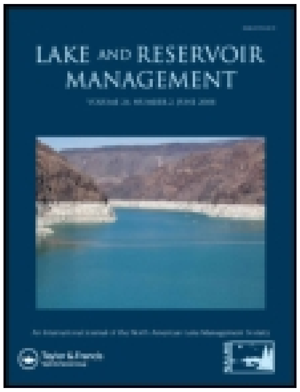

Lake and Reservoir Management
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/ulrm20

Lakes without Landsat? An alternative approach to remote lake monitoring with MODIS 250 m imagery

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To cite this article: Ian M. McCullough , Cynthia S. Loftin & Steven A. Sader (2013): Lakes without Landsat? An alternative approach to remote lake monitoring with MODIS 250 m imagery, Lake and Reservoir Management, 29:2, 89-98

To link to this article: http://dx.doi.org/10.1080/10402381.2013.778926

Lake and Reservoir Management, 29:89–98, 2013
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ISSN: 1040-2381 print / 2151-5530 online
DOI: 10.1080/10402381.2013.778926

Lakes without Landsat? An alternative approach to remote lake monitoring with MODIS 250 m imagery

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Abstract

McCullough IM, Loftin CS, Sader SA. 2013. Lakes without Landsat? An alternative approach to remote lake monitoring with MODIS 250 m imagery. Lake Reserv Manage. 29:89–98.

We evaluated use of MODIS 250 m imagery for remote lake monitoring in Maine. Despite limited spectral resolution (visible red and near infrared bands), the twice daily image capture has a potential advantage over conventionally used, often cloudy Landsat imagery (16 day interval) when short time windows are of interest. We analyzed 364 eligible ($\geq$100 ha) Maine lakes during late summer (Aug–early Sep) 2000–2011. The red band was strongly correlated with natural log-transformed Secchi depth (SD), and the addition of ancillary lake and watershed variables explained some variability in ln(SD) ($R^2 = 0.68$–0.85; 9 models). Weak spectral resolution and variable lake conditions limited accurate lake monitoring to relatively productive periods in late summer, as indicated by inconsistent, sometimes weak regressions during June and July when lakes were clearer and less stable ($R^2 = 0.19$–0.74; 8 models). Additionally, SD estimates derived from 2 sets of concurrent MODIS and Landsat imagery generally did not agree unless Landsat imagery (30 m) was resampled to 250 m, likely owing to various factors related to scale. Average MODIS estimates exceeded those of Landsat by 0.35 and 0.49 m on the 2 dates. Overall, MODIS 250 m imagery are potentially useful for remote lake monitoring during productive periods when Landsat data are unavailable; however, analyses must occur when algal communities are stable and well-developed, are biased toward large lakes, may overestimate SD, and accuracy may be unreliable without non-spectral lake predictors.

Key words: Landsat, Maine, MODIS, remote monitoring, scale, Secchi, water clarity

Satellite-based remote sensing is an effective, efficient approach for routine assessment of regional lake water quality (Chipman et al. 2009). Remote assessments can alleviate potential spatial biases of field sampling programs by delivering complete, regional snapshots. Image archives permit comprehensive historical analyses. Field data from existing monitoring programs (e.g., state, citizen volunteer) can be used to calibrate remote lake clarity estimation models with linear regression (Kloiber et al. 2002a, Chipman et al. 2004, Olmanson et al. 2008, McCullough et al. 2012a).

Remote monitoring of regional lake clarity has relied primarily on Landsat data, which includes advantages of free access, moderate 30 m resolution, and a 40 year archive. Although 2 Landsat satellites (Landsat 5 and 7) currently operate, their reliability has recently declined. The primary sensor (Thematic Mapper) aboard Landsat 5 was lost in 2011, and the satellite is near termination. Landsat 7 imagery contains a 22% data loss owing to a 2003 mechanical failure, although it is usable for lake monitoring (Olmanson et al. 2008). The February 2013 launch of Landsat 8 (Landsat Data Continuity Mission) helps alleviate the loss of Landsat 5; however, additional methods for remote lake monitoring could provide an alternative that addresses inherent limitations of Landsat (e.g., 16 day interval, cloudiness).

Moderate-Resolution Imaging Spectroradiometer (MODIS) imagery offers a potential, low-cost solution. Although the coarse resolution (250, 500, and 1000 m) limits analyses to large lakes, 250 m imagery warrants evaluation given the restriction of MODIS 500 and 1000 m imagery to lakes $\geq$400 ha (Chipman et al. 2009) and 1000 ha (Olmanson et al.

