Predictive Methods, Tests, and Models for Environmental Dredging

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Purpose

- Familiarize with processes of
  - Sediment resuspension due to dredging
  - Contaminant release to water from sediment
  - Contaminant release to air from water and sediment
- Familiarize with physical tests
  - Dredging elutriate test
  - Sediment resuspension chamber (volatilization)
  - VOC Flux Chamber
  - Volatilization Field Test

Purpose

- Familiarize with applicable models
  - DREDGE
  - SSFATE
  - ICM/TOXI
  - EFDC
  - Gaussian Dispersion Air Quality Model

Presentation Outline

- TSS resuspension and transport
  - Resuspension source strength models
  - DREDGE model
  - Particle tracking models
- Contaminant loss to water column and transport
  - Equilibrium partitioning
  - Dredge Elutriate Test
  - Partitioning and transport models
- Volatilization testing and models

Resuspension Source Strength Models

- Limited models and tools available
- Predominantly for cutterhead and bucket dredges
- Empirical
  - applicable only to data like those model derived from
- Current efforts to improve
  - DOER (ERDC)
  - ACCORD international working group (ERDC, HR Wallingford, Dredging Research Limited, CSB)

TGU Method

Nakai, O. (1978). "Turbidity Generated by Dredging Projects," Management of Bottom Sediments Containing Toxic Substances: Proceedings of the Third U.S./Japan Experts Meeting, EPA-600/3-78-084, pp 31-47.

- Widely known and employed

TGU Method

- Multiple dredge types
  - Bucket dredge
  - Cutterhead dredge
  - Hopper dredge
- Questions have persisted for many years
  - Development
  - Applicability
  - Possible over prediction of loss rates

TGU Derivation

$$W(or\ TGU) = \left(\frac{R_{74}}{R_o}\right)\frac{W_o}{Q_s}$$

- W (or TGU) = turbidity generation unit (kg/m^3)
- Q_s = volume of dredged materials (m^3)
- R_{74} = fraction of particles with a diam. smaller than 74 μ
- R_o = fraction of particles with a diameter smaller than the diameter of a particle whose critical resuspension velocity equals the current velocity in the field
- W_o = total quantity of turbidity generated by dredging (kg)

TGU Derivation

- Downstream sampling procedure (30 and 50 m) to derive W_o for the different dredges

$$W_o = \sum AUS$$

- A = area of section concerned (m^2)
- U = tidal current velocity (cm/s)
- S = net concentration of SS measured in the field during dredging (mg/L)

TGU Application

$$W_o = TGU\left(\frac{R_o}{R_{74}}\right)Q_s$$

- Q_s is redefined as production rate (m^3/s) instead of production (m^3)
- W_o is redefined as kg/s
- TGU value selected from table based on dredge, grain size and sediment type
- Production and grain size info all that is necessary for loss rate calculation

Questions and Issues Regarding TGU Method

- Counterintuitive values for presented TGUs
- No mention of dredge operation associated with given TGUs
- No mention of overflow for mechanical dredges
- TGU must be properly selected for GSD and sediment type

Cutterhead Correlation Source Strength Model

- First put forth by Hayes and others in 1996 (published 2000)
- Dimensional Model (DM) and Non-dimensional Model (NDM) developed
- Developed empirically by data sets from:
  - James River
  - Savannah River
  - Acushnet River
  - Calumet Harbor
- Validated against Lavaca Bay data and refined (2001)

Cutterhead Correlation

$$DM: \quad \hat{g}(\%) = \frac{(C_S t_C)^{0.676} V_S^{\ 2.008}}{10^{3.647} L_S^{\ 13.899}} \left(\frac{A_E}{d_C}\right)^{14.575} \left(\frac{Q}{D^2}\right)^{0.805}$$

- $\hat{g}$ = predicted loss rate (%)
- C_S increases, g(%) increases
- t_C increases, g(%) increases
- V_S increases, g(%) increases
- Dredge size parameters interrelated:
- Dredge size increases, g(%) increases

Cutterhead Correlation

$$NDM: \quad \hat{g}(\%) = 10^{-3.3293} \left(\frac{A_E}{L_S d_C}\right)^{13.503} \left(\frac{Q}{D^2 V_S}\right)^{0.388}$$

- $\hat{g}$ = predicted loss rate (%)
- Dredge size increases, g(%) increases
- Different from DM:
- Intake Velocity (Q/D^2) increases, or V_s decreases, g(%) increases

Correlation Method Application Considerations (Hayes et al, 2000)

- The models are most applicable to scenarios similar to those used in their development
- The models should only be applied to dredges within the range of operating characteristics found in the four field sites
- When operated outside the range of operating characteristics from which models derived, very high (conservative) estimates can result

Open Bucket Dredge Correlation Method

- Developed by Collins (1995)
- Developed a model to estimate dredging-induced sediment resuspension rates at the point of dredging
- Rates *f*(dredge, operational characteristics, and sediment properties)

Open Bucket Dredge Correlation Method

- TSS concentrations at the point of dredging were not directly available
- Source concentrations calculated by:
  - plotting measured concentrations at various distances and depths
  - extrapolating to the concentration to dredging location

Bucket Dredge Correlation Development

- Mathematical model for the source concentration based on
  - settling velocity
  - bucket size
  - channel depth
  - cycle time
- A source volume was defined as the apparent bucket footprint multiplied by the channel depth
- Model assumes sediment contributed to control-volume during bucket ascent from the channel bottom towards the water surface

Modeled TSS Release

- When the bucket surfaces, the concentration throughout the cylinder is assumed to be uniform
- This concentration of sediments expelled at assumed linear rate during bucket descent
- When the bucket reaches the channel bottom, assumed that entire mass of suspended sediments in column emptied
- The contribution of sediments to the near-field volume from this source volume is averaged over the duration of the entire dredging cycle

Bucket Correlation Model

$$R = \frac{2(\rho \cdot 10^{-6}) h b^5 (1 + k_{cb})^2}{v_s^3 T^4 (f_u + 2 f_o + f_d)} \qquad b = (2V_b)^{\frac{1}{3}}$$

- R = the rate of sediment resuspension due to bucket dredging operations (g/m^3)
- ρ increases, R increases
- h increases, R increases
- b increases, R increases significantly
- V_b increases, R increases significantly
- k_{cb} = an empirical bucket constant (assumed 1)
- v_s increases, R decreases significantly

Bucket Correlation Model

$$R = \frac{2\left(\rho \cdot 10^{-6}\right) h b^{5} \left(1 + k_{cb}\right)^{2}}{v_s^{3} T^{4} \left(f_u + 2 f_o + f_d\right)} \qquad b = \left(2V_b\right)^{\frac{1}{3}}$$

- *T* increases, R decreases significantly
- f_u is the fraction of the dredging cycle that the bucket is rising through the water column
- f_o is the fraction of the dredging cycle that the bucket is out of the water
- f_d is the fraction of the dredging cycle that the bucket is descending through the water column

Collins' Conclusions

- A reasonable correlation between the field-observed source concentrations and the modeled concentrations was reached
- Nevertheless, Collins also concluded that the sediment generation model should be considered "unverified and rudimentary"
- Suggested that further studies and more complex modeling of the mixing around the bucket be undertaken to verify this model

Other Comments on Bucket Correlation Method

- Hayes et al. (2000) observed that large amounts of solids are spilled as the bucket swings to the scow, for any bucket type

Resuspension Factor Approach (Hayes 2005 Unpublished)

- Derives a "Characteristic Resuspension Factor" and "Characteristic Dredging Operation" for open and enclosed clamshell and cutterhead dredges
- Adjustments to characteristic factor made based on changes in:
  - Dredge type and size
  - Sediment characteristics
  - Controllable aspects of dredge operation
  - Local environmental conditions

Resuspension Factor Equation

$$g = R\left(\frac{f_T}{100}\right)\left(\frac{\dot{V}_S C_s}{360}\right)$$

- g = mass rate of sediment release (g/sec)
- R = resuspension factor or sediment mass loss rate (%)
- f_T = percent of particles smaller than the largest size subject to far-field transport (%)
- $\dot{V}_S$ = volumetric rate of *in situ* sediment removal (m^3/hr)
- C_s = *in situ* solids concentration (kg/m^3)

Open Clamshell Buckets

- Characteristic resuspension factor (*r*) of 0.5%
  - Selected for the characteristic bucket dredge operation and site conditions
  - Value is based upon available data from bucket dredging operations summarized by Hayes and Wu (2001)

Other Characteristic Resuspension Rates

- Cutterhead Dredges
  - Characteristic resuspension factor (r) is 0.1% production
- Enclosed Clamshell Buckets
  - characteristic resuspension factor (r) of 0.3% production

Adjusting the Characteristic Resuspension Factor

$$R = Fr \quad and \quad F = f_1 f_2 \ldots f_n$$

- where f_1, f_2, … f_n = dimensionless adjustment factors for site specific conditions
- F = product of all adjustment factors
- r = characteristic resuspension factor (%)

Characteristic Resuspension Rate Adjustments for Open Bucket Dredge

- f_{area} for changes in bucket size
- $f_{erosion}$ for erosion induced by increased lift speed
- f_{sed} for differences in water content and Atterberg limits of sediment
- f_{debris} for increased resuspension due to bucket loads lost because of debris

Adjusting for Open Bucket Erosive Surface Area (f_{area})

$$f_{area} = \frac{3.08}{d_{eq}} = \frac{1.97}{V_{bucket}^{0.33}} \qquad V_{bucket} = \frac{\pi d_{eq}^3}{12}$$

- Surface area increases by d^2, volume increases by d^3
- Production outpaces SA increase, f decreases

Characteristic Resuspension Rate Adjustments for Enclosed Bucket Dredge

- $f_{descent}$ for erosion of bed sediments due to excessive bucket-induced water velocities
- f_{sed} for differences in Atterberg limits of sediment
- f_{debris} for increased resuspension due to bucket loads lost because of debris

Adjusting For Bed Erosion Due To Excessive Bucket-Induced Water Velocities ($f_{descent}$)

$$f_{descent} = 0.5 + 0.5\left(\frac{u_{descend} + u_{current}}{\hat{u}_{descend}}\right)^3$$

- $f_{descent}$ = resuspension factor adjustment for surface sediment erosion while being lowered to the bottom (fraction)
- $u_{descend}$ = vertical bucket velocity (m/s)
- $\hat{u}_{descend}$ = characteristic vertical bucket velocity during descent (m/s)

Characteristic Resuspension Rate Adjustments for Cutterhead Dredge

- $f_{\text{low P}}$ for decreased intake of loosened sediment by suction
- $f_{\text{high P}}$ for attacking sediment too rapidly for it to be sucked away
- $f_{\text{ex-cut}}$ cutting deeper than diameter of cutter (loosening sediment excessively far from suction intake)
- f_{bank} for cutting against a bank (increasing with increasing bank slope)
- f_{sed} for differences in Atterberg limits of sediment

Adjusting For Low Cutterhead Dredge Production ($f_{\text{low P}}$)

$$f_{lowP} = \frac{P_{characteristic}}{0.2 V_{swing} T_c L_c} \quad OR \quad f_{lowP} = \frac{P_{characteristic}}{P_{actual}}$$

- $f_{\text{low P}}$ = characteristic resuspension factor adjustment for low production (fraction)
- V_{swing} = swing velocity of the cutterhead (m/s)
- T_c = thickness of dredge cut (m)
- L_c = length of cutter (m)
- $P_{characteristic}$ = characteristic production for dredge, pump size (m^3/hr)

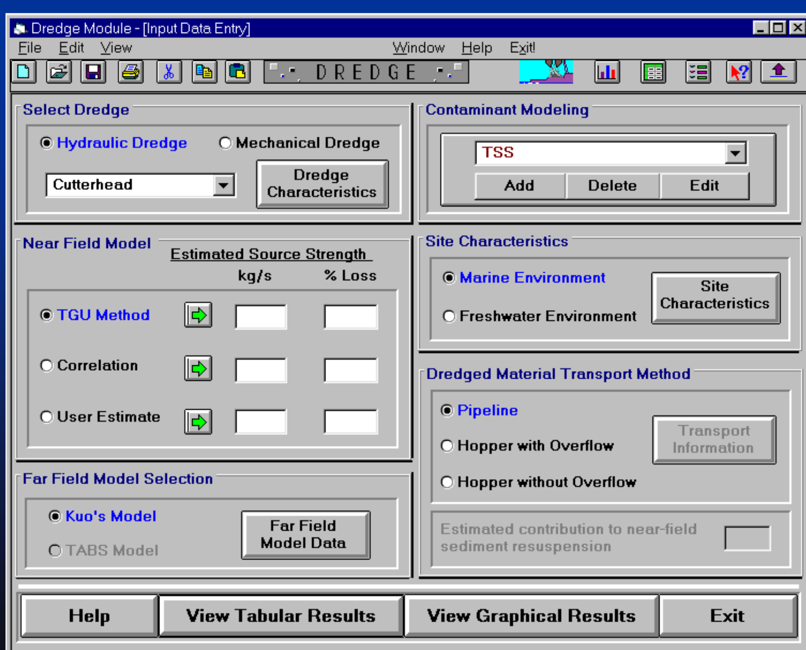
Resuspension Factor Approach

- Provides mechanistic framework for adjusting loss rates
- Of particular interest to environmental dredging
  - Dredge activities often different from data used to derive empirical models
- Currently in ERDC Review
- Expected publication end FY05

The DREDGE Model

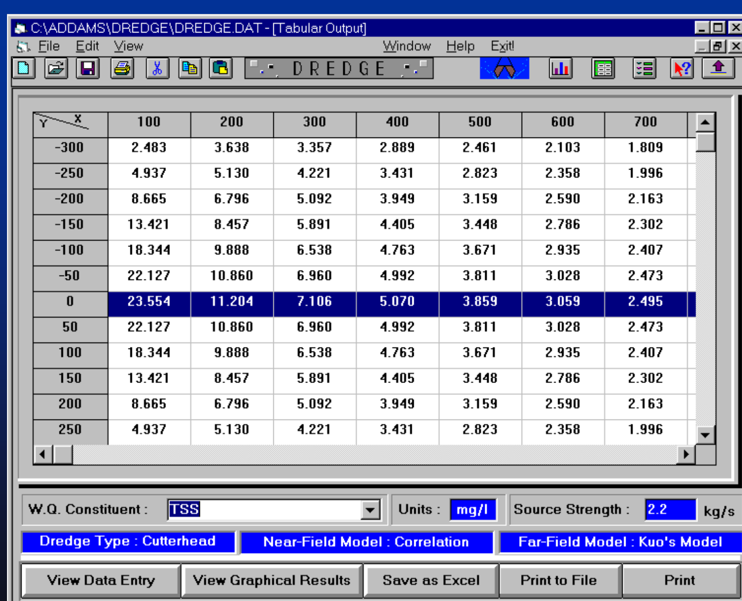
DREDGE Source Models

- Currently works for:
  - Open clamshell dredge (vertical line source)
  - Cutterhead dredge (bottom source)
  - Hopper dredge (not applicable to env.dredging)
- Cutterhead source models incorporated
  - Hayes et al. Correlation
  - Nakai
- Open clamshell source models incorporated
  - Collins Correlation
  - Nakai
- User defined source estimates available for both dredge types

