Long-Term Watershed Monitoring
Statistical Models & Examples

Watershed Monitoring & Reporting Session
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Topics

- Gulf Effort: Challenges & Suggestions
- Statistical Models
  - Allocating Sampling Effort
  - Computing Loads
  - Estimating Power for Detecting Trends
  - Measuring Long-Term Progress
- Examples
  - Onondaga Lake, New York
  - Everglades
Developing a Consistent Long-Term Dataset

- Challenge to Gulf Effort
- Multiple Agencies
- Multiple Sampling Objectives
- Compatibility
  - Over Time
  - Across Sub-Basins
- Potential Inconsistencies
  - Different Baseline Periods
  - Sampling Sites
  - Sampling Methods
  - Sampling Frequencies
  - Analytical Methods
  - Load Computation Methods
Evolution of Long-Term Monitoring Programs

Competing Objectives

“Improve” Methods
Increase Precision
Reduce Cost
Support Other Programs

Vs.

Maintain Consistency
vs. Historical Data
vs. Station Network

THE VALUE OF CONSISTENT METHODOLOGY IN LONG-TERM ENVIRONMENTAL MONITORING

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Abstract. Long-term monitoring has a substantial history in both the biological and physical sciences. Over time the procedures and analytical methods involved in long-term monitoring have changed to improve the quality of data, but even over short time spans, differences occur that can make direct comparison of measurements either difficult or impossible. In many instances the lack of strictly defined methods or practices means that data from one project cannot be used to enhance other projects with any degree of statistical rigour. This is amply demonstrated in the field of soil classification where improvement in soil definitions, refinement of cut-off points and changes in descriptive techniques between soils is such that in many cases direct comparison of old with new data is impossible. The causes of, and safeguards against, such measurement inconsistency are examined here in the context of the United Kingdom Environmental Change Network (ECN) project. Examples of incompatible data arising from environmental studies are given and the efforts used to standardise methods and practices in the ECN programme are described in detail. The need for standard practices is demonstrated and considered in the light of the limitations of operating what are relatively rigid procedures.

Suggestions

• Define Monitoring Objectives
• Develop & Document Consistent Sampling Protocols
• Establish Precision Targets for Yearly Load Estimates
• Use Historical Data to Design/Refine Programs
  • Identify Stations with Baseline Data
  • Assess Variability
  • Estimate Required Sampling Frequencies
• Central Database, Data Reduction, & Reporting
• Consistency Checks
Potential Consistency Checks

- Water Balances (Basin = Σ Sub Basins)
- Mass Balances (Chloride, Nitrate)
- Laboratory Round Robins
- Paired Sampling
- Sensitivity to Agency / Data Source
- Sensitivity to Load Calculation Method
- Trends at Mouth vs. Sub-Basins
- Watershed Models / Cause-Effect
Interpretation Difficulties – Collinearity

Trend in Flow
- Short-Term?
- Climate Change?

Trend in Load
- Climatologic?
- Anthropogenic?
- Reversible?

MRB Nitrate Flux, Goolsby et al, 1999
Allocating Sampling Effort Across Basins

Design Objectives
- Basin Mass Balances
- Support Modeling
- Identify Sources
- Measure Progress

Design Variables
- Agency
- Methods
- Location/Stream Order
- Frequency
Optimal Allocation of Sampling Effort Across Sub-Basins to Estimate Total Load

\[ T = \text{Total Load} = \sum L_i \]

\[ \text{SE}^2(T) = \text{Uncertainty } (T) = \sum \frac{S_i^2}{N_i} \]

\[ N = \text{Fixed Total Samples} = \sum N_i \]

\[ S_i = \text{Standard Deviation of Load for Sub-Basin } i \]

Objective: Find \( N_i \) to Minimize \( \text{SE}(T) \) for Fixed \( N \)

Solution: \( \frac{N_i}{N} = \frac{S_i}{T} \)

Optimal Sampling Freq. \( \propto \) Std Deviation of Load
  - Load Magnitude
  - Variability (Coef. of Variation)
Sampling Program Design for Measuring Loads at a Given Site

Factors

• Load Magnitude
• Concentration & Load Variability
• Concentration/Flow Dependence
• Desired Time Step
• Species (Nutrient, Dissolved vs. Particulate)
• Budget !

Options

• Periodic Grab Sampling
• Additional Grab Sampling at High Flow
  • Seasonal
  • Storm-Event
• Composite Sampling (Spatial, Temporal)
Computing Loads – FLUX Program

Stratified Estimates

- $\geq$ Yearly Time Step
- Stratification Variables (Flow, Season)
- Precision Estimated
- Limitations
  - Sparse Data in Some Years and/or Strata
  - Hysteresis in Flow/Conc Relationship
  - Seasonality in Flow/Conc Relationship
Computing Loads – FLUX Program

**Time Series Methods**

- >= Daily Time Step
- Algorithms
  - Interpolation Between Sampling Dates
  - Regression vs. Flow, Season, Trend (NOAA, 1999)
  - Regression + Interpolation (Walker & Havens, 2002)
- Limitations
  - Precision Difficult to Estimate
  - Data Gaps (Long Interpolation Intervals)
  - Serial Correlation in Residuals (Regression)
  - Change in Regression Slopes
Onondaga Lake, Syracuse, NY
Long-Term Monitoring (1968 – Present)
Onondaga Lake, New York

**FLOWS.WK1**  
Daily Flow Data  
- Inputs: Measured Flows, Daily Precip, Lake Elev  
- Outputs: Precip & Evap Flows, Lake Volume, Lake Outflow

**CREEKS.WK1**  
Tributary Monitoring Data  
- Inputs: Station, Date, Sample Concentrations  
- Outputs: Computed Total N Conc

**LAKE.WK1**  
Lake Monitoring Data  
- Inputs: Station, Date, Depth, Sample Concentrations  
- Outputs: Computed Total N Conc

**AUTOFLUX**  
Load Calculations  
- Inputs: AUTOFLUX Control Files (Date Ranges, Season (Yr, Wtr-Yr, May-Sep), Variables, Output File Names)  
- Outputs: AUTOFLUX Output Files (Year, Season, Station, Variable, Flow, Load, Concentration, CV)

**MASSBAL.XLS**  
Mass Balance Workbook  
- Inputs: User Selection (Variable, Year Range, Season, Outflow Station)  
- Outputs: Mass Balances, Model Results, Trend Analyses, Time Series Plots, Pie Charts
**Mass Balance Framework**  
**Onondaga Lake, New York**

### Onondaga Lake Mass Balance Analysis

W. Walker, for Onondaga County Dept of Water Environment Protection, July 2000

#### Total Phosphorus Balance for 1997-2001

<table>
<thead>
<tr>
<th>Variable</th>
<th>Total Phosphorus</th>
<th>Average for Years: 1997 thru 2001</th>
<th>Seasonal Year</th>
<th>Oriente Term</th>
<th>Load (kg)</th>
<th>Std Error</th>
<th>Conc (ppb)</th>
<th>samplers</th>
<th>Flow Load</th>
<th>Std Error</th>
<th>Conc (ppb)</th>
<th>samplers</th>
<th>Flow Load</th>
<th>Std Error</th>
<th>Conc (ppb)</th>
<th>samplers</th>
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<tr>
<td>Metro Effluent</td>
<td>89.24</td>
<td>30698</td>
<td>276</td>
<td>344</td>
<td>1%</td>
<td>365</td>
<td>21%</td>
<td>53%</td>
<td>2%</td>
<td>77.5</td>
<td>42.2</td>
<td>34.6</td>
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<td>Metro Bypass</td>
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<td>1974</td>
<td>69</td>
<td>1232</td>
<td>3%</td>
<td>36</td>
<td>0%</td>
<td>3%</td>
<td>0%</td>
<td>29.3</td>
<td>27.5</td>
<td>17.9</td>
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<tr>
<td>East Flume</td>
<td>0.32</td>
<td>65</td>
<td>6</td>
<td>203</td>
<td>9%</td>
<td>27</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>11.7</td>
<td>92.0</td>
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<tr>
<td>Crucible</td>
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<td>Harbor Brook</td>
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<td>Industrial</td>
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<td>Municipal</td>
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<td>Precipitation</td>
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<td>0</td>
<td>3%</td>
<td>1%</td>
<td>0%</td>
<td>11.7</td>
<td>16.0</td>
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<tr>
<td>Total Inflow</td>
<td>415.33</td>
<td>58413</td>
<td>1818</td>
<td>141</td>
<td>3%</td>
<td>571</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>738.7</td>
<td>56.2</td>
<td>79.1</td>
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<td>Lake Overflow Rate</td>
<td>34.74</td>
<td>m/yr</td>
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<td>727.0</td>
<td>39.9</td>
<td>25.9</td>
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<td>Lake Residence Time</td>
<td>0.31</td>
<td>years</td>
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<td>727.0</td>
<td>39.9</td>
<td>25.9</td>
<td></td>
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</tbody>
</table>

#### Alternative Estimates of Lake Output

- Outlet 12 Feet: 406.48 m3/yr
- Outlet 2 Feet: 406.66 m3/yr
- Lake Split: 406.66 m3/yr

### Total Phosphorus

- Atmospheric
- NonPoint
- Industrial
- Municipal
Statistical Framework for Onondaga L. Monitoring Program

- AMP Data
- Historical Data
- Literature Data
- AMP Design
- Biological Opinions & Experience
- Variance Components
- Statistical Models
- Precision & Power
- Hypotheses to be Tested
Onondaga Lake Statistical Framework
Precision Estimates: Relative Std. Error of Yearly Mean

- Adult Gamefish
- Adult Fish Rich.
- Juveniles
- Juvenile Rich.
- Pel Larvae
- Pel Larvae Rich.
- Lit Larvae
- Lit Larvae Rich.
- Zooplankton
- Phytoplankton
- Macrophyte Cover
- Lit Macroinv Dens.
- Lit Macroinv NYSDEC
- Trib Macroinv NYSDEC
- Chlorophyll-a
- F Coli
- Secchi
- Ammonia N
- Total Kjel N
- Total N
- Total N
- Total P
- Total P

Rel. Std. Error of Yearly Mean
Onondaga Lake Statistical Framework
Power Estimates: Increases Detectable with 80% Confidence
5 Years of Baseline & 5 Years of Post-Baseline Data
Onondaga Lake Statistical Framework
Precision of Fish Abundance, Richness, & Diversity Indices

RSE of Lake Mean Per Sampling Event

- Total Abundance
- Species Richness
- Species Diversity

Legend:
- Littoral Larvae
- Pelagic Larvae
- Juveniles
- Adult Gamefish
- Adult Total Fish
FIG. 2.6 Daily Flux of Nitrate from the Basin to the Gulf: August 1980-1999

Trend?
Power for Detecting Trends

Given:  N Years of Monitoring Data,  \( H_0 = \) No Trend
Power  = Probability of Rejecting \( H_0 \) when a Trend Exists
Power  = Function \((\alpha, T)\)
\( \alpha \)  = Significance Level of Hypothesis Test
\( T = (\text{Trend Magnitude} \times N^{1.5} / S) \)
Factors Influencing \( S = \) Std. Dev. of Yearly Means
   True Variability in System
   Measurement Precision  = \( F \) ( Sampling Design)
Variance Explained by Hydrologic Factors
Power for Detecting a Linear Trend

Probability of Rejecting Null Hypothesis of No Trend Based upon Yearly Data from a 10-Year Period Using Linear Regression ( alpha  = 0.1)

Year-to-Year Standard Deviation =  50%

Probability of Rejecting Null Hypothesis of No Trend Based upon Yearly Data from a 10-Year Period Using Linear Regression ( alpha  = 0.1)

Year-to-Year Standard Deviation =  50%

Variance Explained by Hydrologic Regression
Power for Detecting Step Change in Long-Term Mean

Probability of Rejecting Null Hypothesis of No Change in Mean
Comparing Yearly Means from Two 5-Year Periods
Using Student's t-test ( alpha = 0.1)
Year-to-Year Standard Deviation = 50%

Variance Explained by Hydrologic Regression
Model for Tracking Management Effects in the Presence of Hydrologic & Other Variations

Given: “Consistent” Long-Term Dataset

Regression Model:

\[ \text{Meas. Load} = \text{Mean} + \text{Management} + \text{Hydrology} + \text{Random} \]

\[ L = M + \Delta M? + B (Q - Q_M) + E \]

\[ Q = \text{Relevant Hydrologic Variable (Flow, Rainfall, Stage, etc.)} \]

Hydrologically Adjusted Load:

\[ L_A = L + B (Q_M - Q) = M + \Delta M? + E \]

Removing Hydrologic Variation Increases Power for Detecting Change
Tracking Phosphorus Loads in the Everglades
Structure TP Loads
WY 1978 - 1991

Flow-Weighted-Mean P Concentrations
Structure TP Loads
&
Marsh Frequencies
TP > 10 ppb
WY 1978 - 1991
<table>
<thead>
<tr>
<th>Time Period</th>
<th>Plan/Project Description</th>
<th>Plan (ppb)</th>
<th>Actual (ppb)</th>
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<tr>
<td>1991</td>
<td>Law Suit Settlement</td>
<td>170</td>
<td>170</td>
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<tr>
<td>1995</td>
<td>Phase 1 BMP's 25% Reduc</td>
<td>130</td>
<td>100</td>
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<tr>
<td>1999-2003</td>
<td>Phase 1 Stormwater Treatment Areas</td>
<td>50</td>
<td>20-40</td>
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<td>1995-2003</td>
<td>Treatment Technology Research</td>
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<td>1995-2002</td>
<td>Marsh P Threshold Research</td>
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<tr>
<td>2003</td>
<td>Adopt Numeric P Standard (~ 10 ppb ?)</td>
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<td>2006</td>
<td>Enhanced BMP's / STA's</td>
<td>10</td>
<td></td>
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Tracking Model Applications to Everglades

- EAA BMP Rule
- C139 BMP Rule
- Loxahatchee Refuge
- Marsh P Levels
- Stormwater Treatment Area
- Discharge Permits
- ENP Inflow P Limits
Total P Analysis - Everglades Round Robin
8 Labs, 33 Samples Collected on 7 Dates, Triplicate Analyses
Lab Result Compared with Median Value for Reference Labs

Low Range (0 – 30 ppb)

High Range (0 – 200 ppb)
EVERGLADES
BEST MANAGEMENT PRACTICES
PROGRAM
SOUTH FLORIDA WATER MANAGEMENT DISTRICT

- Basin Area ~500,000 Acres
- Objectives
  - Implement BMP’s!
  - 25% Reduction in Basin P Load
  - 1979-1988 Baseline
- Regulatory Rule Effective 1995
- Monitoring Program
  - Weekly Composite Sampling
  - Basin-Scale ~35 Sites
  - Farm-Scale ~200 Sites
Software for Tracking EAA & WCA Phosphorus Loads

System-Wide Trends

EAA Basin Compliance

Farm-Scale Data Analysis
Tracking EAA Total P Loads

Model:

\[ \text{TP Load} = \text{Reduction} + \text{Rainfall-Effect} + \text{Random} \]

Objective: 25% Load Reduction vs. 1979-88
Tracking EAA Total P Loads

Model Calibration: \( R^2 = 0.91 \)

TP Load = Reduction + Rainfall-Effect + Random

Objective: 25% Load Reduction vs. 1979-88
Tracking EAA Total P Loads

TP Loads Adjusted to Average Rainfall

Objective: 25% Load Reduction vs. 1979-88
Tracking EAA Total P Loads

\[
\text{TP Load Reduction} = 1 - \frac{\text{LO}}{\text{LP}}
\]

LO = Observed Load
LE = Predicted from Rainfall, 1979-1988

Load Reduction (%)

Water Year


Base Period

Target = 25%

1-Year
3-Year

La Isla Okeechobee EAA Basin WCA EBP
Model:

TP = Reduction + Rainfall-Effect + Random

Objective: 25% Load Reduction vs. 1979-1988
Deriving Sub-Basin Targets to Achieve Basin Target
EAA Farm-Scale Unit Area Loading Rates, ~200 Hydrologic Units

Lake Okeechobee

- 55% of Load from 20% of Area
- 40% of Load from 10% of Area

Farm Max 4 lbs/ac-yr would require additional BMP’s on 6% of the total farm area & provide additional 16% reduction of total load from all farms

Maximum Farm UAL (lbs/acre-yr)

Additional Load Reduc (%)
Tracking C139 Basin P Loads

Model: Effective 2003
TP Load = Rainfall-Effect + Random
Objective: No Increase vs. 1979-1988
Tracking C139 Basin P Loads

Model: \[ R^2 = 0.89 \]

TP Load = Rainfall-Effect + Random

Objective: No Increase vs. 1979-1988
Tracking C139 Basin P Loads

12-Month Rolling Average Loads

Observed & Predicted from Rainfall
Tracking C139 Basin P Loads

TP Loads Adjusted to Average Rainfall

Objective: No Increase vs. 1979-1988

Base Period Mean

Target (>=2003)

Adjusted Total P Load (mtons/yr)

Water Year
Tracking ENP Inflow P Concentration

Model: Effective 2003

TP = Trend + Flow-Effect + Random

Objective: Restore 1978-1979 Levels
Tracking ENP Inflow P Concentration

Model Calibration: \( R^2 = 0.80 \)

\( TP = \) Trend + Flow-Effect + Random

Objective: Restore 1978-1979 Levels
Tracking ENP Inflow P Concentration

Flow-Dependent Compliance Limits

TP = Trend + Flow-Effect + Random

De-trended to 1978-1979 Conditions
Tracking ENP Inflow P Concentration

Inflow P Adjusted to Average Basin Flow

Objective: Restore 1978-1979 Levels
Related Links

This Presentation:  wwwwalker.net

FLUX – Load Calculation Software:
http://www.wes.army.mil/el/elmodels/emiinfo.html
http://www.wes.army.mil/el/elmodels/index.html

Everglades:
http://www.sfwmd.gov/org/wrp/
http://www.sfwmd.gov/org/wrp/wrp_evg/2_wrp_evg_glades/2_wrp_evg_glades.html
http://www.wwwalker.net/clearwtr/index.htm
http://www.wwwalker.net/pdf/wqtrends91.pdf

Onondaga Lake:
http://www.lake.onondaga.ny.us/