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APPLICATION OF MODIS FOR MONITORING WATER  
QUALITY OF A LARGE OLIGOTROPHIC LAKE

by

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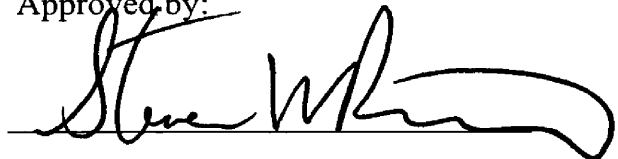
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Master of Science

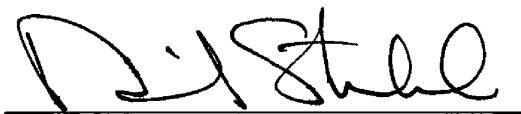
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## Application of MODIS for Monitoring Water Quality of a Large Oligotrophic Lake

Chairperson: Steven Running 

Flathead Lake, located in northwest Montana, is one of the 300 largest natural freshwater lakes in the world, covering an area of 480 km<sup>2</sup> with a maximum depth of 113 m. The lake is oligotrophic, yet experienced an increase in eutrophication from 1977 to 2001, and two lakewide blooms of macroalgae in 1984 and 1994 represented anomalous declines in water quality likely due to increasing nutrient inputs from anthropogenic sources. Summer field surveys in 2004 and 2005 showed surface chlorophyll-a levels from 0.14 to 0.97 mg/m<sup>3</sup>, Secchi depths of 1.5 to 16.5 m, and surface temperatures from 8.3 to 22.6°C. Depth profiles from surface to lake bottom were also obtained using a fluorometer and transmissometer. We examined the potential utility of MODIS medium resolution (250 m and 500 m) data (bands 1-4) and 1 km ocean bands (8-16) to monitor spatial and temporal fluctuations in lake productivity indicators including chlorophyll content and turbidity. Several alternative approaches for retrieving water quality parameters from the MODIS data were evaluated, including atmospherically corrected reflectance products and single scattering corrected radiance data. The zone of peak chlorophyll content and turbidity is found to occur immediately above the thermocline at water depths from 15 to 25 m, but with statistically significant linkages to surface conditions. Initial results indicate that the single scattering corrected radiance data provide the best prediction of chlorophyll-a, Secchi depth, and turbidity of the first 5 m depth ( $r^2 = 0.43$  to 0.75), but these parameters often co-vary at specific times throughout the season, creating difficulties in applying a consistent algorithm. Two complete daily time series from 1 May to 30 September for 2004 and 2005 were created from the single scattering corrected data to assess the sensor's ability to track lake fluctuations in water quality indicators. Mean daily lake reflectance values from these time series are found to be sensitive to wind effects, photosynthetically available radiation, atmospheric particulate deposition, and river discharge inputs at weekly to monthly time scales. Preliminary results show the potential of MODIS for water quality monitoring, but also highlight the need for improved algorithms and products specific to large inland water bodies.

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## **1. Introduction**

Fluctuations in lake water quality can be a proxy to the status of ecological components within a system and the extent of impacts on a system (Ritchie et al., 1994). Watershed disturbances such as road building, urban development, and alteration of riparian zones and shorelines may contribute to an overall decrease in the water quality of lakes (Ritchie et al., 2003; Kalff, 2002). Most freshwater systems in the world are affected by anthropogenic eutrophication, leading to undesirable increases in the biomass of higher plants and/or planktonic algae (Dekker et al., 1995). Eutrophication causes environmental and chemical changes that can adversely impact water quality and lake ecosystems, including major shifts in plant and animal life (Smith & Smith, 1988). It is therefore important to develop efficient methods for detection and monitoring lake water quality for better assessment and understanding of ecosystem integrity. Furthermore, the application of these methods to relatively pristine oligotrophic lakes can provide valuable baseline information for detecting and monitoring long term changes in water quality in the presence of anthropogenic stressors or climatic variability (Jassby et al., 2003).

A great deal of satellite remote sensing research directed toward surface water has focused on ocean color and ocean coastal research using the Coastal Zone Color Scanner (CZCS), the Sea-viewing Wide Field-of-View Sensor (Sea-WiFS) and the Moderate Resolution Imaging Spectrometer (MODIS) ocean bands. The remote sensing community has also made significant strides in addressing inland water quality issues and now satellite imagery offers much potential for regional monitoring (Mertes et al., 2004; Ritchie et al., 2003; Kloiber et al., 2002a). Freshwater remote sensing has made significant advances through the application of relatively fine spatial resolution satellite

sensors such as ASTER (Matthews, 2005), IKONOS (Sawaya et al. 2003), and Landsat MSS / TM (Kloiber et al. 2002b). These sensors were designed primarily for land-based research with relatively low spectral sensitivity to water, which has limited their ability for accurate biophysical monitoring of freshwater ecosystems. The relatively low temporal fidelity of these sensors also limits their utility to consider the dynamic nature of some freshwater systems. However, such limitations have not prevented the advancement of measuring and monitoring efforts with new approaches to atmospheric correction (Hu et al., 2004), multi-sensor collaboration (Dall’Olmo et al., 2005; Hu et al., 2001), surface temperature measurements (Handcock et al., 2006; Steissberg et al., 2005), and extensive algorithm development incorporating *in situ* data and band ratios. For example, the SeaDAS application (Baith et al., 2001) applies multiple proven ocean algorithms using remote sensing data from several different sensors and may prove to be a valuable tool for satellite remote sensing based assessment of inland water bodies.

While multiple satellite-based sensors are potentially available, MODIS aboard NASA EOS TERRA and AQUA platforms provides a unique global dataset that is low cost, well calibrated, and readily available at twice daily intervals from 2002 onward (Justice et al., 1998; Esaias et al., 1998). Capabilities for frequent monitoring are essential for regions such as the Flathead Basin in Montana where cloud cover and atmospheric aerosols are prominent and flow regimes into regional water bodies, including Flathead Lake, are dynamic and can alter regional water quality parameters at daily to weekly time scales.



## 2. Background

Flathead Lake is located in the Flathead River Basin of northwest Montana (Fig. 1). The Basin is 22,241 km<sup>2</sup> extending into Glacier National Park and the Bob Marshall-Great Bear-Scapegoat Wilderness complex. The eastern half of the Basin is dominated by a rugged expanse of mountains including the Mission and Seeley-Swan Ranges and the Continental Divide of the northern Rocky Mountains, and is part of the Crown of the Continent Ecosystem (CCE). The CCE is home to the headwaters of the three major North American river systems, namely the Missouri/Mississippi, the Saskatchewan/Nelson and the Columbia. The Flathead River, a tributary of the Columbia River, is a 5th order montane gravel-bed river (~270 m<sup>3</sup>/sec. yearly mean) and is the primary source of inflow to Flathead Lake and the dominant tributary in the Basin. Typically, river discharge into Flathead Lake is unimodal with a strong pulse beginning in April and extending through July, driven by precipitation and snow melt. Lake discharge is regulated by Kerr Dam with a low mean water flushing time of approximately 3.4 years which results in relatively high water quality. The Kalispell metropolitan area of the Flathead Valley, upstream of Flathead Lake, is a growing center of commerce in the region. This area experienced a 25% population increase between 1990 and 2000 (U.S. Census Bureau, 2000), with dramatic increases in housing development of river and lake shore areas and urbanization of large portions the Flathead River floodplain. In 2003 and 2004, Flathead County was the top residential construction market in the state, experiencing a 92% increase in housing units between 1990 and 2000 (*Ibid*) and a loss of over 42,000 acres of farmland between 1992 and 2002 (USDA Census of Agriculture, 2002). The lake is located in a complex and vibrant

ecosystem and could serve as a keynote indicator of large fluctuations or alterations to ecosystem processes.

Flathead Lake has an extensive long term record of lake water quality data indicating a general increase in eutrophication from 1977 to 2001 (Stanford & Ellis, 2002). The Flathead Lake Biological Station (FLBS) of the University of Montana has maintained regular water quality monitoring of the lake of since 1977; however, sampling is limited by available funding and resources so that temporal fidelity and data continuity is emphasized over the spatial extent of biophysical measurements. Establishing cost effective methods for regional monitoring from satellite remote sensing would enable improved assessment of spatial heterogeneity in lake water quality patterns, anthropogenic and environmental forcings of observed patterns and associated linkages to limited, but relatively detailed, field-based biophysical measurements.

### **3. Extent of Study**

The study consisted of two components. The first was to assess the potential of MODIS to discreetly measure the water quality parameters chlorophyll-a (Chla) and Secchi depth (SD) as indicators of water turbidity in a large oligotrophic water body characterized by relatively high water quality. Relationships between fluorometer and transmissometer readings (proxies to Chla and turbidity, respectively) and MODIS data were also explored. We examined the utility of MODIS 250 m and 500 m resolution data (bands 1-7) and 1 km ocean bands (8-16) to monitor spatial and temporal fluctuations in these parameters. The second component of the project was to take advantage of the high temporal fidelity of the MODIS sensor to determine whether lakewide fluctuations in

water quality and flow regimes could be observed at daily, weekly, or monthly time steps. Applying the algorithms developed from the discrete parameter measurements, daily synoptic maps were generated so that the spatial variation of these parameters could be visually tracked. The spatial variation through time was then used to examine how wind speed, river discharge, solar radiation, and precipitation affect the spatial distribution of Chl<sub>a</sub> and turbidity. The primary goal of the project was to further the understanding and application of MODIS for monitoring inland water quality and to develop a methodology that could be consistently applied to Flathead Lake and, ideally, other lakes in the region. MODIS data were also retrieved and analyzed for four secondary lakes within the Flathead Basin, coinciding with additional field-based biophysical sampling of water quality parameters. These data were used as a feasibility test of the potential for regional extrapolation of the remote sensing algorithms to other oligotrophic lakes in the region.

#### **4. Data and Methods**

##### ***4.1 Flathead Lake***

Flathead Lake (Fig. 1) is one of the 300 largest natural freshwater lakes in the world, covering an area of 480 km<sup>2</sup> with a maximum depth of 113 m. It is monomictic, becoming well stratified in the late summer months with the thermocline reaching a depth of 15-25 m and surface temperatures ranging from freezing to 22°C throughout the year. The lake is oligotrophic (Spencer & Ellis, 1990), as primary productivity is limited by scarcity of both nitrogen (N) and phosphorous (P). Nearly one third of N and P inputs come from atmospheric deposition sources, including forest fires, agricultural burning

and dust deposition from rural roads, while upstream anthropogenic sources of nutrient loading have increased steadily since the 1970's. The lake has experienced an increase in eutrophication from 1977 to 2001, and two lakewide blooms of macroalgae in 1984 and 1994 represented anomalous declines in water quality likely due to increasing nutrient inputs from anthropogenic sources. Even with recent increases in production, the lake remains in a relatively pristine condition in terms of water quality, with Secchi depths averaging 9 m since 1975 and often exceeding 20 m in the fall (Stanford & Ellis, 2002). Total suspended sediment loads average  $0.5 \text{ mg/m}^3$  and surface chlorophyll-a biomass is generally less than  $1.0 \text{ mg/m}^3$  (*Ibid*), so Secchi depth is greatly affected by other sources such as zooplankton populations, algal species composition, and other organic and inorganic particulates. Past FLBS analyses of phytoplankton species composition have shown that large diatoms (Bacillariopyceae), are the most prevalent followed by smaller diatoms (Chrysophyceae and Cryptophyta), and dinoflagellates (Pyrrophyta and Chlorophyta). However, 90% of primary productivity can be attributed to bacteria and green and blue-green algae (Ellis & Stanford, 1982). Although larger species tend to dominate biomass at the peak of productivity, species composition can vary throughout the season causing fluctuations in volume scattering coefficients (Kirk, 1994) and absorption (Carder et al., 1991) while a consistent chlorophyll-a biomass may be maintained, which can hinder the accurate remote measurement of Chla.

The lake water exhibits two distinct periods during spring and summer. From May to mid-July increased wind speeds and river inputs, driven largely by precipitation and rain on snow events, cause disruption and mixing of the epilimnion, resulting in a more turbid system. As the summer progresses, runoff has less impact and average wind

speeds decrease, allowing the epilimnion to stabilize, resulting in less overall variation in turbidity. One assumption made at the outset is that spectral properties of the water will not be dominated by chlorophyll-a biomass and that scattering may vary considerably based on the composition of constituents in the water body throughout the season. However, future lake monitoring efforts would be greatly enhanced from reliable satellite remote sensing based measures of Chla or SD by providing a cost effective and spatially comprehensive form of monitoring that could alert researchers to anomalous changes in water quality.

#### ***4.2 Field Data Collection***

Field data were collected from May to September of 2004 and 2005 under relatively clear days with minimal cloud cover and minimal wind to avoid cloud contaminated pixels and the disturbance effects that waves may have on the daily corresponding MODIS data. Sampling consisted of SD measurements, surface temperature readings, surface to 5 m integrated water samples for Chla biomass, and the deployment of a conductivity-temperature-density unit containing a chlorophyll fluorometer (470 nm excitation and 695 nm emission) and a 10-cm path length transmissometer (660 nm). The unit, a SEA-BIRD SBE25, was lowered on a winch from the surface to 5 m above lake bottom. A complete profile of temperature, transmissivity and fluorescence was recorded at each site. Secchi depth measurements were taken using a standard black and white 8-inch disk lowered to the point where the disk was no longer visible and surface temperature readings were taken using a handheld thermal infrared thermometer.

A majority of remote sensing water quality studies have used surface water samples to measure Chla (Ritchie et al., 1994; Dall'Olmo et al., 2005). The extreme water clarity of Flathead Lake presented a unique circumstance that required deviating from this standard method. A goal of the study was to monitor fluctuations in chlorophyll content as a proxy to lake productivity. Based on years of data collected by the FLBS (and reinforced in this study), it is well documented that the majority of algae is present just above the thermocline, generally 15 to 25 meters below the water surface. However, samples taken at this depth are most likely beyond the detectable limits of satellite remote sensing, as penetrating radiation returned to the sensor is limited to the depth of the informative water layer (Arst et al., 2002). The potential remote sensing detection limits for Flathead Lake were estimated by comparing lake transmissometer readings to the radiation attenuation coefficients of similar oligotrophic lakes. Results from 2004 confirmed an attenuation coefficient ( $K_d$ ) range of 0.11 to 0.21 with a mean of 0.16, resulting in a mean attenuation depth of 6.25 m. A 5 m integrated sample scheme was used to infer the maximum biomass at depth while keeping within the water layer where light may be scattered and returned to the MODIS sensor. A 2 L sample was collected at each site using a 5 m hose. The water samples were filtered through 47  $\mu\text{m}$  glass fiber filters and Chla biomass was measured with a spectrophotometer following the Standard Methods for the Examination of Water and Wastewater (Clesceri et al., 1998).

Eight spatially distributed sites (Fig. 1) were selected on the lake representing various water depths and influences of riverine input and lake flow patterns. All sites were located in areas exceeding 20 m in water depth to avoid bottom substrate influences on spectral reflectance values. Through past aerial observations (and confirmed by

remote sensing data here) the water of Flathead Lake flows in a counter clockwise direction due to Coriolis forcing, where sediment laden plumes input by the Flathead River at the north end of the lake move down the western edge of the lake over the course of several weeks following spring snowmelt and high flows. Much of the plume is composed of coarse sediments that settle out of the surface water column relatively quickly, while finer sediments can reach the southern end of the lake and affect Big Arm Bay which extends to the west. The sample sites were located to capture the characteristic range of seasonal and spatial variability in lake water quality. The three northern sites, Swan River Inlet (SWA), Flathead Delta (FLA), and Somers Bay (SOM) were chosen due to the strong effect river input can have on their status. The midlake sites of Midlake North (MLN), 106 m and Midlake Deep (MLD), 113 m, represent the deepest points in the lake and have been sampled consistently for many years by the FLBS. The Goose Island (GSE) site was chosen as an optimal midpoint where strong riverine inputs would affect the water quality parameters, while weak inputs may not reach this more southern point. Ross Deep (ROS) and Skidoo Bay (SKI) are often affected by unique environmental influences not felt by the rest of the lake. ROS, in Big Arm Bay, is susceptible to consistent winds that the main lake may not experience. SKI, at the southernmost end of the lake, is less affected by river inputs but is susceptible to northern winds due to the large north-south fetch. Although the eight sites are located on the same water body, they exhibit wide variation in their water quality parameters and generally capture the dynamic spatial heterogeneity of the main lake body. Polson Bay, at the southern end of the lake where Kerr Dam and the outlet to the lake is located, was

not included in any portion of this study due to its shallow depth (< 20 m) and potential influence of bottom substrate contamination of MODIS reflectance data.

#### ***4.3 Secondary Field Sites***

Four secondary sites were sampled to test the potential for regional application of the water quality analysis. Four additional lakes throughout the Flathead Basin were chosen based on their size and accessibility for monitoring. The secondary sites included Lake Mary Ronan (LMR), Whitefish Lake (WLK), Swan Lake (SLK), and Hungry Horse Reservoir (HHR). LMR is approximately 6 km<sup>2</sup>, WLK and SLK are each approximately 13 km<sup>2</sup>, and HHR is 95 km<sup>2</sup>. Sample sites were selected through visual inspection of the imagery to identify sample sites within water pixels having minimal contamination by adjacent land, and where water depths were sufficient to minimize the influence of bottom score on spectral reflectance properties. Swan Lake, Whitefish Lake, and Hungry Horse Reservoir are relatively narrow water bodies however, and pure water pixels were difficult to identify from the MODIS imagery. This was especially true with the 1 km imagery, which is reflected in the results. SD and Chla were measured at each site using the same methodology as on Flathead Lake. LMR and WLK were sampled in both 2004 and 2005 while HHR and SLK were sampled during the 2005 season. The in situ measurements and MODIS data from the secondary sites were incorporated into the Flathead Lake analysis to determine whether a common algorithm could be applied on a regional scale.



