Addressing Uncertainty in Watershed Management

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Uncertainty

- A lack of complete knowledge
- Prediction error resulting from limitations in data and models

Important in:

- Assessment
- Planning
- Implementation
- Progress assessment
TMDL

TMDL = $\sum WLA + \sum LA + MOS + \text{Future Growth}$

- **WLA** = point source load allocation
- **LA** = nonpoint source load allocation
- **MOS** = margin of safety to account for uncertainty in analysis
- **Future Growth** = allowance for load derived from future growth in the watershed
Margin of Safety (MOS)

- MOS is included in the TMDL to account for uncertainty in the analysis.
- The inclusion of an MOS term acknowledges our ignorance regarding both the water quality problem and the solution to the problem.
- Fortunately, some uncertainty can be quantified with reasonable success:
  - Weather predictions, flow estimates, concentration.
- Unfortunately, some uncertainty cannot be quantified:
  - Land use changes, social forces, economic forces.
Margin of Safety: Two Approaches

Explicit: Allowable pollutant load is reduced by some percentage before required reductions are calculated.

• More straightforward and defensible (?)
  • Walker (2001) on P TMDL analysis for lakes: use best input estimates and an explicit MOS
• Values have ranged from 5% to >40%
  • Maine’s statewide bacteria TMDL has explicit 10% MOS for bacteria mass loading (ENSR 2009)
• Quantifies the planners’ assessment of uncertainty
• Provides a benchmark for assessing progress for adaptive management
Margin of Safety: Two Approaches

*Implicit*: Conservative assumption(s) about pollutant reductions are made at various steps in the process.

- Common practice to incorporate one or two conservative assumptions into an implicit MOS
  - Malibu Creek CA bacteria: used wet-year scenario for target loads as a “worst case” loading scenario (CRWQCB 2004)
  - Lower Pocomoke MD/VA bacteria: used reduced die-off rate coefficient to calculate target loads (MDE & VDEQ 2009)
  - Buzzards Bay MA pathogens: implicit MOS assuming no bacteria die-off or dilution in receiving waters (MA DEP 2009)
- Can be taken to extremes: too many unquantified assumptions
Assessment Uncertainty

- **Environmental Variability**
  - Distance, direction, and elevation relative to pollution sources
  - Nonuniform distribution of pollution: topography; hydrogeology; meteorology; tides; biological, chemical, and physical redistribution mechanisms
  - Diversity in species composition, sex, mobility, and preferred habitats
  - Variation in natural background levels over time and space
  - Variable source emissions, flow rates, and dispersion parameters over time
  - Buildup or degradation of pollutants over time.

Gilbert 1987
Assessment Uncertainty

- Water Quality Criteria
  - Adequacy to protect uses
    - Stems from incomplete knowledge of how the environment works
    - Relationship of indicator bacteria to pathogens
  - Monitoring protocols used to assess use support
    - Sampling location(s)
    - Sampling frequency
    - Weather/season

Harwood et al. 2005
Match of monitoring parameters to criteria
Turbidity vs. SSC

- Error is introduced (SE)
- Different relationship for each stream
- Data intensive exercise

Power regression equations for estimating SSC from in-stream turbidity (T).

<table>
<thead>
<tr>
<th>Station</th>
<th>Power Model Equation</th>
<th>$R^2$ and Standard Error</th>
</tr>
</thead>
</table>
| 1       | $SSC=1.70 \cdot T^{1.04} \cdot (1.10, \text{Bias Correction Factor})$ | $R^2 = 0.912$  
|         |                      | SE=33.2                  |
| 2       | $SSC=1.85 \cdot T^{0.988} \cdot (1.17, \text{Bias Correction Factor})$ | $R^2 = 0.948$  
|         |                      | SE=39.3                  |
| 3       | $SSC=1.45 \cdot T^{1.08} \cdot (1.13, \text{Bias Correction Factor})$ | $R^2 = 0.964$  
|         |                      | SE=30.1                  |

Uhrich and Bragg 2003
Assessment Uncertainty

- Monitoring
  - Design
    - Site selection – representative?
      - Seasonal
      - Diurnal
      - Habitat
    - Temporal and spatial for chemistry
  - Collection methods
  - Sample handling
  - Sample analysis
  - Data analysis (including modeling)
Seasonal Variation

E. Coli Counts 1995 - 1998
Lake Champlain Basin Ag Watersheds NMP Project

E Coli Counts (#/100 ml)

WS 1
WS 2
WS 3

VT WQS

12-Apr-95 30-Oct-95 15-May-96 16-Dec-96 02-Jul-97 21-Jan-98 29-Jul-98

Meals 2001
Assessment Uncertainty

• **Source Identification**
  • Pollutant pathways understood?
    • Garvin Brook, MN: 15 wells drilled for baseline monitoring later found to yield water from 30 years earlier and not reflect current or near-term land management (Wall et al 1992)
  • False assumptions?
    • e.g., Oak Creek, AZ: ID’d recreation as source of bacteria contamination, finding later that wildlife was the source (NCSU 2009)
    • e.g., RI TMDLs: Septic systems ID’d as source of bacteria, but septic system failure rate <3% and many homes on waterbodies have been on sewers for more than a decade (RI DEM 2008)
Assessment Uncertainty

- **Source Identification (cont.)**
  - Were land use and management assessed properly?
    - **Court Creek, IL:** Crop production assumed source of erosion, yet studies showed streambank erosion to be major sediment source:
      - >50% in Court Creek (Roseboom and White 1990)
      - >40% in Spoon River, IL (Evans and Schnepper 1977)
  - Was the management of sources by people representative of the norm?
Planning Uncertainty

**Target Loads**

- Representativeness of underlying database for modeling
- Point source load assumptions (issues with NPDES data)
  - May report permitted concentration rather than actual concentration
  - May report design, permitted, or actual discharge
- Factoring in CSO, SSO, CAFO, and stormwater
Planning Uncertainty

• **Source Contributions**
  - True natural background
  - Establishing baseline condition
    - How to use historical data
    - Variable loading (e.g., seasonal)

• **The Load Calculation**
  - Simulation study for some Great Lakes tributaries revealed that data from a monthly sampling program, combined with a simple load estimation procedure, gave load estimates which were biased low by 35% or more 50% of the time.

Richards and Holloway 1987
Planning Uncertainty

- **BMP Performance**
  - Effectiveness variability (e.g., research vs. as-built)
  - Dependence on weather
  - Dependence on human behavior in operation & maintenance of structural practices and in management actions for management-based practices
Range in Reported Removal Efficiencies for Vegetated Filter Strips Treating Surface Runoff

<table>
<thead>
<tr>
<th>Reference</th>
<th>TP%</th>
<th>TN%</th>
<th>SS%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dillaha et al. 1988</td>
<td>2%</td>
<td>1%</td>
<td>31%</td>
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<tr>
<td>Mendez et al. 1996</td>
<td>26%</td>
<td>21%</td>
<td>-</td>
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<tr>
<td>Daniels and Gilliam 1995</td>
<td>55%</td>
<td>40%</td>
<td>53%</td>
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<tr>
<td>Chaubey et al. 1995</td>
<td>74%</td>
<td>67%</td>
<td>-</td>
</tr>
<tr>
<td>Dillaha et al. 1989</td>
<td>93%</td>
<td>93%</td>
<td>98%</td>
</tr>
<tr>
<td>Coyne et al. 1995</td>
<td>-</td>
<td>-</td>
<td>99%</td>
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Merriman et al 2009
Planning Uncertainty

- **BMP Performance**
  - Application of expected performance depends on knowledge of pre-BMP conditions and the conditions under which BMP effectiveness was determined
    - Macatawa Watershed Project, MI: (MACC 1999)
      - P reduction strategy based on modeling assuming cropland conventionally tilled
      - Review found 65% of cropland was under residue management system.
      - Sediment and P from cropland overestimated in baseline.
      - Incorrectly focused much of 80% reduction of P on increased residue management on cropland.
Planning Uncertainty

• **Aquatic System Response – Lag Time**
  - Time elapsed between adoption of management changes and detection of measurable improvement in water quality in target waterbody.

