Addressing Uncertainty in Watershed Management

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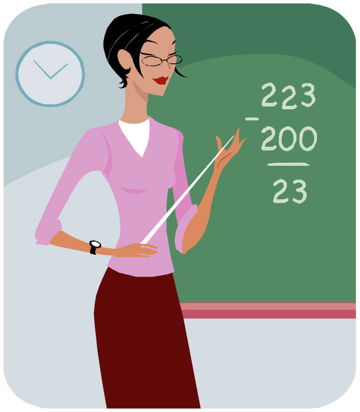
Uncertainty

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

Important in:

- Assessment
- Planning
- Implementation
- Progress assessment

TMDL



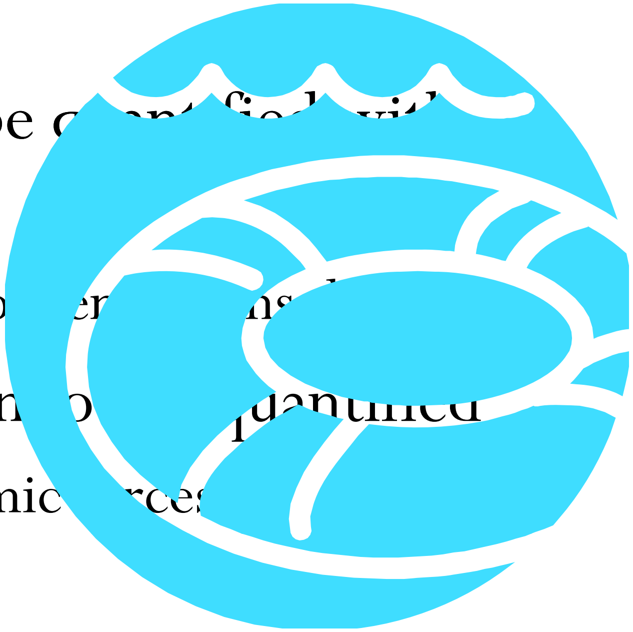
$$\text{TMDL} = \sum \text{WLA} + \sum \text{LA} + \text{MOS} + \text{Future Growth}$$

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

Total Maximum Daily Loads
TMDLs at Work

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, co [illegible]
- 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)

(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).

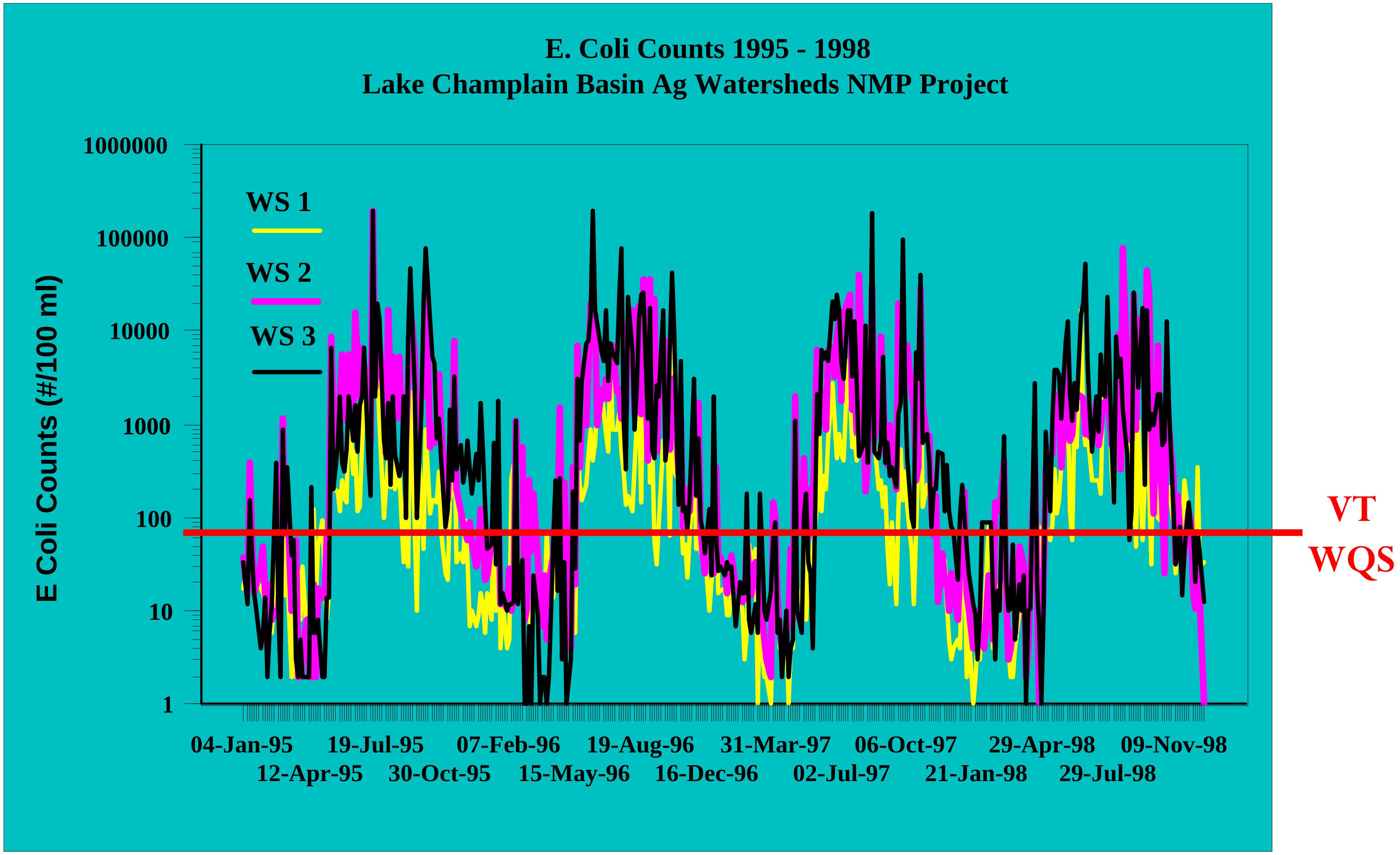
Station	Power Model Equation	R^2 and Standard Error
1	$SSC=1.70 \bullet T^{1.04} \bullet$ (1.10, Bias Correction Factor)	$R^2 = 0.912$ SE=33.2
2	$SSC=1.85 \bullet T^{0.988} \bullet$ (1.17, Bias Correction Factor)	$R^2 = 0.948$ SE=39.3
3	$SSC=1.45 \bullet T^{1.08} \bullet$ (1.13, Bias Correction Factor)	$R^2 = 0.964$ 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



