Spectral analysis of suspended material in coastal waters: A comparison between band math equations

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ABSTRACT.– Clear water reflects very little solar irradiance, but water with suspended material (SM) is capable of reflecting significant amounts of sunlight. Suspended material includes any solids, non-solids, organic material and inorganic material present in the column of water. Aiming to discover a better way to identify SM by remotely sensed data, a new band math equation was developed and called Normalized Suspended Material Index (NSMI). This equation was developed based on two principles: 1) water has a peak reflectance in the blues range of the visible spectrum and 2) the presence of SM increases reflectance through the visible spectrum, including the green and red band where clear water tends to absorb. The equation was applied to an image of southwest Puerto Rico and compared with two other equations to verify its validity, since no field data is available for this research. Other Equations used are Normalized Difference Suspended Sediment Index (NDSSSI) and a Band Ratio (green/blue) used for suspended sediment. NSMI data compared with other equation showed similar patterns, suggesting validity. Differences are the result of spectral ranges used on each equation. In general all equations demonstrate the presence of unclear water. However, a correlation between laboratory data and a NSMI image is still necessary to validate the equation quantitatively.

Keywords.–ENVI, Suspended Material, Band Math Equations, NSMI

INTRODUCTION

Water quality of the ocean coast is a very important factor for marine flora and fauna. Many organisms live in areas close to shore because the largest amount of nutrients is found in these areas. Also many organisms such as corals and phytoplankton are found in shallow waters because they need sunlight to produce photosynthesis. However coastal waters are composed of salt water, terrigenous particles (e. g. river sediments), living organisms (algaes), dissolve organic matter, resuspended sediments, anthropogenic materials and many other constituents. All these are called together suspended material (SM)(includes solids, non solids, organic and inorganic material). To determine the amount of suspended material in waters at the coast is important for maintaining a healthy coastal ecosystem.

The presence of suspended sediment, living organisms, dissolves organic matter and other particles can affect remotely sensed signal by changing the scattering and absorption properties of water (Fiuza Borges et al. 2011) Many factors such as suspended particle size, shape and color can have large influences on spectral properties of water (Azad Hossain et al. 2006). For example: clear water has a peak reflectance on the blue range of the visible spectrum (Fig. 1), however adding sediment to water (turbid water) will increase its reflectance through the visible spectrum (Fig. 2); adding phytoplankton (photosynthetic organisms) increases the reflectance of water in the green portion of the visible spectrum and increase absorption in the blue and red portion; adding organic matter decreases the reflectance of water in the visible spectrum and increases the reflectance in the infrared portion. Based on the complexity of water properties there is no universal algorithm to determine suspended material in water.

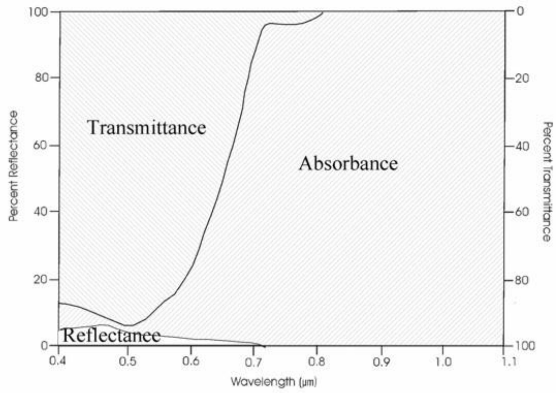

FIG. 1. Spectral curve of clear water. Clear water reflects very little solar irradiance but transmit most of it in the visible spectrum (obtained from Farooq S. 2011).

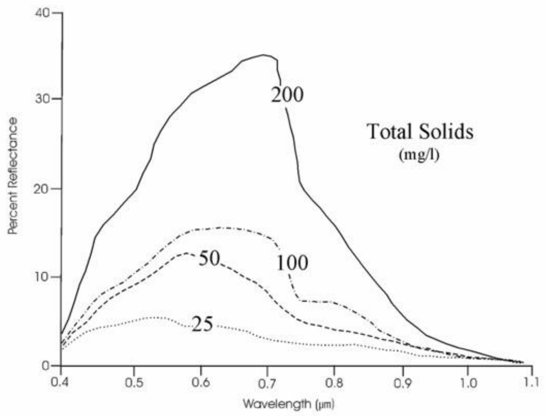

FIG. 2. Spectral curve of water with different concentrations of suspended sediment. The amount of suspended sediment in water is proportional to the reflectance of water (obtained from Farooq S. 2011).

