Remote sensing of chlorophyll *a* concentrations to support the Deschutes Basin lake and reservoir TMDLs

Report to EPA for 104b3 2009 grant, component 4.
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Introduction

In the Deschutes Basin, there are 4 lakes / reservoirs listed on the 303(d) list for algae related parameters (Table 1 and Figure 1).

Table 1. Lakes / reservoirs on the 303(d) list of impaired waterbodies

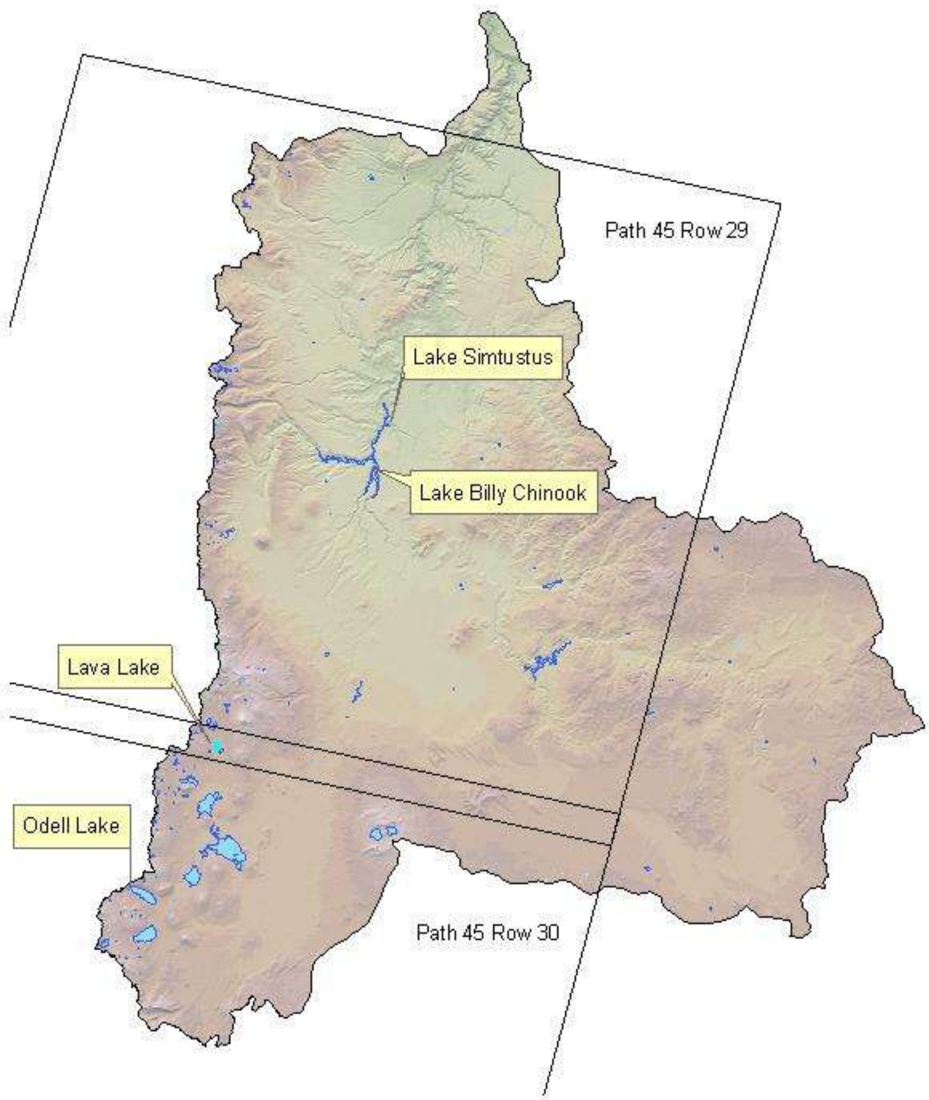
Waterbody	Impairment
Lake Billy Chinook	Chlorophyll a
Lake Billy Chinook	pH
Lava Lake	Dissolved Oxygen
Lake Simtustus	Chlorophyll a
Lake Simtustus	pH
Odell Lake	pH

Lakes in this basin and the surrounding area range from clear, oligotrophic lakes like to lakes that support massive algae blooms. There are lakes in the basin that have been identified as having harmful algae bloom (HABs), identified as eutrophic and that haven't been evaluated. There is no consistent data collection effort of lakes to determine their status. Data collection efforts for the above lakes have focused on particular years, so the annual variability has not been determined. Furthermore, grab samples can miss large algae blooms in other parts of the lakes, especially in reservoirs like Lake Billy Chinook with complex geometries. Chlorophyll *a* is a common measure of algal biomass which in turn impacts the dissolved oxygen and pH of a waterbody. In Oregon, the action level for chlorophyll *a* is 15 µg/L. Given that the presence of algal biomass can be visually detected and the limitations of available datasets, I attempted to use satellite data to answer the following:

1. Are the collection times of chlorophyll a data (a common measure of algae biomass) representative of seasonal and inter-annual lake patterns?
2. How much spatial variability of chlorophyll *a* concentrations does each lake exhibit?
3. Have conditions improved or worsened over time?
4. Are there other lakes in the region which have similar chlorophyll a concentrations?

The data acquired by the Landsat series of satellites appear to be appropriate in answering the above questions. The Landsat satellites have been collecting data since 1972. The satellites collect data at a spatial resolution of 30 meters, in the visible and infrared wavelengths with a frequent repeat cycle (every 16 days). Also, the imagery is available at no cost. I conducted a literature review to familiarize myself with methodologies for using remote sensing to detect water quality impairments (see Appendix A for notes). Others have attempted similar studies with varying amounts of success. There is no commonly accepted methodology for using Landsat data to determine algae concentrations and given the specifications of the satellite, some question its usefulness in analyzing waterbodies. However, I thought that data derived from Landsat could provide insight on lakes where there is limited or no data. Although the focus of the work was to evaluate lakes with the Deschutes basin for TMDL purposes, some areas of the surrounding basins are within the boundary of the satellite data (Figure 1, and more specifically Figure 15).

Figure 1. Map of Deschutes basin with Landsat coverage. The study area was expanded beyond the Deschutes basin to include all lakes within the two scenes (see figures later in report).



Methods

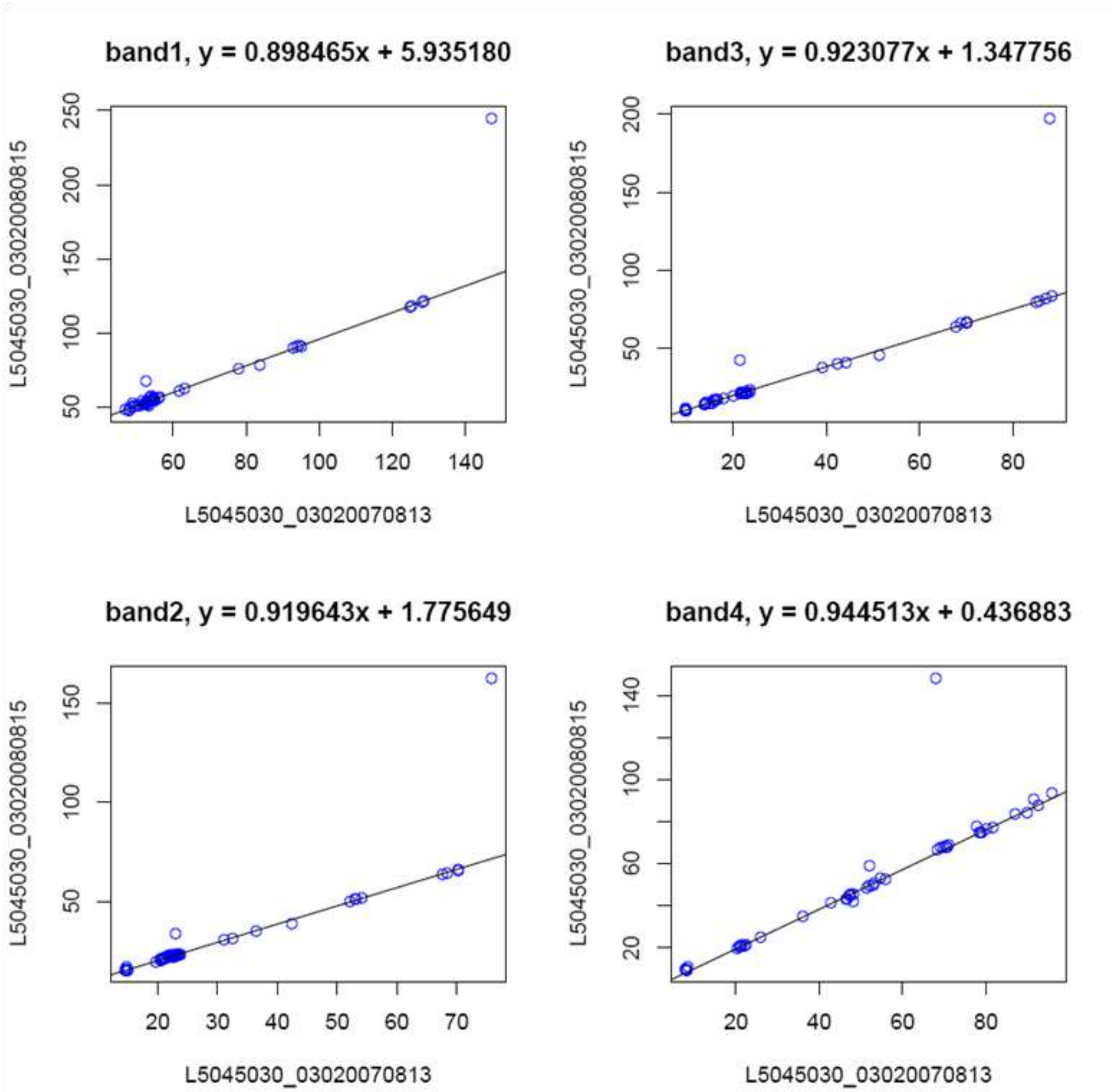
The project utilized two different satellites: Landsat 5 (Thematic Mapper) and Landsat 7 (Enchanced Thematic Mapper plus). Both satellites collect data year round on a 16 day cycle, so the frequency of imagery is every eight days. The range of years for this study is from 1999 to 2008 which was chosen as the most recent 10 year block when this study began (however Landsat 5 data is available back to 1984). Two scenes of satellite imagery cover the area of interest: Path 45, Row 30 and Path 45, Row 29. The image analysis was completed using Erdas Imagine Professional version 9.1.

Images were preliminaryly screened prior to download at http://glovis.usgs.gov/ using the USGS Global Visualization Viewer of the Landsat Archive. 821 images were examined and the estimated cloudiness was recorded. All images with less than 5% cloud cover were downloaded (Level 1G processing with systematic correction applied). Images with a cloud cover greater than 5% were downloaded if visual inspection determined the cloud cover was mainly in areas not of interest (i.e. eastern edge of images or western valley fog). If the images were not available for immediate download, they were requested through the website. The files were unzipped and Band 8 (Landsat 7, panchromatic band) was discarded due to size and limited usefulness for this application. 266 of the 821 images were downloaded. Due to climate cloud cover patterns, most of the downloaded images were from May through September. Using batch commands and scripts in Erdas Imagine, the bands within each scene were combined into a single file and the edges of the image were trimmed so that the file contained only areas with data in all the bands.

In order to make the data within the images comparable between the two scenes and different dates, the images were corrected to account for atmospheric interference. Based on the literature review, this step is very important but there does not appear to be consensus on the best methodology. Hadjimitsis et al (2004) assessed the effectiveness of various atmospheric correction methodologies related specifically to waterbodies. They suggest that standard generic methodologies such as ATCOR-2 and 6S are not sufficiently accurate when dealing with dark targets such as waterbodies. The darkest pixel (aka dark object subtraction) method was found to be appropriate for the visual bands (bands 1,2 and 3). An attempt was made to convert the digital numbers reported in the downloaded imagery into radiance from the earth's surface using improved dark object subtraction model with TAUz = Cos(thetaz) (see Chavez 1996 for method and terminology). I determined the method did not work in this case because lakes like Waldo and Crater showed considerable variability when I expected relatively stable radiance throughout the summer.

Instead I calibrated all the images from different dates and scenes to 'like-value' digital counts using psuedoinvariant features (PIFs) and a reference image (Furby and Campbell 2001). PIFs are image features which are likely to have constant reflectance over time, such as deep water, bare ground, quarries, and gravel pits. This methodology is much simpler than the atmospheric correction described above but it does not compute surface reflectance but rather corrects the at-sensor digital numbers to make the PIFs consistent with a reference image. Unfortunately, that means that the data derived for this project cannot be directly compared to data from areas outside of the geographic scope of this project. However, a similar approach could be developed that would apply to the entire state using a mosaiced statewide image (possibly the Landsat Global Land Survey products) . In the overlapping portion of the two scenes, I chose 8 areas as PIFs: Doris Lake, Mink Lake, a permanent snowfield, four lava fields of varying darkness and an area of sand. Both lakes are deep (95 to 85 feet) and very clear with transparencies of 59 and 56 feet, respectively. Landsat 7 images after May 31, 2003 have stripes of data missing due a sensor malfunction. Therefore, multiple points were chosen for PIFs in the areas that could have missing data. The reference image was chosen for a clear day during the summer: August 15, 2008, row 45 path 30. An example of the regressions used to calibrate the imagery is presented below (Figure 2). Each regression was visually inspected to determine whether the regression line was a good fit. Different linear regressions methodologies were utilized if outliers were too heavily weighted and the original regression was determined not to be representative. Images were rejected from further analysis if a linear relationship was not present. Haze, snow, ice or clouds covering the non-snow PIFs commonly led to rejection of the image.

Figure 2. Example regressions used for image calibration. Each axis is labeled with the image name which includes the satellite number (i.e. L5), the path / row (i.e. 045 and 030) and the date (i.e. 2007, 08, 13). The values are digital numbers which are unitless measures of the radiance received at the satellite.



The reference image was classified using supervised classification techniques focusing on the identification of water. The calibrated images were subsequently classified using the same parameters. Each classification image was visually checked to confirm correct classification of water. This was a useful step because it indicated some errors in the image calibration that were subsequently corrected. A total of 185 images were analyzed further (an average of 9.3 images per year per scene) (Table 2). The average day of the year for the first acceptable image was May 3 and the average day for the last was October 22 which calculates to be an average 21 day sampling frequency. The rejection of images due to atmospheric interference results in a significant drop in temporal resolution from the sensor sampling frequency of 8 days.

Table 2. Count of images for each year in the analysis.

	Path #	
Year	29	30
1999	9	9
2000	11	11
2001	6	5
2002	8	8
2003	7	7
2004	11	11
2005	12	14
2006	10	12
2007	9	9
2008	7	9
Total	**90**	**95**

The GIS layer of lakes within the study area indicated 852 lakes: 493 lakes were named, 89 were documented in the Atlas of Oregon Lakes [termed Atlas in this report] (Johnson et al 1985), and 15 have reported harmful algae blooms (Oregon Department of Human Services, 2009). This analysis is limited to named lakes within the GIS layer. Each classified image was generalized using a focal majority function with a 3 x 3 low pass filter to remove potential effects from the lake edge. The filtering set the minimum lake size at a 3 x 3 contiguous grid (0.07 acres). For each date, the average and variance of the calibrated digital numbers were calculated for grid cells classified as water within the area of a named lake.

Chlorophyll *a* data was gathered for lakes from DEQ's LASAR database (lakes with three or more dates sampled: Diamond, Lava, Lake Billy Chinook, Mirror Pond, Odell and Simtutus) and Klamath Tribes (Upper Klamath Lake, mean concentration). U.S. Forest Service, U.S. Bureau of Reclamation, U.S Geological Survey, U.S Park Service,U.S. Army Corp of Engineers and Portland General Electric were contacted regarding chlorophyll *a* data, however very little was provided. It appears the chlorophyll *a* measurements are a fairly uncommon constituent, compared to secchi depth and algae speciatation. Also, there is no centralized repository for lake data within Oregon.

