Utah Lake Model: Hydrodynamics and Sediment Transport

Utah Lake Water Quality Study
Science Panel Meeting 8/8/2018
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Presentation Outline

1) Model Selection
2) EFDC Model Formulation
   a) Hydrodynamics
   b) Sediment Transport
3) EFDC Preliminary Model Build
4) Data Collection for EFDC Model Calibration
Model Selection
Utah Lake Model Selection

- Formed model sub-workgroup for stakeholder input
- Evaluated potential models to meet objectives and selection criteria
- Preference:
  - Complex, 3D model to capture processes
  - Freeware, public domain for transparency
- Selected coupled model:
  - Hydrodynamics – EFDC
  - Water Quality – WASP
- Models subsequently selected by University of Utah research team for development through EPA ORD grant
Need for Separate Hydrodynamic Model

- Hydrodynamics integrated into WASP are 1-D only
- Lateral mixing and circulation highly dependent on wind induced currents
- Sediment deposition/resuspension identified as key process in eutrophication of shallow lakes
  - Suspended sediment alters light penetration
  - Phosphorus adsorbed to sediment can be released when resuspended
- Sediment resuspension dependent on wave height/frequency and shear stress
EFDC – WASP Model Linkage

EFDC generates WASP hydrodynamic linkage file
- Water depth
- Water velocity in three directions (x, y, z)

Additional EFDC state variables to be simulated not linked to WASP
- Salinity
- Temperature
- Cohesive Inorganic Sediment
EFDC Model Formulation
EFDC (Environmental Fluid Dynamics Code)

- EPA and NOAA supported freeware software
- 3-D hydrodynamic model
- Widely applied to rivers, lakes, reservoirs, wetlands, estuaries, and coastal ocean regions
- Physical characteristics of the waterbody
  - Horizontal grid: Cartesian or curvilinear-orthogonal
  - Vertical grid: sigma terrain following
- Solves transport equations for water velocity and depth, salinity, temperature, suspended cohesive and non-cohesive sediment, dissolved and adsorbed contaminants, and a dye tracer
- Simulates drying and wetting in shallow areas, representation of hydraulic control structures, and vegetative resistance
Hydrodynamics

Sigma terrain following vertical coordinates  \[ H = h + \eta \quad z^* = \frac{z}{H} \]

Conservation of mass: Continuity Equation
\[ \frac{\partial H}{\partial t} + \frac{\partial Hu}{\partial x} + \frac{\partial Hv}{\partial y} + \frac{\partial w}{\partial z^*} = 0 \]

Conservation of momentum: Navier-Stokes Equation

\[ \begin{array}{l}
\text{Accumulation} \\
\frac{\partial Hu}{\partial t} \\
\frac{\partial}{\partial x} \left( \frac{\partial H}{\partial x} + z \frac{\partial H}{\partial x} \right) \frac{\partial p}{\partial z^*} \\
\text{Advection} \\
\frac{\partial}{\partial x} \left( \frac{\partial H}{\partial x} + z \frac{\partial H}{\partial x} \right) \\
\text{Coriolis} \\
\frac{1}{H} \frac{\partial Hv}{\partial x} + \frac{1}{H} \frac{\partial Hv}{\partial y} \\
\text{Pressure} \\
\frac{H \frac{\partial p}{\partial x}}{\partial x} + \frac{\partial}{\partial x} \left( \frac{\partial H}{\partial x} + z \frac{\partial H}{\partial x} \right) \frac{\partial p}{\partial z^*} \\
\text{Buoyancy} \\
\frac{\partial}{\partial x} \left( \frac{\partial H}{\partial x} + z \frac{\partial H}{\partial x} \right) \\
\text{Vertical-momentum diffusion} \\
\frac{\partial}{\partial x} \left( A_v \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial x} \left( A_v \frac{\partial u}{\partial x} \right) \\
\text{Horizontal-momentum diffusion} \\
\frac{\partial}{\partial x} \left( H A_{\mu} \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left( H A_{\mu} \frac{\partial u}{\partial y} \right) \\
\text{Vegetative resistance} \\
-c_p D_p \left( u^2 + v^2 \right)^{\frac{3}{2}} u
\end{array} \]
EFDC Sediment Transport

- Simulates wind-induced currents and wave effects on lakebed shear stress either internally or through externally linked model
- Simulates multiple size classes of cohesive and non-cohesive sediment
- Sediment processes function library has a wide range of accepted parameterizations for settling, deposition, resuspension and bed load transport
- Sediment bed is represented by multiple layers
- Dynamic prediction of bed layer thickness, void ratio and pore water advection
- The sediment transport component can operate in a morphological mode with full coupling with the hydrodynamic component to represent dynamic evolution of bed topography
Cohesive Sediments

Source: Ji 2008
Cohesive Sediment Transport Processes

1) Suspension and Transport
2) Flocculation and Settling
3) Deposition
4) Bed Consolidation
5) Erosion and Resuspension
Sediment Transport

Source: Ji 2008
Flocculation and Settling

- Key parameter: settling velocity
- Six options that relate effective settling velocity to suspended sediment concentration and:
  1. Reference settling velocity, reference suspended sediment concentration, and empirical coefficient $\alpha$ (Ariathurai and Krone 1976)
  2. Empirical coefficients $a$, $b$, $m$, & $n$ (Hwang and Mehta 1989)
  3. Floc diameter, which is related to turbulent shear stress and empirical coefficients $\alpha_f$, $B_1$, & $B_2$ (Ziegler and Nisbet 1994, 1995)
  4. Vertical shear of the horizontal velocity (Shrestha and Orlob 1996)
  5. Flocculation (Lick et al. 1993)
  6. Flocculation with advection (Lick et al. 1993)
Deposition

Key parameter: critical shear stress for deposition, $\tau_{cd}$

\[
J_d = \begin{cases} 
-w_s S_d \left( \frac{\tau_{cd} - \tau_b}{\tau_{cd}} \right) & \tau_b \leq \tau_{cd} \\
0 & \tau_b \geq \tau_{cd}
\end{cases}
\]

$J_d$ – depositional flux
$w_s$ – settling velocity
$S_d$ – near bed sediment concentration
$\tau_b$ – bed shear stress
Wind Waves

- Simulates wind-induced currents and wave effects on lakebed shear stress either internally or through externally linked model (i.e. SWAN)

Source: Ji 2008
Surface Erosion and Resuspension

Key parameters: critical shear stress for erosion, $\tau_{ce}$ and surface erosion rate, $dm_e/dt$

Consolidated bed

$$J_r = \frac{dm_e}{dt} \left( \frac{\tau_b - \tau_{ce}}{\tau_{ce}} \right)^\alpha \tau_b \geq \tau_{ce}$$

or

Partially consolidated bed

$$J_r = \frac{dm_e}{dt} \exp \left( -\beta \left( \frac{\tau_b - \tau_{ce}}{\tau_{ce}} \right)^\gamma \right) \tau_b \geq \tau_{ce}$$

$J_r$ – surface erosion flux
$dm_e/dt$ – surface erosion rate per unit surface area of the bed
$\tau_b$ – bed shear stress
$\alpha, \beta, \gamma$ – site specific parameters
Surface Erosion and Resuspension

Critical shear stress for erosion, $\tau_{ce}$ and surface erosion rate, $dm_e/dt$ are dependent on:

1. Shear strength
2. Sediment physical properties, i.e. bulk density
3. Water content
4. Salt content
5. Ionic species
6. pH
7. Temperature

EFDC allows specification of constant value or dependent on bulk density, $\rho_b$
Mass Erosion and Resuspension

Key parameter: shear strength, \( \tau_s \)

\[
J_r = \begin{cases} 
0 & \tau_b < \tau_s \\
\frac{m_{me}}{T_{me}} & \tau_b \geq \tau_s 
\end{cases}
\]

- \( J_r \) – mass erosion flux
- \( m_{me} \) – surface erosion rate per unit surface area of the bed
- \( T_{me} \) - transfer time scale for the mass erosion
- \( \tau_b \) – bed shear stress

Estimation of shear strength: \( \tau_s = a_s \rho_b + b_s \)
Sediment Bed Consolidation

Four options for simulating consolidation of sediment bed:

1. Constant porosity bed
2. Simple consolidation rate model
3. Finite strain consolidation theory with specified void ratio at the water column-sediment bed interface
4. Finite strain consolidation theory with no excess pore pressure at the water column-sediment bed interface

Source: Ji 2008
EFDC Preliminary Model Build
Water Year 2006-2015
EFDC Input Requirements

1) Inflows
   - flow
   - water temperature
   - suspended sediment
   - salinity

2) Outflows – Jordan River

3) Meteorology
   - precipitation
   - evaporation
   - air temperature
   - relative humidity
   - solar radiation
   - wind

4) Lake bathymetry

5) Lake bottom surface roughness

6) Vegetative resistance
Utah Lake Preliminary Grid

- Cartesian grid
- 500 m cell size
  Recommended by Callister 2008
- 1,694 grid cells
- 5 vertical layers
  Variable depth (sigma stretched)
- 8,470 output cubes
Data Collection to Support Model Calibration
Calibration Approach

- **Constituents**
  - Water depth/water surface elevation
  - Water velocity
  - Wave height
  - Suspended solids
  - Water temperature
  - Salinity

- Collect approx. 6-9 months of observed data
- Estimate parameters using measured data
- Manually adjust calibration parameters
- Minimize error between predicted and observed data using graphical and statistical tests
Data Collection - Hydrodynamics

- **Water Surface Elevation**
  - CUWCD maintains stage gage at Utah Lake Pump House
  - Deploy pressure transducer on south end of lake?

- **Tributary Inflows**
  - Deploy pressure transducers at each major inflow (DWQ)
  - USGS maintains flow gages at Provo River, Hobble Creek

- **Outflow**
  - DWR publishes flow records at Jordan River Narrows

- **Weather Station**
  - Nearby stations: Provo Municipal Airport, BYU Provo
  - Deploy on-lake or near shore?

- **Evaporation**
  - DWR publishes evap records using Blaney-Criddle
  - Calculate using Penman-Monteith
Data Collection - Hydrodynamics

- **Acoustic Doppler Current Profiler (ADCP)**
  - Measure velocities throughout water column
  - Measure wave height
  - Measure bathymetry – boat mounted

- **Acoustic Doppler Velocimeter (ADV)**
  - Measure velocity at water column-sediment interface

- **Water quality sonde**
  - Temperature, conductivity, pH, DO, turbidity, chlorophyll a

- **Sediment trap**
  - Estimate sediment resuspension

- **Grab sampling**
  - Phosphorus, TSS, VSS

- **Deployment**
  - One month at six locations
Data Collection – Sediment

- Turbidity and TSS of water column
- Resuspension rate
  - Sediment trap
- Sediment characterization
  - Surficial sediment cores at each ADCP location
  - Measure properties
    - D50, particle size distribution
    - Bulk density
    - Water content
    - Mineralogy
    - Organic content
    - Sodium Adsorption Ratio (SAR)
    - Cation Exchange Capacity (CEC)
How EFDC Could be Used to Support Water Quality Study

- Provide critical hydrodynamic information to WASP nutrient model
- Improve understanding of sediment deposition and resuspension relationship to wind and waves
- Help support estimates of internal P loading
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