Metier course 6: Remote sensing of the Hydrosphere

• Helsinki, Finnish Environmental Institute
• 3-7 November 2008
• Tuesday 4 November 9:00 – 10:00 & 10:00 – 10:45

• General Lecture 2: Remote Sensing, Water quality and GIS
• Steef Peters
• Institute for Environmental Studies (IVM), Vrije Universiteit, Amsterdam
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With contributions from:

• Hans van der Woerd, Marieke Eleveld, Reinold Pasterkamp (IVM)
• Marnix Laanen (Water Insight)
• Arnold Dekker and group (CSIRO, Australia)
What are the topics of this lecture?

•To illustrate:
  Why and how of water colour observation
  Colour quantification
  Colour measurement (aha, remote sensing J )
  To derive information from colour with
  qualitative and quantitative approaches (remote sensing or GIS??)
•To illustrate how measurements and models of water colour compare
•From observations of colour to maps of constituents
•GIS as presentation and analysis environment
Why & how of colour observation by remote sensing

• WHO guideline: personal sensing of water colour

“Where no scums are visible, but the water shows strong greenish discoloration and turbidity, test if you can still see your feet when standing knee-deep in the water (after wading in without stirring up sediment). If not, avoid bathing—or at least avoid ingestion of water, i.e., submersion of your head.”

• So issues to address are: colour, transparancy, observation without disturbance, information gathering and decision making

Main factors that cause the colouring of an object are:
• absorption (greenish discoloration)
• and scattering (turbidity).

A colour observation is a reflectance spectrum
Light and water
A boathouse perspective

- Reflected images of trees
- Glitter at the water surface
- Color gradient
- Backscattering to the observer
- Wedging
The colours of water
The colours of water

Mitra 21 augustus 2001

Mitra 8 april 2002

2 september 2002

Mitra 3 juni 2002

Squilla 16 augustus 2001
Optical active water quality parameters

- Chlorophyll Pigments (mg/m3) CHL
- Total Suspended Matter (g/m3) TSM
- Inorganic fraction of TSM (g/m3) ISM
- Colored Dissolved Organic Matter CDOM
- Water plants (macrophytes) floating - submerged
- Bottom (depth: m)
- Secchi Depth (m) SD
Why is water blue?

Water spectral absorption

Water spectral scattering
Why is phytoplankton green?

Phytoplankton spectral absorption

specifieke absorbate (m² mg⁻¹)

400 500 600 700 800 900 1000 1100
golflengte (nm)
Why is wastewater yellow / brownish?

CDOM spectral absorption
Why is turbid water gray/white or brownish?

TSM spectral absorption

TSM spectral scattering
The measurement of water colour
Radiance at sensor, Water leaving radiance, IOPs

Light, colour

Reflectance

Water quality
Close sensing (measuring water colour)
Subsurface irradiance reflectance is defined as:

\[
R(0-, \lambda) = \frac{E_{wu}(0-, \lambda)}{E_{wd}(0-, \lambda)} = \frac{QL_{wu}(0-, \lambda)}{E_{wd}(0-, \lambda)}
\]

We measure radiance, therefore:

\[
R(0-) = \frac{Qf \left( L_{au} - r_{sky} L_{sky} \right)}{\left[ E_{ad} - r_{\Theta} (1 - F) E_{ad} - r_{dif} FE_{ad} \right] + (0.48 E_{wu})}
\]
Basic set of measurements

- We need 4 spectra:
  - Water leaving radiance at 42°
  - Down welling (sky) radiance 42°
- Radiance reflected from reference panel
- Diffuse radiance reflected from reference panel (i.e. direct sunlight is blocked)
Examples of measured reflectance spectra

- **a**: North Sea water with some CDOM; little TSM
- **b+c+d**: Estuarine water with various amounts of TSM, some Chl-a
- **e**: High Chl-a + high TSM + CDOM
- **f**: High CDOM + TSM
Modelling of water color
Simple forward simulation models

Calibrated Gordon model:

\[
R(0^-) = f \cdot \frac{b_b}{a + b_b}
\]

\[
a = a_w + a_{TCHL} \cdot TCHL + a_{TSM}^* \cdot TSM + a_{CDOM}^* \cdot CDOM
\]

\[
b_b = b_{b,w} + Bb_{TSM}^* \cdot TSM
\]

*f may vary due to solar and viewing geometry*
# Specific Inherent Optical Properties