#### ***4.4 MODIS and Ancillary Data***

The Moderate Resolution Imaging Spectroradiometer (MODIS), aboard NASA's EOS TERRA and AQUA satellites, has 36 spectral bands ranging in wavelength from 40 nm to 1440 nm. Two bands are imaged at a nadir resolution of 250 m, five bands at 500 m, and the remaining 29 bands at 1 km. The MODIS sensors provide twice daily global coverage (10:30 AM and 1:30 PM equatorial overpass) and were selected for this investigation based on the high temporal repeat and moderate spatial resolution of the data, which also provide global coverage at minimal cost. Relatively high temporal fidelity of the remote sensing data is vital to the application of time series analysis over water bodies because flow regimes, riverine inputs, wind effects, and deposition from precipitation can alter water quality parameters at daily timescales or less. The capability for frequent sampling also increases opportunities for obtaining quality imagery where frequent cloud cover and dynamic weather patterns are generally unfavorable for remote sensing at optical and near-infrared wavelengths.

All MODIS data were acquired via the EOS Data Gateway (Toller et al., 2003; Vermote & Vermeulen, 1999). The following MODIS spectral bands and associated datasets were selected for this investigation: reflectance products for bands 1-2 (250 m resolution) and bands 1-7 (500 m resolution); radiance at sensor swath (RaSS) data for bands 1-7, and RaSS ocean bands 8-16 (1 km resolution) from the TERRA platform with local overpass times ranging from 18:20-19:50 GMT. The daily 1 km resolution Geolocation Fields swath data were also obtained for geoprocessing and atmospheric correction of the imagery. MODIS geolocation accuracy has approached the operational

goal of 50 m at nadir with recent algorithm updates achieving mean geolocation errors of only 18 m across-track and 4 m along-scan (Wolf et al., 2002). We can be confident that extraction of single pixel values over sample sites will be geographically consistent through time and that shifts in pixel location will not present susceptibility to land adjacency effects. Although the 250 m and 500 m bands were not specifically calibrated for water applications, sensor comparisons between MODIS, Landsat-7 ETM+, CZCS, and Sea-WIFS indicate that these bands provide sufficient sensitivity for water applications (Hu et al., 2004).

MODIS imagery were extracted to coincide with days of field data collection. After regression analysis of each dataset's utility in measuring the 2004 in situ water parameters, the 500 m RaSS dataset showed the strongest regression results for SD and percent transmittance. Therefore, daily 500 m RaSS data from 1 May to 30 September for 2004 and 2005 were downloaded for time series analysis. In cases where there were multiple swaths over the study area for any one day, the latest swath was chosen to minimize the solar angle unless cloud cover at that later time was a major inhibitor.

The 250 and 500 m reflectance products and the RaSS data were reprojected and subset over the study region using, respectively, the MODIS Reprojection Tool and the MODIS Swath Reprojection Tool provided by the Land Processes Distributed Active Archive Center (LP-DAAC). To reproject or subset the RaSS data, the 1 km Geolocation Fields product is a necessary input. Clouds were not a concern during the first stage of the project involving discreet parameter measurement at specific sites as all field data collection was conducted under cloud-free conditions, and additional post-hoc visual inspections of imagery were undertaken. Cloud masks were necessary in the time series

analysis. The MODIS Cloud Mask product was applied initially, but errors were found where pixels known to be over water were defined as coastal or land pixels and cloud determination was inconsistent. In light of these discoveries, a band threshold to distinguish clouds from open water was established by viewing a random selection of twenty 500 m RaSS daily images and recording which band would best distinguish the two. A maximum threshold was placed on Band 5 (1240 nm) due to its near complete absorption over water compared to definitively higher reflectance over clouds. The masks were visually checked for errors by again selecting twenty random images and assessing the masks' accuracy. No significant errors were recorded.

Concurrent with the acquisition of MODIS data, a suite of ancillary data was also compiled for use in multiple phases of the study. This data included local wind speed, precipitation and photosynthetically available radiation (PAR) at Yellow Bay Point on Flathead Lake provided by FLBS as well as daily discharge for the Flathead River via the U.S. Geological Survey National Water Information System website (<http://waterdata.usgs.gov/nwis>). Daily aerosol indices and ozone optical thickness from the Total Ozone Mapping Spectrometer (TOMS) were obtained from the NASA GSFC Ozone Processing Team (McPeters et al., 1998) website for use in atmospheric correction and determination of aerosol effects on corrected radiance values.

#### ***4.5 Atmospheric Correction***

Initially, the atmospherically corrected MODIS reflectance product was regressed against in situ water parameter measurements. Product reflectance values over water were often negative in the longer wavelengths (Fig. 2). The general error associated with

atmospheric correction of this product is approximately +/- 1% reflectance (Hu et al., 2004), which is generally acceptable for land applications. However, for an oligotrophic water body, reflectance values are often less than the 1% atmospheric correction error, resulting in a relatively low signal-to-noise ratio. In an effort to reduce the effects of atmospheric correction error on the data, we applied an alternative atmospheric correction to the 500 m and 1 km RaSS data based on the work of Hu et al. (2004), who detailed three methods for atmospherically correcting MODIS data over water. The single scattering approach was applied to estimate remote sensing reflectance ( $R_{rs}$ ) from at sensor radiance. This method incorporates ozone absorption coefficients, solar irradiance, Rayleigh optical thickness and reflectance, diffuse transmittance, solar and sensor zenith and azimuth angles, and estimation of aerosol reflectance. This approach is based on three primary assumptions. First, that aerosol reflectance is spectrally flat. Second, the single scattering estimation of Rayleigh reflectance is moderately correct due to relatively small optical thickness values for green, red, and NIR bands. Third, the water is spectrally dark in the NIR (859 nm), which is used to estimate aerosol reflectance on a pixel by pixel basis. Band 16 (870 nm) was used to estimate aerosol reflectance for the 1 km RaSS data.

The single scattering approach provided a simple yet relatively robust atmospheric correction of the MODIS time series data, allowing an improved signal-to-noise ratio for water applications. Figure 2 depicts histograms of lake reflectance values for bands 1(645 nm), 3(469 nm), and 4(555 nm) from the atmospherically corrected product and the single scattering approach. Reflectance values from the standard MODIS product show a majority of negative reflectance values for band 1 pixels, and much less spectral

range and separation than reflectance derived from the single scattering approach. The standard product histogram also shows generally lower reflectance in band 3 relative to band 4, which is contrary to the principle that blue light shows the highest scattering and reflectance over ultra-oligotrophic waters (Mobley, 1994). Alternatively, the results of the single scattering approach show greater reflectance in the blue band, increases the mean and standard deviation of each band, and the spectral separation between bands.

As further comparison between the single scattering atmospheric correction and the reflectance product, a band ratio that was the best predictor of turbidity was applied to two corresponding images (Fig. 3). The reflectance product shows a relatively normal distribution of pixels while the in-house corrected image shows an abundance of clear water pixels and a small number of turbid pixels (decreasing band ratio corresponds to decreasing water clarity). When visually examining the imagery, it is apparent that there is only a small plume in the north and the majority of the lake shows clear water reflectance values (Polson Bay is excluded from histogram results). The range is also greatly enhanced by the single scattering approach, allowing for more specific estimates of turbidity.

#### ***4.6 Time Series Data***

Daily 2004 and 2005 MODIS 500 m RaSS data from 1 May to 30 September were selected for the time series analysis. Cloud masks were applied based on a maximum threshold analysis of Band 5 (1240 nm). The single scattering atmospheric correction scheme was applied to each image, producing daily spectral (RGB)  $R_{rs}$  images of the study area. As the processing involved over 300 images, the same visual quality

assurance measures that were conducted on the images corresponding to field data collection days could not be performed (i.e. manual screening for bad data pixels, misclassification of clouds, and wave or whitecap effects), so an alternative series of quality checks were performed. Uncertainty indices provided with the RaSS images were used to flag bad data and local daily average and maximum surface wind speeds were used to screen the data for potential wave effects. Figure 4 shows daily average and maximum wind speed versus daily mean lake reflectance for each band. No discernable trend in reflectance is present as wind speed increases, which is most likely due to the early local overpass time (18:20-19:50 GMT) and generally calm conditions in the early part of the day, with wind and waves increasing in the afternoon. Daily incoming radiation was a concern as it would increase with the solar zenith angle as the season progressed. Although this is accounted for to some degree in the atmospheric correction, cloud cover or smoke and haze from forest fires could have an effect on spectral reflectance properties and incident photosynthetically available radiation (PAR). We found no evidence of a significant relationship between daily PAR data collected from the east lakeshore of Flathead Lake and lake daily mean reflectance properties for each spectral band (Fig. 5). As a check for potential atmospheric aerosol effects, daily lake mean values for each band were regressed against TOMS (McPeters et al., 1998) aerosol indices over the study region, and we also found no evidence of a significant relationship between MODIS spectral reflectance values and optical aerosol concentrations inferred from the TOMS data (Fig. 6). These results indicate that pixel by pixel subtraction of the NIR band was a good estimator of aerosol contributions to reflectance.

## 5. Field Survey Results

### 5.1 Field Data Summary

The 2004 and 2005 Flathead Lake field seasons showed Chla levels from 0.07 to 0.97 mg/m<sup>3</sup> and SD from 1.5 to 16.5 m. Figure 7 shows the range and means by site and year for SD and Chla. Note that the Flathead Delta site (FLA) was only sampled in the 2005 season. Chla exhibits wide variation at each site, especially in the 2004 season, but the means remain relatively constant across all sites for each year. Secchi depths exhibit more spatial variation for sites more strongly influenced by Flathead River input (FLA, SOM, SWA, and GSE), with greater SD variation and minimums indicative of sediment driven turbidity. The two deep water sites (MLN and MLD) are least affected by river sediment and showed minimal SD variation and high means, while ROS and SKI maintained high SD means, but exhibited some temporal variation likely due to their susceptibility to wind driven mixing. Surface temperature readings across both seasons ranged from 8.3°C in late May to 22.6°C in late July.

Surface transmissometer readings were averaged into 0 to 5 m depth bins and ranged from 49.1% to 92.4% with a mean of 86.9%. The 49.1% reading at the GSE site on day 145, 2005 was a clear anomaly (the next lowest reading was 69.9%), with a corresponding SD of 1.5 m and the second highest Chla reading of 0.93 mg/m<sup>3</sup>. The anomaly may represent a local surge in productivity or resuspension of particulates resulting from several days of consistent rain, intense winds and a strong river pulse followed by calm days with the highest PAR readings recorded across both years. Surface fluorometer readings averaged into 0 to 5 m depth bins and converted to fluorometer estimated Chla (Fl-Chla) values ranged from 0.53 to 2.32 mg/m<sup>3</sup> with a mean

of  $1.06 \text{ mg/m}^3$ . Surface to bottom profiles of fluorescence showed maximum chlorophyll content at approximately 15 to 25 m depth for each year regardless of which stage in the season measurements were taken. Both years exhibited increases in chlorophyll content as the season progressed and the 2005 season showed greater vertical dispersion of chlorophyll versus the more discrete spikes in vertical concentrations exhibited in 2004 (Fig. 8). The decision to collect an integrated 0 to 5 m water sample for Chla measurement was assessed by examining the relationship between the mean daily fluorometer readings within the first 5 m depth and the maximum reading at depth. Figure 9 shows a significant relationship between the two with the exception of one outlier on 16 July, 2004. The outlier can be explained by the relatively calm period prior to measurement as river discharge was leveling off, there had been a seven day lapse in precipitation and winds were at season minimums. This calm period allowed algae to settle to the thermocline creating a dearth near the surface. There was no significant relationship between transmissometer readings and Fl-Chla or measured Chla (Fig. 10), which further demonstrates that algae is not the primary scattering component in the system.

Two of the secondary sites showed similar results to Flathead Lake while two were more turbid systems. HHR and WLK shared a mean SD of 8 m with mean Chla readings of  $0.61$  and  $0.43 \text{ mg/m}^3$ , respectively. LMR and SLK offered the lowest consistent SD readings sharing a mean of 5.6 m and the highest mean Chla readings of  $2.89$  and  $1.07 \text{ mg/m}^3$ , respectively.



## ***5.2 MODIS Results***

The four MODIS datasets were regressed against the five measured parameters of Chla, FI-Chla, Uncorrected Chla (Unc-Chla), SD, and Percent Transmittance (PT). A wide array of MODIS data transformations were performed based on previous research on remote sensing band ratio and log transform algorithms for water (Hu et al., 2004; summaries in Ritchie et al. 2003; see table in Dekker et al., 1995). A majority of these results were inconclusive, regardless of the dataset or transformation. The best Flathead Lake regression results for each dataset are summarized in Table 1. Uncorrected Chla was tested as it may more accurately represent the optical properties of algae in the water. This measurement does not correct for the presence of pheophytin, a degrading form of chlorophyll that absorbs light in the same range, and therefore may have a significant effect on scattering and absorption at the same wavelengths (Moss, 1967).

No significant relationships were found between the MODIS reflectance data and uncorrected Chla or measured Chla data for Flathead Lake, and further incorporation of published band ratios or data transformations did not improve results. The strongest relationship (Fig. 11), was found between FI-Chla and the single scattering atmospherically corrected 500 m RaSS data where the blue/green band ratio accounted for 43% ( $P < .001$ ) of the variation. On the other hand, 82% ( $P < .001$ ) of the variation in measured Chla at the secondary sites was accounted for by the same band ratio (Fig 12). This relationship however, is dependent on only five Chla samples above  $1.0 \text{ mg/m}^3$ . For values below the sensitivity threshold of  $1.0 \text{ mg/m}^3$ , unexplained variation in the blue/green ratio increases. A similar unexplained variation is observed at low Chla levels

on Flathead Lake, indicating a similar  $1.0 \text{ mg/m}^3$  sensitivity threshold for the remotely sensed data.

SD and PT readings showed positive results and three of the four data sets exhibited potential for measuring turbidity. Both the 500 m reflectance product and the 1 km ocean bands showed  $r^2$  values from 0.31 ( $P=.008$ ) to 0.55 ( $P<.001$ ). The most significant results were found using the single scattering atmospherically corrected 500 m RaSS data, where approximately 75% ( $P<.001$ ) of the variation in SD and 71% ( $P<.001$ ) of the variation in PT could be explained by the band ratio,  $\Delta R = [R_{rs}(469) - R_{rs}(645)] / [R_{rs}(555) - R_{rs}(645)]$  (Figs. 13 and 14). The strong relationship between turbidity and band ratio  $\Delta R$ , and inconclusive results for chlorophyll indicate that multiple factors contribute to the scattering properties of the water body.

### ***5.3 Synoptic Maps of Turbidity***

The algorithm resulting from the Secchi depth regression,  $y=0.329*\exp(1.2419*X)$ , where  $X = \Delta R$ , was applied to the daily single scattering atmospherically corrected 500 m RaSS imagery to obtain synoptic time series maps of SD for Flathead Lake. The synoptic maps showed generally good agreement with field measured SD values. When successive days are examined the counter-clockwise flow pattern of the lake and associated migration of sediment inputs from the Flathead River are clearly indicated. As Figure 15 indicates, a sediment pulse from the Flathead River can be seen migrating down the west side of the lake. Turbidity in Big Arm Bay increases as sediment laden flows from the north enter the bay and the eastern half of the lake grows more turbid from the dispersion of this input. Past research reveals a distinct

relationship between the river plumes and lake productivity patterns in which increased sediment levels in the water column did not inhibit primary productivity as expected; instead, the additional nutrients provided by the sediment plume stimulated a delayed onset of algal productivity (Stanford et al., 1981). Synoptic maps allow spatial analysis and temporal monitoring of sediment inputs, offer the potential for assessing more detailed biophysical relationships with temporal spikes and spatial patterns of lake primary production.

## **6. Time Series Results**

### ***6.1 Lake Regions of Interest***

In order to examine season long trends in turbidity and to track its north to south movement, the lake was partitioned into distinctive regions of interest based on the known counter-clockwise flow pattern. North, mid, and southern regions of the lake were designated, excluding Big Arm Bay, Polson Bay, and other near-shore or shallow pixels to minimize contamination of MODIS reflectance data by adjacent land areas or bottom substrate effects. The regions were designated by two longitudinal lines, one drawn through the MLN site, and the other drawn ~2km north of the MLD site (Fig. 1). The band ratio that showed the strongest correspondence to lake turbidity,  $\Delta R = [R_{rs}(469) - R_{rs}(645)] / [R_{rs}(555) - R_{rs}(645)]$ , was applied to each daily single scattering atmospherically corrected RaSS image, and daily means were extracted for each region. Numerous days of cloud cover throughout the season created gaps in each year's time sequence or often limited the number of pixels available in a region. A minimum threshold of 20 pixels (5.0 km<sup>2</sup>) under cloud free conditions was required for including

daily mean regional reflectance values in the time sequence, which further limited the number of available days. Out of a possible 153 days, only 59 and 71 days were selected for 2004 and 2005, respectively. Large gaps in daily time series data made comprehensive analysis of seasonal patterns difficult, and available days were often sporadic resulting in a very patchy time sequence. A seven day running mean of regional band ratio results for the three regions of interest is presented in Figure 16; breaks in the trend lines depict seven day intervals without sufficient clear-sky data.

Two distinct periods are discernable in Figure 16. Lower band ratios (depicting decreased water clarity) are evident throughout the early months of May and June, especially in the northern portion of the lake where turbid water inputs from the Flathead River have the most impact. The north end of the lake maintains a relatively low band ratio throughout the season most likely due to the continual influence of the river and the resuspension of particulates from a relatively shallow river mouth and delta. Fluctuations in turbidity also occur from July through September, but the system is largely stabilized relative to the early portion of the season as spatial patterns are more similar across the various regions and temporal peaks and troughs are less extreme. Aside from the consistently lower value in the north, regional differences are minimal and observed primarily in the early months. Regional oscillations often mimic each other in the later months, reinforcing the concept that lakewide environmental effects such as precipitation, wind, and incoming radiation are the driving factors during this period, rather than tributary influences.