• Uncertainties introduced by lag time:
  - Time required for installed practice to produce desired effect
  - Time required for effect to be delivered to receiving water
  - Time required for waterbody to respond to effect.

Meals et al 2010
Lag Time

- Range of reported lag times between treatment and response
  - <1 year for stream nutrients and indicator bacteria to respond to livestock exclusion
  - 10 years for macroinvertebrates to respond to treatment of mine drainage
  - 10 – 50 years for stream nitrate levels to respond to improvements in agricultural nutrient management.
Planning Uncertainty

- Weather and Flow

More Flow = Greater NPS Load
Management Measures Implemented in Year 10

Meals et al 2008
Planning Uncertainty

- Land Use and Management Changes
  - Urbanization: affected by local, national, or even global economy;
  - Federal, State, or municipal planning, zoning, and regulation may radically change the way stormwater is managed;
  - Demand for ethanol or other biofuels: expanded corn acreage, including conversion of CRP land
  - Influence of commodity programs: e.g., the dairy herd buy-out in the 1980s, changing tillage, crop rotations, or animal density across large areas;
Planning Uncertainty

- **Land Use and Management Changes (cont.)**
  - Changes in animal agriculture:
    - Dairies moving from grazing to total confinement
    - Dairies changing from daily manure spreading to manure storage
    - May alter extent and timing of livestock waste applications
  - Food supply contamination: e.g., *E. coli* outbreak in spinach
    - Changed potential for land application of animal waste and stimulated waste composting and treatment;
  - Environmental disasters such as BP oil spill or emerging long-term environmental issues such as hypoxia may redirect technical, political, and financial resources to different regions or different land uses as remediation efforts proceed.
Planning Uncertainty

- Uncertainty regarding behavior of people.
  - Which are contributing to the problem?
  - Who will step forward to address problems?
  - What will be done by those who step forward?

**Disproportionality hypothesis:** A small proportion of inappropriate management behaviors in vulnerable time or space cause a disproportionate amount of the degradation in any agroecological system.

- ~60% TP load from 16% of fields in WI watershed managed by 8 of the 61 land managers.
- Design remedial solutions after learning why these inappropriate behaviors are occurring.

Nowak and Ward-Good 2010
Implementation Uncertainty

• Planned BMPs may be superseded by improved practices or shown to be ineffective or worse, e.g.,
  • Conservation tillage may lead to stratification of nutrients or pesticides in upper soil layers, leaving them more vulnerable to runoff losses;
  • Riparian buffers without the capacity to ensure sheet flow may be short-circuited by concentrated overland flow;
  • Tile and ditch drainage now shown to have deleterious effect; new conservation drainage practices are under development.
Implementation Uncertainty

- Urban infrastructures can fail or decline at any time:
  - Recent gas explosion in California
  - Multiple dam and levee failures due to heavy rains
  - Broken water mains and sewer pipes
  - Need to address these events to achieve watershed goals
- Fairfax County, VA, owns and must:
  - Maintain:
    - >1,500 miles of pipe and paved channels
    - 42,000 stormwater structures
    - 1,300 stormwater management facilities
    - 18 state regulated dams
  - Inspect ~3,000 private stormwater management facilities

Fairfax County 2009
Implementation Uncertainty

- Short-term weather patterns (e.g., wet, drought) can:
  - Influence agricultural management (e.g., fallow cropland, failed crops, changes in crop rotations)
  - Stress municipal stormwater management facilities
  - Influence pollutant loads (even with BMPs).

- Long-term climate change (e.g., more frequent and larger storm events) can threaten roads, drainage systems, dams, etc. in new & unpredictable ways.

- Federal, state, and local elections can result in major changes in:
  - Regulatory environment
  - Conservation programs
  - Commitment of resources to address watershed needs
Implementation Uncertainty

- Economic pressures, corporate lobbying, public I&E campaigns, and social movements can broadly influence human behavior and change management of land and activities associated with pollutant loads.