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

Reference	**TP%**	**TN%**	**SS%**
Dillaha et al. 1988	2%	1%	31%
Mendez et al. 1996	26%	21%	-
Daniels and Gilliam 1995	55%	40%	53%
Chaubey et al. 1995	74%	67%	-
Dillaha et al. 1989	93%	93%	98%
Coyne et al. 1995	-	-	99%

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.

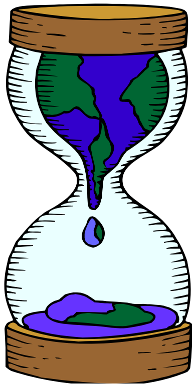
Planning Uncertainty

- 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.

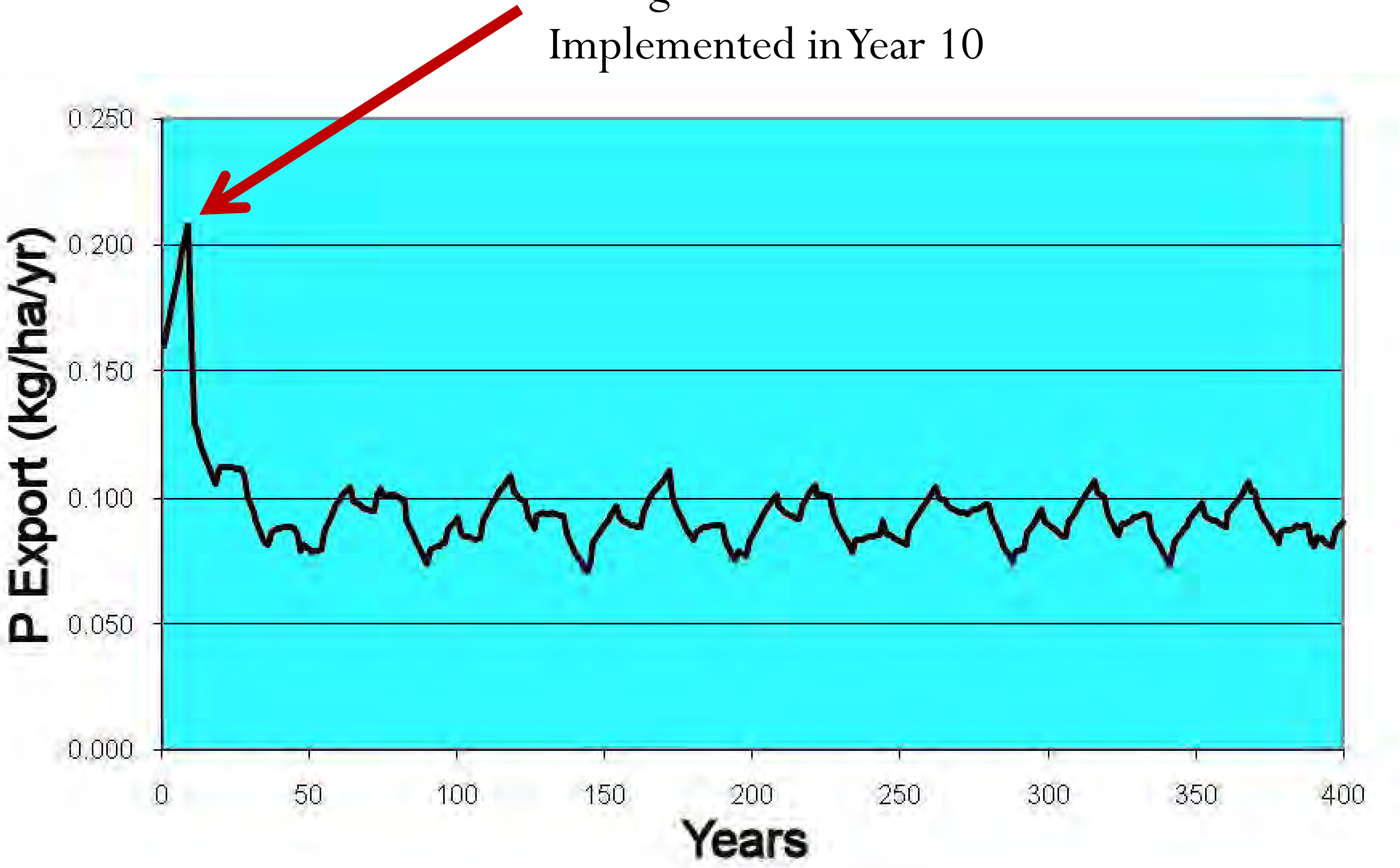


Planning Uncertainty

- 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.

