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Developing Landsat Based Algorithms To Augment In Situ Monitoring Of Freshwater Lakes And Reservoirs

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DEVELOPING LANDSAT BASED ALGORITHMS TO AUGMENT IN SITU MONITORING OF FRESHWATER LAKES AND RESERVOIRS

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Lakes and reservoirs often lack adequate water quality monitoring programs. With little information on the state of these systems, managing them and their contributing watersheds becomes a challenge. The use of remote sensing presents an opportunity to better characterize these freshwater systems and abate this challenge. The full potential of using the Landsat program to measure optically active water quality parameters, such as chlorophyll-a, suspended sediments, water clarity, and water temperature was explored using the Qaraoun Reservoir in Lebanon as a pilot study. An in situ monitoring program was developed and synchronized with the overpass of both the Landsat 7 and the newly launched Landsat 8 satellites in an effort to develop, calibrate, and validate empirical relationships that link water quality parameters with sensor radiances. Field data revealed that the reservoir was hypereutrophic, with median summer chlorophyll-a concentrations exceeding 70 ug/L. The generated models showed promise in capturing the state of the reservoir, with some differences between the models developed for Landsat 7 and 8 which are expected to affect the transferability of developed algorithms and the blending of data from both satellites. Yet, the results highlight the importance of using Landsat data as part of future monitoring activities as well as for hindcasting surface water quality, both required to track temporal changes in the system.

INTRODUCTION

Water quality of freshwater systems in most developing countries is poorly characterized due to lack of adequate monitoring data. The costs and technical requirements needed to develop, operate, and maintain a traditional in situ monitoring program have invariably limited their adoption, leaving many important freshwater systems with little to no data to guide mitigation and management plans. Remote monitoring programs may provide an important means for data acquisition in these cases, particularly as several satellite programs have started offering free open access to their imagery. In this context, NASA's Landsat Satellite program is the longest serving program with a focus on environmental applications. It has been successfully used to monitor water quality in inland water bodies [1], [2]. Currently Landsat 7 and 8 are in operation; the former has the Enhanced Thematic Mapper Plus (ETM +) sensor that is capable of measuring reflectance at 8 spectral bands, while the latter has the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS) that provide data across 11 bands. In this paper, we assess the suitability of using the sensors on Landsat 7 and 8 to monitor the water quality of hypereutrophic small reservoirs, using the Qaraoun Reservoir in Lebanon as a pilot study.

Statistical algorithms are developed to predict chlorophyll a, suspended sediments (TSS), and secchi disk depth (SDD) to the optical properties of the water in the visible and near infrared (NIR) regions of the electromagnetic spectrum. Satellite specific models are explored and compared to models developed by pooling data from both satellites.

STUDY SITE

The Qaraoun Reservoir in the eastern Mediterranean is located in Lebanon's Bekaa valley. It is the largest freshwater body in the country, with a useable water volume of 220 MCM. The climate of the area is typical Mediterranean, with hot, dry summers and relatively cold, wet winters. As such, snowmelt from the surrounding mountains plays an important role in recharging the reservoir. The reservoir was constructed in 1959 for the purpose of generating hydroelectric power and irrigating approximately 68,000 acres of farmland. Water quality in the reservoir remains a serious concern given that the upper Litani River, which drains into the reservoir, is known to be highly polluted due to discharge of untreated domestic and industrial wastewater as well as agricultural-irrigation water return. Large-scale eutrophication problems have been recorded previously in the reservoir [3–5].

METHODS

Nine sampling stations were seleted on the Qaraoun Lake (Figure 1) to capture spatial patterns within the reservoir. At each station, temperature and secchi disk depth were measured in the field and a water sample was collected and analyzed for chlorophyll-A and TSS using standard methods 10200H 2540D, respectively [6]. In situ sampling extended between July 4and November 17, 2013, with a bimonthly sampling frequency. All sampling campaigns were synchronized with the overpass of either the Landsat 7 (three images) or the Landsat 8 (four images) satellite. Sampling was restricted to relatively clear days, with minimal cloud cover to guarantee minimal atmospheric noise when retrieving satellite data.

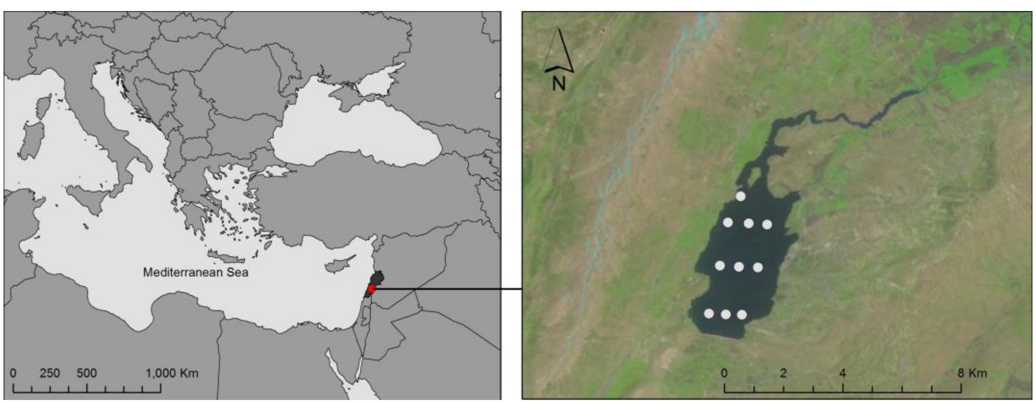

Figure 1. Sampling stations on the Qaraoun Reservoir

Landsat 7 and 8 images were downloaded from the US Geological Services (http://earthexplorer.usgs.gov/). Both satellites have sensors that measure reflectance across multiple spectral bands that have been used to assess water quality in water bodies. Images were processed within the software R [7] using the Landsat Package [8]. Downloaded image digital numbers were first converted to radiances before generating reflectance grids for each sampling date across all bands. Landsat 7 images were corrected for the failure of the Scan Line Corrector on the sensor by using provided gap masks. Additionally, land mask layers were developed using the histogram splicing method to trace the outline of the reservoir over time and remove contamination with land pixels. For each in situ sampling location, corresponding reflectance values were extracted by averaging the values of the pixels located within a 60 m window centered around the sampling station to ensure spatio-temporal matching between the in situ program and satellite-based monitoring. Different regression based algorithms were tested before undergoing local calibration using the in situ data.

RESULTS

The chlorophyll-a concentrations in the reservoir ranged from 21 to 414 µg/L over the sampling period. The highest levels were observed in July and October. The latter is likely to have occurred following lake turnover. Suspended sediment concentrations ranged from 2-69 mg/L, with the concentrations following the same temporal distribution as chlorophyll-A. SDD ranged from 0.2-1.8 m over the sampling period. All three water quality parameters highlighted the hypereutrophic status of the Reservoir; a direct consequence of excessive nutrient loading from the upper Litani River that discharges into the reservoir.

Regression based algorithms that make use of Landsat's most sensitive bands with respect to capturing the spectral signatures of chlorophyll-A, SDD, and TSS were initially selected. As such, the chlorophyll-A algorithm made use of the NIR/Red ratio, which is reportedly effective in regional lakes with high chlorophyll-A concentrations [9–12]. For TSS, algorithms that were based on the Red band were commonly reported in the literature and as such were chosen [10; 13–15]. Similarly, algorithms that made use of the Blue/Red ratio were selected as they have shown to be effective in describing SDD [16–18].

The functional form of the selected algorithms were adopted and regionalized to fit the in situ data collected from the Qaraoun Reservoir. The NIR/Red ratio based chlorophyll-A algorithm performed poorly with Landsat 7; yet the algorithm worked reasonably well with Landsat 8 (Table 1). These differences can be attributed to dissimilar band spacings in the two satellite sensors, with the two Landsat sensors capturing slightly different features of the chlorophyll-A spectral signatures. Landsat 8 seems to be more capable of characterizing the chlorophyll fluorescence peak in the Red to NIR boundary as compared to Landsat 7. As such, pooling the results from both satellites together before calibration resulted in a model that was dominated by the Landsat 8 algorithm.

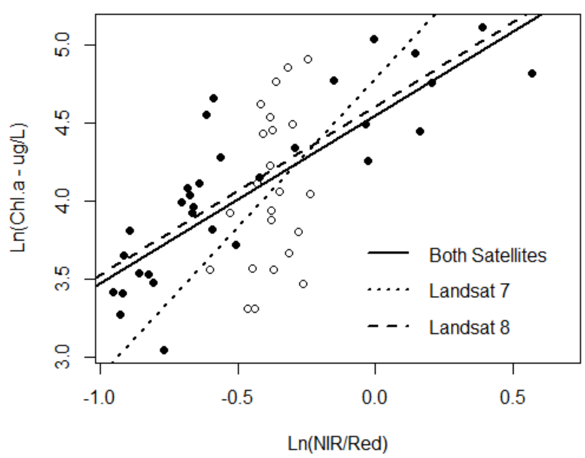

Figure 1. NIR/Red algorithm as related to in situ chlorophyll A concentrations. Open circles represent Landsat 7 data points. Closed circles represent Landsat 8.

Table 1. Developed satellite-based algorithms used to test water quality in Qaraoun Reservoir

			Fit metrics		
Parameter	Landsat	Model	F	P	R^2
Chlorophyll-A	7+8	ln(Chl.a) = 4.6 + 1.1 ln(NIR/Red)	$F_{1,52} = 44.2$	$1.8e^{-8}$	0.46
	7	ln(Chl.a) = 4.8 + 1.9 ln(NIR/Red)	$F_{1,21} = 2.7$	0.12	0.11
	8	ln(Chl.a) = 4.6 + 1.2 ln(NIR/Red)	$F_{1,29} = 66.6$	$5.3e^{-9}$	0.70
TSS	7+8	ln(TSS) = 0.4 + 36.6 Red	$F_{1,56} = 48.7$	$3.8e^{-9}$	0.47
	7	ln(TSS) = -0.3 + 49.5 Red	$F_{1,23} = 29.3$	$1.7e^{-5}$	0.56
	8	ln(TSS) = 0.9 + 29.3 Red	$F_{1,31} = 16.3$	0.0003	0.34
SDD	7+8	SDD = 0.4 + 1.0 ln(Blue/Red)	$F_{1,57} = 34.9$	$2.0e^{-7}$	0.38
	7	SDD = -1.3 + 2.7 ln(Blue/Red)	$F_{1,23} = 102.2$	$6.2e\text{-}^{-10}$	0.82
	8	SDD = 0.2 + 1.4 ln(Blue/Red)	$F_{1,32} = 28.5$	$7.4e\text{-}^{6}$	0.47

The Red-based algorithm used to predict TSS levels showed some inter-satellite differences. Landsat 7 based models proved to be more accurate. As such, the pooled model proved to be closer to the Landsat 7 model as compare to the Landsat 8 based model. SDD predictions varied significantly between the two satellite sensors. Landsat 8 exhibited a low skill in accurately predicting the water clarity in the reservoir. On the other hand, the Landsat 7 based model showed more promising predictive capabilities with an R^2 of 0.82.

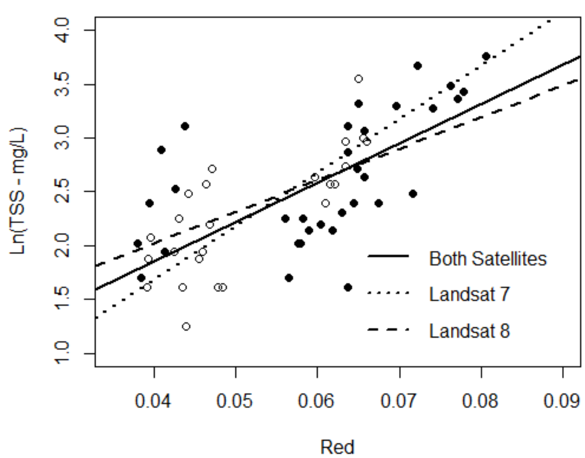

Figure 2. Red algorithms as related to in situ TSS concentrations. Open circles represent Landsat 7 data points. Closed circles represent Landsat 8.

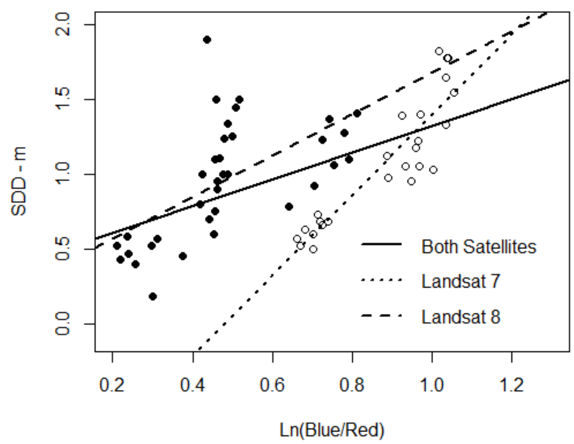

Figure 3. Blue/Red algorithms as related to in situ SDD. Open circles represent Landsat 7 data points. Closed circles represent Landsat 8.

CONCLUSION

While the model results are encouraging and underscore the great potential of using Landsat to monitor inland lakes and reservoirs in developing countries and remote areas, where in situ monitoring is often unfeasible, it is evident the two satellites vary in their predictive powers across the assessed water quality indices even though they share common spectral characteristics. These findings underscore a limitation with the seamless transferability of algorithms between the two Landsat satellites and emphasize the need to develop satellite specific algorithms.

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