## ***6.2 Sensitivity to Environmental Factors***

The seven day running means of MODIS band ratio results for each region were plotted against daily Flathead River discharge, precipitation, average PAR, and average wind speed to assess potential drivers of temporal oscillations in lake turbidity inferred from MODIS band ratio results. River discharge is chaotic during the early months which make relationships difficult to track, but in 2004 two minor mid-season flood pulses (days 203 & 220) and two major late season pulses (days 240 & 260) appear to have delayed effects on turbidity (Fig. 17a). To further examine this delayed effect, daily values for each region were regressed against daily river discharge. Each region's value was then advanced one day, and the regression performed again in an effort to determine the time delay between pulses in discharge and turbidity response for each region. The regressions were repeated for successive one-day advances until  $r^2$  values were maximized. Both the north and mid regions showed increasing  $r^2$  values, starting at 0.49 and 0.46 respectively, and reaching maximums of 0.59 and 0.58 with a five day offset. The southern region began with an  $r^2$  of 0.28 and reached a maximum of 0.47 with a nine-day offset. These results imply that effects of river discharge on lake turbidity in 2004 are most apparent in the north and mid regions of the lake after a five-day lapse, and in the south after a nine-day lapse. The nine day lapse is visually confirmed from Figure 15, where the southern portion of the lake does not show a visible increase in turbidity until eight or nine days following the initial entry of the sediment plume in the north.

Important to note is how the effects of late season pulses are mirrored in the mid and south region band ratios almost immediately, which should not be as affected by such small late season pulses. Lake wide effects may better explain such variation.

Atmospheric deposition from precipitation is a main driver in lake productivity (Miranda & Matvienko, 2003; Villar-Argaiz, 2001) and increased deposition could affect lake reflectance values. In examining isolated precipitation events, such as the week long event straddling day 260 in 2004 and a late season storm at day 255 in 2005, regions generally showed a drop in water clarity (Fig. 17b). In such instances, differences in remote sensing reflectance may be driven by atmospheric effects more than water quality effects. Deposition of this particulate matter (removal of atmospheric particulates responsible for backscattering) may decrease reflectance in the shorter blue and green wavelengths with less effect on the red band, which would cause decreases in the band ratio and appear as a decrease in water clarity.

Temporal peaks and troughs in seven day running means for PAR (Fig. 17c) and wind speed (Fig 17d) generally coincided with temporal shifts in regional band ratio results. For both 2004 and 2005, many instances can be noted where temporal increases in incident PAR preceded decreases in water clarity, perhaps as a result of heightened productivity. Average daily wind speed shows the best coincidence with fluctuations in region means and is the most environmentally plausible explanation of these oscillations. A majority of increases in wind speed are closely followed by a resulting decrease in water clarity. As stated previously, Flathead Lake develops a thick epilimnion as the summer progresses and the majority of phytoplankton sit just above the thermocline at depths of 15 to 25 m. Wind events cause mixing of the epilimnion and resuspension of phytoplankton, which may result in more turbid surface waters and possibly rises in productivity as phytoplankton are shifted to a brighter environment. Wind events also drive the resuspension of near shore particulates, further enhancing turbidity. The

contributing factors of daily to weekly fluctuations in remote sensing measures of turbidity are numerous and often co-vary. Future research is required to better understand these relationships which is beyond the scope of this study. It is apparent, however, that relationships do exist which encourages future exploration of time series analysis.

## **7. Discussion**

### ***7.1 Discreet Parameter Measurement***

Although the 500 m MODIS bands were not specifically designed for inland water quality applications, the results demonstrated here are promising. Broad scale monitoring of water quality requires repetitive and spatially extensive techniques, which MODIS offers. The incorporation of a simple yet effective atmospheric correction scheme proved to be a vital element in this application. Not only did it prove effective for deriving turbidity measurements, it is simple enough that researchers and land managers not familiar with remote sensing techniques could apply the algorithm with only limited input from a specialist, further enhancing the cost effectiveness of such monitoring.

Unlike a majority of remote sensing inland water studies, the focus of this project was an oligotrophic water body with parameter levels closer to ocean systems rather than inland systems. This resulted in reflectance values less than 0.03% and  $R_{rs}$  values less than 0.4, making the impact of atmospheric effects, sensor noise, or land adjacency affects more of a concern. When examining historical efforts, the majority of inland bio-optical algorithms were based on parameter levels far greater than those found in

Flathead Lake, except for ocean studies where Chla levels are often below 1.0 mg/m<sup>3</sup>. For this reason the ocean bands were incorporated into the study, but they proved less valuable than the 500m bands. The reason for the poor performance of the ocean bands could be due to a number of factors. First, such a simple atmospheric correction may not be comprehensive enough for relatively narrow sensor spectral bandwidths with significantly higher signal-to-noise ratios. Second, the relatively near shore location of some sites made the 1 km resolution of these bands more susceptible to contamination from adjacent land areas, especially for secondary sites located on smaller lakes. Third, unlike ocean systems, the variation of Chla or turbidity across one km<sup>2</sup> may be significantly greater than that found across a 250 x 250 m or 500 x 500 m square area. The relatively poor performance of the data for this investigation does not discount potential future application of these bands as more comprehensive inland water atmospheric correction schemes become available or water bodies with higher levels of constituents are tested. Further testing of the ocean bands is encouraged using SeaDAS (Baith et al., 2001) which utilizes MODIS ocean bands and applies ocean algorithms for the detection of Chla.

As mentioned, Chla is not the primary scattering component within the Flathead Lake oligotrophic system, hence the difficulty in deriving an algorithm that consistently measures Chla biomass at such low levels among variations in other components. The strong relationship among the secondary sites and the MODIS blue/green band ratio is further proof of this concept. The blue/green band ratio results accounted for approximately 93% (P<.001) of the variation when Chla levels were above 1.0 mg/m<sup>3</sup>, while the strength of this relationship was greatly diminished as water clarity increased.



The methodology used in this study may have sensitivity limitations based on a number of factors. The relative uncertainty of the basic atmospheric correction scheme and wide spectral bandwidths of the 500 m MODIS data, the volume scattering coefficients dependent upon algal species size and composition, and the variation between tributary plume dominated waters and late season stratified waters all may contribute to this sensitivity threshold.

The method of collecting an integrated surface to 5 m sample may also have reduced correspondence between remotely sensed reflectance and biophysical measurements. The FLBS protocol for Chla biomass sampling on Flathead Lake involves collecting a sample at the depth of maximum fluorescence, which is more closely linked to lake productivity. Biophysical data collection for a remote sensing study could adopt a similar approach, but the integrated sample should be restricted to the informative water layer at the given site. By first recording SD or PT, the attenuation coefficient could be calculated and an integrated sample taken from that site specific attenuation depth, since approximately 90% of the upwelling radiance detected by remote sensors comes from this depth (Arst et al., 2002).

Since SD and PT are more comprehensive in their measure of clarity, it follows that their relationships to band ratios are more significant. The synoptic maps of SD created using the derived algorithm demonstrated the benefit of this method and its future application. It also lends itself to further studies of lake flow patterns and the effect of river plume extent on lake productivity. One goal of the study was to create a baseline dataset of MODIS data over Flathead Lake. The resulting two years of imagery, both in atmospherically corrected form and the synoptic maps, have established this baseline and

an algorithm that can be applied and tested in the future. The code written to perform the corrections and apply the algorithms is transferable and could easily be compiled so that future monitoring in this form requires minimal time or cost.

## ***7.2 Time Series***

One of the greatest benefits of MODIS is its temporal resolution. With the sensor aboard two satellite platforms, at least two daily images are available. The dynamic nature of water bodies, especially those susceptible to varying flow regimes and a range of environmental factors, require high temporal repeatability if monitoring efforts are to be comprehensive. Flathead Lake proved to be a prime testing ground for the benefit of such temporal resolution. The region's susceptibility to cloud cover, especially early in the season, proved to be a significant setback to the compilation of data. With only 39% and 46% of possible collection days, from 2004 and 2005 respectively, providing useful data the large gaps hindered analysis. On the other hand, the number of images available is far beyond what a majority of conventional sensors could offer. In situations where the researcher or land manager is not located near the study area, cloud cover could be checked prior to field data collection or download using the MODIS Rapid Response System website (<http://rapidfire.sci.gsfc.nasa.gov>), which supplies near real-time images. Also, in relation to field data collection, we were not restricted to specific overpass dates. If the conditions were ideal for data collection, we were usually guaranteed MODIS imagery for that day.

Time series analysis also provided initial checks on the effects of environmental factors on water quality parameters. One major difficulty was the co-variance between

these factors, but trends were observed that could not be discounted. Even though the trends may be the result of atmospheric or aerosol variation, this would still be a benefit as it may allow for the creation of improved correction algorithms. Considering the extensive time scales generally associated with ecosystem restoration or deterioration, trend detection has received much attention among ecologists and related disciplines (Esterby, 1996) in identifying interannual variability among long term systematic change. Application of this cost effective method to historical as well as future MODIS data could be key in identifying broad systematic variation.

## **8. Conclusion**

This study suggests that MODIS has the potential to measure and monitor turbidity on a large oligotrophic lake. MODIS also hold promise for remotely measuring Chla, especially in more productive systems. The strong relationship between Chla and the MODIS band ratio on secondary sites inspires future application in this region, but also identifies the limitations of this method in that sensitivity to low Chla measurements is an issue and should be explored in more detail. Even if this limitation is not immediately resolved, it can still be used as a monitoring tool to detect anomalous declines in water quality, the onset of algal blooms, or the dispersion of river inputs and their link to productivity patterns. The results show the potential of MODIS for water quality monitoring, but also highlight the need for improved algorithms, atmospheric correction methods and products specific to large inland water bodies.

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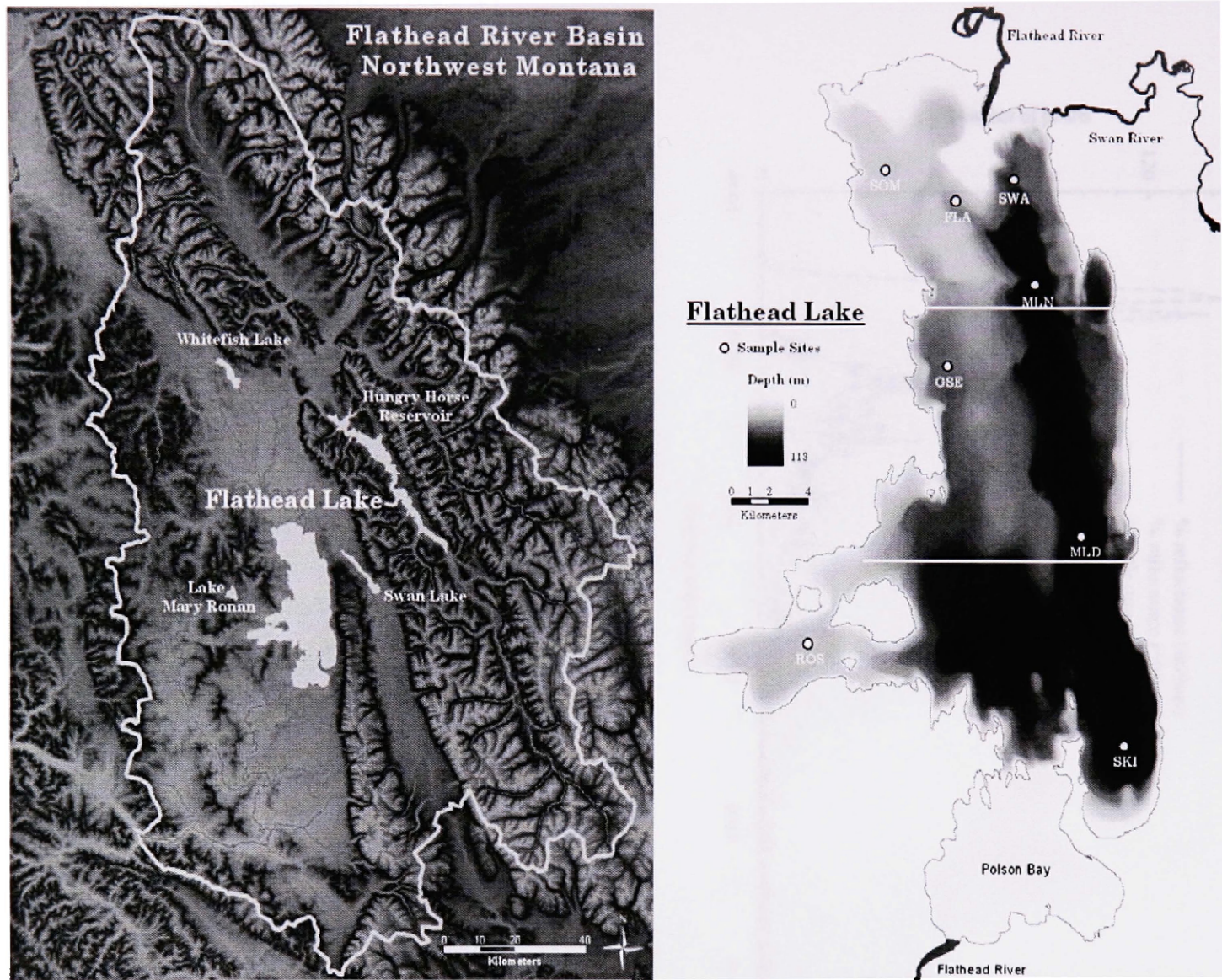


Figure 1. The Flathead River Basin of Northwest Montana and the five lakes sampled. At right, focus on Flathead Lake and the eight sample sites as well as the longitudinal lines separating the north, mid, and south regions of interest used for the time series analysis.



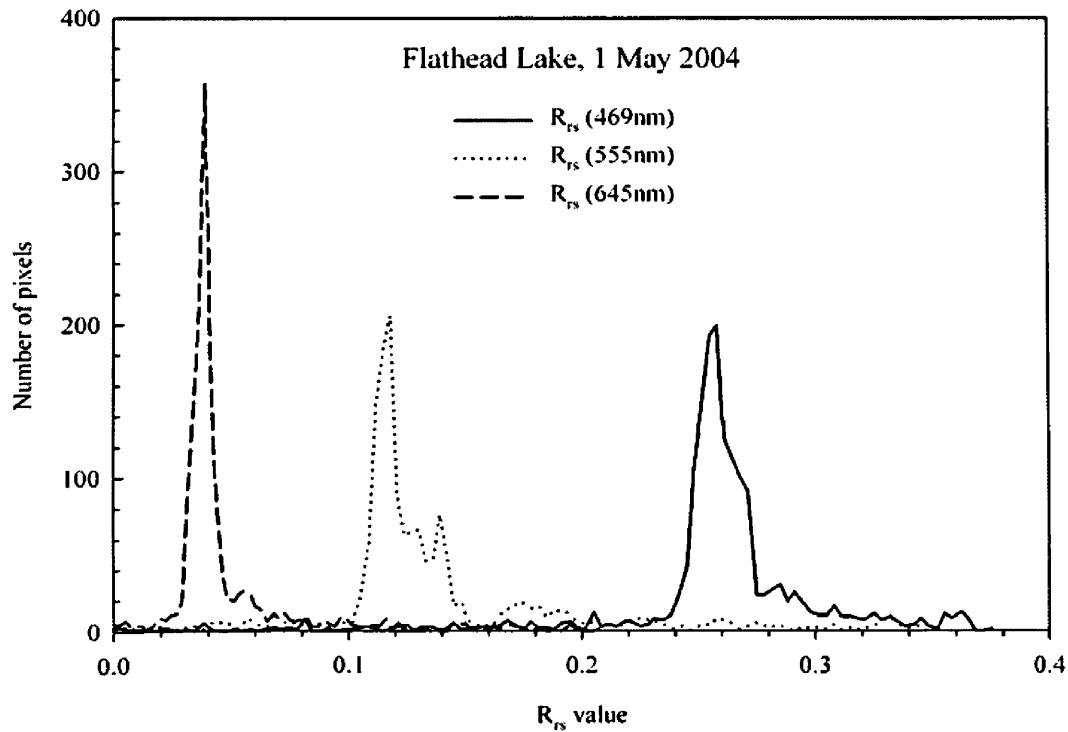
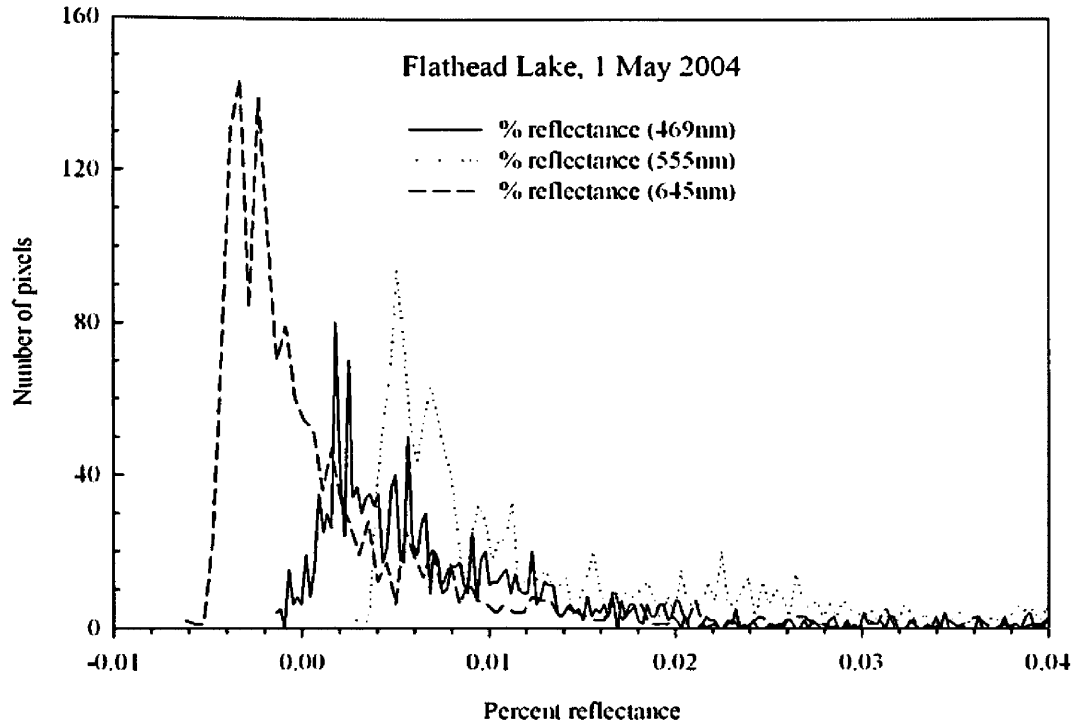
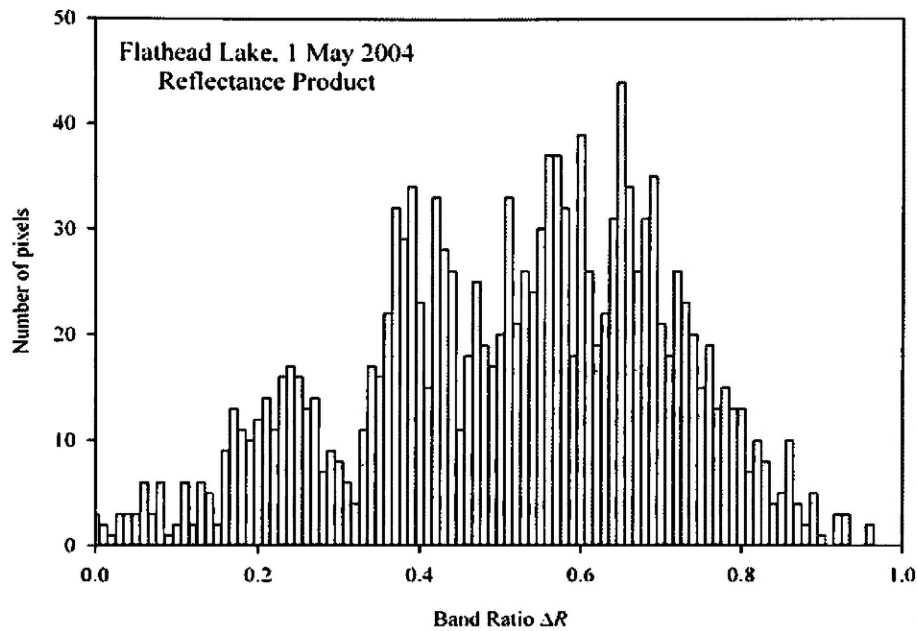