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2011), respectively. MODIS 250 m imagery has not been widely used for regional lake monitoring (Koponen et al. 2004, Olmanson et al. 2011), likely because it contains only one band (visible red) strongly correlated with Secchi depth (SD). Olmanson et al. (2011) produced relatively weak R^2 (0.65) in models using the 250 m red band. In previous work, we found that including landscape-scale drivers of SD considerably improves accuracy of SD estimates derived from Landsat data; average lake depth and the proportion of lake watersheds covered by wetlands are significant predictors of SD in Maine lakes (McCullough et al. 2012a). Our objectives were to examine the utility of MODIS 250 m imagery to estimate lake SD and to determine if additional variability in SD explained by ancillary lake and landscape variables sufficiently improves MODIS-based predictions. We analyzed MODIS 250 m imagery captured during June to early September 2000–2011 to test the applicability of our methods throughout late spring and summer and compared results to available, concurrent Landsat-derived SD data from 2000 and 2011.

Study site

Located in the northeastern United States, Maine has more than 5500 lakes >1 ha in surface area distributed across approximately 90,000 km^2. Maine ranks first among states east of the Great Lakes in total area of inland surface waters (Davis et al. 1978), and 26% of the state is covered by wetlands (Tiner 1998). Average annual SD consistently has remained 4–6 m, with a historical average of 5.28 m during 1970–2011, and was 5.46 m in 2011 (n = 367 lakes; MDEP 2012, VLMP 2012).

Materials and methods

MODIS image selection

We selected Level 1B MODIS 250 m surface reflectance imagery from Terra (MOD09) and Aqua (MYD09) satellites captured during 2000–2011. These image products can be downloaded free of charge from the US Geological Survey Global Visualization Viewer (http://glovis.usgs.gov/). We selected 10 images (scenes 13:4, 12:4) captured during August and early September 2000–2011 based on clear image availability. The late summer period captures peak algal abundance in lakes and stability prior to destratification and is ideal for lake water quality change assessment (Stadelmann et al. 2001). Clear imagery was available in each year except 2003 and 2006 (we attempted to use marginally clear imagery in these years unsuccessfully). We selected 8 additional clear images (4 in June, 4 in July) to compare use of MODIS 250 m imagery during early and midsummer 2000–2011.

Image processing

MOD09 (and MYD09) image products arrive preconverted to surface reflectance, which theoretically estimates earth surface conditions independent of atmospheric interference (NASA 2010). Although these corrections are intended for analysis of land features, we previously found MODIS 500 m surface reflectance imagery produces accurate lake SD estimates (McCullough et al. 2012b). Despite twice-daily temporal resolution and the atmospheric corrections of MODIS 250 m imagery, our focus on late summer (to capture peak algal growth) necessitated using imagery containing some clouds. We used unsupervised classification (ISODATA clustering) to identify cloud pixels for removal. Lakes including pixels affected by cloud shadows were manually identified and removed if necessary.

Ancillary lake data

We included average lake depth (ft) and the proportion of wetland coverage in lake watersheds (hereafter, wetland/watershed ratio) in our models because these variables are strong predictors of SD in Maine lakes based on analyses of Landsat (McCullough et al. 2012a) and MODIS 500 m imagery (McCullough et al. 2012b); however, other ancillary variables may better predict SD in other regions. Wetlands are a source of colored dissolved organic matter, which negatively affects water clarity, and these effects can be represented adequately on a landscape scale with the wetland/watershed ratio (Detenbeck et al. 1993). We acquired bathymetric data (MDEP 2012) and a watershed boundary geographic information system (GIS) layer (MDEP 2011) from MDEP. We calculated the wetland/watershed ratio with the watershed layer and an updated National Wetlands Inventory dataset (Houston 2008). Only one lake in our dataset was missing ancillary data (wetland/watershed ratio).

Lake eligibility determination

Although Kloiber et al. (2002b) recommended using no fewer than 9 pixels in Landsat analyses, we found that 3–5 contiguous, water-only MODIS pixels adequately balanced accurate characterization of lake surfaces with maximization of the number of lakes suitable for remote monitoring. We successfully used 3–5 pixels for lake clarity estimation in our previous study of MODIS 500 m imagery (McCullough et al. 2012b). We determined that 364 Maine lakes contained sufficient water-only pixels for remote monitoring with 250 m imagery (Fig.1a), constituting 73% of Maine lakes ≥100 ha; however, 2 lakes >500 ha with particularly convoluted shorelines lacked the necessary water-only pixels. Therefore, size does not fully determine lake eligibility for remote monitoring because large lakes may contain complex shorelines that potentially cause spectral interference.

Satellite data extraction and model development

We digitized field Secchi sampling locations delineated on bathymetric maps (available online: http://www.lakesofmaine.org/) into a remote sampling site GIS layer. We created 457 remote sample stations for the 364 eligible lakes; some larger lakes with multiple basins contained more than one sample station. We created 250 m buffers around each station from which we extracted averages of the 3–5 contained pixels with zonal statistics. These averages were then compared to natural log-transformed, field-collected SD and ancillary lake data with forward stepwise regression. The red band variable was included first because it explained the most variability in ln(SD).

