Remote Sensing of Water

Water exists in various states on Earth, including: freshwater, saltwater, water vapor, rain, snow, and ice.

It is possible to obtain in situ measurements of various hydrologic (water) parameters such as precipitation, water depth, temperature, salinity, velocity, volume, etc., at very specific locations on the Earth.

• USGS maintains a dense network on in situ river-flow gages on major streams and rivers that provide continuous records of river stage (height) and velocity.
• Weather stations: collect in situ precipitation (rain, snow,…)
• Dept. of Health and Environmental Control: collect in situ water quality samples
• …

It is always difficult to obtain regional spatial information using in situ observation for a number of the most important hydrologic variables, including:

• Water-surface area (streams, rivers, ponds, lakes, reservoirs, and oceans)
• Water constituents (organic and inorganic)
• Water-surface temperature
• Snow-surface area and snow-water equivalent
• Ice-surface area and ice-water equivalent
• Cloud cover
• Precipitation, and
• Water vapor

Remote sensing has the advantages of obtaining such types of data.
**Water Surface, Subsurface Volumetric, and Bottom Radiance**

The total radiance, \((L_t)\) recorded by a remote sensing system over a water body is a function of the electromagnetic energy from four sources:

\[
L_t = L_p + L_s + L_v + L_b
\]

- \(L_p\) is the radiance recorded by a sensor resulting from the downwelling solar \((E_{sun})\) and sky \((E_{sky})\) radiation. This is unwanted *path radiance* that never reaches the water.
- \(L_s\) is the radiance that reaches the air-water interface (*free-surface layer or boundary layer*) but only penetrates it a millimeter or so and is then reflected from the water surface. This reflected energy contains spectral information about the near-surface characteristics of the water.
Water Surface, Subsurface Volumetric, and Bottom Radiance

- $L_v$ is the radiance that penetrates the air-water interface, interacts with the organic/inorganic constituents in the water, and then exits the water column without encountering the bottom. It is called *subsurface volumetric radiance* and provides information about the internal bulk characteristics of the water column.
- $L_b$ is the radiance that reaches the bottom of the waterbody, is reflected from it and propagates back through the water column, and then exits the water column. This radiance is of value if we want information about the bottom (e.g., depth, color).

\[
L_t = L_p + L_s + L_v + L_b
\]

Examples of Absorption of Near-Infrared Radiant Flux by Water and Sun-glint

Black and white infrared photograph of water bodies in Florida
Black and white infrared photograph with Sun-glint
Molecular water absorption dominates in the ultraviolet (<400 nm) and in the yellow through the near-infrared portion of the spectrum (>580 nm). Almost all of the incident near-infrared and middle-infrared (740 - 2500 nm) radiant flux entering a pure water body is absorbed with negligible scattering taking place.

### Optical Properties of Pure Water

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Absorption (g)/cm²</th>
<th>Scattering (g)/cm²</th>
<th>Total Attenuation (g)/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>250 - ultraviolet</td>
<td>0.190</td>
<td>0.052</td>
<td>0.243</td>
</tr>
<tr>
<td>300 - ultraviolet</td>
<td>0.040</td>
<td>0.042</td>
<td>0.082</td>
</tr>
<tr>
<td>350 - ultraviolet</td>
<td>0.010</td>
<td>0.004</td>
<td>0.013</td>
</tr>
<tr>
<td>400 - violet</td>
<td>0.006</td>
<td>0.004</td>
<td>0.009</td>
</tr>
<tr>
<td>420 - violet</td>
<td>0.004</td>
<td>0.002</td>
<td>0.006</td>
</tr>
<tr>
<td>440 - violet</td>
<td>0.004</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>480 - dark blue</td>
<td>0.002</td>
<td>0.003</td>
<td>0.005</td>
</tr>
<tr>
<td>490 - dark blue</td>
<td>0.002</td>
<td>0.003</td>
<td>0.005</td>
</tr>
<tr>
<td>500 - light blue</td>
<td>0.006</td>
<td>0.001</td>
<td>0.007</td>
</tr>
<tr>
<td>510 - green</td>
<td>0.014</td>
<td>0.001</td>
<td>0.015</td>
</tr>
<tr>
<td>520 - green</td>
<td>0.022</td>
<td>0.001</td>
<td>0.023</td>
</tr>
<tr>
<td>530 - green</td>
<td>0.030</td>
<td>0.001</td>
<td>0.031</td>
</tr>
<tr>
<td>540 - yellow</td>
<td>0.034</td>
<td>0.001</td>
<td>0.035</td>
</tr>
<tr>
<td>600 - orange</td>
<td>0.037</td>
<td>0.001</td>
<td>0.037</td>
</tr>
<tr>
<td>620 - orange</td>
<td>0.041</td>
<td>0.001</td>
<td>0.041</td>
</tr>
<tr>
<td>640 - red</td>
<td>0.047</td>
<td>0.001</td>
<td>0.047</td>
</tr>
<tr>
<td>680 - red</td>
<td>0.050</td>
<td>0.001</td>
<td>0.050</td>
</tr>
<tr>
<td>700 - near infrared</td>
<td>0.053</td>
<td>0.001</td>
<td>0.053</td>
</tr>
<tr>
<td>740 - near infrared</td>
<td>0.056</td>
<td>0.001</td>
<td>0.056</td>
</tr>
<tr>
<td>780 - near infrared</td>
<td>0.059</td>
<td>0.001</td>
<td>0.059</td>
</tr>
<tr>
<td>850 - near infrared</td>
<td>0.063</td>
<td>0.001</td>
<td>0.063</td>
</tr>
</tbody>
</table>

The least amount of absorption and scattering of incident light.
**Spectral Response of Water as a Function of Wavelength**

How pure water (free from organic and inorganic matters) selectively absorbs and/or scatters the incident sunlight in the water column?

1. The least amount of absorption and scattering of incident light in the water column (therefore the best transmission) takes place in the blue wavelength region from 0.4 - 0.5 µm, with the minimum located at approximately 0.46 - 0.48 µm). These wavelengths of violet to light blue light penetrate further than any other type of spectrum into the water column.

2. Incident green and yellow light from 0.52 - 0.58 µm is absorbed very well by the water with little scattering taking place.

3. Scattering of orange and red wavelength (0.58 - 0.74 µm) by water molecules becomes insignificant when compared to absorption water molecules.

4. Almost all of the incident near- and middle-IR (0.74 - 3.0 µm) radiant flux entering a deep pure water body is absorbed with negligible scattering taking place.

Thus, molecular scattering of violet and blue light in water column and significant absorption of green, yellow, orange, and red wavelength in the same water column, cause pure water to appear blue to our eyes.
Monitoring the Surface Extent of Water Bodies

The best wavelength region for discriminating land from water is the near-IR and mid-IR (0.74 - 2.50 µm).

In the near- and middle-infrared regions, water bodies appear very dark, even black, because they absorb almost all of the incident radiant flux, especially when the water is deep and pure and contains little suspended sediment or organic matter.

Care must be exercised when there are organic and inorganic constituents in the water column, especially those near the surface, because these materials will cause near-IR surface reflection.

Water Penetration

SPOT Band 1
(0.5 - 0.59 µm)
green

SPOT Band 2
(0.61 - 0.68 µm)
red

SPOT Band 3
(0.79 - 0.89 µm)
NIR

Palancar Reef
Bathymetry derived using LIDAR and SONAR
Remote Sensing of Water Quality?

When conducting water-quality studies using remotely sensed data, we are usually most interested in measuring the subsurface volumetric radiance, $L_v$ exiting the water column toward the sensor.