- When “being green”
- Agrichemical manufacturer’s disputing claims of leaching problems may derail efforts to change pesticide use (e.g., MO CEAP)
- Major reductions in milk or crop prices can decrease producers’ ability and willingness to adopt conservation practices
- Economic downturns leading to budget cuts can cause delays in upgrading stormwater or wastewater infrastructure.
Progress Assessment Uncertainty

- Same uncertainty issues as for assessment

**BUT**

- Change detection requires greater sensitivity
- Applies to both monitoring and modeling
Cumulative Uncertainty

Assessment Uncertainty + Planning Uncertainty + Implementation Uncertainty + Progress Assessment Uncertainty ≠ Total Uncertainty

or

Assessment Uncertainty X Planning Uncertainty X Implementation Uncertainty X Progress Assessment Uncertainty ≠ Total Uncertainty
Cumulative Uncertainty

- So what IS the cumulative uncertainty?
- We are uncertain, but
  - Should consider how these uncertainties might inter-relate (i.e., combine and propagate through system)
  - Seems unlikely that source ID uncertainty and lag time uncertainty would cancel?
  - Assessment and implementation uncertainty are probably at least additive?
  - Hence, the Margin of Safety (MOS) in TMDLs…
Cumulative Uncertainty

- Can’t quantify all terms of uncertainty
  - Potential land use change
  - Social forces

- Can quantify some sources
  - Predictions of weather, flow, pollutant measurements, load calculations
Recommendations

- **Acknowledge it.** Be clear with the public and other stakeholders that uncertainty exists and results may not be exactly as hoped or flat-line stable.

- **Prepare for it.** In the assessment phase, conduct effective investigations of the causes and sources of the water quality impairment before beginning an implementation effort.

- **Quantify it.** Use existing data to quantify and understand variability in natural world, pollutant generation, BMP performance. The Data Uncertainty Estimation Tool for Hydrology and Water Quality (UDET-H/WQ) (Harmel et al 2009)
Recommendations

- **Model it.** Acknowledge uncertainty in modeling procedures and results and use appropriate procedures (e.g., Monte Carlo) to estimate the effects of uncertainty.

- Physical-based modeling should include the human dimensions of land management (e.g., the influence of human behavior on BMP effectiveness) to adequately consider uncertainty in outcomes.
Recommendations

- Loading reduction targets should incorporate components that address acceptable variability in short and long-term source allocations.
  - e.g., 15% if adaptive management factored in
  - e.g., >15% if adaptive management NOT included
  - Concentration-based goals must account for the variability in the natural system and its response to treatment.
Recommendations

- **Track it.** Effective water quality and land use monitoring tells you where you are and allows for mid-course corrections.
  - Use minimum detectable change (MDC) to estimate the monitoring frequency needed to detect:
    - The load reduction required by the TMDL
    - Interim reductions that trigger adaptive management actions
Recommendations

- **Accommodate it.**
  - Use the best available scientific principles and data
  - Use MDC and other techniques to guide monitoring and evaluation programs
  - Use reasonable – but not excessive – MOS

- **Wait for it.** Accept the notion of lag time and adjust expectations accordingly.

- **Adapt to it.**
  - Use a nimble and flexible planning and implementation process so that the inevitable surprises do not derail the program
  - Use adaptive management principles, supported by good information
Costs of Not Addressing Uncertainty

- Errors in problem assessment
- Errors in planning
- Implementation of wrong BMPs
- Excessive costs to achieve goals
- Anger, Confusion and frustration
  - Those who need to implement controls
  - Those who would benefit
- Failure to achieve water quality objectives
- Decreased funding support
References

- California Regional Water Quality Control Board. 2004. Total maximum daily loads for bacteria Malibu Creek Watershed. RWQCB, Los Angeles, CA. 
  http://www.epa.gov/waters/tmdl/docs/MalibuBacteri%20TMDL%20Staff%20Report.pdf


- Fairfax County. 2009. Fairfax County stormwater service district, 


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- MA DEP, ENSR, and USEPA Region I. 2009. Final pathogen TMDL for the Buzzards Bay watershed, March 2009 CN: 251.1
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