Development of Remote Sensing Based Index for Estimating/Mapping Suspended Sediment Concentration in River and Lake Environments

A. K. M. Azad Hossain

Post Doctoral Research Associate
National Center for Computational Hydroscience and Engineering
The University of Mississippi, 102 Carrier Hall, University, MS, 38677, USA

Xiaobo Chao

Research Scientist
National Center for Computational Hydroscience and Engineering
The University of Mississippi, 102 Carrier Hall, University, MS, 38677, USA

Yafei Jia

Research Professor
National Center for Computational Hydroscience and Engineering
The University of Mississippi, 102 Carrier Hall, University, MS, 38677, USA

Abstract: This research explored the potential of remote sensing to develop an index and estimate co-efficients that can be used in riverine/lake environments, especially during extreme events when routine in-situ measurements are not available. Normalized Difference Suspended Sediment Index (NDSSI) was calculated using the Landsat data and was correlated to the near real-time in-situ measurements of suspended sediment concentrations using a power equation for quantitative estimation of SS concentration in the Mississippi River. This technique, using the obtained coefficients was applied to estimate/map the SS concentration in the Mississippi River during the Mid West USA 2008 flood and in Lake Pontchartrain during (1) Bonnet Carre Spill Way opening event and (2) before and after Hurricane Katrina. The results were compared by the simulation results of CCHE2D (a numerical model developed at NCCHE) and found in a good general agreement qualitatively and quantitatively. The preliminary results indicate that (1) NDSSI has the potential to estimate (relative variation) and map the spatial distribution of SS concentration in both river and lake environments, (2) NDSSI can be used for quantitative estimation of SS concentration in these environments when coupled with two co-efficients in a power equation, and (3) the same approach can be used to estimate SS concentration in both river and lake water within reasonable error limits using NDSSI. Acquisition of more in-situ measurements of SS concentrations are on going to derive more general co-efficients and achieve more validation results.

Keywords: Remote Sensing, NDSSI, Suspended Sediment Concentration, CCHE2D, Mississippi River, Lake Pontchartrain, Hurricane Katrina.

Introduction

Water quality is one of the most important factors for lake and riverine ecosystems. Sediment concentration in the water is considered to be a critical water quality parameter that affects the lake and river habitats negatively. Typically suspended sediments (SS) are the non-dissolved matters in the water that reflects the physical and chemical property of water. They Influence the total primary productivity as the quantity of SS affects the transmission of light in water, as well as the transition of heavy metal and the micro-pollutant. Suspended sediment concentration is a spatially inhomogeneous parameter and its spatial distribution is difficult to measure with the routine in-situ monitoring method. Numerical modeling has been used to estimate SS concentration in river channels, over their flood plains and other surface waters. Remote sensing is an efficient method, which can provide realistic water quality data with large spatial distributions for water resource study. In this study, remote sensing techniques are used for mapping SS concentration in the Mississippi River and the Lake Pontchartrain, LA. A normalized difference suspended sediment index (NDSSI) was developed for this purpose. The study finds this as an effective approach, the estimated SSC has reasonable values and special distributions. The estimated results and the numerical model prediction agreed very well.

Numerical Model vs. Remote Sensing

Numerical models are based on hydrodynamic principles, methodologies and algorithms. The results are predicted continuous data with short time steps usually validated by physical experiments and/or limited in-situ measurements. Remote sensing techniques are based on correlation between near real-time observations of spectral reflectance and discrete in-situ measurements. The results are compared with observed continuous data with large temporal gap also validated by physical experiments and/or limited in-situ measurements. During extreme events like hurricane and flood usually no ground measurements of sediment concentration are done in the waters of inundated areas. Therefore, satellite data derived SSC data serves as the only means to provide observed sediment concentration information during natural disasters.

Estimation of SS Concentration Using Remote Sensing

Suspended sediment concentration has been estimated and mapped successfully using remote sensing for the last three decades. Different approaches and algorithms had been developed over time for SS concentration estimation/mapping using optical satellite data. The available techniques can be categorized in four general groups: (1) simple regression (correlation between single band and in-situ measurements)[e.g., Williams and Grabau (1973) – Chesapeake Bay early in 1973], (2) spectral unmixing techniques [e.g., Gomez, et al., 1997], (3) Band ratio technique using two and more bands [e.g., Lathrop ,1992; Populus et al., 1995; Wang et al., 2000], and (4) multiple regressions (using multiple bands and in-situ measurements)[e.g., Binding et al., 2005].