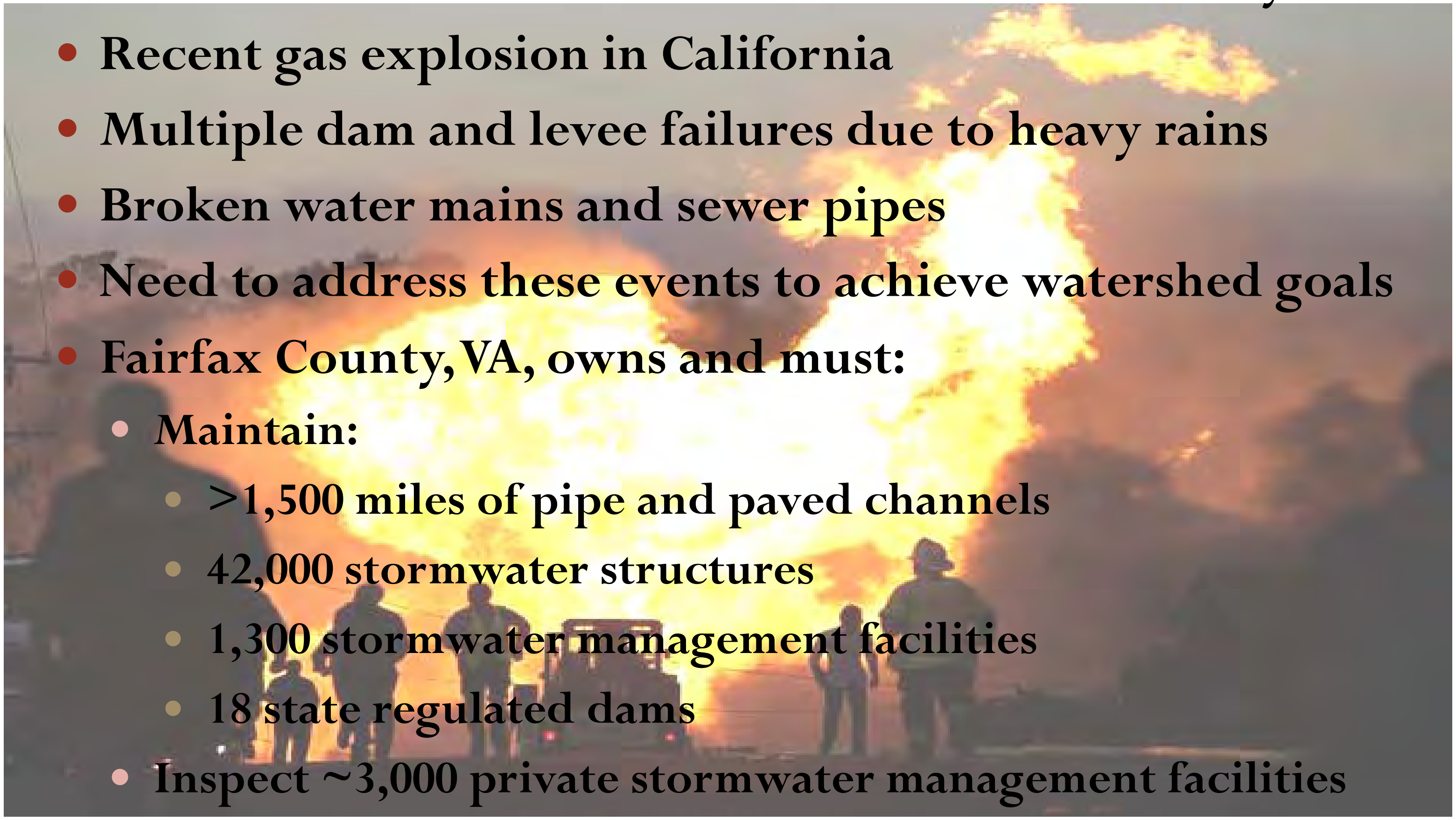
Nowak and Ward-Good 2010

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

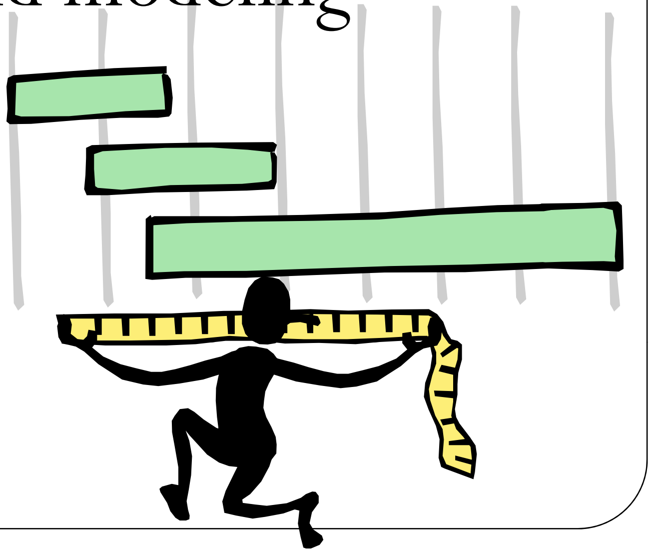
- Economic pressures, corporate lobbying, public I&E campaigns, and social movements can broadly influence human behavior and change management of land and activities associated with pollutant loads.
  - When "being green"
  - Agrichemical manufacturer's disputing claims of leaching problems may derail 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