<table>
<thead>
<tr>
<th>SIOP</th>
<th>formula</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>specific phytoplankton pigment absorption</td>
<td>$a^*<em>{\text{pigment}}(\lambda) = \frac{a</em>{\text{pigment}}(\lambda)}{TCHL}$</td>
<td>m$^2$ mg$^{-1}$</td>
</tr>
<tr>
<td>specific tripton absorption</td>
<td>$a^*<em>{\text{tripton}}(\lambda) = \frac{a</em>{\text{tripton}}(\lambda)}{\rho_{\text{TSM}}}$</td>
<td>m$^2$ g$^{-1}$</td>
</tr>
<tr>
<td>specific seston scattering</td>
<td>$b^*<em>{\text{seston}}(\lambda) = \frac{b</em>{\text{seston}}(\lambda)}{\rho_{\text{TSM}}}$</td>
<td>m$^2$ g$^{-1}$</td>
</tr>
<tr>
<td>normalised CDOM absorption</td>
<td>$a^*<em>{\text{CDOM}}(\lambda) = \frac{a</em>{\text{CDOM}}(\lambda)}{a_{\text{CDOM}}(440\text{nm})}$</td>
<td>1</td>
</tr>
</tbody>
</table>
Some arithmetic: \( a + b = c \)

- \( a_{\text{seston}} \) and \( a_{\text{tripton}} \) and \( a_{\text{cdom}} \)
- \( c_{\text{beam}} \)

Now derive:

- \( a_{\text{pigment}} = a_{\text{seston}} - a_{\text{tripton}} \)
- \( b_{\text{seston}} = c_{\text{beam}} - a_{\text{seston}} - a_{\text{cdom}} \)
Inherent Optical Properties

- specific tripton absorption
- specific phytoplankton pigment absorption
- normalized CDOM absorption
- specific scattering
Examples of modelled spectra
Gordon Model Ocean R(0-)

- Ocean water (case I)

![Graph showing the relationship between R(0-) and wavelength (nm)](image-url)

- chl-a = 0.1; TSM = 0.5; g440 = 0.01
Gordon Model coast R(0-)

- Turbid coastal water (case II)

![Graph showing the modeled R(0-) as a function of TSM with chl-a = 10 g/440=1.7. The graph plots R(0-) against wavelength (nm) with different TSM values: TSM = 20, TSM = 40, TSM = 60, TSM = 80, and TSM = 100. The saturation point is indicated.](image)
Gorden Model Inland R(0-)

- Eutrophic lake

![Graph showing Gorden Model Inland R(0-) with varying chlorophyll-a concentrations (chl-a = 20, 40, 60, 80, 100) and TSM = 30; g440 = 1. The graph plots R(0-) against wavelength (nm) from 400 to 700 nm.]
Reflectance just below the water surface

![Graph showing reflectance over different wavelengths with lines representing different data entries: (10,10.7), (100,17), (10,60.7), and (100,67).]
Comparing Model & measurement
Comparing measurements with modelled reflectance spectra

\[
\frac{b_{bi}}{a_i + b_{bi}} f = R(0-) = \frac{E_{wu}}{E_{wd}}
\]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>R(0-)</td>
<td>subsurface irradiance reflectance</td>
</tr>
<tr>
<td>E_{wu}</td>
<td>measured subsurface upwelling irradiance</td>
</tr>
<tr>
<td>E_{wd}</td>
<td>measured subsurface downwelling irradiance</td>
</tr>
<tr>
<td>b_{bi}</td>
<td>backscatter coefficients</td>
</tr>
<tr>
<td>a_i</td>
<td>absorption coefficients</td>
</tr>
<tr>
<td>i</td>
<td>water, CHL, TSM (DW), CDOM</td>
</tr>
</tbody>
</table>
Matching measured and simulated spectra

Markermeer, June 1999 (high TSM, high chlorophyll, high CDOM)

filename: 99176M12_reflectance
operator: R.Pasterkamp, IVM/VU
creation: 08-Sep-2001 14:13:35
SL version: 4.1.20011107T145400Z
© Institute for Environmental Studies
SZA: 29.46 °
f-factor: 0.35
B-factor: 0.028
σ_R: 0.0047
TCHL: 46.4
TSM: 38.0
g_440: 1.20
Matching measured and simulated spectra
Western Scheldt, March 1999 (high TSM, low chlorophyll, high CDOM)

filename: 99070HW_reflectance
operator: R.Pasterkamp, IVM/VU
creation: 08-Sep-2001 14:42:34
SL version: 4.1.20011107T145400Z
© Institute for Environmental Studies

SZA: 58.02°
f-factor: 0.39
B-factor: 0.045
σ_R: 0.0079
TCHL: 5.4
TSM: 27.5
g_440: 1.43
Hypothesis underlying Model inversion

- If the model predicts accurately the measured spectrum
- (given a certain set of SIOPs)
- Then the concentrations that belong to the model run are the concentrations that belong to the measurement site
But major uncertainties:

- Is the spectrum measured accurately?
- Are the SIOPs representative for the station?
- Is the model formulation sufficient?
Therefore: simple algorithms

- Can be used for a single parameter (Chl-a, TSM, CDOM, PC,...).
- Use only parts of the spectrum
- Can be empirical or semi-analytical (based on Gordons equation)
A useful and robust CHL algorithm was published by Gons (1999)

\[
T_{\text{CHL}} = \left( \frac{R(0^-)_{704}}{R(0^-)_{665}} \right) \left( a_w,704 + b_b - a_w,665 - b_b \right) \left( a^{*}_{\text{TCHL},665} \right)
\]

\[
b_b = \left( \frac{R(0^-)_{704}}{f} a_w,704 \right) \left( 1 - \frac{R(0^-)_{704}}{f} \right)
\]

Assuming: absorption of CDOM, TSM, TCHL = 0 at 704 nm

Necessary: \( a^{*}_{\text{TCHL}} \) at 665 nm, water absorption
A validation of optical CHL-a measurements

CHL-a from PR650 observations (mg m⁻³)

CHL-a lab measurements (mg m⁻³)
Phycocyanin: ratio algorithm by Stefan Simis

Fig. 8. Chlorophyll-a (mg m\(^{-3}\)) distribution in the IJssel Lagoon as derived from MERIS imagery, July 14, 2003.

Fig. 9. Phycocyanin (mg m\(^{-3}\)) distribution in the IJssel Lagoon as derived from MERIS imagery, July 14, 2003.

Fig. 1. \(R_{\text{es}}(\lambda)\) spectra representing the variation in spectral shape and magnitude of reflectance data encountered in the dataset. MERIS bands used to obtain PC\(_{\text{RAD}}\) are indicated by vertical bars (centered at 620, 665, 708.75 and 778.75 nm). The trough around 625 nm is primarily caused by pigments PC and Chl \(a\). The trough around 675 nm is attributed to Chl \(a\). Spectra from L. 1' Albufera (Spain) corresponded with pigment measurements PC\(_{\text{FL}}\) = 120–728 and Chl \(a\) 29–439 mg m\(^{-3}\). PC\(_{\text{FL}}\) and Chl \(a\) measurements for the Rosario spectra displayed here were both in the 35–80 mg m\(^{-3}\) range. PC\(_{\text{FL}}\) and Chl \(a\) measurements of the displayed L. Ijsselmeeer samples ranged 20–329 and 26–109 mg m\(^{-3}\), respectively.
Understanding the complexities of satellite observed spectra
The problem of remote sensing in a nutshell

Remote sensing of water colour is (worst case) like looking
• at a small bottle of coloured water (say 4x4 cm)
• from a rather large distance.

Using a normal sensor (MERIS 800km 1x1 km pixels)
And supposing the bottle is 1 pixel
then the sensor is at 32 m
in a room with some smoking persons (clouds)
and a leaking sauna (water vapour)
Various processes that contribute to the signal as measured by a remote sensor in an optically shallow water atmosphere:

- Molecules and aerosols
- Air-water interface: waves and whitecaps
- Water: pure water
- Algae (CHL), silt (TSM)
- Dissolved matter (DOM)
- Bottom reflection
Model inversion
General model inversion tools

1) Matrix Inversion Method
   (singular value decomposition)
2) Levenberg Marquard curve fitting method
   (Non-linear regression methods)
3) Neural Network
4) Look-up table approach
IVM HYDROPT MODEL LUT approach to calculating concentrations

Results of HYDROPT MERIS Calibration: 2003

Geometric mean in situ Chl a [mg m\(^{-3}\)]

Geometric mean remote sensing Chl a [mg m\(^{-3}\)]

Input # = 15
Valid output # = 13
RMA regression in log-log scale
(1) Slope = 1.070  (2) Intercept = -0.026
(3) \(R^2\) = 0.948  (4) RMS = 0.08 (20%)

Geometric mean in situ TSM [g m\(^{-3}\)]

Geometric mean remote sensing TSM [g m\(^{-3}\)]

Input # = 15
Valid output # = 11
RMA regression in log-log scale
(1) Slope = 0.800  (2) Intercept = 0.124
(3) \(R^2\) = 0.983  (4) RMS = 0.08 (20%)
Fig. 2. Monthly median Chl-a for March-May 2003 from MERIS data, processed by the REVAMP project (Peters et al. 2005). Early blooms, mainly dia-
Example of a Total Suspended Matter Map
Global applications based on satellite observations of NASA and ESA

- NASA: SeaWIFS & MODIS Aqua
- ESA: MERIS (+ Sentinel 3 in 2012)