Usually when suspended sediment concentrations are high, the backscatter/ reflectivity of water is high. There are three matters dominate the reflectance of inland water, which are yellow substance, suspended sediment and phytoplankton. Yellow substance is a soluble matter, which has no scatter capability, but it has a strong absorption effect on short-wave bands that highly reduce the underwater downwelling irradiance. Therefore, when the absorption of water itself and yellow substance is small, actual suspended sediment information could be obtained (Wang et al., 2003).

Goal and Objectives

It has been observed that although remote sensing has been considered as a proven technique for SS concentration estimation all the developed models and algorithms are applicable for specific areas and environments. Due to this reason it is not possible to use any existing remote sensing based technique to estimate and map SS concentration during extreme events like hurricane, flush flood etc. To address this issue in this research we attempted to explore the potential of remote sensing to develop an index and estimate co-efficients that can be used in different riverine/lake environments, especially during extreme events when routine in-situ measurements are not available.

Study Site

This research involves three different sites for model development, calibration, validation and applications. The sites are located in the Midwest and Southeast USA. Selected parts of the Mississippi River along the western part of Missouri were used for the model development and calibration (Figure 1). Mississippi River and the adjacent areas between Alexandria, MO and Warsaw, IL areas and Lake Pontchartrain in Louisiana were used for model application and validation.

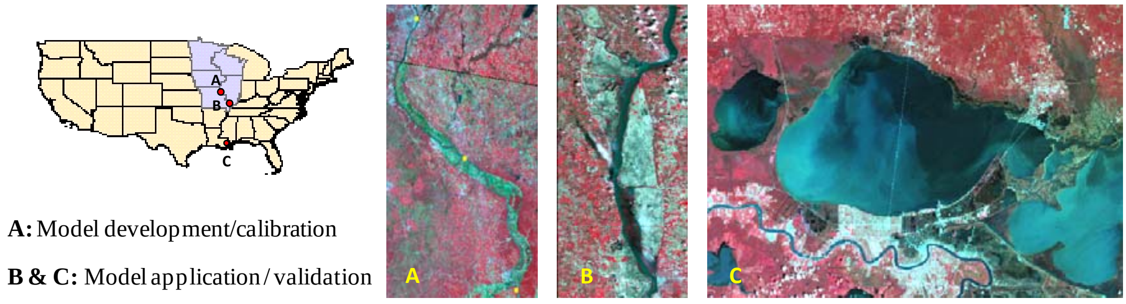

Figure 1. Location and extent of study sites (A and C shown on Landsat 5 TM 4,3,2 false color composite imagery; and B shown on ALOS AVNIR 2 4,3,2 false color composite imagery)

Materials and Methods

Inspired by the concept of Normalized Difference Vegetation Index (NDVI) [Rouse, et al., 1976] we calculated Normalized Difference Suspended Sediment Index (NDSSI) using Landsat 7 ETM+ imagery to determine spatial distribution of the relative variation of SS concentration in the river/lake water. We correlated the NDSSI values to near real time in-situ measurements of SS concentration to estimate the SS concentration quantitatively.

Normalized Difference Suspended Sediment Index (NDSSI)

It has been observed for Landsat TM/ETM imagery that Band 1 (Blue band/~ 0.450-0.515 microns) and Band 4 (Near-infrared/~0.750-0.900 microns) are most sensitive to water and water transparency (turbidity). Band 1and Band 4 usually gives the highest and lowest reflectance values respectively for water. These characteristics have been observed for water with different levels of turbidity (Figure 2). NDVI was calculated on the basis of the responses of Band 3 (Red band) and Band 4 (Near infra-red band) on green vegetation. According to Rouse et al., (1976) for any vegetation Band 4 and band 3 of Landsat 5/7 TM/ETM+ data always gives the highest and lowest reflectance respectively. Equation 1 shows the calculation of NDVI. The values of NDVI range from -1 to +1 where higher values indicate the presence of more green vegetation and lower values indicate stressed vegetation or bare soil/concrete etc. To achieve the capability of similar data interpretability we calculated NDSSI as shown in Equation 2. Like NDVI the values of 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.