Figure 2. Histograms of lake reflectance values from 1 May 2004; MODIS reflectance product (top) and in-house single scattering atmospherically corrected remote sensing reflectance,  $R_{rs}$  (bottom). The red band (645 nm) is primarily negative in the reflectance product and the green band (555 nm) shows higher values than the blue band (469 nm), which is contrary to the standard that the blue wavelengths show higher reflectance in oligotrophic waters. The in-house correction resolves these issues and increases band range and between band variation.



Flathead Lake,  
1 May 2004

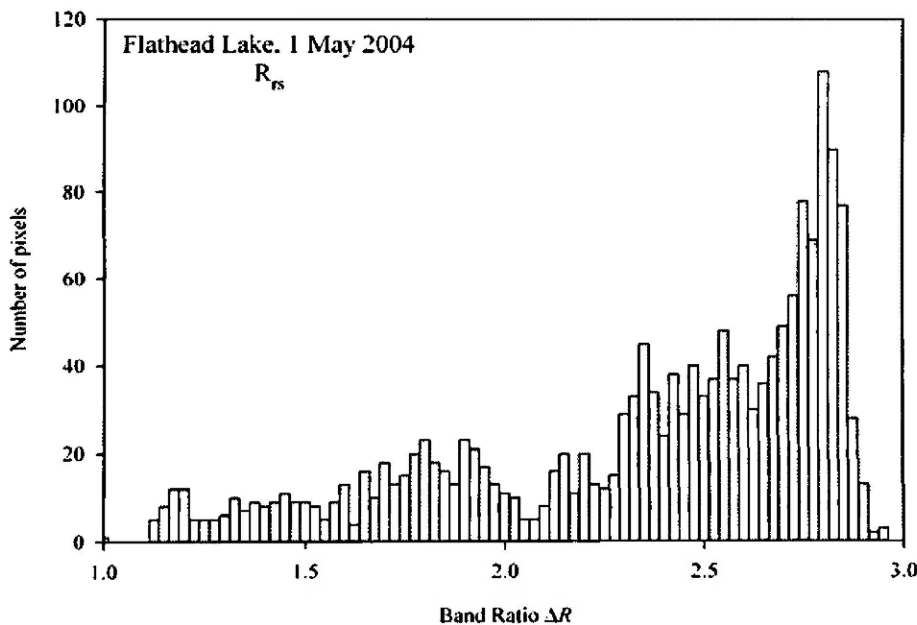


Figure 3. Histograms of band ratio  $\Delta R = R_{rs}(469) - R_{rs}(645) / R_{rs}(555) - R_{rs}(645)$  over Flathead Lake on 1 May 2004 (Polson Bay excluded). The MODIS reflectance product (top) and the in-house atmospheric correction (bottom). The 1 May lake image shown here is a RGB of the reflectance product converted to grayscale which shows a small bright plume in the northern portion of the lake. Increases in the band ratio have been shown to coincide with increases in water clarity. The normal distribution found in the reflectance product does not match the dominant number of clear water pixels in the image. The in-house correction shows a dominance of clear water (high band ratio) pixels and a small portion of turbid pixels, which is far more representative of lake conditions.

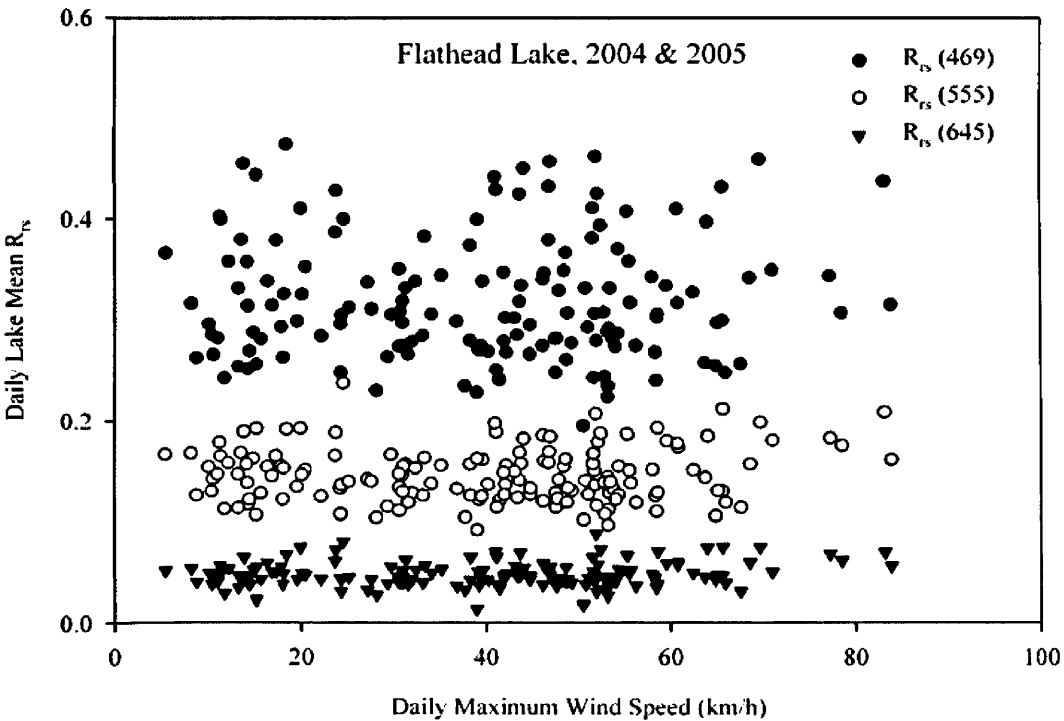
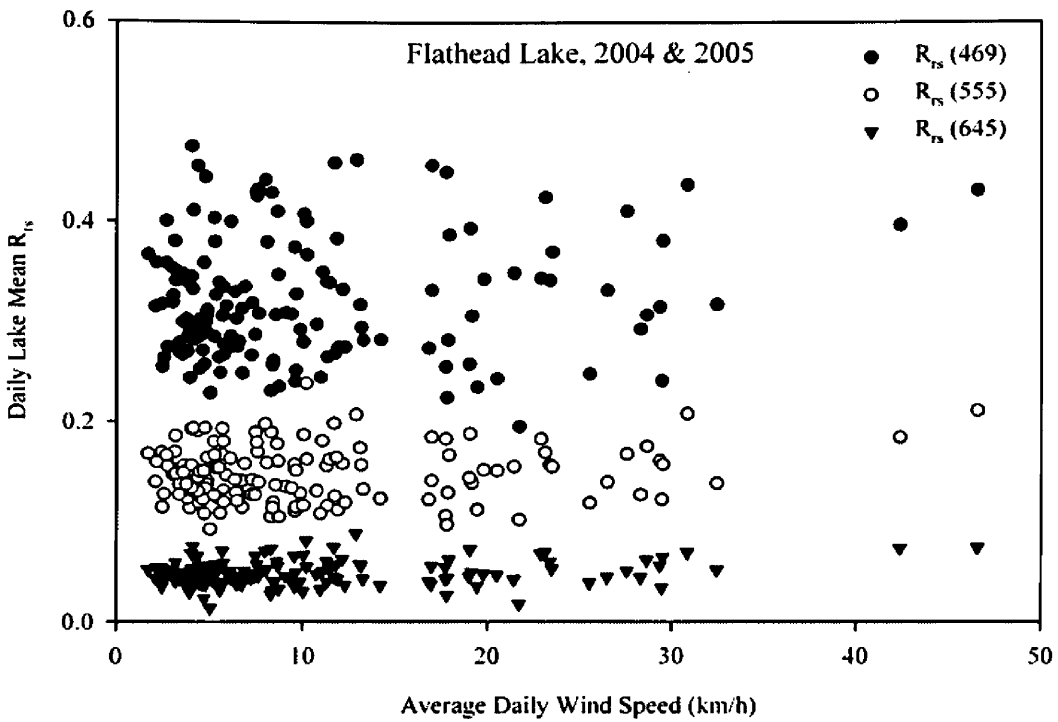


Figure 4. Daily lake mean remote sensing reflectance ( $R_{rs}$ ) values from 2004 & 2005 versus average (top) and maximum (bottom) daily wind speeds taken at Yellow Bay Point on Flathead Lake. No correlation is present between increases in wind speed and mean reflectance values and the increased variation and reflectance in the shorter wavelengths is indicative of oligotrophic waters.

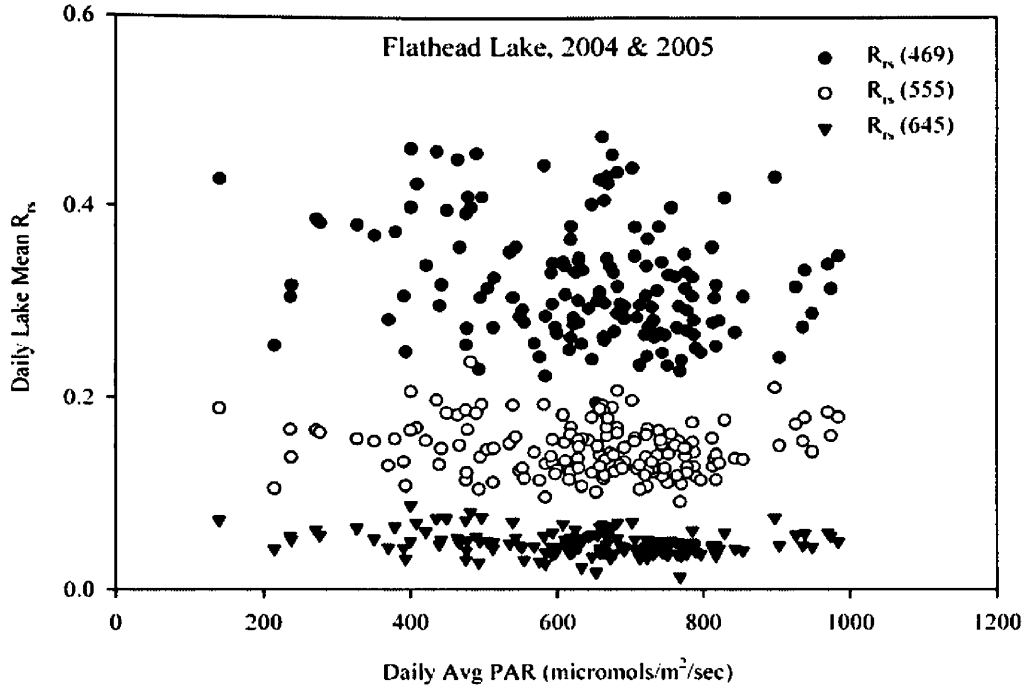


Figure 5. Daily lake mean remote sensing reflectance ( $R_{rs}$ ) values from 2004 & 2005 versus average daily PAR at Yellow Bay Point. No correlation is present between increases in PAR and mean reflectance values and the increased variation in the shorter wavelengths is indicative of oligotrophic waters.

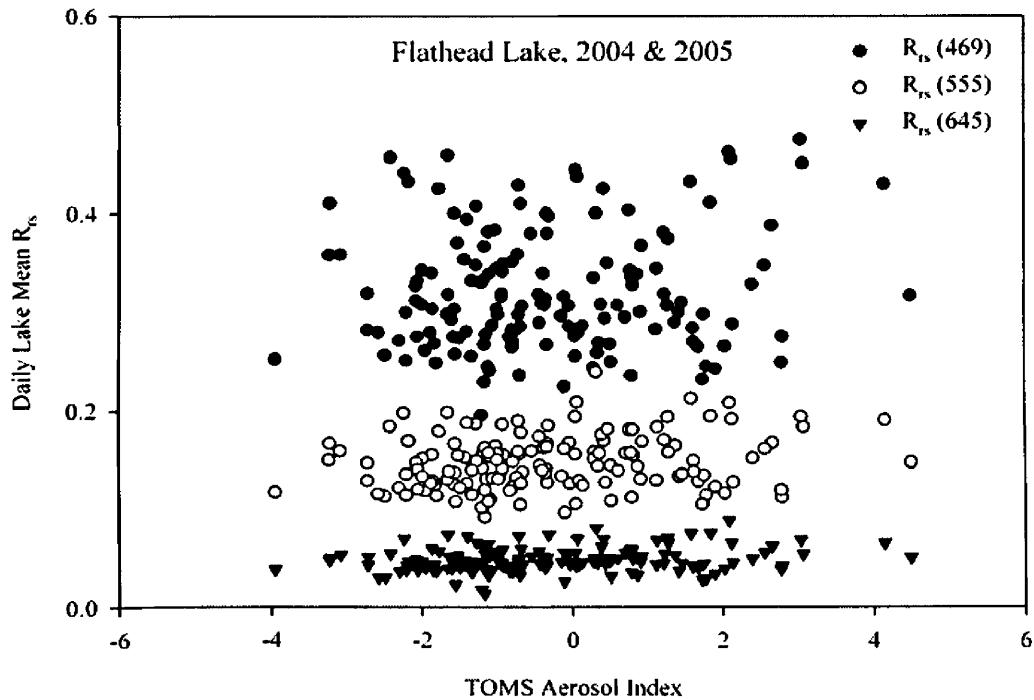


Figure 6. Daily lake mean remote sensing reflectance ( $R_{rs}$ ) values from 2004 & 2005 versus daily TAMS aerosol indices over the study region. No correlation is present between increases in aerosol indices and mean reflectance values and the increased variation in the shorter wavelengths is indicative of oligotrophic waters. This furthers the concept that NIR band subtraction is a good estimator of aerosol reflectance.

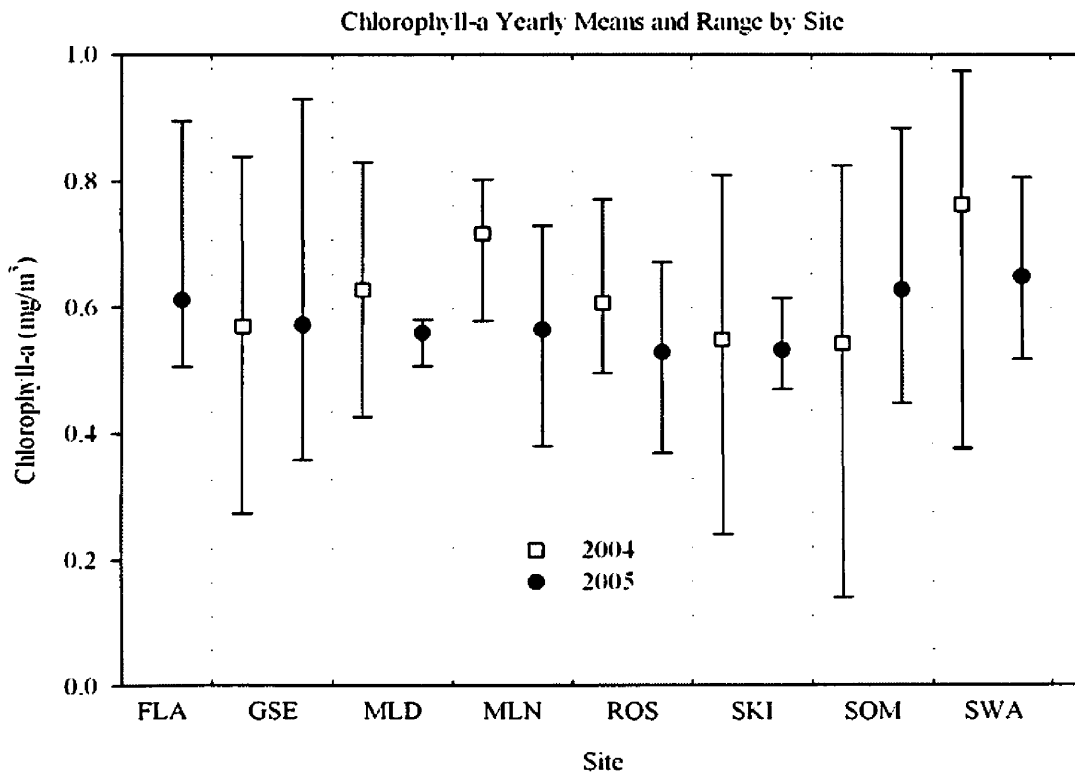
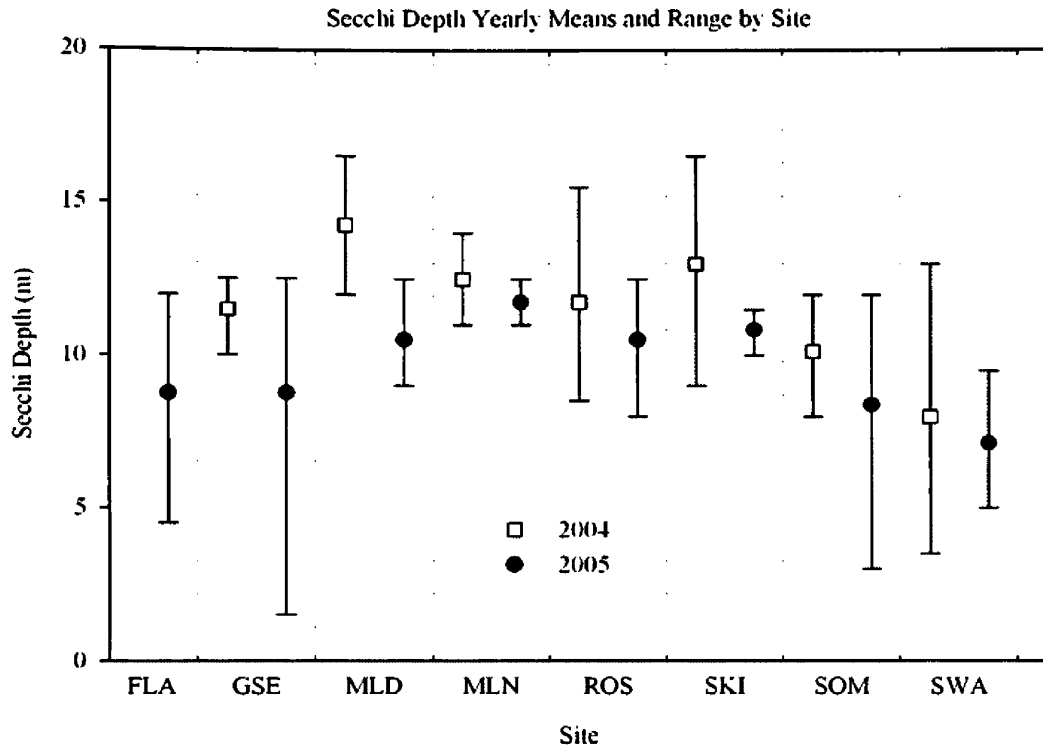


Figure 7. Field data results (range and means) for Secchi depth (m) and Chlorophyll-a ( $\text{mg}/\text{m}^3$ ) across 8 sites for the 2004 and 2005 season. Secchi depth (SD) means decreased from 2004 to 2005 and Chlorophyll-a (Chla) showed a similar trend. Generally decreases in Chla lead to increases in SD, so this reinforces the concept that Chla is not the primary scattering component in the system. Note the Flathead Delta site (FLA) was only measured in 2005.

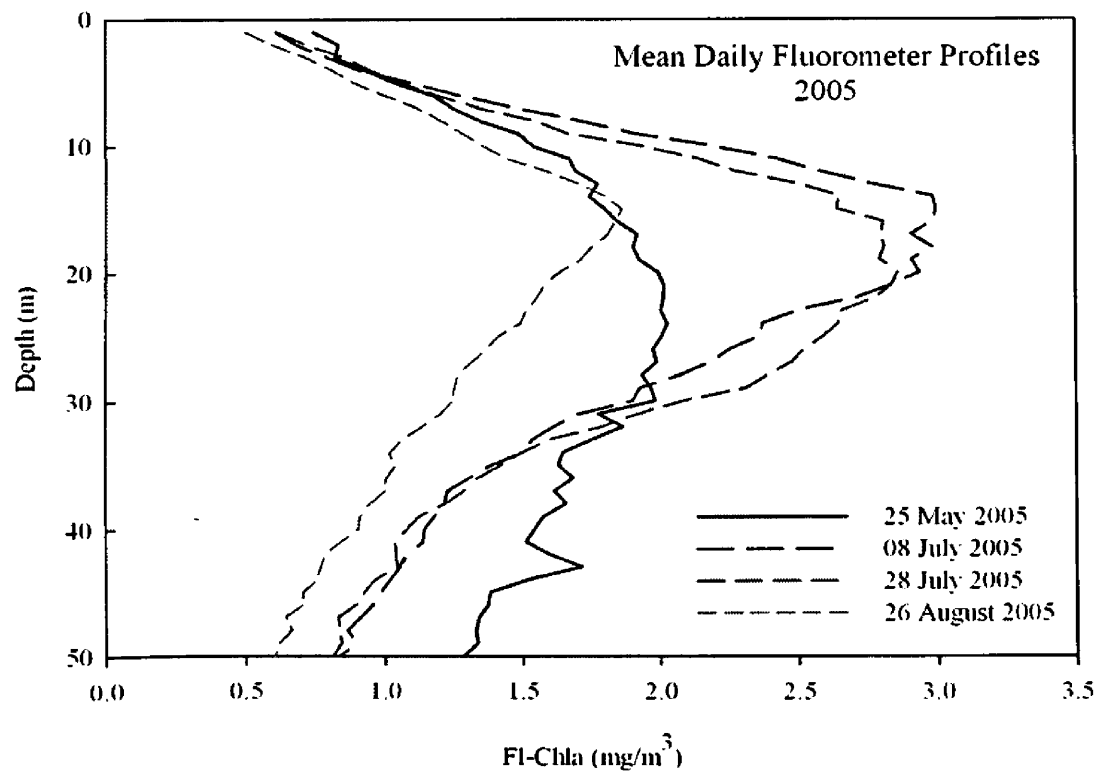
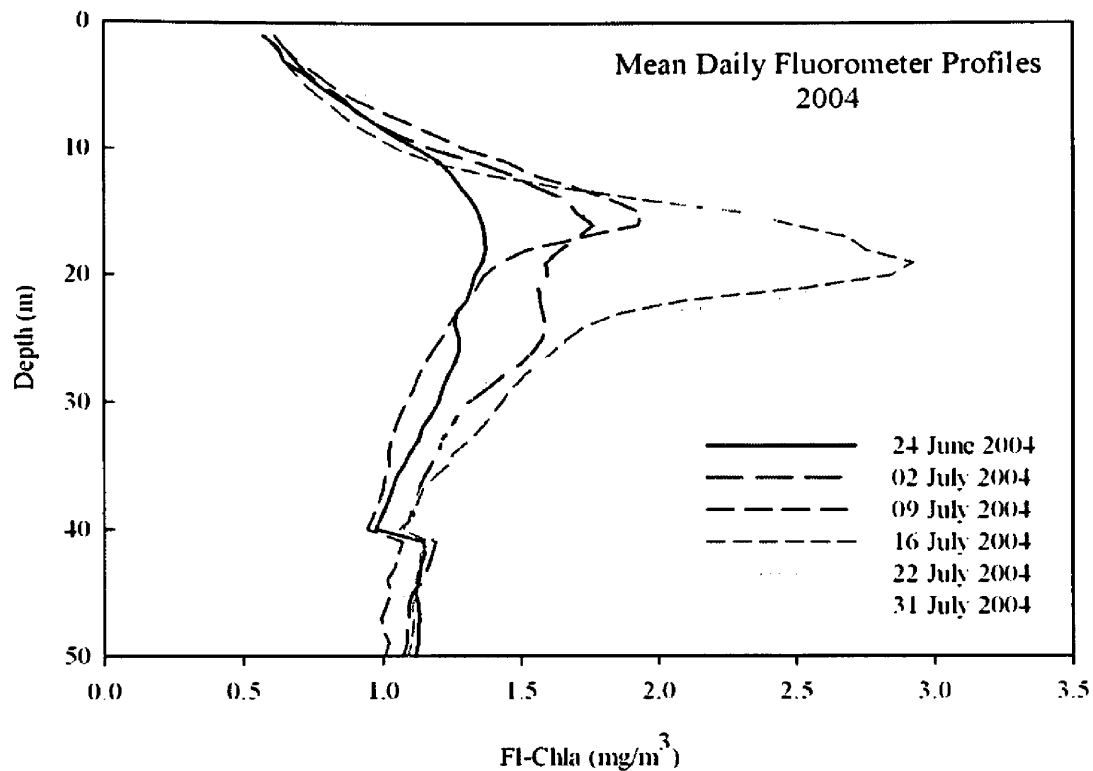


Figure 8. Mean Daily Fluorometer Profiles of estimated chlorophyll-a (FI-Chla) for Flathead Lake in 2004 and 2005. Both years exhibit overall increases as the season progresses, and 2005 exhibits greater vertical dispersion of chlorophyll-a as opposed to the more discrete spikes found in 2004.

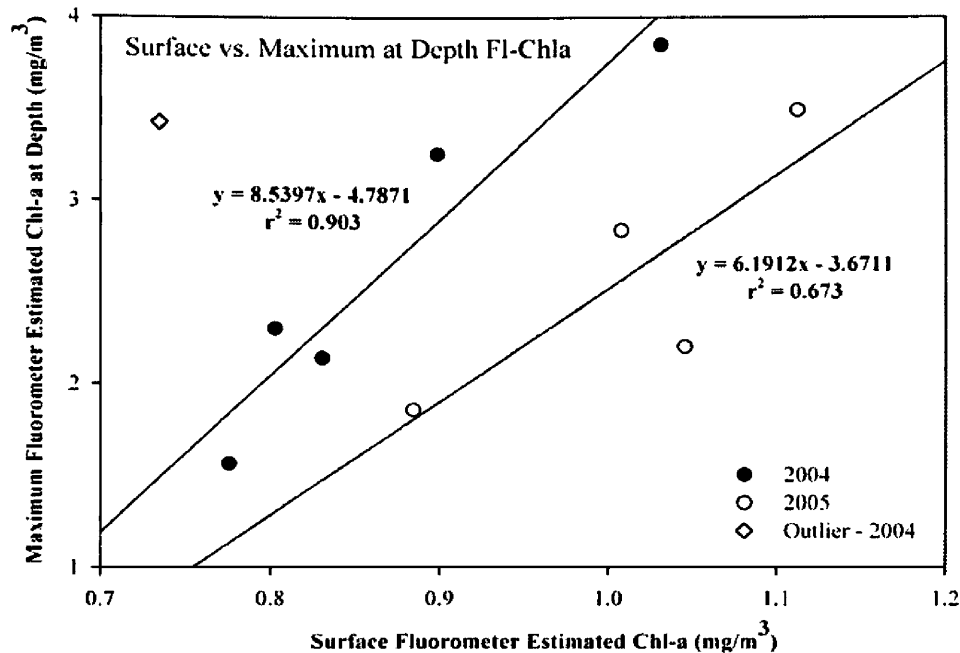


Figure 9. Mean daily surface to five meter fluorometer estimated chlorophyll-a (FI-Chla) versus the maximum reading at depth. The single outlier from 2004 was not included in equations and can be explained by a week long calm period prior to measurement that allowed algae to settle to the thermocline.

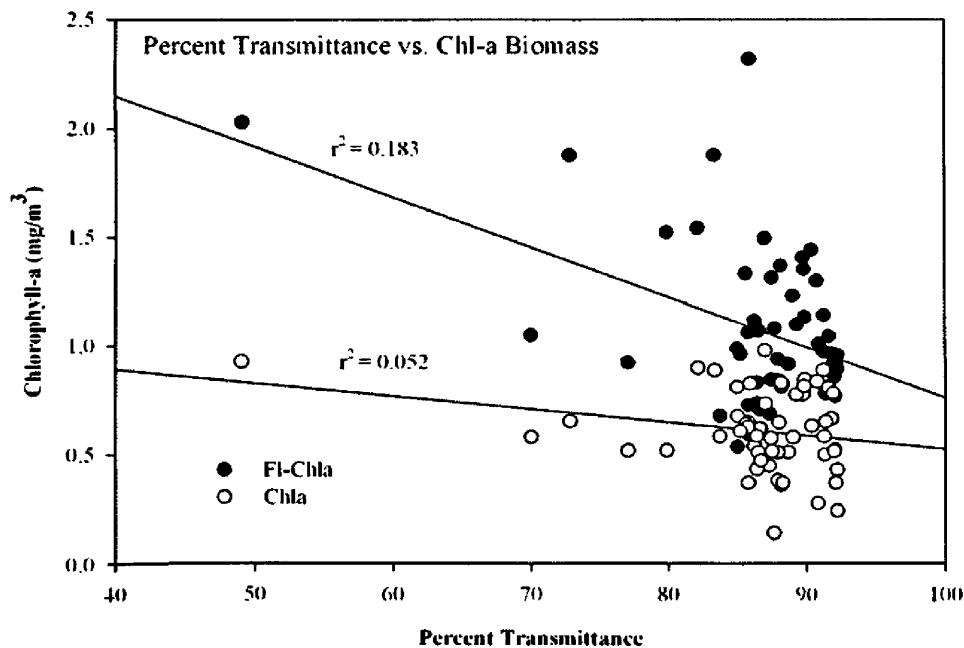


Figure 10. Surface to five meter transmittance (%) by site versus fluorometer estimated Chla (FI-Chla) and measured Chla. The relationship between turbidity and either measurement of Chla is not significant, reinforcing the concept that chlorophyll-a is not the primary scattering component in the system.

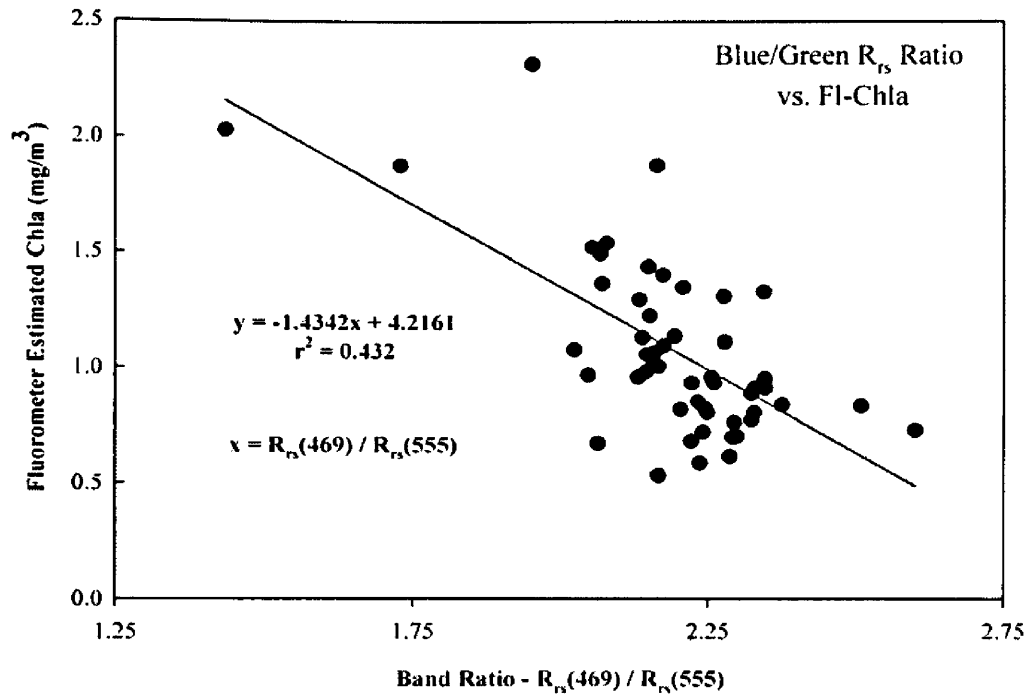


Figure 11. The blue/green [ $R_{rs}(469) / R_{rs}(555)$ ] remote sensing reflectance ( $R_{rs}$ ) band ratio versus fluorometer estimated chlorophyll-a

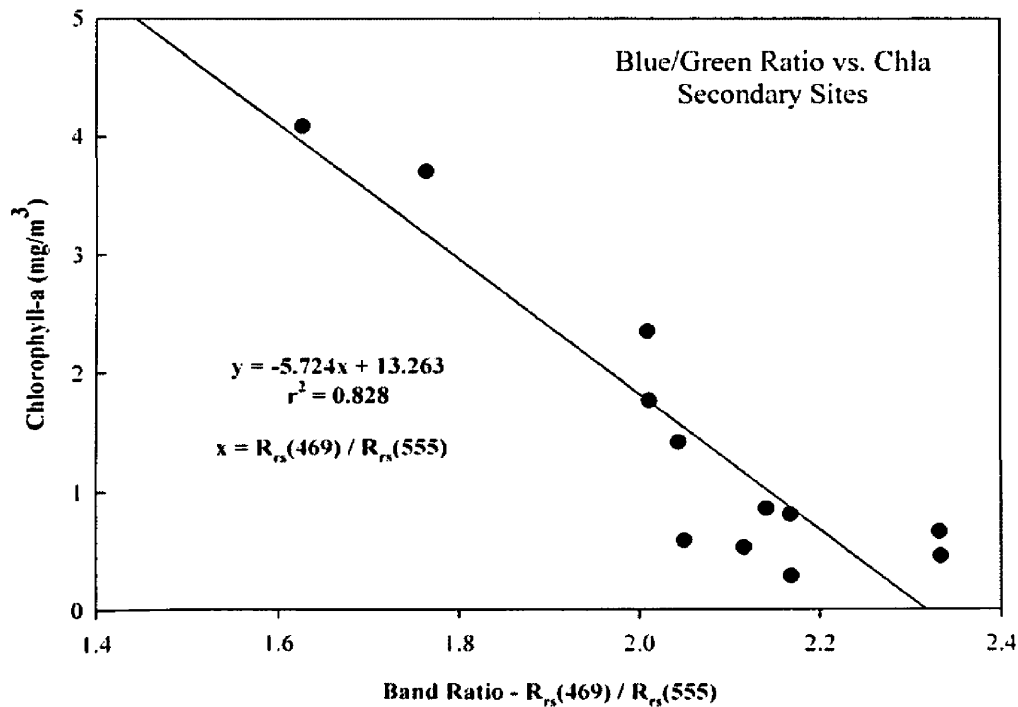


Figure 12. The blue/green [ $R_{rs}(469) / R_{rs}(555)$ ] remote sensing reflectance ( $R_{rs}$ ) band ratio versus Chla on secondary sites (non-Flathead Lake). Notice the regression's dependence on the five samples greater than  $1.0 \text{ mg}/\text{m}^3$ , indicating a possible sensitivity threshold using this methodology.



