A Framework for Ensuring Selection of the Proper Receiving Water & Watershed Model

How to Avoid Inappropriate Model Selection and Ensure Developing a Useful Problem Solving Tool

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Workshop Outline

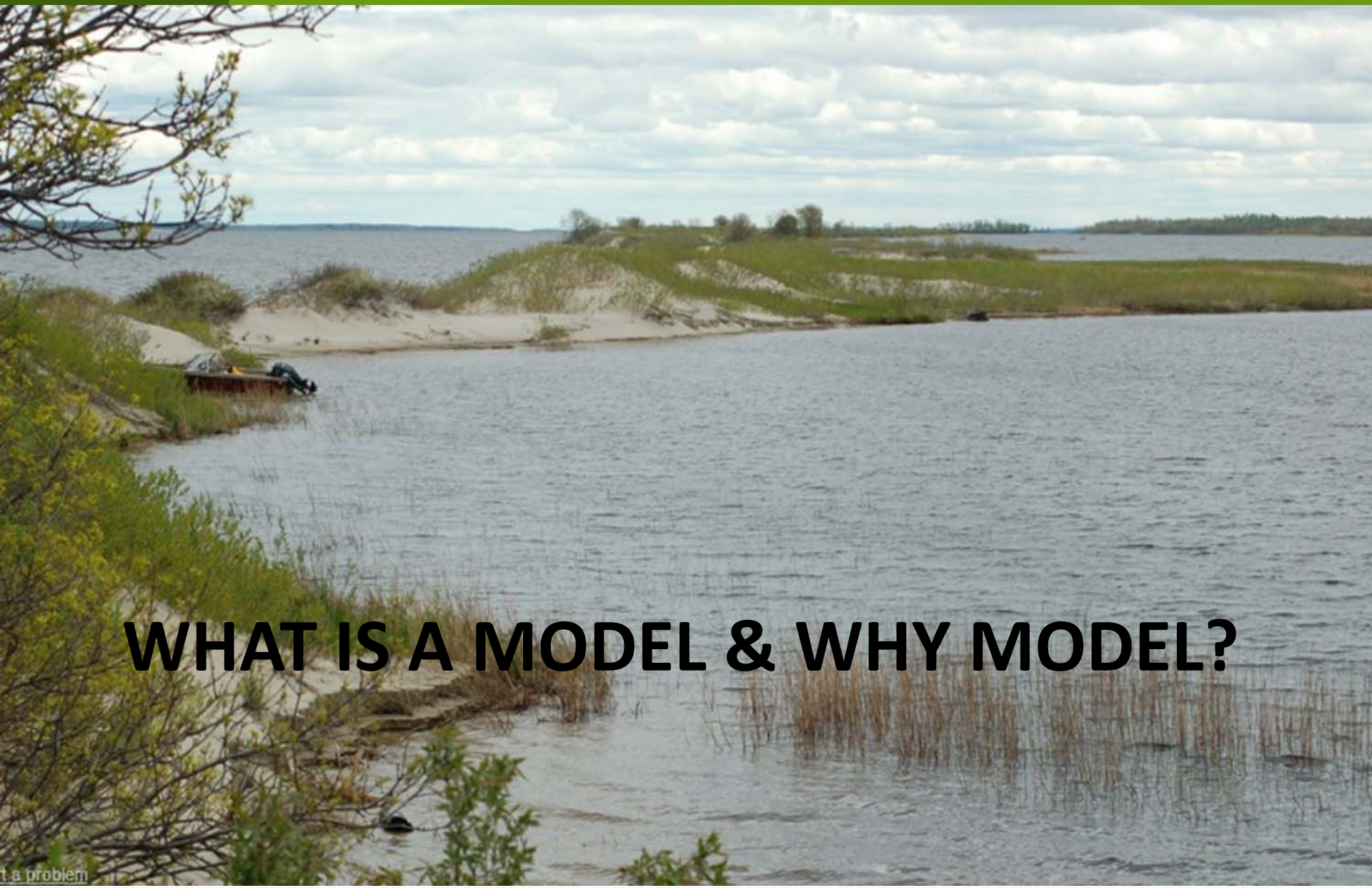
- Introductions & LGU Exposure to Model Use
- Workshop goal
- Things models can and can’t do
- Types of models
- What is a model and why model?
- Model selection framework and dealing with uncertainty
- How to know you are being buffaloed
- How much should it cost?
- Questions (and hopefully answers)
- Fill out your action plan

Possible Reasons for LGU Staff "Exposure" to Models & Modeling

- Writing a work plan for a project
- Selecting a model for a project
- Hiring someone (staff / consultant)
- Reviewing model results (contractually)
- Interpreting & using modeling results
- Implementation plan development
- Forced to

Workshop Goal

- Provide you with basic information so you can:
  - Ask questions to ensure proper model selection
  - Understand model use limitations
  - Receive a model (tool) suitable for making your resource decisions
  - Protect your fiscal investment
  - Know when your leg is being pulled



WHAT IS A MODEL & WHY MODEL?