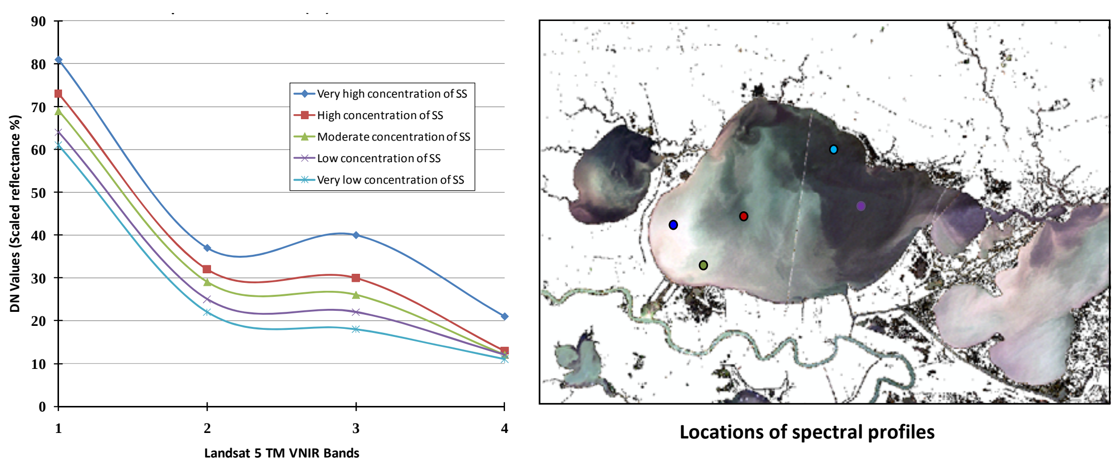

Figure 2. Spectral profiles of water at different levels of suspended sediment (SS) concentrations observed in Landsat 5 TM VNIR imagery

$$NDVI = \frac{\rho_{NIR} - \rho_R}{\rho_{NIR} + \rho_R} \quad (1)$$

$$NDSSI = \frac{\rho_B - \rho_{NIR}}{\rho_B + \rho_{NIR}} \quad (2)$$

Where, $\rho_{B,}$ $\rho_{R,}$ and $\rho_{NIR,}$ are the reflectance values of Landsat 5/7 TM/ETM+ Band 1, Band 3 and Band 4 respectively.

Figure 3 shows the nature of NDSSI imagery prepared from Landsat 5 TM VNIR imagery acquired over Lake Pontchartrain at different periods. These imagery captured the snapshots of different levels of SS concentrations in the water.

Data Used

Landsat 7 ETM+ VNIR imagery acquired over the Site ‘A’ (Fig. 1) for 16 dates were obtained from USGS/NASA (from GLOVIS) to calculate and calibrate the NDSSI imagery. Total 16 Landsat 7 ETM+ imagery were used in this purpose. Each image dates include two scenes. Table 1 shows the image acquisition dates. Near real time (of the corresponding image acquisition dates) in-situ measurements of SS concentrations in the Mississippi River were obtained from 3 USGS stations. TheIDs of these stations are 7010000, 7020500 and 7022000. Table 1 shows the measurements of SS concentrations for each date. One scene of ALOS AVNIR2 imagery acquired over the Site ‘B’ was obtained from ASF to estimate/map SS concentration in the flood water (during Midwest Flood event in June 20080 using NDSSI. Three scenes of Landsat 5 TM VNIR imagery acquired over the Site ‘C’ were obtained from USGS/ NASA (from GLOVIS) to estimate/map SS concentrations (1) in the water of Lake Pontchartrain during the Bonnet Care Spillway flooding event, and (2) study the changes occurred in the SS concentrations in the water of lake Pontchartrain due to Hurricane Katrina. The imagery used in this purpose were acquired on April 10, 1997; August 22, 2005 and September 07, 2005.