The characteristics of this radiant energy are a function of the concentration of pure water ($w$), inorganic suspended minerals ($SM$), organic chlorophyll $a$ ($Chl$), dissolved organic material ($DOM$), and the total amount of absorption and scattering attenuation that takes place in the water column due to each of these constituents, $c(l)$:

$$L_v = f [wc(l), SMc(l), Chlc(l), DOMc(l) ].$$

It is useful to look at the effect that each of these constituents has on the spectral reflectance characteristics of a water column.

Spectral Response of Water as a Function of Inorganic and Organic Constituents

Minerals such as silicon, aluminum, and iron oxides are found in suspension in most natural water bodies. The particles range from fine clay particles ($3 - 4 \mu m$ in diameter), to silt ($5 - 40 \mu m$), to fine-grain sand ($41 - 130 \mu m$), and coarse grain sand ($131 - 1250 \mu m$). Sediment comes from a variety of sources including agriculture erosion, weathering of mountainous terrain, shore erosion caused by waves or boat traffic, and volcanic eruptions (ash). Most suspended mineral sediment is concentrated in the inland and near-shore water bodies. Clear, deep ocean (Case 1 water) far from shore rarely contains suspended minerals > $1 \mu m$ in diameter.
Space Shuttle Photograph of the Suspended Sediment Plume at the Mouth of the Mississippi River near New Orleans, Louisiana

Examples of SeaWiFS Images
In situ Spectroradiometer
Measurement of Water with Various Suspended Sediment and Chlorophyll \( a \) Concentrations

The spectral reflectance of suspended sediment in surface waters is a function of both the quantity and characteristics (particle size, absorption) of the materials in the water.

In situ Spectroradiometer
Measurement of Clear Water with Various Levels of Clayey and Silty Soil Suspended Sediment Concentrations

Reflectance peak shifts toward longer wavelengths as more suspended sediment is added.

Lodhi et al., 1997; Jensen, 2007
Research results suggested that:

The visible wavelength range of 0.58 - 0.69 µm may provide information on the type of suspended sediments (soil) in surface waters; and

The near-IR wavelength range from 0.714 - 0.88 µm may be useful for determining the amount of suspended minerals in surface waters where suspended minerals are the predominant constituent.

Spectral Response of Water as a Function of Organic Constituents - Plankton

All phytoplankton in water bodies contain the photosynthetically active pigment *chlorophyll a*.

*Plankton* is the generic term used to describe all the living organisms (plant and animal) present in a water-body that cannot resist the current (unlike fish). Plankton may be subdivided further into algal plant organisms (*phytoplankton*), animal organisms (*zoolankton*), bacteria (*bacterio-plankton*), and lower plant forms such as *algal fungi*. *Phytoplankton* are small single-celled plants smaller than the size of a pinhead. Phytoplankton, like plants on land, are composed of substances that contain carbon.

Phytoplankton sink to the ocean or water-body floor when they die and soon be covered by other sediments.
**Chlorophyll**

Phytoplankton use carbon dioxide and produce oxygen during photosynthetic process. In this way, the water bodies and oceans act as a carbon sink, a place that disposes of global carbon, which otherwise can accumulate in the atmosphere as carbon dioxide. Other global sinks include land vegetation and soil.

No one knows exactly how much carbon the inland water and ocean accumulate. As such, the characteristics of phytoplankton and zooplankton are very important to our knowledge of the global carbon cycle as it represents a significant carbon sink for increased level of carbon dioxide in the atmosphere.

**Sea-viewing Wide Field-of-view Sensor (SeaWiFS)** was launched on August 1, 1997.

The purpose of the SeaWiFS Project is to provide quantitative data on global ocean bio-optical properties to the Earth science community. Subtle changes in ocean color signify various types and quantities of marine phytoplankton, the knowledge of which has both scientific and practical applications.