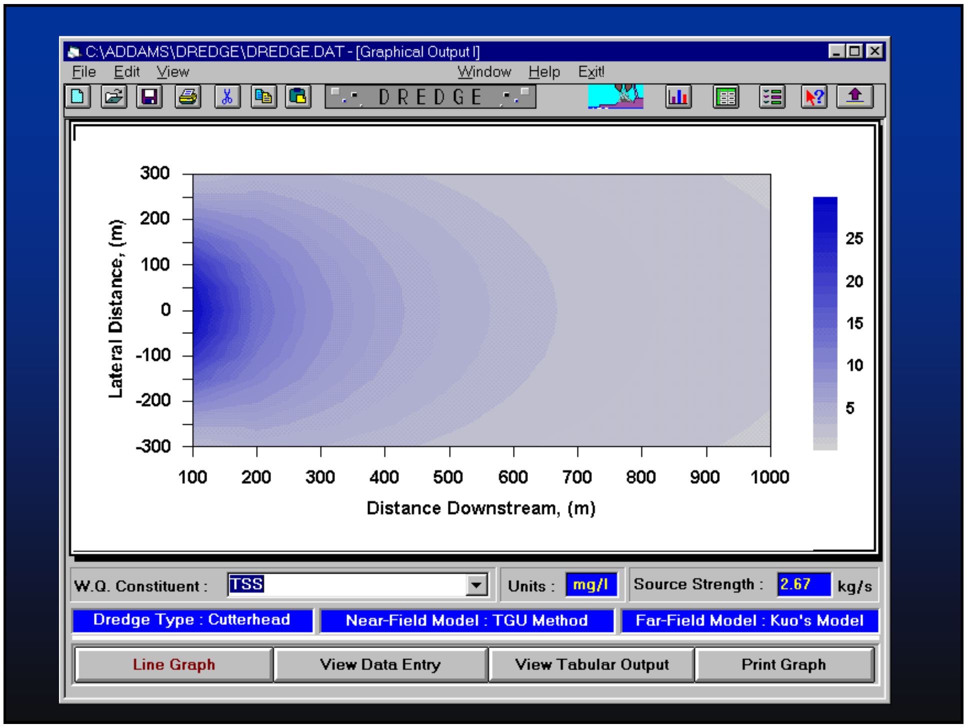


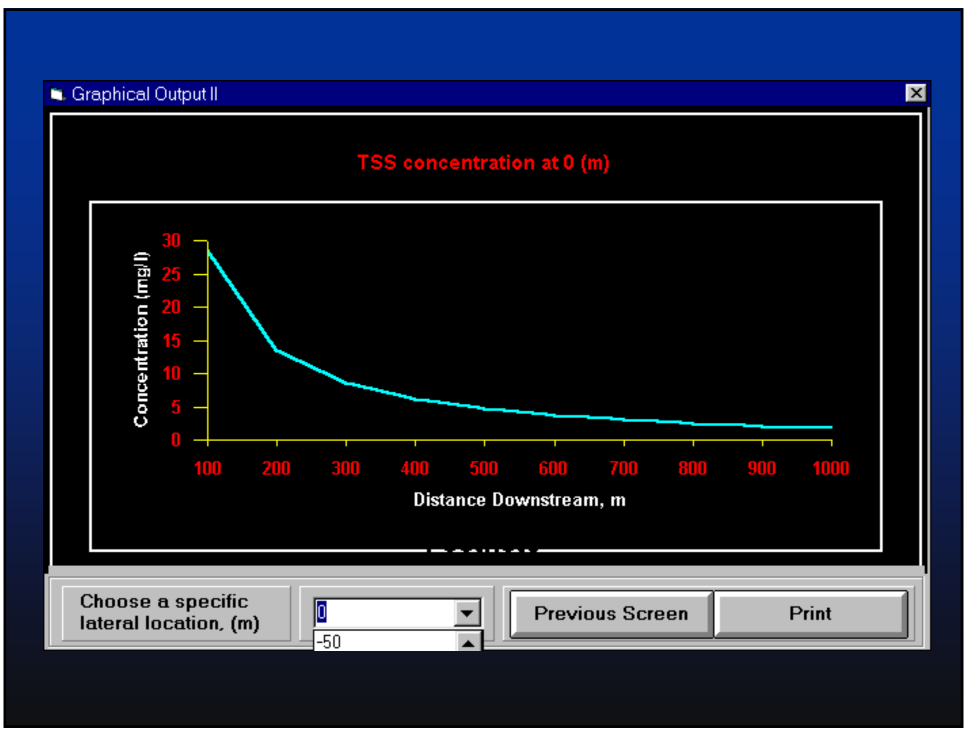
DREDGE Model

- Analytical transport solution after Kuo et al (1985) and Kuo and Hayes (1991)
- Transport solution:
  - Steady-state
  - Uniform depth and flow field (average velocity used at all locations)
  - Unbounded solution (no reflection due to shorelines), valid in intermediate field
  - Stokes' Law Settling
- Tabular and graphical output available



