The Role of Spatial Resolution in Quantifying SSC from Airborne Remotely Sensed Data

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Abstract

Suspended solids concentration (SSC) was measured at 90 positions when aerial photographs were being taken. The aerial photographs were scanned at 300 dpi, geometrically and radiometrically rectified, and mosaicked. The mosaicked image was resampled from 1 m to 5 m, 10 m, and 20 m from which the digital numbers (DN) at the SSC sampling positions were obtained. There was a significant linear relationship between SSC and its DN at all four resolution levels. The regressed relationship between SSC and its DN is the most accurate at a spatial resolution of 10 m.

Introduction

Suspended solids concentration (SSC) within a water body may be determined from the analysis of *in situ* water samples. Although this approach can yield accurate measurement, the results are point-based and available only at a limited number of sampled positions. Considerable errors may be introduced if the measured results have to be extrapolated spatially over a large area (Nanu and Robertson, 1990). The accuracy of the estimated SSCs can be improved by increasing sampling density, which makes this method too time-consuming and expensive. If combined with remotely sensed data, however, this *in situ* sampling approach is valuable in quantifying SSC and in studying its spatial distribution pattern within a water body.

The success of accurately quantifying SSC from remotely sensed data depends on the correlation between SSC and its reflectance recorded in the data. A positive correlation between the two variables has been identified (Forster *et al.*, 1994; Lyon *et al.*, 1988; Mertes *et al.*, 1993; Ritchie and Cooper, 1988; Tassan, 1993) in the visible and near infrared wavelengths if SSC is less than 100 mgl^{-1}. If the SSC is low and has a small range (20 to 50 mgl^{-1}), the relationship between the two variables is non-linear (e.g., logarithmic) (Xia, 1993). The established relationship between SSC and its digital number (DN) in the remotely sensed data is affected by a number of factors, such as wavelength, viewing angle, and the spatial resolution of the remotely sensed data. Novo *et al.* (1991) found that the correlation coefficient between the two variables peaks in the green/red wavelengths. The optimum wavelength for the sensing of SSC is 0.55 to 0.65 μm (Novo *et al.*, 1989). The effect of viewing geometry on the relationship appears to be wavelength-dependent and is small (Novo *et al.*, 1989). Although spatial resolution may not alter the relationship directly, it affects the accuracy at which SSC levels are quantified, and the cost of analysis. If the remotely sensed data are recorded in a graphic form such as aerial photographs, the radiometric characteristics of the data are also affected by exposure falloff (Lillesand and Kiefer, 1987). With the use of a modern camera, however, such an effect can be limited to a minimum.

SSC has been studied from various types of satellite-borne remotely sensed data. They include the Landsat Multispectral Scanner (MSS) (Reddy 1993), Thematic Mapper (TM) (Mertes *et al.*, 1993), SPOT HRV (Froidefond *et al.*, 1991), and the NOAA Advanced Very High Resolution Radiometer (AVHRR) (Stumpf, 1991). The spatial resolution of these data ranges widely from 20 m for SPOT HRV to 1.1 km for AVHRR. Regardless of their spatial resolution, these satellite remote sensing data have to be rectified for atmospheric attenuation before they can be used to accurately quantify SSC. On the other hand, the atmospheric effect does not need to be taken into consideration if airborne remote sensing data are used due to the low flight altitude of the platform. Airborne remote sensing data may be obtained directly in digital form. The Airborne Visible-Infrared Imaging Spectrometer (AVIRIS) system is one such example. Calibrated AVIRIS data have been used to study coastal oceanic environment, including estimation of SSC (Carder *et al.*, 1993). Because the data are obtained pixel by pixel, the geometry of a scene is not well preserved in the captured image. Furthermore, scale and pixel size vary considerably across an image. For instance, the spatial resolution of AVIRIS data ranges from 17 m at the nadir position to 20 m near the edge of a scene (Vane, 1987). The variation in ground pixel size is even larger at a lower flight altitude. However, all these problems can be avoided if the remotely sensed data are first captured in a graphic form such as photograph and then converted to digital form. Obtained at the instant of exposure, all the pixels in one photograph share the same geometric relationship. Thus, the entire photograph is very reliable geometrically.

With the emergence of powerful and high resolution scanners, the conversion of photographs to digital images can be accomplished readily. Unlike in all previous cases where remotely sensed data were available only at a given resolution, the obtained aerial photographs may be scanned at various spatial resolutions. If an aerial photograph is scanned at a finer resolution, the spatial variation of SSC exhibited on it is undoubtedly better preserved. However, a finer resolution

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implies that a large volume of data has to be stored, which drastically increases the cost of and slows down all subsequent analyses. Conversely, fewer data need to be stored at a coarser resolution. If the resolution is too coarse, the spatial variation of SSC on the photographs may not be captured sufficiently accurately to warrant the existence of a significant relationship between SSC and its DN on the scanned image, not to mention the reliable quantification of SSC from its DN recorded in the remotely sensed data.

The objective of this study is to explore the relationship between SSC and its DN on scanned aerial photographs based on a limited number of *in situ* water samples. The impact of spatial resolution on the relationship will also be examined to determine the optimal resolution at which SSC may be quantified from scanned aerial photographs.

Method

Study Area

The study area is located in the Middle Waitemata Harbour, Auckland, New Zealand (Figure 1). Surrounded by a large catchment, the harbor encompasses an area of approximately 45 km². With soils being moderately well to well drained silt loam and clay loam, the catchment is especially vulnerable to denudation and erosion. Urban development in the form of land conversion from pasture to residence has greatly increased the quantity of sediment entering the intertidal zone through the Henderson Creek estuary. Sediment deposition is particularly noticeable on the lower areas where substrates are extremely soft (Auckland Regional Authority, 1983). It is important to understand how suspended sediment is redistributed over the harbor and to quantify the amount of SSCs in the harbor as a navigable channel must be maintained at all times for the purposes of recreational and commercial activities, especially after the construction of the Westpark Marina.

Data Used

Color aerial photographs and *in situ* water samples are the primary data sources. The aerial photographs were taken with a KA2 mapping camera between 1330 and 1340 hours on 1 June 1994. The camera had a focal length of 305 mm and was carried onboard a Cessna 72 aircraft. With dimensions of 23 by 23 cm, the 1:12,500-scale photographs were taken from an altitude of 3,800 m at high tide with Kodak Aerocolor negative film. Five such overlapping photographs are needed to cover the area completely. They exhibit some variations in color due to non-uniform film processing.

The collection of *in situ* water samples was synchronized as closely as possible with the taking of the aerial photographs. Although the collection took slightly longer than aerial photographing, it is assumed that the SSC patterns recorded on the photographs did not change significantly during the hour when the *in situ* water samples were collected. In total, 90 water samples were collected at a depth of 0.3 m along north-south transects (Figure 1). Sampling locations were so designed as to cover the broadest area within the shortest time frame. These samples were later analyzed in the laboratory to derive the concentration of suspended solids.

Data Processing

In order to preserve as much information as possible, the negatives of the photographs were scanned using a Hewlett Parkard ScanJet IIcx Color/Greyscale scanner with a green filter at 300 dots per inch, an equivalent of about 1-m resolution at the ground. At such a resolution, each image required 22 megabytes of space to be stored. During scanning, the reflectance of all objects at the ground as recorded on the photographs was converted to DNs in the images at eight bits. The pixels' value thus ranged from 0 to 255. The acquired data were then exported to the ERDAS image processing system.

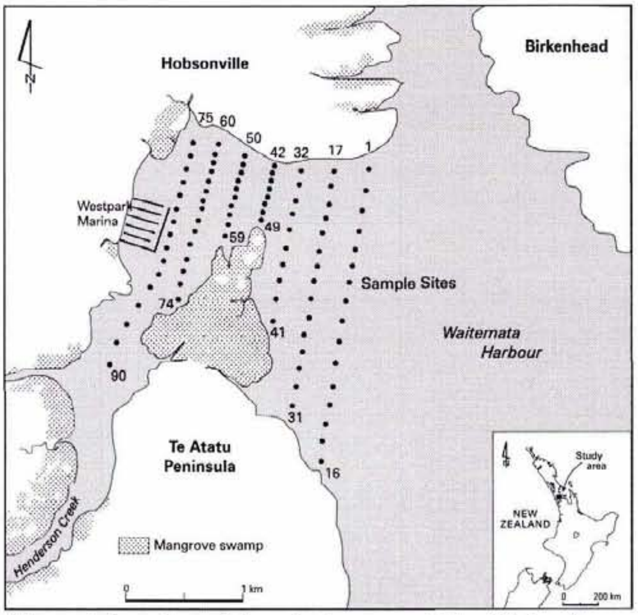

Figure 1. Location of the study area and the 90 *in situ* water samples.

A minimum of seven ground control points (GCPs) was selected from each photograph for geometric rectification and projection transformation to the New Zealand Map Grid (NZMG). Those GCPs having a large residual were eliminated from the rectification. In spite of the superior geometry of the scanned images, the accuracy of geometric correction was achieved at a root-mean-squared (RMS) error from less than 2 m to over 4 m. Being several times the pixel size, such a large RMS error was attributed to the absence of definite features as suitable GCPs over the water portion of the study area.

Prior to mosaicking the scanned images, histogram matching was undertaken to make their tone spatially uniform. One of them was arbitrarily selected as the reference. The others were made to match its mean and standard deviation by applying a gain and bias factor. After rectification, the individual images were mosaicked to form a single image, which was later resampled to 5 m, 10 m, and 20 m by maintaining every fifth, tenth, and twentieth pixels, respectively. The DNs of the 90 *in situ* samples were obtained from these images through their NZMG coordinates.

The relationship between the rectified DNs and 60 SSCs randomly selected from the 90 *in situ* samples was determined by plotting the two variables as scatterplots. The graphs suggested the existence of a linear relationship. The measured SSCs were hence regressed linearly against DN. The regressed equations were then applied to derive the estimated SSCs for the remaining 30 *in situ* samples. The RMS errors of the measured and estimated SSCs at these locations were calculated and used to validate the regressed equations.

Results

Relationship between SSC and DN

The SSCs obtained from the laboratory analysis of the 90 *in situ* samples range from 23.1 $\mathrm{mgl^{-1}}$ to 96.7 $\mathrm{mgl^{-1}}$ with a

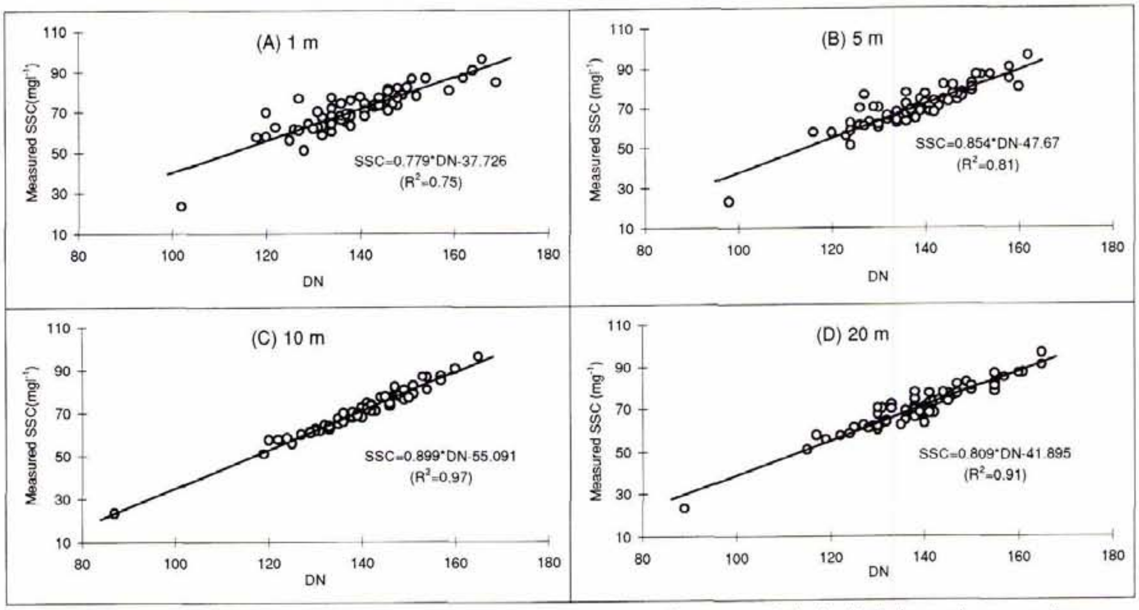

Figure 2. Regressed relationship between the *in situ* measured SSCs and their digital numbers on the scanned aerial photographs at four resolutions.

mean of 71.1 mgl^{-1}. These calculations suggest that a linear relationship is the most appropriate for SSCs and their DNs on the images. All regressed linear models show that the measured SSCs are positively correlated with reflectance at each of the four resolutions (Figure 2). Their R^2 values vary from a minimum of 0.75 at 1 m to a maximum of 0.97 at 10 m. Therefore, as resolution decreases from 1 m to 10 m, the relationship becomes stronger with increasingly large R^2 values. The increase rate from 1 m to 5 m is much smaller than that from 5 m to 10 m. After 10 m, the R^2 value decreases slightly to 0.91, a value still greater than its counterpart at 5 m.