For lake studies, typically the first four bands of Landsat data are the most useful (Sass et al. 2006). Each band collects the reflectance within a designated portion of the electromagnetic spectrum. Bands 1 to 3 are in the visible protion of the spectrum: blue, green and red, respectively. Band 4 collects data in the near-infrared portion of the spectrum. I attempted linear regression between the average calibrated digital numbers from bands 1 to 4 and ratios of the bands with reported chlorophyll *a* data. The most successful regression, based on R^2 values, was with the ratio of band 2 to band 1 (the blue band divided by the green band, termed "B2/B1 ratio" herein). This ratio also has the advantage of relating directly to the visible spectrum: greater values are greener and lower values are bluer. This relationship was tested with satellite data from the same day, within two days and within 10 days (Table 3 and Figure 3). Most of the data was from Upper Klamath Lake which would be expected to have different optical properties that the Deschutes TMDL lakes due to its shallow depth, dense beds of macrophytes, dissolved organic solids from surrounding wetlands and resuspended sediment from its bed. However, there was not enough data to generate regressions without the Upper Klamath Lake dataset. Based on the lower R^2 values and influence of Upper Klamath Lake regression, further analysis did not derive chlorophyll *a* concentration from satellite imagery but instead uses the B2/B1 ratio as a related, relative surrogate for algae biomass. Furthermore, the three regressions estimate that 15 µg / L of chlorophyll *a* is approximately equivalent to the band 2 / band 1 ratio of 0.4 which serves as a useful benchmark (Figure 3). In Diamond Lake, the B2/B1 ratio captures the temporal pattern of chlorophyll *a* data and shows general agreement with the B2/B1 ratio of 0.4 indicating the presence of an algae bloom (Figure 4, note: this chlorophyll *a* data not included in regression because was not readily available at the time of analysis). The B2/B1 ratio also generally agrees with the reported trophic status of lakes, with Waldo and Crater Lake having lower values than Upper Klamath Lake and Odell Lake.

Table 3. Number of images and sampling events that occurred within the same time period.

Days between satellite and field data	Count of total field data	Count of field data from Upper Klamath Lake
0	10	7
2	60	38
10	157	108

Figure 3. Regression of Band 2 / Band 1 ratio to chlorophyll *a* measurements.

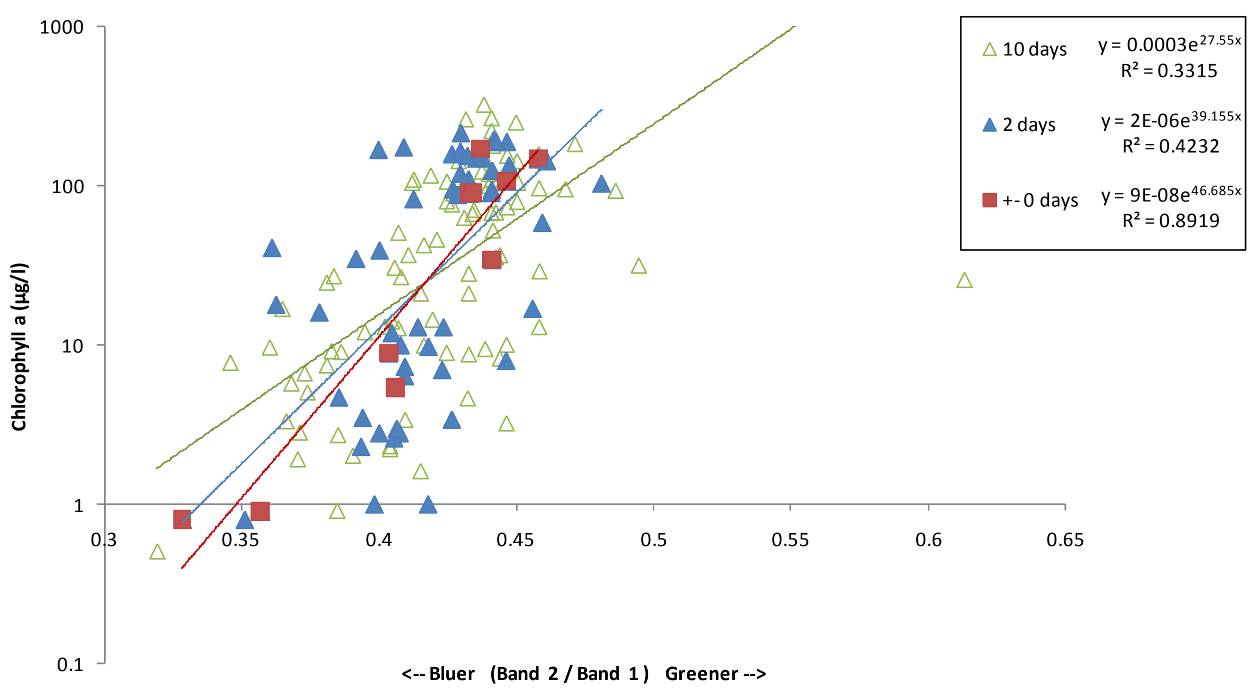
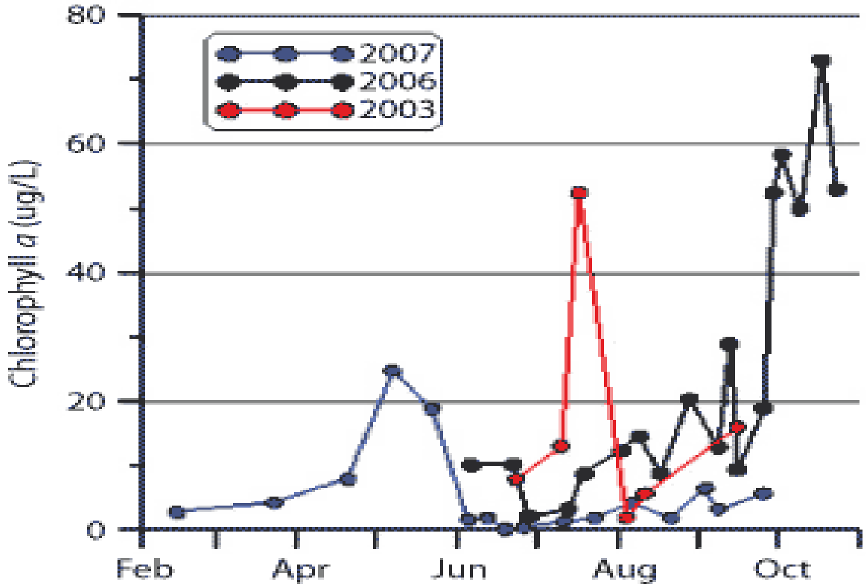
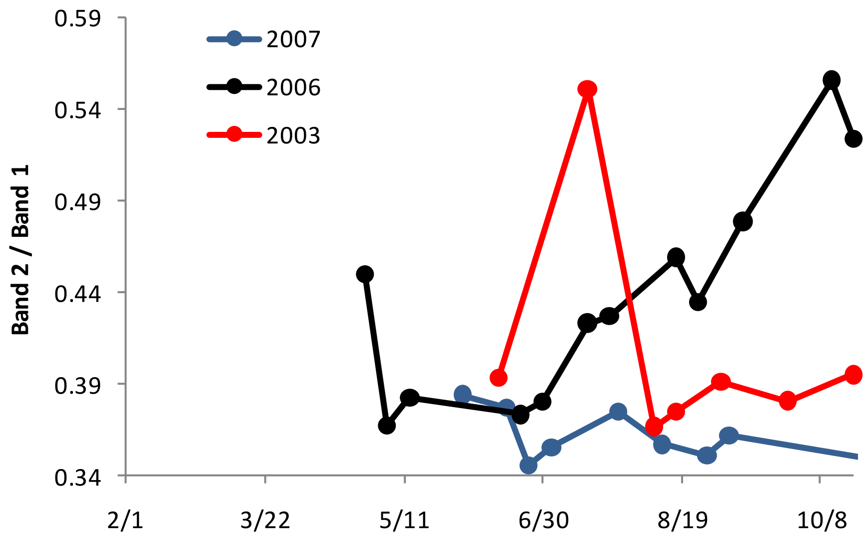


Figure 4. Diamond Lake comparison of chlorophyll a measurements (top) and Band 2 / Band 1 ratio from satellite (bottom).





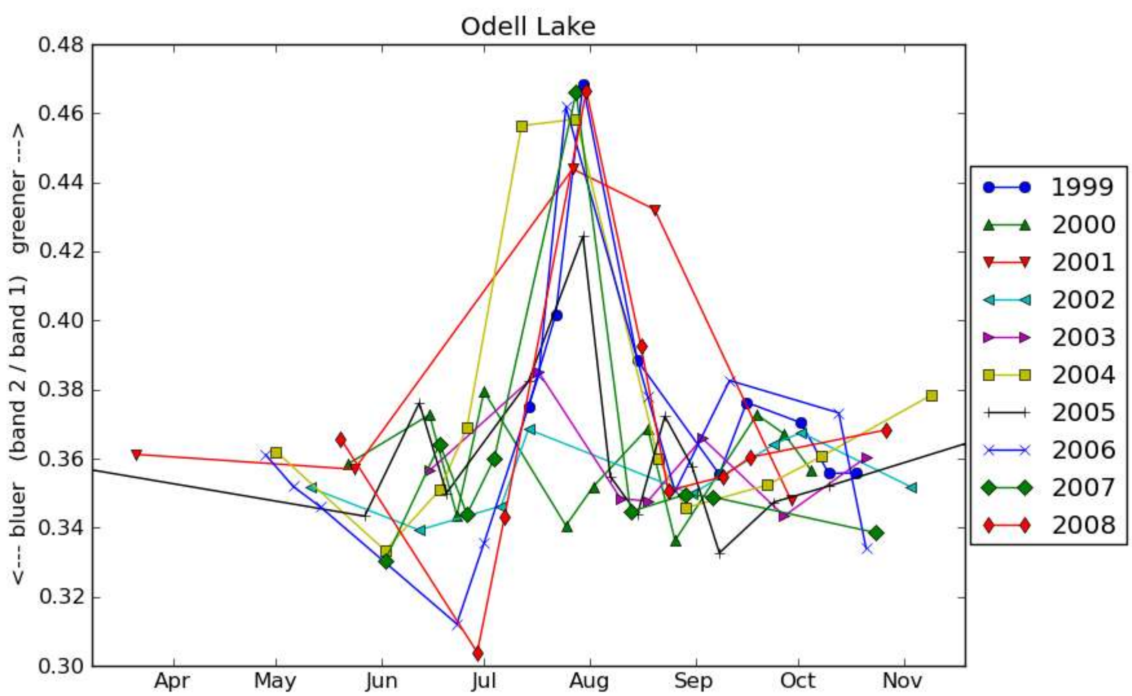
Results

The results section is organized by the four questions that the study was designed to address.

Question One: Are the times of chlorophyll a data collection representative of seasonal and inter-annual lake patterns?

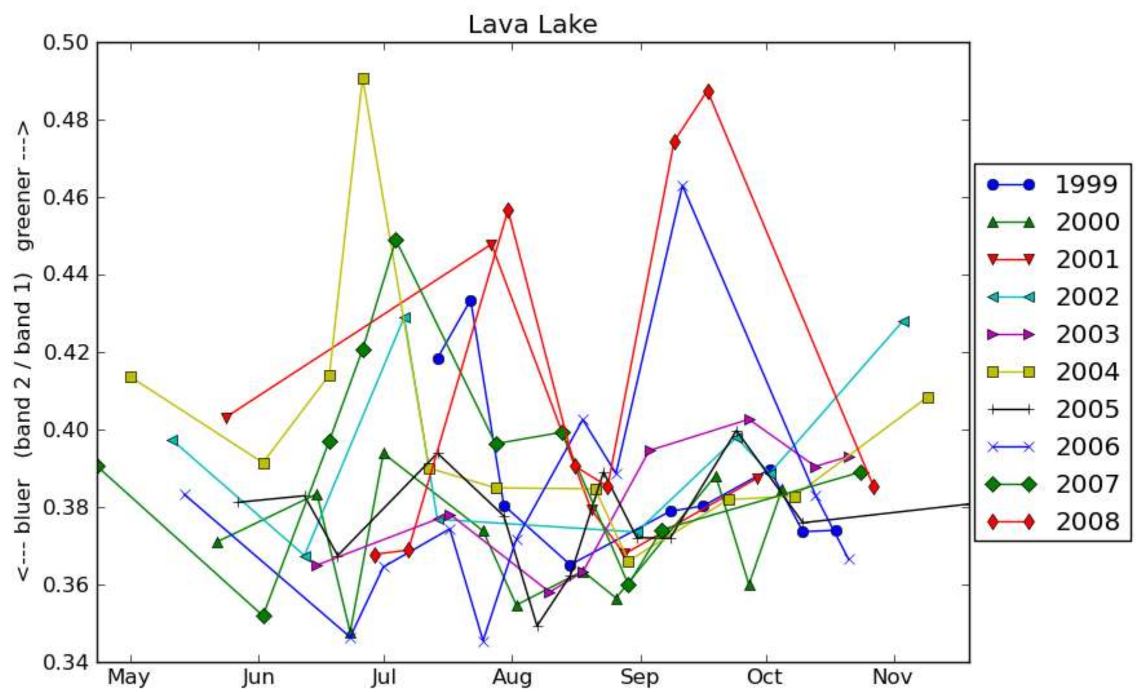
Odell Lake chlorophyll *a* data was collected in 2001 (9 samples, peak 8/6/2001 36.6 ug/L) and 2004 (4 samples, peak 7/21/2004 with 29 ug/L). The B2/B1 ratio peaked on 7/27/2001 with 0.44 and 7/27/2004 with 0.46 and an average annual peak of 0.43. The satellite data did not indicate a bloom (> 0.4) in 2002, 2003 and 2007, however neither 2002 nor 2003 had good coverage during the time of peaks in other years(late July). Compared to other lakes in this analysis, the Odell Lake pattern of B2/B1 ratios is remarkably consistent with many peaks greater than 0.45 occurring in late July. Based on this information, it does appear that the DEQ sample years are representative of years with significant algae blooms on Odell Lake.

Figure 5. Band 2 / Band 1 ratio for Odell Lake, 1999 – 2008.



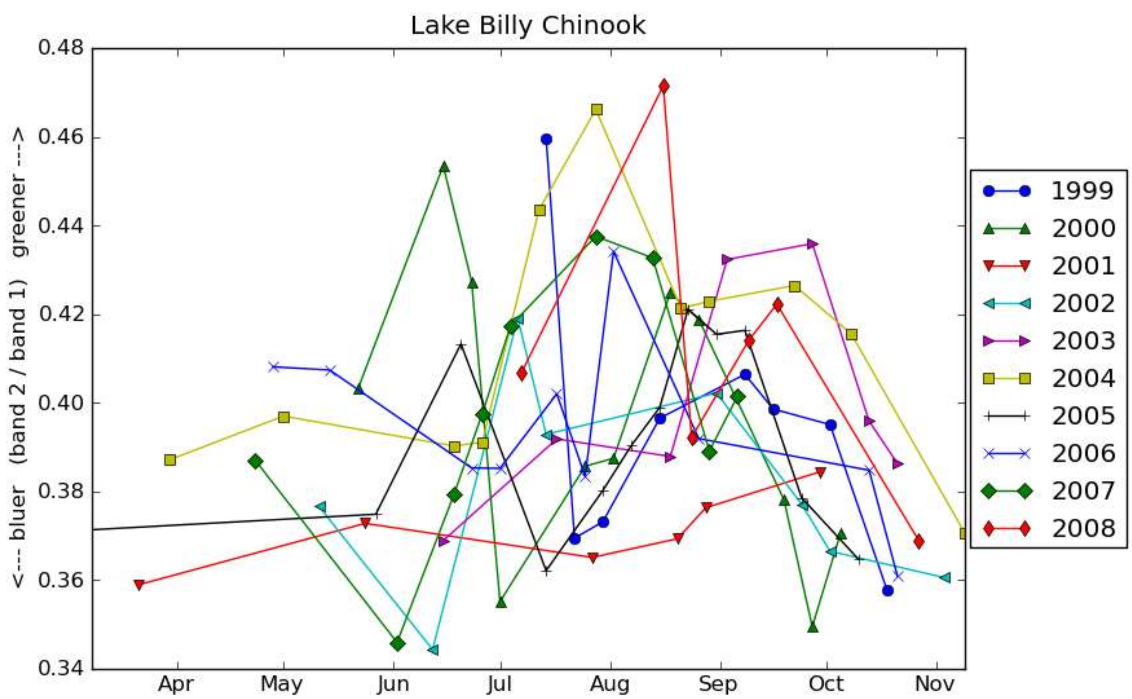
Lava Lake chlorophyll *a* data was collected in 2004 (4 samples, peak 6/15/2004 at 13 µg/L). Out of 11 images in 2004, the B2/B1 ratio peaked on 6/25/2004 with 0.49 and an annual average peak of 0.44 (Figure 6). The B2/B1 ratio on 6/17/2004 of 0.41 was closest in time to the peak chlorophyll *a* measurement. Based on this information, I suspect that the chlorophyll *a* measurements did not capture the peak algae biomass in 2004. Only two years did not have a clear peak above the 0.4 threshold: 2003 and 2005. Unlike Odell Lake, there is not consistent timing of the peak B2/B1 ratio which ranges from June through September. Based on this information, I suspect the sampling missed the 2004 peak algae bloom and that there is not likely a typical year for algal dynamics on Lava Lake, so the question of whether 2004 is representative is not appropriate.

Figure 6. Band 2 / Band 1 ratio for Lava Lake, 1999 – 2008.



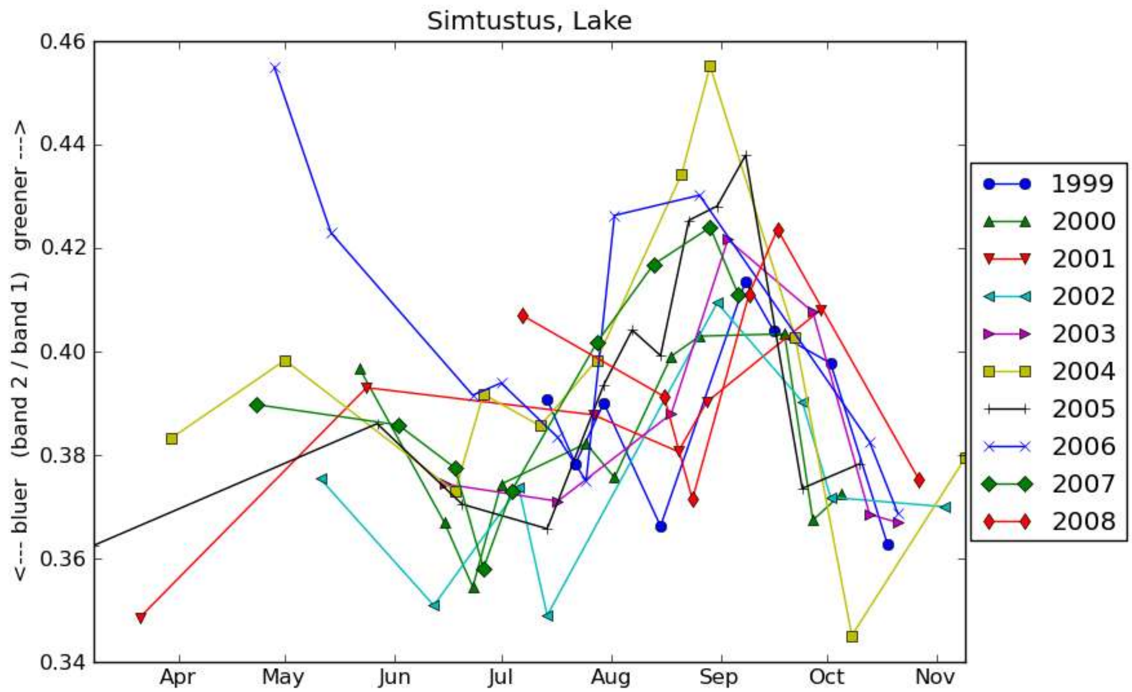
Lake Billy Chinook chlorophyll *a* data was collected in 2006 (6 sampling events at multiple locations, peak 10/19/2006, 41 µg/L from this site nearest the dam). The B2/B1 ratio (for the Deschutes and Metolius Arms) peaked on 8/2/2006 with 0.43 and had an average annual peak of 0.44 (Figure 7). The closest in time field data to the B2/B1 ratio peak were on 7/12/2006 at 13 ug/L and on 8/17/2006 at 10 µg/L (neither indicative a significant bloom). The closest in time satellite to the field data peak was on 10/21/2006 with 0.36 (not indicative a significant bloom). Although there was some variability in field sites and between the different arms of Lake Billy Chinook, I could not find a matching pattern between the field data and the satellite prediction. The satellite data for 2006 had a different pattern than the lake measurements which could be indicative of: a failure of this approach, the sampling frequency of field and satellite data is too sparse, or spatial averaging is not representative of the grab sample location. There does not appear to be a distinct pattern the B2/B1 ratio besides that there is a peak greater than 0.4 in every year but one, 2001.

Figure 7. Band 2 / Band 1 ratio for Lake Billy Chinook (Deschutes and Metolius Arms), 1999 – 2008.



Lake Simtustus chlorophyll *a* data was collected in 2006 (6 samples, peaks on 6/22/2006, 35 µg/L and 9/20/2006, 36 µg/L). The B2/B1 ratio peaked on 4/28/2006 with 0.45 and 8/26/2006 with 0.43 and had an average annual peak of 0.43 (Figure 8). The earliest field data was collected on 5/16/2006 and was 7 ug/L. The late June peak in field data is one day from the 6/23/2006 image with a B2/B1 ratio of 0.39. There was no satellite imagery within 20 days to compare to the 9/20/2006 field data. The satellite data indicate that 2006 may have been unique with a significant spring algae bloom. The satellite data also indicate a more consistent pattern of peak algae activity in late August or early September.

Figure 8. Band 2 / Band 1 ratio for Lake Simtustus, 1999 – 2008.



The Landsat dataset does appear to be able evaluate the seasonal and inter-annual patterns of algal biomass and whether the grabs samples were collected at representative times and years.

Question Two: How much spatial variability of chlorophyll *a* concentrations does each lake exhibit?

The B2/B1 ratios and enhanced color imagery show similar patterns to observed chlorophyll *a* concentrations, however I did not attempt a quantified analysis. In Odell Lake, surface chlorophyll *a* concentration ranged from 2, 29, 50 µg/L in the western, middle and eastern portions of the lake, respectively on July 21, 2004. A similar pattern was observed in the B2/B1 ratios and enhanced imagery with a west to east gradient of increasing values (Figure 9).

The chlorophyll *a* seasonal averages of 2006 sampling from Lake Billy Chinook did not show much spatial variability: Deschutes River arm = 13 µg/L, Crooked River arm = 16 µg/L, and Metolius River arm = 12 µg/L although some individual sampling events showed much more variability. There was not a sampling event with variability and high chlorophyll *a* measurements with a close satellite image. The satellite image from 8/2/2006 shows the middle portions of each arm with consistent B2/B1 ratios but further up the Metolius arm, much lower B2/B1 ratios (Figure 10).

Figure 9. Odell Lake, enhanced true color image from 7/27/2004 with B2/B1 ratios for two locations. The black stripes in the image are areas of no data due to a satellite malfunction.

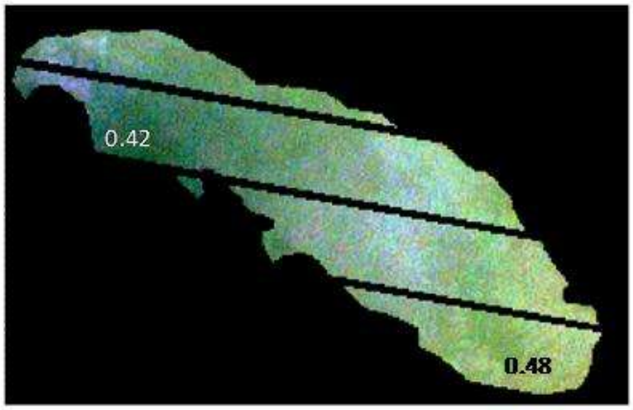
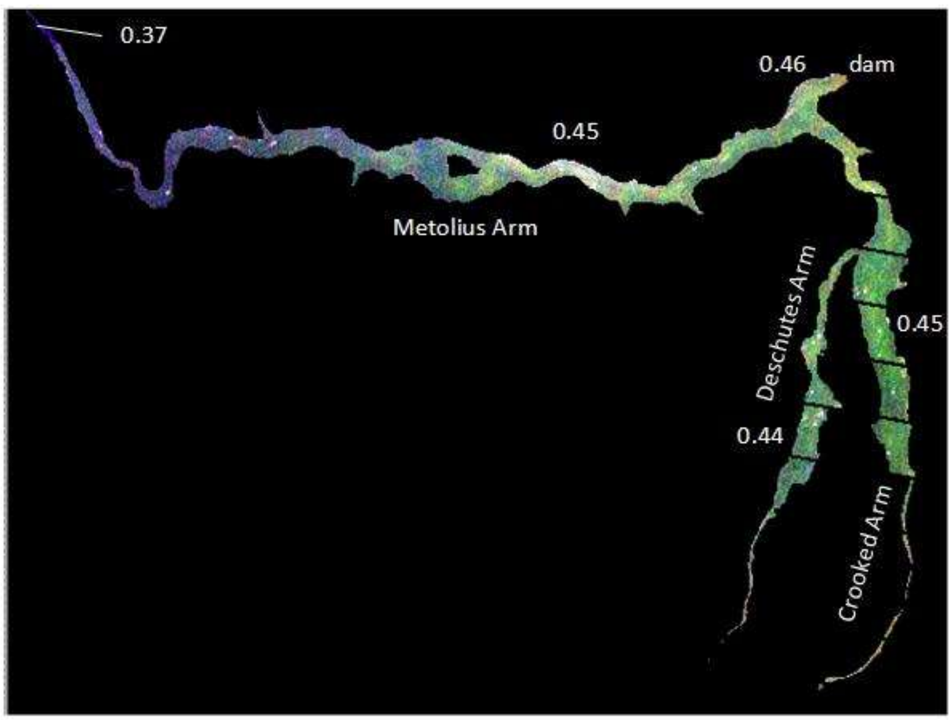


Figure 10. Lake Billy Chinook, enhance true color image from 8/2/2006 with B2/B1 ratios for various locations.



Question Three: Have conditions improved or worsened over time?

Given the average acceptable image frequency of 21 days between May and October (i.e. after filtering out images with atmospheric interference), I suspect that there are years when the peak algae bloom was not captured. For example, this methodology did not indicate a significant bloom on Odell Lake in 2002 or 2003, however there were no images from late July when the period when peaks in the other years occurred. Given this limitation, I did not attempt a trend analysis. This methodology does hold some promise for a more qualitative assessment thought.

For example, Nan Scott Lake had one year, 2005, when the B2/B1 ratio indicates a significant algae bloom (Figure 11). This pattern was not observed in other lakes and I have not been able to track down any anecdotal evidence of what might have occurred during 2005. The lake appears to be surrounding by private land. Also, impact of restoration of Diamond Lake in late 2006 with water drawdown and rotenone treatment to control tui chub was evaluated (Figure 12). Years 2007 and 2008 did not have B2/B1 ratio values which would indicate a significant mid-summer bloom, like years 2000 through 2006.

Figure 11. Band 2 / Band 1 ratio for Nan-Scott Lake, 1999 – 2008.

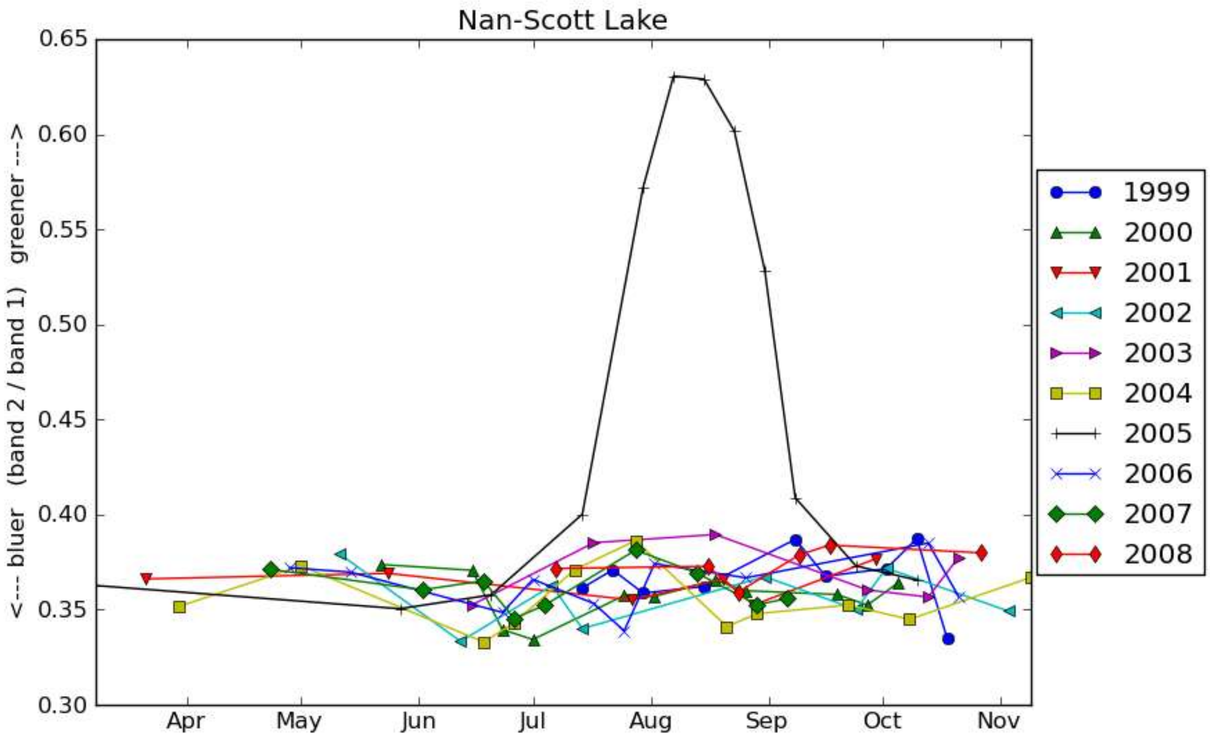
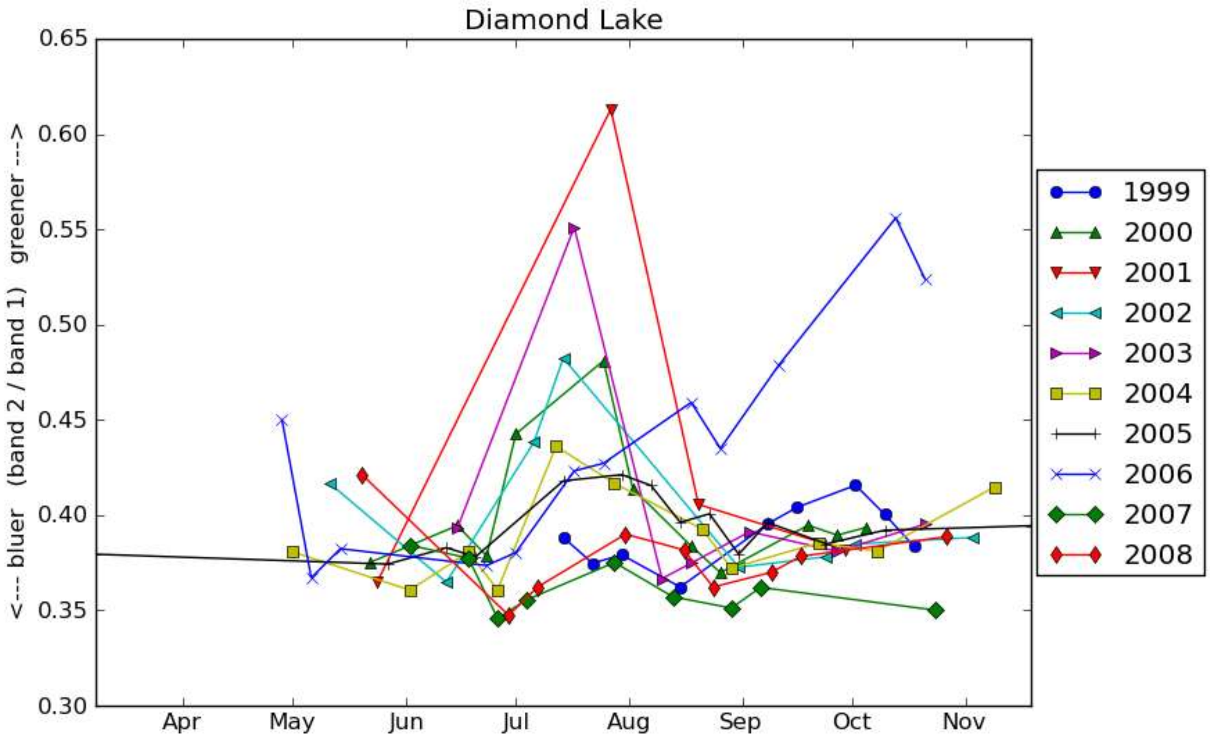


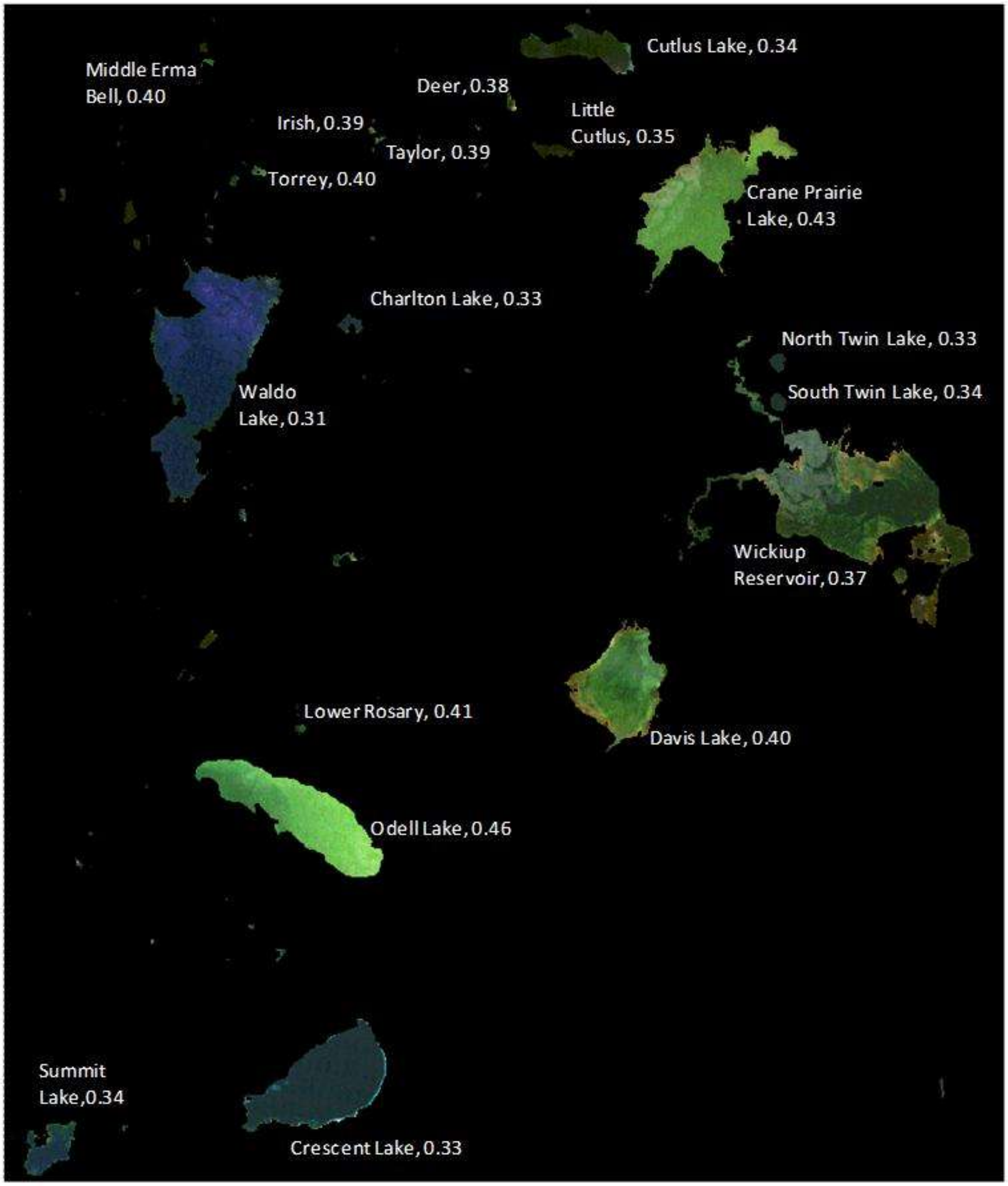
Figure 12. Band 2 / Band 1 ratio for Diamond Lake, 1999 – 2008.



Question Four: Are there lakes in the region which have similar chlorophyll *a* concentrations to the lakes on the 303(d) list?

I think this could be the strength of this methodology. Visual inspection of enhanced true color imagery shows notable difference in the optical properties of lakes. For example, Figure 13 shows lakes with known algae problems (i.e. Odell and Crane Prairie) as bright green and known high quality lakes (i.e. Waldo) as dark blue.

Figure 13. Stretched true color image from 7/25/2006 of some central Cascade lakes with lake average B2/B1 ratios.



To quantify these differences, I plotted the average of the annual peak B2/B1 ratios against the corresponding Band 2 / Band 3 (Green / Red) ratio (Figure 14). The plot generally segregates lakes into a classification scheme similar to the trophic status indices in the Atlas. Only lakes with satellite data for each of the 10 years were plotted. I used the Band 2 / Band 3 ratio to indicate whether the peak B2/B1 ratio might have been caused by an algae bloom (higher Band 2 / Band 3 ratio indicating more green) or inorganic suspended solids (lower Band 2 / Band 3 ratio indicating a redder color). Prineville Reservoir is an example of where I suspected influence of inorganic suspended solids causing turbidity. I suspect that a lower Band 2 / Band 3 ratio does not preclude significant algae blooms but rather indicates the presence of turbidity from a different source.

I generated a simple, classification system based by graphically comparing the optical properties of the lakes to the Atlas trophic statuses: ulatraoligotrophic, oligotrophic, mesotrophic, eutrophic and hypereutrophic of 89 lakes in the study area. The classification of "UltraBlue", "Blue" and "Middle" were meant to be roughly equivalent to ultraoligotrophic, oligotrophic and mesotrophic, respectively while both "Green" and "Red and Green" capture most of the eutrophic and hypereutrophic classes. Lakes with HABs primarily fall within the "Green" category. Maps of the lakes according to this classification scheme are presented in Figure 15 and Figure 16. Appendix B is a table with results from all the named lakes within the study area.

Figure 14. Scatter plot of average of the annual peak Band 2 / Band 1 ratios with average Band 2 / Band 3 ratios of the same dates. Lakes with HABs are presented as different symbols and, where available, the Altas trophic status is indicated by color. LBC = Lake Billy Chinook.

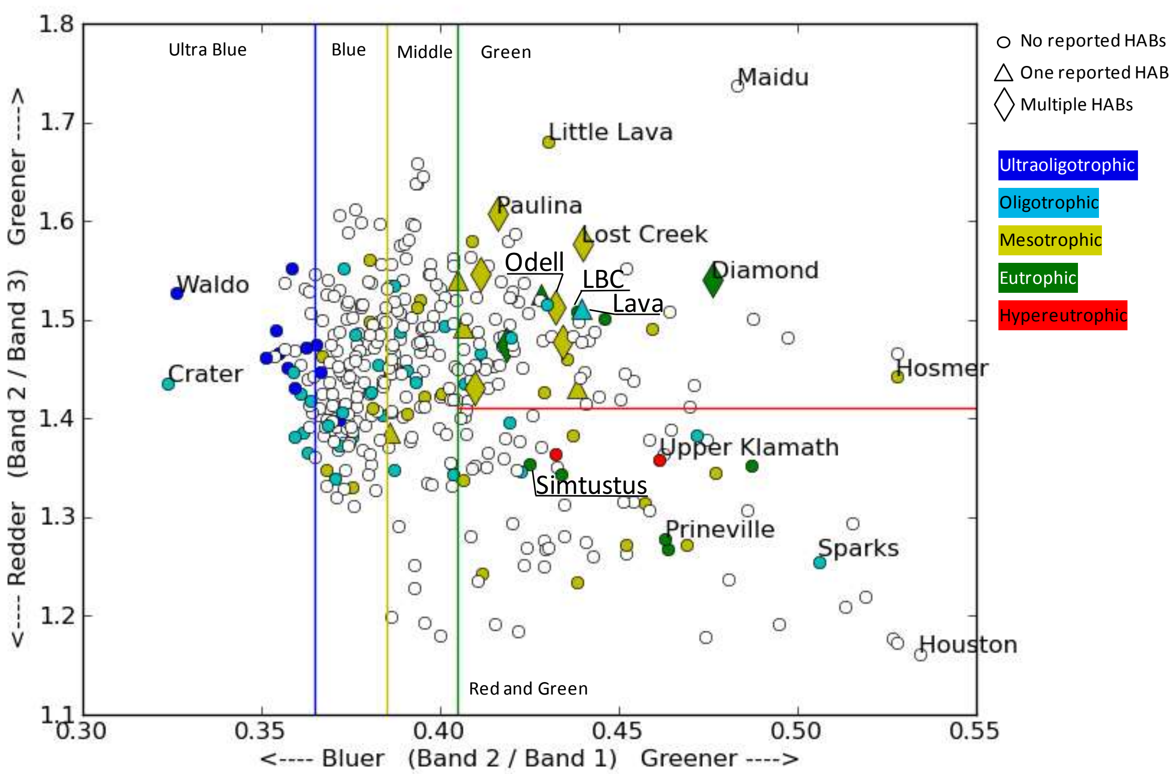


Figure 15. Larger lakes (> 173 acres) classified using the ratios of the visible bands of the Landsat satellites.

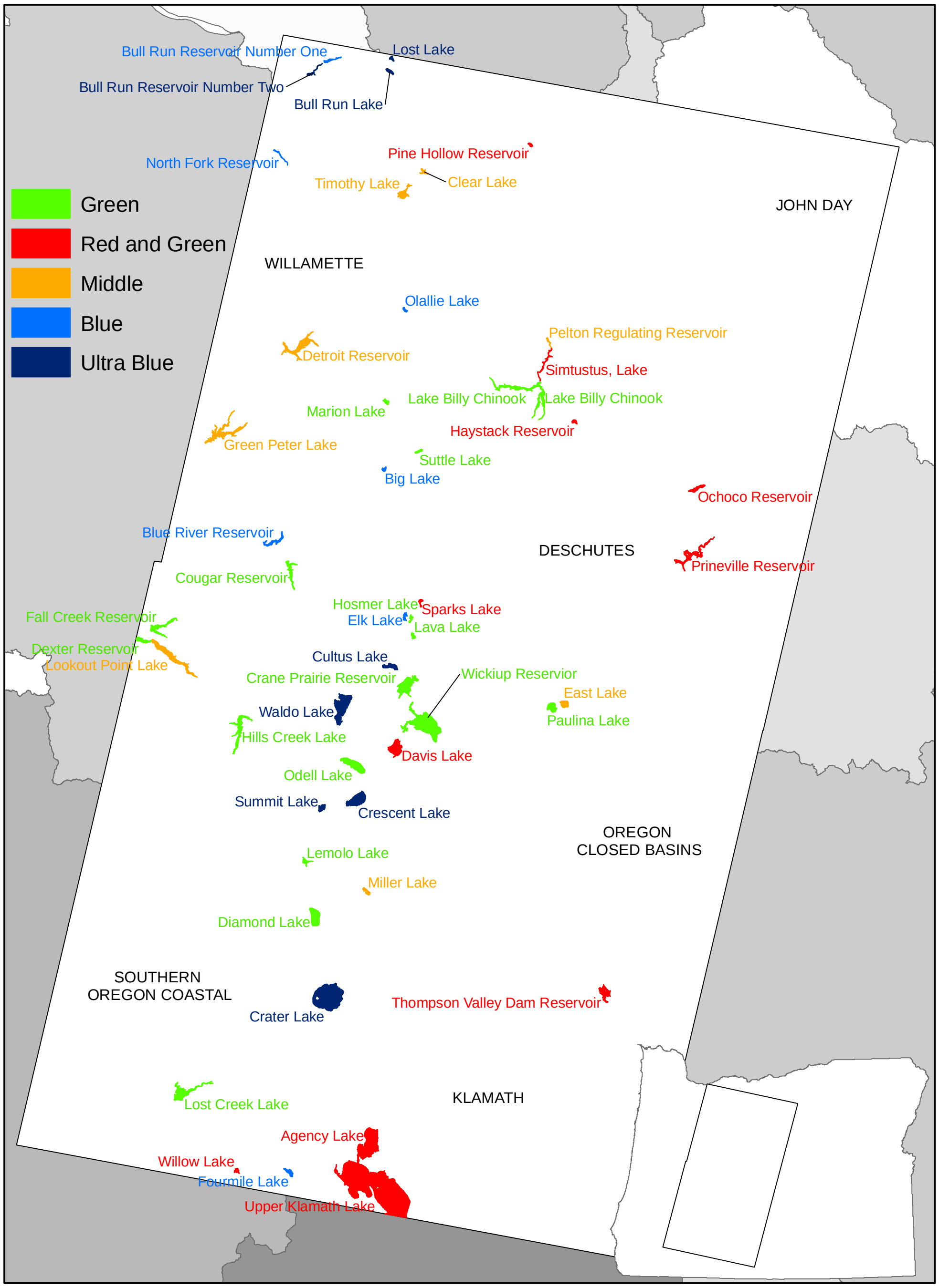
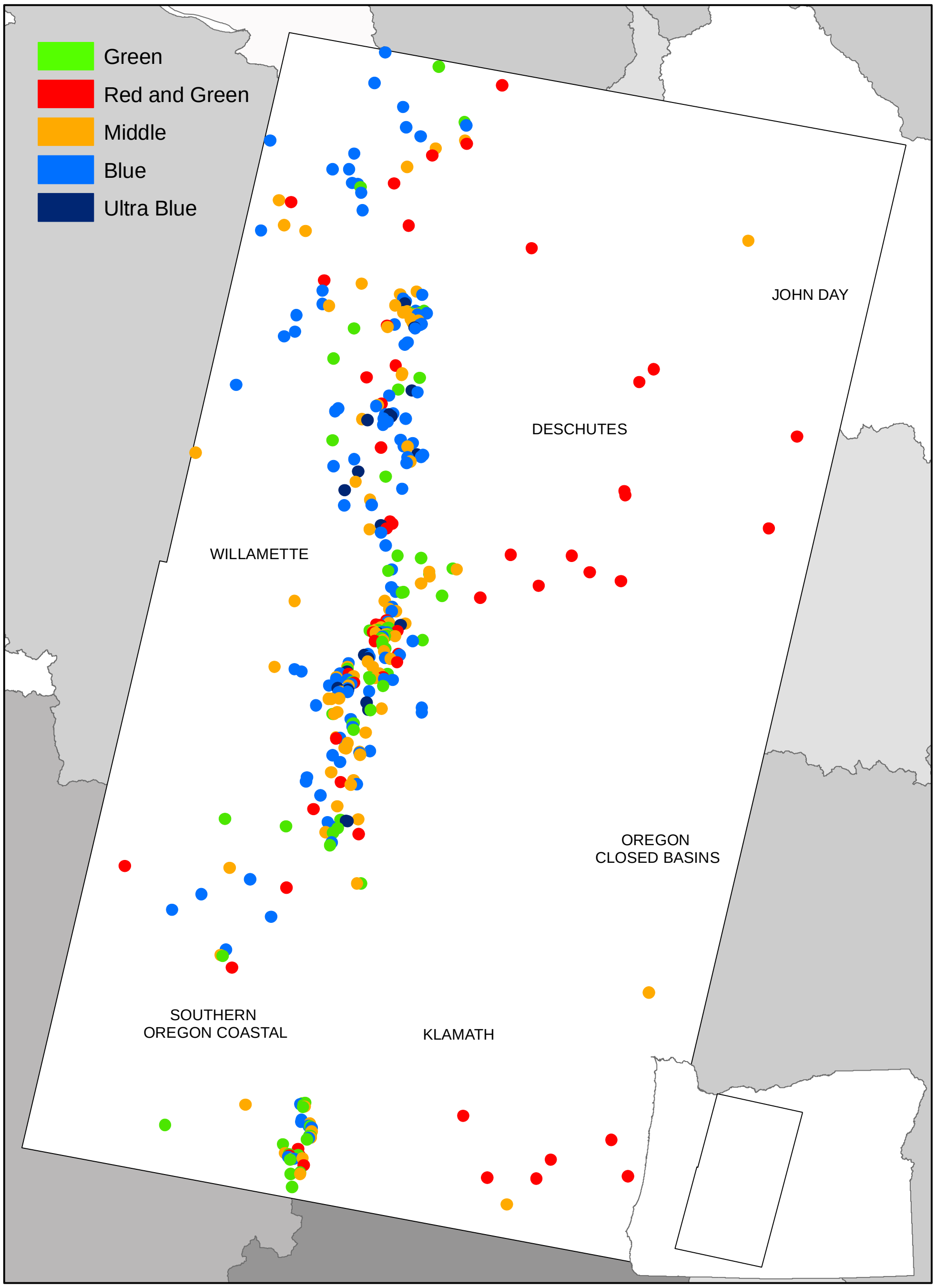


Figure 16. Smaller lakes (< 173 acres) classified using the ratios of the visible bands of the Landsat satellites.



Evaluation of satellite-based classification system

I think the satellite classification generally agreed with the lakes with identified HABs and the Atlas classification. Twelve of the 15 HAB lakes where classified as Green, two as Red/Green (Upper Klamath Lake and Haystack Reservoir, know problems but not on DHS website in 2009, so not identified in Figure 14) and one as Middle (Detroit Reservoir). None of the Atlas lakes classified as hypereutrophic or eutrophic were classified as Middle, Blue or Ultra Blue. However, 10 Atlas lakes classified as oligotrophic and ultraoligotrophic were classified Red/Green or Green (Table 4). These inconsistencies are described in more detail below.

Table 4. Comparison of the Atlas trophic classification and satellite classification by color.

		Satellite Status				
		Red / Green	Green	Middle	Blue	Ultra Blue
Atlas Classification	hypereutrophic	2				
	eutrophic	5	5			
	mesotrophic	8	13	7	6	
	oligotrophic	4	5	7	10	7
	ultraoligotrophic		1		3	8

Altas: Ultraoligotrophic, Satellite: Green

One lake (Monon Lake) was an ultraologiotrophic lake which ranked as "green" using the satellite classification scheme. Large areas of the lake are shallow (average depth 7 feet) and the lake is very clear (transparency > 39 feet) with the entire bottom of the lake visible (Johnson et al 1985). The B2/B1 ratio shows elevated summer values (B2/B1 =0.41, B2/B3 = 1.45, hidden in Figure 14 behind other points) causing to be classified as "green" but there are no distinct peaks like Odell Lake and a consistent seasonal pattern of increasing ratio from early to late summer (Figure 17). Maidu is another lake with similar B2/B1 ratio pattern but even higher values with an average of annual peaks of 0.48 (see Figure 14). It is a small natural lake (elevation 5,980 ft) and is considered the source of the North Umpqua River (Wikipedia, 5/6/2010). A photograph confirms the clarity of the lake and it appears that there are shallow areas (Figure 18). Also, of note, is the greenish hue of the water in the middle ground. Both of these lakes are likely 'false positives' in the satellite based classification and do not have nuisance algae problems.

Figure 17. Band 2 / Band 1 ratio for Monon Lake, 1999 – 2008.

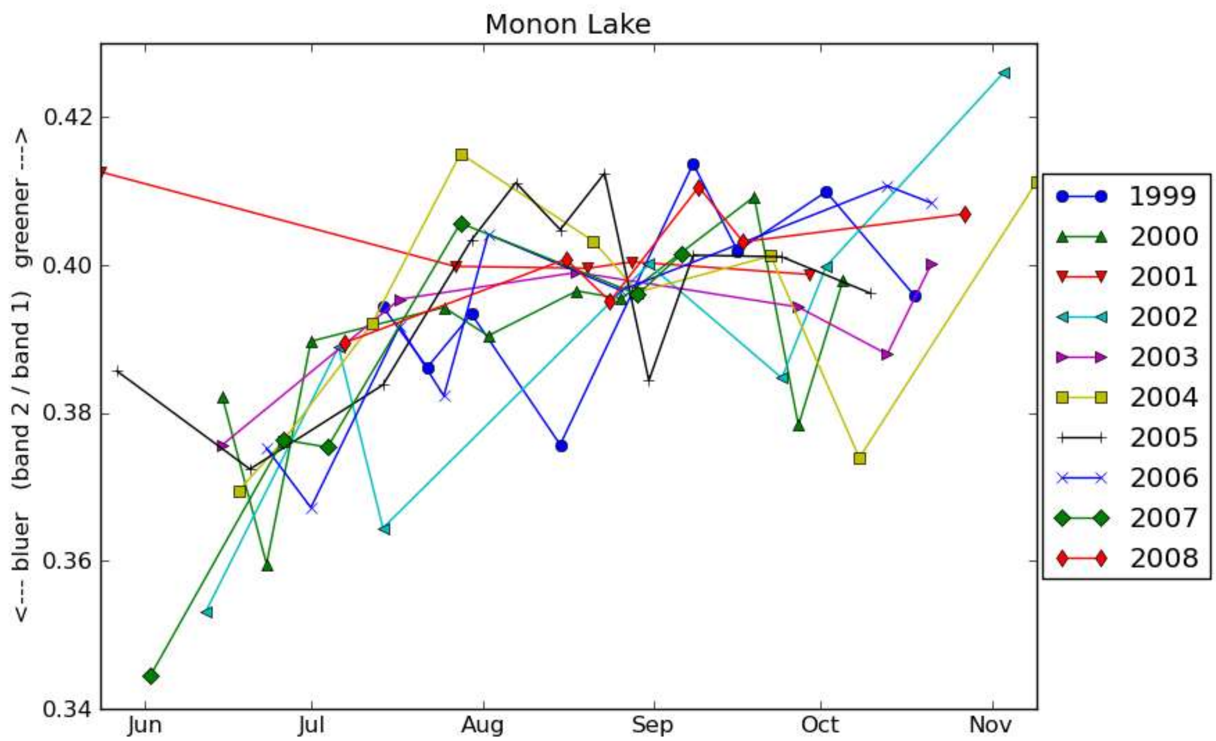


Figure 18. Photo of Maidu lake on 8/3/2008 (from Picasa, used with permission, photo by "Mark" at http://picasaweb.google.com/lh/photo/O7oAVhMGs9OgFWEyR6QXbQ accessed on 5/17/2010).

Atlas: Oligotrophic, Satellite: Green

Five lakes fell within this category. These are identified below in three different groupings.

Likely False Positive (similar to Monon, shallow and clear leading to a greenish hue):

Heavenly Twin Lakes (average depth 5 ft, >9.8 ft transparency)

Deer Lake (Deschutes County), (average depth 9 ft, >26 ft transparency)

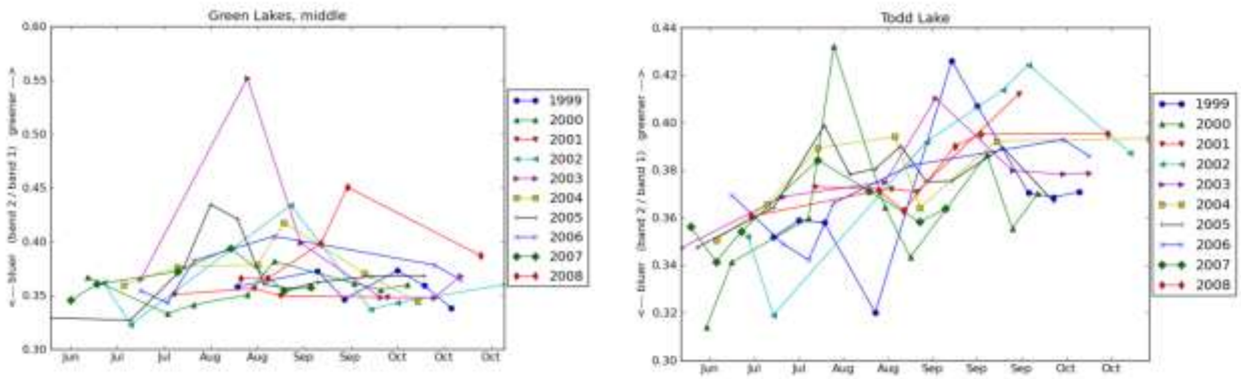
Documented algae blooms:

Lava Lake, high natural phosphorus, 0.53, likely misclassified due to lack of data.

Possible summer peaks, more investigation necessary (Figure 19):

Middle Green Lakes, (average depth 18 ft, 23.6 ft transparency), Todd Lake (average depth 21 ft however northern part shallower, 23 ft transparency, high P, stratification)

Figure 19. Band 2 / Band 1 ratio for Middle Green Lake (left) and Todd Lake (right), 1999 – 2008.



Atlas: Oligotrophic, Satellite: Red/Green:

<u>Four lakes fell within this category. These are identified below in two different groupings.</u>

<u>Likely False Positive (similar to Monon):</u>

Island Lake (average depth 5 ft, >21 ft transparency, phosphorus: 0.009 ug/L, moderate phytoplankton density)

Scott Lake (average depth 4 ft, >19 ft transparency, phosphorus: 0.010)

Sparks Lake (average depth 7 ft, >7 ft transparency, phosphorus: 0.022), possible influence of wet meadows?

<u>Possible summer peaks, more investigation necessary:</u>

Torrey Lake (average depth 5 ft, > 12.8 transparency, low phosphorus)

I used the satellite classification to identify the lakes below that may have significant algae blooms that had not been identified as having a HAB or as eutrophic in the Atlas. For lakes greater than 10 acres that were classified as Green or Red/Green, I examined the timeseries of B2/B1 ratio to filter out lakes with a pattern similar to Monon Lake (see above). The segregation between Green and Red/Green may be significant because most lakes with HABs were classified as Green.

Green:

Little Lava Lake, Little Three Creek Lake, Marion Lake (see Appendix C for graph), Trout Lake (Jefferson County), Middle Erma Bell Lake, Squaw Lake, Indigo Lake, Laurance Lake, Whig Lake, Horseshoe Lake, Windy Lakes, Rainbow Lake, Rock Lake, Budger Lake (Klamath County, not Badger lake) and Indian Lake Reservoir.

Red/Green:

Sandy Lake, Frog Lake (Wasco County), Diamond View Lake, Nan-Scott Lake, Pine Hollow Reservoir, Slipper Lake, Davis Lake, Pamelia Lake, Hawks Lake, Walton Lake, Upper Tumalo Reservoir, Little Willow Creek Reservoir, Dinger Lake, O'Connors Puddle Reservoir, Happy Valley Reservoir, Lost Lake (Linn County), Thompson Valley Reservoir, Penn Lake, Stump Lake, Crown Lake, Brewer Reservoir, Hand Lake (Lane County, going dry?), Summit Lake (Clackamas County), Mirror Pond, Wild Billy Lake, Hyde Reservoir, Tumalo Lake, Reynolds Pond, Riddle Field (going dry?), Smokey Lake, Horse Heaven Reservoir (going dry?), Little Houston Lake, and Houston Lake.

Discussion

A region-wide lake radiance to chlorophyll *a* relationship was not possible given the difficulty of calculating radiance (as opposed to a relative digital number) and interference of inorganic suspended solids and dissolved solids. However, the data was used to develop relative, regional relationships that appear to be related to algal biomass. The strength of this methodology was the relative values in space and time, so that for each lake potential timing of blooms, inter-annual variability and intra-annual variability could be identified. Furthermore, lakes across the region could be compared to one another and lakes without sampling programs could be monitored for potential impairment.

Suggestions for further work

- More research into methods of atmospheric correction so data could be comparable throughout the state and to other locations.
- Evaluations of patterns to segregate which lakes have spikes and which have consistently high summer values. This might tease out possible false positives like Monon and Maidu.
- Statewide database for lakes data. There are many different agencies and volunteers collecting data, however it was difficult to centralize the data for this project.
- Evaluate the use of other satellite, especially in conjunction with Landsat. Explore whether it would be possible to combine the higher spatial resolution of Landsat with the higher spectral and temporal resolution of other platforms.
- Expand the classification scheme in this study to the entire state. One could use an existing Landsat imagery that has been stitched together for the entire state as a reference image.
- Compare results to EPA lake survey.

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Sudfeer, K.P., Chaubey, I., and Garg, V., 2007, Lake water quality assessment from Landsat Thematic Mapper data using neural network: an approach to optimal band combination selection. JAWRA, 42,6, 1683 - 1695

Waldron, M.C., Steeves, P.A., and Finn J.T., Use of Thematic Mapper Imagery to Assess Water Quality, Trophic State, and Macrophyte Distributions in Massachusetts Lakes, 2001, Water Resources Investigations Report 01-4016.

Appendix A: Literature Review Notes

1. Gitelson A.A., Yacobi, Y.Z., Rundquist, D.C., Stark, R., Han, L., and Etzion D., 2000, Remote estimation of chlorophyll concentration in productive waters: Principals, algorithm development and validation

Paper copy only

Paper presents reflectance spectra of chlorophyll with low to high concentrations. Good graphs.

400 – 500 nm: All water constituents have significant optical activity in spectral range 400 to 500 nm. Absorption by pigments (i.e. Chl) is masked by absorption of dissolved organic matter and scattering by suspended matter . Of special importance is a relectance mimum near 440 nm, caused by Chl absorption; this feature is used in oligotrophic water, in a reflectance (R) ratio at 440 nm and 550 nm (R_{440}/R_{550}), to estimate Chl concentration. However, the minimum near 440 nm is often indistinct in reflectance spectra of productive water, due to strong absorption by dissolved organic matter and scattering by particulate matter.

500 – 700 nm: (a) peak in the green range near 550 – 570 nm (reflectance of green), (b) trough near 625 nm, (c) trough at 670-680 nm (absorption in red range) and (d) distinctive peak near 700 nm (red-NIR boundary).

Discussion of blue-green v green algae septra. Chl flouresence at 685 nm in waters with low Chl concentrations. In higher Chl concentrations there is re-absorption of fluorescence signal. Presentation of spectra / chl model for high resolution spectral data: ratio of 700 to 670 v. chlorophyll a concentration. MERIS and MODIS have potential for using this ratio.

"In order to harness the satellite acquired data for water quality monitoring several steps of operation are mandatory:

- Adjustment of algorithms for Chl estimation, developed by the use of high-resolution spectroradiometers at ground level, to the capabilities offered by satellite-carried sensors;
- Establishment of a routine for satellite image acquisition, processing and analysis, including geometrical and atmospheric corrections of the images, and selection of the relevant optical information;
- Validation of the satellite data by ground observations in diverse aquatic productive ecosystems."

2. Ritchie, J.C., Zimba, P.V., and Everitt, J.C., 2003, Remote Sensing Techniques to Assess Water Quality, Photogrammetric Engineering & Remote Sensing, Vol. 69, No. 6, June 2003, pp 695 – 704.

T:\Article_repository\Remote Sensing\lakes\Ritchie et al 2003 Remote sensing techniques to assess water quality.pdf

Review article.

TSS: If the range of suspended sediments is between 0 and 50 mg/L, reflectance from almost any wavelength will be linearly related to suspended sediment concentrations. Curvilinear relationships from 50 – 150 mg/L.

Algae / Chlorophyll: empirical relationship developed between radiance/reflectance in narrow band or band ratios and chlorophyll. Broad wavelength spectral data (i.e. Landsat) do not permit discrimination of chlorophyll in water with high suspended sediments (how high?). Presentation of spectral signatures. SeaWiFS, Modular Optical Scanner (MOS), Ocean Color and Temperature Scanner (OCTS), and Iknonos are available and hold great promise for measuring chlorophyll in aquatic systems.

3. Waldron, M.C., Steeves, P.A., and Finn J.T., Use of Thematic Mapper Imagery to Assess Water Quality, Trophic State, and Macrophyte Distributions in Massachusetts Lakes, 2001, Water Resources Investigations Report 01-4016.

T:\Article_repository\Remote Sensing\lakes\Waldron et al 2001 Use of Thematic Mapper WQ Lake in MA.pdf

Case study of 97 lakes, snapshot.

Attempts to develop predictive relationships between phytoplankton-chlorophyll concentration, Secchi depth, lake color, dissolved organic carbon and various combinations of TM band 1, 2, 3 and 4 digital numbers (DNs) were unsuccessful. The poor relationships were primarily the result of the extremely low chlorophyll concentrations (median = 3.1 ug/L) in the lakes studied, and also because of the highly variable DOC concentrations. Used Wilkie and Finn (1996) to correct for haze using visible (1-3) versus IR (4) regression and shifting the line so the intercept was a zero.

4. Sass, G.Z., Creed I.F., Bayley, S.E., and Devito K.J., 2007, Understanding variation in trophic status of lakes on the Boreal Plain: A 20 year retrospective using Landsat TM imagery, Remote Sensing of Environment, 109, 127-141.

T:\Article_repository\Remote Sensing\lakes\Sass 2007 Understanding variation in trophic status of lakes on the Boreal Plain.pdf

Good introduction section with lots of references. Images converted to "exoatmospheric reflectance" (Coppin and Bauer, 1994)? Used simple image-to-image radiometric normalization. Open-water was identified by the band 5 reflectance using a threshold that was equal to the local minimum in the bimodeal distribution that differentiated water and land pixels (Frazier et al 2003). The average normalized exoatmospheric reflectance for a 3X3 window centered on the center lake (assumed to be the deepest spot) was used as the satellite "sample". Manual masking of cloud and shadow areas. Lake selection for regression: (1) minimum lake area limited of 100 pixels (about 5 ha), (2) criterion that the standard deviation of normalized relectance for B5 for the 3x3 window had to be < 2 (scaled %), (3) upper threshold of 200 pixels (12.5) because of misalignment of sampling locations. Regression with B3 chosen. We conclude that normalized exoatmospheric reflectance completed from Landsat imagery can be used to explain the majority of the variance in CHLa. Regional spatial factors explained 50% while 10% was explained by temporal factors.

5. Sudfeer, K.P., Chaubey, I., and Garg, V., 2007, Lake water quality assessment from Landsat Thematic Mapper data using neural network: an approach to optimal band combination selection. JAWRA, 42,6, 1683 - 1695

T:\Article_repository\Remote Sensing\lakes\Sudheer 2006 Lake WQ Assess from landsat using neural network.pdf

Complex analysis using artificial neural networks and discussion of appropriate inputs.

6. Oyama, Y., Matsushita, B., Fukushima, T., Nagai, T., and Imai, A., 2007, A new algorithm for estimating chlorophyll-a concentration from multi-spectral satellite data in case II waters: a simulation based on a controlled laboratory experiment. International Journal of Remote Sensing, Vol 28, Nos. 7-8, April 2007, 1437-1453.

Presents spectral decomposition algorithm for estimating CHLa concentrations with higher accuracy than conventional methods. Based on laboratory analysis and unclear if scalable and if applicable to other phytoplankton types. Does not consider DOC.

7. Brivio, P.A., Giardino, C., and Zilioli, E., Validation of satellite data for quality assurance in lake monitoring applications, 2001, The Science of the Total Environment, 268, 3-18.

Image-based atmospheric correction for Landsat-5 data derived from lakes tested with reflectance data. Tests Cosine and Tau-mean methods (Chavez 1996) and quantifies errors. "For the Landsat-7 ETM+ the signal to noise ratio ranges from two to 10 times higher than that of the Landsat-5 TM."

T:\Article_repository\Remote Sensing\lakes\Brivio 2001 Validation of satellite data for quality assurance in lake monitoring applications.pdf

8. Hadjimitsis, D.G., Clayton, C.R.I. and Hope, V.S., 2004, An assessment of the effectiveness of atmospheric correction algorithms through the remote sensing of some reservoirs, International Journal of Remote Sensing, Vol 25, No 18, 3651 – 3674.

T:\Article_repository\Remote Sensing\lakes\Hadjimitsis 2004 An assessment of the effectiveness of atmospheric correction algorithms through the remote sensing of some reservoirs.pdf

Very good review of atmospheric correction methods related specifically to remote sensing of water.

Darkest pixel (DP, aka DOS) method: For Landsat TM band 4, the DP was not adequate. Most appropriate for bands 1,2,3. Required mimimum values in each band cannot, in our experience, be generated automatically. Used plotted histograms for suitable dark parts of image, such as clear water, and ignoring outliers thought to be due to noise and data errors. DP method was found to perform best on band 1,2,3. Covariance Matrix, Regression and Regression Intersection produced unreliable results in most cases.

Our results suggest that the standard generic models of the atmospheres included in codes such as ATCOR-2 and 6S code are not sufficiently accurate when dealing with dark targets such as water bodies.

9. Kobayashi, S., and Sanga-Ngoie, K., 2009, A comparative study of radiometric correction methods for optical remote sensing imagery: the IRC vs. other image-based C-correction methods, International Journal of Remote Sensing, Vol. 30, Nos. 1-2, 285-314.

T:\Article_repository\Remote Sensing\lakes\Kobayashi 2009 A comparative study of radiometric correction methods for optical remote sensing imagery The IRC vs other image based C correction methods.pdf

Seems mainly concerned with corrected for inclined surfaces and LULC mapping. Concerned mainly with "C-correction" methods.

10. Giardino, C., Pepe, M., Brivio, P.A., Ghezzi, P., and Zilioli, E., 2001, Detecting chlorophyll, Secchi disk depth and surface temperature in a sub-alpine lake using Landsat imagery, The Science of the Total Environment, vol. 268, 19-29.

T:\Article_repository\Remote Sensing\lakes\Giardino 2001 Detecting chlorophyll, Secchi disk depth and surface temperature in a sub-alpine lake using Landsat imagery.pdf

Landsat-5. One lake and one scene. Chavez 1996 atmo-correction. Dark pixel values from topographic shadow. Very high R2 values for CHLa and Secchi depth.

11. Oyama, Y., Matsushita, B., Fukushima, T., Matsushige, K., and Imai, A., 2009, Application of spectral decomposition algorithm for mapping water quality in a turbid lake (Lake Kasumigaura, Japan) from Landsat TM Data, Journal of Photogrammetry and Remote Sensing, vol. 64, 73-85.

T:\Article_repository\Remote Sensing\lakes\Oyama 2009 Application of spectral decomposition algorithm for mapping water quality in a turbid lake (Lake Kasumigaura Japan from Landsat TM data.pdf

Application of algorithms developed for spectral signature of CHLa and suspended sediment in tanks to a lake using Landsat-5 TM. About 10% and 15 % error for CHLa and SS, respectively. High potential but unclear if I could to apply to this project.

Appdendix B: Status of Lakes

Using the methodology described in the body of the report, the following statuses were determined. “Atlas Status” refers to the status reported in the Atlas of Oregon Lakes (Johnson et. al., 1985). “Green / Red” refers to ratio of digital numbers of calibrated images for band 2 and band 1, respectively. Likewise, “Green / Red” is band 2 divided by band 3. HABs is the number of years with harmful algae blooms recorded through 2009. See also Figure 14 for presentation of this data.

Name	County	Acres	Atlas Status	HABs	Satellite Status	Green / Blue	Green / Red
Maidu Lake	Douglas	22			Green	0.48	1.74
Little Lava Lake	Deschutes	130	mesotrophic		Green	0.43	1.68
Paulina Lake	Deschutes	1361	mesotrophic	4	Green	0.42	1.61
McKee Lake	Jackson	5			Green	0.42	1.59
Woods, Lake of the	Linn	6			Green	0.41	1.58
Last Lake	Lane	10			Green	0.42	1.58
Lost Creek Lake	Jackson	3360	mesotrophic	4	Green	0.44	1.58
Middle Lake	Klamath	26			Green	0.41	1.56
Denude Lake	Lane	4			Green	0.41	1.56
Amos and Andy Lake	Douglas	7			Green	0.45	1.55
Hills Creek Lake	Lane	2623	mesotrophic	5	Green	0.41	1.55
Diamond Lake	Douglas	2993	eutrophic	5	Green	0.48	1.54
Questionmark Lake	Lane	8			Green	0.42	1.54
Horseshoe Lake	Klamath	21			Green	0.42	1.54
Grass Lake	Klamath	29			Green	0.42	1.53
Suttle Lake	Jefferson	260	eutrophic	1	Green	0.43	1.53
Beal Lake	Klamath	5			Green	0.42	1.52
Jean Lake	Hood River	7			Green	0.41	1.52
Trio Lake Number 3	Lane	7			Green	0.42	1.52
Lower Betty Lake	Lane	6			Green	0.43	1.52
Merrill Lake	Lane	5			Green	0.42	1.52
Heavenly Twin Lakes	Klamath	22	oligotrophic		Green	0.43	1.52
Odell Lake	Klamath	3432	mesotrophic	5	Green	0.43	1.51
Lava Lake	Deschutes	345	oligotrophic	1	Green	0.44	1.51
Jefferson Lake	Jefferson	5			Green	0.46	1.51
Lake Billy Chinook (Deschutes and Metolius Arms)	Jefferson	2966	eutrophic		Green	0.44	1.51
Trio Lake Number 2	Lane	6			Green	0.42	1.51
South Lake	Klamath	9			Green	0.49	1.50
Taylor Lake	Deschutes	38			Green	0.41	1.50

Name	County	Acres	Atlas Status	HABs	Satellite Status	Green / Blue	Green / Red
Trapper Lake	Klamath	16			Green	0.42	1.50
Lake Billy Chinook (Crooked River Arm)	Jefferson	856	eutrophic		Green	0.45	1.50
Little Three Creek Lake	Deschutes	11			Green	0.44	1.50
Shellrock Lake	Clackamas	16			Green	0.41	1.50
Eileen Lake	Lane	4			Green	0.42	1.50
Cougar Reservoir	Lane	1386	mesotrophic	1	Green	0.41	1.49
Marion Lake	Linn	357	mesotrophic		Green	0.46	1.49
Mud Lake	Lane	4			Green	0.41	1.49
Charline, Lake	Douglas	4			Green	0.44	1.49
Isherwood Lake	Klamath	18			Green	0.44	1.48
Irish Lake	Deschutes	30			Green	0.42	1.48
Leone Lake	Marion	5			Green	0.43	1.48
Camp Lake	Deschutes	7			Green	0.42	1.48
Green Lakes, middle	Deschutes	104	oligotrophic		Green	0.42	1.48
Island Lake	Jefferson	31			Green	0.50	1.48
Trout Lake	Jefferson	29			Green	0.43	1.48
Middle Erma Bell Lake	Lane	41			Green	0.44	1.48
Squaw Lake	Klamath	29			Green	0.44	1.48
Wickiup Reservior	Deschutes	10153	mesotrophic	3	Green	0.43	1.48
Found Lake	Deschutes	6			Green	0.41	1.48
Lizard Lake	Douglas	3			Green	0.42	1.48
Crane Prairie Reservoir	Deschutes	4146	eutrophic	4	Green	0.42	1.48
S Lake	Lane	6			Green	0.42	1.47
Indigo Lake	Douglas	15			Green	0.41	1.47
Bullpup Lake	Douglas	6			Green	0.42	1.47
Deer Lake	Deschutes	52	oligotrophic		Green	0.41	1.47
Crescent Lake	Linn	6			Green	0.53	1.47
Laurance Lake	Hood River	91	mesotrophic		Green	0.44	1.46
Whig Lake	Lane	14			Green	0.41	1.46
Deer Lake	Klamath	4			Green	0.42	1.45
Cliff Lake	Douglas	6			Green	0.41	1.45
Monon Lake	Jefferson	93	ultraoligotrophic		Green	0.41	1.45
Sisters Mirror Lake	Deschutes	5			Green	0.41	1.45
Horseshoe Lake	Lane	19			Green	0.42	1.45
Freye Lake	Klamath	4			Green	0.41	1.45
Lemish Lake	Deschutes	15			Green	0.41	1.45
Copepod Lake	Lane	7			Green	0.41	1.45
Vogel Lake	Lane	11			Green	0.44	1.45
North Lake	Klamath	9			Green	0.45	1.44
Hosmer Lake	Deschutes	252	mesotrophic		Green	0.53	1.44

Name	County	Acres	Atlas Status	HABs	Satellite Status	Green / Blue	Green / Red
Windy Lakes	Klamath	14			Green	0.44	1.44
Snowshoe Lake	Deschutes	15			Green	0.41	1.44
Upper Snowshoe Lake	Deschutes	26			Green	0.45	1.44
Patjens Lakes	Linn	8			Green	0.42	1.44
Todd Lake	Deschutes	27	oligotrophic		Green	0.41	1.43
Long Lake	Deschutes	10			Green	0.47	1.43
Lemolo Lake	Douglas	449	mesotrophic	4	Green	0.41	1.43
Dexter Reservoir	Lane	843	mesotrophic	2	Green	0.44	1.43
Rainbow Lake	Linn	13			Green	0.41	1.43
Fall Creek Reservoir	Lane	1752	mesotrophic		Green	0.43	1.43
Rock Lake	Lane	11			Green	0.44	1.42
Budger Lake	Klamath	11			Green	0.45	1.42
Kidney Lake	Lane	7			Green	0.41	1.42
Dee Lake	Klamath	19			Green	0.44	1.41
Indian Lake Reservoir	Jackson	60			Green	0.47	1.41
Sandy Lake	Lane	11			Red / Green	0.41	1.41
Frog Lake	Wasco	19			Red / Green	0.43	1.40
Temple Lake	Linn	9			Red / Green	0.41	1.40
Top Lake	Lane	6			Red / Green	0.41	1.40
Torrey Lake	Lane	68	oligotrophic		Red / Green	0.42	1.40
Diamond View Lake	Klamath	12			Red / Green	0.46	1.39
Nan-Scott Lake	Linn	22			Red / Green	0.41	1.38
Island Lake	Klamath	44	oligotrophic		Red / Green	0.47	1.38
Pine Hollow Reservoir	Wasco	200	mesotrophic		Red / Green	0.44	1.38
Slipper Lake	Lane	10			Red / Green	0.42	1.38
Jay Lake	Deschutes	10			Red / Green	0.47	1.38
Triangle Lake	Douglas	6			Red / Green	0.46	1.38
Campers Lake	Lane	8			Red / Green	0.42	1.38
Lindh Lake	Lane	5			Red / Green	0.43	1.37
Memaloose Lake	Clackamas	5			Red / Green	0.41	1.37
Agency Lake	Klamath	9035	hypereutrophic		Red / Green	0.43	1.36
Lake Camp Baldwin	Wasco	5			Red / Green	0.46	1.36
North Corral Lake	Deschutes	5			Red / Green	0.42	1.36
Upper Klamath Lake	Klamath	42621	hypereutrophic	Yes	Red / Green	0.46	1.36
Simtustus, Lake	Jefferson	586	eutrophic		Red / Green	0.43	1.35
Willow Lake	Jackson	307	eutrophic		Red / Green	0.49	1.35
Senoj Lake	Deschutes	13			Red / Green	0.41	1.35
Mud Lake	Lane	7			Red / Green	0.41	1.35
Little Boulder Lake	Wasco	8			Red / Green	0.43	1.35
Lower Island Lake	Lane	5			Red / Green	0.41	1.35
Mosquito Lake	Lane	4			Red / Green	0.42	1.35

Name	County	Acres	Atlas Status	HABs	Satellite Status	Green / Blue	Green / Red
Scott Lake	Lane	11	oligotrophic		Red / Green	0.42	1.35
Davis Lake	Deschutes	3016	mesotrophic		Red / Green	0.48	1.35
Haystack Reservoir	Jefferson	260	eutrophic	1	Red / Green	0.43	1.34
Pamelia Lake	Linn	53	mesotrophic		Red / Green	0.41	1.34
Punsy Lake	Clackamas	6			Red / Green	0.45	1.32
Hawks Lake	Klamath	111			Red / Green	0.45	1.32
Walton Lake	Crook	21	mesotrophic		Red / Green	0.46	1.32
Infiltration Pond	Deschutes	61			Red / Green	0.43	1.31
Long Lake	Klamath	53			Red / Green	0.49	1.31
Upper Tumalo Reservoir	Deschutes	144	mesotrophic		Red / Green	0.46	1.31
Comma Lake	Deschutes	16			Red / Green	0.52	1.29
Little Willow Creek Res.	Jefferson	51			Red / Green	0.42	1.29
Dinger Lake	Clackamas	24			Red / Green	0.41	1.28
O'Connors Puddle Reservoir	Klamath	22			Red / Green	0.43	1.28
Prineville Reservoir	Crook	2798	eutrophic		Red / Green	0.46	1.28
Happy Valley Reservoir	Wasco	18			Red / Green	0.43	1.28
Mud Lake	Klamath	4			Red / Green	0.44	1.27
Lost Lake	Linn	45	mesotrophic		Red / Green	0.45	1.27
Thompson Valley Dam Reservoir	Lake	1802	mesotrophic		Red / Green	0.47	1.27
Penn Lake	Lane	13			Red / Green	0.43	1.27
Stump Lake	Douglas	22			Red / Green	0.42	1.27
Crown Lake	Marion	12			Red / Green	0.43	1.27
Ochoco Reservoir	Crook	841	eutrophic		Red / Green	0.46	1.27
Brewer Reservoir	Jefferson	56			Red / Green	0.45	1.26
Hand Lake	Lane	10			Red / Green	0.44	1.26
Sparks Lake	Deschutes	240	oligotrophic		Red / Green	0.51	1.26
Paris Reservoir	Douglas	5			Red / Green	0.42	1.25
Summit Lake	Clackamas	10			Red / Green	0.43	1.25
Mirror Pond	Deschutes	129	mesotrophic		Red / Green	0.41	1.24
Wild Billy Lake	Klamath	125			Red / Green	0.48	1.24
Hyde Reservoir	Klamath	64			Red / Green	0.41	1.24
Tumalo Lake	Deschutes	12			Red / Green	0.44	1.23
Reynolds Pond	Deschutes	11			Red / Green	0.52	1.22
Nip and Tuck Lakes	Klamath	5			Red / Green	0.51	1.21
Red Lake	Klamath	28			Red / Green	0.49	1.19
Riddle Field	Klamath	122			Red / Green	0.42	1.19
Smokey Lake	Klamath	37			Red / Green	0.42	1.19
Horse Heaven Reservoir	Crook	27			Red / Green	0.47	1.18
Little Houston Lake	Crook	20			Red / Green	0.53	1.18
Mayfield Pond	Deschutes	7			Red / Green	0.53	1.17

Name	County	Acres	Atlas Status	HABs	Satellite Status	Green / Blue	Green / Red
Houston Lake	Crook	49			Red / Green	0.53	1.16
Lookout Point Lake	Lane	4000	mesotrophic		Middle	0.40	1.54
Boulder Lake	Hood River	15			Middle	0.40	1.42
Cliff Lake	Klamath	8			Middle	0.40	1.52
Sunset Lake	Lane	14			Middle	0.40	1.45
Puppy Lake	Deschutes	11			Middle	0.40	1.56
Brahma Lake	Deschutes	10			Middle	0.40	1.42
Green Lakes, upper	Deschutes	10			Middle	0.40	1.50
West Hanks Lake	Deschutes	6			Middle	0.40	1.55
Breitenbush Lake	Marion	52	oligotrophic		Middle	0.40	1.34
Clear Lake	Wasco	350	oligotrophic		Middle	0.40	1.35
Lower Salmon Lake	Lane	9			Middle	0.40	1.33
Corner Lake	Lane	28			Middle	0.40	1.42
Leech Lake	Deschutes	34			Middle	0.40	1.35
Land, Lake	Klamath	3			Middle	0.40	1.43
Medca Pond	Jackson	67			Middle	0.40	1.38
Bobby Lake	Deschutes	78	oligotrophic		Middle	0.40	1.49
Cardiac Lake	Lane	5			Middle	0.40	1.52
Foster Lake	Linn	168	mesotrophic		Middle	0.40	1.43
Merle Lake	Deschutes	7			Middle	0.40	1.53
Woodpecker Lake	Klamath	4			Middle	0.40	1.51
Foster Lake	Lake	104			Middle	0.40	1.18
Averill Lake	Marion	12			Middle	0.40	1.42
Surprise Lake	Clackamas	4			Middle	0.40	1.39
Fay Lake	Linn	8			Middle	0.40	1.46
Saddle Lake	Klamath	6			Middle	0.40	1.54
Meek Lake	Klamath	12			Middle	0.40	1.50
Dumbbell Lake	Lane	8			Middle	0.40	1.49
Upper Island Lake	Lane	6			Middle	0.40	1.33
Si Lake	Marion	7			Middle	0.40	1.47
Martin Lake	Lane	7			Middle	0.40	1.56
Lucile, Lake	Douglas	9			Middle	0.40	1.55
Stag Lake	Klamath	17			Middle	0.40	1.55
North Rosary Lake	Klamath	10			Middle	0.40	1.49
Twin Lakes	Wasco	20			Middle	0.40	1.48
Pelton Regulating Reservoir	Jefferson	174			Middle	0.40	1.33
Horton Reservoir	Klamath	99			Middle	0.40	1.19
Junction Lake	Lane	19			Middle	0.40	1.41
Timothy Lake	Clackamas	1332	mesotrophic		Middle	0.40	1.42
Teddy Lake	Deschutes	30			Middle	0.40	1.45
Upper Salmon Lake	Lane	10			Middle	0.40	1.49

Name	County	Acres	Atlas Status	HABs	Satellite Status	Green / Blue	Green / Red
Deep Lake	Klamath	4			Middle	0.40	1.65
Cleo Lake	Linn	5			Middle	0.39	1.49
Lost Lake	Jefferson	7			Middle	0.39	1.48
Green Peter Lake	Linn	3489	mesotrophic		Middle	0.39	1.52
Moraine Lake	Deschutes	9			Middle	0.39	1.41
Green Lakes, south	Deschutes	8			Middle	0.39	1.48
Platt Lake	Lane	5			Middle	0.39	1.48
Horseshoe Lake	Jefferson	16			Middle	0.39	1.47
Pear Lake	Klamath	16			Middle	0.39	1.48
East Lake	Deschutes	968	mesotrophic		Middle	0.39	1.51
Photo Lake	Lane	6			Middle	0.39	1.64
Buckeye Lake	Douglas	9			Middle	0.39	1.66
June Lake	Douglas	9			Middle	0.39	1.64
Miller Lake	Klamath	514	oligotrophic		Middle	0.39	1.44
Lower Marilyn Lake	Lane	21			Middle	0.39	1.44
Bingham Lakes	Klamath	17			Middle	0.39	1.60
Frying Pan Lake	Clackamas	32			Middle	0.39	1.25
Rotten Lake	Wasco	8			Middle	0.39	1.23
Soda Springs Reservoir	Douglas	33			Middle	0.39	1.38
Helen Lake	Lane	7			Middle	0.39	1.60
Hunts Lake	Linn	7			Middle	0.39	1.50
Long Lake	Jefferson	14			Middle	0.39	1.38
Lower Rosary Lake	Klamath	42			Middle	0.39	1.58
Big Three Creek Lake	Deschutes	70			Middle	0.39	1.45
Gold Lake	Lane	86	mesotrophic		Middle	0.39	1.40
Prince Lake	Lane	4			Middle	0.39	1.46
Blow Lake	Deschutes	51			Middle	0.39	1.56
Hanks Lake	Linn	7			Middle	0.39	1.42
Moody Lake	Lane	5			Middle	0.39	1.58
Claggett Lake	Marion	6			Middle	0.39	1.52
Huckleberry Lake	Lane	6			Middle	0.39	1.54
Chetlo, Lake	Lane	19			Middle	0.39	1.49
Cougar Lake	Clackamas	7			Middle	0.39	1.40
Marie, Lake	Jefferson	10			Middle	0.39	1.45
Yoran Lake	Klamath	29			Middle	0.39	1.45
Russ Lake	Marion	8			Middle	0.39	1.48
Timber Lake	Jefferson	19			Middle	0.39	1.51
Lower Erma Bell Lake	Lane	39	oligotrophic		Middle	0.39	1.49
Mile Lake	Lane	6			Middle	0.39	1.58
Hand Lake	Jefferson	10			Middle	0.39	1.29
Hidden Lake	Lane	18			Middle	0.39	1.51

Name	County	Acres	Atlas Status	HABs	Satellite Status	Green / Blue	Green / Red
View Lake	Jefferson	9			Middle	0.39	1.45
Dunlap Lake	Marion	7			Middle	0.39	1.47
Heavenly Twin Lakes	Klamath	5	oligotrophic		Middle	0.39	1.53
Winopee Lake	Deschutes	73	oligotrophic		Middle	0.39	1.35
Stormy Lake	Deschutes	4			Middle	0.39	1.52
Johnny Lake	Deschutes	17			Middle	0.39	1.47
Robinson Lake	Linn	9			Middle	0.39	1.56
Upper Lake	Jefferson	15			Middle	0.39	1.41
Carmen Reservoir	Linn	30			Middle	0.39	1.47
Upper Marilyn Lake	Lane	22			Middle	0.39	1.46
Lower Quinn Lake	Lane	13			Middle	0.39	1.45
Plumb Lake	Lane	8			Middle	0.39	1.45
Center Lake	Klamath	4			Middle	0.39	1.20
Round Lake	Marion	8			Middle	0.39	1.41
Detroit Reservoir	Marion	3561	mesotrophic	1	Middle	0.39	1.39
Harvey Lake	Lane	18			Middle	0.39	1.53
Moonlight Lake	Lane	5			Middle	0.39	1.45
Round Lake	Lane	23			Middle	0.39	1.45
Williams Lake	Clackamas	5			Middle	0.39	1.37
Round Lake	Jackson	3			Middle	0.39	1.53
Hemlock Lake	Klamath	8			Blue	0.38	1.51
Holst Lake	Klamath	5			Blue	0.38	1.50
South Corral Lake	Deschutes	3			Blue	0.38	1.44
Badger Lake	Hood River	68	oligotrophic		Blue	0.38	1.40
Slideout Lake	Marion	7			Blue	0.38	1.44
Blue Lake	Lane	13			Blue	0.38	1.50
Long Lake	Jefferson	30			Blue	0.38	1.43
Calamut Lake	Douglas	12			Blue	0.38	1.56
Ann, Lake	Linn	23			Blue	0.38	1.38
Sonya, Lake	Klamath	8			Blue	0.38	1.48
Shadow Lake	Lane	6			Blue	0.38	1.60
Elk Lake	Deschutes	379	oligotrophic		Blue	0.38	1.45
Wahanna Lake	Lane	46			Blue	0.38	1.50
Alta, Lake	Klamath	16			Blue	0.38	1.48
Raft Lake	Deschutes	7			Blue	0.38	1.41
Island Lake	Jefferson	9			Blue	0.38	1.33
Porky Lake	Lane	34			Blue	0.38	1.47
Cabot Lake	Jefferson	6			Blue	0.38	1.48
Skookum Lake	Douglas	12			Blue	0.38	1.50
South Twin Lake	Deschutes	101	mesotrophic		Blue	0.38	1.41
Lorin Lake	Lane	7			Blue	0.38	1.54

Name	County	Acres	Atlas Status	HABs	Satellite Status	Green / Blue	Green / Red
Linton Lake	Lane	58	oligotrophic		Blue	0.38	1.43
Eastern Brook Lake	Lane	10			Blue	0.38	1.40
Burnt Lake	Clackamas	6			Blue	0.38	1.35
Green Peak Lake	Linn	8			Blue	0.38	1.50
Huxley Lake	Clackamas	4			Blue	0.38	1.36
Toketee Lake	Douglas	82	mesotrophic		Blue	0.38	1.50
Blue River Reservoir	Lane	1003	mesotrophic		Blue	0.38	1.56
Scout Lake	Jefferson	7			Blue	0.38	1.43
Blue Lake	Klamath	9			Blue	0.38	1.48
Grenet Lake	Linn	5			Blue	0.38	1.48
Mirror Lake	Clackamas	5			Blue	0.38	1.34
Opal Lake	Douglas	11			Blue	0.38	1.54
Parish Lake	Linn	7			Blue	0.38	1.47
Aerial Lake	Lane	3			Blue	0.38	1.39
Hickman Lake	Clackamas	10			Blue	0.38	1.43
Kuitan Lake	Linn	5			Blue	0.38	1.44
Otter Lake	Lane	9			Blue	0.38	1.45
Maiden Lake	Klamath	5			Blue	0.38	1.52
Plaza Lake	Clackamas	4			Blue	0.38	1.37
Spirit Lake	Lane	10			Blue	0.38	1.52
Twin Lakes	Douglas	15			Blue	0.38	1.60
Lindick Lake	Deschutes	7			Blue	0.38	1.51
Wasco Lake	Jefferson	20			Blue	0.38	1.47
Teto Lake	Linn	11			Blue	0.38	1.49
Russell Lake	Marion	8			Blue	0.38	1.43
Daly Lake	Linn	10			Blue	0.38	1.41
Serene Lake	Clackamas	22			Blue	0.38	1.47
George Lake	Deschutes	5			Blue	0.38	1.42
Shining Lake	Clackamas	14			Blue	0.38	1.40
Fawn Lake	Klamath	41			Blue	0.38	1.61
Devils Lake	Lane	7	oligotrophic		Blue	0.38	1.49
Long Lake	Lane	29			Blue	0.38	1.46
Margurette Lake	Klamath	14			Blue	0.38	1.46
Krag Lake	Lane	6			Blue	0.38	1.31
Fish Lake	Marion	36			Blue	0.38	1.44
Trillium Lake	Clackamas	60	mesotrophic		Blue	0.38	1.33
Upper Rigdon Lake	Lane	22			Blue	0.38	1.50
Elk Lake	Marion	64	oligotrophic		Blue	0.38	1.38
Horse Lake	Lane	31			Blue	0.38	1.39
Hemlock Lake	Douglas	50			Blue	0.37	1.39
Happy Lake	Lane	9			Blue	0.37	1.44

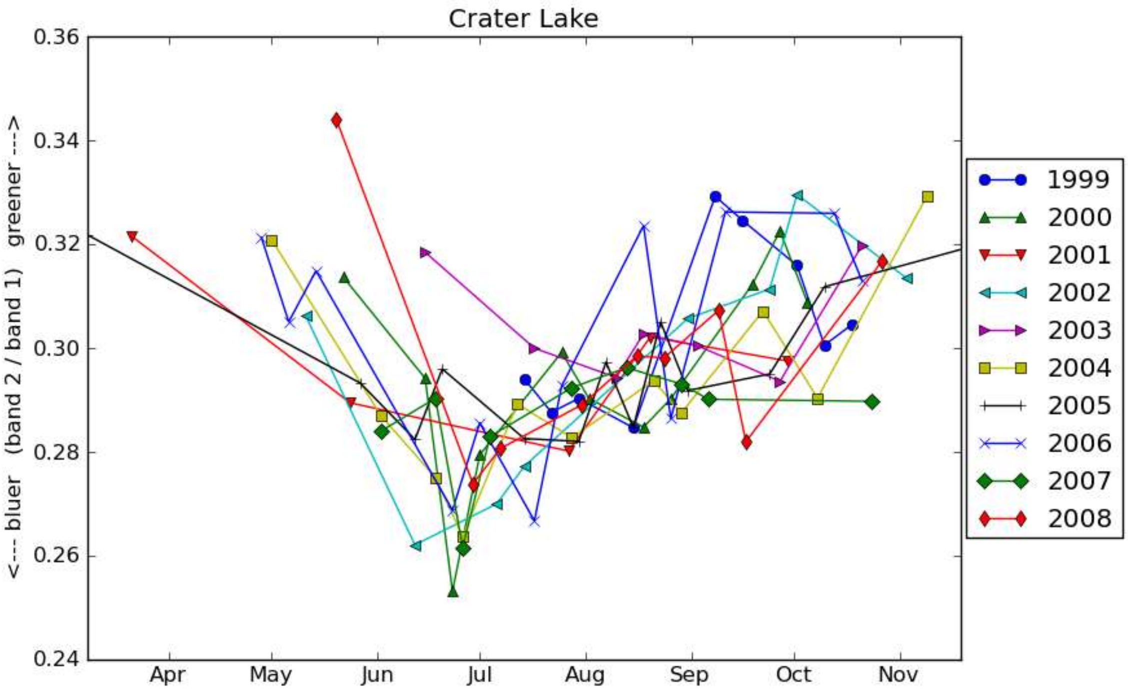
Name	County	Acres	Atlas Status	HABs	Satellite Status	Green / Blue	Green / Red
Heart Lake	Linn	8			Blue	0.37	1.38
Ernie Lake	Lane	23			Blue	0.37	1.46
Muskrat Lake	Deschutes	6			Blue	0.37	1.37
Duffy Lake	Linn	24			Blue	0.37	1.44
Blue Lake	Wasco	25			Blue	0.37	1.40
Notasha, Lake	Klamath	5			Blue	0.37	1.52
Moolack Lake	Lane	11			Blue	0.37	1.40
Turpentine Lake	Linn	9			Blue	0.37	1.59
Hideaway Lake	Clackamas	14			Blue	0.37	1.41
Melakwa Lake	Lane	18			Blue	0.37	1.50
Middle Rock Lake	Clackamas	12			Blue	0.37	1.39
Middle Rosary Lake	Klamath	9			Blue	0.37	1.52
Blair Lake	Lane	22			Blue	0.37	1.44
Meadow Lake	Deschutes	16			Blue	0.37	1.35
Honey Lake	Lane	8			Blue	0.37	1.41
Big Cliff Reservoir	Marion	116			Blue	0.37	1.33
Harriet	Clackamas	17			Blue	0.37	1.41
Fish Lake	Douglas	87	oligotrophic		Blue	0.37	1.55
Twin Lakes	Marion	10			Blue	0.37	1.38
Fourmile Lake	Klamath	653	oligotrophic		Blue	0.37	1.41
Mac Lake	Lane	20			Blue	0.37	1.44
Betty Lake	Lane	42			Blue	0.37	1.61
Midnight Lake	Lane	8			Blue	0.37	1.53
Gander Lake	Lane	42			Blue	0.37	1.45
Upper Quinn Lake	Lane	14			Blue	0.37	1.49
Trail Bridge Reservoir	Linn	58	oligotrophic		Blue	0.37	1.37
Olallie Lake	Jefferson	182	ultraoligotrophic		Blue	0.37	1.40
Dark Lake	Jefferson	14			Blue	0.37	1.37
Carey Lake	Klamath	7			Blue	0.37	1.45
Abernethy Lake	Lane	3			Blue	0.37	1.32
Scout Lake	Marion	8			Blue	0.37	1.47
Faraday Lake	Clackamas	37			Blue	0.37	1.39
Tumble Lake	Marion	19			Blue	0.37	1.41
Bull Run Reservoir No. 1	Multnomah	426	oligotrophic		Blue	0.37	1.34
Rockpile Lake	Lane	6			Blue	0.37	1.52
Nash Lake	Lane	26			Blue	0.37	1.38
Francis Lake	Jefferson	7			Blue	0.37	1.48
Harvey Lake	Jefferson	26			Blue	0.37	1.42
Round Lake	Jefferson	22			Blue	0.37	1.41
Upper Eddeeleo Lake	Lane	43			Blue	0.37	1.42
Top Lake	Lane	10			Blue	0.37	1.40

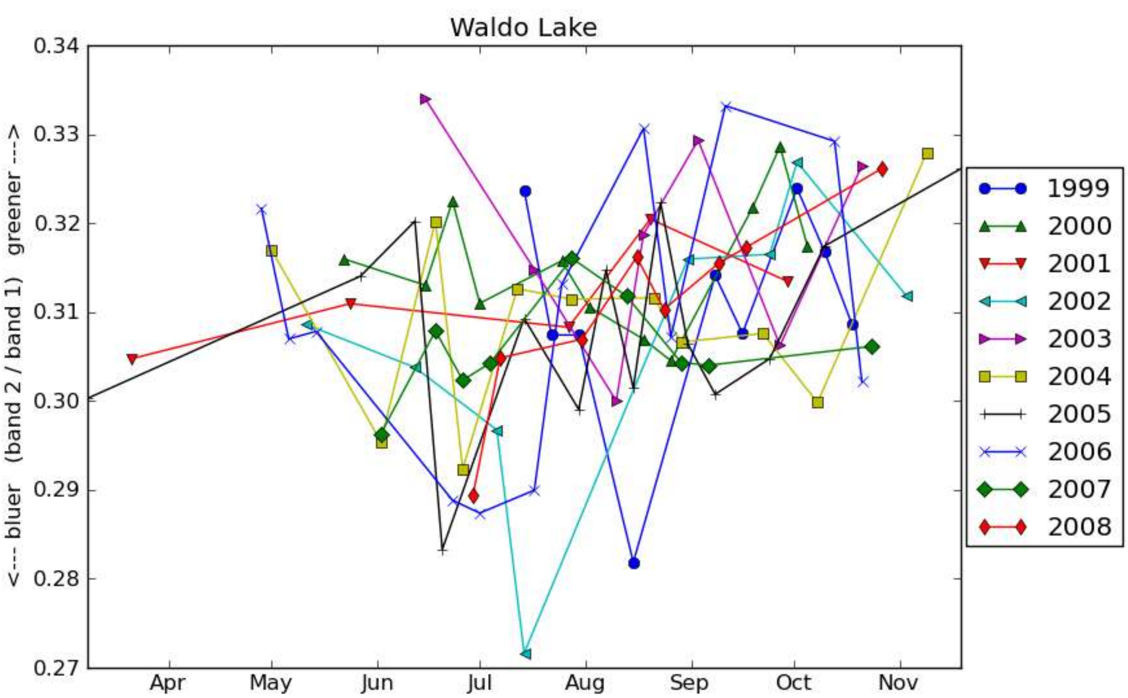
Name	County	Acres	Atlas Status	HABs	Satellite Status	Green / Blue	Green / Red
Lucky Lake	Deschutes	27			Blue	0.37	1.47
Booth Lake	Jefferson	7			Blue	0.37	1.40
Blue Lake	Multnomah	15			Blue	0.37	1.39
Boulder Lake	Jefferson	60			Blue	0.37	1.40
Timpanogas Lake	Douglas	37			Blue	0.37	1.46
Square Lake	Jefferson	45			Blue	0.37	1.44
Little Cultus Lake	Deschutes	172	oligotrophic		Blue	0.37	1.39
Cliff Lake	Lane	19			Blue	0.37	1.54
East McFarland Lake	Lane	7			Blue	0.37	1.53
North Fork Reservoir	Clackamas	285	mesotrophic		Blue	0.37	1.35
Fish Lake	Linn	31			Blue	0.37	1.33
Alice, Lake	Jefferson	7			Blue	0.37	1.40
Crabtree Lake	Linn	7			Blue	0.37	1.39
Opal Lake	Marion	14			Blue	0.37	1.38
Lily Lake	Deschutes	14			Blue	0.37	1.50
North Twin Lake	Deschutes	103	mesotrophic		Blue	0.37	1.46
Sarah, Lake	Jefferson	13			Blue	0.37	1.43
Big Lake	Linn	224	ultraoligotrophic		Blue	0.37	1.45
Dark Lake	Jefferson	25			Blue	0.37	1.41
Emerald Lake	Clackamas	6			Blue	0.37	1.40
Mowich Lake	Linn	53	ultraoligotrophic		Blue	0.37	1.48
Lower Lake	Marion	13			Blue	0.37	1.36
Suzanne Lake	Klamath	8			Ultra Blue	0.36	1.55
Fir Lake	Linn	8			Ultra Blue	0.36	1.44
Hilda, Lake	Jefferson	9			Ultra Blue	0.36	1.41
Hidden Lake	Deschutes	9			Ultra Blue	0.36	1.51
Blue Lake	Jefferson	55	oligotrophic		Ultra Blue	0.36	1.42
Upper Erma Bell Lake	Lane	13			Ultra Blue	0.36	1.39
Carl Lake	Jefferson	20			Ultra Blue	0.36	1.41
Darlene Lake	Klamath	11			Ultra Blue	0.36	1.53
Middle Lake	Marion	9			Ultra Blue	0.36	1.44
Bull Run Lake	Multnomah	438	oligotrophic		Ultra Blue	0.36	1.37
Cultus Lake	Deschutes	1144	ultraoligotrophic		Ultra Blue	0.36	1.47
Lower Rigdon Lake	Lane	17			Ultra Blue	0.36	1.53
Lost Lake	Hood River	249	oligotrophic		Ultra Blue	0.36	1.39
Smith Reservoir	Linn	157	oligotrophic		Ultra Blue	0.36	1.43
Blue Lake	Linn	12			Ultra Blue	0.36	1.45
Bull Run Reservoir No. 2	Multnomah	435	oligotrophic		Ultra Blue	0.36	1.38
Jorn Lake	Linn	37			Ultra Blue	0.36	1.47
Lower Eddeeleo Lake	Lane	104	ultraoligotrophic		Ultra Blue	0.36	1.43
Crescent Lake	Klamath	3680	oligotrophic		Ultra Blue	0.36	1.45

Name	County	Acres	Atlas Status	HABs	Satellite Status	Green / Blue	Green / Red
Summit Lake	Klamath	695	ultraoligotrophic		Ultra Blue	0.36	1.55
Charlton Lake	Deschutes	130	ultraoligotrophic		Ultra Blue	0.36	1.45
McFarland Lake	Lane	39			Ultra Blue	0.36	1.47
Dennis Lake	Deschutes	9			Ultra Blue	0.36	1.54
Clear Lake	Linn	124	ultraoligotrophic		Ultra Blue	0.35	1.47
Doris Lake	Deschutes	71	ultraoligotrophic		Ultra Blue	0.35	1.49
Benson Lake	Lane	17			Ultra Blue	0.35	1.46
Mink Lake	Lane	140	ultraoligotrophic		Ultra Blue	0.35	1.46
Waldo Lake	Lane	6035	ultraoligotrophic		Ultra Blue	0.33	1.53
Crater Lake	Klamath	13132	oligotrophic		Ultra Blue	0.32	1.44

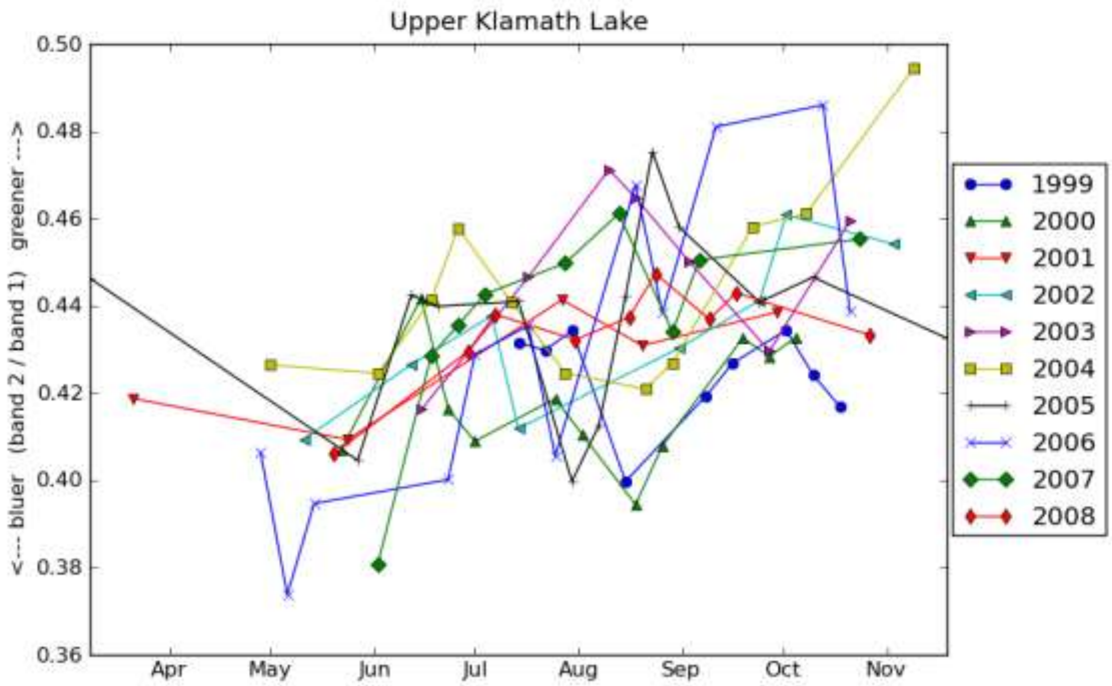
Appendix C. Band 2 / Band 1 ratios for various lakes.

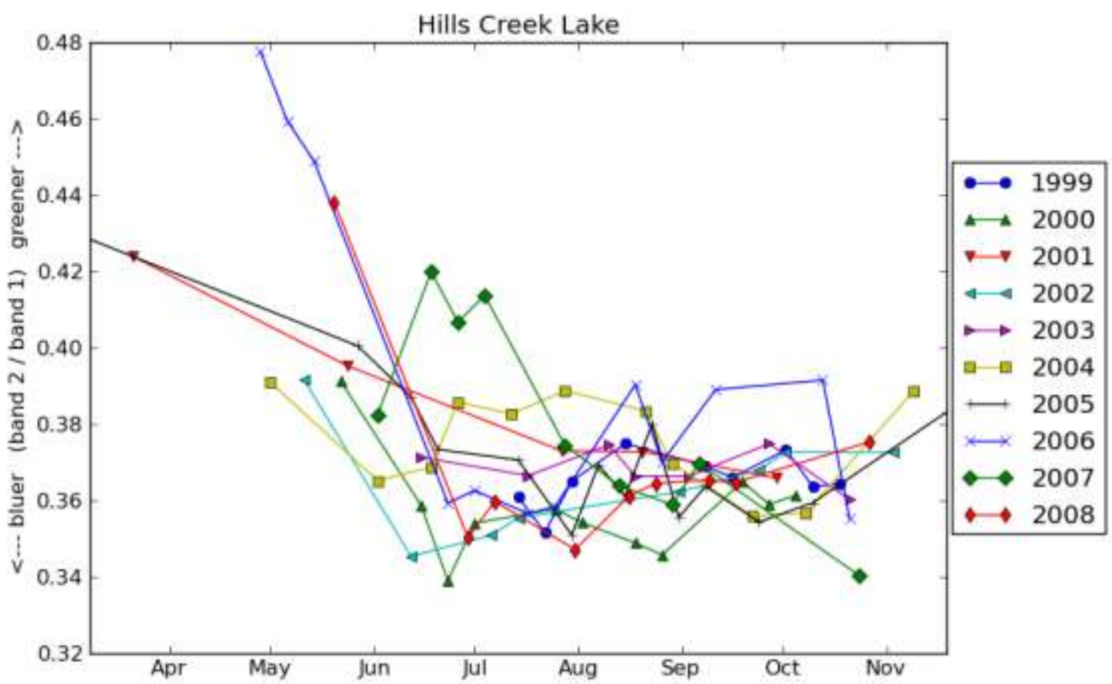
Famous Clean Lakes:

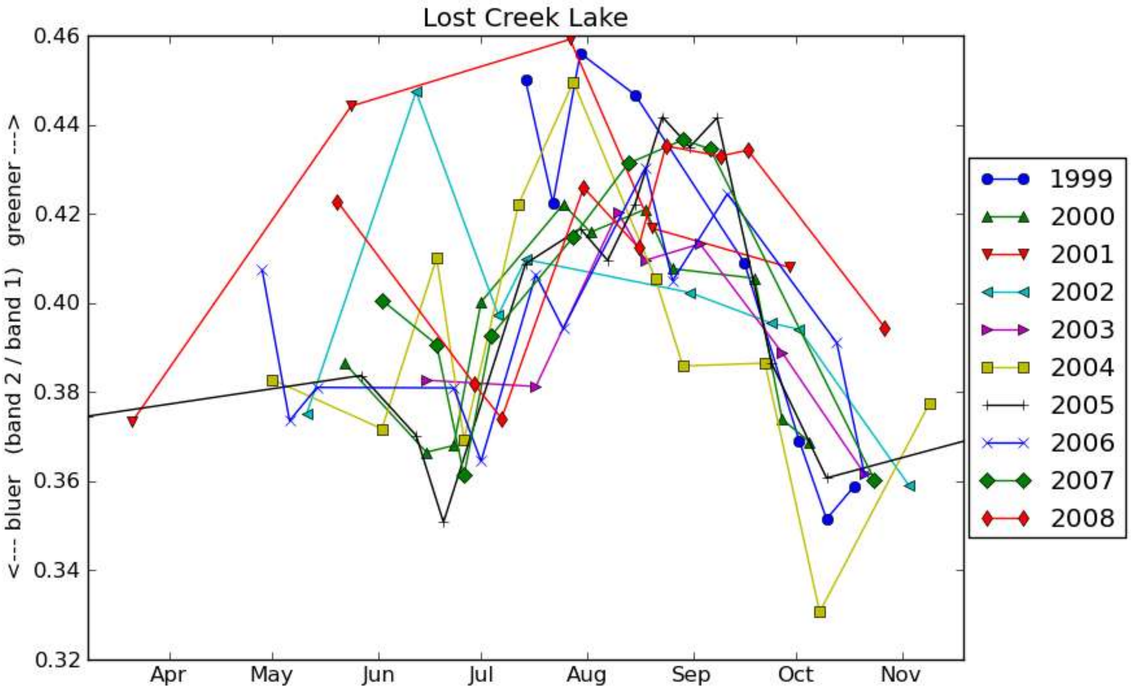


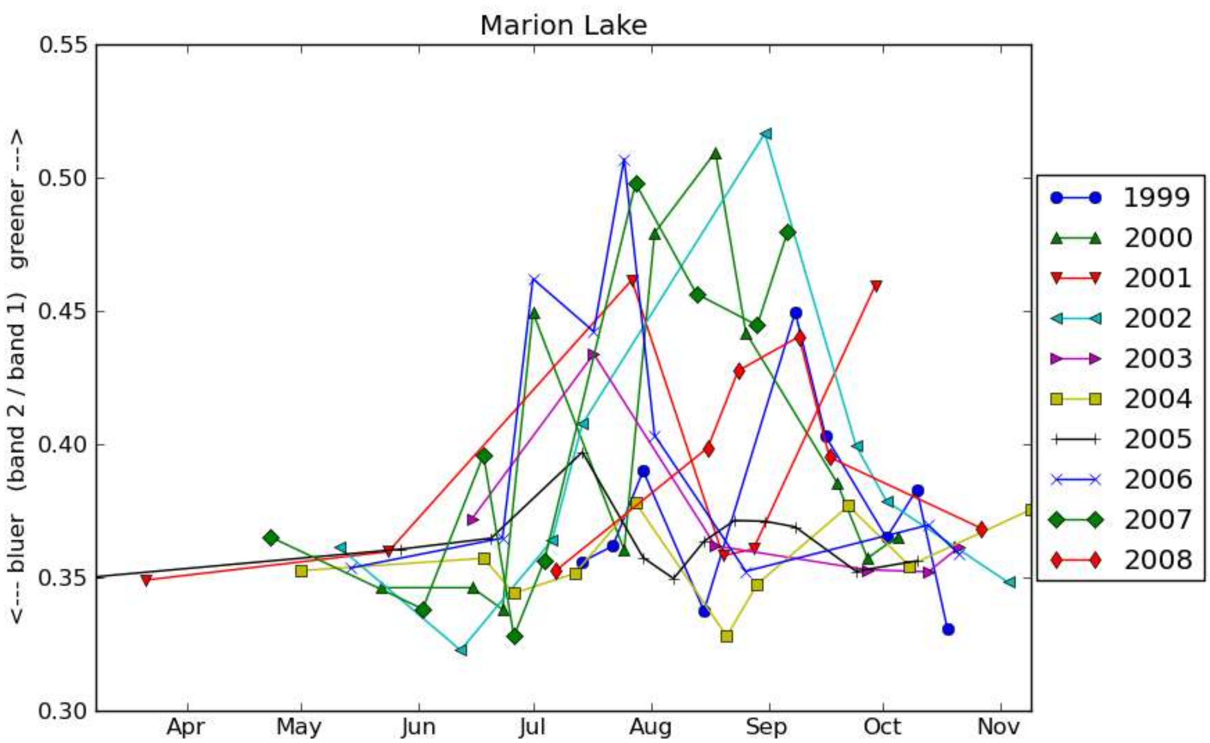


Lakes with known algae blooms:






Lost Creek Lake
<--- bluer (band 2 / band 1) greener --->
0.46
0.44
0.42
0.40
0.38
0.36
0.34
0.32
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008


Marion Lake
<--- bluer (band 2 / band 1) greener --->
0.55
0.50
0.45
0.40
0.35
0.30
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008

Interesting, consistent seasonal pattern: