Bubbly Creek Sediment Oxygen Demand Study and Implications for Water Quality Improvement

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Illinois Water Science Center
(Jim Duncker, Ryan Jackson)
OUTLINE:

1. Background
   a. Water quality standards (UAA)
   b. Hydrology of Bubbly Creek
   c. 2D modeling of Bubbly Creek
   d. 3D modeling of Chicago waterways
2. SOD field observations
3. 3D modeling with SOD from field observations
4. Remediation alternatives in light of SOD studies
5. Implications for water quality management
6. Conclusions
Current Chicago Waterway System Dissolved Oxygen Standards

- Indigenous Aquatic Life: Except for Calumet-Sag Channel (minimum > 3 mg/L) Minimum D.O. 4 mg/L at any time
- General Use: Hourly Avg. > 6 mg/L 16 out of 24 hours Minimum > 5 mg/L at any time

Proposed Chicago Waterway System Dissolved Oxygen Standards

- Limited Warm Water Aquatic Life: General Use, or Minimum of 4, 5 or 6 mg/L
- Modified Warm Water Aquatic Life: General Use, or Minimum of 4, 5 or 6 mg/L

From CTE, Zenz (2007)
Flow Augmentation & Supplemental Aeration of Bubbly Creek

From CTE, Zenz (2007)
Costs for Flow Augmentation and Supplemental Aeration of Bubbly Creek

- Capital Costs of 60.4 million to $102.9 million
- Annual costs of $1.0 million to $2.8 million

From CTE, Zenz (2007)
Hydrology of Bubbly Creek

HISTORIC CSO EVENTS

Sources
MWRDGC: CSO events 2005-2007

Characteristics
17 CSO events per year on average in the period 1992-2001
The CSO events usually last from few hours to as long as a day or more (depending on the amount and duration of rainfall).
CSO VOLUMES 2000-2007

CORRELATIONS RAINFALL-VOLUME-DURATION

Relation between the mean rainfall depth in the Central Basin and the CSO volume discharged at RAPS

Relation between the mean rainfall depth in the Central Basin and the CSO discharge duration at RAPS
RAPS Service Area
Catchment Description

• The service area contributing to the Racine Pumping Station (RAPS)
• Area ~ 36 square miles,
• Population ~463400
• households ~169900, all susceptible to basement backup flooding
Pumping Station

• The Racine Pumping Station (RAPS) receives flows from the entire service area. This station currently pumps flows to the Stickney Water Reclamation Plant (SWRP) and also pumps overflows during CSO events to the South Fork of the South Branch (SFSB) of the Chicago River.

• The existing station has fourteen individual pumps. Five pumps pump to SWRP and the remaining nine pumps pump to the SFSB during CSO events.
Data

Long Term Rainfall Data (ISWS Rain Gages)

Date

Precipitation (in)

ISWS-G10
ISWS-G13
ISWS-G14
• Daily mean discharges diverted to the Bubbly Creek during CSO events. Period 01/01/2005 to 3/30/2007.
Modeling Results

A. Historical Long term rainfall runoff simulations

Comparison of simulated and measured CSO volumes discharged to Bubbly Creek. Connection to TARP included (DS-27, DS-28, DS-29).
The effect of an additional DS on the SW10-39St conduit on CSO diverted to Bubbly Creek (SFSB).
Summary

• Even though five sub-catchments were adopted for the analysis to characterize the service area of each one of the main interceptors draining to the pump station, reasonable estimates of the inflows to RAPS are obtained after comparing with measured outflows to SFSB during CSO events for Historical run made for the WY2006.

• Discharging into TARP via drop shafts 27, 28, and 29 decreases the total inflow to RAPS.

• Adding another drop shaft could reduce the inflow to RAPS and therefore to Bubbly Creek.

• Exclusion of snow depths on the simulations of continuous rain, WY2006, will lead to miscalculation of more realistic infiltration and runoff values, hence affecting the calculations of the total amount of flows draining to the pump station.
2D modeling of Bubbly Creek (2008)

Bubbly Creek, South Fork of the South Branch of the Chicago River

- **historically** used as a drainage channel for the waste resulting from Chicago’s stockyards;
- **nowadays** there is flow in the creek only during rainfall events resulting in Combined Sewer Overflows (CSO) and water quality is a very important issue, particularly during the summer months. Revived interest in Bubbly Creek.

