Biological Effects and Restoration for Submerged Oil Spills

Modeling and Analytical Approaches

Deborah French McCay, PhD

Applied Science Associates, Inc.

Biological Effects

Submerged Oil Pathways

- If denser than water -- sink
  - API<10 in freshwater
  - API<6.5 in full seawater
- Otherwise:
  - Combine with suspended sediments (such as in storms, or in near shore where wave action) and combined particles are denser than water so sink
  - Strand on shore, mix with sediment, remobilized off shoreline, settling in near shore subtidal
- Resuspension and transport, resettling (dynamic process, remobilized when currents/turbulence high)

Fates Modeling – Submerged Oil

- Floating or sinking (as in SIMAP)
  - Stokes Law: sinking rate = f (Δ density, particle size, turbulence)
  - Density of combined particles
    - Neat oil sinks, if density oil > density water
    - Amount of adhered sediment changes density
    - Oil-suspended sediment adherence model (Kirstein, Payne et al. 1987)
  - Turbulence – related to current shear or user input

- Transport – need accurate 3d hydrodynamic model

- Remobilization – need sediment transport model
  - Resuspension
  - Adherence of sediments
  - Boundary layer turbulence

Potential Effects of Oil: Whole oil

- Smothering / Coating
  - Mechanical (smothering, prevention of uptake and depuration, interference with motility, etc.)
  - Thermal regulation (birds, mammals)
  - Absorption of toxic compounds (via skin or gut)
- Mechanical interference
  - Clogging of feeding appendages and gills
  - Impeding movements
- Behavioral interference
  - Avoidance (leave area or shut down)
  - Attraction (more exposure)

Potential Effects of Oil: Toxicity

Pathways involving uptake of hydrocarbons into tissues (membrane processes) → toxicity

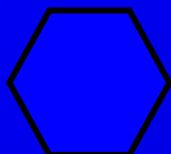
- Via gill and body surfaces (absorption)
- In gut (assimilation)

- From dissolved phase
- Dissolved originating from droplets adhering to external or internal surfaces

Toxic Components of Oil

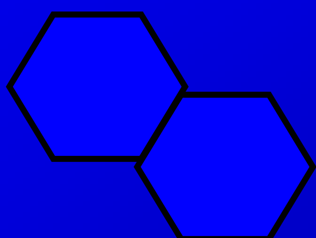
C-C-C-C-C-C

Aliphatics = Straight chain hydrocarbons (e.g., alkanes) –more volatile than soluble



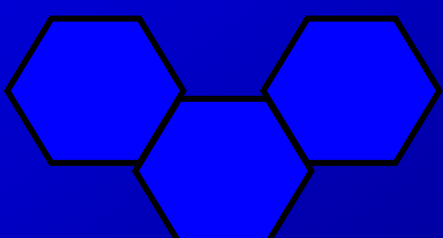
Monoaromatic Hydrocarbons (MAHs)

- Benzene, Toluene, Ethylbenzene and Xylenes = BTEX – highly soluble, highly volatile, moderately toxic
- Alkyl-substituted Benzenes – soluble, less volatile, more toxic



Polynuclear Aromatic Hydrocarbons (PAHs)

- Naphthalenes (2-ring PAHs)
  - soluble, less volatile, more toxic
  - with more alkyl chains, less soluble but more toxic



- 3 ring PAHs
  - Phenanthrenes
  - Fluorenes
  - Dibenzothiophenes
- 4-ring PAHs – parent compounds bioavailable
- larger PAHs insoluble

Pseudo-components Representing Oil Mixture (SIMAP)

	Volatiles	Semi-volatiles	Low Volatility	Residual
Boiling Pt (°C)	<180	180-265	265-380	>380
Aromatics	MAHs	2-ring PAHs	3-ring PAHs	$\geq$ 4rings
Aliphatics	C4 - C10	C10–C15	C15–C20	> C20