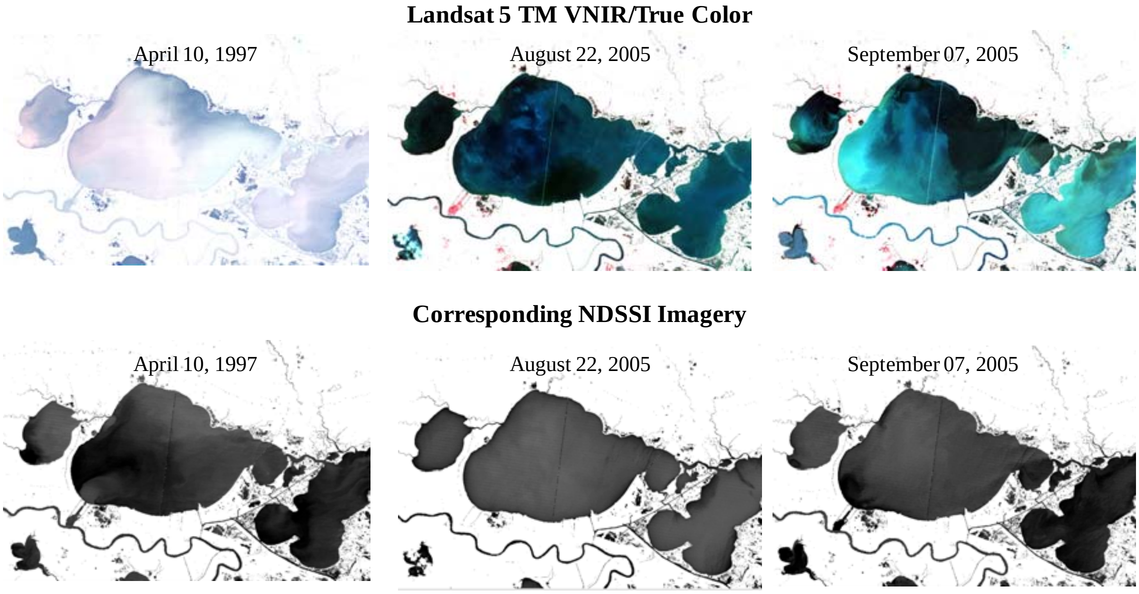

Figure 3. NDSSI imagery for different levels of suspended sediment (SS) concentrations in Lake Pontchartrain as observed in Landsat 5 TM imagery

Table 1. Image acquisition dates, in-situ measurements of SS concentrations and corresponding values of NDSSI obtained from the acquired Landsat 7 ETM+ imagery.

USGS Stations	Landsat 7 ETM + Data Acquisition	Sediment Concentration (mg/lit)	NDSSI
7010000	5/12/2003	888	0.35
	4/26/2003	132	0.58
	4/10/2003	115	0.64
	10/16/2002	114	0.61
7020500	5/12/2003	765	0.37
	4/26/2003	227	0.52
7022000	5/12/2003	591	0.38
	4/26/2003	337	0.49
	10/16/2002	96	0.62
	9/30/2002	97	0.60
	7/28/2002	78	0.55
	10/29/2001	156	0.44
	9/27/2001	317	0.45
	9/11/2001	191	0.58
	10/10/2000	151	0.47
	10/24/1999	119	0.47

Calibration of NDSSI

NDSSI was calculated for each Landsat data and correlated with the acquired USGS SSC measurements. It was noticed that all three USGS stations are located on top of a bridge over the Mississippi River. Therefore, it was not possible to get the NDSSI value exactly at the same location of the in-situ SS concentration measurements. NDSSI values were obtained from the closest 25 pixels downstream the in-situ measurement stations and an average value was calculated to represent the NDSSI value for the corresponding measuring station. The obtained NDSSI value for each station is shown in Table 1. Figure 4 shows the locations of the USGS stations and the corresponding 25 pixels of NDSSI calculation for each station.