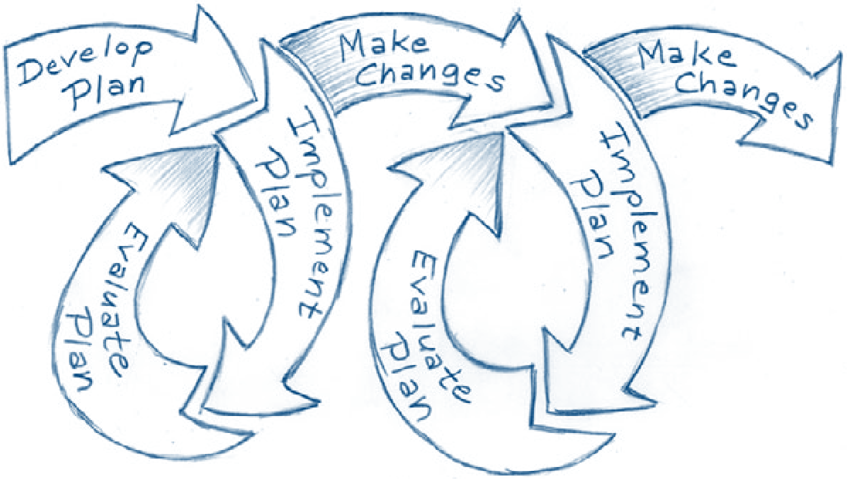
- **Acknowledge it.** Be clear with the public and other stakeholders that uncertainty exists and results may not be exactly as hoped or flat-line stable
- **Prepare for it.** In the assessment phase, conduct effective investigations of the causes and sources of the water quality impairment before beginning 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

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