<table>
<thead>
<tr>
<th>Instrument Bands</th>
<th>Band Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>402-422 nm</td>
</tr>
<tr>
<td>2</td>
<td>433-453 nm</td>
</tr>
<tr>
<td>3</td>
<td>480-500 nm</td>
</tr>
<tr>
<td>4</td>
<td>500-520 nm</td>
</tr>
<tr>
<td>5</td>
<td>545-565 nm</td>
</tr>
<tr>
<td>6</td>
<td>660-680 nm</td>
</tr>
<tr>
<td>7</td>
<td>745-785 nm</td>
</tr>
<tr>
<td>8</td>
<td>845-885 nm</td>
</tr>
</tbody>
</table>
True-color SeaWiFS image of the Eastern U.S. on September 30, 1997
And the derivative of Chlorophyll $a$ distribution

Global Chlorophyll $a$ (g/m3) Derived from SeaWiFS Imagery
Obtained from September 3, 1997 through December 31, 1997
All phytoplankton in water bodies contain the photosynthetically active pigment chlorophyll \( a \), which changes water’s spectral reflectance characteristics, \( i.e. \) its color.

Four pronounced scattering/absorption features of chlorophyll are evident in the algae-laden water:

- Strong chlorophyll \( a \) absorption of blue light between 0.40 and 0.50 µm
- Strong chlorophyll \( a \) absorption of red light at approximately 0.675 µm.

- Reflectance maximum around 0.55 µm (green peak) caused by relatively lower absorption of green light by algae; and

- Prominent reflectance peak around 0.69 - 0.70 µm cause by an interaction of algae-cell scattering and minimum combined effect of pigment and water absorption. The height of this peak above the baseline can be used to accurately measure chlorophyll amount.
As chlorophyll concentration increases in the water column, there is a significant decrease in the relative amount of energy reflected in the blue and red wavelength but an increase in green wavelength.

When both suspended mineral sediment and chlorophyll are presented in the water body at the same time, a dramatically different spectral response it produces.

Location of estuaries and bays along the southern New England coast surveyed using hyperspectral aircraft remote sensing.

Location of sampling stations in Narragansett Bay used to collect in situ hyperspectral data and water samples for band-ratio model development.
USEPA/National Coastal Assessment Program
Criteria for assessing Chlorophyll \(a\) condition

<table>
<thead>
<tr>
<th>Condition</th>
<th>Site Criteria</th>
<th>Regional Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Good</strong></td>
<td>&lt; 5 (\mu g/l)</td>
<td>&lt;10% of coastal area in poor condition and &gt;50% in good condition</td>
</tr>
<tr>
<td><strong>Fair</strong></td>
<td>5 to 20 (\mu g/l)</td>
<td>10% to 20% of the coastal area in poor condition or &gt; 50% in combined poor and fair condition</td>
</tr>
<tr>
<td><strong>Poor</strong></td>
<td>&gt; 20 (\mu g/l)</td>
<td>&gt;20% of coastal area in poor condition</td>
</tr>
</tbody>
</table>

**Spectral Response of Water as a Function of Dissolved Organic Constituents**

Phytoplankton within the water column consume nutrients and convert them into organic matter via photosynthesis. This is called *primary production*.

Zooplankton eat the phytoplankton and create organic matter.

Bacterioplankton decompose this organic matter.

All this conversion introduces *dissolved organic matter (DOM)* into oceanic, near-shore, and inland water bodies.
Cloud Type Determination Based on Multispectral Measurements in the Visible and Thermal Infrared Regions of the Spectrum
Reflectance of Clouds and Snow in the Wavelength Interval 0.4 - 2.5 \( \mu \text{m} \)

Sea-surface Temperature (SST) Maps Derived from A Three-day Composite of NOAA AVHRR Infrared Data Centered on March 4, 1999

Adjusted to highlight nearshore temperature differences

Adjusted to highlight Gulf Stream temperature differences

Jenness, 2006
Composite Sea-surface Temperature (SST) Map of the Southeastern Bight Derived from AVHRR Data

Worldwide Sea-surface Temperature (SST) Map Derived From NOAA-14 AVHRR Data

Three-day composite of thermal IR data centered on March 4, 1999. Each pixel was allocated the highest surface temperature that occurred during the three days.