Various Band Math Equations (or indexes) have been developed to determine many components of SM in water, such as suspended sediment and chlorophyll. Aiming to discover a new mathematical relationship to identify and discriminate SM in coastal waters, a new Band Math Equation was developed using images of Landsat 7 Enhanced Thematic Mapper (ETM+).

MATERIALS AND METHODS

Study Site

The area of study covers the entire region surrounding the coast of Cabo Rojo. It is located in the South West of the island of Puerto Rico, the smallest of the Greater Antilles in the Caribbean Ocean. It is located to the south of the Guanajibo River mouth, whose sediments travel south towards the coastal waters of Cabo Rojo. No other river in the region supplies sediments to the coast.

Cabo Rojo is known for rich sea life and microorganisms (e. g. phytoplankton) may be found in large quantities, enough to affect the spectral reflectance of the water. There is also a lot of boating activity in the area that contributes with a discharge of inorganic compounds. In the last decades there has been much deforestation due to an increase of urbanization in the coastal regions. Deforestation causes the exposure of bare soil that can be washed away by runoff and deposited on the ocean as suspended sediment.

Besides the ocean, other water bodies found are: mangrove swamps and tidal flat lagoons. All these water bodies are part of the study area since the equations can be applied to any water body.

Image Processing

Step 1

A satellite image obtained on August 31, 2000 from the Landsat ETM+ Scanner was used. The image was obtained from row 50 and path 48, and covers the southwestern corner of the island of Puerto Rico and part of the Caribbean Ocean surrounding it. The image file was encoded in a TIFF format and all the bands were merged into one single file to ease the processing of the image. Before processing the image, a subset of the coast of Cabo Rojo was made (Fig. 3).

Step 2

Two atmospheric corrections were used: Dark Subtract and Internal Average Relative Reflectance (IARR). Dark

Subtraction is used to reduce image noise and it is applied to an image by the subtraction of the smallest value in a band from every other value in that band.

FIG. 3. A true color subset of Landsat ETM+ Image from row 50 and path 48 from August 31, 2000.

The IARR is a simple way to change digital values of an image to physical values, which is reflectance. This function calculates the average spectrum of a complete image and then the spectrum of any pixel in the scene is divided by the average spectrum to estimate the relative reflectance spectrum for the pixel. The IARR correction is mostly used when no field data is available; such is the case for this research.

Step 3

Unsupervised classification using the K-means algorithm was performed to the image (Fig. 4). The classification was successful in discriminating between water and land. Afterwards a mask was developed to cover everything that is not water. This was performed using the "Band Threshold to ROI" function in ENVI to create ROI's out of the classes. The different classifications were used as the input values. In this case classes 1 to 3 were choose to create a new set of ROI. This training data (ROI) was then used to develop a mask (Fig. 5).

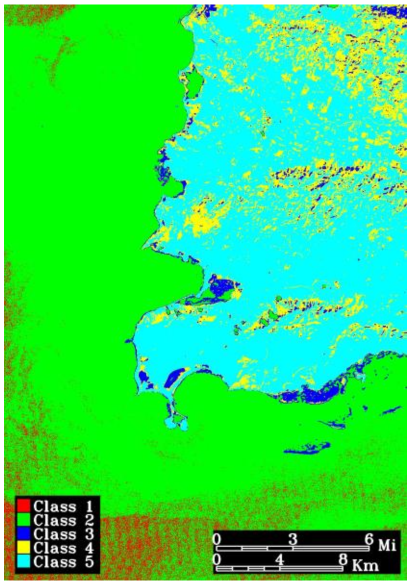

FIG. 4. Unsupervised classification of the K-means algorithm. Classes 1 to 3 are water bodies (on the coast) and/or highly forested areas (inland). Classes 4 and 5 is land cover.

FIG. 5. True Color Image with the mask developed from the K-means image data.

Step 4

Finally, we developed a new band math equation to identify SM and it was applied to generate a new image. The equation was called Normalized Suspended Material Index (NSMI) and it is explained on the next section. The resulting value from band math equations is often calibrated with data measured in the field. This research lacks field data and for this reason the resulting image was compared with results from other published equations to validate the proposed equation.

Normalized Suspended Material Index (NSMI)

NSMI (Eq. 1) was developed based on the principles that clean water has a peak reflectance in the blue range (ρ_{blue}), while the presence of SM promotes an increase of reflectance in the whole visible spectrum, especially in the range of green and red ($\rho_{red} + \rho_{green}$) where clear water tends to absorb radiation (Fiuza Borges et al. 2011).

