CEE 577: Surface Water Quality Modeling

Lecture #40

Limnology (cont.): Carbon & Precursor Models I

(Scientific Literature)
Full cycle analysis

- Dishwashing detergent causes
  - Miscarriages
  - Birth defects
  - Cancer

- How?

137,000 at risk in US

See: Gray et al., 2001 [Consider the Source, Environmental Working Group report]
241,000,000 people in US are served by PWSs that apply a disinfectant

High THMs are levels of at least 80 ppb over a 3 month average
New York Water Supply System Tunnels and Aqueducts
Front half of cycle

- Causal pathways for eutrophication effects on water supplies

Watershed Variables
  - Land use
  - Morphometry
  - Watershed Mgmt.
  - Climate
  - Geology
  - Hydrology

Reservoir Eutrophication
  - Nutrients
  - Algae
  - Transparency
  - Oxygen Depletion

Raw Water Quality
  - pH
  - Turb.
  - Odor
  - Fe
  - Mn
  - Ammonia
  - DOC
  - Color
  - Precursors

Treatment & DWS Mgmt.
  - Filtration
  - GAC
  - Disinfection
  - Doses
  - Dist. Sys.
  - Monitoring
  - Color
  - Fe/Mn
  - Odor
  - DBPs
  - Biodegradables

Treated Water Quality
  - Plumbing
  - Clothing
  - Aesthetics
  - Disease
  - Chronic Effects

User Impacts
  - Health
  - Costs

Modified from: Walker, 1983
Nature of NOM in Water

- Most systems are dominated by DOC
  - 85-98% of TOC

<table>
<thead>
<tr>
<th>Autochthonous</th>
<th>Particulate</th>
<th>Dissolved</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Algae</td>
<td>Excretion or lysis of Littoral sources (macrophytes, attached microflora) and Pelagic sources (phytoplankton)</td>
</tr>
<tr>
<td>Allochthonous</td>
<td>Soil, terrestrial plant detritus</td>
<td>Soluble components from terrestrial plants; soil organics (fulvic acids)</td>
</tr>
</tbody>
</table>
NOM Modeling

- An important current issue
  - Affects Drinking water treatment
  - Not well studied
- Bears similarities to N&P modeling
  - Natural and human sources
  - Biologically active (consumed & produced)
  - May be closely linked to primary productivity
  - Empirical & mechanistic approaches
- Complex
  - Many types of NOM, some produce DBPs, most don’t
Empirical Models: Algae and TOC

- Walker, 1983
  - Pointed out the long held knowledge that P and primary productivity (e.g., chlorophyll) were positively correlated
  - Also pointed out that primary productivity means more TOC
  - Tied this to drinking water reservoir management
  - Presented some new data showing this correlation in 38 US lakes

Walker, 1983, J. AWWA, 75(1)38-42
Empirical Models: P and C

- From Walker’s paper
- Slightly better correlation than with Chl a
- Is this causal or just autocorrelation with another parameter
- autochthonous source for TOC?

Walker, 1983, J. AWWA, 75(1)38-42
Other Empirical Models: DBPs

- Disinfection byproduct (DPB) precursors
- Empirical modeling hypotheses:
  - P-loading controls P concentration
  - P concentration controls algal growth
  - Algal growth controls TOC
  - DBP precursors are a sub-fraction of TOC
  - Therefore, P-loading controls DBP precursors
Chapra et al., 1997

- Chapra, Canale & Amy
- Added more data to Walker’s correlation
  - **TOC = 0.55 TP^{0.655}**
    - Where TOC is in mg/L
    - TP is total phosphorus in µg/L

Chapra et al., 1997, *J. Env. Eng. ASCE*, 123(7)714-715
Chapra et al., 1997 (cont.)