**Two scenarios analyzed**

- CSO events;
- potential “purification” solutions, such as flow augmentation and supplemental aeration, with the goal of increasing the DO levels in the creek during dry weather periods.

**Modeling**

2-D depth-averaged numerical model **STREMR-HySedWq** which couples hydrodynamics, sediment transport and water quality (BOD-DO).
Bubbly Creek, Chicago

Regimes
- dry periods: no flow
- heavy storms: Combined Sewer Overflow (CSO)
CSO event of September 13, 2006

Phase 1

Phase 2

- DO at I-55
- DO at 36th Street
- CSO flow rate

Graph showing DO concentration (mg/l) and CSO flow rate (m³/s) from 9/13/06 to 9/17/06.

Map showing I-55 and 36th Street.
BOD bed/water column exchange

\[ H \]

**water column**

\[ C_{ss,w} \]
\[ C_{BOD,w} \]
\[ C_{BOD,w,d} \]
\[ C_{BOD,w,p} \]

**sediment**

\[ F_{res,ss} \]
\[ F_{sed,ss} \]

\[ F_{res} \]
\[ F_{sed} \]

\[ F_{diff} \]

\[ H_b \]

**bed top layer**

\[ C_{ss,b} \]
\[ C_{BOD,b} \]
\[ C_{BOD,b,d} \]
\[ C_{BOD,b,p} \]

**bed lower layer**
Motta, D., Abad, J.D., Garcia, M.H.  
A modeling framework for organic sediment resuspension and oxygen demand: the case of Bubbly Creek in Chicago, Illinois  
Journal of Environmental Engineering (Sep 2010)
“Purification” scenarios

**SCENARIO 1**: flow recirculation of 50 MGD (2.19 m$^3$/s), northward flow in the creek. Summer or after CSO event scenario; abstraction of daily fluctuation due to photosynthesis and respiration.

- **BOD**: oxidation and settling $\rightarrow$ BOD concentration decreases;
- **DO**: oxidation and sediment oxygen demand (SOD) from the bed $\rightarrow$ DO concentration decreases; reaeration from the atmosphere $\rightarrow$ DO concentration increases.

SOD = 2.32 g/m$^2$/day, no resuspension
**“Purification” scenarios (contd.)**

**SCENARIO 2:** flow recirculation (northward flow in the creek) plus supplemental aeration (1.31 g/s) in one location in the creek

**SCENARIO 3:** flow recirculation (northward flow in the creek) plus supplemental aeration (1.31 g/s) in the recirculation pipe

---

*But what is the true value of SOD?*
Summary of 2D modeling

• Two-dimensional depth-averaged water quality BOD-DO model in the numerical code STREMR-HySedWq. Quantitative framework for the evaluation of the BOD transport across the bed/water interface in rivers was derived, in order to capture the additional oxygen demand in the water

• SOD estimation is important for analysis of purification scenarios
3D modeling of Chicago waterways

Bed elevation in comparison with Chicago city datum (CCD)
CCD = 176.63 m above sea level

Bed elevation (m)
-9.5 -7.5 -5.5 -3.5 -1.5

Towards Lake Michigan

Grand avenue

Bubbly Creek

Stickney Avenue

RAPS
Closer Look at Bathymetry near Turning Basin
Computational mesh with 4400 cells in horizontal and 8 layers in vertical.
**Setting of the 3D Hydrodynamic Simulation**

8-day (192 hrs) event was simulated, starting at 12:00 am on **10th of September 2008** and continuing till 12:00 am on 18th of September.

Boundary data are based on USGS gauging stations and information from MWRD for flow information through lock and gates.
Velocity Magnitude 40 hrs after Start of Simulation

Umag (m/s) 0.00 0.04 0.09 0.13 0.18

North

10th to 18th of September 2008

Bubbly Creek

RAFS
Velocity Magnitude **40 hrs** after Start of Simulation

10th to 18th of September 2008

Flow from Grand Av.

South Branch

Main Branch

U_{mag} (m/s): 0.00 0.04 0.09 0.13 0.18

 München 

LOCK & GATES
Velocity Magnitude 80 hrs after Start of Simulation

Umag (m/s) 0.00 0.20 0.40 0.60 0.80

North

10th to 18th of September 2008

Bubbly Creek

RAPS
Velocity Magnitude 80 hrs after Start of Simulation

10th to 18th of September 2008

Flow from Grand Av.

South Branch

Main Branch

U_{mag} (m/s) 0.00 0.20 0.40 0.60 0.80

LOCK & GATES
Depth in Turning-Basin 80 hrs after Start of Simulation

10th to 18th of September 2008

Notice dam/barrier effect
Velocity Magnitude 110 hrs after Start of Simulation

10th to 18th of September 2008
Velocity Magnitude 110 hrs after Start of Simulation

10th to 18th of September 2008
Velocity Magnitude 150 hrs after Start of Simulation

U_{mag} (m/s) 0.00 0.06 0.13 0.19 0.25

North

10th to 18th of September 2008

Bubbly Creek

RAFS
Velocity Magnitude 150 hrs after Start of Simulation

10th to 18th of September 2008

South Branch

Main Branch

Flow from Grand Av.

Umag (m/s) 0.00 0.06 0.13 0.19 0.25

LOCK & GATES
Comparison of Modeled and Observed Stage Values at the Validation Point
Upstream Flow and Transport

Salt was used as a surrogate for dealing with the problem of upstream intrusion.

In this simulation, as long as the RAPS stayed on 2 gms/l of salt was supplied with the flow.

Finally the concentration of salt was recorded in the whole domain and it’s evolution in time was examined.
Grand Av.

CRCW gates opened

92 hrs after start of simulation

RAPS

CRCW gates opened

108 hrs after start of simulation

10th to 18th of September 2008
Grand Av.

CRCW gates opened

Salt (gm/l) 0 0.5 1 1.5 2

116 hrs after start of simulation

RAPS

CRCW gates opened

119 hrs after start of simulation

10th to 18th of September 2008
Objectives of the Study:

For a non-resuspension condition:
1) What is the background SOD?
2) How does the SOD vary with increasing velocity (up to the point of resuspension)?

For a sediment resuspension condition:
1) At what bed shear stress is sediment resuspension initiated?
2) What is the magnitude of resuspension with increasing bed shear stress?
3) What is the oxygen demand associated with varying degrees of resuspension?
The U of I Hydrodynamic SOD Sampler
FIELD OBSERVATIONS AND RESULTS

3 or 4 Phases of Sediment Resuspension

No resuspension  "Flaking" phase  "Slurry" phase

(Note: an intermediate “Bedload” phase in coarse-grained sediment.)
NO SEDIMENT RESUSPENSION

Sample Station #3: Q = 25 L / min

WITH SEDIMENT RESUSPENSION

Sample Station #3: Q = 120 L / min
### SOD_{NR20} RESULTS

<table>
<thead>
<tr>
<th>Sediment Type</th>
<th>SOD_{NR20} (g/m²/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine-grained organic muck</td>
<td>12.1</td>
</tr>
<tr>
<td>Fine sandy organic muck</td>
<td>6.7</td>
</tr>
<tr>
<td>Fine sand</td>
<td>6.8</td>
</tr>
<tr>
<td>Medium to coarse sand</td>
<td>9.2</td>
</tr>
</tbody>
</table>

(All values normalized to 20°C)

\[ SOD_{20} = SOD_T \times 1.065^{(20-T)} \]

**Sample Station #2: Trial 2A, Q = 59 L/min**

\[ SOD_{NR} = \frac{V}{A} \times (\frac{dC}{dt} - BOD) \]

**Sample Station #6: Trial 6A, Q=30L/min**
BED SHEAR STRESS AND EROSION ANALYSIS

During Field Measurements, Q was recorded. But we need to analyze in terms of bed shear stress or shear velocity. So we turn to CFD.

[Modeling by Yovanni Cataño-Lopera using Flow-3D]

3-D rendering of the Horizontal Velocity $u$ (cm/s) using Flow-3D's FAVOR
Shear Velocity \( (u_*) \) is often used as a surrogate for Bed Shear Stress \( (\tau_B) \):

\[
\begin{align*}
\tau_B &= \frac{k g m}{s^2 m^2} \\
\rho &= \frac{k g}{m^3}
\end{align*}
\]

Where:
- \( \tau_B \): Bed Shear Stress (N/m²)
- \( u_* \): Shear Velocity (m/s)
- \( \rho \): Fluid Density (kg/m³)

Field tests were performed under:
\[ 0.13 \leq u_* \leq 0.93 \text{ cm/s} \]
Shear Velocities within SOD chamber

Sediment Class 1: D50=10μm
Sediment Class 2: D50=30μm
Sediment Class 3: D50=125μm
Sediment Class 4: D50=250μm
Sample Station #3 (Fine-grained Organic Muck: Shallow)

- **No Resuspension Phase**
- **Flaking Phase**
- **Slurry Phase**

**Trial 3A**
- TSS is the ambient water level

**Trial 3B**
- Linear relation based on the points: (0.17,90) and (0.253,236)

**Trial 3C**
- Linear relation based on the points: (0.475,3440) and (0.774,10528)

**Trial 3D**
From 2D model

For $Q=2.19 \text{ m}^3/\text{sec}$

**LEGEND**

- $u^*$, SHEAR VELOCITY (m/sec)
  - 0.0028
  - 0.0026
  - 0.0024
  - 0.0022
  - 0.002
  - 0.0018
  - 0.0016
  - 0.0014
  - 0.0012
  - 0.001
  - 0.0008
  - 0.0006
  - 0.0004

**CRITICAL SHEAR VELOCITIES (cm/sec):**
- 0.17 (Flaking)
- 0.37 (Full Resuspension, Muck, Shallow)
- 0.61 (Full Resuspension, Muck, Deep)
- 0.76 (Full Resuspension, Sandy Muck)
- 0.91 (Bedload, Sand)
- 2.54 (Full Resuspension, Sand)

NOT: This figure shows the same shear velocities as the figure on the left; only the ranges are shown with respect to the critical values so that the resuspension phase is more evident.

**SCALE:** Each tick mark is 100 m
For $Q=12 \text{ m}^3/\text{sec}$
For $Q=24$ m$^3$/sec

**LEGEND**

- **u\*, SHEAR VELOCITY (m/sec):**
  - 0.026
  - 0.024
  - 0.022
  - 0.02
  - 0.018
  - 0.016
  - 0.014
  - 0.012
  - 0.01
  - 0.008
  - 0.006
  - 0.004

**LEGEND:**

- **FLAKING**
- **FULL RESUSPENSION (SLURRY)**
- **SANDY SEDIMENT MOBILIZED AS BEDLOAD**
- **SANDY SEDIMENT TRANSITIONS FROM BEDLOAD INTO FULL SUSPENSION**

**NOTE:** This figure was generated by overlaying the shear velocities from the figure on the left onto the map of sediment types. (Resuspension phase is dependent on both sediment type and shear velocity.)

**CRITICAL SHEAR VELOCITIES (cm/sec):**

- 0.17 (Flaking)
- 0.37 (Full Resuspension, Muck, Shallow)
- 0.61 (Full Resuspension, Muck, Deep)
- 0.76 (Full Resuspension, Sandy Muck)
- 0.91 (Bedload, Sand)
- 2.54 (Full Resuspension, Sand)
**OXYGEN DEMAND ANALYSIS FOR RESUSPENDED SEDIMENT**

**Standard Equation for DO sink exerted by BOD**

\[
d\frac{C_{DO}}{dt} = -K_D \Theta_D^{T-20} \left( \frac{C_{DO}}{K_{BOD} + C_{DO}} \right) C_{BOD}an

- \(K_D\) is the deoxygenation (oxidation) rate coefficient at 20 \(^°\)C (1/day)
- \(\Theta_D^{(T-20)}\) is the temperature correction factor, whose standard value is 1.047
- \(C_{DO}\) is the concentration of dissolved oxygen (mg/L)
- \(C_{BOD}\) is the concentration of oxidizable material remaining in terms of how much oxygen it will require to oxidize it (mg/L)
- \(K_{BOD}\) is a half-saturation constant for BOD oxidation (mg/L)

**Proposed Parallel Equation for TSS**

\[
d\frac{C_{DO}}{dt} = -K_D \Theta_D^{T-20} \left( \frac{C_{DO}}{K_{BOD} + C_{DO}} \right) C_{BOD}an

Replace \(C_{BOD}\) with \(C_{TSS}\)

Assumptions:
1. \(C_{TSS} \propto C_{\%\text{ Organic}} \propto C_{BOD}\)
2. Depletion of \(C_{BOD}\) was negligible for the time scale of the field tests

**Rate constant:** Establish using the relation between oxygen demand and \(C_{TSS}\) at a set concentration of DO

**Temperature constant:** This term characterizes oxygen demand as a function of temperature. This term will not change

**DO dependent term:** This term dictates how oxygen demand decreases as a function of the DO present. Establish an appropriate function to substitute for this term.

Calibrate these parameters using field data
The Final Formulation for Oxygen Sink term associated with Resuspended Sediment:

\[
S_{O2} = 0.112 \frac{1}{\text{day}} \times 1.047^{(T-20)} \times \left[2.22 \times \frac{C_{DO}}{(C_{DO}+2.44)}\right] \times C_{TSS}
\]

(SOD_R)

Simulations of the Oxygen Sink term on Field Experiments:

\[
C_{DO}(t+1) = C_{DO}(t) - SOD_R(t) \times \Delta t
\]

Trial 1B: TSS=2984mg/L; Temp=26.5°C

- Field Data
- Simulation using Kd=0.112/day
3D modeling with SOD from field observations

36 Street observation point

I-55 observation point
- Incoming BOD from RAPS for event-1 and event-2, 108.79 mg/l and 92.15 mg/l respectively.
- Incoming SS from RAPS for event-1 and event-2, 384.92 mg/l and 379.49 mg/l respectively.
- Incoming DO from RAPS for event-1 and even-2, 4 mg/l and 6.73 mg/l respectively.
- Settling velocity for particle 4.5 m/day. SOD = 8.7 g/m²/day
Simulation results starting from 12:00 am Aug-27, 2009

a) 6 hrs after start of simulation
   $Q = 21.36 \text{ m}^3/\text{s}$
   $DO = 4 \text{ mg/l}$

b) 12 hrs after start of simulation
   $Q = 25 \text{ m}^3/\text{s}$
   $DO = 6.5 \text{ mg/l}$
   RAPS switches off
   10.75 hrs after start of simulation

(c) 18 hrs after start of simulation
   RAPS is off

(d) 24 hrs after start of simulation
   RAPS is off
Simulation results starting from 12:00 am Aug-27, 2009

a) 30 hrs after start of simulation
Q = 35 m³/s
DO = 6 mg/l

b) 36 hrs after start of simulation
Q = 25 m³/s
DO = 6.5 mg/l

RAPS switches off
31.75 hrs after start of simulation

RAPS is off

c) 42 hrs after start of simulation

RAPS is off
d) 48 hrs after start of simulation
Simulation results starting from 12:00 am Aug-27, 2009

a) 6 hrs after start of simulation

Q = 21.38 m$^3$/s
Sus Sed. = 385 mg/l

b) 12 hrs after start of simulation

Q = 25 m$^3$/s
Sus Sed. = 10 mg/l

RAPS switches off
10.75 hrs after start of simulation

c) 18 hrs after start of simulation

RAPS is off

d) 24 hrs after start of simulation

RAPS is off
Simulation results starting from 12:00 am Aug-27, 2009

a) 30 hrs after start of simulation
   \[ Q = 35 \text{ m}^3/\text{s} \]
   \[ \text{Sus Sed.} = 380 \text{ mg/l} \]

b) 36 hrs after start of simulation
   \[ Q = 25 \text{ m}^3/\text{s} \]
   \[ \text{Sus Sed.} = 10 \text{ mg/l} \]
   RAPS switches off
   31.75 hrs after start of simulation

RAPS is off

c) 42 hrs after start of simulation

RAPS is off

d) 48 hrs after start of simulation
Simulation results from DO-BOD model covering two CSO events between Aug 27-28, 2009

**DO variation at 36th street Aug-27-28,2009**
Simulation results from DO-BOD model covering two CSO events between Aug 27-28, 2009

DO Variation at I-55 Aug 27-28, 2009

- **DO (mg/l)**
- **Time (hrs)**

**Legend:**
- **DO(observed)**
- **DO(Simulated)**
Remediation alternatives in light of SOD studies

Zero-th order analysis of “purification” scenarios based on flow augmentation

→ in absence of sediment resuspension
→ in presence of sediment resuspension

1D analysis of “purification” scenarios based on flow augmentation and supplemental aeration

• All the analyses are based on a balance between:
  
  flow reaeration → source term for Dissolved Oxygen
  bed and suspended sediment oxygen demand → sink terms for Dissolved Oxygen
Analytical Solution for DO Dynamics in the Water Column

Assumptions for the water column:

- steady state
- BOD has settled or been oxidized
- net advection effect is zero ($\partial/\partial x = \partial/\partial y = 0$)
- balance between reaeration on the top and SOD on the bottom
Zero-th order analysis (contd.)