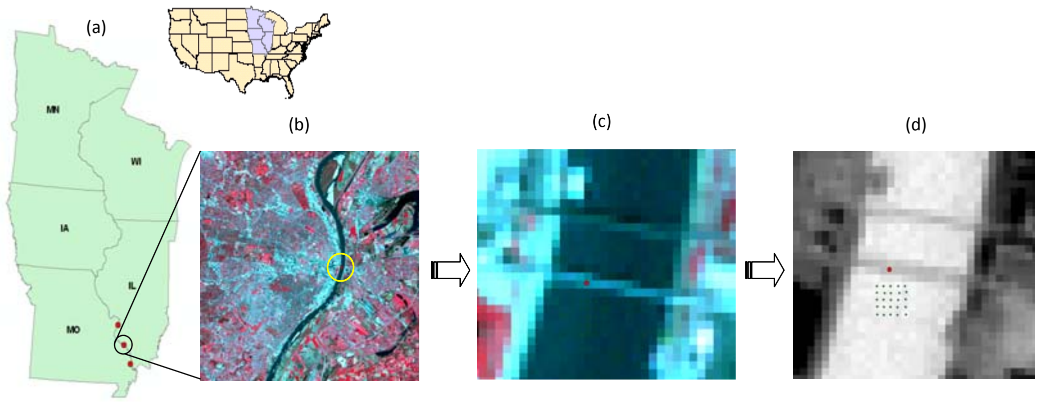

Figure 4. NDSSI calculation for each in-situ SS concentration measuring stations

To determine the most suitable coefficients to estimate the SS concentrations in the river/lake water using NDSSI, the obtained NDSSI values were plotted against the corresponding near real time in-situ measurements. The relationship between the correlated NDSSI and in-situ measurements were interpreted using different numerical equations including linear, exponential, logarithmic, polynomial and power function. Figure 5 shows the comparisons among the plots.

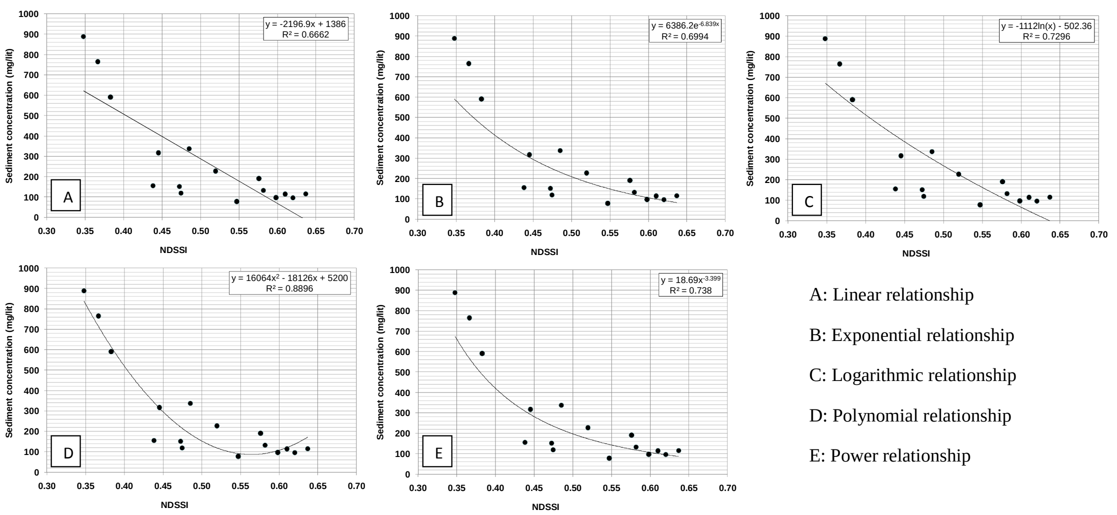

Figure 5. Relationship between NDSSI and in-situ measurements of SS concentrations in water

The coefficients associated with the equation that achieved highest correlation coefficient (R^2) value were considered suitable to use for SS concentration estimation in the lake/river water. Accordingly the polynomial (2^{nd} order) equation was found to have a R^2 value of about 0.89 and considered the most suitable equation initially. After a careful observation it was noticed that the polynomial equation has a potential to provide accurate estimation of SS concentration in low turbid and high turbid water because it has the best fit. However, the curve is very flat in the low turbid region and seems not to be capable of detect variation in the estimation. More importantly, the trend of increase in concentration at high NDSSI values may result in unphysical predictions. The power equation, although posses lower R^2 value than the polynomial equation it shows the potential to detect the variability in SS concentration in both low and high turbid water. Therefore, the power equation was considered to be the most suitable approach to estimate the SS concentration in the water.

$$SSC = a \times NDSSI^{-b} \quad (3)$$

$$SSC = 18.69 \times NDSSI^{-3.399} \quad (4)$$

Where, SSC = Suspended sediment concentration, *a* and *b* are the coefficients

Results and Discussion

The concept of NDSSI was applied using the obtained coefficients (from Equation 4) on (1) the obtained ALOS AVNIR2 VNIR imagery to estimate and map suspended sediment concentration in the Midwest USA 2008 flood water (Figure 6), (2) the obtained Landsat 5 TM VNIR imagery to estimate and map the suspended sediment concentrations in the Lake Pontchartrain during the Bonnet Care Spillway flooding event (Figure 7a), and before and after the Hurricane Katrina (Figure 7b and 7c).

