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High-frequency remote monitoring of large lakes with MODIS 500 m imagery☆

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ABSTRACT

Satellite-based remote monitoring programs of regional lake water quality largely have relied on Landsat Thematic Mapper (TM) owing to its long image archive, moderate spatial resolution (30 m), and wide sensitivity in the visible portion of the electromagnetic spectrum, despite some notable limitations such as temporal resolution (i.e., 16 days), data pre-processing requirements to improve data quality, and aging satellites. Moderate-Resolution Imaging Spectroradiometer (MODIS) sensors on Aqua/Terra platforms compensate for these shortcomings, although at the expense of spatial resolution. We developed and evaluated a remote monitoring protocol for water clarity of large lakes using MODIS 500 m data and compared MODIS utility to Landsat-based methods. MODIS images captured during May–September 2001, 2004 and 2010 were analyzed with linear regression to identify the relationship between lake water clarity and satellite-measured surface reflectance. Correlations were strong ($R^2 = 0.72–0.94$) throughout the study period; however, they were the most consistent in August, reflecting seasonally unstable lake conditions and inter-annual differences in algal productivity during the other months. The utility of MODIS data in remote water quality estimation lies in intra-annual monitoring of lake water clarity in inaccessible, large lakes, whereas Landsat is more appropriate for inter-annual, regional trend analyses of lakes ≥8 ha. Model accuracy is improved when ancillary variables are included to reflect seasonal lake dynamics and weather patterns that influence lake clarity. The identification of landscape-scale drivers of regional water quality is a useful way to supplement satellite-based remote monitoring programs relying on spectral data alone.

1. Introduction

Water clarity is a widely used metric of lake water quality often measured as secchi disk depth (SDD). Lake water clarity is closely associated with water quality indicators such as trophic status, chlorophyll-a, and total phosphorus and is a strong indicator of overall lake productivity (Carlson, 1977). Increased lake clarity increases lakefront property value in Maine (Boyle et al., 1999; Michael et al., 1996) and New Hampshire (Gibbs et al., 2002), and enhances user-perception of lake health in Minnesota (Heiskary & Walker, 1988). Because clarity assessments are easy to administer and have important ecological and economic implications, clarity is an ideal metric of regional lake water quality. Regional assessments, however, are logistically challenging and expensive to perform regularly. Consequently, field assessments tend to exclude rural and relatively inaccessible areas, thereby producing spatially irregular, non-random samples.

An approach to reducing costs and eliminating problems associated with lake accessibility is use of remote sensing. Recently, there has been an emergence of published procedures for remote monitoring of regional lake water clarity with satellite imagery (Chipman et al., 2004; Kloiber et al., 2002a; McCullough et al., 2012; Olmanson et al., 2008). These procedures rely on continued access to Landsat Thematic Mapper (TM) data. The Landsat platform has a number of key advantages including nearly 30 years of archived imagery, a 185 km scene width suitable for regional analyses, free data access, and good resolution in the visible and infrared portions of the electromagnetic spectrum. The 30 m spatial resolution of Landsat permits simultaneous assessment of hundreds of lakes ≥8 ha and within-lake assessment of large lakes. Repeated application of Landsat underscores its usefulness in regional water quality monitoring; however, Landsat still has limitations. Of two Landsat satellites currently in operation, Landsat 7 (ETM+) has compromised image quality owing to the 2003 scan-line corrector (SLC) failure. Landsat 5 (TM), launched in 1984, has long exceeded its life expectancy and was suspended in November 2011 in an attempt to restore operation after an amplifier malfunction. Image availability limitations could be mitigated by the intended launch of the Landsat Data Continuity Mission (LDCM) in 2013. In addition, Landsat has a

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16 day temporal resolution, which can be problematic when short time windows are of interest, particularly in the presence of cloud cover.

Moderate-Resolution Imaging Spectroradiometer (MODIS) sits aboard two NASA satellites: Terra, launched in 1999, and Aqua, launched in 2002. Each satellite captures daily images of the entire Earth surface, yielding two images per day. Many MODIS image products arrive pre-converted to surface reflectance, eliminating potential need for radiometric correction. MODIS contains 29 bands at 1000 m, 5 bands spectrally similar to Landsat at 500 m, and 2 bands (red visible and near infrared) at 250 m resolution. Scenes are approximately 2300 km wide. The large pixel size restricts application only to large area analyses; however, the greater temporal resolution and pre-conversion to surface reflectance are notable, potential advantages over Landsat.

There are relatively few previous applications of MODIS for lake water quality monitoring. Koponen et al. (2004) classified water quality of Finnish lakes into broad categories (i.e., excellent, good, satisfactory and fair) with 250 m MODIS data, and various MODIS band combinations were used to estimate seasonal chlorophyll-a of Taihu Lake, China (Zhu et al., 2005). Dall'Olmo et al. (2005) found simulated MODIS and SeaWiFS imagery could be used to estimate chlorophyll-a concentrations in turbid, productive waters including lakes. MODIS data were used to estimate chlorophyll-a, total phosphorus, total nitrogen and water clarity in Chaohu Lake, China, with R^2 values >0.60 for clarity and chlorophyll-a (Wu et al., 2009). Chipman et al. (2009) showed that the visible blue (500 m resampled to 250 m)/visible red (250 m) MODIS band ratio was strongly correlated ($R^2=0.79$) with natural log-transformed chlorophyll-a in Minnesota and Ontario lakes and used various band combinations at 500 m to map water clarity in Lake Michigan. Olmanson et al. (2011) were the first to demonstrate that MODIS 250, 500 and 1000 m imagery can be effectively used in regional estimation of clarity and chlorophyll-a in Minnesota lakes using concurrent August imagery; however, they note that the number of lakes monitored is limited by spatial resolution.