- Related this to THM precursor content
  - $\text{THMFP} = 43.78 \text{ TOC}^{1.248}$
- Used data from:
  - Amy, Edzwald, Miller, Bader
- No quantitative assessment of uncertainty

Chapra et al., 1997, *J. Env. Eng. ASCE*, 123(7)714-715
The next step that they chose not to take just yet was to combine the two models

- THMFP = 20.8 TP^{0.79}

- Probably not a good idea because the two models were from completely different data bases

- Uncertainty in both models probably makes this an “order of magnitude” estimate

- Perhaps the final step in this process is to combine with a THM formation model incorporating actual chlorination conditions

Weaknesses

- Does not account for allochthonous sources

- No site-specific considerations

- No spatial or temporal resolution
DBP Precursor Case Studies

- Deer Creek Reservoir, UT
  - 1981-83
    - Cook et al., 1984, White & Adams, 1985
- Lake Rockwell, OH
  - 1985-87
    - Palmstrom et al., 1988
- Lake Youngs, WA
  - 1992
    - Canale et al., 1997
- Cannonsville Reservoir, NY
  - 1995
    - Stepczuk et al., 1998a, b, c
- San Jaoquin Delta, CA
  - 1996
    - Fuji et al., 1998
- Cambridge Reservoirs, MA
  - 1997-98
    - Waldron & Bent, 2001
- Chickahominy River, VA
  - 1998
    - Speiran, 2000
- Boston Reservoirs, MA
  - 1997-2002
    - Garvey, Takiar, Bryan et al.
Deer Creek Reservoir Study

- **TOC/THM Precursor Studies**
  - Adams and others

- **Deer Creek**
  - Supply for Salt Lake City, UT
  - Meso-Eutrophic (impounded in 1941)
    - \( P_{\text{avg}} = ? \mu g/L \)

- **Characteristics for 1985-87**
  - **Hydraulics**
    - \( H_{\text{mean}} = 18.4 \text{ m} \)
    - \( V = 193.9 \times 10^6 \text{ m}^3 \)
    - \( \tau_{\text{mean}} = 6 \text{ months} \)
    - \( SA = 2787 \text{ ac} = 11.28 \times 10^6 \text{ m}^2 \)
    - \( DA = 1451 \times 10^6 \text{ m}^2 \)
  - **Loading**
    - \( \text{TOC} = ? \times 10^2 \text{ kg/yr} \)
    - \( P = ? \times 10^3 \text{ kg/yr} \)

White & Adams, 1985; UWRL Report #Q-85/01

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Deer Creek Res.: Loading

- Tributary Concentrations
Deer Creek Res: Microcosms

- Impact of:
  - Light
  - Phosphorus
  - sediments
Deer Creek Res.: Conclusions

- **Reservoir/Tributary Studies**
  - No change in THMFP across reservoir (in vs. out)
  - THMPF concentrations in tributaries were greatest in June and lowest in November
  - No correlation between TOC and THMFP

- **Microcosm Studies**
  - Sediments had no effect on THMFP
  - Algal activity (light) resulted in higher THMFP
  - Elevated P resulted in higher THMFP
  - Algal growth products were more important than decay products
  - Application of CuSO\(_4\) had no impact
  - No correlation between TOC and THMFP
Lake Rockwell Study

- THM Precursor Budget
  - Palmstrom, Carlson & Cooke

- Lake Rockwell
  - Supply for Akron, OH
  - Very Eutrophic (impounded in 1919)
    - $P_{avg} = 50 \mu g/L$

- Characteristics for 1985-87
  - Hydraulics
    - $H_{mean} = 3.9 \text{ m}$
    - $V = 10.2 \times 10^6 \text{ m}^3$
    - $\tau = 20 \text{ d}$
    - $SA = 311 \text{ ha} = 3.1 \times 10^6 \text{ m}^2$
  - Loading
    - $\text{THMFP} = 3-14 \times 10^2 \text{ kg/yr}$
    - $P = 2.8 \times 10^3 \text{ kg/yr}$

Palmstrom et al., 1988, *Lake & Res. Mgmt.*, 4(2)1-15
Input-output for 1985

- Low levels in winter
  - 160 µg/L average
- Increase across reservoir in early summer
  - ~ 30% increase

Palmstrøm et al., 1988, *Lake & Res. Mgmt.*, 4(2)1-15
Input-output for 1986-87

- Sometimes increase across reservoir in early summer
  - ~ 30% increase on average
  - Seen in 1985 and 1986
- Sometimes no increase
  - 1987

Palmstrom et al., 1988, Lake & Res. Mgmt., 4(2)1-15
Macrophyte Growth

- Microcosm studies with
  - Artificial lake water (control)
  - Sediments & water
  - Macrophytes, sediments & water

Macrophyte Degradation

- *Myriophyllum spicatum*
- Degradation in the dark
- Precursors released only under aerobic conditions

Palmstrom et al., 1988, *Lake & Res. Mgmt.*, 4(2)1-15
Release from Sediments

- Aerobic
  - High production

- Anaerobic
  - Far less production

Martin et al., 1993, Wat. Res., 27(12)1725-1729
Sediment Release (cont.)

- Summary of rate experiments
  - $\mu g$ THMFP/m$^2$/day

Martin et al., 1993, Wat. Res., 27(12)1725-1729
Model

- No mention of biodegradation of THM precursors
- Used site-specific macrophyte data

Palmstrom et al., 1988, *Lake & Res. Mgmt.*, 4(2)1-15
Estimated Loadings

- **Modeling results**
  - Riverine
  - Macrophyte
    - Degradation
    - Active growth
  - Sediments
    - Littoral
    - Profundal
  - Algae

<table>
<thead>
<tr>
<th></th>
<th>Palmstrom et al., 1988</th>
<th>Martin et al., 1993</th>
</tr>
</thead>
<tbody>
<tr>
<td>Riverine</td>
<td>47</td>
<td>63-204</td>
</tr>
<tr>
<td>Macrophyte</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Degradation</td>
<td>22</td>
<td>0.08-2.1</td>
</tr>
<tr>
<td>Active growth</td>
<td>0.85</td>
<td>0.82</td>
</tr>
<tr>
<td>Sediments</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Littoral</td>
<td>0.014</td>
<td>0.26</td>
</tr>
<tr>
<td>Profundal</td>
<td>0.23</td>
<td></td>
</tr>
<tr>
<td>Algae</td>
<td>0.1 – 100</td>
<td>21-103</td>
</tr>
</tbody>
</table>

Palmstrom’s algae loading based on a single net algal carbon production rate (0.33 g/m²/d) and a fixed THM/TOC ratio from the literature (Hoehn et al., 1980)

Reference:
- Martin et al., 1993
- Palmstrom et al., 1988

Re-evaluated some of the earlier data
Lake Youngs Study

- Mechanistic Carbon Model
  - Canale, Chapra, Amy & Edwards

Lake Youngs

- Supply for Seattle, WA
- Oligotrophic (impounded in 1923)
- Characteristics for 1992
  - Hydraulics
    - $H_{\text{mean}} = 14.7$ m
    - $H_{\text{max}} = 30.5$ m
    - $V = 41.6 \times 10^6$ m³
    - $\tau = 125$ d
    - $SA = 2.83 \times 10^6$ m²

- Loading
  - Total C = $2.38 \times 10^3$ kg/yr
  - P = $1.12 \times 10$ kg/yr

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Mechanistic Development

- 3 Carbon types
  - DOC (decays)
    - Allochthonous
    - Autochthonous
  - PtOC (settles)
    - From both
- Processes excluded
  - based on Lake Rockwell papers
- Macrophyte release of DOC
- Sediment DOC release set to zero

Parameter Estimation

- Site-specific measurements (2)
  - Settling rate
  - Sediment traps used
- THMFP yield

- Other parameters (14)
  - Literature values
  - With “model calibration”
    - Included some use of in-situ algal data

