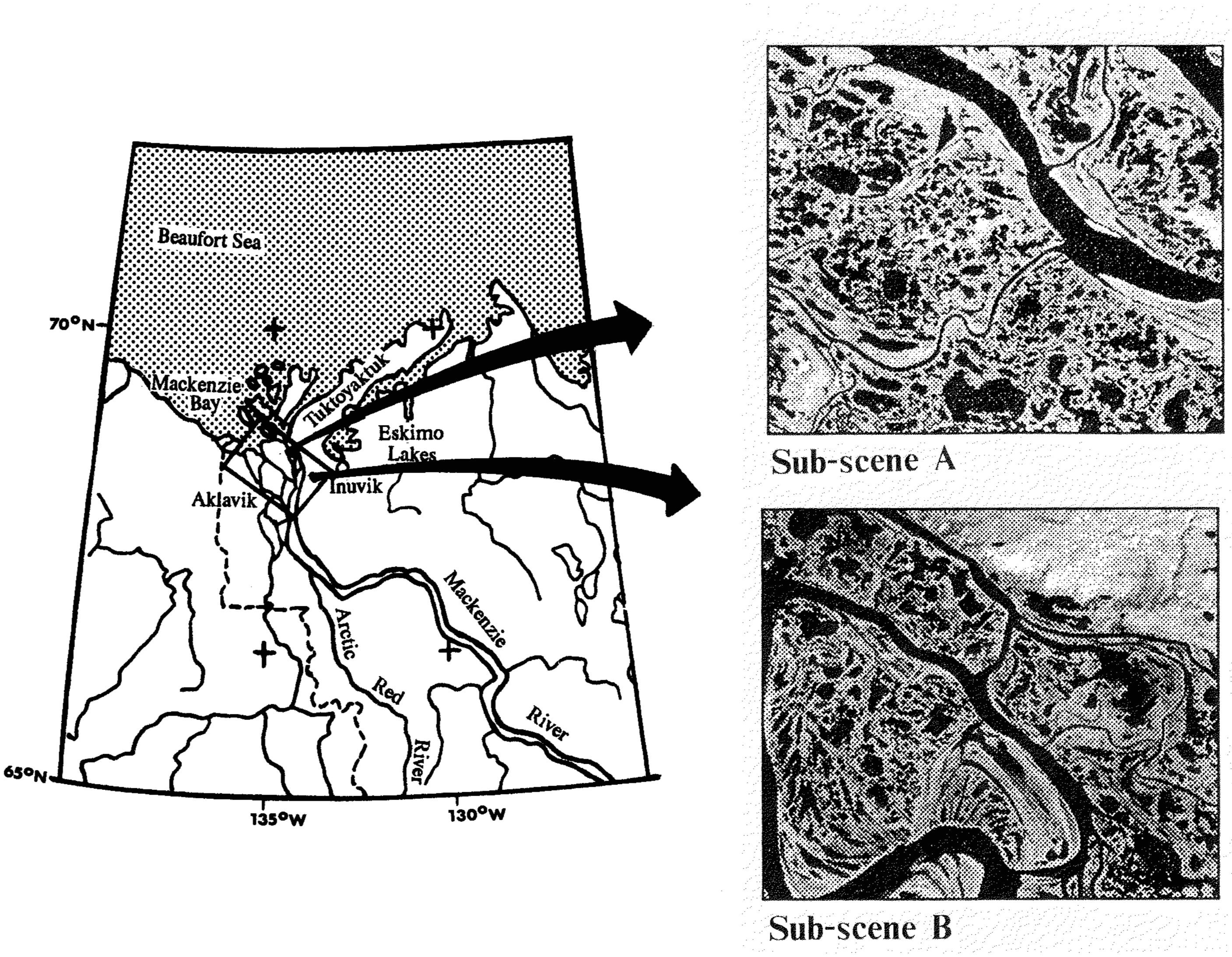

FIG. 1. Site map of the Mackenzie Delta study area and original Landsat TM sub-scenes (August 1986).

In this study, we investigated the value of "morphology" (shape) and "chromaticity" (colour) analyses and also blended them to extract the maximum available information from the imagery. PC-based image analysis techniques were used to facilitate the subsequent distribution of these methods.

Two sub-sites of 512 x 512 pixels of an August 1986 TM scene were used for analysis by both morphological and chromaticity methods. The locations of the test sites are shown in Figure 1. Although the processing of only a few sub-scenes limits the utility of the analysis and particularly hampers the morphological analysis results, it was found sufficient for the "proof of concept" attempted here. Both algorithms used were applied on a 80386 processor-based PC, which allowed quick results for the limited numbers of test sites.

In situ sampling in the Mackenzie Delta was a prerequisite for this work. It allowed for the calibration of the satellite data for suspended sediment concentration estimation. It also enabled us to directly appreciate the nature and complexity of this unique area. Whereas the geometric characteristics of the TM image had little or no influence on our work, the radiometric inconsistencies (i.e., banding) within the scene had profound influence on the chromaticity analysis, which depends on absolute radiometric calibration and suffers from any residual radiometric banding effects.

Morphological Analysis

Background: The first processing method involved a software package called Visilog, which was developed at l'École des Mines de Paris (Laÿ and Lantuéjoul, 1983; Laÿ, 1984). Based on the morphological principles described by Matheron (1975), Serra (1982) and Fabbri (1984), it has been previously applied to remotely sensed images (Flouzat and Merghoub, 1983; Destival, 1985; Mouchot *et al.*, 1989).

Theory: Morphological analysis is a topological process for the mathematical manipulation of shapes. In this study, the "shapes" used were the two-dimensional (satellite) image representations of water bodies of the Mackenzie Delta. While a thorough review of morphological analysis is given in the documents cited above, here we can identify some of the more basic features of this methodology used by the authors.

The interconnected water bodies we want to isolate and characterize are called particles. Each particle can be analyzed separately by comparing its shape with the shape of a so-called "structuring element." The topological processes of "erosion," "dilation," "opening" and "closing" are mathematical operations of the structuring element on the binary image representing the water bodies. They are most concisely described by their graphical representations in Figure 2a.

"Thinning" is a further process that reduces a particle to its boundary. By contrast, the "skeleton" of a binary image is the locus of centres of "balls" of a maximum size, fitting into the boundary (Fig. 2b). These operations were used to establish the "connectivity" of water bodies and the relative size of the connectivity.

Application: Thresholding the brightness values of Landsat TM band 5 (mid-infrared) was used to isolate the water areas from land features. Some of the very narrow water channels (about 1 pixel in width) were lost in this process due to the mixed pixel (water+land) effect (Fig. 3a). A second thresholding at a slightly higher brightness level (Fig. 3b) included the lost water pixels, but also encompassed extraneous land pixels. Using the special characteristic of small channels, namely, that the channel itself is equivalent to its morphological "skeleton" (Fig. 3c), most of the lost water pixels were recovered and water body connectivity re-established. The resulting small channels were then added to the "pure water" bodies of the image at the lower threshold in order to get a binary image of the total surface water extent (Fig. 3d). The complete processing procedure is charted in Figure 4. Thereafter, this was the basis for "shape" extraction and particle demarcation, as shown commencing for test site A in Figure 5a.

The complete and proper morphological analysis of the Delta would require the simultaneous processing of data from more than one full TM scene. For the purpose of this study, two sub-scenes were chosen for processing and several assumptions were made. The most important assumption was that a water mass touching the edge of the image will continue on the following one, and so on until it reaches the sea.

The first step in categorizing the "particles" is to identify those not connected to the main river channels (Fig. 5b), based on their apparent isolation within the target sub-scene. The remaining particles can belong to the main channel network. Of these, inspection of neighbouring sub-scenes allows us to eliminate those that clearly do not belong to the main channel network (Fig. 5c).

Morphological analysis allows us to further subdivide the water bodies (particles) found to be connected to the main channel network according to their degree of connectivity, which is calculated on the basis of the width of the "connection."

By means of an iterative morphological approach, we were able to isolate those channel segments that were 1-2 pixels wide (Fig. 5d), as well as the water bodies directly connected to them (Fig. 5e). On the remaining network (Fig. 5f) we repeated the process for channels 3-4 pixels wide and so on, to 7-8 pixel width. These various networks, each connected to a channel of a specific size, are represented by colour coding in Figures 6a and 7a.