Despite these recent advances in the use of MODIS imagery for remote lake monitoring, previous research has not yet evaluated the application of the high temporal resolution of MODIS data for intra-annual lake monitoring, which is a potentially major advantage of MODIS over conventionally-used Landsat. Additionally, our past analyses of Maine lakes using Landsat imagery indicate that incorporation of physical lake features and watershed characteristics improve accuracy of remote SDD estimates (McCullough et al., 2012); however, it is unclear if these findings are applicable at the scale of MODIS-based lake monitoring. The objectives of this study were to (1) investigate the effectiveness of MODIS 500 m data in regional lake clarity monitoring during May–September, (2) evaluate the contributions to MODIS model performance of physical lake features and watershed characteristics that drive regional water clarity at the scale and resolution of Landsat, and (3) compare the respective utilities of MODIS and Landsat data in regional lake clarity monitoring. We developed a reliable and efficient MODIS-based remote monitoring protocol for water clarity of large lakes that is applicable over time and incorporates knowledge of seasonal lake dynamics and landscape characteristics that contribute to regional water clarity. We propose that MODIS is a valuable complement to Landsat-based monitoring programs and hypothesize that whereas Landsat is useful for long-term, low-frequency lake assessment, especially of historical clarity owing to its long data archive, MODIS may be more effective for recent and future intra-annual monitoring of large lakes.

2. Methods

2.1. Description of study area

Maine, USA contains over 1500 lakes ≥ 8 ha in surface area distributed across approximately 90,000 km². Maine ranks first among all 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). The climate is cold-temperate with long, cold winters and short, warm summers. Maine is dominated by the Northeastern Highlands (#58) and the Acadian Plains and Hills (#82) Level III Ecoregions (Omernik, 1987). The Northeastern Highlands are remote, mostly forested, mountainous, and contain numerous high-elevation, glacial lakes. The Acadian Plains and Hills are comparatively more populated and less rugged; however, the area also is heavily forested and contains many glacial lakes (U.S. EPA, 2010). Lakes range in size from small ponds <1 ha to Moosehead Lake (30,542 ha), the largest lake in Maine. The average SDD of Maine lakes was 5.14 m in 2009 ($n=457$; Maine Department of Environmental Protection; MDEP, Maine Volunteer Lake Monitoring Program; VLMP, 2010). Since statewide monitoring began in 1970, average annual SDD consistently has ranged 4–6 m, with a statewide average of 5.27 m during 1970–2009. The number of lakes sampled annually generally has increased since 1970 and consistently has exceeded 400 lakes since 1999 (MDEP, VLMP, 2010).

2.2. Selection of MODIS imagery

We retrieved archived, free Level 1B daily surface reflectance imagery (MOD 09) at 500 m resolution collected on Aqua and Terra satellites (http://glovis.usgs.gov/). We selected 500 m over 250 m resolution because the spectral sensitivity of MODIS 250 m imagery does not span both the blue and red visible portions of the electromagnetic spectrum correlated with lake water clarity (Chipman et al., 2004; Kloiber et al., 2002a; McCullough et al., 2012; Olmanson et al., 2008). We conducted date-specific analyses of images in 2001, 2004 and 2010 during May–September to evaluate within-year lake clarity monitoring with MODIS data. We analyzed additional images captured 20 October 2004 and 5 October 2010 to evaluate model accuracy in mid-fall. We also analyzed images captured 9 August 2002, 5 September 2009 and 30 August 2010 to compare respective SDD predictions derived from concurrently captured Landsat TM imagery (McCullough et al., 2012). We restricted our dataset to imagery with minimal cloud cover, although imagery chosen to coincide with Landsat imagery contained some clouds owing to comparative lack of flexibility in Landsat image selection. We attempted to analyze MODIS and Landsat imagery collected on 9 August 2005; however, clouds obscured too many of the large lakes necessary to calibrate MODIS models.

2.3. Ancillary lake data

Physical lake variables and landscape characteristics improve Landsat-based predictions of SDD of Maine lakes (McCullough et al., 2012). We included average lake depth and the proportion of wetland coverage in lake watersheds (wetland area) in our calibrations of MODIS data because we found these variables to be significant predictors of Maine lake clarity using Landsat imagery (McCullough et al., 2012); however, different ancillary variables may be strongly correlated with lake clarity in other regions. We obtained bathymetric data (MDEP; Bacon, 2010) and a watershed boundary geographic information system (GIS) layer (MDEP; Suitor, 2011). We used the watershed layer to calculate wetland area (ArcGIS ® version 10.0; Environmental Systems Research Inc., Redlands, CA, United States). Our wetland dataset was an updated NWI (National Wetlands Inventory) GIS layer (Houston, 2008). No lakes in our calibrations were missing ancillary data because we selected large, relatively well-mapped lakes for model development.

2.4. Lake size and shape limitations

Clarity of many small lakes cannot be estimated reliably with MODIS imagery owing to the 500 m spatial resolution. Lakes <400 ha were omitted from a statewide study of Wisconsin (Lillesand, 2002) and Minnesota (Olmanson et al., 2011) lakes conducted at 500 m resolution. Although lake size provides a threshold for unsuitable lakes, shape also affects lake eligibility. Pixels overlapping with lake boundaries introduce spectral interference from shoreline features (Chipman et al., 2009). Lakes with a large surface area owing to a long axis and convoluted shoreline will be represented with few water-only pixels. At 500 m resolution, 385 lakes can be monitored in Minnesota (Olmanson et al., 2011), and 108 and 90 lakes can be monitored in Michigan and Wisconsin respectively (Chipman et al., 2009). We used the lake perimeter (m)/surface area (m^2) ratio to characterize lake shape and determine eligibility for remote monitoring with MODIS 500 m data. We generated this ratio with GIS-derived lake perimeter and area metrics and limited our dataset to lakes with a perimeter/surface area ratio <0.019. The smaller this ratio, the greater the likelihood of avoiding mixed pixels. Based on size and shape requirements, 83 Maine lakes can be routinely monitored using MODIS 500 m imagery (Fig. 1).

2.5. Image pre-processing

Level 1B images are pre-converted to surface reflectance, requiring only minimal additional pre-processing. We reprojected all images to WGS1984 UTM Zone 19N with nearest neighbor resampling with the MODIS Reprojection Tool (https://lpdaac.usgs.gov/lpdaac/tools/modis_reprojection_tool). We mosaicked images (ERDAS Imagine ® version 10.0; ERDAS Inc., Norcross, GA, USA) and clipped them to the state boundary. We mostly used completely cloud-free imagery; however, if clouds were present, we used an unsupervised classification (ISODATA clustering) to identify cloud pixels, which we reclassified as null values and removed from further analysis. Cloud shadows could not be removed by unsupervised classification without simultaneously removing unaffected lake pixels, so images were visually inspected to remove lakes affected by shadows.

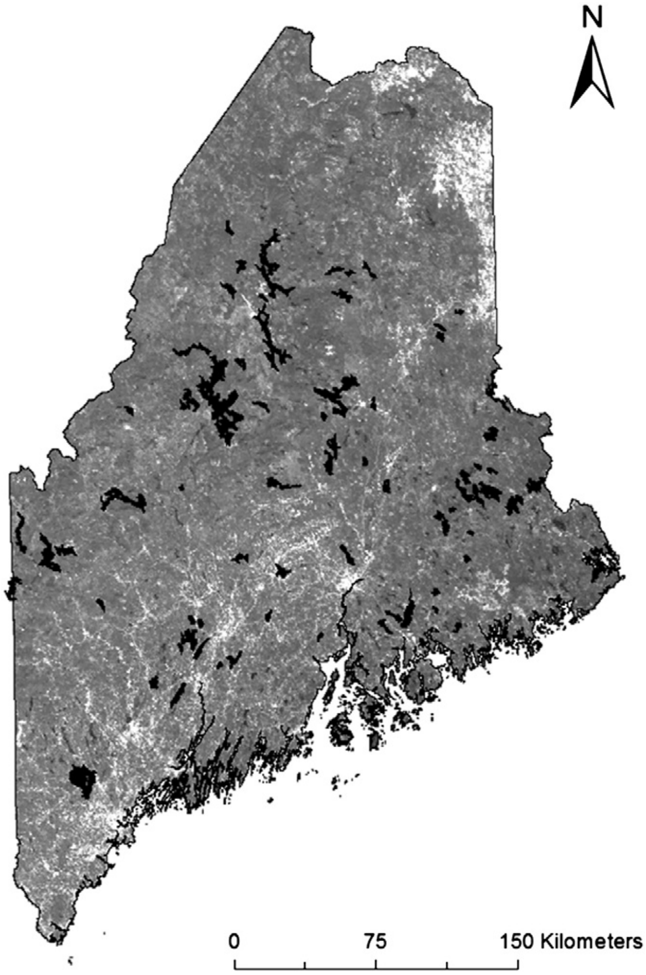

Fig. 1. Eighty-three Maine lakes can be monitored routinely with MODIS 500 m imagery. This imagery was captured by the Aqua satellite on 2 September 2004.