<table>
<thead>
<tr>
<th>Name</th>
<th>bands</th>
<th>spatial resolution</th>
<th>spectral resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPOT</td>
<td>3</td>
<td>30x30 m²</td>
<td>~80</td>
</tr>
<tr>
<td>SeaWiFS</td>
<td>8</td>
<td>1x1 km²</td>
<td>~20</td>
</tr>
<tr>
<td>MERIS</td>
<td>15</td>
<td>0.3x0.3 km²</td>
<td>~10</td>
</tr>
<tr>
<td>HyMAP</td>
<td>126</td>
<td>high</td>
<td>~15</td>
</tr>
<tr>
<td>AVIRIS</td>
<td>71</td>
<td>high</td>
<td>~15</td>
</tr>
<tr>
<td>GOME</td>
<td>4x1024</td>
<td>320x40 km²</td>
<td>0.17-0.33</td>
</tr>
</tbody>
</table>
What do we want to know on the global scale?

Major science questions & societal benefits


✓ “How are ocean ecosystems and the biodiversity they support influenced by climate and environmental variability and change, and how will these changes occur over time?
✓ How do carbon and other elements transition between ocean pools and pass through the Earth System, and how do biogeochemical fluxes impact the ocean and Earth’s climate over time?
✓ How (and why) is the diversity and geographical distribution of coastal marine habitats changing, and what are the implications for the well-being of human society?
✓ How do hazards and pollutants impact the hydrography and biology of the coastal zone? How do they affect us, and can we mitigate their effects?”
The globcolour project merges MODIS and MERIS data

GlobColour - CHL1 - Merged monthly product (GSM)

www.globcolour.info
GIS & water quality maps

- Very few examples yet
- Discrepancy between large software programs (such as arcgis) and large spatial (raster) datasets coming from remote sensing
- Meta-data standards under development
- Successful applications mostly on the local scale
GIS & Water quality example: WATeRS
A Web Map Service with near-teal time MODIS standard chlorophyll products of the North Sea

Marieke Eleveld, Alfred Wagtendonk, Reinold Pasterkamp,
Nils de Reus, Hans van der Woerd

22 September 2006
Objectives & user requirements

The objectives of the project:
- Initiate a WATeRS portal
- an information service that provides products from RS of WQ
- and to firmly establish its position within the WQ field

User Requirements:
- Compliant with own geodata infrastructures.
- Near-real time information (particularly on chlorophyll) and time series
- Context through additional vector data in GIS
Internet Dissemination

pre-processing

database

atmospheric correction and SeaDAS processing

reflectance R(0-)
L2MUMM.hdf

TSM retrieval with bi-optical algorithms

TSM image products TSM

import into a GIS

TSM maps TSM.grd

import into Web mapping software

TSM layers in ArcIMS TSM.img
User interface WATeRS map service (at 15 September 2006)
Unfolding grouped layers and displaying them on the map.
Using the spatial bookmarks for zooming
Comparison: RS value with monitoring data
Example GIS analysis: MWTL stations falling inside buffer 
(12 km buffer around 12 miles zone)
Metadata catalogue WATeRS

MODIS Chlorophyll maps

This item has been newly created

<table>
<thead>
<tr>
<th>Name case study area</th>
<th>WATeRS MODIS CHL North Sea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>MODIS Standard Chlorophyll (CHL) concentrations</td>
</tr>
<tr>
<td>Acronym</td>
<td>MODIS CHL</td>
</tr>
<tr>
<td>Summary / definition</td>
<td>Chlorophyll (CHL) concentrations that are derived from data of the MODIS sensor on the Aqua satellite using the standard MODIS CHL algorithm.</td>
</tr>
<tr>
<td>Purpose</td>
<td>Monitoring of chlorophyll-a (CHL) concentrations in the North Sea is important for assessing changes in the environmental state of this European regional sea. CHL is a pigment in phytoplankton, which is the main source of food for life in the sea. High CHL concentrations also indicate high nutrient levels and thus it is an important water quality parameter. CHL products</td>
</tr>
</tbody>
</table>
WEB based GIS systems have the following advantages

- The remote sensing (RS) monitoring techniques capture spatio-temporal variability
- The web mapping allows interactive viewing, composing, and analysing (e.g. spatial querying, zooming in)
- The information is easily accessible, and is presented with extensive meta-information and in context (e.g. allows comparison with trends, and additional parameters)
- Open (used in ArcGIS, MultiService)
Concluding remarks

- Remote sensing of water quality is still under development
- Operational products are available for most European waters
- There are many uncertainties in the process
- A thorough insight in the variability of SIOPs is required
- An insight in the effect of inaccuracies in the observed spectra is required

Further reading

www.ioccg.org

And e.g.: