Assessing Biological Effects of Toxic Contaminants in the Chesapeake Bay

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Slide courtesy: NASA

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NOAA does not develop regulations for toxic substances or water quality criteria

- Regulations
  - U.S. Environmental Protection Agency (EPA)
  - Occupational Safety and Health Administration (OSHA)
  - Food and Drug Administration (FDA)
- Recommendations or guidelines [cannot be enforced by law]
  - Agency for Toxic Substances and Disease Registry (ATSDR)
  - National Institute for Occupational Safety and Health (NIOSH)
  - NOAA, e.g. Sediment Quality Guidelines

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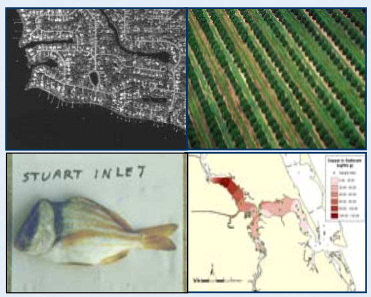
NOAA's mandates and "institutional authority"

"widespread" decline in water quality … contaminated sediments are poisoning local fish and shellfish and presenting risks to public health.



Spatial extent?
Severity?

33 USC 1441 (MPRSA)
33 USC 2801 (NCMA)
33 USC 1271 (WRDA 92:§ 503)
NRC (1989)
CWAP (1998) – National Report Card
OAP (2007 update): indicators and information

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NOAA's Water Quality Data Needs

Establishing connections between water [and air] quality and undesirable ecosystem conditions or outcomes (e.g., nuisance or harmful algal blooms, eutrophication, fish diseases and deformities, hypoxic conditions, and loss of species, habitats and biodiversity)

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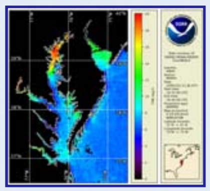
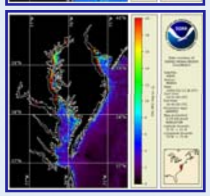
Water Quality Data Needs – contd.

Understanding the role of physical processes (including episodic events, decadal changes, and global warming) on coastal and Great Lakes ecosystems.



TSS



Chl

Loading from a Runoff Event in Chesapeake Bay, March 2008
(High-Resolution Ocean Color Satellite Data)
http://coastwatch.noaa.gov/

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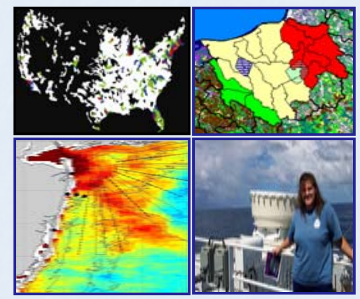
Water Quality Data Needs – contd.

- Fostering collaboration between NOAA, universities, and states
- Enhancing environmental literacy (through education, outreach and training)



Impervious surface area; ISAT; Rutgers COOL; Teachers at Sea

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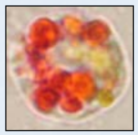
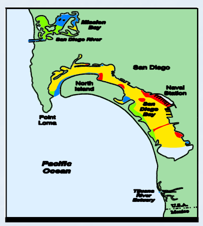
Environmental Toxicity Approaches

- Contaminant(s) of concern
  - Biologically non-essential – truly xenobiotic (PCBs, DDTs, arsenic, lead, mercury)
  - Biologically essential (copper, selenium)
- Area(s) of concern (e.g., in Great Lakes, San Diego Bay)





Theophrastus Philippus Aureolus Bombastus von Hohenheim (1493-1541) -- aka Paracelsus

- *Highly controversial but brilliant mineralogist, chemist and surgeon*
- *Provided clinical description of a number of diseases, for example syphilis, goiter and silicosis*
- *Introduced remedies, some of which contained mercury, copper sulfate, opium and other "poisons"*
- *Often rejected established thought and procedures; burned books of Galen (Claudius Galenus) and Ibne-Sina (Avicenna) – the recognized medical authorities of that era*
- *Pronounced himself as "para-Celsus" meaning beyond Celsus, a renowned Roman encyclopedist – "De Medicina"*

Paracelsus

Most noted for the phrase: "What makes a man ill also cures him."