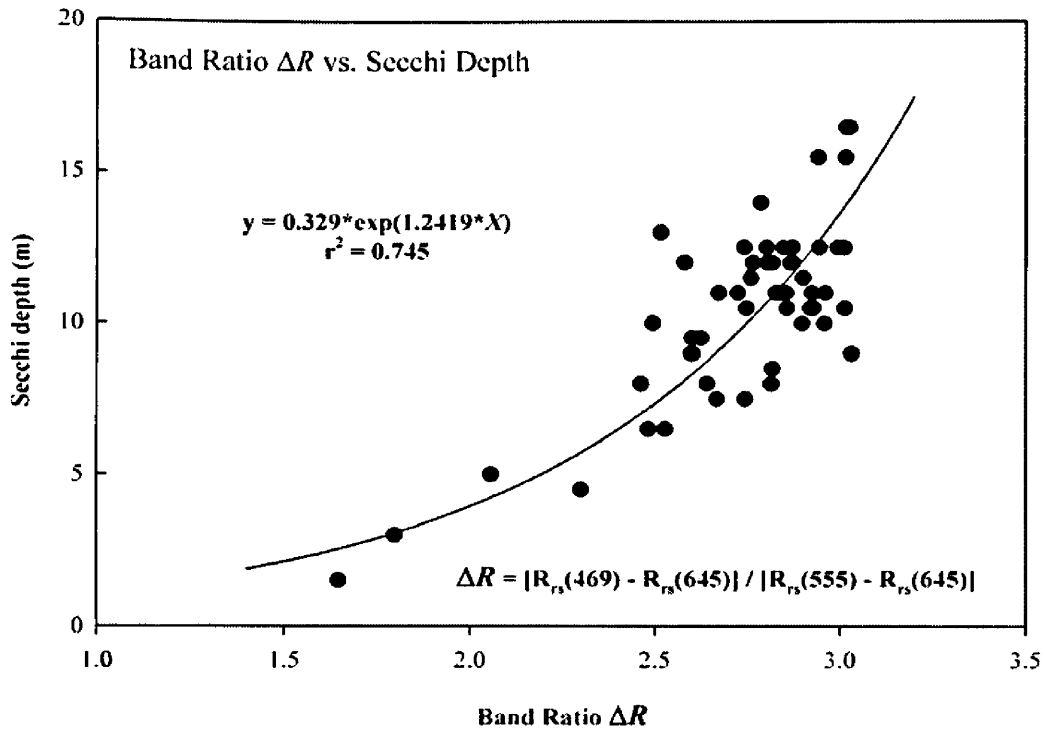


Figure 13. The remote sensing reflectance band ratio  $\Delta R = [R_{rs}(469) - R_{rs}(645)] / [R_{rs}(555) - R_{rs}(645)]$  versus Secchi depth (m).

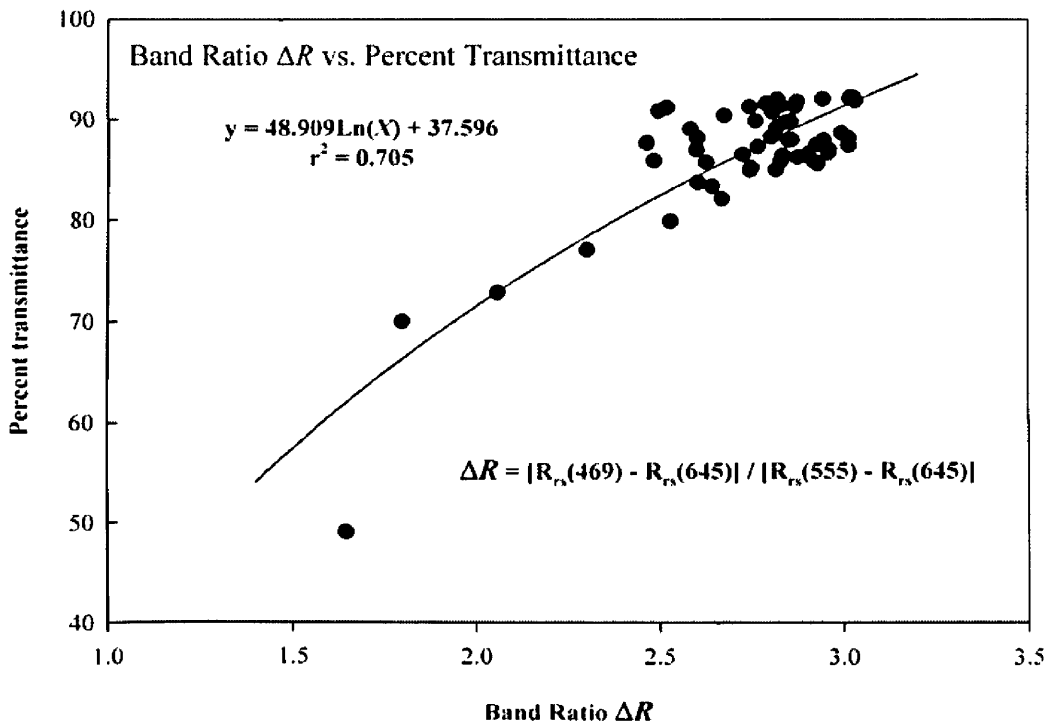


Figure 14. The remote sensing reflectance band ratio  $\Delta R = [R_{rs}(469) - R_{rs}(645)] / [R_{rs}(555) - R_{rs}(645)]$  versus surface to five meter percent transmittance.

## Remote Sensing Reflectance ( $R_{rs}$ ) Estimated Secchi Depth

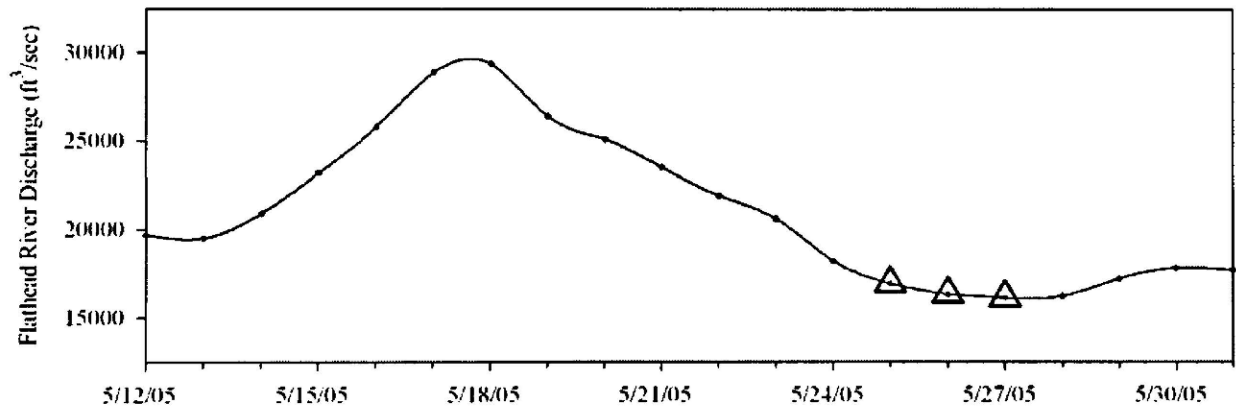
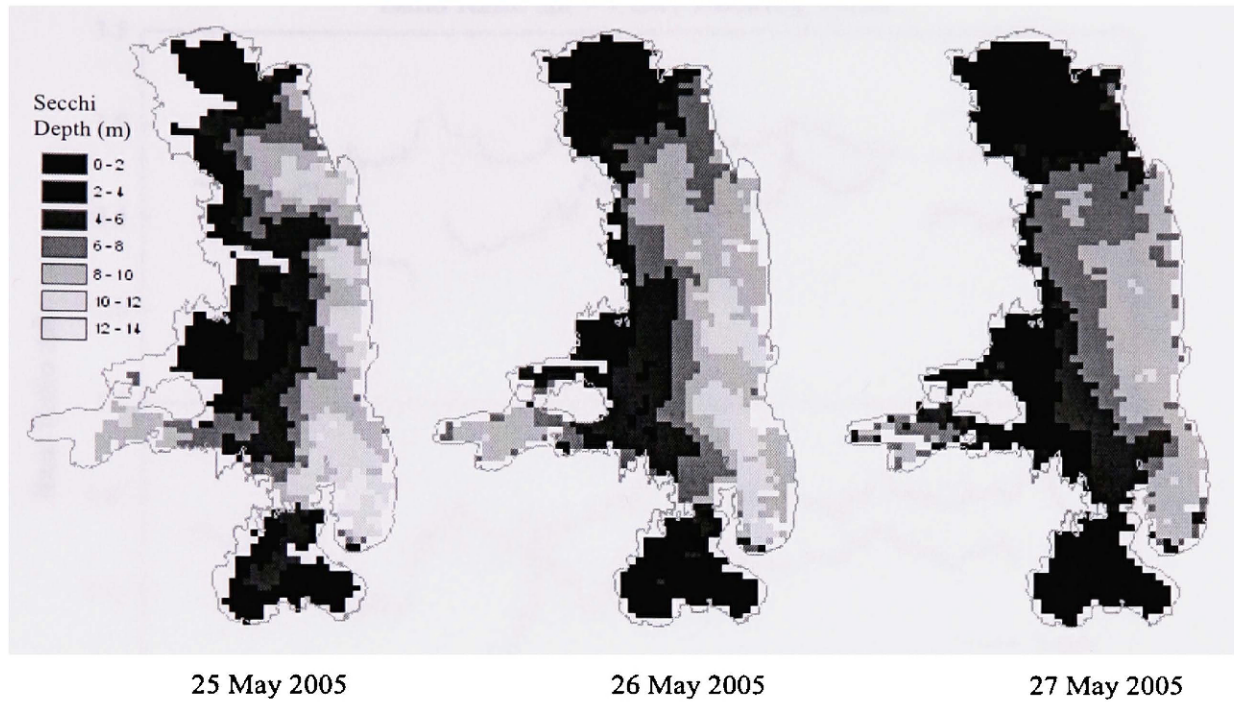


Figure 15. Synoptic maps of remote sensing reflectance ( $R_{rs}$ ) estimated Secchi depth from 25 May 2005 to 27 May 2005 (white pixels are cloud cover or no data) and Flathead River discharge from the same period. Triangles are the three sequential days represented in the synoptic maps. The impacts from the 18 May plume can be seen migrating down the western side of the lake and are beginning to affect the southern portion of the lake most dramatically on the ninth day, 27 May.

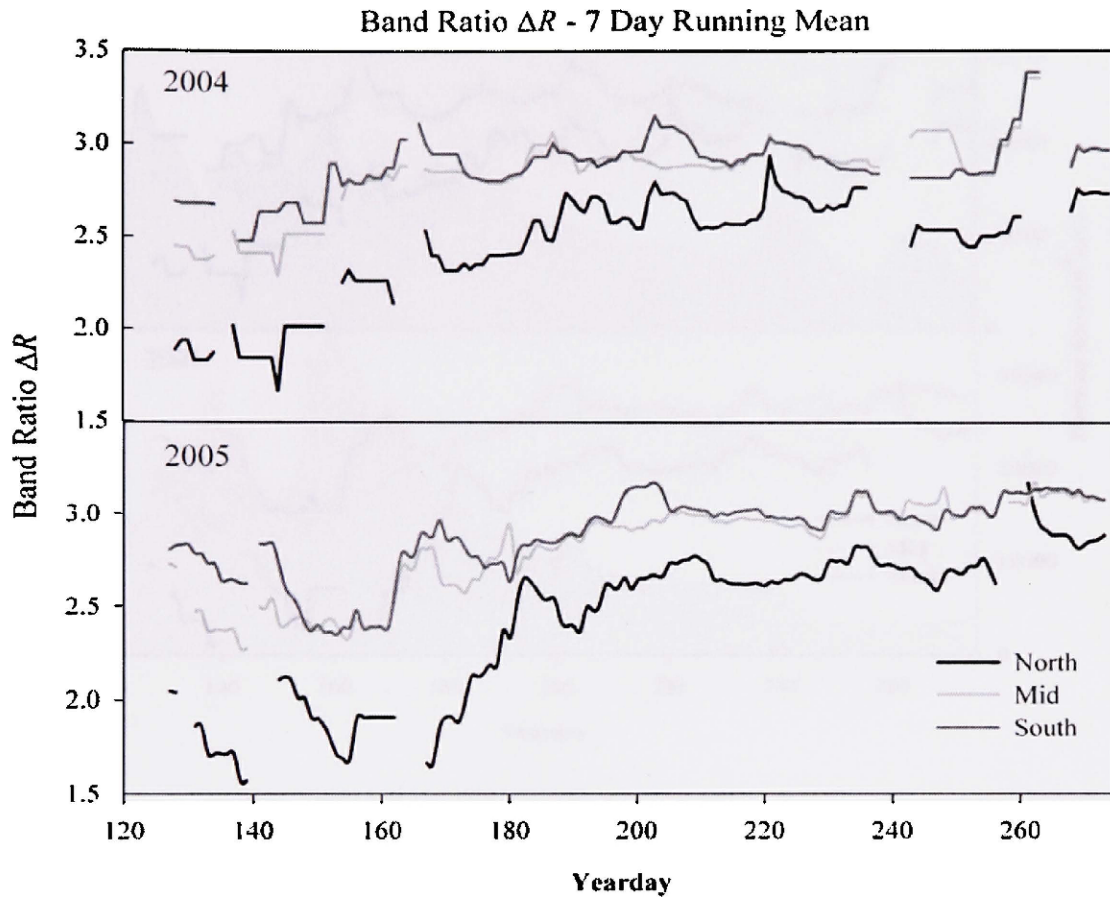


Figure 16. Seven day running means of band ratio  $\Delta R = [R_{rs}(469) - R_{rs}(645)] / [R_{rs}(555) - R_{rs}(645)]$ , over the north, mid, and south lake regions for 2004 and 2005. Gaps indicate seven or more consecutive days without cloud-free data and decreasing band ratio depicts decreasing water clarity. The large fluctuations associated with spring run off are apparent early in the season.

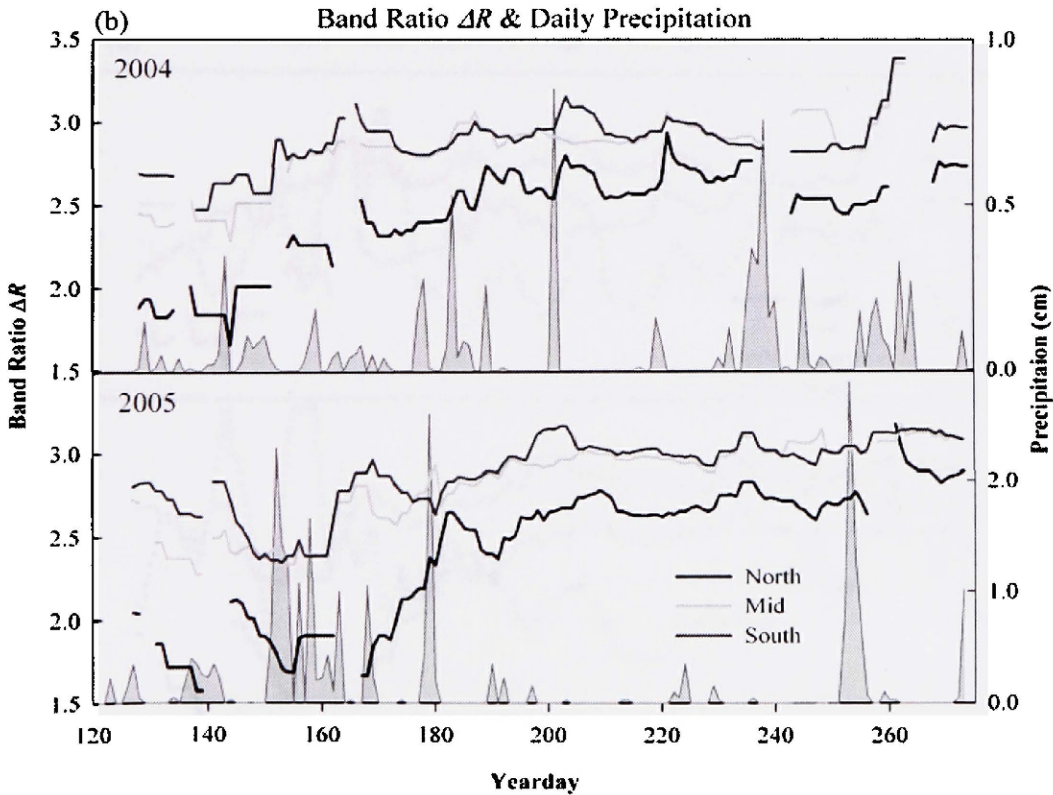
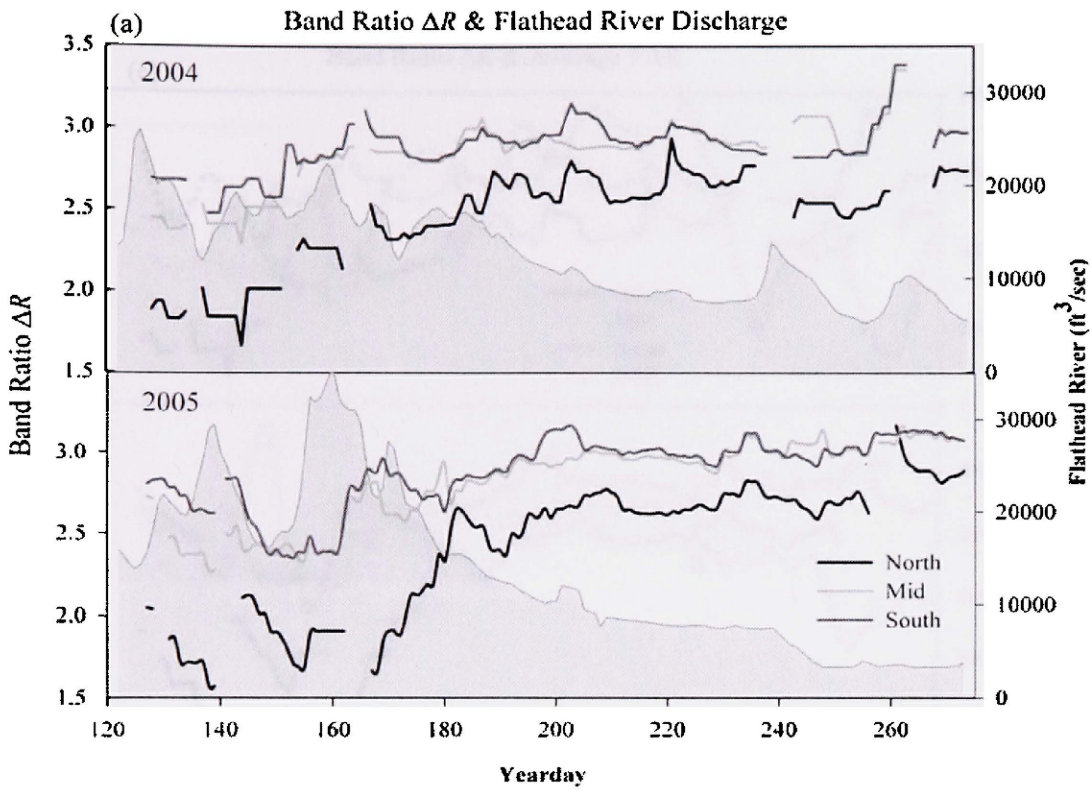


