Using New Enhanced Satellite Remote Sensing Systems for Regional Water Quality Measurements in Optically Complex Inland Waters

Leif Olmanson, Patrick Brezonik, Marvin Bauer & Jacques Finlay

UNIVERSITY OF MINNESOTA

Terrestrial Water Cycle Seminar, Earth Sciences Division, NASA Goddard Space Flight Center. Greenbelt, Maryland, August 16, 2016
Outline

• Overview of regional remote sensing of water clarity

• Airborne hyperspectral sensors to explore appropriate bands for water quality measurements on optically complex waters

• Capabilities of new satellite sensors

• Recent activities to prepare for their use in measuring optical water quality characteristics

• Prospects for retrieving regional water quality (Chl a, MSS & CDOM) with Landsat 8 and Sentinel 2 & 3
Landsat Imagery for Regional and Statewide Secchi Depth (SD) Monitoring

- **Landsat 5 TM**
  - launched in 1984
  - Suspended 2011

- **Landsat 7 ETM+**
  - launched in 1999

- **Landsat 8 OLI**
  - Launched Feb 2013

- Strong relationship between water clarity (SD) and spectral-radiometric response
- Relationship based on well understood optical principles
- Coverage ~12,000 sq. mi. in one image - survey thousands of lakes over large areas
- 30-m resolution is suitable for all lakes and can provide information on in-lake variability
- Imagery has been regularly collected since 1972
- Until recently the only cost-effective imagery available for state and regional assessments

http://landsat.usgs.gov/
Lake Clarity Monitoring: Review

1. Citizens measure lake clarity

2. Near the same time, satellites collect imagery

3. Build statistical models

4. Classify clarity of all lakes

~1,000 Lakes monitored

Over 10,000 Lakes monitored

\[ y = -15.583x + 4.6742 \]

\[ R^2 = 0.84 \]
Minnesota Lake Clarity
Lake Level 2005

33-year “Census” of Minnesota lake clarity with 7 assessments for 1975–2008

Over 10,000 lakes classified for each time period
All lakes >8 hectares are included
Database includes 1-4 measurements per time period
Used for statistical analysis of lake water clarity and causative factors
Statistical analysis of lake water clarity

- Land cover vs. water clarity at ecoregion level
- Water clarity trends
- Land cover versus water clarity by lake depth at lake watershed level
Lakes / Water Website

Unique Visitors

2015 & 2016 >8,000 month

2014 - 73,695
2013 – 45,583
2012 – 45,495
2011 – 48,543
2010 – 50,249
2009 – 54,433
2008 – 58,955
2007 – 65,984
2006 – 67,603
2005 – 61,080

Plans to update with 2010, 2015 water clarity and 2015 CDOM and more variables with Sentinel
The capability of satellite imagery to measure optical water quality characteristics (OWQC) beyond water clarity depends on finding wavelength bands where light reflectance is affected by a given OWQC and having satellite sensors with those bands.

Water clarity of lakes and rivers is controlled by three main factors:

- Organic color
- Algae
- Suspended sediment
Colored dissolved organic matter (CDOM)
Why is it important?

- CDOM is increasing in many areas
- DOM is important for denitrification
- CDOM attenuates solar radiation
  - Controls lake temperatures and stratification
  - Hypolimnetic O₂ needed for cold water fish
  - Reduced light suppresses primary productivity
- Mediates transfer of contaminants into food webs (e.g., mercury in fish)
- Negative effects on production of safe drinking water (↑ costs)
  - Water treatment chemicals
  - Reacts with chlorine to form harmful by-products
  - Stimulates bacterial growth, and fouls membranes
- Needed for global-scale models of carbon cycling
Airborne hyperspectral imagery: a good tool to find appropriate bands and retrieve water quality characteristics

Measured water quality of optically complex Mississippi and Minnesota Rivers, where phytoplankton and/or inorganic sediment may be optically dominant

Collaborative effort between UMN, PCA, DNR, Metropolitan Council & CALMIT
# River Water Quality Model Development

<table>
<thead>
<tr>
<th>LN of variable</th>
<th>Bands</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>T Tube (cm)</td>
<td>705</td>
<td>0.77 – 0.91</td>
</tr>
<tr>
<td>Turbidity (NTU)</td>
<td>705</td>
<td>0.77 – 0.93</td>
</tr>
<tr>
<td>TSS (mg/L)</td>
<td>705</td>
<td>0.77 – 0.93</td>
</tr>
<tr>
<td>VSS (mg/L)</td>
<td>705/670</td>
<td>0.80 – 0.94</td>
</tr>
<tr>
<td>Chl a ($\mu$g/L)</td>
<td>705/670 or 705/620</td>
<td>0.75 – 0.93</td>
</tr>
<tr>
<td>NVSS (mg/L)</td>
<td>705 &amp; 705/670</td>
<td>0.85 – 0.97$^a$</td>
</tr>
<tr>
<td>NVSS/TSS (%)</td>
<td>705 &amp; 705/620</td>
<td>0.73 – 0.91$^a$</td>
</tr>
</tbody>
</table>

$^a$R^2

Data from aircraft-mounted hyperspectral radiometer

### Characteristic Reflectance Spectra

![Characteristic Reflectance Spectra](image-url)
Water Quality Map created from Hyperspectral Imagery
August 30, 2007
Pig’s Eye Lake and Mississippi River at St. Paul showing the transition from phytoplankton-dominated to inorganic sediment-dominated conditions.
Regional Remote Sensing Systems for Optically Complex Waters
Landsat 8 Launched February 11, 2013

• 8 VIS/NIR/SWIR bands (new blue, NIR & cirrus) 30 m spatial resolution
• Two TIR bands 100 m
• Pushbroom sensor: improved radiometric resolution, S/N & calibration
• 16-day revisit
**Sentinel-2**
- Launch June 12, 2015 1\textsuperscript{st}, 2016 2\textsuperscript{nd}
- Large swath 290 km
- Spatial resolution 10(4), 20(6) & 60(3) m (# bands)
- 13 spectral bands; visible, NIR, SWIR
- 10 day revisit – 5 days with 2 satellites and 2-3 for Midwest

**Sentinel-3**
- Launch Feb 16, 2016, 2\textsuperscript{nd} 2017
- Very large swath 1269 km
- Spatial resolution 300 m (8.5% MN)
- 21 spectral bands; programmable visible, NIR, SWIR, TIR
- 2.8 day revisit – 1.4 days with 2 satellites ~daily for Midwest
Recent Activities

• Measuring optical properties and collecting water quality data on optically complex lakes (varying color, trophic status, SS) for algorithm development (~300 lakes for 2016 in MN, WI and MI)

• Landsat 7 & 8 for regional measurements of CDOM and HICO imagery to simulate Sentinel-2 imagery for MSS and Chl $a$

• Evaluating atmospheric correction and normalization methods with in situ data for regional water quality monitoring: First Minnesota CDOM map
Ore-be-gone

- ultraoligotrophic
- very low color;
- water-dominated spectrum
- 46 ft SD

German L.

- eutrophic
- 0.8 ft SD
- low color, large blue-green algal bloom

Embarrass L.

- high color
- low chlorophyll
- 4.1 ft SD

Johnson Bog L.

- dystrophic
- very high color
- low chlorophyll
- 1.6 ft SD
Representative Reflectance Spectra Showing Some of the Optical Complexity of Water Bodies in Minnesota.

Colored Dissolved Organic Matter (CDOM)
# CDOM Model Development from Brezonik et al. 2014

Simulated sensor bands from 2013 & 2014 in situ spectra

<table>
<thead>
<tr>
<th>Model</th>
<th>Equation form*</th>
<th>$r^2$</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kutser et al. (2005)</td>
<td>$a_{440} = a_1(\text{OLI3green/OLI4red})^{a_2}$</td>
<td><strong>0.83</strong></td>
<td>0.480</td>
</tr>
<tr>
<td>Brezonik et al. (2005)</td>
<td>$\ln(a_{440}) = a_0 + a_1(\text{OLI2Blue2}) + a_2(\text{OLI2blue2/OLI5NIR})$</td>
<td>0.58</td>
<td>0.774</td>
</tr>
<tr>
<td>Menken et al. (2006)</td>
<td>$a_{440} = a_1(R_{670}/R_{550})^{a_2}$</td>
<td>0.83</td>
<td>0.480</td>
</tr>
<tr>
<td>&quot;</td>
<td>$a_{440} = a_0R_{412} + a_2(R_{700}/R_{670})$</td>
<td>0.38</td>
<td>5.895</td>
</tr>
<tr>
<td>Ficek et al. (2011)</td>
<td>$a_{440} = a_1(R_{570}/R_{655})^{a_2}$</td>
<td>0.84</td>
<td>0.469</td>
</tr>
<tr>
<td>Griffin et al. (2011)</td>
<td>$\ln(a_{440}) = -1.145 + 26.529(\text{OLI4}) + 0.603(\text{OLI3:OLI2})$</td>
<td>0.19</td>
<td>1.075</td>
</tr>
<tr>
<td>This study:</td>
<td>$\ln(a_{440}) = a_1 + a_2\ln(b5greenlow:b12NIR)$</td>
<td><strong>0.86</strong></td>
<td>0.438</td>
</tr>
<tr>
<td></td>
<td>$\ln(a_{440}) = a_1 + a_2\ln(b7redlow:b8redhigher)$</td>
<td>0.80</td>
<td>0.523</td>
</tr>
<tr>
<td></td>
<td>$\ln(a_{440}) = a_1 + a_2\ln(b2highblue:b6nir)$</td>
<td><strong>0.86</strong></td>
<td>0.443</td>
</tr>
</tbody>
</table>

*Band key:* **O1** (violet deep blue); **O2** (blue); **O3** (green); **O4** (red); **O5** (near IR)
$a^{440}$ in situ vs. $a^{440}$ using in situ spectra to simulate current inland lake sensors: best two term model (band or band ratio) from 2013, 2014 and 2015 spectra

Landsat 8

- $R^2=0.82$
- $N=86$

Sentinel-2

- $R^2=0.85$

Sentinel-3

- $R^2=0.86$
A “Kutser-like” model, $a_{440} = a_0 (O3/O4)^{a1}$, yielded a poor fit ($R^2 = 0.24$) of calibration data for northern MN, but exclusion of 5 data points from the St. Louis River, which had high color and high TSS, yielded much better fit.

Two-term models similar to Brezonik et al. 2005 yielded good fit for all the data:

$$\ln(a_{440}) = b_0 + b_1 (O3/O5) + b_2 (O4) \quad (R^2 = 0.82; n = 28)$$

$$\ln(a_{440}) = b_0 + b_1 (O2/O5) + b_2 (O1) \quad (R^2 = 0.79; n = 28)$$

Band key: O1 (violet deep blue); O2 (blue); O3 (green); O4 (red); O5 (near IR)
CDOM distribution in lakes near Ely, NE MN based on 9/16/2013 Landsat 8 image.
CDOM mapping with Landsat 8 -- September 16, 2013 OLI
CDOM mapping with Landsat 7 --September 24, 2013 ETM+

Also works for legacy Landsat imagery

- Potential for historical CDOM mapping
Evaluation of Image Atmospheric Correction and Normalization Techniques for Regional Water Quality Mapping in Optically Complex Inland Waters

- Radiometric Rectification
- EROS Surface Reflectance v. 2.2
- ACOLITE
- SeaDas Atmospheric Correction
- FLAASH
Normalized Imagery Using Radiometric Rectification

Examples of Invariant Objects and Landsat 8 OLI Band Relationships Between Base and Target Images

- Green: $R^2 = 0.999$
- Red: $R^2 = 0.999$
- NIR: $R^2 = 0.999$

* Urban
* Conifer
* Water
Landsat 8 OLI Imagery Used for Minnesota CDOM Map

Provisional Surface Reflectance v 2.2

Radiometric Rectification
Evaluating Atmospheric Correction/Normalization Methods for Landsat 8 OLI Imagery Using In Situ Secchi Disk Transparency (SD) Within One Day: Acolite and SeaDas also being evaluated

Radiometric Rectification

\[ R^2 = 0.828 \]

Provisional Surface Reflectance v 2.2

\[ R^2 = 0.824 \]
a^{440} \text{ in situ vs. } a^{440} \text{ using Landsat 8 data from multiple dates normalized to surface reflectance using radiometric rectification}

green/red model

$\ln(a^{440}) \text{ Actual}$ vs. $\ln(a^{440}) \text{ Predicted}$

- $r^2 = 0.79$
- $\text{RMSE} = 0.582$
- $N = 63$

green/red + $\ln(\text{red/NIR})$

$\ln(a^{440}) \text{ Actual}$ vs. $\ln(a^{440}) \text{ Predicted}$

- $r^2 = 0.86$
- $\text{RMSE} = 0.482$
- $N = 63$

Image

+ 11/09/15
X 8/14/15
O 9/29/15
Two-variable model (green/red + ln(red/NIR)),

\[ a_{440} = -5.478 \times \text{OLI3/OLI4} - 0.633 \times \ln(\text{OLI4/OLI5}) + 8.135 \]
St. Louis River Estuary Western Lake Superior

Landsat 8
Aug 31, 2013

MSS mapped as chlorophyll in optically complex waters

Map Legend

SD (m)  Chl-a (ug/L)  TSI

>4  <3  <40
2-4  3-7  40-50
1-2  7-20  50-60
0.5-1  20-55  60-70
<0.5  >55  >70

Models developed from available lake data
N= 260 SD, 71 Chl a
St. Louis River Estuary Western Lake Superior

**Sentinel-2**
Aug 31, 2013
Simulated from HICO ISS imagery

Capability to discriminate MSS from chlorophyll in optically complex waters

Models developed from SLRE data

Map Legend

<table>
<thead>
<tr>
<th>CDOM $a_{	ext{ext}}$ $\text{m}^{-1}$</th>
<th>Chl-a (µg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>&lt;3</td>
</tr>
<tr>
<td>2</td>
<td>3-7</td>
</tr>
<tr>
<td>4</td>
<td>7-20</td>
</tr>
<tr>
<td>6</td>
<td>20-55</td>
</tr>
<tr>
<td>8</td>
<td>&gt;55</td>
</tr>
</tbody>
</table>

Pokégama Bay
donated water

Sediment not phytoplankton

Duluth MN

Superior WI

Allouez Bay
Potential of New Remote Sensing Products

- The constellation of Landsat 8 and Sentinel 2 will greatly improve temporal coverage.
  - Potential for near real time measurements.

- Sentinel 2 spectral bands will provide the capability to measure more than water clarity and CDOM.
  - Chlorophyll, mineral suspended sediment, CDOM and water clarity mapping of >10,000 Minnesota lakes will be possible.

- Sentinel 3 and MERIS (for historical) spectral bands also will allow mapping of cyanobacteria in large lakes (>150 ha).
  - Historic mapping using MERIS and near real time monitoring of toxic algal blooms with Sentinel 3.

- Will lead to greatly enhanced understanding of the climatic, landscape and anthropogenic factors that control chlorophyll, MSS, CDOM and DOM in inland waters.
Acknowledgments

University of Minnesota U-Spatial Project, Minnesota Agricultural Experiment Station, Minnesota Environment and Natural Resources Trust Fund, and National Science Foundation