In terms of toxicology: "No substance is a poison by itself … all substances can be poisonous. It is the dose that makes a substance a poison … and the right dose differentiates a poison and a remedy."

Substance	Non-Toxic or beneficial	Toxic dose	Lethal dose
Alcohol (in blood)	0.05%	0.1%	0.5%

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Aspirin (tablets)	0.65 g (2)	9.75 g (30)	34 g (105)

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Sleeping pill (Seco-barbital in blood)	0.1 mg/dL	0.7 mg/dL	> 1 mg/dL

Selenium – both essential and toxic

Essential	Poison
Anti-carcinogen	Carcinogen
Anti-oxidant	Pro-oxidant
Anti-neurotoxic factor	Neurotoxic
Pregnancy-protective element	Teratogenic
Anti-genotoxic	Genotoxic

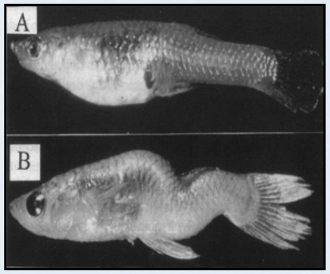
However, unlike most other metals and metalloids, the difference in concentrations between selenium's toxic and essential roles is very small; generally, the safety factors overlap! Thus it is very difficult to define its safe level.

Selenium Impact on Aquatic Resources

Selenium contamination is one of the few clear cases where environmental contamination has led to "devastation of wildlife populations" (Fan, et al., 2002)

Case examples:

- Belews Lake (Greenboro), NC (fly ash; fish)
- Colorado River Basin (agriculture drainage; fish)
- San Francisco Bay (agriculture drainage, sewage; fish and wildlife)
- Nordfjord, Norway (atmospheric; fish)



Dennis Lemly -- USFS

Selenium: invisible poisoning in fish (Lemly, 2002)

- Primary impact is through accumulation in egg (10 µg/g) through the female's diet
- Disrupted development; teratogenic deformities and death may occur
- Reproductive failure – 19 of 20 fish species in Belews Lake were eliminated
- Selenium discharge was stopped in 1986, but effects continued
- No longer (2000) listed as "impaired" (303(d) list)

North Carolina Tourism

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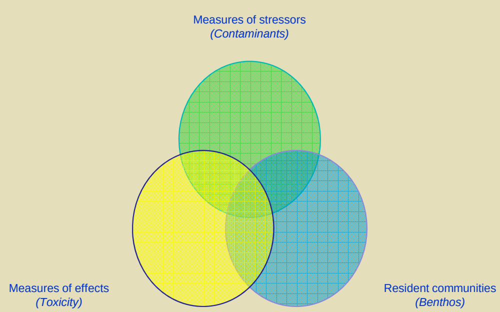
NOAA has used the SQT approach (1990s)

Several other approaches are available, e.g., Stepwise “effects” assessment (AMAP/EEA/ICES, 1999), Decision tree approach (Batley, 2001), etc.



Sediment Quality Triad
(incorporates both observational and experimental data)

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Study design

- Geographically comprehensive and unbiased
- Stratified-random sampling design
- A synoptic set of data on contaminant levels, results from a suite of toxicity tests, and metrics of benthic infaunal distribution
- Studies done in close cooperation with state and local governments, academia, and others

<u>Toxicity Bioassays</u>
- Amphipod survival (solid phase)
- Sea urchin fertilization and larval development (pore water)
- Microtox test (organic extract)
- HRGS-P450 bioassay (organic extract)
- Comet assay (DNA strand breakage)
- Juvenile clam mortality (whole sediment)
- FluoroMetPlate Bioassay (pore water)

<u>Contaminant Levels</u>
- Trace elements
- Chlorinated pesticides
- Polychlorinated biphenyls
- Polycyclic aromatic hydrocarbons
- Butyltins
- Dioxins, dibenzofurans, planar PCBs, PBDEs, APEs, PFOS
- Current use pesticides

<u>Benthic Biological Community</u>
- Species richness
- Species diversity
- Indicator species (pollution tolerant, pollution sensitive)
- Benthic Index

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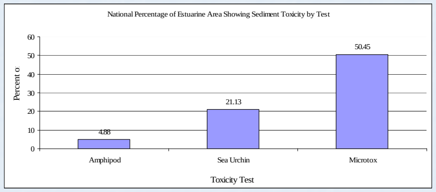
The approach is used to estimate fraction of a population [total estuary area] that is not meeting a socially defined value, threshold or criterion.



- Estimates can be generated for individual strata, or for the whole target population (above, 25 estuaries) based on weighted sums.
  - Newark Bay (spatial extent of toxicity, amphipod test): 84%
  - Clear Lake stratum, Galveston Bay (spatial extent of toxicity: sea urchin fertilization test): 100%
  - Boston Harbor (spatial extent of toxicity, Microtox): 45%

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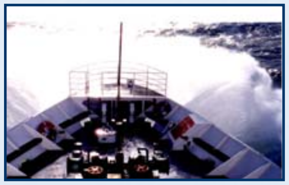
Chesapeake Bay Study

- 210 sampling sites in 65 strata (irregularly shaped polygons)
- Suite of toxic chemicals
  - Metals, PAHs, chlorinated pesticides, PCBs, butyltins, etc.
- Toxicity tests
  - Amphipod, sea urchin fertilization success, HRGS (P450) response, Microtox [no results]
- Benthic infaunal community measures
- Sampling (1998-2001); spatial coverage = 9,120 sq km



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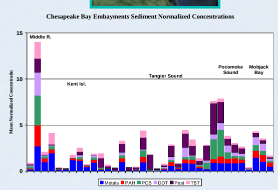
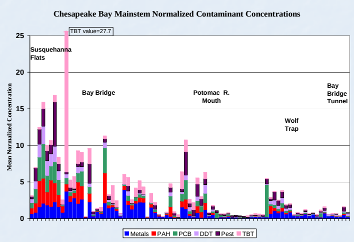
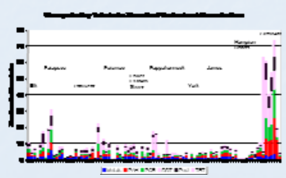
Composite profiles of sediment contamination

(ordinate scale is different)







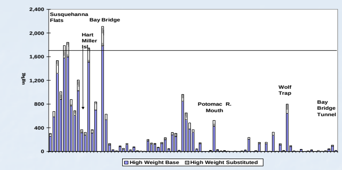
HMW PAH concentration, µg/kg

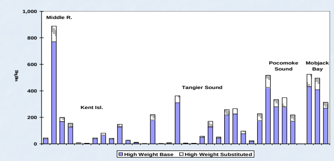
a) Mainstem (top)
b) Bays and sounds (middle)
c) Tributaries (bottom)

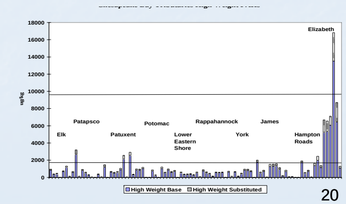
Panel concentrations have different scales

Concentrations in tributaries, notably in the Elizabeth River region, exceed ER-L and ER-M guidelines

ER-L: 1,700 µg/kg
ER-M: 9,600 µg/kg







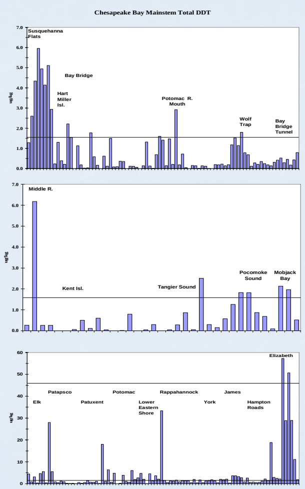
tDDT concentration, μg/kg

a) Mainstem (top)
b) Bays and sounds (middle)
c) Tributaries (bottom)

Panel concentrations have different scales

Higher concentration in Susquehanna Flats (exceeding ERL) and Elizabeth River (exceeding ERM)

ER-L: 1.6 μg/kg
ER-M: 46.1 μg/kg



Spatial Extent of Sediment Toxicity: Chesapeake Bay

Amphipod mortality	0%
Sea urchin fertilization impairment	32%
Microtox response	N/A
HRGS (P450) response	3%

Elucidating benthic infaunal community changes with SQT data

- Very difficult
  - Highly diverse sub-environments within an estuary
  - Different stress in tributaries (contaminants) and the deep trough (low oxygen)
  - Incomplete taxonomy – affecting species richness and diversity calculations
  - "Too many" approaches for measuring diversity
  - Varied or unknown biological response to contaminant exposure
  - Biological attributes are not included (competition, migration, reproduc tion, etc.)

Examples of statistical methods:

- Principal Component Analysis
- Factor Analysis
- Correspondence Analysis
- Detrended Correspondence Analysis
- Canonical Correlation Analysis
- Procrustes Analysis
- Mantel's Test
- Cluster Analysis followed by MANOVA

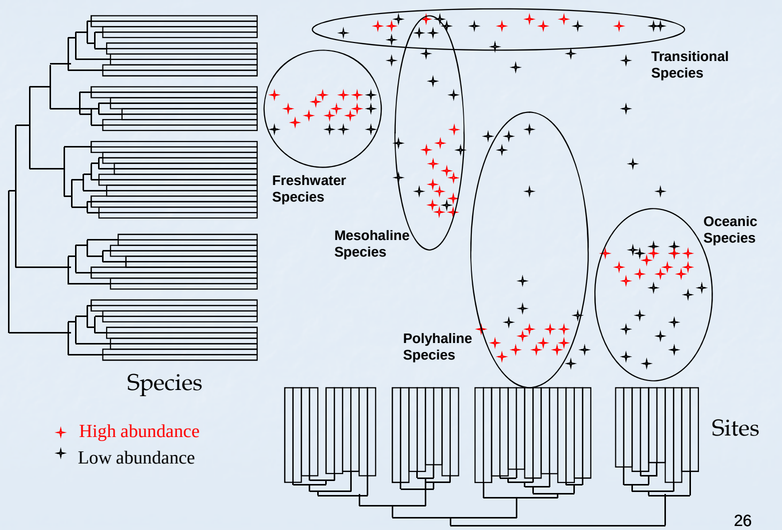
Chesapeake Bay has very complex physiography and habitats; environmental data are highly varied

- Our PCA showed separation of principal components; the fraction of total variance explained by the three principal factors (contaminants, species diversity measures, and pollution tolerant species) accounted for 55 % of the variance; the first component accounted for 24%.
- Too many "self-propagating" and "seldom justified" benthic indices (Suter, 1993; Diaz, et al., 2004)
- "Expert judgment" and consensus opinion are being viewed as more useful evaluation benchmark (Muxika, et al., 2007; Weisberg, et al., 2008)

Nodal Analysis
(Lambert and Williams, 1962)

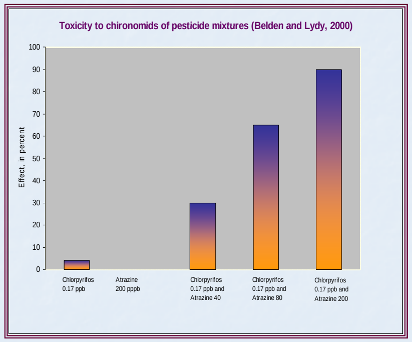
- Combines independent cluster analyses in a graphical array
- Creates a pattern of species associations; each group can be characterized by the physico-chemical habitat features, contaminant concentrations, and other site-specific data
- It was possible to discern the most contaminated sites (Baltimore Harbor, and Elizabeth River)
- In general, chemical contamination and toxicity responses are more closely related to each other than with the benthic community matrices.

Nodal Analysis – Species/Site Associations



Toxicity of “current use pesticides” in estuaries

- Little or no information on occurrence or effects
- Effects of <u>mixtures</u> of toxic chemicals are nearly impossible to describe [just 25 chemicals will form 300 pairs of compounds; their possible combinations would be in millions!]
- Knowledge of additive, synergistic or antagonistic effects is nearly non-existent in estuaries.



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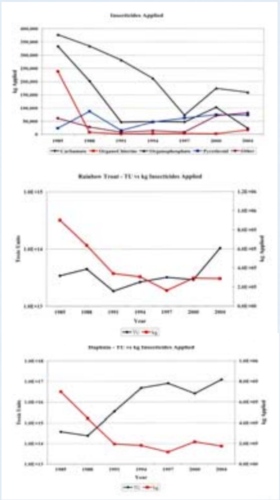
Pesticide Toxicity Index

- Toxicity quotient: measured concentration of a pesticide divided by its toxicity value (e.g., EC_{50}, LC_{50})
- Assume an “Additive Model,” i.e., summing the toxicity-normalized concentrations of multiple pesticides (Deneer, 2000).
  - Panel 1: Insecticides applied
  - Panel 2: Inferred toxicity to rainbow trout
  - Panel 3: Inferred toxicity to Daphnia



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Last Point!
If estimating environmental toxicity of chemicals were a game …
we would be behind the 8 ball … always!

- Some 70,000 commercial and industrial compounds are now in use, and an estimated 1,000 new chemicals are introduced each year (2007 State of the Great Lakes Report)
- What to do?
  - Select, extrapolate, and model carefully, and hope that we are not off base completely!

- Muir and Howard (2007) – the Great Lakes – categorized chemicals in terms of their potential environmental persistence and bioaccumulation
  - US EPA High Production Volume (HPL) and Enhanced High Production Volume (EHPV) lists: 4,000+ chemicals
  - US EPA Toxic Substances Control Act (TSCA): 14,000 chemicals
  - Canadian Domestic Substances List: 11,000+ chemicals
- No information on their environmental toxicity was used

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Thank You

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Hartwell, S.I., and J. Hameedi. 2007. Magnitude and Extent of Contaminated Sediment and Toxicity in Chesapeake Bay. NOAA Technical Memorandum NOS NCCOS 47, Silver Spring, MD

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Selenium – a case example
Its toxicity is well known

Wide Range of Toxicity

- Marco Polo (13th Century) reported on its toxicity in the Chinese province of S'uh-cheu-lu (Succiur) – nail loss and discoloration in animals of various kinds
- Experimental data since 1890s
- Now known to be associated with a wide range of ailments (cancer, neurotoxicity, reproductive impairment, dermatological problems, immune system compromise, among others)

Selenium in estuaries

- Sources
  - Agricultural drainage
  - Sewage sludge
  - Fly ash from coal-fired power plants
  - Mining of phosphate and metal ores

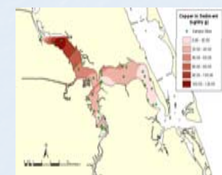
Selenium-related Effects: Fish and Wildlife

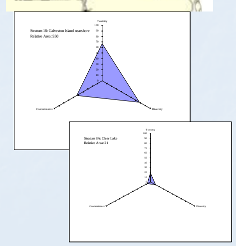
- Effects include: mortality, impaired reproduction with teratogenesis, reduced
  growth, histopathology, ovarian lesions, and alteration of glutathione metabolism and increased oxidative stress (Hoffman, 2002)
- *Potamocorbula amurensis* (Asian clam), an invasive species in San Francisco Bay, effectively accumulates Se and is a direct trophic link to several predatory species [oysters, mussels and clams are not as effective] (Linville, et al., 2002)

Advantage of defining the spatial extent and severity of sediment contamination

Identify areas of concern for remediation, restoration, focused research and monitoring

- Recent studies
  - Chesapeake Bay
  - Puget Sound
  - St. Lucie Estuary, FL
  - San Francisco Bay





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Glenn Suter – critiquing ecosystem health or integrity indices, such as the Benthic Index (Suter, 1993)

- Indices … are justified on the basis of field studies rather than any theory of ecosystem health or any societal or ecological value of the index or its components. *That is, an ecosystem's health is bad because the index is low, and a low index value indicates bad health because the index is low for unhealthy ecosystems*.
- Now, that's tautology. It is like saying, either it will rain tomorrow or it will not rain tomorrow! You can't be wrong.

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