Generally, we included SD measurements collected within 1–3 days of satellite overpass; however, we used data collected within 7 days in one model owing to enhanced model fit. Time windows of up to 7 days yield reasonably accurate SD predictions owing to relative lake stability during late summer, although shorter time windows are preferable (Kloiber et al. 2002b). Variance inflation factors (VIF), a measure of potential multicollinearity among predictor variables, were calculated for each regression. VIF values >10 indicate considerable multicollinearity (Kutner et al. 2005). We validated regression models with random subsets (25%) of calibration datasets containing >50 data entries by comparing predicted residual sum of squares (PRESS) statistics to sum of squared errors (SSE) of regressions. We used leave-one-out jackknifing for models containing <50 calibration points.

Comparison to concurrent Landsat imagery

Analysis of concurrent Landsat imagery followed the same methods described for MODIS imagery with a few notable exceptions. We included all eligible lakes ≥8 ha located in Landsat path 12, rows 27–30 (Fig. 1b) and used calibration windows of only ±1 day owing to the larger set of lakes. We excluded wetland/watershed ratio area from Landsat models because it is not a strong predictor of SD in Maine lakes encompassed by Landsat path 12 owing to the relative lack of wetlands in rugged western Maine (path 12) compared to coastal, flat eastern Maine (path 11; McCullough et al. 2012a). The larger number of lakes and finer scale of Landsat analyses allow us to make this distinction, whereas a single

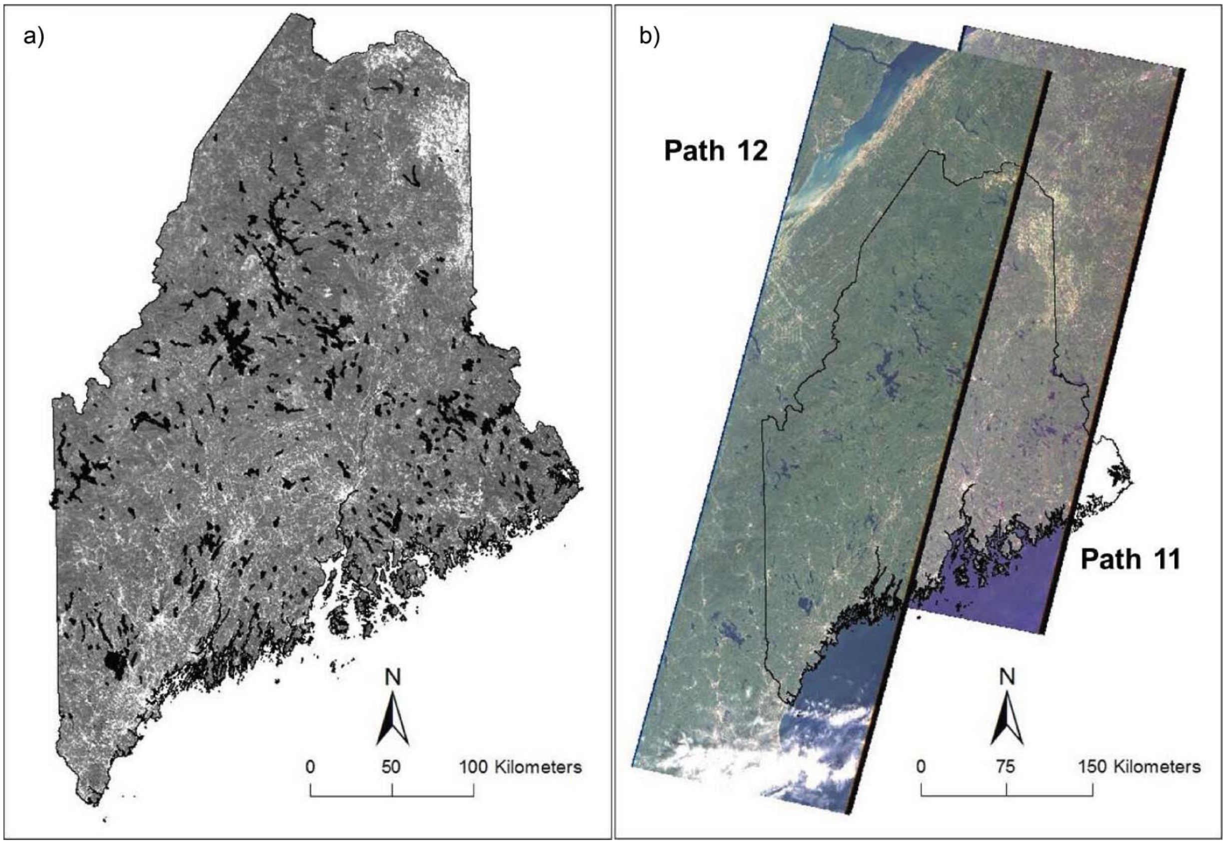

Figure 1.-(a) 364 lakes (highlighted in black) are eligible for remote monitoring with MODIS 250 m imagery in Maine. This image was captured by the Terra satellite on 27 Aug 2008. (b) Landsat paths 11 and 12 over Maine. Respective images were captured on 9 Aug 2002 and 1 Sept 1999. A combined 1511 Maine lakes ≥8 ha in both paths can be assessed with Landsat imagery. Landsat path 12 contains 214 of the 364 lakes eligible for assessment with MODIS 250 m imagery (color figure available online).

approach in large-scale MODIS analyses is more appropriate. We performed radiometric normalization to account for potential effects of haze (Rayleigh scatter) because Landsat imagery is not atmospherically corrected.

We assessed differences between remotely estimated SD predictions from concurrent Landsat and MODIS imagery captured on 2 dates (26 August 2000 and 17 August 2011) with paired t-tests ($\alpha = 0.05$). Landsat path 12 contains 214 (57%) of the 364 MODIS-eligible lakes in Maine. We had the option of comparing MODIS and Landsat images captured 2–3 days apart; however, we did not wish to introduce unnecessary error associated with changing lake conditions that could confound potential satellite disagreement, despite relative lake stability during late summer. Although this seems contradictory to our use of model calibration windows up to 7 days long, even a 1 day difference in image capture date between Landsat and MODIS 500 m imagery can create significant differences between SD estimates (McCullough et al. 2012b).

Results

Regression results and estimated statewide lake clarity

We found strong regression relationships ($R^2 = 0.68$–0.85) among ln(SD), the MODIS 250 m red band, average lake depth, and wetland/watershed ratio (Table 1). The red band and wetland/watershed ratio were consistently negatively correlated and average depth was consistently positively correlated with ln(SD) (Table 1, Fig. 2). These findings are consistent with our previous studies of Maine lakes using Landsat (McCullough et al. 2012a) and MODIS 500 m imagery (McCullough et al. 2012b). Predictive capacities (r^2) of the red band alone ranged from 0.54 to 0.68; the inclusion of ancillary data considerably improved model fit (Table 1, Fig. 2). We also eliminated images captured 25 August 2004, which although of sufficient quality, lacked a balanced numeric distribution of concurrent field calibration data; the calibration dataset consisted disproportionately of lakes with shallow SD values. Consequently, SD estimates were unrealistic under-predictions.

A wide distribution of field Secchi values is necessary for strong fit of remote lake clarity estimation models (Nelson et al. 2003). Based on the remaining 9 late summer regression models, average statewide SD mostly remained between 5 and 6 m during 2000–2011 (Table 2). The exception was 1 August 2001 on which the average statewide SD was 6.47 m and unrepresentative of late summer lake conditions. Sample size was consistent at approximately 440 lake stations, with the exception of 2005, when clouds obscured parts of Maine. Variance inflation factors were approximately 1.5 or less for all regressions.

Early and midsummer analysis

Regression results were inconsistent during June and July. The R^2 values for full models (including ancillary data) ranged from 0.44 to 0.69 in June and 0.19 to 0.74 in July (Table 3). The r^2 values of the red band only ranged from 0.02 to 0.29 in June and 0.04 to 0.51 in July, evidence that the red band alone is insufficient for remote lake monitoring in Maine during June and July. The contribution of ancillary data brought full model R^2 within the range of late summer ($R^2 = 0.68$–0.84) on just 3 of 8 dates (Table 3).

Concurrent Landsat - MODIS comparison

We found mixed results in our comparison of remotely estimated SD from concurrent Landsat and MODIS models for 26 August 2000 and 17 August 2011 (Table 4). We initially found significant disagreement between Landsat and MODIS-derived SD in 2000 ($t = -6.318$, $df = 273$, $p < 0.001$) and 2011 ($t = -5.296$, $df = 277$, $p < 0.001$); however, we discovered that the unsupervised classification failed to detect sparse fog over large lakes in 2011. Upon removal of affected lakes, we obtained strong agreement between Landsat and MODIS ($t = 0.689$, $df = 209$, $p = 0.492$; Table 5).

The 2000 Landsat image contained little fog, and we speculated that differences in SD estimates might be attributable to scale. We resampled the Landsat red band (30 m) to 250 m, refit the Landsat model (Table 5), and subsequently obtained strong agreement ($t = -0.370$, $df = 283$, $p = 0.713$). We also resampled the 2011 Landsat imagery to test the scale hypothesis further and found similarly strong agreement ($t = 0.207$, $df = 277$, $p = 0.837$), despite presence of fog.

Discussion

Scale as a source of MODIS-Landsat disagreement

We attribute disagreement between MODIS and Landsat-derived SD predictions largely to scale-related factors, as evidenced by the results of resampling Landsat data to 250 m (Table 4). Effects of fog or small algal blooms may be averaged over a 250 m pixel and may therefore be difficult to detect at the larger scale. We encountered fog in the 2011 Landsat image, particularly over large lakes, demonstrating a potential "lake effect"; however, fog was undetectable in the concurrent MODIS image (Fig. 3). Similar to fog, algal blooms do not necessarily occur at scales detectable at 250 m resolution. Consequently, MODIS may overpredict SD under certain lake conditions, such as those we suspect occurred in 2000.

Resampling the mostly fog-free 2000 Landsat image to 250 m reduced disagreement between Landsat and MODIS average statewide SD from 0.34 to 0.02 m (Table 4). We

Table 1.-Remote lake clarity estimation models using MODIS 250 m imagery. SD = Secchi depth (m), Red = visible red band, AvgDepth = average lake depth (ft), Wetland = proportion of lake watershed covered by wetlands, ± Days = time from satellite overpass from which field data were used to calibrate models. No late summer imagery was available during 2003 and 2006. Insufficient field calibration data resulted in failure to use clear imagery captured 25 Aug 2004.

Date	Satellite	Model	R^2	RSE	± Days	N
26 Aug 2000	Terra	$\ln(SD) = -6.27\times10^{-3}$ (Red) $+ 9.85\times10^{-3}$ (AvgDepth) $- 4.07\times10^{-4}$ (Wetland) $+ 2.07$	0.82	0.25	3	72
1 Aug 2001	Terra	$\ln(SD) = -5.58\times10^{-3}$ (Red) $+ 1.35\times10^{-2}$ (AvgDepth) $- 4.19\times10^{-4}$ (Wetland) $+ 2.00$	0.85	0.19	3	65
31 Aug 2002	Terra	$\ln(SD) = -8.41\times10^{-3}$ (Red) $+ 5.78\times10^{-3}$ (AvgDepth) $- 4.97\times10^{-4}$ (Wetland) $+ 2.59$	0.77	0.31	3	51
7 Aug 2005	Terra	$\ln(SD) = -7.14\times10^{-3}$ (Red) $+ 2.75\times10^{-3}$ (AvgDepth) $- 3.61\times10^{-4}$ (Wetland) $+ 2.47$	0.79	0.22	3	50
29 Aug 2007	Terra	$\ln(SD) = -6.09\times10^{-3}$ (Red) $+ 2.09\times10^{-3}$ (AvgDepth) $- 4.01\times10^{-4}$ (Wetland) $+ 2.42$	0.68	0.28	7	102
27 Aug 2008	Terra	$\ln(SD) = -8.34\times10^{-3}$ (Red) $+ 9.97\times10^{-4}$ (AvgDepth) $- 3.98\times10^{-4}$ (Wetland) $+ 2.49$	0.78	0.21	3	56
1 Sep 2009	Terra	$\ln(SD) = -7.95\times10^{-3}$ (Red) $+ 8.72\times10^{-4}$ (AvgDepth) $- 5.54\times10^{-4}$ (Wetland) $+ 2.60$	0.84	0.20	3	61
19 Aug 2010	Terra	$\ln(SD) = -9.19\times10^{-3}$ (Red) $+ 6.25\times10^{-3}$ (AvgDepth) $- 1.59\times10^{-4}$ (Wetland) $+ 2.48$	0.79	0.24	3	60
17 Aug 2011	Aqua	$\ln(SD) = -7.59\times10^{-3}$ (Red) $+ 1.37\times10^{-3}$ (AvgDepth) $- 2.01\times10^{-4}$ (Wetland) $+ 2.39$	0.69	0.25	1	39