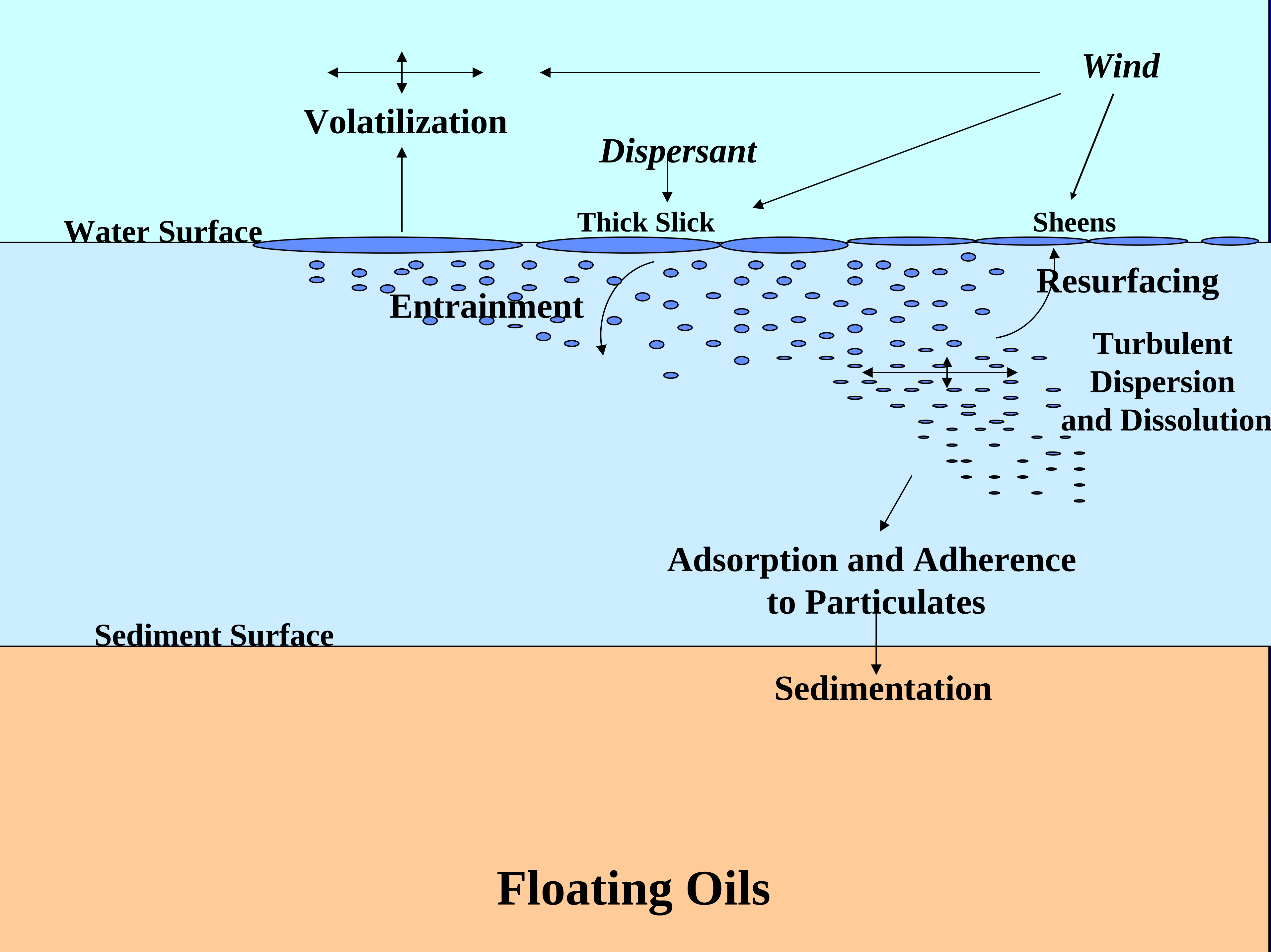
Volatile

Volatile and soluble (so bioavailable)

Not volatile and not soluble

Weathering

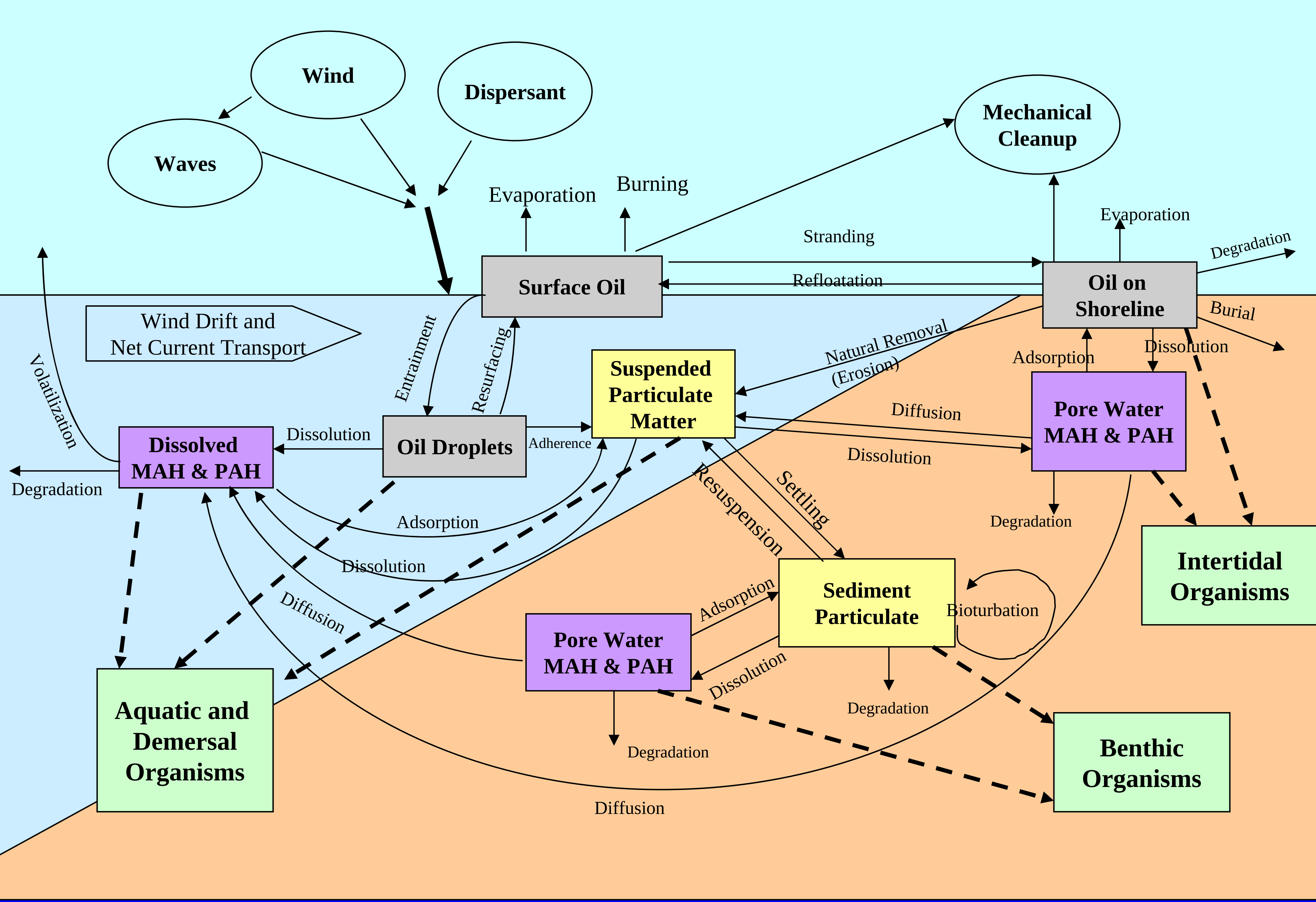
- Sinking oils
  - Little or no atmospheric exposure -- negligible volatilization
  - Dissolution depends on surface area:volume
  - MAH content – negligible
  - PAH content – from diluent
- Floating oils
  - May weather before transported to sediments


Wind
Volatilization
Dispersant
Thick Slick
Sheens
Water Surface
Resurfacing
Entrainment
Turbulent
Dispersion
and Dissolution
Adsorption and Adherence
to Particulates
Sediment Surface
Sedimentation
Floating Oils

Entrainment → Subsurface Concentrations

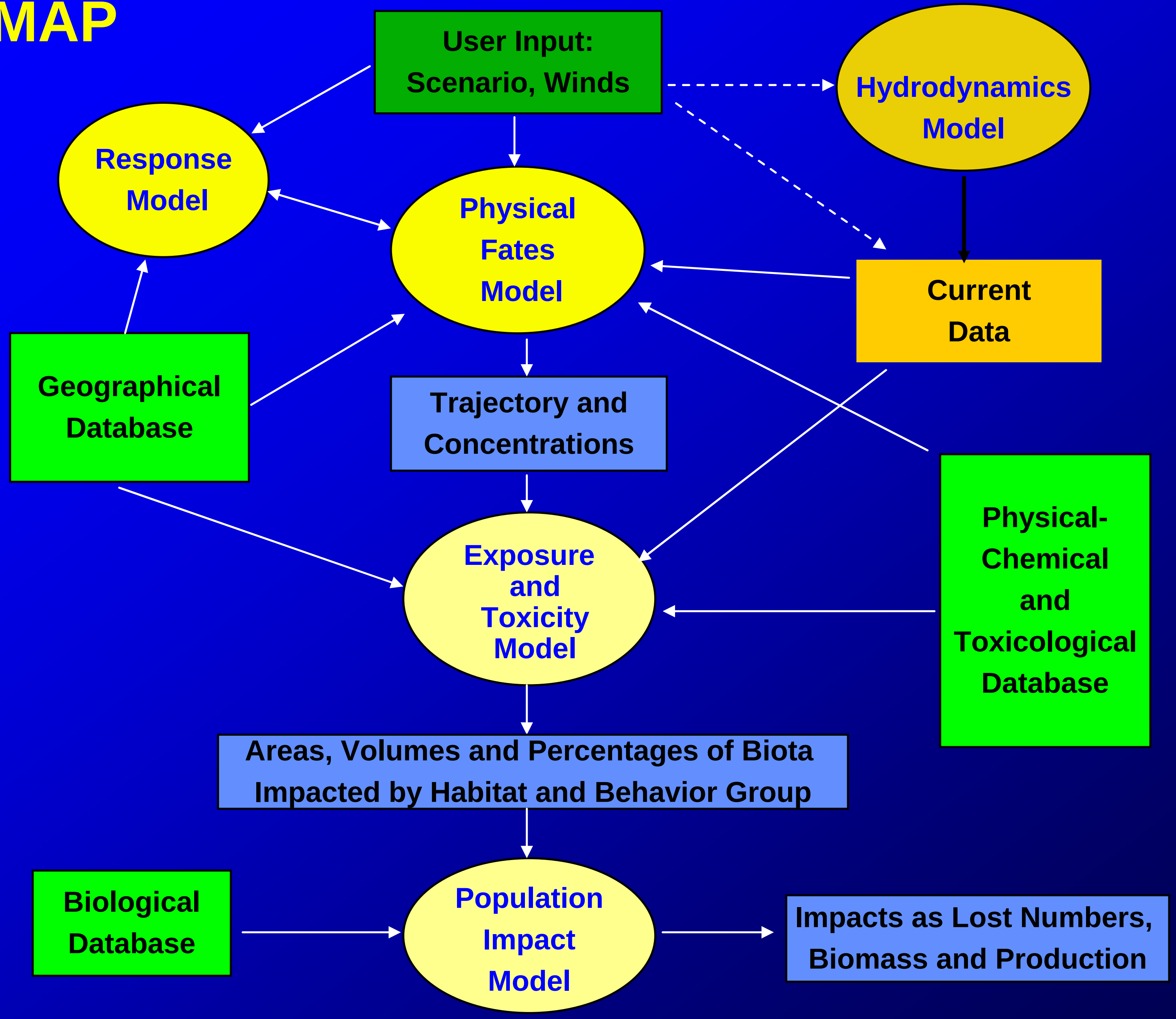
- Forcing:
  - Bouyancy (oils denser than water)
  - Subsurface release
  - From breaking of wind-driven waves
  - Surf entrainment
  - Dispersant application

- Particle sizes
  - Smaller with more turbulent energy
  - Important to fate of toxic components



Oil Fates Processes and Exposure to Aquatic and Sediment Biota

SIMAP


User Input: Scenario, Winds
Hydrodynamics Model
Response Model
Physical Fates Model
Current Data
Geographical Database
Trajectory and Concentrations
Exposure and Toxicity Model
Physical-Chemical and Toxicological Database
Areas, Volumes and Percentages of Biota Impacted by Habitat and Behavior Group
Biological Database
Population Impact Model
Impacts as Lost Numbers, Biomass and Production

Biological Exposure Model

- Organisms classified by behavior
  - Wildlife
    - % of time on water surface vs on/in water
    - Habitats used
    - Feathers & fur
  - Fish and Invertebrates
    - Swimming
    - Drift with currents
    - Stationary

- Movements of organisms are tracked to calculate exposure of individuals

- Impact a function of dose
  - Wildlife – g floating oil
    - Area swept
    - Slick thickness
  - Wildlife – g subsurface oil
    - Droplet concentration
    - Time underwater
  - Fish and Invertebrates
    - Concentration (water, sediment pore water)
    - Exposure time
    - Temperature

Wildlife: Probability of Oiling from Surface Oil

Wildlife Group	Probability
Dabbling waterfowl	99%
Nearshore aerial divers	35%
Surface seabirds	99%
Aerial seabirds	5%
Waders and shorebirds	35%
Wetland wildlife	35%
Terrestrial wildlife	0.1%
Cetaceans	0.1%
Furbearing mammals	75%
Pinnipeds, manatee, turtles	1%

Oil Toxicity

- 1-3 ring aromatics cause most of acute toxicity
  - in diesel, heavy fuel and crude oil, most from PAHs
  - for gasoline, MAHs also
- Dissolved aromatic concentration bioavailable
- Additive toxicity – all dissolved aromatics contribute (Toxic Units approach)
- $LC50_{mix}$ from published and verified estimates, based on review of laboratory bioassays with aromatics and oils

Validation – Toxicity Model

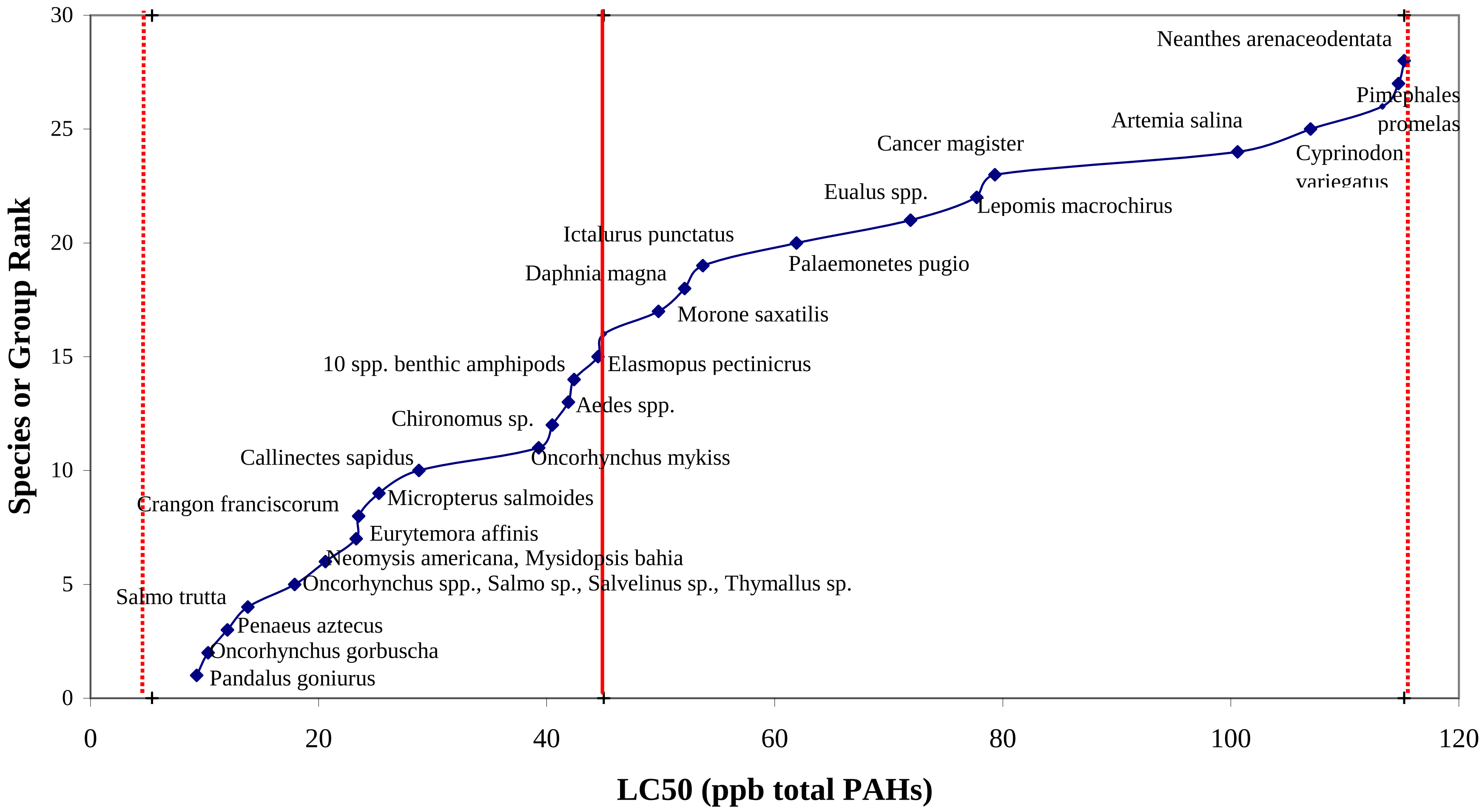
- Oil bioassays (French McCay, 2002; Envir. Tox & Chem Vol. 10)
  - 24 data sets (2 to 91 species tested)
  - For all data sets: model not significantly different from observed

- Additional information more recently
  - McGrath and DiToro
  - Mitchelmore and baker
  - Newman and Unger
  - Chandler and Coulls
  - Tjeerdema et al.

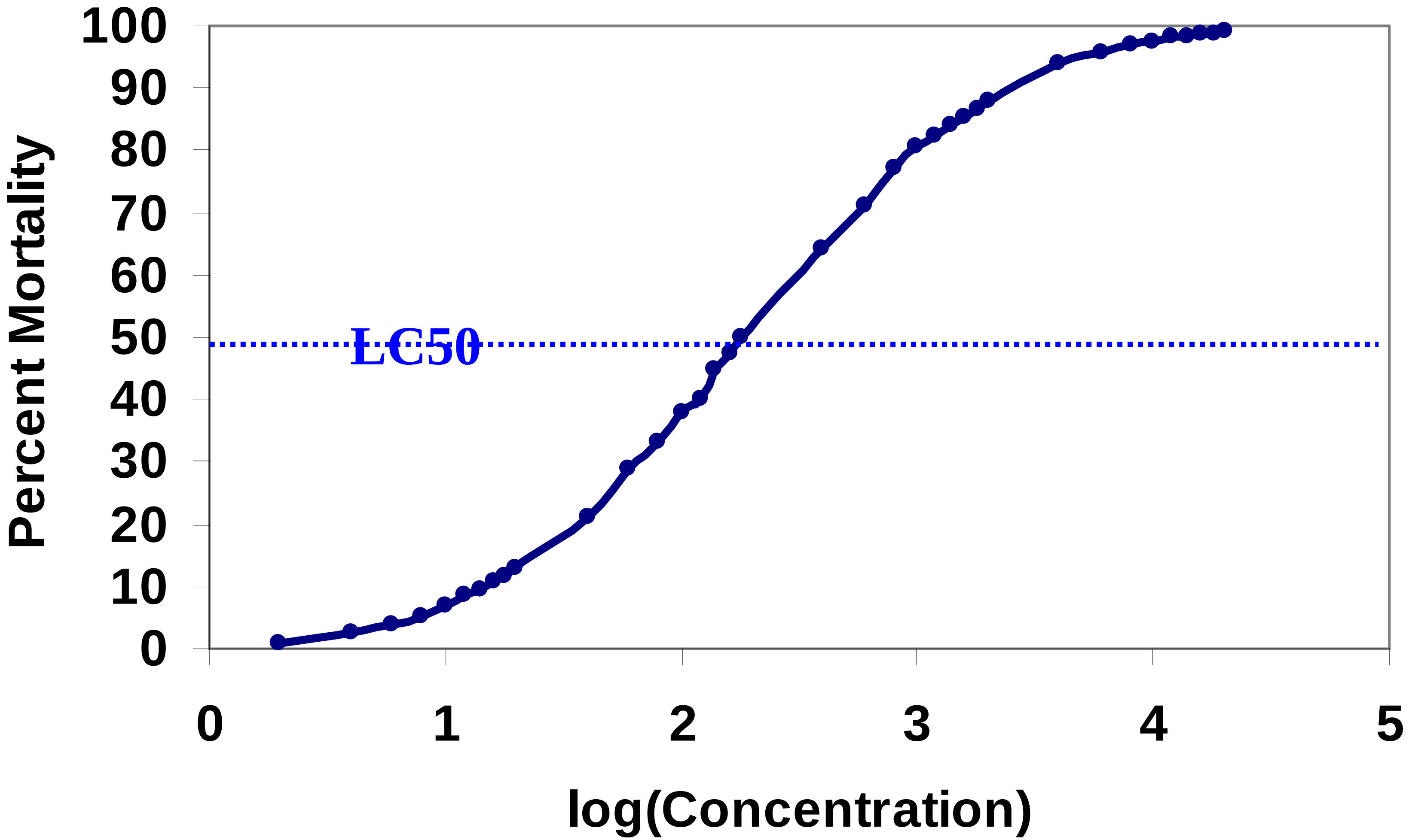
Species Sensitivity Ranking -- PAHs in Crudes and Fuel Oils

Vertical Red Lines are Geometric Mean and Range for 95% of Species

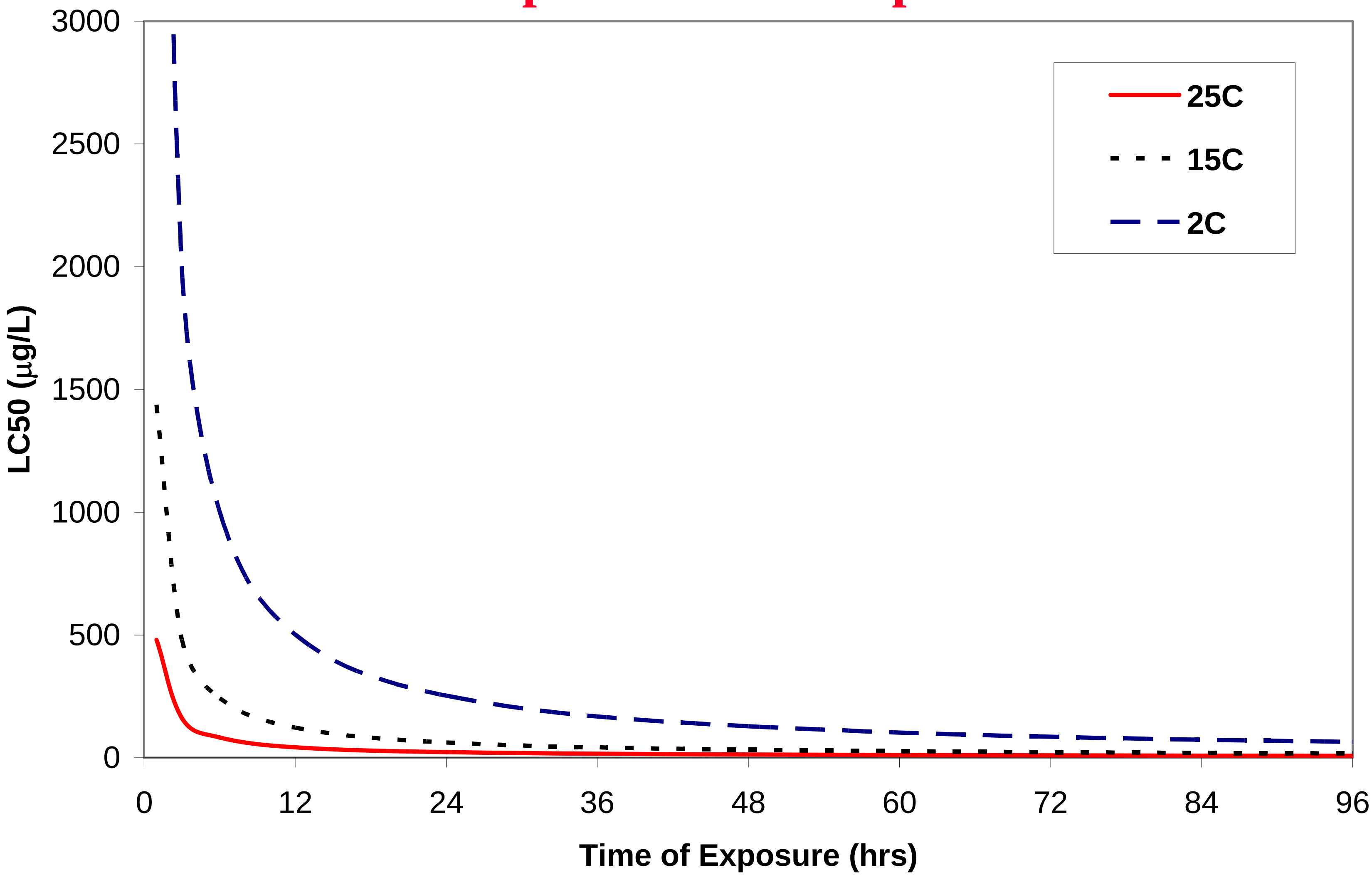
(French McCay, 2002)



Model Calculates Percent Mortality from LC50 and Concentration



Model Corrects LC50 for Duration of Exposure and Temperature



Biological Model Output

- Mortality by species/behavior group and life stage
  - Percentage of exposed population
  - Equivalent area or volume of 100% loss
  - If pre-spill abundance known, #s and kg

- Population-level impacts
  - Population structural changes
  - Production forgone = growth that would have been produced over remaining lifetime if there had not been a spill
  - Catch loss (yield foregone) for fished species

Other Effects on Aquatic Biota

- Smothering
  - Need effects threshold or dose-response curve based on mass per surface area
- Mechanical interference
  - Need concentration threshold or dose-response curve
  - Little or no *quantitative* data
  - How relate to injury?
- Behavioral interference
  - Little or no *quantitative* data
  - Need to model change in exposure because of the avoidance/attraction

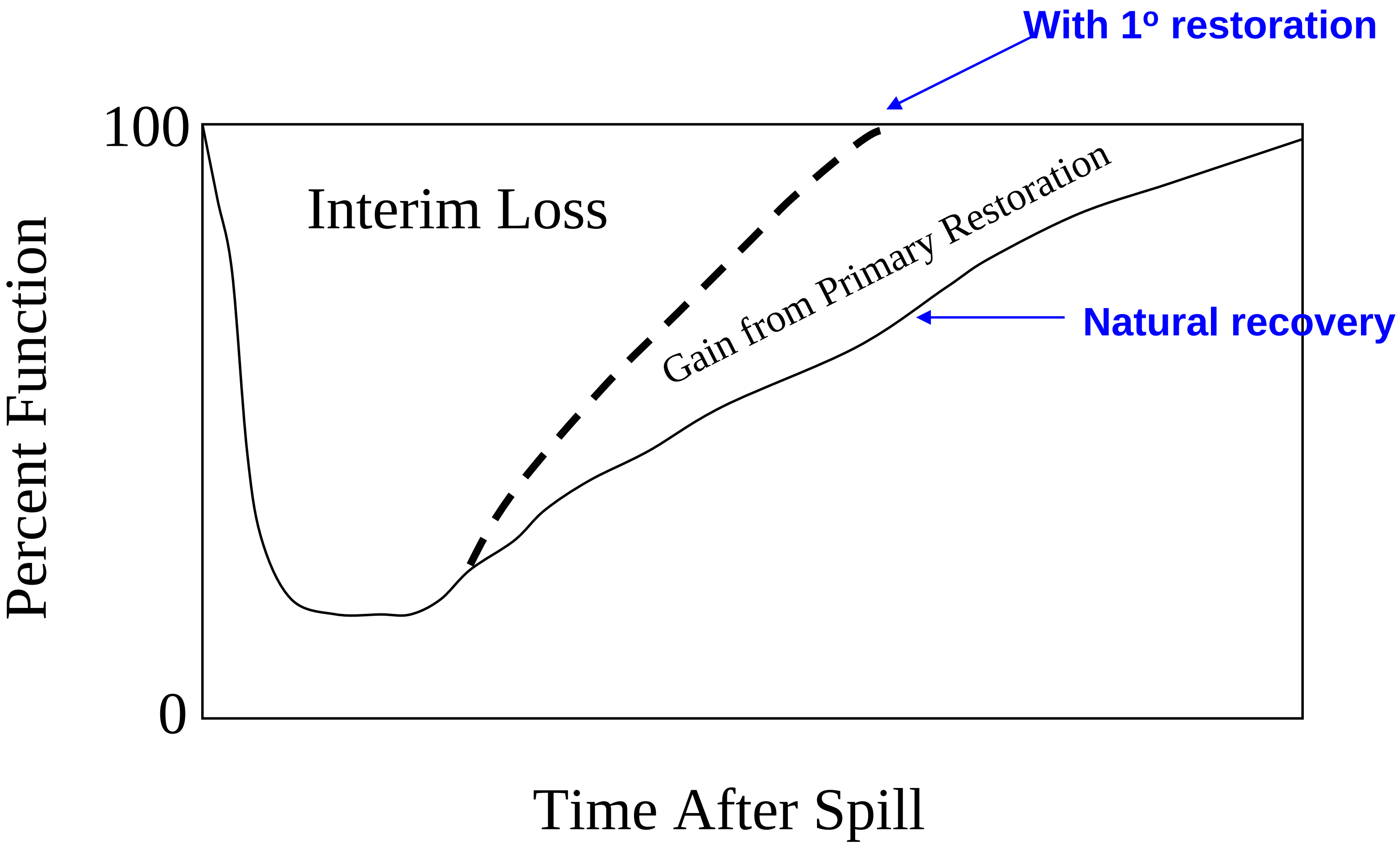
Phototoxicity

- Certain PAHs are photoactive
- Need to take up PAHs into tissues
- Need sufficient UV light dose
  - Low latitude
  - Very shallow water and intertidal zone

- Modeling
  - Uptake and bioaccumulation
  - UV exposure
  - Effects

Restoration Scaling Approaches

Theoretical Model of Primary and Compensatory Restoration



Options

- Cleanup submerged oil
  - Feasibility?
  - More harm than good?
  - Interim loss – compensatory restoration

- Approaches
  - Replacement species by species
    not normally feasible
    If specific species of high concern
  - Remediate other contaminated sediments
  - Habitat restoration elsewhere

Removal of Equivalent Toxic Units by Dredging (or Capping)

- Chemical mass remains in the environment and contributes to background
- Higher background concentrations
  - potential chronic effects
  - reduce assimilative capacity for pollutants in general
- Compensation: removal of equivalent toxic mass

Cost of Restoration: Removal of Equivalent Toxic Units

- Removal of highly-contaminated sediments could mitigate considering both
  - Toxic units removed
  - Disturbance of sediment habitat and recovery

- Remove same amount of toxicity as spilled chemicals remaining (normalize to LC50)

- Correct for relative degradability of spilled chemical to mitigating toxic sediment contamination

Scaling Based on Toxic Units

Area of remediated sediment / Area of submerged oil:

$$\Sigma (C_{ir} / LC50_{ir}) / \Sigma (C_{is} / LC50_{is})$$

where

- C_i is the concentration of chemical i
- $LC50_i$ is the LC50 of chemical i
- **r or s indicates the sediment location**

- **Divide each C_i by half-life to correct for relative persistence**

Habitat Equivalency Analysis (HEA) with Food Web Model

- In-kind or Out-of-kind habitat restoration

- Metric = production
- Additional production to food web increases production of resources injured

- Scale to account for:
  - Delay in benefits (discounting)
  - Development time for habitat
  - Trophic transfer efficiencies from restored resource to injured resource

HEA for In-Kind Restoration

$$\text{Restored Habitat Area} = \frac{\left[\begin{matrix}\text{Injury}\\\text{Area}\end{matrix}\right]\left[\begin{matrix}\text{Delay}\\\text{Factor}\end{matrix}\right]\left[\begin{matrix}\text{Recovery}\\\text{Factor}\end{matrix}\right]}{\text{Factor for Benefits over Project Life}}$$

Injury area = area equivalent of resource injured

If 3 year lag, delay factor = $\sum (1/(1+d))^3 = 1.09$

If 100 year project life, benefits factor = $\sum (1/(1+d))^{100} = 31.6$

Recovery Factor: Accounts for Time Delay for Development of Function in Restored Habitat

$$\text{Recovery Factor} = \frac{\text{Production in created habitat}}{\text{Production in full-function habitat}} = \frac{\sum F_y\,(1/(1+d))^y}{\sum (1/(1+d))^y}$$

F_y = fraction of full function in year y

HEA for Out-of-Kind Restoration

$$\text{Restored Habitat Area} = \frac{\left[\text{Production Lost}\right]\left[\text{Trophic Factor}\right]\left[\dfrac{D\,R}{B}\right]}{\text{Production Gain for Scaling Trophic Level}}$$

Trophic Factor -- Ecological Efficiencies each step in food chain above scaling trophic level

D = Delay factor

R = Recovery factor

B = Benefits factor

Additional plant production as:

Food Services

Macrophytes

4%

Detritivores

Micro-algae

20%

20%

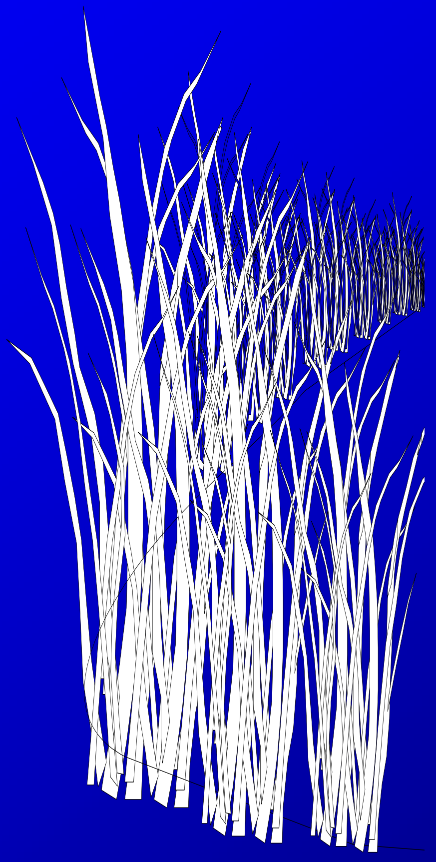
Small Fish & Invertebrates

20%

2%

Large Fish & Invertebrates

Birds & Mammals



Production in habitat

-

Production in unvegetated habitats

Production due to additional food services

Additional plant production as:

Food Services

(primary production)

Macrophytes

↓ 4%

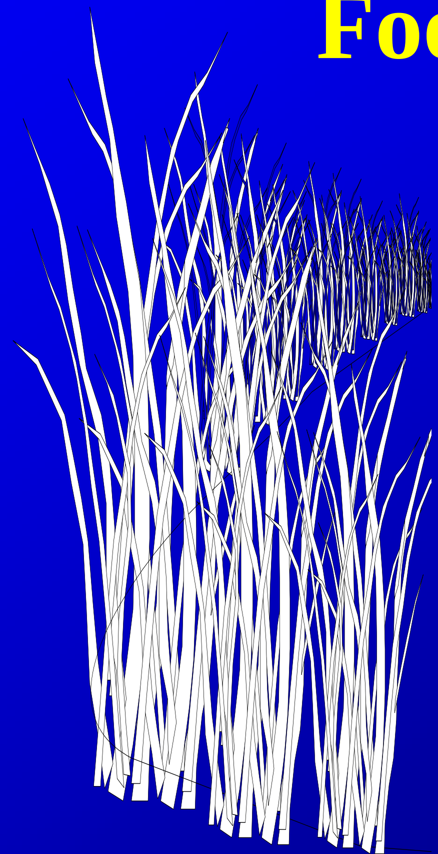
Detritivores

↓ 20%

Fish & Invertebrates

↓ 20% → **Fish & Invertebrates**

↓ 2% → **Birds & Mammals**



Food and Habitat

(secondary production)

Benthic production in habitat

-

Benthic production in unvegetated habitats

Production due to additional food and habitat services

Ecological Efficiency per Trophic Step

Consumer	Prey/food	% Efficiency
Invertebrate or fish	Invertebrate	20
Birds, mammals	Invertebrate	2
Invertebrate or fish	Finfish	20
Birds, mammals	Finfish	2
Invertebrate detritivore	Macrophytes	4
Finfish detritivore	Macrophytes	4
Birds, mammals (herbivores)	Macrophytes	0.03

Summary: Restoration

- Options for Net Increase in Production Rate
  - More Productive Habitat
    - Seagrass
    - Wetlands
    - Mangroves
    - Oyster reef
    - Coral reef (?)
  - Lower contamination – 2 metrics
    - Remove equivalent toxic units
    - Increase productivity (scale with HEA)