The SSC residuals (Figure 3) do not exhibit any apparent patterns. While extremely low SSCs are generally overestimated, extremely high SSCs are underestimated at 1 m. Such a pattern of erroneous quantification applies to only a limited number of observations. The two patterns of residuals at 1 m and 5 m are strikingly similar to each other. At 10 m, the magnitudes of all residuals are much smaller. They become much more dispersed again at 20 m. The strongest relationship between SSC and DN is described as

$$\text{SSC} = 0.899\text{DN} - 55.091 \qquad (1)$$

at 10 m. This explains 97 percent of the variation in SSC. At the 95 percent confidence level, the computed χ^2 value is 6.10, much smaller than the expected value of 69.126. Hence, this model is considered statistically significant.

Model Verification

In order to reveal their errors, the estimated SSCs were plotted against the measured SSCs as a scatter diagram with an equal scale for the remaining 30 *in situ* samples (Figure 4). At 1 m and 5 m, the two diagrams are very similar to each other in that those observations with a medium SSC were accurately quantified. The reliability of quantification is much lower for extremely large and small SSCs. At 10 m, the two results correspond well with one another. The correspondence degrades at 20 m, but is still better than at 5 m. The patterns of underestimation and overestimation remain similar to those of the regression residuals. The RMS error decreases progressively from 7.13 mgl^{-1} at 1 m to 2.27 mgl^{-1} at 10 m, but increases to 3.68 mgl^{-1} at 20 m.

Discussion and Conclusions

The spatial resolution that is regarded as the most suitable for quantifying SSCs from remotely sensed data depends on the scale of a study. With the use of airborne remotely sensed data, the scale is usually limited to a local one as in this study. At such a scale, a fine spatial resolution of 1 or 5 m allows the variation in SSC to be better preserved in the scanned images. However, such a fine spatial resolution also enhances the uncertainty inherent in the positions of the *in situ* water samples which were determined with reference to onshore landmarks in this study. Consequently, it is difficult to accurately correlate the *in situ* SSC sampling positions on the ground and their positions in the mosaicked image.

Although the use of the Global Positioning System (GPS) may greatly increase the positional reliability of the *in situ* samples, it is still difficult to correlate the actual sampling positions with their coordinates on the scanned images because there are geometric errors in the rectified and mosaicked image and because GPS technology itself is not error-free. Geometric errors were still present in the rectified image due to the lack of geometric control over the water surface where no distinctive features can be used as suitable GCPs. Furthermore, even with a differential GPS the *in situ* samples cannot be positioned to sub-metre accuracy. Therefore, it may not be the most accurate to quantify SSCs from airborne remotely sensed data at the 1 m or 5 m spatial resolution.

Although the SSC patterns recorded on the aerial photographs are generalized more at 10 m than at 5 m during scanning, the coarser resolution considerably minimizes the positional uncertainty of the *in situ* water samples. Consequently, the SSCs measured in the field resemble their DNs on the scanned image better. Thus, the regressed relationship between SSC and reflectance has the largest R^2 value and the smallest RMS error. If the spatial resolution continues to decrease further from 10 m to 20 m, the SSC spatial pattern exhibited on the aerial photographs is resampled at such a coarse resolution that it is over generalized. The values of

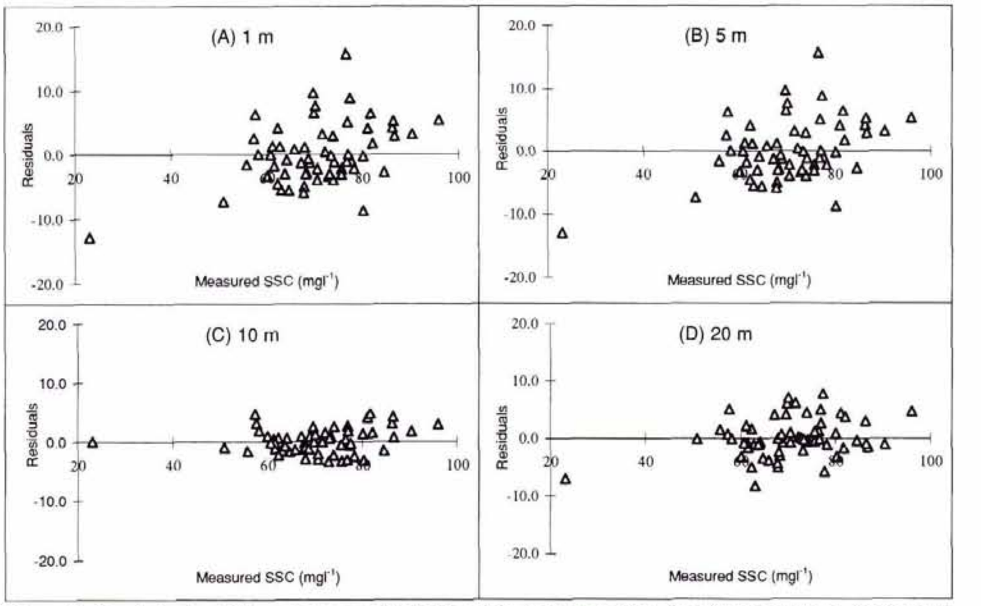

Figure 3. Residuals of the regressed relationship between the *in situ* measured SSCs and their digital numbers on the scanned aerial photographs at four resolutions.

the sampled pixels on the scanned image presumably do not correspond with the *in situ* sampled SSC as closely as they do at 10 m, resulting in a reduced R^2 value and an increased RMS error.

In addition to the scattering effect of the atmosphere, the aerial photographs themselves are subject to the inconsistency in film processing and uneven illumination on the film plane during exposure. These factors, however, do not seem to exert a profound impact on the radiometry of the obtained aerial photographs to alter the linear and significant relationship between SSC and its DN on the scanned images at all four resolutions studied.

To conclude, there was a close, linear, and statistically significant relationship between SSC measured in the field and its DN on the image scanned and mosaicked from the rectified aerial photographs at spatial resolutions ranging

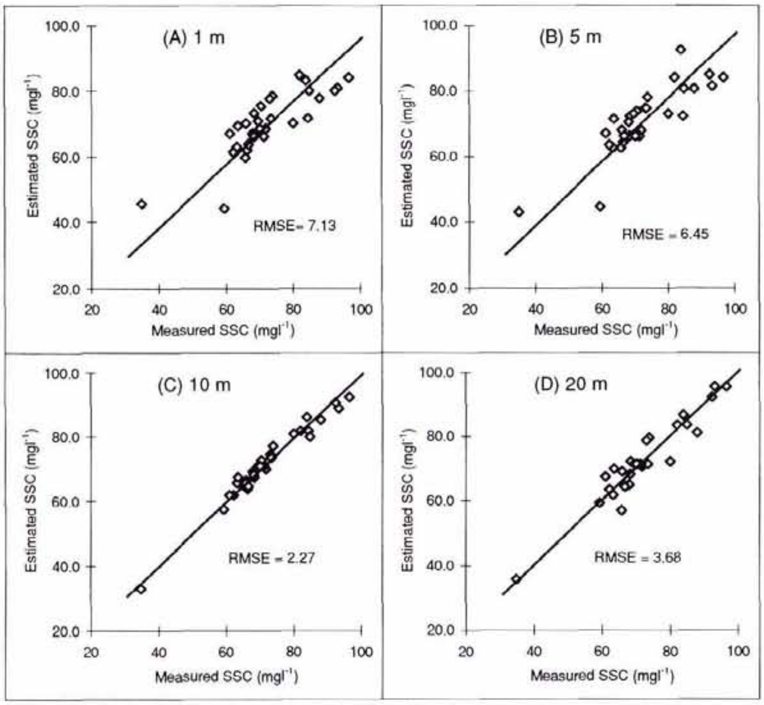

Figure 4. Correlation between the *in situ* measured SSCs and those estimated from the regressed equations based on 30 random samples.

from 1 m to 20 m. The relationship becomes increasingly stronger and more accurate as the spatial resolution decreases from 1 m to 10 m. At 20 m both the R^2 value of the regressed relationship and its RMS error become larger than at 10 m. Therefore, the finest spatial resolution does not allow SSCs to be estimated from airborne remotely sensed data with the highest accuracy because of geometric registration errors. In this study a spatial resolution of 10 m appears to be the optimal resolution for estimating SSCs from scanned airborne photographs at a local scale.

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