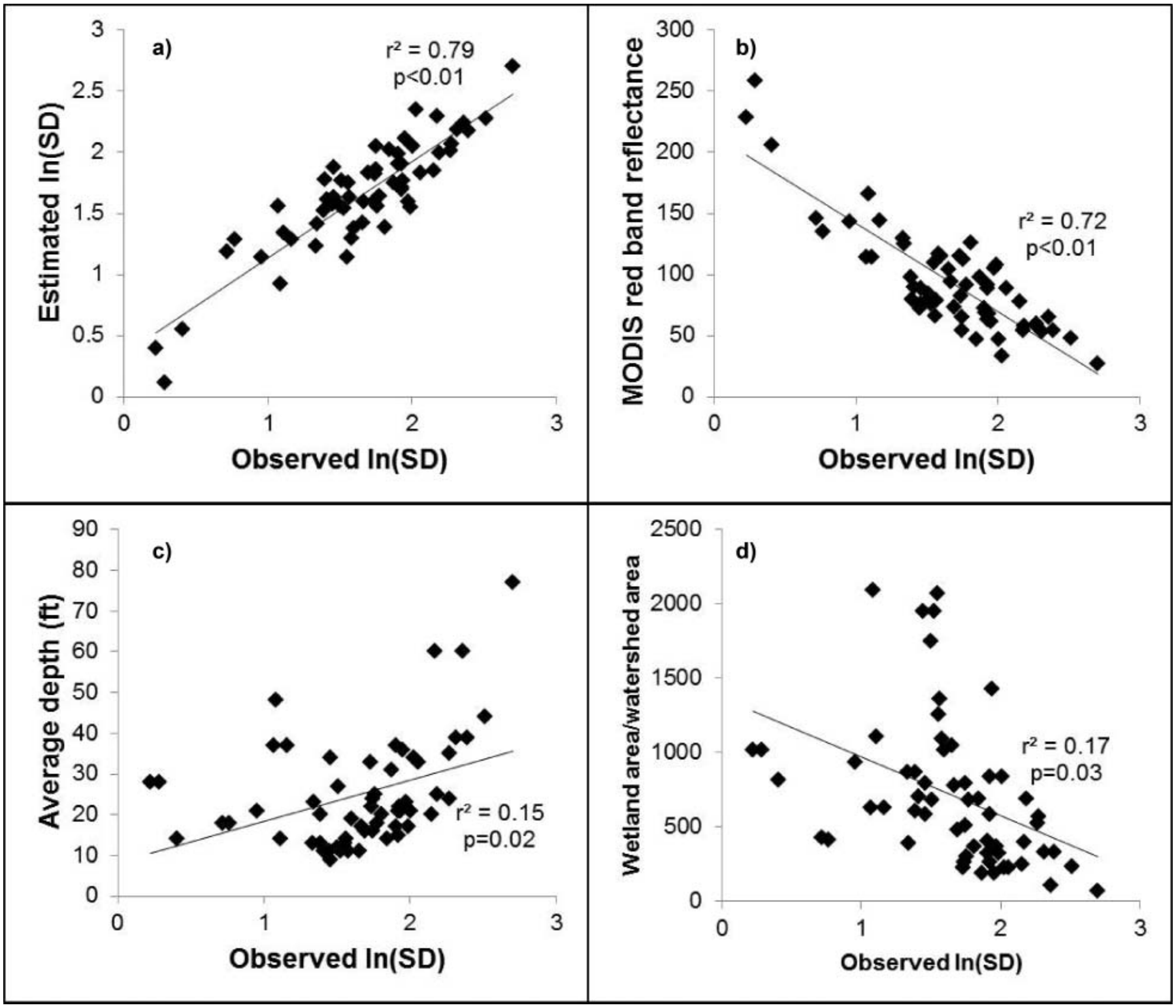

Figure 2.-(a) regression relationships of observed ln(SD) vs. full model-estimated ln(SD), b-d) Respective correlations between observed ln(SD) and MODIS 250 m red band reflectance, average lake depth (ft), and wetland area (m^2) per watershed area (m^2). All scatter plots are based on the regression for 19 Aug 2010 (Table 1). SD = Secchi depth (m).

initially were surprised to encounter disagreement between MODIS and Landsat-derived SD predictions, given that previously we found strong agreement between 4 concurrent Landsat and MODIS 500 m images (McCullough et al. 2012b); however, we believe that smaller sample size ($n \leq 81$ lake stations) and absence of fog and small patches of algae in these 4 images produced statistically similar SD predictions.

Table 2.-Descriptive statistics of statewide Secchi depth (m) of Maine lakes during 2000–2011 based on available MODIS 250 m imagery during late summer.

	26 Aug 2000	1 Aug 2001	31 Aug 2002	7 Aug 2005	29 Aug 2007	27 Aug 2008	1 Sep 2009	19 Aug 2010	17 Aug 2011
Average	5.24	6.47	5.56	5.84	5.62	5.02	5.14	5.84	5.60
Median	5.07	5.91	5.17	5.80	5.62	5.06	5.16	5.62	5.51
Max	14.80	17.98	15.67	12.04	10.82	10.03	10.44	15.60	12.51
Min	0.66	0.58	0.42	1.01	0.81	0.46	0.40	1.07	1.05
n	448	466	442	305	446	447	437	441	425

Table 3.-Early and mid-summer remote lake clarity estimation models using MODIS 250 m imagery. Full models include ancillary variables (average lake depth, wetland/watershed ratio). Response variables = ln(SD) (SD = Secchi depth (m)). ± Days = time from satellite overpass from which field data were used to calibrate models.

Date	Satellite	Full Model R^2	Red Band R^2	± Days	N
5 Jun 2004	Terra	0.44	0.28	3	43
23 Jun 2005	Terra	0.51	0.02	3	81
15 Jun 2007	Terra	0.69	0.29	3	40
15 Jun 2010	Aqua	0.55	0.21	3	60
20 Jul 2001	Terra	0.74	0.51	3	55
7 Jul 2004	Aqua	0.74	0.50	3	46
3 Jul 2005	Terra	0.55	0.14	3	56
10 Jul 2011	Terra	0.19	0.04	3	63

Table 4.-Paired t-test comparison of Secchi depth (SD) estimates (m) from concurrent MODIS and Landsat remote lake clarity estimation models pre- and post-resampling of the Landsat red band. Landsat = Landsat-estimated statewide SD. MODIS = MODIS-estimated statewide SD. Sample size varied in 2011 owing to fog. Spatial extent of analyses was restricted to Landsat path 12.