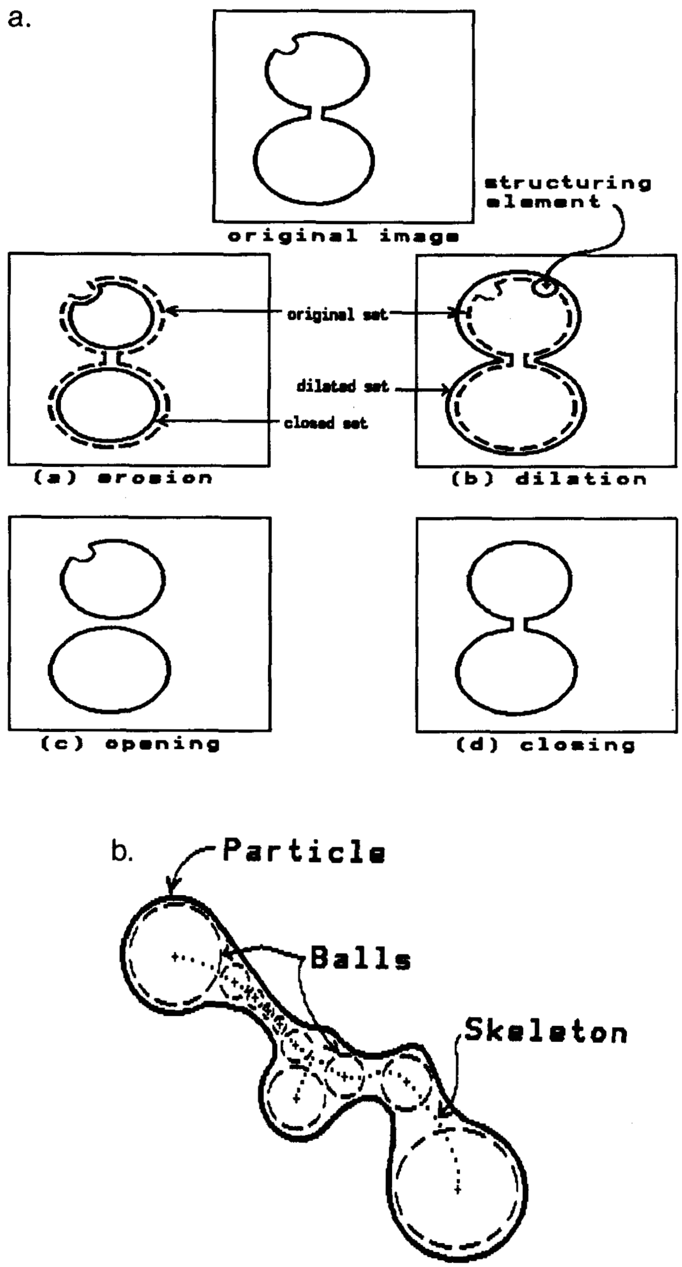

FIG. 2. Morphological analysis terminology. a) Elementary operations on a boundary image, intended for establishing connectivity. b) Morphological skeleton, used for identifying very narrow channels in a binary image of water bodies.

The Chromaticity Analysis Method

When using satellite imagery for quantitative estimates of suspended sediment concentration (SSC), it is common to make *in situ* measurements simultaneously to the satellite overpass. The reflected radiation recorded as the satellite image is then correlated to the surface data, and that relationship can be used thereafter throughout the image for SSC measurement. The *in situ*/satellite data relationship breaks down when it is used in another part of the image where the atmospheric conditions are different.

Since haze plays a significant part in the nature of the satellite-recorded light reflected from water, differing haze conditions can severely distort the SSC calibration of an image. In other words, the SSC calibration established (*in situ* and coincident satellite data) in one location can only be extrapolated within that part of the image that has similar and constant atmospheric conditions.

Since atmospheric conditions cannot be assumed to be stable from one date to the next (without on-site atmospheric measurements), the SSC calibration of one image cannot be applied to another image unless atmospheric similarity is verified. On-site measurements for this purpose are impractical, since one is trying to avoid repeated visitations to the target site. It remains, then, to find information within the images

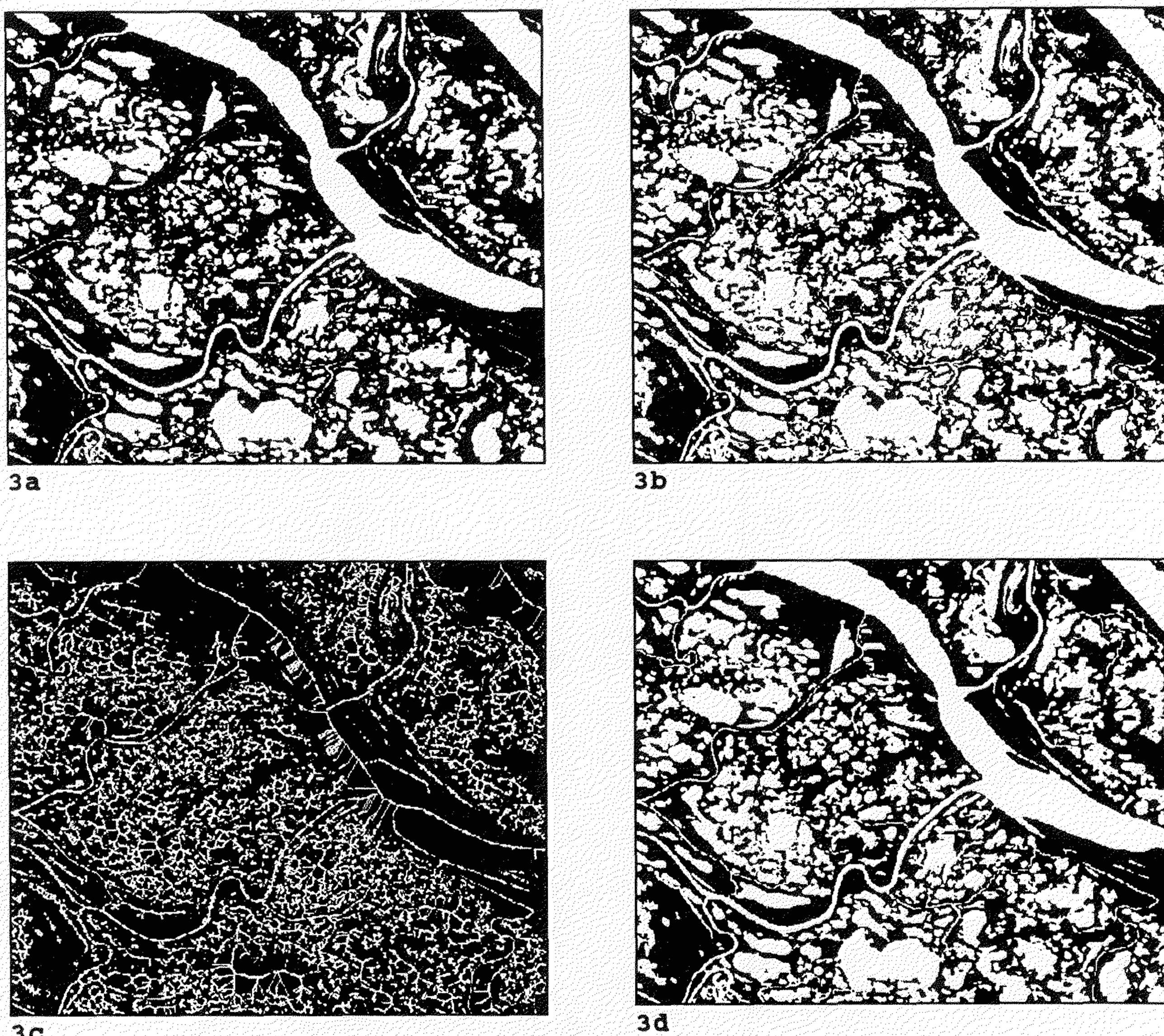

FIG. 3. Morphological operations for defining all surface water areas. a) Brightness thresholding for identification of all "pure" water pixels. b) Brightness thresholding at a higher level than in 3a, for identifying surface water and narrow water channels that would include some mixed water/land pixels. c) "Skeleton" image of data presented in 3b, identifying very narrow water channels. d) Binary image of water bodies, produced by the addition of images 3a and 3c.

themselves to establish the (dis-)similarity of their atmospheric "noise."

It has been established by Munday *et al.* (1979) and Alföldi (1982) that the chromaticity transformation of Landsat Multispectral Scanner (MSS) data establishes two dimensions, wherein atmospheric variability can be discerned and manipulated. Atmospheric attenuation resulting in a constant multiplicative error on each of the bands is removed by the chromaticity transform itself. The transform, here applied to Thematic Mapper data, consists of a simple brightness normalization: $x = R2/(R2+R3+R4)$ [1] and $y = R3/(R2+R3+R4)$ [2], where x,y are the coordinates in the chromaticity plane and R_i is the radiance of Thematic Mapper band "i." The process uses up one of the original three degrees of freedom (TM bands), leaving two more to define the chromaticity "plane."

To remove constant additive noise in the bands (resulting most often from atmospheric haze), the data points of suspended sediment on the chromaticity plane must be manipulated. It is convenient to use polar coordinates to manipulate points on the chromaticity plane. The central point "E" is the achromatic point, where any non-coloured target resides (Fig. 8). This is the point of maximum colour desaturation and the origin for the radial and angular measures of plotted points. The edges of the chromaticity triangle show the maximum colour saturation. It follows, then, that any satellite image point represented on the chromaticity plane that experiences increased atmospheric path radiance will show colour desaturation and will be shifted radially towards "E." Thus the radial direction on the chromaticity plane is used to detect and remove atmospheric path differences. The orthogonal direction to this is the angular direction around "E," which is used for the measurement of suspended sediment concentration.

On the chromaticity transform plane for MSS data (Fig. 8), the locus of points representing a wide range of SSC has an arc shape. This arc is moved radially towards the achromatic point "E" (0.333, 0.333) when haze is increased. Thus locus

A-B represents image points of suspended sediment of equal concentration range as locus A-C; however, locus A-C is from an image with more haze. The points on the locus near "A" have larger SSC values, while those near "B" (or "C") have smaller SSC values.

The radial direction (colour saturation) on the chromaticity plane is used for adjusting the atmospheric condition of one image date to coincide with the conditions of another date. Then the SSC calibration established for one date can be applied to the other (which, presumably, did not have coincident *in situ* sampling).

As with any technique that tries to make indirect measurements of an environmental phenomenon, the chromaticity technique has its limitations. Chromaticity analysis for SSC works best when a large range of SSC is present in the image, with no other significant water feature present (e.g., large concentrations of chlorophyll, algal blooms, benthic or floating vegetation, floating oil or debris). Other limitations of satellite-borne optical sensors apply (e.g., opaque cloud cover, bottom effects, low solar angle).

DISCUSSION

The composite morphological analysis results for sub-scene A are shown in Figure 6a and for sub-scene B in Figure 7a. The colour coding in these two figures represents the different sizes of the "connectivity" to the main channel. Yellow identifies those lakes not connected to the main channel, while the colour sequence (blue → red → pink → green) shows increasing size in the width of the sub-channels, connecting directly to the main channel.

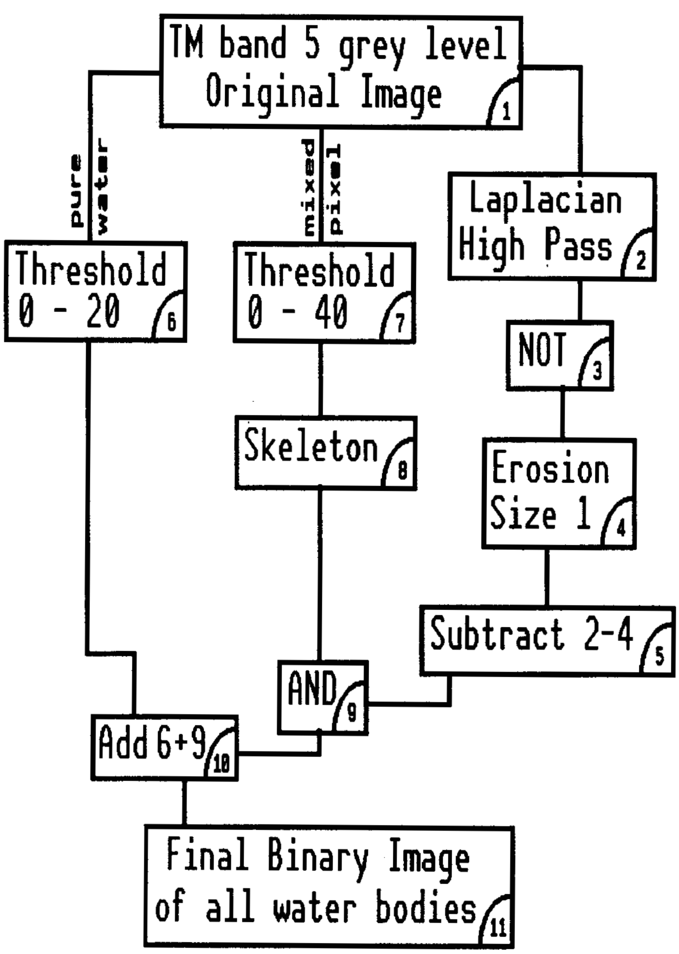

FIG. 4. Morphological analysis flow chart of binary image creation.

A "connectivity" map, as exemplified in Figures 6a and 7a, has several potential uses. Local fishing interests would be able to make use of such maps to identify unconnected water bodies that have low probability of harbouring fish stocks. Those water bodies that are either closely linked to the main channel or with wide connecting channels have the better conduit for water-borne nutrients and thus are likely to provide a more attractive fish habitat.

River transportation/navigation can be greatly aided by using connectivity maps. With such a convoluted network of water bodies and connecting channels in the Delta, a "road map" of water routes that morphological analysis provides becomes essential for any extensive surface travel.

Hydrologists, biologists and engineers also have much interest in these analyses, because connectivity maps identify lakes with continuous water sources, disconnected lakes, inflow and outflow locations, water volume changes and the varying shapes of the water bodies. Biological (aquatic) activity can be postulated from knowledge of the geographical distribution of active and disconnected lakes and channels. Pipeline and other utility and transportation corridors require detailed knowledge of the hydrologic conditions and their dynamics over time.

The chromaticity analyses resulted in the sediment concentration maps of Figures 6b and 7b. Colour coding was used to identify increasing sediment concentration levels (dark blue → light blue → yellow → red → green). An overlay of the surface water map produced by the morphological process helped to identify land/water boundaries in these images. Despite the time difference of one week between the satellite image and surface data collection, a high degree of correlation was observed between the two variables. The R^2 value (coefficient of determination) for 18 observations relating the natural logarithm of SSC with chromaticity X was calculated to be 0.829, with a standard error of estimate (of chromaticity X) of 0.015. With a more coincident timing of surface and satellite data collection, the correlation should be even higher.

Because the chromaticity technique attempts to measure an environmental variable quantitatively, it is subject to various sources of error from the environment. The two degrees of freedom within the chromaticity plane are used for atmospheric adjustment and for SSC estimation. Thus, additional intervening variables cannot be dealt with simultaneously. Environmental phenomena that interfere with accurate measurement of SSC include very shallow and clear water (bottom reflectance), high concentrations of chlorophyll, aquatic vegetation, high concentrations of dissolved organics and flotsam.

It was anticipated that there would be occasions where low turbidity coincided with shallow water and that this situation would lead to ambiguities between turbidity and bathymetric effects. In order to remove this possibility from the *in situ*/satellite sediment calibration process, all *in situ* measurements where the Secchi Depth was within 1 m of the bottom of the water body were removed. Since detailed bathymetric charts for the Delta were not available, the sediment mapping process, culminating in the maps of Figures 6b and 7b, did not consider this source of error.

The SSC maps quickly and conveniently identify those water bodies, or parts thereof, that have similar, dissimilar,

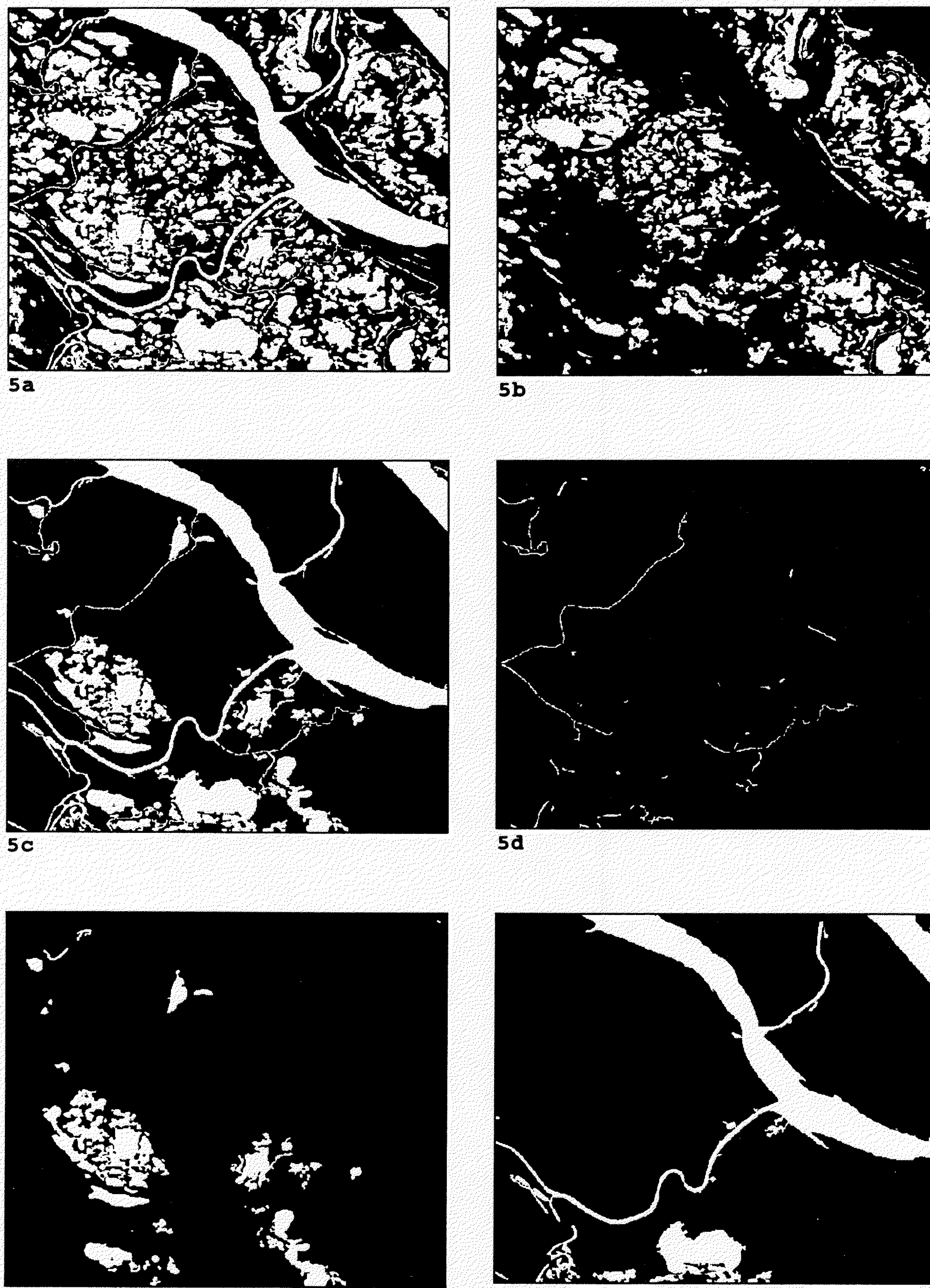

FIG. 5. Morphological analysis of water features. a) Binary image of the water bodies. b) Unconnected water bodies. c) Connected water bodies. d) One- to two-pixel-wide channels. e). Water bodies connected to (2d) features. f) Remaining network.

very high or very low sediment concentrations. If more than one area or date are to be compared, chromaticity allows for direct (relative) comparison. With the availability of *in situ* data, absolute measures of SSC can be made.

Using Figure 7b as an example, one may notice several hydrologic phenomena that would be of interest to limnologists. It may be observed that the main channel (with a flow direction toward the top of the image) is fed by smaller channels from the right with a lower sediment load (red). The main channel maintains an identifiable separation of this low SSC for several kilometres. On both Figures 6b and 7a, there are several lakes with higher sediment levels (yellow and red coding). Some of these are isolated, while others occur in groups. Whereas chromaticity analysis is able to identify these (and monitor them with the availability of image sequences), a lack of site-specific surface observations does not allow a compelling explanation.

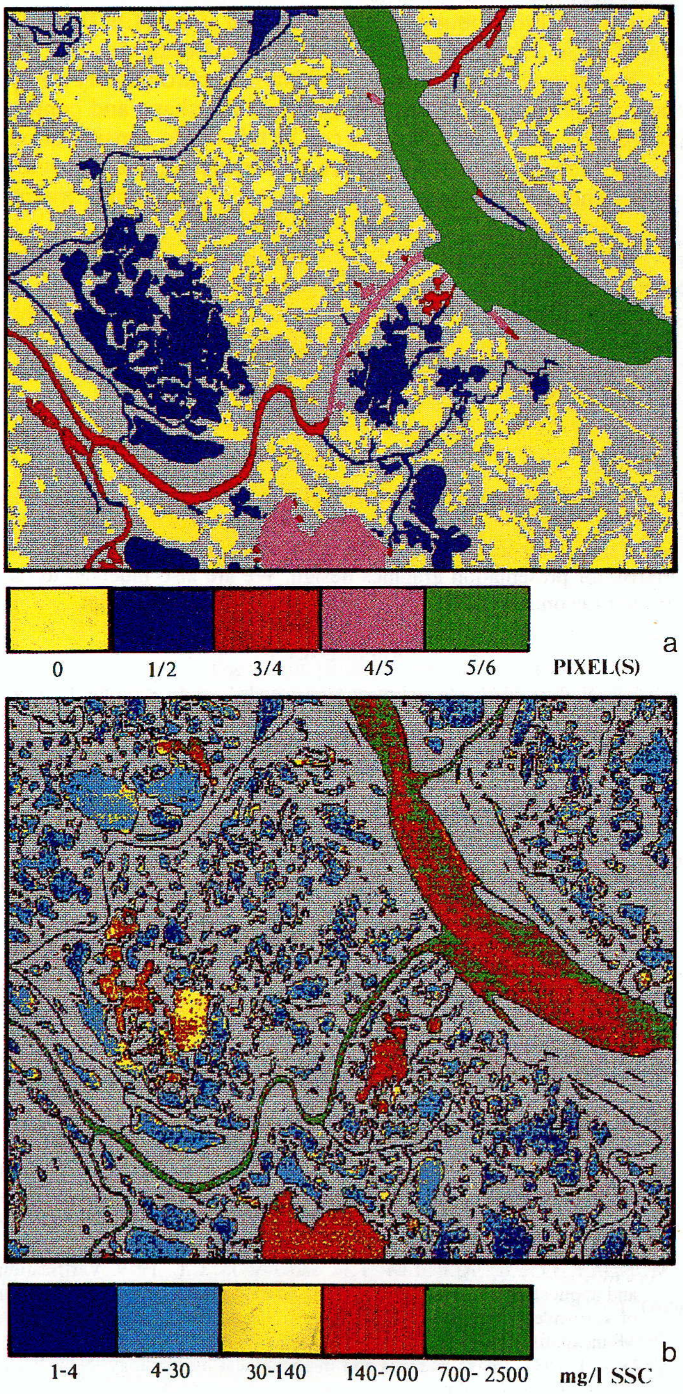

FIG. 6. a) Morphological analysis of connectivity. The colours represent a classification of the water areas of the TM image sub-site into categories of connectivity defined by channel width in units of pixels. b) Chromaticity analysis of sediment levels in test site "A." The colours represent a classification of the water areas of the TM image sub-site into suspended sediment concentration levels in mg/l.

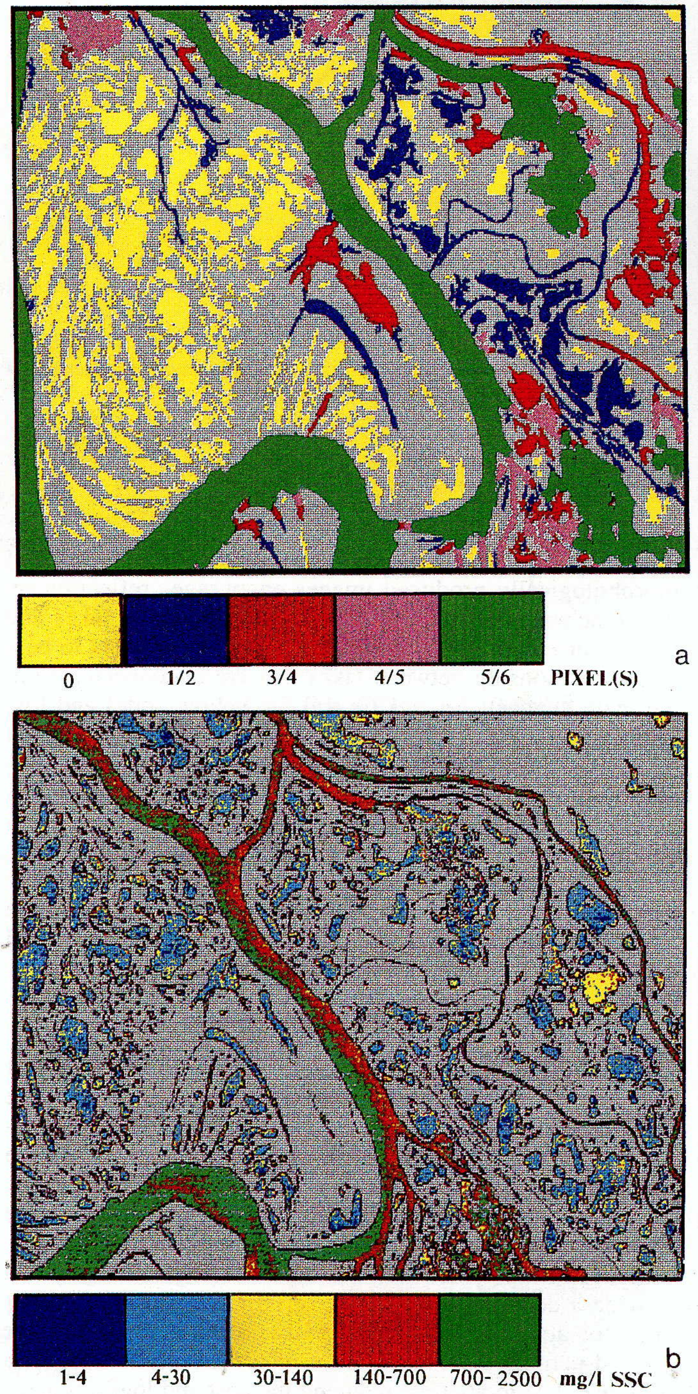

FIG. 7. a) Morphological analysis of connectivity. The colours represent a classification of the water areas of the TM image sub-site into categories of connectivity defined by channel width in units of pixels. b) Chromaticity analysis of sediment levels in test site "B." The colours represent a classification of the water areas of the TM image sub-site into suspended sediment concentration levels in mg/l.

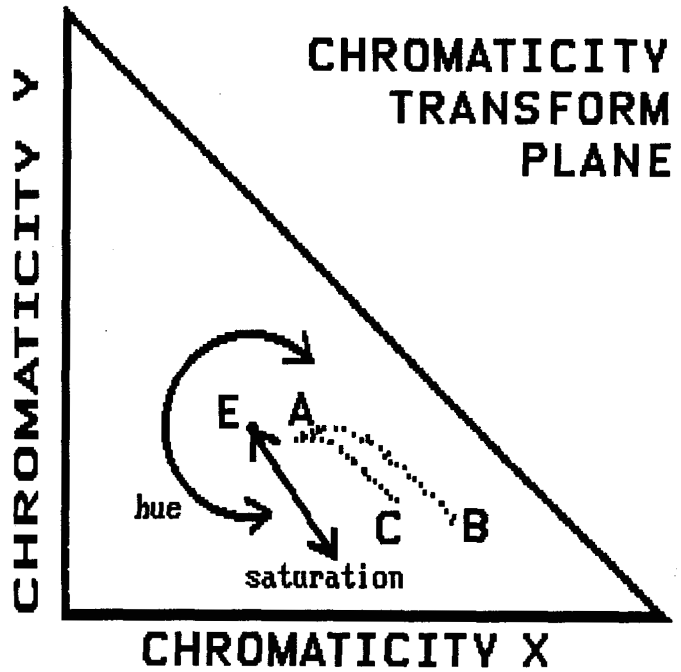

FIG. 8. Chromaticity triangle. This is the two-dimensional feature plane resulting from the brightness transformation of TM bands 2, 3 and 4.

A comparative evaluation between the chromaticity and morphologically produced images encourages reflection on the coincidence of high sediment levels in certain lakes and their connectivity sizes. As an example, there appears to be a strong relationship between lakes that are unconnected from the main channel (Figures 6a and 7a; yellow code) and low sediment levels (Figures 6b and 7b; light and dark blue codes), which appears to be reasonable, since water movement promotes higher concentrations of sediments in suspension.

The combined use of morphology- and chromaticity-derived maps offers a novel way of exposing certain anomalous water features related to sediment loading. The interpreter may deduce the nature or cause of such anomalies, or at the least pinpoint their precise location for subsequent ground investigation.

CONCLUSIONS AND RECOMMENDATIONS

The morphological methodology allows for a convenient study of the inter-connectivity of water bodies. Assessing the morphology (shape and boundary configuration) of water bodies over time enables one to monitor the change of surface water network. These can have substantive uses for fisheries, surface transportation, engineering applications and wildlife habitat monitoring.

By contrast, chromaticity analysis of satellite imagery can provide a detailed, flexible and quantitative mapping procedure for aquatic suspended sediment concentration. The method permits the extrapolation of ground verification data from one date to another, reducing the cost and logistics associated with field sampling. Sediment concentration maps may be used to evaluate sediment budgets, study erosion and accretion, and compare SSC levels over space and time. Since sediment is a natural tracer for water flow, hydrological studies can benefit from SSC maps as well as projects involving the tracing of pollution sources. It should be noted that chromaticity analysis is sensitive to environments where water contaminants other than suspended sediments are present. Further, the procedure has to rely on reasonably homogeneous atmospheric conditions throughout the study site, and it benefits from the presence of a large range of sediment concentration.

The use of morphological analysis and chromaticity methods can be complementary in that both the shape and content of the network of water bodies can be taken into consideration. Since these two techniques are uncorrelated, they provide comprehensive information for any study of complex hydrologic networks.

When studying a hydrological network as extensive as the Mackenzie Delta, it would be beneficial to encompass as much of the whole area into one study site as practicable. This is of particular concern to topological studies such as morphology, which has analysis constraints at the edge of any (sub)scene.

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