**TABLE 1. Kinetic Coefficient Values for Lake Youngs THMFP Model**

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Value (2)</th>
<th>Basis (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Settling velocity</td>
<td>66 m/yr</td>
<td>Entranco (1993, 1994); direct measurement</td>
</tr>
<tr>
<td>THMFP yield</td>
<td>2.5%</td>
<td>Entranco (1993, 1994); direct measurement</td>
</tr>
<tr>
<td>Algal maximum growth rate</td>
<td>1.5/d</td>
<td>Bowie et al. 1985; model calibration</td>
</tr>
<tr>
<td>Algal respiration</td>
<td>0.25/d</td>
<td>Bowie et al. 1985; model calibration</td>
</tr>
<tr>
<td>Light half-saturation</td>
<td>250 μE/m²/s</td>
<td>Bowie et al. 1985; model calibration</td>
</tr>
<tr>
<td>Phosphorus half-saturation</td>
<td>3 mg/m³</td>
<td>Bowie et al. 1985; model calibration</td>
</tr>
<tr>
<td>Zooplankton grazing</td>
<td>2.5 L/(mgC d)</td>
<td>Bowie et al. 1985; model calibration</td>
</tr>
<tr>
<td>Zooplankton respiration</td>
<td>0.075/d</td>
<td>Bowie et al. 1985; model calibration</td>
</tr>
<tr>
<td>Grazing efficiency</td>
<td>0.5</td>
<td>Bowie et al. 1985; model calibration</td>
</tr>
<tr>
<td>Algal carbon half-saturation</td>
<td>0.2 mg/L</td>
<td>Bowie et al. 1985; model calibration</td>
</tr>
<tr>
<td>Sediment P release</td>
<td>1 mg/m²/d</td>
<td>Nürnberg 1988; model calibration</td>
</tr>
<tr>
<td>Sediment oxygen demand</td>
<td>0.3 g/m²/d</td>
<td>Thomann and Mueller 1987; model calibration</td>
</tr>
<tr>
<td>TOC oxidation</td>
<td>0.025/d</td>
<td>Bowie et al. 1985; model calibration</td>
</tr>
<tr>
<td>Refractory TOC</td>
<td>0.5 mg/L</td>
<td>Bowie et al. 1985; model calibration</td>
</tr>
<tr>
<td>Hydrolysis</td>
<td>0.025/d</td>
<td>Bowie et al. 1985; model calibration</td>
</tr>
<tr>
<td>Reaeration</td>
<td>0.2/d</td>
<td>Bowie et al. 1985; model calibration</td>
</tr>
</tbody>
</table>

Used the same fixed THMFP:TOC relationship as in Chapra et al., 1997

**Canale et al., 1997, J. Wat. Res. Planning & Mgmt., 33:259-265**
Resolution

- **Spatial**
  - 2 vertical layers

- **Temporal**
  - Time variable for
    - Temperature
      - Determines vertical exchange coefficient
    - Light
    - Flow
    - loading

*Canale et al., 1997, J. Wat. Res. Planning & Mgmt., 33:259-265*
Algae

TOC & FP

- TOC and D.O. models

- THMFP = 0.25 \times TOC

Sources

- Based on existing loading & P levels

- Based on hypothetical elevated P and low TOC loading


Dissolved Autochthonous/Allochthonous = 0.1-0.5
Implications

**TABLE 3. Calculated Days of Violation of 50 μg/L THMFP Goal for Various TP and TOC Load Combinations**

<table>
<thead>
<tr>
<th>Total P (1)</th>
<th>Loading conditions TOC (2)</th>
<th>Days of Violations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Surface waters (3)</td>
</tr>
<tr>
<td>Current</td>
<td>Current</td>
<td>79</td>
</tr>
<tr>
<td>Decrease (90% reduction)</td>
<td>Current</td>
<td>66</td>
</tr>
<tr>
<td>Current</td>
<td>Decrease (25% reduction)</td>
<td>0</td>
</tr>
<tr>
<td>Increase (double)</td>
<td>Current</td>
<td>91</td>
</tr>
<tr>
<td>Current</td>
<td>Increase (25% increase)</td>
<td>114</td>
</tr>
<tr>
<td>Increase (double)</td>
<td>Decrease (25% reduction)</td>
<td>34</td>
</tr>
</tbody>
</table>

*Canale et al., 1997, J. Wat. Res. Planning & Mgmt., 33:259-265*
Leaching of NOM from litterfall, soils etc.
• To next lecture