Figure 17 a,b. Seven day running means of band ratio  $\Delta R = [R_{rs}(469) - R_{rs}(645)] / [R_{rs}(555) - R_{rs}(645)]$ , over the north, mid, and south lake regions for 2004 and 2005, plotted with Flathead River discharge (a) and daily precipitation (b)



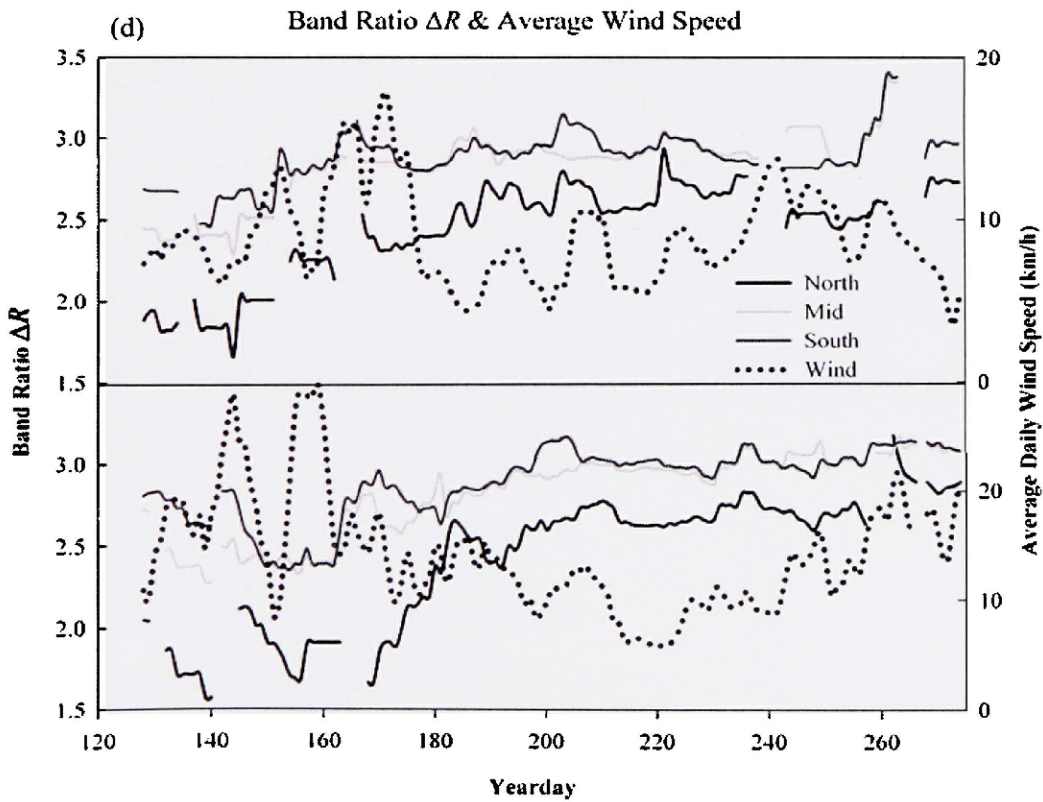
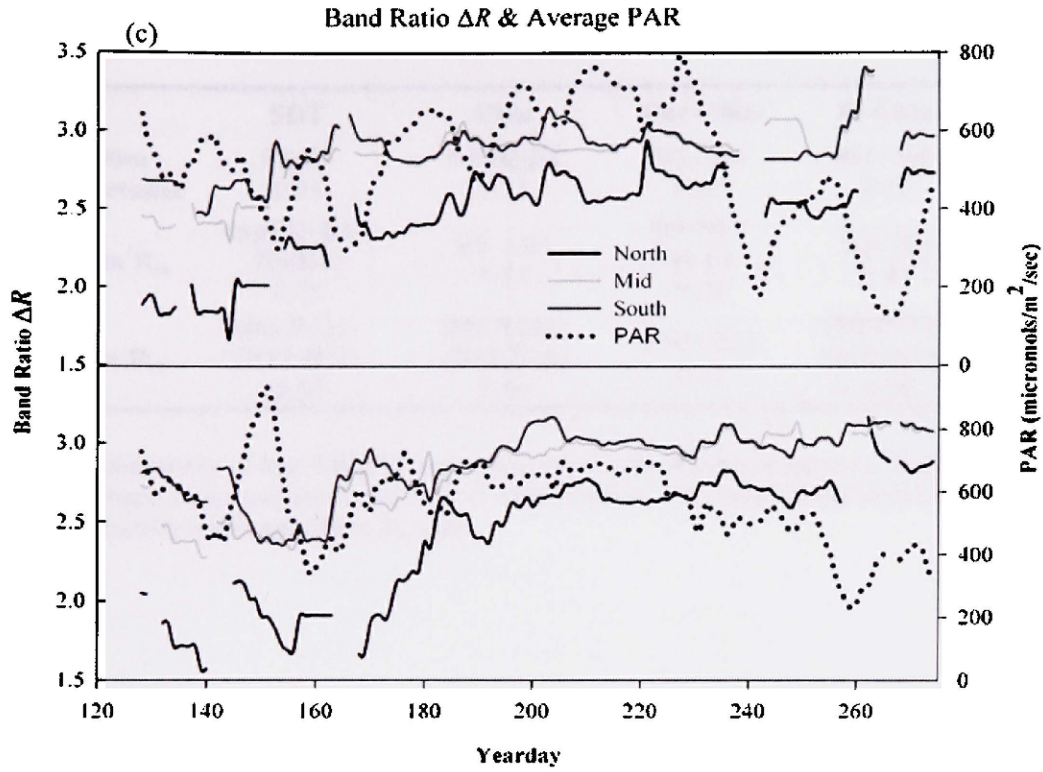


Figure 17 c,d. Seven day running means of band ratio  $\Delta R = [R_{rs}(469) - R_{rs}(645)] / [R_{rs}(555) - R_{rs}(645)]$ , over the north, mid, and south lake regions for 2004 and 2005, plotted with seven day running means of PAR (c) and wind speed (d)

	<b>SDT</b>	<b>Chla</b>	<b>Unc-Chla</b>	<b>Fl-Chla</b>	<b>PT</b>
<b>500m Reflectance</b>	B3;B4 0.35	B1;B2;B4 0.21	B3 / B4 0.27	B3 / B4 0.12	B3 / B4 0.22
<b>500m R<sub>rs</sub></b>	exp(B3-B1 / B4-B1) 0.75	B3 / B4 0.16	B3-B1 / B4-B1 0.08	B3 / B4 0.43	Ln(B3-B1 / B4-B1) 0.71
<b>1km R<sub>rs</sub></b>	(B8-B13) / (B12-B13) 0.55	(B8-B13) / (B12-B13) 0.06	B10 / B12 0.12	(B8-B13) / (B12-B13) 0.26	B11 0.46

Table 1. Summary of best MODIS regression results for *in situ* parameters, Flathead Lake data only. Bands or band ratios are listed and their  $r^2$  values below. The best results were achieved using the in-house atmospherically corrected 500m R<sub>rs</sub> data.

**Appendix A.**  
**2004 & 2005 Water Sampling Protocol**

**Variables to be Measured:**

Secchi Depth Transparency (meters)  
Chlorophyll-a ( $\text{mg}/\text{m}^3$ )  
Surface Temperature ( $^{\circ}\text{C}$ )  
Turbidity Profiles (% Transmittance)  
Fluorometer Profiles (Fluorometer estimated Chl-a)

**Equipment List:**

Boat, Trolling Motor, Oars, & PFD or FLBS Research Vessel Jessie B.  
SeaBird Conductivity Temperature Density (CTD) Unit  
Handheld GPS  
Infrared Thermometer  
Secchi Disk on at least 20m line  
10 - 20 L Container (NOT clear plastic)  
1 L samples bottles (2 for each site - NOT clear plastic)  
5m hose, with ball valves at each end and lead weight at one end  
Field Notebook  
Cooler filled with ice - large enough to store 16 sample bottles

**Initial Note on Differences Between 2004 & 2005 Season:**

It is important to note that changes were made after the 2004 season based on results from 2004 MODIS analysis. Initially, the 250m MODIS bands were applied, so data collection was restricted to within a 250m pixel at each site. Due to poor results using the red and near-infrared (NIR) 250m bands, it was decided to expand the study and apply the 500m data, which includes the blue and green bands as well as the red and NIR. In 2004, five points within the 250m pixel were measured to account for the variability of the water quality parameters within a single pixel. It was determined that this variability was not significant enough considering the trade-off that was being made. That trade-off was that measuring five points at each site required an extensive amount of time and memory usage on the SeaBird CTD. It was therefore difficult to reach all seven sites in one day, so the decision was made to sample only one point at each site so all

sites could be accessed in one day. This allowed the addition of the Flathead Delta site as time and CTD memory were no longer constraints. The sample points were adjusted after the 2004 season to center points within the 500m pixels.

### **Purpose of Field Sampling:**

The purpose of this campaign is to gain an accurate measurement of chlorophyll-a (Chla), from water samples and fluorometer profiles, and turbidity, from Secchi depth transparency (SD) and transmissometer profiles, within a given MODIS pixel on Flathead Lake and the secondary sites. The data was used to formulate an equation/model to relate the MODIS data to the measured parameters.

### **Selection of Sampling Points:**

The selection of points for water sample collection were based on multiple criteria. The first was to choose areas that are of interest to current researchers at the FLBS where past collection had taken place. Under the direction of Bonnie Ellis, those points were Mid-Lake Deep, Ross Deep, Skidoo Bay, and Somers Bay (Table 2). Additional points beyond these four were needed. The criteria in selecting the additional points were based on; areas where the depth was greater than 20m (so that there would be no interference from bottom substrate), boat launch access points, and spatial distribution throughout the lake to compensate for the water's natural counter-clockwise flow. Of the possible points, three were selected, Swan River Inlet, Midlake North, and Goose Island (Figure 1 & Table 2). The Flathead Delta site was added for the 2005 season. Four



secondary sites were chosen outside of Flathead Lake, those were Whitefish Lake, Lake Mary Ronan, Swan Lake and Hungry Horse Reservoir (Table 3).

Exact point locations were determined by choosing a MODIS pixel at each of these locations and then calculating the center point of that pixel. From that center point a grid of 5 points was created where water samples were taken and integrated into one sample (2004 season). For the 2005 field campaign, samples were collected only at the center point.

<b>Site Name</b>	<b>Site ID</b>	<b>Easting</b>	<b>Northing</b>
Somers Bay	SOM	708158	5324645
Swan Inlet	SWA	714658	5323895
Midlake North	MLN	716158	5318895
Goose Island	GSE	711658	5314895
MidLake Deep	MLD	718908	5306145
Ross Deep	ROS	705158	5301145
Skidoo Bay	SKI	721408	5295895
Whitefish Lake	WLK	694782	5366769
Lake Mary Ronan	LMR	693782	5310269

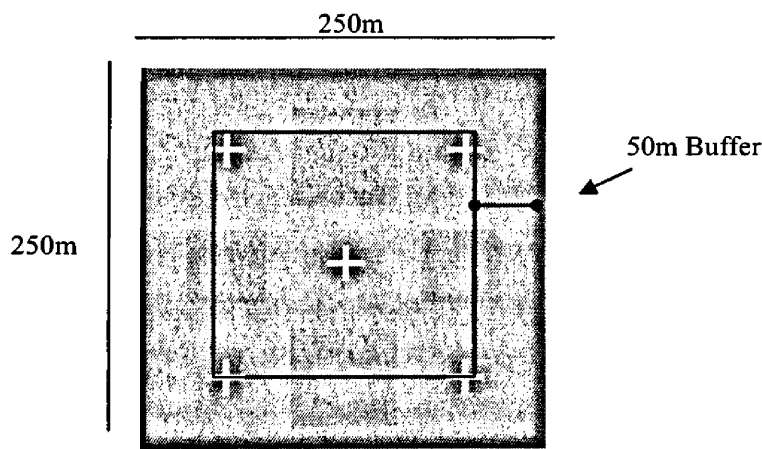
Table 2 - 2004 Sampling points. Center Point Coordinates are in UTM, Zone 11 NAD83.

<b>Site Name</b>	<b>Site ID</b>	<b>Easting</b>	<b>Northing</b>
Flathead Delta	FLA	712407	5322894
Somers Bay	SOM	708407	5324644
Swan Inlet	SWA	714907	5323894
Midlake North	MLN	716407	5318894
Goose Island	GSE	711907	5314894
MidLake Deep	MLD	719157	5306144
Ross Deep	ROS	705407	5301144
Skidoo Bay	SKI	721657	5295894
Whitefish Lake	WLK	694596	5367407
Lake Mary Ronan	LMR	694654	5311188
Swan Lake*	SLK	286633	5312659
Hungry Horse Reservoir*	HHR	278815	5357865

Table 3 - 2005 Sampling points. Center Point Coordinates are in UTM, Zone 11 WGS84. \*Note: SWA and HHR are UTM, Zone 12 WGS84.

### Creation of Sampling Grid:

As mentioned above, a grid of 5 points was created within each pixel. This grid was based on the center point of the pixel, and the application of a 50m buffer within the pixel (see diagram below). The 50m buffer was created to prevent the occurrence of samples being taken across more than one pixel. Due to drift and accuracy variability in GPS units, it is well understood that navigating to an exact point and remaining there, without an anchor, for any period of time is an unrealistic idea. The 50m buffer will be enough to compensate for such drift. The resulting grid contains points that are approx. 106m from the center point.



Five point sampling grid

### Determination of Integrated Sample Depth:

Past research has concluded that 90% of upwelling photons originate within the first attenuation depth ( $K_d$ ). An attenuation depth or attenuation coefficient for Flathead Lake was determined based on the attenuation depth of similar lakes, and by calculations after the first field season. The original approximate attenuation depth was 5 m, and the calculated depth after the 2004 season was 6.25 m. A 5 m integrated water sample was taken at each site for both seasons.

## **Collection Methods:**

*Note* – Lab Methods for measuring Chla are not included here as they will follow the same procedures that are currently being used in the Freshwater Lab at the Flathead Lake Biological Station which can be found in the Standard Methods for Examination of Water and Wastewater (Clesceri et al.,1998).

## **Steps for Data Collection on Flathead Lake:**

- 1.) Record SITE\_ID, Weather conditions, and Date in notebook
- 2.) Navigate to center point of site using GPS unit.
- 3.) Store point in GPS unit, and record by hand exact location and time of day.
- 4.) Cast Seabird CTD from surface to 5 m above lake bottom.
- 5.) Take a SDT reading, being sure to take it from the ‘shaded’ side of the boat.
- 6.) Record Surface Temperature using handheld infrared thermometer.
- 7.) Rinse 20L storage container and 1L containers with water at site.
- 8.) Rinse 5m hose with water at site.  
\*Note - Rinse containers and hose on sunny side of boat.
- 9.) On shady side of boat, ideally under a tarp, submerge 5m hose into water. Close top of hose to hold sample. Bring bottom of hose to surface of water and close bottom of hose before pulling hose from water. Release the water sample into 20L container.
- 10.) Under shade, pour sample from 20L container into two 1L containers. Place samples in cooler on ice. Empty remaining water from large container into lake.  
\*Note - Steps 11 through 13 were not conducted during 2005 season. So step nine was repeated 3 times to ensure that at least 2 L of water was collected at each site.
- 11.) Navigate to second point of grid, and then repeat steps 3 - 6. As the boat will drift some during the collection process, be sure that navigation to the next point takes this drift into account. Refer to table of points to ensure that samples are being taken at correct locations.
- 12.) Complete Steps 3 - 6 at each of the gridded points (5 total).
- 13.) Navigate to next sample site and repeat the process.