Y \ X	100	200	300	400	500	600	700
-300	2.483	3.638	3.357	2.889	2.461	2.103	1.809
-250	4.937	5.130	4.221	3.431	2.823	2.358	1.996
-200	8.665	6.796	5.092	3.949	3.159	2.590	2.163
-150	13.421	8.457	5.891	4.405	3.448	2.786	2.302
-100	18.344	9.888	6.538	4.763	3.671	2.935	2.407
-50	22.127	10.860	6.960	4.992	3.811	3.028	2.473
0	23.554	11.204	7.106	5.070	3.859	3.059	2.495
50	22.127	10.860	6.960	4.992	3.811	3.028	2.473
100	18.344	9.888	6.538	4.763	3.671	2.935	2.407
150	13.421	8.457	5.891	4.405	3.448	2.786	2.302
200	8.665	6.796	5.092	3.949	3.159	2.590	2.163
250	4.937	5.130	4.221	3.431	2.823	2.358	1.996


C:\ADDAMS\DREDGE\DREDGE.DAT - [Graphical Output I]
File Edit View Window Help Exit!
DREDGE
300
200
100
0
-100
-200
-300
Lateral Distance, (m)
100 200 300 400 500 600 700 800 900 1000
Distance Downstream, (m)
25
20
15
10
5
W.Q. Constituent : TSS
Units : mg/l
Source Strength : 2.67 kg/s
Dredge Type : Cutterhead
Near-Field Model : TGU Method
Far-Field Model : Kuo's Model
Line Graph
View Data Entry
View Tabular Output
Print Graph


Graphical Output II
TSS concentration at 0 (m)
Concentration (mg/l)
30
25
20
15
10
5
0
100 200 300 400 500 600 700 800 900 1000
Distance Downstream, m
Choose a specific lateral location, (m)
0
-50
Previous Screen
Print

Particle Tracking Models

- Particle tracking models:
  - 3D, dynamic transport
  - Virtual particles (≈1/1000000 the number of actual) are assigned the same mass as actual particles
  - Accept external hydrodynamic time series data
  - Accept external source term (e.g. a loss rate calculated in DREDGE)
- Concentrations and deposition post-processed based on particle fate

Particle Tracking Models

- SSFATE (ASA and ERDC)
  - Integrated GIS interface
    - Geographical location of any size and resolution
  - Calculates deposition
  - Does not handle re-entrainment of settled particles
- PTM (ERDC)
  - Capabilities of SSFate
    - GIS capabilities through Surface Water Modeling System (SMS)
    - Readily interfaces with other Corps models through SMS
  - Ability to compute deposition and re-entrainment

Contaminant Loss to Water Column and Transport

Contaminant Release and Transport

- Laboratory tests
  - Dredge elutriate test
- Screening level predictions
  - DREDGE model
- In depth predictions
  - ICM/TOXI
  - EFDC
  - others…

Equilibrium Partitioning

- A consistent relationship between particulate and dissolved phase contaminant exists under equilibrium conditions
- K_d (L/kg) is the linear equilibrium partitioning coefficient:

$$K_d = \frac{Contaminant\ concentration\ on\ sediment\ (mg/kg)}{Contaminant\ concentration\ in\ water\ (mg/l)}$$

K_d For Organics

- The Partitioning coefficient for hydrophobic organic contaminants is computed via (Karichhoff et al. 1979)

$$K_d = 0.617 f_{oc} K_{ow}$$

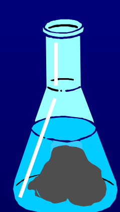
- f_{oc} = the weight fraction of organic carbon in the solid matter, g-orgC/g
- K_{ow} = octanol-water partition coefficient, (mg/m^3-octanol)/(mg/m^3-water)

Dredge Elutriate Test (or DRET)

- Gives partitioning information for contaminated sediment and site water
- Partitioning info. inputted into tools to predict contaminant release based on TSS concentrations
- Elutriate results often used as conservative estimate of contaminant release at point of dredging

DRET elutriate

10 g/l sediment



→ Mix Thoroughly 1 hour

↓

Settle for 1 hour

↓

Centrifuge Supernatant *
(2,000 x g for 30 min)

↓

Chemical Analysis of Dissolved Components of Elutriate

* Filtration can be used in place of centrifugation

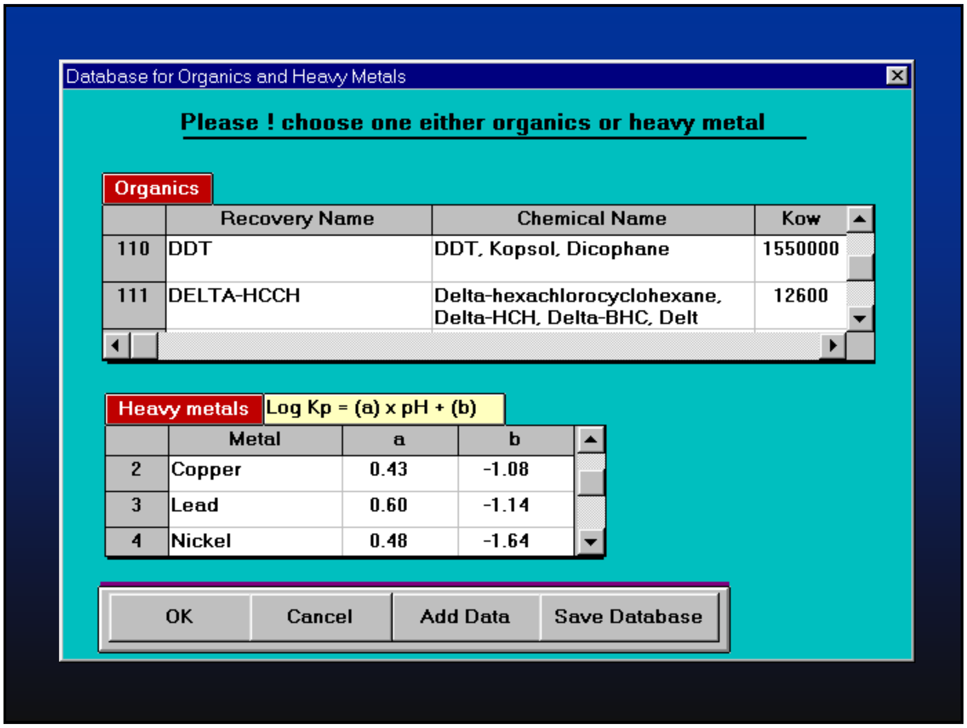
DREDGE Model

- Tabular and graphical output available, as shown for TSS
- Literature values for partitioning available,
- Empirical equations for K_d for metals available
- User defined parameters from site testing (e.g. Dredge Elutriate Test) can be substituted

DREDGE MODEL Contaminant Loss

$$C_{ss} = \frac{10^3 K_d q_i (TSS_{wc})^2}{1 + K_d TSS_{wc}} \qquad C_{diss} = \frac{10^3 q_i TSS_{wc}}{1 + K_d TSS_{wc}}$$

- C_{ss} = contam. concentration on sediment (µg/L)
- C_{diss} = water dissolved contam. concentration (µg/L)
- K_d = contam. linear partitioning coefficient (L/kg)
- q_i = sediment contam. concentration (µg/g)
- TSS_{wc} = TSS concentration (kg/L)

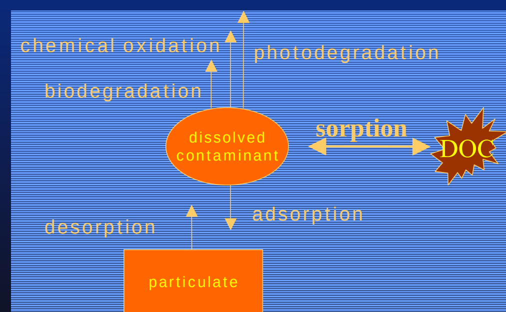


CE-QUAL-ICM/TOXI

- Based on the 3D eutrophication model, CE-QUAL-ICM for contaminant F/T
  - ICM numerical framework and transport
  - WASP5 chemical routines
- Contains robust benthic submodel
- Provide dynamic solids transport/mass balance in bed and water column (computed internally or externally [SED2D])

CE-QUAL-ICM/TOXI

- Fully 3D, time-variable; link to hydrodynamics
- Physical processes:
  - Sorption to DOC and 3 solid classes
  - Volatilization
  - Sedimentation
- Chemical processes:
  - Ionization
  - Hydrolysis
  - Photolysis
  - Oxidation
- Biodegradation



ICM/TOXI, continued

- State variables:
  - Temperature
  - Salinity
  - 3 solids classes (sand, silt, and clay)
  - 3 contaminants (organics and trace metals)
- Total chemical distribution:
  - Each contaminant can exist in 5 phases:
  - Dissolved (water)
  - DOC
  - 3 solids via local equilibrium partitioning

Benthic Submodel

- Solids and chemical mass balance in multiple layers (vertical transport only)
  - Fixed number of layers (Eulerian)
  - Variable number of layers (Lagrangian)
- Dynamic linkage with water column via deposition, resuspension, and diffusion
- Layer physical processes: accretion, resuspension, burial, pore water diffusion, compaction with pore water extrusion, and groundwater flow
- Chemical partitioning and kinetic processes

Benthic Submodel, continued

- Porosity and bulk density can vary from layer-to-layer and over time
- Dry sediment density is constant for each solid class. Particulate chemical migrates with solids
- Pore water chemical is transported vertically via diffusion, upward extrusion during compaction, and groundwater flow
- Crank-Nicholson FDM used for pore water transport

Environmental Fluid Dynamics Computer Code (EFDC)

- EFDC has fully integrated simulation capabilities for:
  - Hydrodynamic transport (including temperature and salinity transport)
  - Water quality
  - Sediment contaminant loss
- EFDC can simulate water and water quality constituent transport in geometrically and dynamically complex water bodies of all sorts
  - Rivers
  - Vertically mixed shallow estuaries
  - Lakes
  - Coastal areas

EFDC

- Multiple size classes of cohesive and noncohesive sediments and associated deposition and resuspension processes and bed geomechanics are simulated
- EFDC model also allows for drying and wetting in shallow areas by a mass conservative scheme
- For the simulation of flow in vegetated environments, the EFDC model incorporates both two and three-dimensional vegetation resistance formulations
- The model provides output formatted to yield transport fields for water quality models, including WASP5 and CE-QUAL-ICM

EFDC References

- http://www.epa.gov/athens/research/modeling/efdc.html
- http://www.epa.gov/athens/wwqtsc/html/efdc.html

Volatilization Tests

Volatilization Considerations

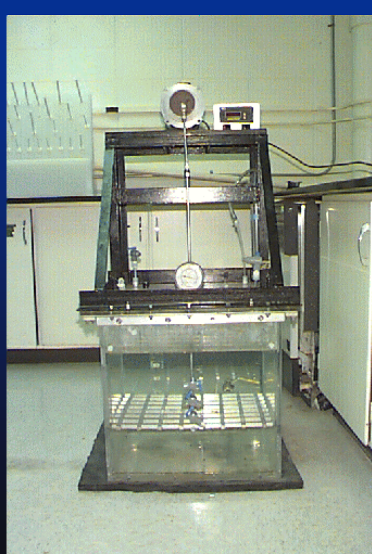
- Sediment physical characteristics
  - Moisture content, porosity, aging, oil and grease concentration
- Contaminant chemical properties
  - Henry's Law Constant, vapor pressure, sediment contaminant concentrations
- Environmental Variables
  - Relative air humidity, temperature
  - Mechanical movement (mixing) of the sediment

Evaluation of Volatile Losses

- Laboratory procedures to quantify volatile losses in the field
- Predictive models to describe the loss of volatile organic compounds from DM disposal sites, etc. can compute transport and dosage

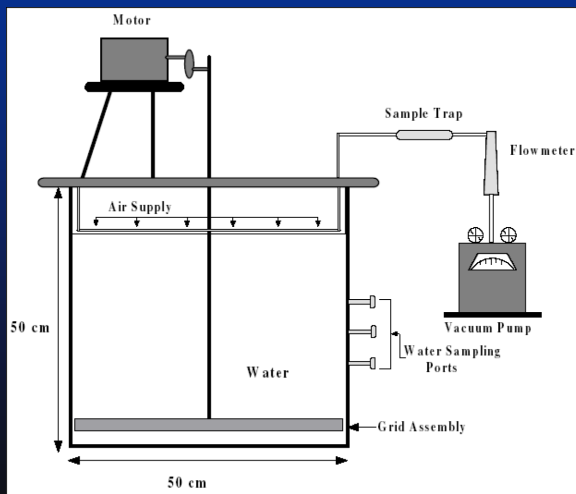
Volatile Losses From Suspended Sediment

Sediment Resuspension Chamber



Provide information on the emission of VOCs from contaminated sediments when they are resuspended in the water column

Sediment Resuspension Chamber



Sediment Resuspension Chamber Procedure

- Use oscillating grid at necessary frequency to maintain sediment resuspension
- Mix sediment concentration to be representative of desired volatilization case
  - TSS plume from dredging
  - Concentrated TSS plume due to silt curtains
  - Initial concentration for hydraulic placement in CDFs

Sediment Resuspension Chamber Procedure

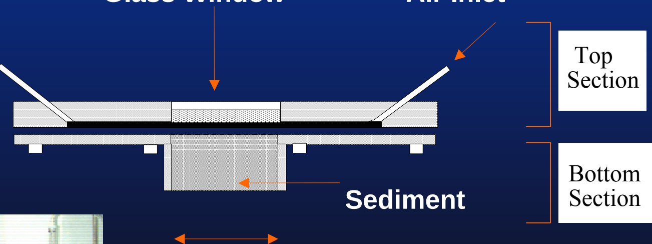
- Attach a contaminant-specific air sampling trap that contains 2 grams of XAD-2 resin (Supelco, Inc.) to the chamber exit port
- Pull air through the trap for a 2-hr period while oscillation is maintained
  - Simulates worst case, volatilization during dredging operation or CDF placement

Sediment Resuspension Chamber Procedure

- Discontinue oscillation, sample air as one continuous run with samples at 2, 6, 24, 48, 72 and 144 hr
  - These samples simulate contaminant emissions after dredging is stopped and suspended solids begin to settle
- Remove traps at the end of each sampling interval and solvent was extracted and analyzed according to EPA method 8270 (1982)

Volatile Losses From Sediment Exposed to Air

Flux Chamber for Sediment Exposed to Air



VOC Flux Chamber

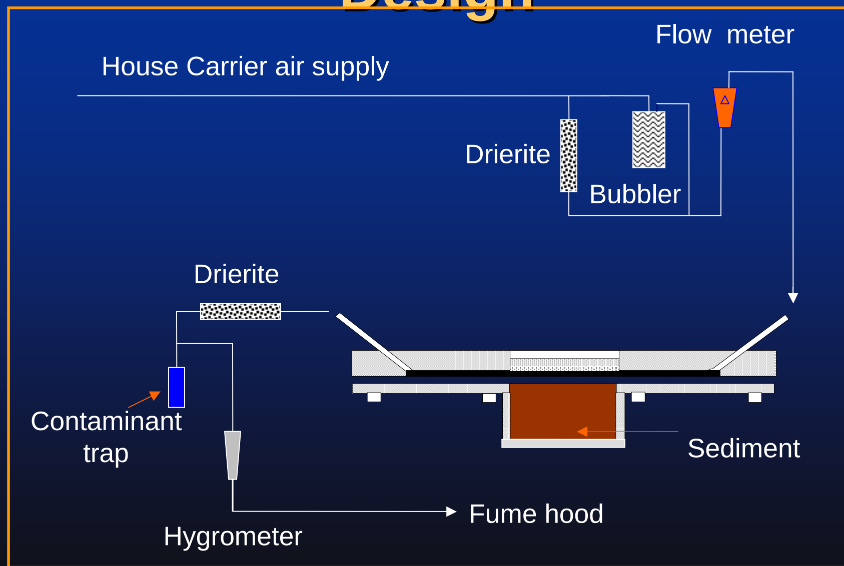
- Two-piece construction of anodized aluminum
- Bottom section
  - Sediment chamber-25 cm x 15 cm x 10 cm deep
- Top portion
  - Designed with channels to distribute airflow uniformly across sediment surface
  - Fitted with glass window to allow visual monitoring of sediment surface
- Chamber is sealed with an O-ring and threaded fasteners to produce an airtight fit

Components

- Air Supply – laboratory "house" air or compressed gas cylinder; vacuum pump
- Sampling Traps - contaminant-specific air sampling tubes (Supelco, Inc.)
- Flow Meter (able to handle flows > 1 L/min
- Tygon tubing
- *Humidity Meter (for in-line monitoring)
- *Water Bubbler (air humidity adjustment)

  * optional (dependent upon sampling conditions)

Laboratory Experimental Design



Test Protocol (Laboratory)

- Carrier air – “house” air; compressed gas of sufficient purity, or vacuum pump
- Flow rate - 1.7 L/min
- Trapping material - dependent upon contaminants of interest
- Humidity - controlled via water bubbler
- Sampling regime - dependent upon: contaminant concentrations, trapping material and retention capacity, experimental conditions (i.e., soil moisture)

Example Sampling Protocol for Dewatering

- Sampling times / intervals:
  - 6, 24, 48, 72 hours, 5, 7, 10, and 14 days
    - Sample continuously (replace trap at each sample interval making sample intervals anywhere from 6 to 96 hours each)
    - Sampling length dependent on contaminant concentrations and analytical detection limits
- Experimental conditions:
  - Initiate experiment with field moist sediment and apply dry air over sediment surface (14-day experiment)
  - Apply humid air over sediment surface for 7 days
  - Rework sediment and repeat with dry air

Volatile Losses Sediment Exposed to Air (Field Tests)

Field Test Protocol

- Field apparatus - constructed of top portion identical to that of laboratory chamber; bottom portion has central opening for sediment surface and is surrounded by 2-inch-long side plates to seal the apparatus from the surrounding air
- Carrier air - “outside” air is pulled through a trap (to assure uncontaminated air) across sediment surface with battery-operated vacuum pump
- All other materials and sampling procedures identical to those in the laboratory

Field Apparatus

Field Measurements

Flux Calculations (Applicable to all 3 Tests)

- Contaminant flux is calculated by determining the total mass of material captured in a given time interval using the equation:

$$N_A(t) = \frac{\Delta m}{\Delta t A_c}$$

Δm = mass (ng) of compound collected on the trap in time Δt (hr)

A_c = area of the sediment-air interface (cm^2)

$N_A(t)$ is expressed in $ng/cm^2/hr$

Example of Available Models for Prediction of Volatile Emissions

Model Simulation of Phenanthrene Flux from Indiana Harbor Sediment

Flux1 Model flux with no surface mass transfer resistance

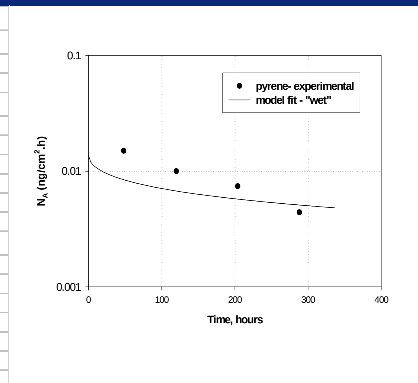
Flux2 Model flux with surface mass transfer resistance

Flux 1 - Model

$$Flux(t) = C_0 \cdot \sqrt{\frac{D_{eff} \cdot R_f}{\pi \cdot t}}$$

Flux 2 - Model

$$Flux(t) = k_a \cdot C_0 \cdot \exp(\frac{k_a^2 t}{D_{eff} R_f}) \cdot erfc(k_a \sqrt{\frac{t}{D_{eff} R_f}})$$



Gaussian Dispersion Air Quality Model

- Steady-state, area source, Gaussian models for simple terrains
- SCREEN3
- ISC3 (Industrial Source Complex Model)
- Other complex models available for Tier IV
- http://www.epa.gov/scram001/tt22.htm#isc

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Questions?