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WATER QUALITY

Utah Lake Model: Hydrodynamics and Sediment Transport

Utah Lake Water Quality Study
Science Panel Meeting 8/8/2018
Nicholas von Stackelberg

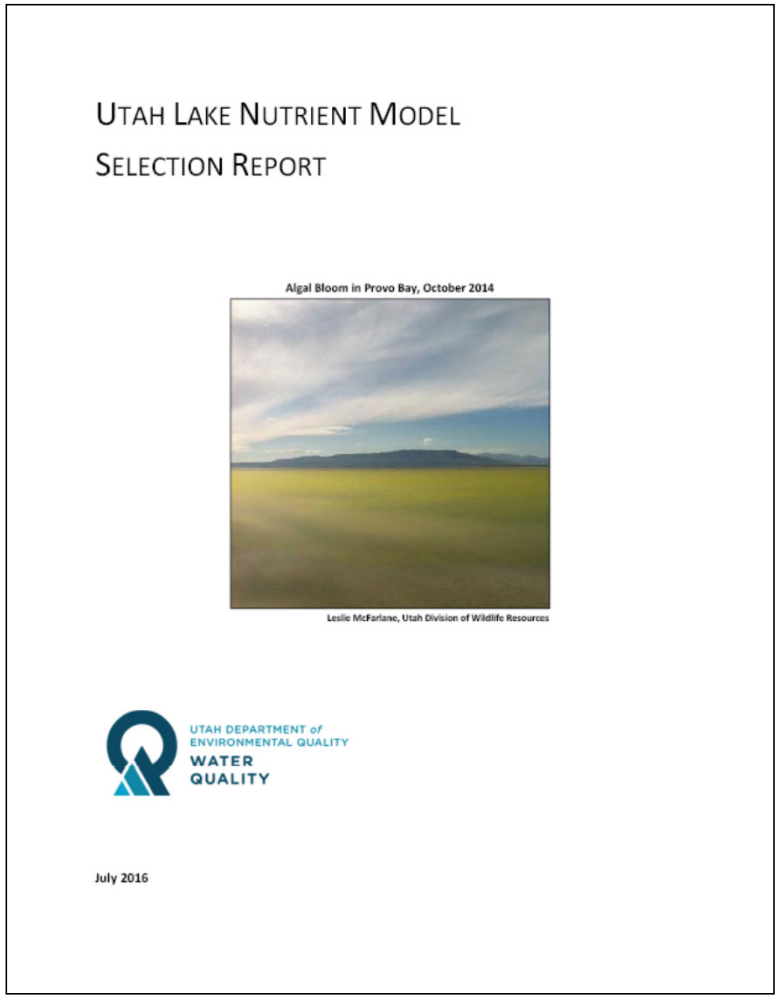
Presentation Outline

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


UTAH LAKE NUTRIENT MODEL
SELECTION REPORT

Algal Bloom in Provo Bay, October 2014

Leslie McFarlane, Utah Division of Wildlife Resources

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July 2016

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

$$H = h + \eta \qquad z^* = \frac{z}{H}$$

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

Accumulation Advection Coriolis

$$\frac{\partial Hu}{\partial t} + \frac{\partial Huu}{\partial x} + \frac{\partial Hvu}{\partial y} + \frac{\partial wu}{\partial z^*} - fHv =$$

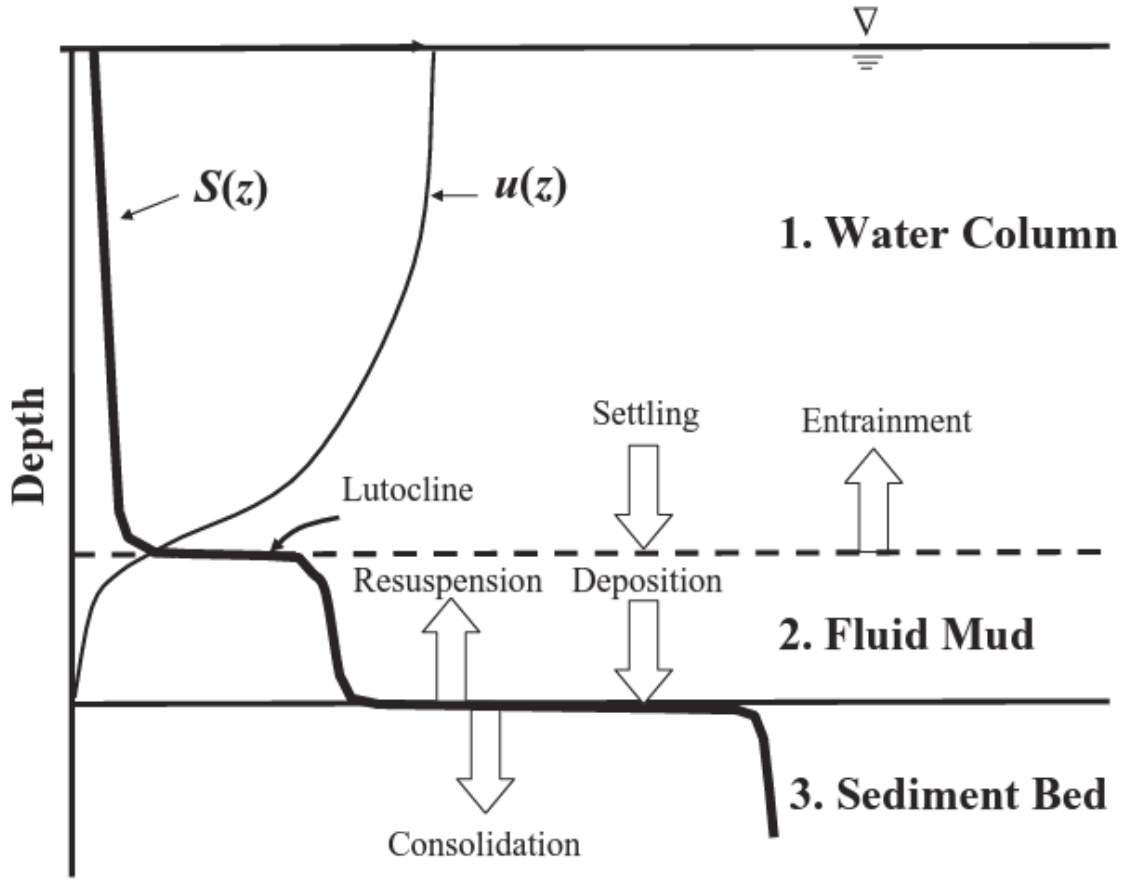
$$-H\frac{\partial p}{\partial x} + \left(\frac{\partial z_b^*}{\partial x} + z\frac{\partial H}{\partial x}\right)\frac{\partial p}{\partial z^*} + \frac{\partial}{\partial z^*}\left(\frac{A_V}{H}\frac{\partial u}{\partial z^*}\right) + \frac{\partial}{\partial x}\left(HA_H\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(HA_H\frac{\partial u}{\partial y}\right) - c_p D_p \left(u^2 + v^2\right)^{1/2} u$$

Pressure Buoyancy Vertical-momentum diffusion Horizontal-momentum diffusion Vegetative resistance

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

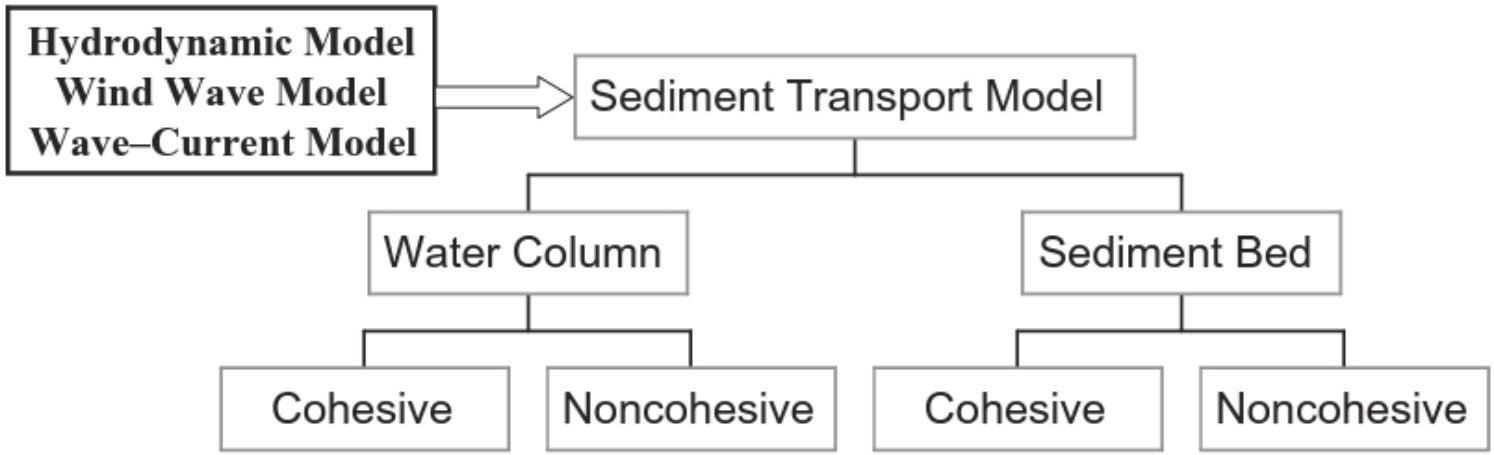


Source: Ji 2008

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 α (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 α_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)

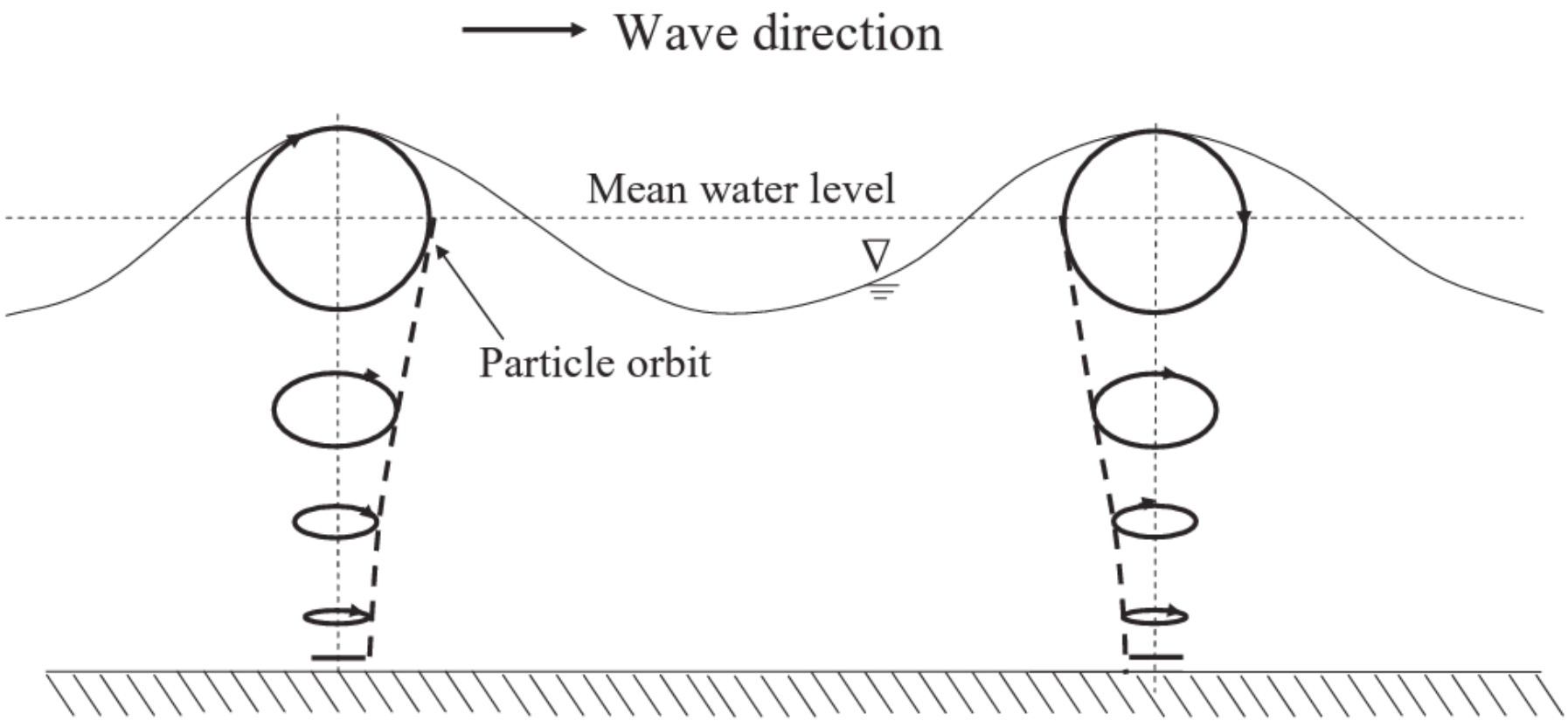
Deposition

Key parameter: critical shear stress for deposition, τ_{cd}

$$J_d = \begin{cases} -w_s S_d \left(\dfrac{\tau_{\mathrm{cd}} - \tau_b}{\tau_{\mathrm{cd}}} \right) & \tau_b \leq \tau_{\mathrm{cd}} \\ 0 & \tau_b \geq \tau_{\mathrm{cd}} \end{cases}$$

J_d – depositional flux
w_s – settling velocity
S_d – near bed sediment concentration
τ_b – bed shear stress

Wind Waves



Source: Ji 2008

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

Surface Erosion and Resuspension

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

Consolidated bed

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

or

Partially consolidated bed

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

J_r – surface erosion flux
dm_e/dt – surface erosion rate per unit surface area of the bed
τ_b – bed shear stress
α, β, γ – site specific parameters

Surface Erosion and Resuspension

Critical shear stress for erosion, τ_{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, ρ_b

Mass Erosion and Resuspension

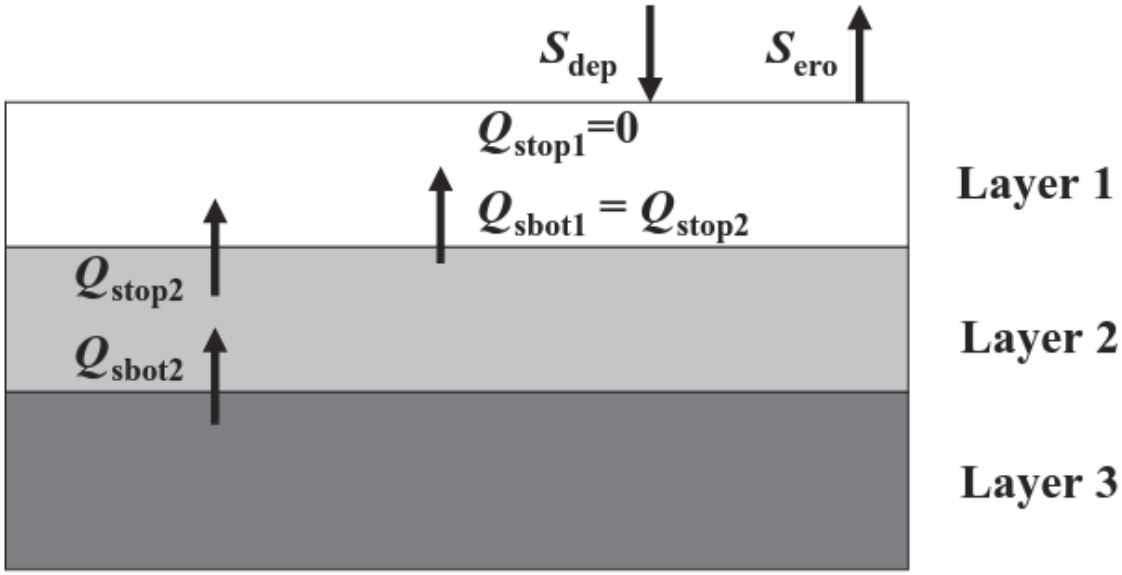
Key parameter: shear strength, τ_s

$$J_r = \begin{cases} 0 & \tau_b < \tau_s \\ \dfrac{m_{\mathrm{me}}}{T_{\mathrm{me}}} & \tau_b \geq \tau_s \end{cases}$$

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
τ_b – bed shear stress

Estimation of shear strength: $\tau_s = a_s \rho_b + b_s$

Sediment Bed Consolidation



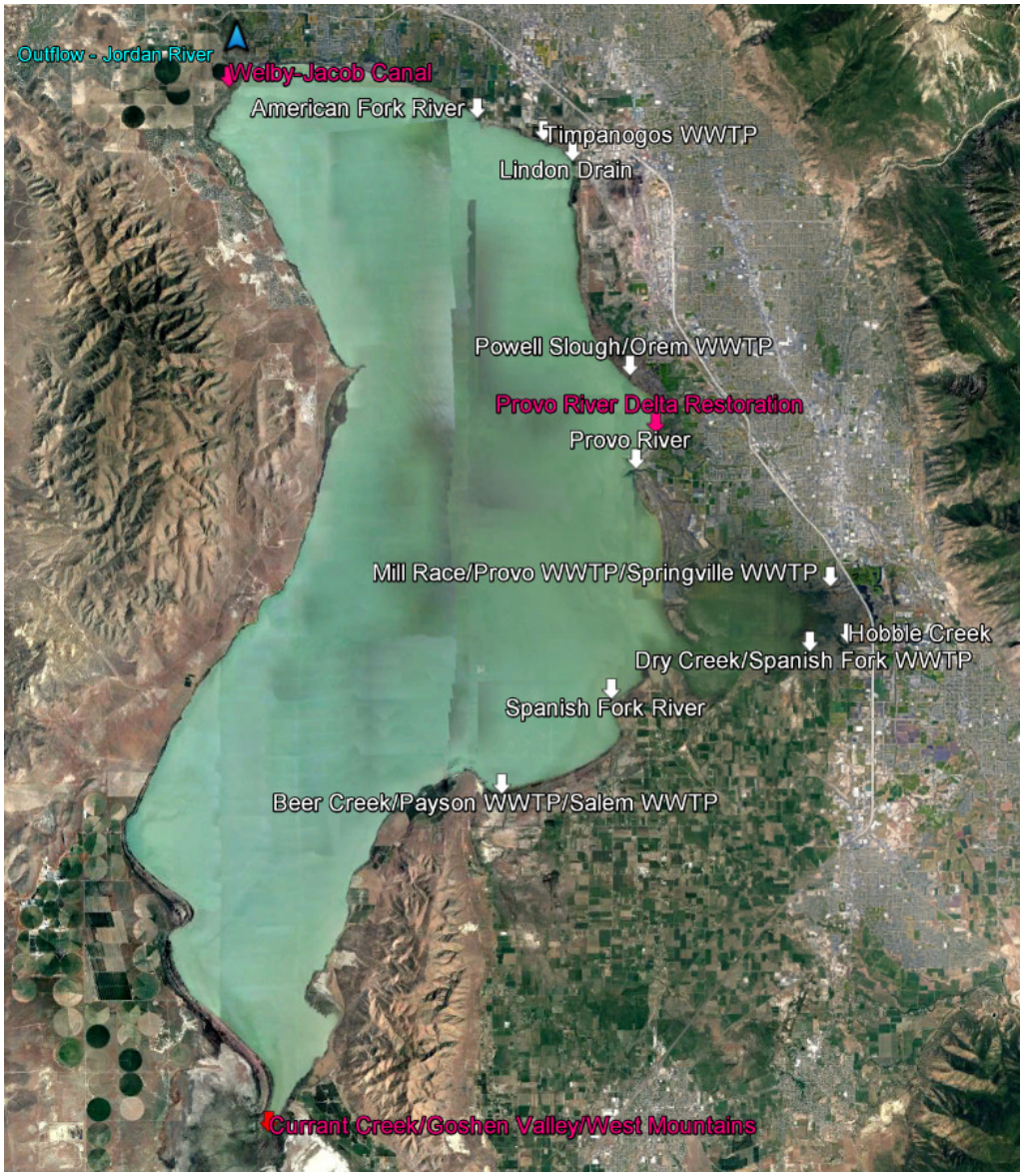
Source: Ji 2008

- 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

EFDC Preliminary Model Build
Water Year 2006-2015

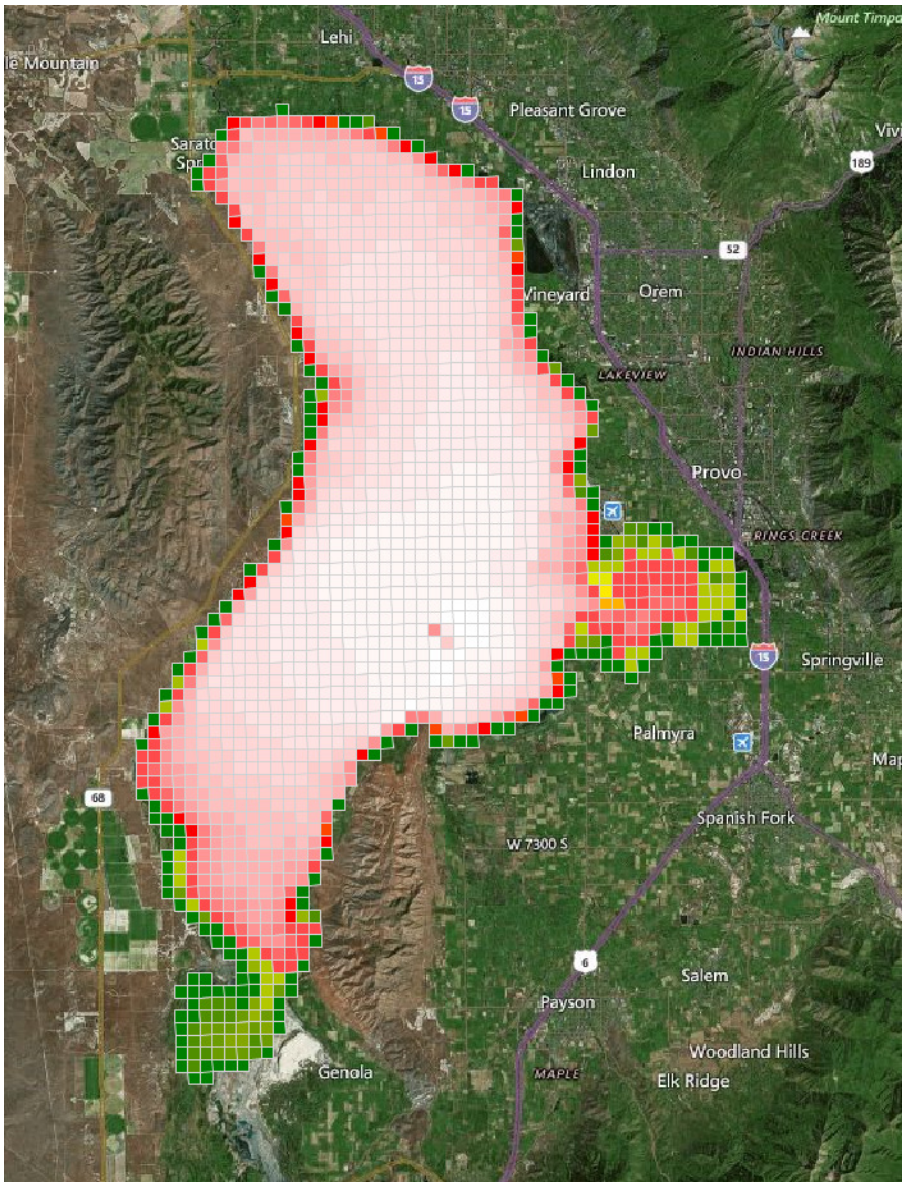
EFDC Input Requirements

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



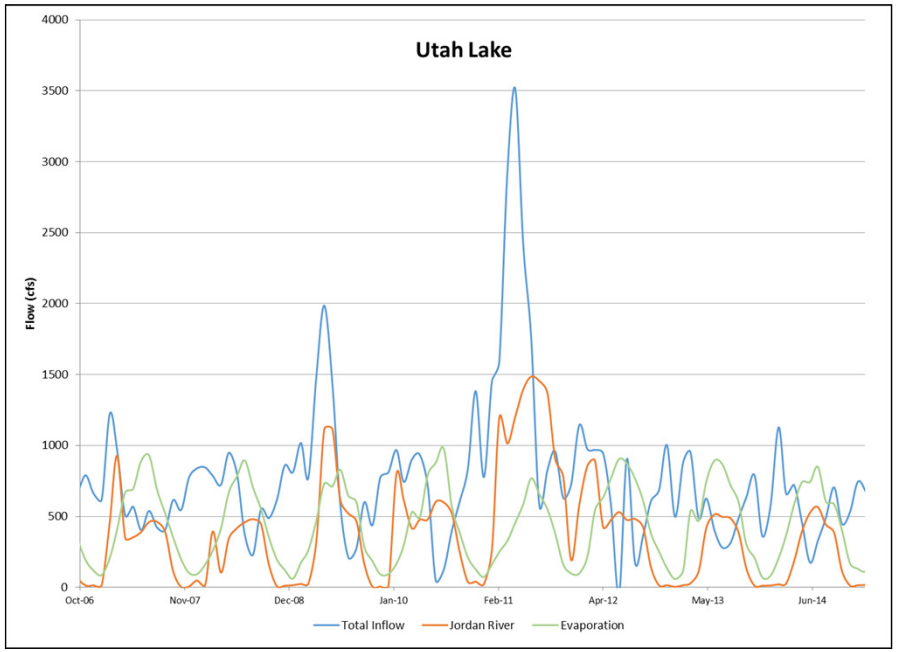
Data Collection to Support Model Calibration

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

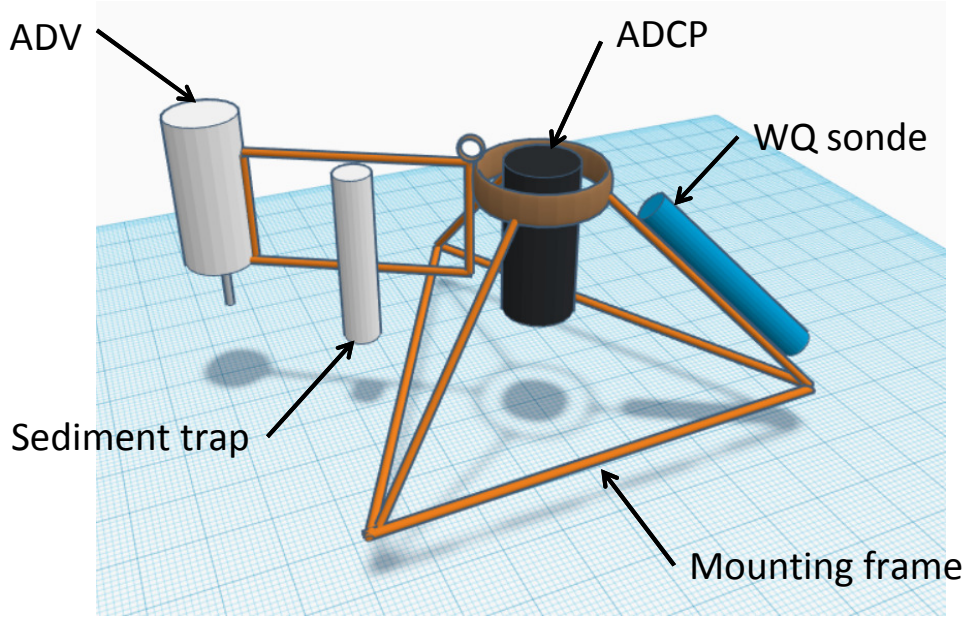
Data Collection - Hydrodynamics

- 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



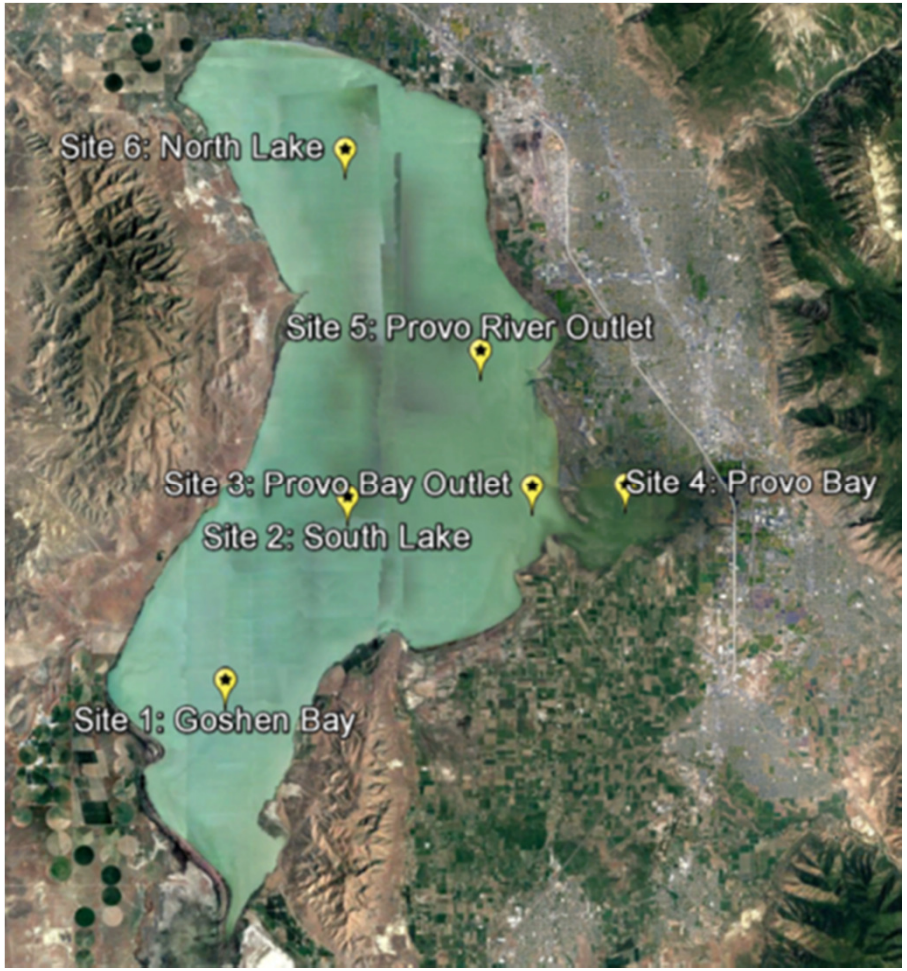
Data Collection - Hydrodynamics

- 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

Nicholas von Stackelberg, P.E.
Utah Dept of Environmental Quality
(801) 536-4374
nvonstackelberg@utah.gov

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