2.6. Data extraction and model development

We created a remote sampling GIS points layer of SDD sampling stations delineated on bathymetric maps (Maine PEARL, 2011). SDD sampling stations generally are located in the deepest areas of lakes; however, we manually relocated these sites to lake centers when lake boundaries compromised water-only pixels. We assigned sampling stations to lake centers in the absence of established locations. We buffered the points by 500 m for pixel extraction. A buffer size of 500 m captures 3–5 pixels and provides a general characterization of lake surface reflectance. Larger samples may improve correlation with SDD; Kloiber et al. (2002b) found including up to 25 pixels improved model fitness with Landsat imagery. Use of >3–5 pixels at 500 m resolution, however, restricts assessment to a small number of very large lakes. We also applied 300 and 400 m buffers as well as single pixels; however, a 500 m buffer yielded the greatest R^2 values. A disadvantage of this method is that the requirement of several water-only pixels inevitably limits the number of lakes sampled. We calculated the average pixel value for MOD 09 bands 1 (red visible; 620–670 nm) and 3 (blue visible; 459–479 nm) in each buffered area with zonal statistics. Bands 1 and 3 correspond to the visible portions of the electromagnetic spectrum most strongly correlated with clarity of Maine lakes using Landsat (McCullough et al., 2012). Other Landsat-based studies determined the blue/red band ratio is a strong predictor of SDD (Chipman et al., 2004; Kloiber et al., 2002a; Olmanson et al., 2008); however, we found the individual red and blue TM bands were more consistently, strongly correlated with SDD in Maine than green or near infrared TM bands or various combinations and ratios of TM bands 1–4 (McCullough et al., 2012).

SDD data collected ±10 days of the satellite overpass in mid-late summer (July 15–September 15) are acceptable for use in remote clarity estimation models because water clarity is relatively stable at this time of year (Kloiber et al., 2002a); however, time windows of ±10 days are not ideal and should be used only when insufficient data are available within shorter time frames. Lake clarity usually is at a seasonal low during late summer owing to peak development in algal communities, making late summer the optimal period for remote clarity estimation (Stadelmann et al., 2001). Outside late summer, however, field calibration data should be collected as closely as possible to satellite image capture dates to minimize variability associated with changing lake conditions, such as stratification and mixing, which may vary across a landscape. We used time windows of ±3–7 days of the satellite overpass based on SDD data availability, using ±7 day windows during August only when necessary.

We used spectral data (bands 1 and 3) average depth and wetland area to estimate natural log-transformed SDD with linear regression (R Version 2.12.0; R Foundation for Statistical Computing, Vienna, Austria). We included the MODIS band 1/3 ratio owing to its established, strong correlation with ln(SDD) (Chipman et al., 2004; Kloiber et al., 2002a; Olmanson et al., 2008). We validated all regression models with leave-one-out jackknifing (Sahinler & Topuz, 2007) and verified standard regression assumptions. We identified and eliminated outliers with the Bonferroni outlier test and case-by-case inspection of residuals and input parameters. Non-outlying influential cases were not removed unless considerable model fitness was gained.

3. Results

3.1. Regression results

We found strong correlations ($R^2 = 0.71$–0.94; RMSE = 1.18–1.39 m) between ln(SDD), MODIS bands 1 and 3, average depth and wetland area (Table 1). Band 1 was negatively correlated and band 3 was positively correlated with ln(SDD). Band 3 was generally correlated with ln(SDD) during May–August, although during May only in 2010. The band 1/3 ratio created model redundancies and was less consistently correlated with ln(SDD) than individual bands 1 and 3. Average lake depth was positively correlated with ln(SDD) during the stratified period (mid-June–August), and wetland area was consistently negatively correlated with ln(SDD) in May. Our best-performing MODIS models were produced for July–September, however, models with $R^2 > 0.70$ were produced throughout the study (Table 1, Fig. 2). We failed to calibrate models for 9 May 2004 and October dates owing to lack of calibration data.

The average absolute difference between all observed and model-estimated SDD values was 1.04 m (±0.88; one standard deviation); however, lake trophic status affected this difference (Table 2). Eutrophic lakes (SDD < 4 m) generally were estimated most accurately, differing 0.77 m (±0.58) on average from observed conditions. Estimates for mesotrophic lakes (SDD = 4–7 m) averaged 0.96 m (±0.71) from observed SDD, and estimates for oligotrophic lakes (SDD > 7 m) were the least accurate, differing 1.50 m (±1.07) on average from observed conditions.

3.2. Comparison to same-date Landsat models

Predictive capacities (R^2) were greater for Landsat than MODIS models on three of four occasions (Table 3). Significant predictors generally were similar in corresponding models (Table 3). R^2 values of Landsat models were greater on all occasions, except on 14 September 2004. Similarly, the average absolute difference between model-estimated and field-collected SDD measurements consistently was less in Landsat models, except on 14 September 2004. The window of days for usable calibration data varied in all years except 2009 based on calibration data availability (Table 3). The same calibration datasets could not be used in respective MODIS and Landsat models owing to lake size/shape requirements for MODIS models and the larger geographic extent of MODIS imagery. SDD estimates from MODIS and concurrently collected Landsat data were not different across all years ($n = 279$; paired t-test, $p = 0.243$), nor in any individual year (Table 4). The absolute difference between annual average MODIS and Landsat SDD estimates ranged 0.06–0.33 m across all 4 years (Table 4).

4. Discussion

4.1. Application of MODIS imagery in remote lake water clarity monitoring

MODIS 500 m imagery is usable for regional remote clarity estimation of large lakes from late spring through late summer; however, MODIS predictions of lake clarity are more consistently accurate in mid–late summer. Inconsistency during late spring and early summer likely reflects seasonally unstable, unpredictable lake conditions that result from annual fluctuations in algal community development. Algal growth peaks consistently cause water clarity to be at its lowest in late summer, creating conditions most easily detectable by remote platforms sensitive to the visible portions of the electromagnetic spectrum correlated with lake water clarity (Chipman et al., 2004; Kloiber et al., 2002a; Olmanson et al., 2008). Given seasonally dynamic clarity conditions, mid-late summer estimates potentially are more valuable indicators than estimates outside this window. Furthermore, volunteers gather more calibration data in summer than in spring or fall, accounting for our inability to calibrate models for October or consistently for May.

Various combinations of MODIS bands 1 and 3 and physical lake parameters provided best-fitting models across years and seasons, which can be explained by seasonal lake dynamics and fluctuations in weather. The short wavelength of the visible blue band (band 3) poorly penetrates turbid or productive water and is less strongly correlated with ln(SDD) than the visible red band (band 1) (Lathrop, 1991). Consequently, we would expect band 3 to be a weak predictor of water clarity during periods of high algal biomass, which typically occurs in late summer. This was the case in our study in 2001 and 2004, but not in 2010, which experienced an unusually dry and warm summer (June–August) (NOAA, 2011) that likely lowered lake levels and concentrated algal productivity in lake water columns. Statewide lake clarity was at a 15 year low in August 2010 (McCullough et al. in review), which coupled with weather likely explains the lack of predictive capacity of band 3 after late May. Average depth is a major determining factor in lake water clarity during the stratified period, which begins between late April and early June and typically lasts 4–6 months in Maine (Davis et al., 1978). Therefore, we would expect that average depth would not be a consistent predictor of SDD during May, early June and early–mid September,

Table 1

Summary of clarity estimation models with MODIS 500 m imagery.

Date	Satellite	Model	R^2	±Days	n
9/18/2010	Terra	-1.31×10^{-2} (Band 1) + 2.65[a]	0.94	3	20
8/29/2010	Terra	-1.08×10^{-2} (Band 1) + 1.37×10^{-2} (AvgDepth) + 2.58[b]	0.79	3	19
8/19/2010	Terra	-9.65×10^{-3} (Band 1) + 9.29×10^{-3} (AvgDepth) + 2.41	0.82	3	20
6/15/2010	Terra	-9.04×10^{-3} (Band 1) + 2.16×10^{-2} (AvgDepth) + 2.25	0.80	3	22
5/21/2010	Terra	-1.02×10^{-2} (Band 1) + 7.25×10^{-3} (Band 3) − 3.61×10^{-4} (Wetland) + 2.20[c,d]	0.77	3	13
9/14/2004	Aqua	-8.63×10^{-3} (Band 1) + 2.60	0.88	3	20
9/2/2004	Aqua	-3.58×10^{-2} (Band 1) + 3.54×10^{-2} (Band 3) + 1.99	0.94	3	10
8/24/2004	Aqua	-1.53×10^{-2} (Band 1) + 1.22×10^{-2} (Band 3) + 6.08×10^{-3} (AvgDepth) + 1.83	0.82	7	37
7/7/2004	Aqua	-1.29×10^{-2} (Band 1) + 1.48×10^{-2} (Band 3) + 7.27×10^{-3} (AvgDepth) + 1.46	0.89	3	15
6/5/2004	Aqua	-1.24×10^{-2} (Band 1) + 2.18×10^{-2} (Band 3) + 0.866	0.72	3	17
9/9/2001	Terra	-7.91×10^{-3} (Band 1) + 2.21	0.74	3	22
8/1/2001	Terra	-1.42×10^{-2} (Band 1) + 1.11×10^{-2} (Band 3) + 5.48×10^{-3} (AvgDepth) + 1.80	0.77	7	31
7/20/2001	Terra	-6.24×10^{-3} (Band 1) + 5.31×10^{-3} (Band 3) + 4.83×10^{-3} (AvgDepth) + 2.47	0.71	3	18
5/25/2001	Terra	-1.11×10^{-2} (Band 1) + 1.50×10^{-2} (Band 3) − 3.58×10^{-4} (Wetland) + 1.70	0.89	3	13
5/8/2001	Terra	-9.29×10^{-3} (Band 1) + 2.16×10^{-2} (Band 3) − 5.37×10^{-4} (Wetland) − 0.877	0.72	4	13

We failed to create models for imagery captured 5/9/2004, 10/20/2004 and 10/5/2010 owing to lack of calibration data.

[a] Band 1 = visible red (620–670 nm).

[b] AvgDepth = average lake depth.

[c] Band 3 = visible blue (459–479 nm).

[d] Wetland = proportion of watershed covered by wetland.

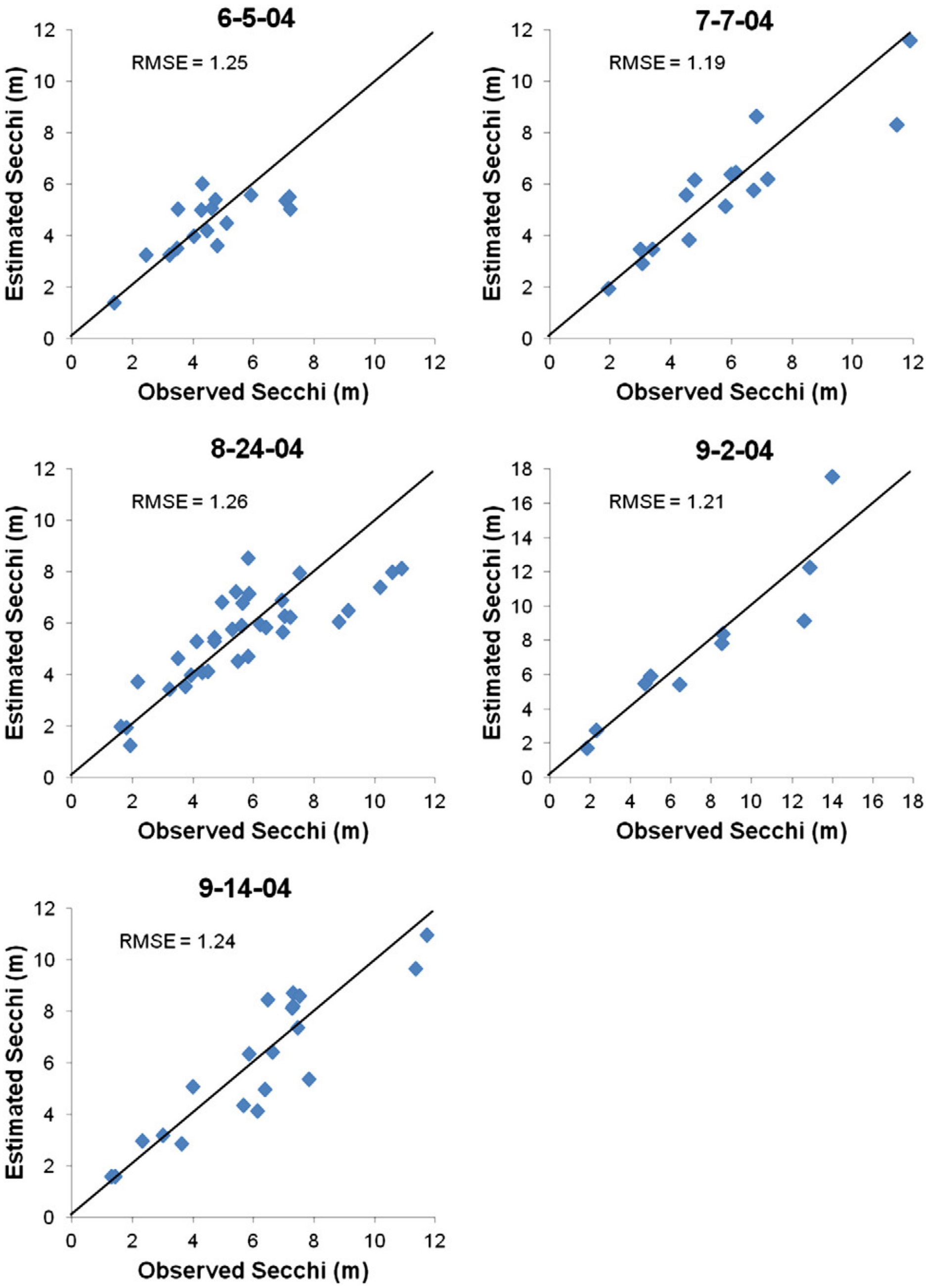

Fig. 2. Plotted relationships between observed and estimated secchi disk depth (m) for 2004 MODIS models with 1:1 fit line. Observed values are based on field data gathered by the Maine Volunteer Lake Monitoring Program (VLMP) ±3–7 days of satellite overpass. RMSE = root mean squared error.

which our results confirm (Table 1). Wetlands contain the most water in spring as a result of snowmelt and decrease in volume later during the year. Consequently, we would expect the effects of wetlands on lake water clarity to be most pronounced in May, which our results also confirm; however, 2009 experienced record summer rainfall (NOAA, 2011), which explains the significance of wetlands in our 5 September 2009 MODIS model (Table 3). Although we found wetlands to be a consistent predictor of late summer lake clarity only in eastern Maine in our Landsat-based study (McCullough et al., 2012), it is likely that the 500 m resolution, inclusion of additional months, and the wider geographic extent of this study accounted for the lack of similar findings.

The temporal resolution of MODIS data makes annual and intra-annual lake clarity estimation possible, whereas retrieving cloud-free Landsat imagery at these frequencies is less likely, particularly in areas with frequent cloud cover. Many cloud-free MODIS images of Maine were available during mid–late summer 2001–2010, whereas few cloud-free Landsat images were available during this period. Given that cloud-free imagery may not be available for several weeks at a time, the greater temporal resolution of MODIS increases the probability that high-quality imagery would be available at some point each summer, which represents a considerable advantage over Landsat. Although we proposed that pre-conversion to surface reflectance was a similar advantage over Landsat, loss of spatial resolution may negate potential benefits, which are unproven at this time. MODIS Level 1B corrections were designed to improve analyses of land features, and research is needed to evaluate potential effects on water quality assessment. Although Olmanson et al. (2011) found uncorrected MODIS imagery performed as well, if not better than corrected MODIS imagery in estimation of SDD, we hypothesize that the use of cloud-free imagery may mask potential effects of atmospheric correction. Comparative analyses of cloud-free and marginally

Table 2
Average absolute difference (m) between MODIS-estimated and observed SDD by lake trophic state.[a]

Date	Satellite	Eutrophic	Mesotrophic	Oligotrophic	Overall
9/18/2010	Terra	0.36	0.67	1.21	0.67
8/29/2010	Terra	0.77	0.96	1.64	1.09
8/19/2010	Terra	0.68	1.07	1.39	1.12
6/15/2010	Terra	0.43	0.83	1.29	0.91
5/21/2010	Terra	1.42	0.65	2.14	1.17
Average		0.64	0.86	1.47	0.98
Std Dev		0.58	0.61	0.93	0.78
9/14/2004	Aqua	0.53	1.23	1.15	0.99
9/2/2004	Aqua	0.30	0.89	1.70	1.17
8/24/2004	Aqua	0.55	0.94	1.78	1.11
7/7/2004	Aqua	0.16	0.92	1.48	0.83
6/5/2004	Aqua	0.49	0.66	1.82	0.81
Average		0.45	0.92	1.57	1.00
Std Dev		0.47	0.62	1.08	0.86
9/9/2001	Terra	0.76	0.86	2.43	1.41
8/1/2001	Terra	0.61	1.64	1.57	1.38
7/20/2001	Terra	1.10	0.85	1.17	0.94
5/25/2001	Terra	0.42	0.83	1.12	0.83
5/8/2001	Terra	1.04	0.95	1.91	1.28
Average		0.77	1.09	1.50	1.13
Std Dev		0.97	0.67	1.21	0.97

[a] Eutrophic SDD <4 m, mesotrophic SDD = 4–7 m, oligotrophic SDD > 7 m.

Table 4
Paired *t*-test comparisons of MODIS and Landsat estimates.

Date	Abs diff (m)[a]	*p* value	*n*
2010	0.06	0.779	72
2009	0.07	0.828	47
2004	0.33	0.106	81
2002	0.11	0.555	79
All	0.13	0.243	279

[a] Abs diff (m) = absolute difference between annual average MODIS and Landsat SDD estimates.

usable imagery may clarify the effects of MODIS atmospheric corrections on water quality estimation; however, the temporal resolution of MODIS potentially eliminates the need for use of all but the best quality imagery with minimal atmospheric interference.

4.2. Limitations of MODIS for lake clarity estimation

MODIS visible red data (band 1) consistently provided stronger predictions of SDD than visible blue data (band 3). MODIS data at 250 m resolution are not available at the visible blue wavelength (459–479 nm); however, the smaller resolution would considerably increase the number of lakes that could be remotely monitored, though at the expense spectral sensitivity. As the blue band is a relatively weak predictor of lake clarity in late summer or in productive waters in Maine, 250 m imagery may be particularly useful under these conditions. Chen et al. (2007) used 250 m Level 1B imagery to map turbidity in Tampa Bay with strong model fitness ($R^2 = 0.73$), conditions in which we would expect little penetration of visible blue radiation. Olmanson et al. (2011) successfully estimated SDD of 1257 lakes >125 ha using 250 m MODIS imagery captured in August; however, further research is needed to evaluate the utility of MODIS 250 m imagery during other months. Inclusion of additional lakes would increase calibration data availability. Model predictions potentially are affected by the selected lake calibration dataset, including sample size, and geographic and numeric distribution of SDD values. The numeric distribution of lake water clarity values may be reduced when fewer lakes are included in the model-building dataset, which subsequently affects model fitness (Nelson et al., 2003).

Average lake depth and wetland area seasonally improve accuracy of lake clarity estimation models; however, these variables may not be readily available in other locations and may require site-based sampling, which potentially is difficult in inaccessible areas. Lake depth and wetland area likely are sufficiently stable year-to-year at the landscape scale such that reassessment is unnecessary. Knowledge of lake depth relativizes the proportion of the water column penetrable by light and is useful regardless of predictive capacity. We have shown that average lake depth and wetland area improve model fitness in some cases; however, SDD estimates with reduced accuracy are useful when these variables are not available (McCullough et al., 2012). Average depth and wetland area were strong predictors of Maine lake clarity; however, other ancillary variables may be better predictors in other regions based on the landscape and season of interest.

Utility of remote sensing data for lake water clarity monitoring is affected by cloud cover. Although daily MODIS imagery potentially provides multiple opportunities for cloud-free imagery each year, cloud cover remains a major limitation of satellite remote sensing. Despite the temporal frequency of MODIS image capture, availability of cloud-free imagery on specific dates is unlikely, especially in frequently clouded areas, requiring that remote monitoring protocols be flexible with regard to image selection.

4.3. Comparison of MODIS and Landsat models

Although we found no significant differences between SDD estimates from Landsat and MODIS models across all dates and models, the generally better accuracy of Landsat models can be attributed to finer resolution and smaller scale (individual TM paths). Olmanson et al. (2011) found that Landsat imagery performed better in terms

Table 3
Comparison of MODIS and Landsat models predicting SDD on coincident dates.

Date	Satellite	Model	R^2	±Days	*n*	Abs Diff (m)[a]
8/30/2010	Aqua	-8.08×10^{-3} (Band 1) $+ 7.71\times10^{-4}$ (AvgDepth) $+ 2.52$[b,c]	0.65	3	22	1.51
8/30/2010	Landsat	-0.244 (TM3)[d] $+ 8.39\times10^{-3}$ (AvgDepth) $+ 5.22$	0.73	1	65	1.03
9/5/2009	Terra	-1.31×10^{-2} (Band 1) $+ 1.62\times10^{-2}$ (Band 3) $- 3.41\times10^{-4}$ (Wetland) $+ 1.95$[e,f]	0.77	3	22	1.45
9/5/2009	Landsat	-3.20×10^{-1} (TM3) $+ 3.72\times10^{-2}$ (TM1) $+ 7.78\times10^{-3}$ (AvgDepth) $- 3.61\times10^{-4}$ (Wetland) $+ 5.51$[g]	0.86	3	66	0.73
9/14/2004	Aqua	-8.63×10^{-3} (Band 1) $+ 2.60$	0.88	3	20	0.99
9/14/2004	Landsat	-0.298 (TM3) $+ 6.44$	0.67	1	44	1.27
8/9/2002	Terra	-1.13×10^{-2} (Band 1) $+ 8.26\times10^{-3}$ (Band 3) $+ 1.06\times10^{-3}$ (AvgDepth) $+ 1.57$	0.78	3	16	1.37
8/9/2002	Landsat	-3.22×10^{-2} (TM3) $+ 1.29\times10^{-2}$ (AvgDepth) $- 7.51\times10^{-4}$ (Wetland) $+ 4.25$	0.90	1	36	0.65

[a] Avg Abs Diff = average absolute difference between observed and satellite-estimated SDD values.
[b] Band 1 = MODIS visible red.
[c] AvgDepth = average lake depth.
[d] TM3 = Landsat visible red.
[e] Band 3 = MODIS visible blue.
[f] Wetland = proportion of watershed covered by wetlands.
[g] TM1 = Landsat visible blue.

of R^2 than concurrent MODIS 250, 500 and 1000 m imagery, and different band combinations provided best-fitting models across image products. These findings are consistent with ours. The difference in scale accounts for differences in significant predictor variables in 2009 and 2002 MODIS and Landsat models. Landsat models contained lakes located in individual TM paths, whereas MODIS models encompassed all of Maine. It was not practical to use common calibration datasets owing to the small number of MODIS-eligible lakes; differences in resolution affected calibration data availability.

Landsat and MODIS imagery can be used to estimate SDD accurately despite differences in resolution and scale; however, Landsat and MODIS models have entirely different applications in remote water clarity monitoring. The 83 lakes in Maine that can be monitored simultaneously with 500 m MODIS imagery constitute <10% of the approximately 1000 lakes (≥8 ha) that potentially can be monitored with either Landsat path 11 or 12 (McCullough et al., 2012). In Wisconsin, 60% of lakes >400 ha can be reliably monitored with MODIS 500 m imagery (Chipman et al., 2009) whereas the 83 MODIS-eligible Maine lakes represent 49% of lakes >400 ha. Although Landsat data provide generally more accurate water clarity assessments, an important advantage of MODIS data is the ability to assess water clarity multiple times during spring and summer over a considerably larger geographic area. The 16 day temporal resolution of Landsat may require the use of marginal imagery when short time windows are of interest (e.g., late summer), whereas use of MODIS data substantially increases the probability of obtaining high-quality imagery.

5. Conclusion

MODIS 500 m imagery is a reliable tool in characterizing water clarity of large lakes from late spring through late summer, and the frequency of MODIS image capture potentially enables assessment of lake clarity change during this period. MODIS-based lake monitoring is less dependable in May; however, owing to model calibration data availability and seasonally unstable lake dynamics that result in inconsistent relationships between spectral reflectance and water clarity. Average lake depth and watershed wetland area improved model accuracy for Maine lakes when knowledge of seasonal lake dynamics and recent weather are considered in model calibration. Only large lakes (83 in Maine) can be reliably assessed with MODIS 500 m data; considerably more lakes can be monitored with Landsat. The effects of MODIS atmospheric corrections on water clarity assessment are unknown; however, the temporal resolution of MODIS increases the probability of obtaining clear imagery with minimal atmospheric interference. Although the utility of MODIS data is biased toward large lakes, frequency of image capture is a notable advantage of MODIS over Landsat and allows selection of only the best quality imagery. A comprehensive lake water clarity monitoring program combines MODIS and Landsat TM data with rigorous field sampling programs that capture the ground-truthed SDD data on which a satellite-based monitoring program depends.

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