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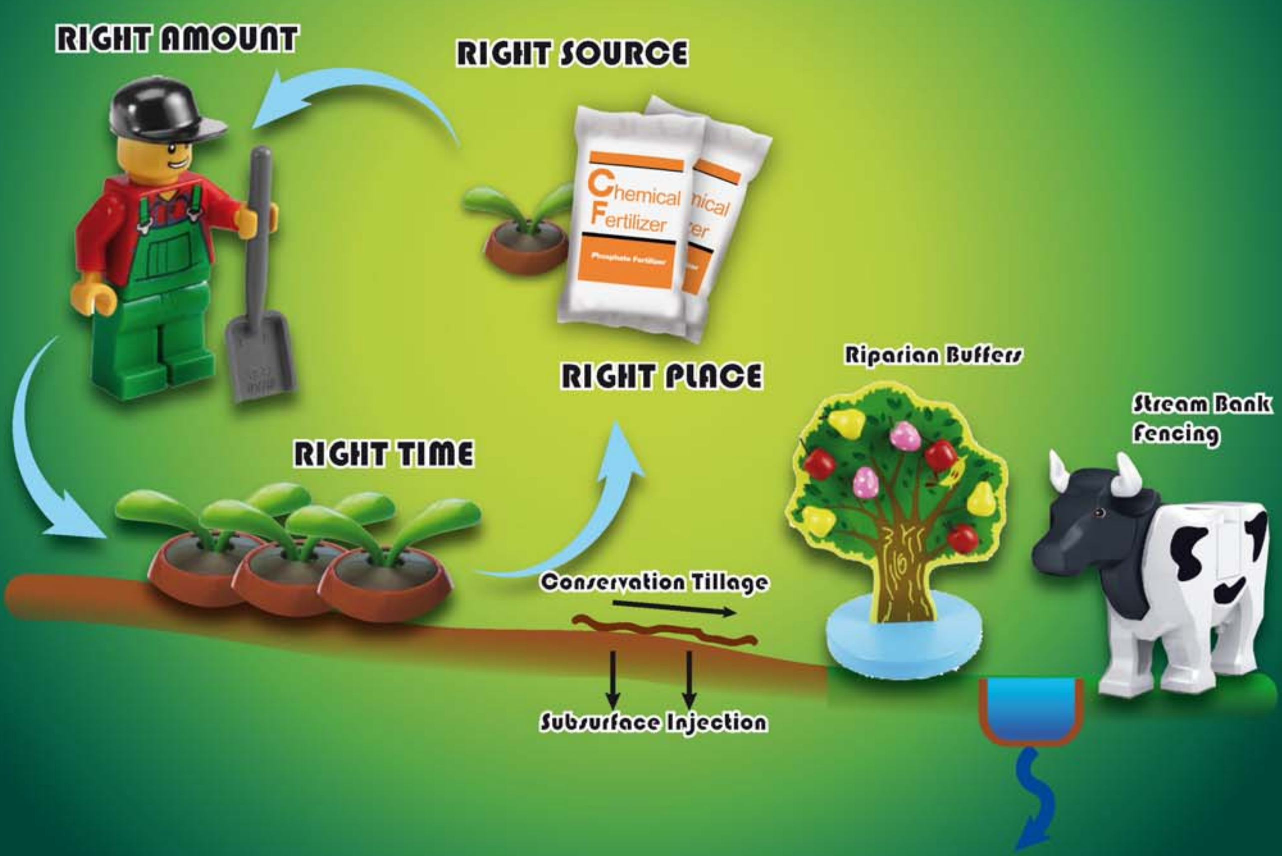

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Assessment of nutrient distributions in Lake Champlain using satellite remote sensing

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The introduction of nutrients to lakes causing eutrophic conditions is a major problem around the world. Proper monitoring and modeling are important to effectively manage eutrophication in lake waters. The goal is to develop remote sensing models for nutrients, total phosphorus and total nitrogen, in Lake Champlain. The remote sensing models were created using multivariate linear regression with the unique band combinations of Landsat Enhanced Thematic Mapper Plus (ETM+) imagery based on the empirical relationship with the field observations. The resulting models successfully showed nutrient distributions in the most eutrophic part of Lake Champlain, Missisquoi Bay, with reasonable adjusted coefficient of determination values ($R^2 = 0.81$ and 0.75 for total phosphorus and total nitrogen, respectively). The results show the feasibility and the utility of satellite imagery to detect spatial distributions of lake water quality constituents, which can be used to better understand nutrient distributions in Lake Champlain. This approach can be applicable to other lakes experiencing eutrophication assisting decision making when implementing Best Management Practices and other mitigation techniques to lakes.

Introduction

Excess nutrient addition to a water body causes algae species to flourish, taking over the lake's ecosystem. This excess nutrient loading, or eutrophication, is one of the most urgent issues facing freshwater systems such as lakes (Conley et al., 2002). Despite the current efforts to reduce nutrient loading from wastewater discharge and surrounding urban and agricultural runoff, eutrophication continues to be a severe problem around the world.

If spatial distributions of the nutrients can be quantified, better management of these pollutants can be implemented to mitigate eutrophication in lakes. Because of the lack of appropriate models and methods, however, spatial distributions of nutrients are rarely studied on a large scale. Conventional field sampling methods are costly, time consuming, and labor intensive. Another limitation to field sampling is that some areas of water may be inaccessible or logistically difficult for conventional field-based methods (Chen and Quan, 2012). Field sampling will only provide *in situ* measurements at pinpoint locations, which may not be representative of the entire water body.

The development of remote sensing technology has the potential to solve the cost, time, and accessibility issues posed by traditional sampling methods, and can also provide wide coverage of an entire water body. For example, Landsat satellite imagery is a convenient resource because of its long operational period allowing for retrospective analysis. The imagery is freely available from US Geological Survey (USGS) and is a popular choice because of its fine spatial resolution (30 m), which is essential for modeling inland waters. Enhanced Thematic Mapper Plus (ETM+) sensor on board the Landsat 7 satellite is the latest generation of the Landsat series. Landsat 8 was just launched in February of 2013 allowing for continuous monitoring

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with improved technology which can lead to more accurate future remote sensing models.

Satellite remote sensing, *e.g.*, Landsat and MODIS, has been used to detect optical water quality in both ocean and freshwater systems (Walczykowski et al., 2013). Fine resolution satellite imagery, *e.g.*, Landsat (30 m), is appropriate for freshwaters whereas moderate resolution imagery, *e.g.*, MODIS (1000 m), is more appropriate for oceans. Universal algorithms were developed for retrieving optical water quality constituents in open oceans (*e.g.*, ocean color) but are not available for complex freshwaters (Odermatt et al., 2012). Common remote sensing approaches are empirical algorithms and analytical algorithms (Garg and Chaubey, 2010; Matthews, 2011). Analytical algorithms, mainly applied to open oceans, are physical model based approaches using a radiative transfer equation to calculate the reflectance of constituents of interest based on its optical properties whereas empirical algorithms, often used for freshwaters, are based on statistical relationships between spectral properties and constituents (Ritchie et al., 2003; Matthews, 2011). The analytical algorithms are theoretically sound but are complex, requiring substantial fieldwork and expensive for algorithm training and computing (Matthews, 2011). The empirical algorithms are relatively simple approaches in computation and implementation, providing robust assessment of site-specific freshwater constituents (Matthews, 2011).

Previous studies have shown the usefulness of Landsat Thematic Mapper (TM) and ETM+ imagery to provide statistically significant results for models dealing with lake water (Chen and Quan, 2012; Vincent et al., 2004; Wheeler et al., 2012), but most satellite remote sensing studies have chosen optical property parameters such as chlorophyll *a*, turbidity or colored dissolved organic matters (Coskun et al., 2008). Recently, there have been some studies advocating for the use of a satellite remote sensing approach to determine nutrient distributions in lakes because of the advantage of synoptic coverage that is not available from traditional sampling methods (Chen and Quan, 2012). Few studies have attempted to monitor and model nutrient data, since these models do not yield results as statistically strong or consistent as constituents that have optical properties (Chen and Quan, 2012; Dewidar and Khedr, 2001; Wu et al., 2010). Dewidar and Khedr (2001) studied phosphorus and nitrogen levels in Egypt's waters using Landsat TM imagery with statistically significant results for these parameters. Chen and Quan (2012) used Landsat TM imagery to attempt to predict nitrogen and phosphorus concentrations in Tiahu Lake, China with some successful results for phosphorus ($R^2 = 0.63$), and less successful results for nitrogen ($R^2 = 0.24$).

This study investigates whether a combination of Landsat ETM+ bands could detect the general patterns of total phosphorus and total nitrogen. These models are compared to Secchi disk distributions, which are more widely studied using remote sensing. The study aims to define models that can show the spatial distributions of these different nutrient parameters with statistically significant results and accuracy.

1. Methodology

1.1. Study area

Lake Champlain is an international lake that borders New York, Vermont, and Quebec, Canada (LCBP, 2006). The lake spans 193 km in length with a maximum width of 19 km, an average depth of 19.5 m and a maximum depth of 122 m. The lake has a surface area of 1269 km^2 and contains 25.7 trillion m^3 of water (LCBP, 2006), and is used recreationally and as a drinking water source.

One of the issues facing the lake is its highly eutrophic conditions that have become more frequent and severe over the last 20 years (Smeltzer et al., 2009). Nutrients are mainly introduced by diffuse pollution from urban and agricultural sources as well as waste discharge from the 98 waste water treatment plants (WWTPs) located in the Lake Champlain basin (Smeltzer et al., 2009). Currently, WWTP discharges contribute to 5% of the overall nutrient loading while diffuse pollution contributes to the other 95% (Smeltzer et al., 2009). The most prominent places where severe eutrophication occurs in Lake Champlain are Missisquoi Bay and St. Albans Bay. This study focuses specifically on Missisquoi Bay, though the model development is applicable for the entire lake (Fig. 1).

1.2. Data collection

The *in situ* data measurements were provided by the Vermont Department of Environmental Conservation (VT DEC, 2012). The VT DEC has collected data for 40 different water quality parameters at different monitoring stations in Lake Champlain. There are a total of 15 monitoring stations set up for data collection including in Missisquoi Bay. The remote sensing models were developed using 2006–2010 data and validated using 2011 data.

Ten Landsat ETM+ images of Lake Champlain (Path 14, Row 29) were collected from the USGS Earth Resources Observation and Science Center. The images of good quality (ratings of 9) without cloud or haze cover for summer months from 2006 to 2011 were collected based on the *in situ* data that was available. This study used a 1 day time window when selecting between a satellite overpass date and the field measurement date (Stadelmann et al., 2001).

1.3. Preprocessing of satellite imagery

The image processing was completed in ENVI (EXELIS Visual Information Solutions, Version 5). Landsat ETM+ bands except thermal and panchromatic bands were used for model development. Each band for all Landsat images was converted to top-of-atmosphere reflectance to normalize the images for comparison between different days. For atmospheric correction, dark object subtraction was used, which takes the minimum value in each band and subtracts it from each pixel (Vincent et al., 2004). In order to remove any bias or outlier that could be present if just analyzing a single pixel, a 3 × 3 low-pass filter was applied to each band. The 3 × 3 filter causes the Landsat imagery to be smoothed to 90 m × 90 m spatial resolution, which is consistent with other literature that recommends not using greater than 100 m resolution for inland water quality modeling (Brezonik et al., 2005).

1.4. Development of nutrient models

To determine the optimal models for total phosphorus and total nitrogen, multivariate linear regression models were developed in R (Version 2.11.1, R Development Core Team), a free software for statistical computing. Best subset regression was adopted as a multivariate linear regression, and evaluated by statistical

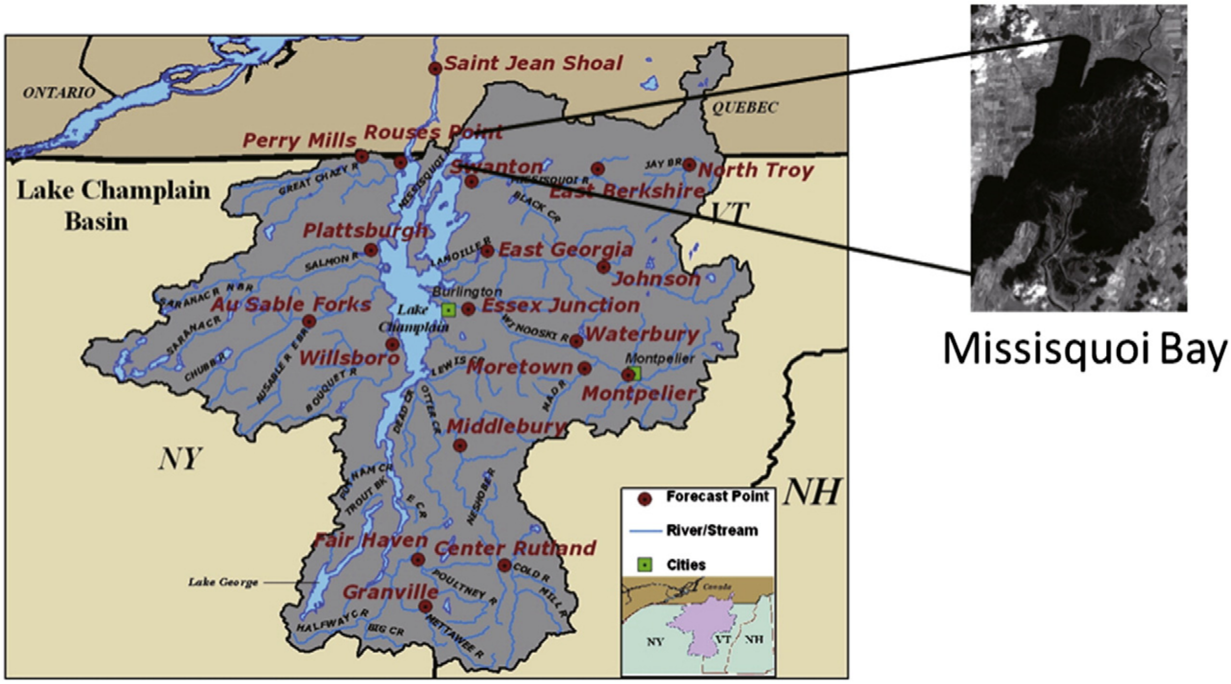

Fig. 1 – Location of Lake Champlain Basin and Missisquoi Bay (left image: http://www.erh.noaa.gov/nerfc/lch_photo.shtml).

analyses such as the Mallows' C_p Criterion, adjusted R^2, and root mean square error (RMSE). The model that performed the best was chosen as the optimal model. Logarithmic or square root transformations were applied to the dataset when the residuals were non-normally distributed which is mandatory for multivariate regression models of this form. When the final models were completed, each empirical nutrient model was composed of a combination of the Landsat ETM+ bands. Each single band regression follows the formula shown below:

$$\text{Constituent} = \alpha_0 + \alpha_1 \times \text{Band}_1 + \ldots + \alpha_n \times \text{Band}_n + \varepsilon \quad (1)$$

where, Constituent is the response (dependent) variable such as total phosphorus, total nitrogen, and Secchi disk, Band_1, ..., Band_n represents the predictors (independent variables) such as individual multispectral bands of Landsat ETM+ data, α_1, ..., α_n represents the coefficient corresponding to each band, and ε is the error term of the linear relation between Constituent and the predictors, Band_1, ..., Band_n.

The optimal models were applied to the satellite imagery in a 2006 time series to present the spatial distribution of constituents in Missisquoi Bay.

2. Results

2.1. Remote sensing optimal models

The optimal model for each constituent and the model performances are shown in Table 1. The Secchi disk in the lake encompasses sediments, algae, and other particulates found in the water. The Secchi disk model included bands 3 and 7 with logarithmic transformation, resulting in adjusted R^2 of 0.80. The total phosphorus model was square root transformed to normalize the distribution of residuals. The regression model was composed of two bands: band 3 from the visible region and band 7 from the mid infrared region, resulting in an R^2 of 0.61. The total nitrogen model consisted of all bands except band 3 with an excellent adjusted R^2 of 0.77 and lower root mean square error compared to the total phosphorus model.

2.2. Validation

Both models for total phosphorus and total nitrogen were well calibrated using the 2006–2010 dataset and also were fairly accurate in terms of predicting the 2011 dataset. While both models have reasonable adjusted R^2 values, the large variability that exists in the calibration dataset (Fig. 2) should cause the validation data points to simulate the same variability. Given the spread of the data, the models captured the trends of data variation and none of the validation data points appeared to be extreme predictions. The results demonstrate the utility of remote sensing models to detect nutrients in lake waters.

2.3. Distribution of nutrients using satellite imagery

Fig. 3 shows the distribution of nutrients after applying the optimal models to the satellite imagery in a 2006 time series (July, August, and September). Missisquoi Bay had total phosphorus ranges from 0 to 0.1 mg/L, total nitrogen ranges from 0 to 1 mg/L, and most of the bay had a Secchi disk range of 0 to 1 m but ranges as far as 3 m. July image result showed high turbidity distributed throughout the bay and the total phosphorus and total nitrogen concentrations also showed similar patterns. August image result showed more

Table 1 – Statistical results of nutrient models.

Constituent parameter	Total phosphorus		Total nitrogen		Secchi disk	
	Coeff.	*p*-Value	Coeff.	*p*-Value	Coeff.	*p*-Value
Intercept	1.84	2.82e−02	0.11	1.82e−01	1.28	1.46e−06
b1	n/a	n/a	48	5.64e−04	n/a	n/a
b2	n/a	n/a	12	2.49e−02	n/a	n/a
b3	354	8.90e−06	n/a	n/a	−66.2	3.82e−05
b4	n/a	n/a	−25.1	7.88e−05	n/a	n/a
b5	n/a	n/a	−65.1	1.77e−03	n/a	n/a
b7	−444	4.49e−04	65.6	2.40e−02	55.4	4.84e−03
Model adj. R^2	0.61		0.77		0.80	
%RMSE	45.5		37.5		36.4	

Coeff.: coefficient of each parameter in the regression model; *p*-value: *p*-value of individual band; Adj. R^2: adjusted coefficient of determination; %RMSE: root mean square error in percentage, n/a: insignificant band information not used in the model.

concentrated turbidity in the upper right portion of the bay. Both total phosphorus and total nitrogen showed a similar highly concentrated cluster in the same part of the bay. September image results showed higher levels of turbidity towards the bottom of the bay and this was the area where the highest concentrations of total phosphorus were located. Total nitrogen was more evenly distributed in the September image result, although it was at high concentrations throughout the bay.

3. Discussion

3.1. *Model justifications*

Previous studies were consistent with our Secchi disk model by including band 3 and some also included band 7 (Duan et al., 2007, 2009; Hellweger et al., 2004; Kallio et al., 2008; Wang et al., 2006). Moore (1980) showed that high concentrations of particles would be best captured by Landsat's band 7. Lake Champlain is highly turbid which supports the use of this band information in the Secchi disk model.

The total phosphorus model result has the same band information as the Secchi disk regression model, implying that most of the phosphorus adhering to particulates in the water, represented as Secchi disk, can be captured by satellite remote sensing. Previous studies have tried to predict phosphorus concentrations through linear relationships between Secchi disk with excellent results (R^2 = 0.77), so it is reasonable that total phosphorus might share similar band information with Secchi disk (Wu et al., 2010). Suspended solid concentrations are also very closely related to total phosphorus (R^2 = 0.9) (Chen and Quan, 2012). Our result was comparable to the work by Song et al. (2006) that predicted total phosphorus concentrations in China using Landsat TM bands 1, 2 and 3 with reasonable R^2 values (R^2 = 0.65), using stepwise regression with limited statistical analysis.

Dewidar and Khedr (2001) found total nitrogen to have the strongest correlation with TM bands 1 and 2; the same was found in this study. Chen and Quan (2012) predicted total nitrogen concentrations with TM bands 1, 2, 3, and 4, however these results were not very successful (R^2 = 0.24). The Chen and Quan's (2012) study did not consider band 5 or 7 in their study, nor did they perform any statistical analysis to see if a different combination of TM bands would yield better results. They did find, however, that total nitrogen related to the suspended solid concentration and chlorophyll *a* concentrations (R^2 = 0.65). These studies show that nitrogen may need more band information than other water quality constituents, which is consistent with the results found in this study.

3.2. *Spatial distributions*

The optimal models applied to the satellite imagery allowed an analysis for the spatial distributions of the nutrients (Fig. 3). The Secchi disk distribution showed that the turbid areas of the lake, and therefore the areas where there were more particles in the water column, were related to the

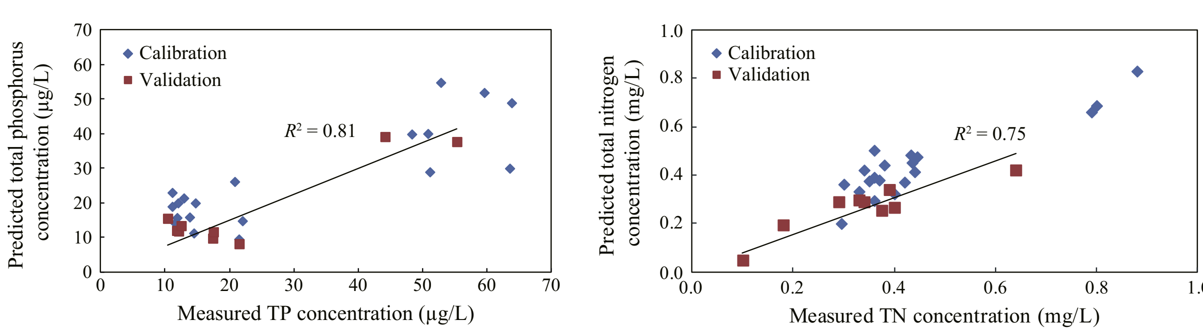

Fig. 2 – Validation of nutrient data models.

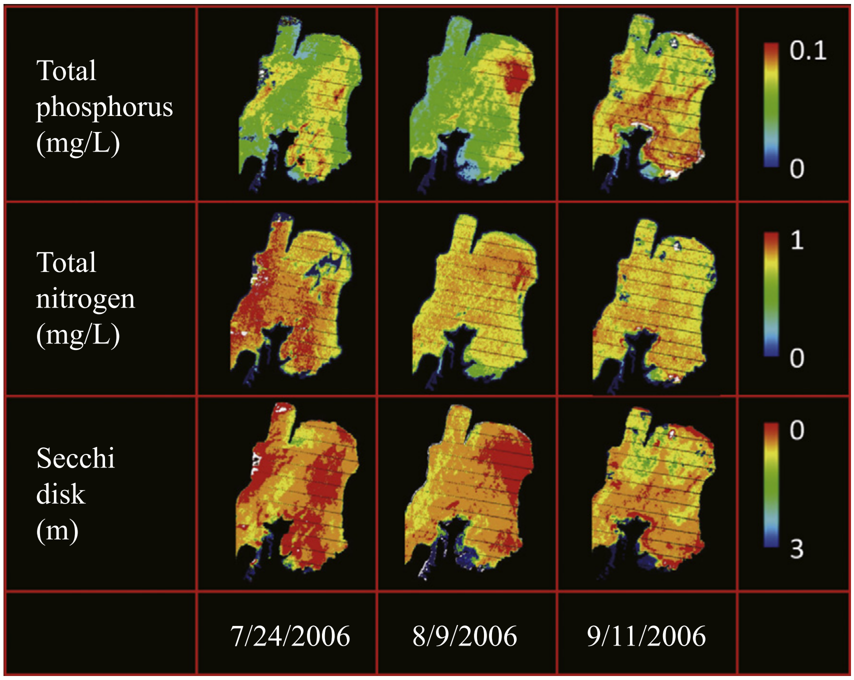

Fig. 3 – Total phosphorus, total nitrogen, and Secchi disk distributions in Missisquoi Bay in a 2006 summer time series.

areas with the highest phosphorus concentrations. The nitrogen distributions did not line up spatially with any of the other models as clearly as the phosphorus models did. However, the higher concentrations of total nitrogen corresponded to the highest areas for Secchi disk and total phosphorus. Previous studies have shown a relationship between total phosphorus and total nitrogen (Dewidar and Khedr, 2001). The range of total phosphorus is much wider than the range of the total nitrogen concentrations. This result highlights the importance of total phosphorus to the system compared to total nitrogen since nitrogen is approximately uniformly distributed. These color maps demonstrate the benefits of using remote sensing models to gain insight into nutrient concentrations and distributions in a water system.

3.3. *Effects of precipitation*

Since urban and agricultural runoffs are a significant contribution to the eutrophication problem in Lake Champlain, precipitation data was gathered from Phillipsburg Station near Missisquoi Bay to investigate the effects of rainfall compared to the nutrient concentrations. Two days before the July Landsat image was taken, a large precipitation event occurred (12 mm) resulting in high concentrations of phosphorus and nitrogen as well as low Secchi disk graph representing high turbidity. Nine days before the August image was taken, an even bigger rain event (23 mm) occurred and a small rainfall event (2 mm) occurred the day before the image was taken. The results shown in the image are most likely continuing effects of the major rainfall event. Two rainfall events 2 and 3 days (4 mm) before the September image was taken could contribute to the high concentrations at the southern part of the bay. These results demonstrate the potential impact of precipitation on the eutrophication in the water.

3.4. *Broader implications*

While this is an empirical model created for predicting nutrient water quality constituents in Lake Champlain, a similar approach can be employed in other freshwater systems. Most statistical remote sensing models are site-specific due to the unique properties of a given water body. However, the methods used in this study could be applied to a different freshwater system with recalibration (Cracknell et al., 2001). The Landsat band ranges that were the most significant in this study can be the most significant for nutrient predictions in other eutrophic lakes, and model coefficients will need to be adjusted for more accurate results in a new area. Eventually, this study can offer the feasibility of the application of statistical remote sensing models to deriving standard products of nutrients in freshwater systems.

4. Conclusions

This study primarily focused on the investigation of nutrient distributions in Lake Champlain, specifically Missisquoi Bay using satellite remote sensing. Remote sensing models were developed for total phosphorus and total nitrogen, and were compared to Secchi disk models. The resulting models show the relationship between particulates represented as Secchi disk and nutrients, especially phosphorus.

This study has expanded the research capability of the Landsat satellite imagery and shown the feasibility of being able to monitor and develop models for data with non-optical properties, such as nutrient data. This study was still able to provide a reasonable fit for total phosphorus and total nitrogen (R^2 = 0.81 and 0.75, respectively). Not many previous studies have been able to provide both total phosphorus and total nitrogen models with statistically significant results or reasonable adjusted R^2 values.

These models are useful for monitoring nutrient distributions in Lake Champlain, which can lead to a better understanding of eutrophication and their interaction with other water problems. This process can be applicable to other freshwater systems and to develop standard products that could contribute to the mitigation of excess nutrient concentration by implementing Best Management Practices or other reduction techniques. The recently launched Landsat satellite imagery will provide information to give a greater capability of monitoring and modeling these nutrients in the future with potentially more accuracy.

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