### **Steps for Data Collection at Secondary Sites:**

- 1.) Record SITE\_ID, Weather conditions, and Date in notebook
- 2.) Navigate to center point of site using GPS unit.
- 3.) Store point in GPS unit, and record by hand exact location and time of day.
- 4.) Take a SDT reading, being sure to take it from the 'shaded' side of the boat.
- 5.) Record Surface Temperature.
- 6.) Rinse 20L storage container and 1L containers with water at site on sunny side of boat.
- 7.) Rinse 5m hose with water at site on sunny side of boat.
- 8.) On shady side of boat submerge 5m hose into water. Close top of hose to hold sample. Bring bottom of hose to surface of water and close bottom of hose. Then pull hose from water and release the water sample into 20L container.  

\*Note - Steps 9 and 10 were not conducted during 2005 season. So step eight was repeated 3 times to ensure that at least 2 L of water was collected at each site.
- 9.) Navigate to second point of grid, and then repeat steps 3 - 8. As the boat will drift some during the collection process be sure that navigation to the next point takes this drift into account. Refer to table of points to ensure that samples are being taken at correct locations.
- 10.) Once all five points within the grid have been sampled, under shade, pour sample from 20L container into two 1L containers. Place samples in cooler on ice. Empty remaining water from large container into lake.

**Appendix B.**

**Table 4. Flathead Lake *In Situ* Data and MODIS R<sub>rs</sub> Summary Table**

Site	Year	Day	Surface Temp. (C)	Secchi Depth (m)	Chlorophyll-a (mg/m <sup>3</sup> )	CTD Temp. (C)	CTD PAR	CTD Fluor-ometer (volts)	CTD Trans- missometer (%)	Band 1 Rrs	Band 3 Rrs	Band 4 Rrs
SOM	2004	176	15.8	8	0.14	12.74	423.84	0.373	87.63	0.051	0.340	0.168
GSE	2004	184	16.1	10	0.27	14.67	556.46	0.357	90.81	0.026	0.260	0.120
ROS	2004	184	17.6	12	0.49	15.50	672.76	0.310	91.28	0.043	0.295	0.131
SKI	2004	184	17.8	15.5	0.37	14.71	569.82	0.338	92.10	0.040	0.281	0.120
MLN	2004	191	18	14	0.80	15.70	437.34	0.365	91.57	0.055	0.334	0.155
SOM	2004	191	15.6	12	0.57	16.13	546.36	0.407	88.99	0.039	0.310	0.144
SWA	2004	191	16.6	13	0.88	16.33	667.18	0.348	91.17	0.050	0.327	0.160
GSE	2004	198	18.2	12.5	0.66	17.79	585.96	0.346	91.76	0.046	0.316	0.140
MLD	2004	198	19.8	16.5	0.43	15.98	465.86	0.329	92.18	0.048	0.322	0.139
ROS	2004	198	17.7	15.5	0.52	16.73	432.64	0.300	92.02	0.047	0.321	0.140
SKI	2004	198	19.8	16.5	0.24	15.76	346.16	0.344	92.22	0.045	0.317	0.135
GSE	2004	204	18.5	12	0.51	19.35	394.40	0.321	91.98	0.032	0.223	0.100
MLN	2004	204	18.4	12.5	0.58	17.00	486.40	0.387	91.23	0.035	0.242	0.111
ROS	2004	204	17.9	11	0.64	17.61	411.60	0.303	91.35	0.026	0.219	0.094
SKI	2004	204	18.9	9	0.78	19.14	461.30	0.335	91.89	0.052	0.349	0.150
SOM	2004	204	19	11	0.63	17.83	415.20	0.457	90.36	0.035	0.242	0.112
SWA	2004	204	19.2	6.5	0.82	13.17	263.10	0.662	85.86	0.050	0.272	0.139
GSE	2004	213	19.9	11.5	0.84	19.47	635.84	0.385	89.83	0.048	0.289	0.135
MLD	2004	213	19.5	12	0.83	19.92	216.73	0.424	90.72	0.052	0.299	0.140
MLN	2004	213	20.2	11	0.77	19.19	329.68	0.449	89.70	0.048	0.287	0.132
ROS	2004	213	21.2	8.5	0.77	20.14	497.88	0.377	89.23	0.047	0.288	0.133
SKI	2004	213	22.6	11	0.81	19.56	318.88	0.436	89.78	0.046	0.290	0.132
SOM	2004	213	20.2	9.5	0.82	18.83	511.72	0.440	88.13	0.045	0.284	0.137
SWA	2004	213	19.9	9	0.97	19.38	452.02	0.470	86.94	0.046	0.287	0.139
FLA	2005	145	9.2	4.5	0.51	9.24	593.31	0.146	77.03	0.065	0.368	0.197
GSE	2005	145	8.8	1.5	0.93	9.25	212.93	0.262	49.08	0.096	0.420	0.293

Site	Year	Day	Surface Temp. (C)	Secchi Depth (m)	Chlorophyll-a (mg/m3)	CTD Temp. (C)	CTD PAR	CTD Fluorometer (volts)	CTD Transmissometer (%)	Band 1 Rrs	Band 3 Rrs	Band 4 Rrs
MLD	2005	145	8.8	9	0.58	8.41	429.44	0.120	83.69	0.051	0.315	0.153
MLN	2005	145	9.5	11	0.64	9.41	681.24	0.111	85.77	0.047	0.320	0.143
ROS	2005	145	8.3	8	0.67	8.43	642.45	0.105	84.95	0.054	0.326	0.150
SKI	2005	145	13	11.5	0.61	9.14	152.47	0.123	86.56	0.042	0.298	0.130
SOM	2005	145	9.8	3	0.58	9.54	472.03	0.159	70.00	0.074	0.371	0.239
SWA	2005	145	10.3	5	0.65	5.20	603.41	0.246	72.82	0.064	0.353	0.204
FLA	2005	189	19.6	12	0.53	18.06	420.65	0.166	86.20	0.051	0.368	0.162
GSE	2005	189	19	10.5	0.64	17.09	382.38	0.188	85.57	0.047	0.363	0.155
MLD	2005	189	17.4	10.5	0.57	14.46	516.78	0.137	87.39	0.049	0.365	0.154
MLN	2005	189	18.5	12.5	0.51	15.73	341.18	0.145	88.63	0.051	0.367	0.156
ROS	2005	189	17	10.5	0.64	14.15	648.22	0.137	87.96	0.025	0.328	0.131
SOM	2005	189	18.2	8	0.88	17.41	492.64	0.246	83.31	0.048	0.361	0.167
SWA	2005	189	19	9.5	0.62	16.73	687.79	0.160	85.71	0.050	0.365	0.170
FLA	2005	209	20.2	11	0.51	16.68	587.52	0.161	86.46	0.044	0.292	0.135
GSE	2005	209	19.4	12.5	0.36	19.81	639.01	0.134	88.15	0.043	0.292	0.126
MLD	2005	209	19.4	12.5	0.51	19.00	346.79	0.147	87.90	0.046	0.296	0.131
MLN	2005	209	19.3	12.5	0.38	19.00	346.79	0.147	87.90	0.044	0.290	0.130
ROS	2005	209	19.6	12.5	0.37	19.96	434.91	0.135	88.24	0.043	0.288	0.131
SKI	2005	209	22.1	11	0.51	19.46	120.34	0.186	87.47	0.042	0.287	0.126
SOM	2005	209	19.3	12	0.45	19.30	987.30	0.121	87.27	0.039	0.284	0.128
SWA	2005	209	0	6.5	0.51	15.81	508.14	0.208	79.85	0.045	0.298	0.145
FLA	2005	238	17.2	7.5	0.89	17.72	451.31	0.210	82.08	0.045	0.263	0.127
GSE	2005	238	17.9	10.5	0.37	18.06	403.55	0.125	85.74	0.041	0.262	0.117
MLD	2005	238	17.7	10	0.58	18.08	278.77	0.136	86.38	0.038	0.248	0.110
MLN	2005	238	17.9	11	0.73	18.28	340.07	0.123	86.99	0.037	0.250	0.109
ROS	2005	238	18	11	0.43	18.65	420.47	0.126	86.39	0.010	0.207	0.080
SKI	2005	238	18.8	10	0.47	19.03	573.47	0.114	86.64	0.038	0.250	0.109
SOM	2005	238	17	10.5	0.60	17.74	877.01	0.150	85.17	0.043	0.262	0.123
SWA	2005	238	17.5	7.5	0.80	17.95	538.50	0.152	84.93	0.042	0.259	0.121

**Table 5. Secondary Sites *In Situ* Data and MODIS R<sub>rs</sub> Summary Table**

Site	Year	Day	Secchi Depth (m)	Surface Temp. (C)	Chlorophyll-a (mg/m3)	B1 Rrs	B3 Rrs	B4 Rrs
LMR	2004	181	5.5	20.2	2.35	0.032	0.244	0.122
WHT	2004	195	8.5	16.8	0.28	0.030	0.251	0.116
LMR	2004	196	6.5	19.6	3.70	0.042	0.251	0.142
LMR	2004	210	4.0	20.4	4.09	0.045	0.245	0.151
SLK	2005	171	3.5	14.1	1.76	0.037	0.231	0.115
HHR	2005	172	8.0	16.9	0.45	#N/A	0.194	0.083
WHT	2005	172	7.5	14.8	0.58	0.026	0.233	0.114
HHR	2005	195	7.5	18.4	0.52	0.027	0.283	0.134
SLK	2005	195	6.5	19.0	0.80	0.020	0.207	0.095
HHR	2005	208	8.5	19.9	0.85	0.021	0.246	0.115
LMR	2005	208	6.5	19.9	1.41	0.040	0.259	0.127
SLK	2005	208	7.5	18.8	0.65	0.021	0.226	0.097

**Site Abbreviations and Coordinates**

Site Name	Site ID	Easting	Northing
Somers Bay	SOM	708158	5324645
Swan Inlet	SWA	714658	5323895
Midlake North	MLN	716158	5318895
Goose Island	GSE	711658	5314895
MidLake Deep	MLD	718908	5306145
Ross Deep	ROS	705158	5301145
Skidoo Bay	SKI	721408	5295895
Whitefish Lake	WLK	694782	5366769
Lake Mary Ronan	LMR	693782	5310269

Table 2 - 2004 Sampling points. Center Point Coordinates are in UTM, Zone 11 NAD83. (identical to table found in Appendix A.)

Site Name	Site ID	Easting	Northing
Flathead Delta	FLA	712407	5322894
Somers Bay	SOM	708407	5324644
Swan Inlet	SWA	714907	5323894
Midlake North	MLN	716407	5318894
Goose Island	GSE	711907	5314894
MidLake Deep	MLD	719157	5306144
Ross Deep	ROS	705407	5301144
Skidoo Bay	SKI	721657	5295894
Whitefish Lake	WLK	694596	5367407
Lake Mary Ronan	LMR	694654	5311188
Swan Lake*	SLK	286633	5312659
Hungry Horse Reservoir*	HHR	278815	5357865

Table 3 - 2005 Sampling points. Center Point Coordinates are in UTM, Zone 11 WGS84. \*Note: SWA and HHR are UTM, Zone 12 WGS84. (identical to table found in Appendix A.)

The data summary tables are separated by Flathead Lake sites and Secondary Sites. The  $R_{rs}$  (Remote Sensing Reflectance) values are those derived from MODIS 500m Radiance at Sensor Swath data with the in-house atmospheric correction applied. They are pixel values corresponding to collection sites. The Flathead Lake table contains the additional Conductivity-Temperature-Density (indicated by CTD in the column headings) Instrument Data which was not collected over the secondary sites. CTD values are zero to five meter depth means. The Fluorometer was sent to the manufacturer and re-calibrated after the 2004 season. The result was a far lower set of volt readings for the 2005 season. Application of the calibration coefficients to calculate chlorophyll-a concentration in  $\text{mg}/\text{m}^3$  did not normalize the data, and 2005 readings were still consistently lower. Therefore, the Fluorometer estimated chlorophyll-a content should be considered relative measurements.

To calculate estimated Chlorophyll-a content apply the following equation:

$$\text{Fluorometer Estimated Chl-a} = (\text{volts} - \text{blank\_offset}) * \text{scale}$$

$$2004: \text{blank\_offset} = 0.123 \quad \text{scale} = 4.3$$

$$2005: \text{blank\_offset} = 0.050 \quad \text{scale} = 9.6$$



## **Appendix C.**

### **Compact Disc Data**

This appendix can be found as a text file entitled Appendix\_C.txt on the enclosed compact disc which also includes the following data:

- 1.) Daily images of Flathead Lake of Remote Sensing Reflectance with in house atmospheric correction applied
- 2.) Daily synoptic maps of estimated Secchi depth based on in-situ and MODIS data regressions. Cloud and Land masks applied.
- 3.) The Field Data Summary Tables in Microsoft Excel Format (Field\_Summary.xls) and Appendix B (Appendix\_B.doc) in full which describes in detail the contents of the tables.

The images were derived from the MODIS sensor aboard NASA's Terra satellite platform. The images were processed using the LP-DAAC MODIS Swath Reprojection Tool, IDL (Interactive Data Language) and RSI's ENVI and are in GeoTIFF format. There are two distinct datasets each within a separate directory (or folder). The daily images are from May 1 - September 30, 2004 and 2005.

#### **Remote Sensing Reflectance**

The **Remote\_Sensing\_Reflectance** directory contains the results of the single scattering atmospheric correction algorithm which can be found in Hu et al., 2004 ("Assessment of estuarine water-quality indicators using MODIS medium-resolution bands: Initial results from Tampa Bay, FL." Remote Sensing of Environment 93(3): 423). Each daily image is split into three files that correspond to the three MODIS Bands; 1 (Red - 645nm), 3 (Blue - 469nm), and 4(Green - 555nm). The naming convention is:

Rrs\_MOD02HKM\_YYYYDDD\_bandX.tif

e.g. Rrs\_MOD02HKM\_2005236\_band1.tif

where:

Rrs is abbreviation for Remote Sensing Reflectance,

YYYY is the four digit year,

DDD is the three digit day of year (Note: 2004 was a leap year)

X is the single digit MODIS band number.

These images are NOT standard red, green, blue images. The near-infrared (NIR) band value has been subtracted on a pixel by pixel basis from each of the three bands as an estimation of scattering (or reflectance contribution) from aerosols. It is assumed that NIR band reflectance over oligotrophic waters is zero, and therefore any value recorded by the NIR represents aerosol contributions to reflectance values. Only the values over oligotrophic water bodies should be considered accurate reflectance values in these images. Important to note is that cloud cover is prominent in this region and therefore many of the included images will be unusable due to cloud contamination. Below are the basic image processing steps.

1.) MODIS MOD02HKM (500m Radiance at Sensor Swath) daily images over the study area were downloaded from NASA's EOS Data Gateway. The corresponding MOD03 Geolocation swaths were also downloaded as they are necessary in both steps 2 and 3 below. (<http://edcimswww.cr.usgs.gov/pub/imswelcome/>)

2.) Swath images were reprojected and subset using the LP-DAAC's MODIS Swath Reprojection Tool (<http://edcdaac.usgs.gov/datapool/datapool.asp>), saved in .tif format. Only bands 1 - 5 were processed in this step as bands 6 and 7 were not used in analysis.

3.) The Single Scattering Atmospheric Correction algorithm as described by Hu et al. 2004, was applied to each image using the subtraction of the near-infrared band as a correction/estimation of aerosol scattering. Most necessary input values can be found in the publication as well as the proper reference for estimating Rayleigh reflectance. Solar and sensor zenith and azimuth angles are found in the corresponding MOD03 files.

### **Synoptic Maps of Estimated Secchi Depth**

The **Secchi\_Depth** directory contains synoptic maps of estimated Secchi depth on Flathead Lake. Secchi depth is measured by lowering a black and white weighted disk on a line off the shady side of a boat. The depth at which the disk disappears from view is considered the Secchi depth. It is a basic standard measure of water clarity that is used throughout water research and monitoring. Based on Secchi depths taken during the 2004 and 2005 field seasons (see Table in Appendix A or digital version included in compact disc), an algorithm was developed based on the relationship to MODIS  $R_{rs}$  values. Regression results showed a logarithmic relationship ( $r^2 = .75$ , Fig. 13) based on the equation:

$$\text{Secchi depth (meters)} = 0.329 * \exp(1.2419 * X)$$

where:

$$X = [R_{rs}(469) - R_{rs}(645)] / [R_{rs}(555) - R_{rs}(645)]$$

This algorithm was applied pixel by pixel resulting in lakewide maps of estimated Secchi depth in meters. As cloud cover is common over Flathead Lake, a cloud mask was applied to every daily image. The mask was based on a threshold on MODIS Band 5 (1240nm), which shows near complete absorption over water, yet significant reflectance over clouds. Therefore many images contain NoData values where clouds were present,

or occasional instances of bad/unusable MODIS data. A land mask based on GIS layers was also applied so that the algorithm was applied to lake pixels only. The naming convention is:

SDT\_MOD02HKM\_YYYY\_DDD.tif  
e.g. SDT\_MOD02HKM\_2004\_122.tif

Where:

SDT is abbreviation for Secchi Depth Transparency

YYYY is the four digit year

DDD is the three digit day of year (Note: 2004 was a leap year)

If this algorithm is applied to future images further calibration is strongly encouraged. A majority of the literature based on remote sensing of inland water quality states that algorithms are accurate on a daily basis, and sometimes a seasonal basis. Seasonal calibration of any algorithm is necessary for maintaining accurate synoptic maps.

### **Field Data Summary Tables**

The Field Data Summary Tables are in Microsoft Excel Format (Field\_Summary.xls). For a description of tables refer to Appendix B (Appendix\_B.doc).