- The water column is taken as control volume.
- At steady state, the reaeration flux is balanced by the SOD flux.
- We solve for the control volume-averaged equilibrium concentration of Dissolved Oxygen

\[
k_a \theta_a^{T-20} (C_s - C_{DO}) = \frac{SOD}{H} \theta_s^{T-20}
\]

\[
\Rightarrow C_{DO} = C_s - \frac{SOD}{Hk_a} \frac{\theta_s^{T-20}}{\theta_a^{T-20}}
\]

with

\[
C_s = \exp[7.71 - 1.31 \ln(T + 45.93)]
\]

\[
K_a [\text{day}^{-1}] = \frac{3.93 (U [\text{m/s}])^{1/2}}{(H [\text{m}])^{3/2}}
\]
Zero-th order analysis (contd.)

Reaeration coefficient as function of the discharge

Reaeration coefficient increases as discharge increases

Equilibrium Dissolved Oxygen concentration as function of the discharge with SOD = 3.30 g/m²/day

Equilibrium Dissolved Oxygen concentration increases as discharge increases
Zero-th order analysis (contd.)

Sensitivity to SOD

MWRDGC measurements (2006)

<table>
<thead>
<tr>
<th>Sediment Type</th>
<th>SOD (g/m²/day)</th>
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<td>Fine-grained organic muck</td>
<td>12.1</td>
</tr>
<tr>
<td>Fine sandy organic muck</td>
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</tr>
<tr>
<td>Fine sand</td>
<td>6.8</td>
</tr>
<tr>
<td>Medium to coarse sand</td>
<td>9.2</td>
</tr>
<tr>
<td>Average</td>
<td>8.7</td>
</tr>
</tbody>
</table>

Waterman et al. (2009)

Effect of velocity on SOD even in absence of resuspension (increased mixing)

The higher the SOD, the lower the Dissolved Oxygen concentration at equilibrium

![Graph showing the relationship between velocity (Q) and dissolved oxygen (CDO). The graph illustrates how increased SOD leads to lower CDO concentrations.](attachment:image-url)
Zero-th order analysis (contd.)

- The water column is taken as control volume.
- At steady state, the reaeration flux is balanced by the SOD flux and the oxygen demand by the suspended sediment (SSOD).
- We solve for the control volume-averaged equilibrium concentration of dissolved oxygen

\[
k_a \theta_a T^{-20} (C_s - C_{DO}) = \frac{SOD}{H} \theta_s T^{-20} + 0.112 \cdot 1.047 T^{-20} \left[ \frac{2.22 C_{DO}}{C_{DO} + 2.44} \right] C_{ss}
\]

This is a relation that links Suspended Sediment and Dissolved Oxygen.
An expression which links suspended sediment concentration and discharge was derived for Bubbly Creek.

Average values of shear velocity in Bubbly Creek, obtained with 2D hydrodynamic simulation:

\[
\frac{u_*}{U} = \sqrt{C_f} \quad \Rightarrow \quad u_* \propto U \quad \Rightarrow \quad u_* \propto Q
\]

\[
Q = UA \quad \Rightarrow \quad Q \propto U
\]

Relation between shear velocity and Suspended Sediment concentration, from in situ data by Waterman et al. (2009):

\[ C_{ss} = a_1 u_*^2 + a_2 u_* \]

Recall:

\[ u_* = \sqrt{\frac{\tau_b}{\rho}} \]
Therefore the expression which links suspended sediment concentration and discharge for Bubbly Creek is

For high flow rates, the curve needs a "cap", since the concentration cannot increase indefinitely.

Summary of the hydrodynamics quantities for different discharge values:

<table>
<thead>
<tr>
<th>Q</th>
<th>2.19</th>
<th>12.00</th>
<th>24.09</th>
<th>38.55</th>
<th>69.43</th>
<th>m³/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>2.19</td>
<td>2.19</td>
<td>2.19</td>
<td>2.19</td>
<td>2.19</td>
<td>m</td>
</tr>
<tr>
<td>U</td>
<td>0.02</td>
<td>0.12</td>
<td>0.23</td>
<td>0.36</td>
<td>0.65</td>
<td>m/s</td>
</tr>
<tr>
<td>u_star</td>
<td>0.001</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.04</td>
<td>m/s</td>
</tr>
<tr>
<td>Tau_bed</td>
<td>0.002</td>
<td>0.06</td>
<td>0.23</td>
<td>0.59</td>
<td>1.89</td>
<td>Pa</td>
</tr>
</tbody>
</table>
Zero-th order analysis (contd.)

The oxygen demand exerted by the Suspended Sediments causes a decrease of Dissolved Oxygen at equilibrium for high values of discharge.

Possible Q range for “purification”, but supplemental aeration is needed.
In absence of suspended sediment

\[ \frac{dC_{DO}}{dt} = k_a \theta_a^{T-20} (C_s - C_{DO}) - \frac{SOD}{H} \theta_s^{T-20} \]

With \[ u = \frac{dx}{dt} \]

\[ u \frac{dC_{DO}}{dx} = k_a \theta_a^{T-20} (C_s - C_{DO}) - \frac{SOD}{H} \theta_s^{T-20} \]

In presence of suspended sediment

\[ \frac{dC_{DO}}{dt} = k_a \theta_a^{T-20} (C_s - C_{DO}) - \frac{SOD}{H} \theta_s^{T-20} - 0.112 \cdot 1.047^{T-20} \left[ \frac{2.22}{C_{DO} + 2.44} \right] C_{ss} \]

With \[ u = \frac{dx}{dt} \]

\[ u \frac{dC_{DO}}{dx} = k_a \theta_a^{T-20} (C_s - C_{DO}) - \frac{SOD}{H} \theta_s^{T-20} - 0.112 \cdot 1.047^{T-20} \left[ \frac{2.22}{C_{DO} + 2.44} \right] C_{ss} \]

Recall

\[ C_{ss} [mg/l] = 500 \left( 0.0006 \cdot 100Q \left[ m^3/s \right] \right)^2 + 50 \left( 0.0006 \cdot 100Q \left[ m^3/s \right] \right) \]

→ 1D profiles of Dissolved Oxygen concentration can be obtained, for the evaluation of “purification” scenarios based on flow recirculation and supplemental aeration
1D analysis (contd.)

Considering a recirculation discharge of 2.19 m$^3$/s (50 MGD), characterized by:

- Average flow velocity = 0.02 m/s
- Average depth = 2.19 m

we analyze a “purification” scenario of this type. Oxygen demand from the sediments in the bed and in suspension compete with the flow reaeration.
If sediment resuspension is not considered, only one location is needed for supplemental aeration, in the pipe, with reaeration rate = 8.63 g/s, with a bottom SOD of 8.7 g/m²/day to get a Dissolved Oxygen concentration of at least 4 mg/l in the creek.
If sediment resuspension is considered ($C_{ss} = 15 \text{ mg/l}$), two locations are needed for supplemental aeration, in the pipe and in the creek, with a total reaeration rate = 15.38 g/s, with a bottom SOD of 8.7 g/m²/day to get a Dissolved Oxygen concentration of at least 4 mg/l in the creek.

IEPA DO = 4 mg/l
Flow Augmentation & Supplemental Aeration of Bubbly Creek

From CTE, Zenz (2007)
If sediment resuspension is considered ($C_{ss} = 15$ mg/l), two locations are needed for supplemental aeration, in the pipe and in the creek, with a total reaeration rate = 15.97 g/s, with a bottom SOD of 8.7 g/m²/day to get a Dissolved Oxygen concentration of at least 4 mg/l in the creek

IEPA DO = 5 mg/l
Implications for water quality management

Sediment Oxygen Demand - Chicago Area Waterways

FLOW AUGMENTATION OF THE UPPER NORTH SHORE CHANNEL

- Linden Street
- Simpson Street
- Proposed 450 mgd Forcemain (approx. 4 miles)
- Main Street
- Proposed 450 mgd Flow Augmentation Pump Station
- NORTH SIDE WRP
- NORTH SHORE CHANNEL
- NORTH BRANCH
- LAKE MICHIGAN

Wilmette Pumping Station

From CTE, Zenz (2007)
Conclusions

✓ Strategies to improve water quality in the waterways have to take into account benthic sediment oxygen demand (SOD)

✓ Sediment oxygen demand due to resuspension of bottom material can result in very low oxygen levels in the water column

✓ Correct modeling of the impact of sediment resuspension and transport on oxygen demand is crucial to assess the effectiveness of different alternatives for water quality improvement and the impact of CSO events on Bubbly Creek and the South Branch of the Chicago River.
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