Date	Landsat	MODIS	p value	N
Pre-resampling				
26 Aug 2000	5.23	5.57	<0.001	284
17 Aug 2011	5.46	5.89	<0.001	278
17 Aug 2011*	5.64	5.57	0.492	210
Post-resampling				
26 Aug 2000	5.55	5.57	0.713	284
17 Aug 2011	5.93	5.89	0.837	278

*excluding foggy lakes

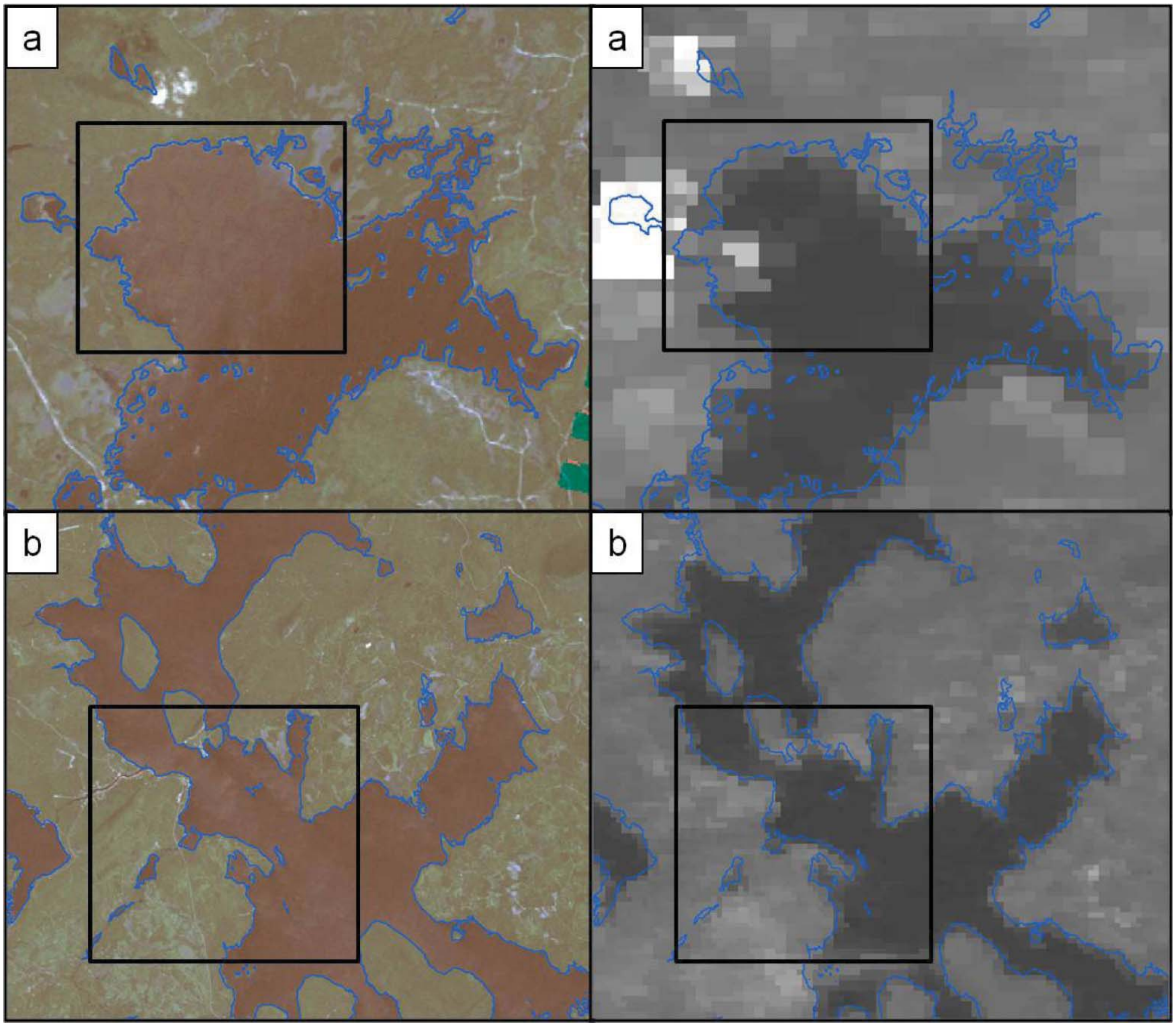

Figure 3.-Fog detected on 17 Aug 2011 Landsat imagery (left) over (a) Millinocket Lake and (b) Moosehead Lake is indiscernible from unaffected areas on concurrent MODIS 250 m imagery (Aqua satellite; right). Foggy areas are indicated by boxes. A drifting cloud that appeared between satellite overpasses is responsible for bright pixels over Millinocket Lake (color figure available online).

Table 5.-Comparison of concurrent MODIS and resampled Landsat remote lake clarity estimation models. SD = Secchi depth (m), Red = visible red band, AvgDepth = average lake depth (ft), Wetland = proportion of lake watershed covered by wetlands, Blue = visible blue band ± Days = time from satellite overpass from which field data were used to calibrate models.

Date	Satellite	Model	R^2	RSE	± Days	N
26 Aug 2000	Terra	$\ln(SD) = -6.27\times10^{-3}$ (Red) $+ 9.85\times10^{-3}$ (AvgDepth) $- 4.07\times10^{-4}$ (Wetland) $+ 2.07$	0.82	0.25	3	72
26 Aug 2000	Landsat 7	$\ln(SD) = -0.23$ (Red) $+ 3.37\times10^{-3}$ (AvgDepth) $+ 4.39$	0.67	0.26	1	34
17 Aug 2011	Aqua	$\ln(SD) = -7.59\times10^{-3}$ (Red) $+ 1.37\times10^{-3}$ (AvgDepth) $- 2.01\times10^{-4}$ (Wetland) $+ 2.39$	0.69	0.25	1	39
17 Aug 2011	Landsat 5	$\ln(SD) = 0.13$ (Blue) $- 0.37$ (Red) $+ 8.72\times10^{-3}$ (AvgDepth) $+ 5.17$	0.80	0.27	1	23

Applications and limitations

Seasonal application of MODIS 250 m imagery

MODIS 250 m imagery is primarily applicable for remote lake monitoring during late summer, whereas application in early to midsummer is unreliable owing to weak spectral resolution and instability of undeveloped lake algal communities. The timing of algal development varies among different lakes across the landscape during early to midsummer, which helps explain our inability to establish strong regressions during this season. Algal communities reach peak abundance during late July through early October in Maine lakes (Davis et al. 1978). Although peaks in primary productivity are relatively short and late-starting in Maine, other regions that experience considerable algal growth by early to midsummer may find MODIS 250 m imagery useful during this period.

Maine's lakes are relatively clear and generate relatively weak spectral responses compared to more productive lakes (McCullough et al. 2012a) that MODIS 250 m imagery might be able to monitor more effectively. Average SD in Minnesota lakes during 1985–2005 was 2.25 m (Olmanson et al. 2008), whereas average Maine SD has never been <4 m. Applicability of 250 m data may also increase in the future in the midst of a warming climate and lengthening growing seasons.

MODIS 250 m imagery as a regional assessment tool

MODIS 250 m data may not be an ideal assessment tool for regional water quality monitoring owing to its inherent bias toward large lakes ($\geq$100 ha). Landsat imagery, despite its smaller geographic extent, gathers a larger sample of lakes that better represents lake size variability ($\geq$8 ha). From an applied perspective, if a state were to use Landsat or MODIS 250 m data to assess statewide water quality, conclusions could differ greatly according to the satellite data used. For example, in 2000, MODIS and Landsat data estimated average Maine lake clarity at 5.24 m (357 lakes) and 4.52 m (1077 lakes), respectively (without Landsat resampling).

Another limitation of the 250 m resolution is the general inability to detect intra-lake variability of SD. Of the 364 Maine lakes eligible for monitoring with 250 m data, approximately 75% contain only a single remote sampling location in lake centers. Smaller, shallow lake basins may be more susceptible to algae blooms and sudden changes in water clarity that would not necessarily be detected if sampling is focused on a single area in the center of lakes. Consequently, MODIS 250 m data may fail to detect water quality declines in lakes. Furthermore, we had thought the twice-daily MODIS image capture rate might be an important advantage for water quality change detection purposes; however, as we have shown, clear imagery is not necessarily available each year when short time windows are of interest.

Finally, our study used nonspectral data, which if absent, would have rendered the 250 m red band an inadequate, incomplete predictor of SD in some cases, even during late summer ($r^2 \sim 0.54$). We realize that lake management agencies in other regions may not have access to widespread ancillary data; however, knowledge of lake and landscape characteristics may contextualize causes of local water quality trends. For example, a remotely generated SD estimate of 3 m has greater meaning when lake depth and watershed conditions are known.

Acknowledgments

This study was made possible through financial support from the Maine Department of Environmental Protection (MDEP), the US Geological Survey Maine Cooperative Fish and Wildlife Research Unit, and the University of Maine. Field-collected Secchi data used in this study were gathered, compiled, and shared by MDEP and the Maine Volunteer Lake Monitoring Program. Spatial and lake bathymetric data were provided by MDEP and the Maine Office of GIS. Comments and suggestions provided by Dr. Aram J.K. Calhoun of the University of Maine and 3 anonymous reviewers improved this manuscript. Mention of trade names and commercial parts does not constitute endorsement or recommendation for use by the US Government.

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