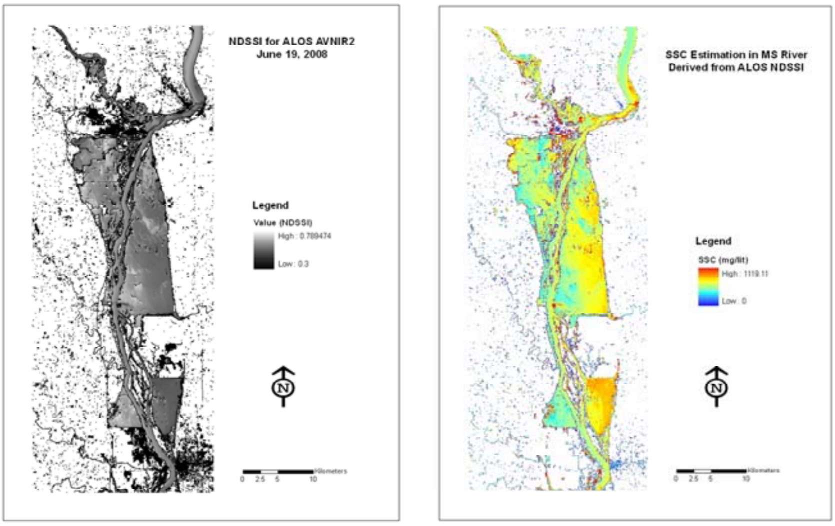

Figure 6. Suspended sediment concentration estimation in the Mississippi River flood water within Alexandria, MO and Warsaw, IL areas during the Mid West USA 2008 Flood.

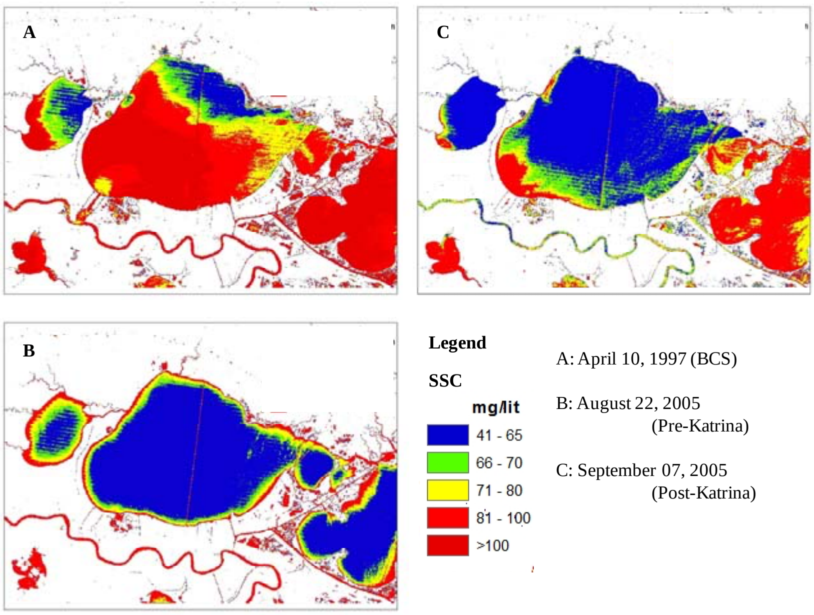

Figure 7. Suspended sediment concentration estimation in Lake Pontchartrain in different times

CCHE2D, a two- dimensional depth-averaged model, developed at the National Center for Computational Hydroscience and Engineering (NCCHE), was applied to simulate the sediment transport in the Midwest USA 2008 flood water and Lake Pontchartrain during the Bonnet Carre Spillway flooding event in April 1997 . CCHE2D is a 2D hydrodynamic model that can be used to simulate unsteady turbulent flows with irregular boundaries and free surfaces (Jia et al., 1999, 2002). The simulation results were compared with suspended sediment concentration estimation by NDSSI and were found in good general agreement (Figure 8 and Figure 9).