The equation was generated by adding the spectral response of the Red and Green bands and subtracting it from the Blue band, then dividing the result by the sum of the Red, Green and Blue bands to normalize the result. The equation gives values ranging from -1 to +1. Lower values correspond to more clear water. Note that, when the blue band has a higher value than the sum of the red and green band, the equation gives a negative value, indicating the presence of more clear water. Higher values correspond to water with more SM.

$$\text{NSMI} = \frac{(\rho_{red})+(\rho_{green})-(\rho_{blue})}{(\rho_{red})+(\rho_{green})+(\rho_{blue})}$$

EQ. 1. Normalized Suspended Material Index.

Other Band Math Equations

To verify the validity of the NSMI the result was compared with the following two equations:

a. Normalize Difference Suspended Sediment Index (NDSSI)

NDSSI has been used by many authors (Azad Hossain et al. 2006) to develop models of suspended sediment in rivers, lakes, estuaries and many other water bodies. It has been observed that Landsat ETM imagery is more sensitive to water transparency on the blue (ρ_{blue}) and near infrared (ρ_{nir}) bands (Azad Hossain et al. 2006). The index is applied by subtracting the near infrared band from the blue band and the divining the result by the sum of both bands (Eq. 2). NDSSI also range from -1 to +1 where higher values indicate the presence of more clear water and lower values indicate the presence of more turbid water or land (Azad Hossain et al. 2006).

$$\text{NDSSI} = \frac{(\rho_{blue})-(\rho_{nir})}{(\rho_{blue})+(\rho_{nir})}$$

EQ. 2. Normalized Suspended Material Index.

b. Band Ratio (Green/Blue)

The simple band ratios are used for many purposes in remote sensing. For Landsat ETM+ imagery the band ratio used to determine suspended sediment in water is the green band divided by the blue band (Eq. 3)(Aber, 2011). For this equation the green band is used because sediment increases the reflectance in the green range of the spectrum while clear water has the peak reflectance in the blue range. Band Ratios range from 0 to infinite. In this case the highest value indicates the presence of more suspended sediment (Aber, 2011).

$$\text{Band Ratio} = \frac{(\rho_{green})}{(\rho_{blue})}$$

EQ. 3. Band Ratio (Green/Blue) used for suspended sediments.

DISCUSSION

Many Band Math Equations are used to generate models of different component of suspended materials present in water bodies. Aiming to discover a new suspended material index for Landsat 7 ETM+ imagery, NSMI was generated. The result of adding this equation to a satellite image of Cabo Rojo is shown in figure 6.

The NSMI equation appeared to be successful discriminating between clear water and suspended material. At least that can be inferred when we see that the Guanajibo River plume was detected as suspended material. Also the areas identified with a high concentration of suspended material are located close to shore where the wave base is expected to redistribute the bottom sediments and increase reflectance of the water column. Near shore is influenced by upwelling currents that bring nutrients to the surface where many microorganisms live (e. g. phytoplankton), thus increasing the reflectance of water. Areas with the highest amount of suspended material are shown in white color. These areas are all located on the shore where the mangrove swamps are located. Mangrove swamp waters are relatively calm but are not detected as clear water because they are either too shallow or they contain large amounts of suspended clay and silt material. Note that one disadvantage of NSMI is the identification of SM in shallow areas (e. g. coral reefs, swamps).

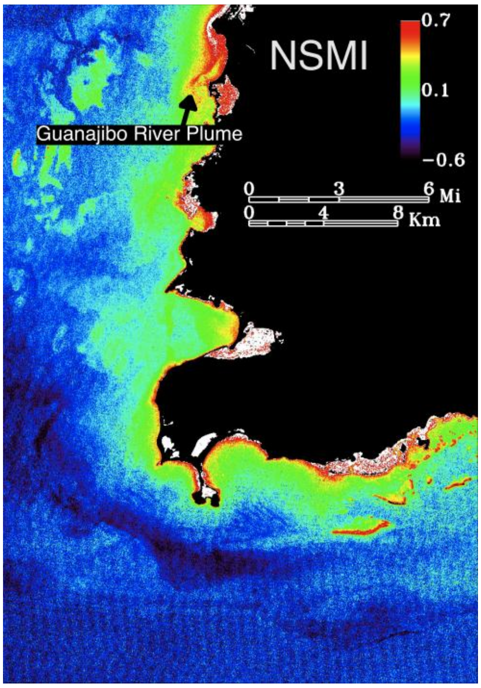

FIG. 6. Normalized Suspended Material Index (NSMI) for coastal waters of Cabo Rojo. Cold colors are more clear water and hot colors are water with more SM.

To validate the NSMI equation two other equations indexes where applied to the same image of Cabo Rojo coastal waters. One index used was the NDSSI and is shown in figure 7. This equation is one of the most used in literature to determine suspended sediment. Note that the high concentrations of sediment are found near the shore. The Guanajibo River plume is also identified but not as detailed like the NSMI image. Also the mangrove regions are shown in white, similar to the NSMI image. Note that the lowest value in this equation might be either land or very high amounts of suspended sediment.

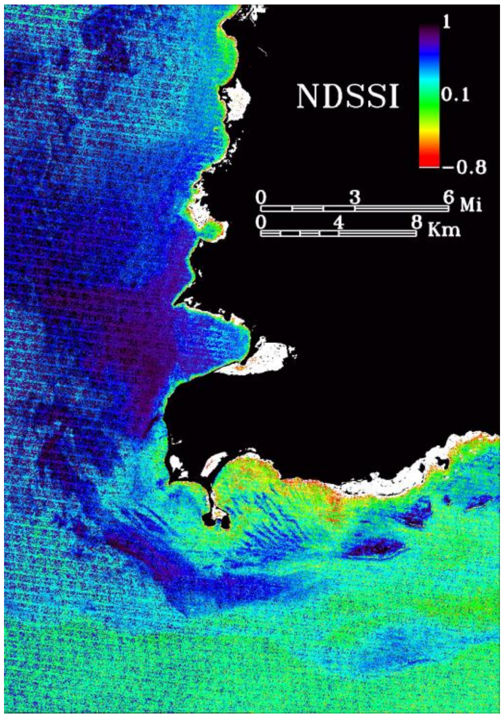

FIG. 7. Normalized Difference Suspended Sediment Index (NDSSI) for coastal waters of Cabo Rojo. Cold colors are more clear water and hot colors are water with more suspended sediment.

The other index used was the Band Ratio (Green/Blue) used for suspended sediments. The resulting image from the Band Ratio is shown in figure 8. Evidently this image is more similar to the NSMI results. There is a major difference in the sensitivity of the equations. One can see this by the large extension of the greener values in the Band Ratio image in comparison with the NSMI image. Another example to see this is near the shore where mangrove swamps are found; note that they appear whiter on the NSMI image than on the Band Ratio image. However the spectral range of both images can be responsible for these differences. Similar to the NSMI the Band Ratio equation has a disadvantage in the identification of SM in shallow areas.

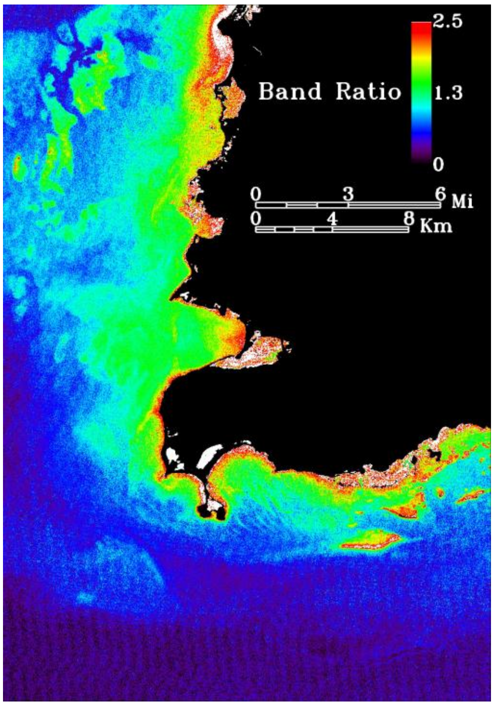

FIG. 8. Sediment Band Ratio (Green/Blue) for coastal waters of Cabo Rojo. Cold colors are more clear water and hot colors are water with more suspended sediment.

CONLCUSSION

The results of this study showed that the NSMI equation developed to identify suspended material might yield accurate values. However, NSMI is expected to detect suspended material while the NDSSI and Band Ratio are expected to detect only suspended sediment. For this reason neither equation is assumed to give exactly similar values, although similar patters are expected since ocean currents are responsible for the movement of many components found in suspended material (sediments, nutrients, organisms, etc.).

To approve the validity of this equation it is necessary to do a numerical correlation between the results of a NSMI image and field/laboratory work. This will demonstrate the accuracy and the usefulness of the equation. It will also corroborate our hypothesis of identifying suspended material with the NSMI.

Acknowledgements.– I will like to thank Dr. Fernando Gilbes Santaella for showing me the principles of Remote Sensing and guiding me through the process of developing this research. Special thanks to Felix Rivera for helping me throughout the processing of the images. It shouldn't be out of this list the students of the Advanced Remote Sensing class for their suggestions in making this the best paper possible.

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