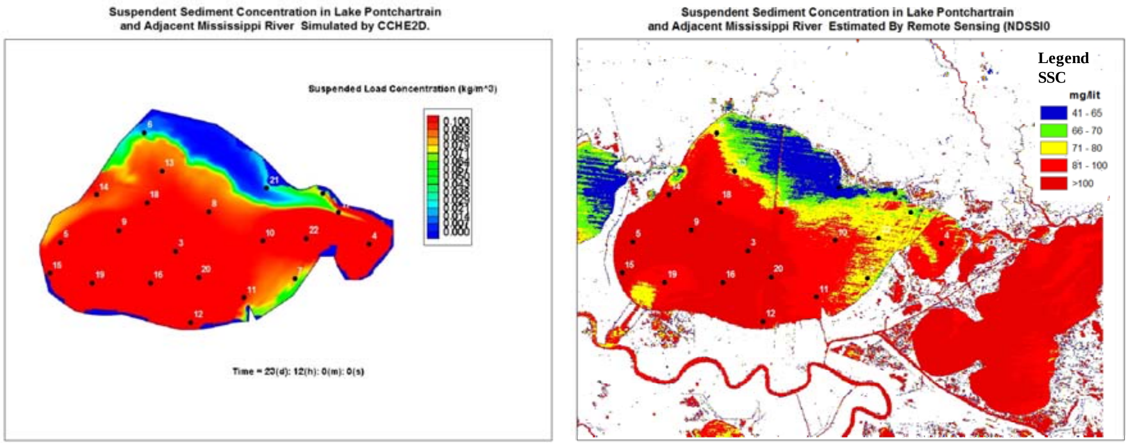

Figure 8. Qualitative comparison (by visual inspection) between simulated SS concentration (by CCHE2D) and remote sensing derived SS concentration estimation (By NDSSI).

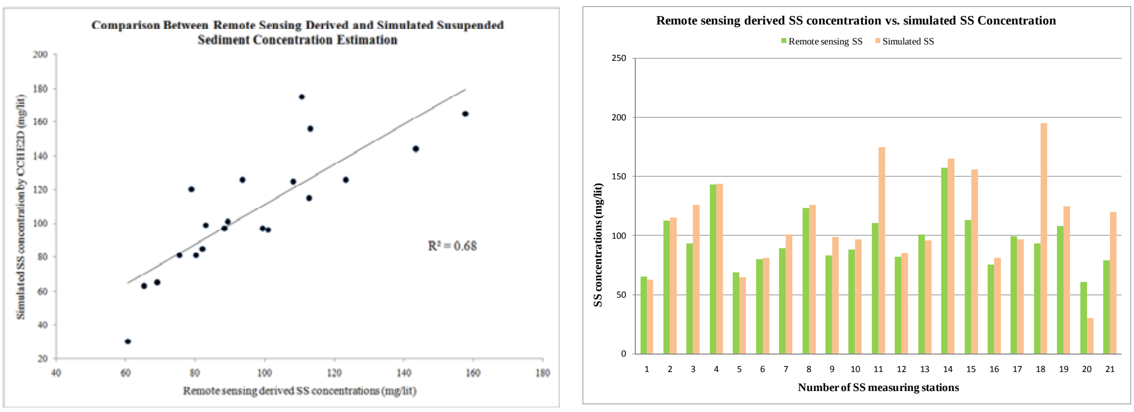

Figure 9. Quantitative comparison between simulated SS concentration (by CCHE2D) and remote sensing derived SS concentration estimation (By NDSSI).

Conclusion

Normalized Difference Suspended Sediment Index (NDSSI) was calculated using the Landsat 7 ETM+ VNIR imagery to map the spatial distribution (relative) of suspended sediment concentration in the water of Mississippi River at different levels of turbidity. NDSSI index values were correlated with the near real-time in-situ measurements of suspended sediment concentrations using different numerical approaches. The relationship between NDSSI and in-situ measurements of SS concentration expressed by power equation was found most suitable for quantitative estimation of SS concentration in the Mississippi River. This technique, using the obtained coefficients was applied to estimate/map the SS concentration in the Mississippi River during the Midwest USA 2008 flood and in Lake Pontchartrain during (1) Bonnet Carre Spill Way flooding event and (2) before and after Hurricane Katrina. The results were compared by the near real time simulated SS concentration data generated by CCHE2D numerical model developed at NCCHE and found in good general agreement qualitatively and quantitatively. This research is still evolving and this initial results indicate that (1) NDSSI has the potential to estimate (relative variation) and map the spatial distribution of SS concentration in both river and lake environments, (2) NDSSI can be used for quantitative estimation of SS concentration in these environments when coupled with two co-efficients in a power equation, and (3) the fact that the same coefficients obtain from the data of the Mississippi River can be used to estimate SS concentration in the Lake Pontchartrain indicates the usefulness of the developed NDSSI. Acquisition of more in-situ measurements of SS concentrations are on going to derive more general co-efficients and achieve more validation results.

Acknowledgments

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