What is a Model?

"Idealized formulation that represents the response of a physical system to external stimuli"
– Chapra, 1997; Surface Water Quality Modeling

Hydrology

Precipitation

Characteristics of System
(e.g., land use/ cover, slope, soils)

Streamflow

Receiving Water Quality

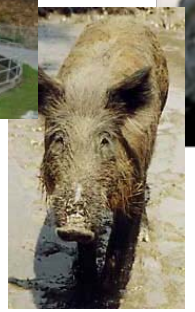
Pollutant Load (Watershed)

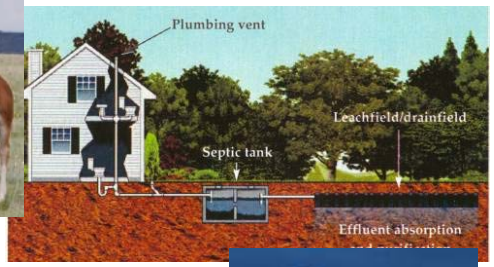
Characteristics of Waterbody
(e.g., mixing, plants/ bugs, chemical reactions)

Pollutant Concentration

Watershed loading models include hydrology and quality.

Modeling: A Simulation of Nature





Bacterial Load into System (CFU/year)

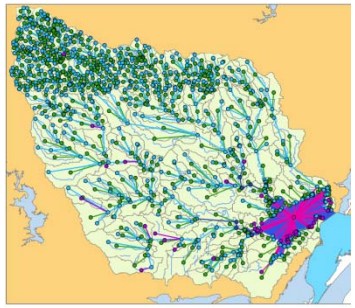
Loading Inputs

Other Inputs

- Decay rate (years^{-1})
- Flows (m^3/yr)
- Tides (m^3/yr)
- Bacteria moving with tides (CFU/100mL)

MODEL

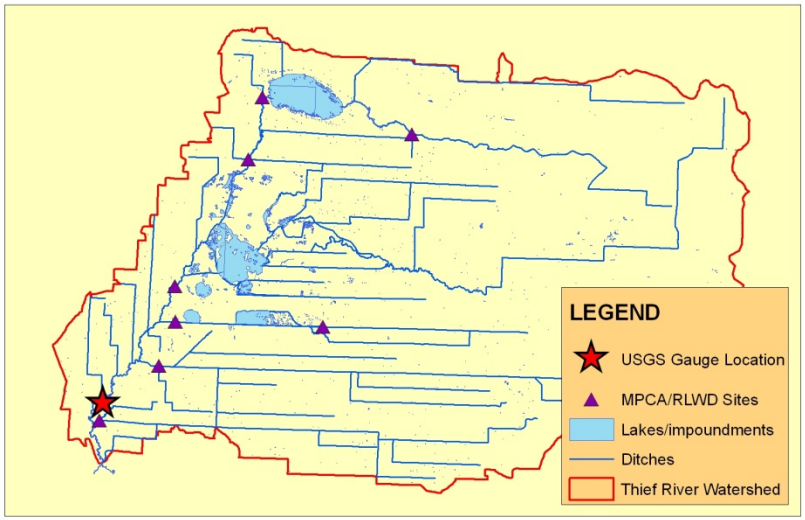
- Sums up total bacteria
- Moves bacteria downstream
- Transforms bacteria (i.e., decay)



Concentration of Bacteria in the System (CFU/mL)

Model Outputs

Why Model?



- Simulate current conditions
  - Extend understanding of water quality (spatially/temporally)
  - e.g., estimate loads at un-gauged locations
- Understand system behavior
- Determine relationship between variables
- Predict future conditions
  - Estimate impacts of “what if” scenarios on your study area

TYPES OF MODELS

Classifying the Types of Models

- Engineering Applications
  - Hydrology (peak rate an volume of runoff)
  - Hydraulics (water elevation and velocity)
  - Hydrodynamic (2-d and 3-d hydraulics)
- Environmental Applications
  - Watershed (runoff volume, runoff rate, concentration and load)
  - Receiving water

Focus of this workshop is environmental applications.

Importance of Scale: Space and Time

- Watershed
  - Load and runoff volume estimation
  - Relative to monitoring locations
  - Receiving waters (for loads)
  - Implementation strategies (e.g., BMPs)
- Receiving Water
  - Depth, longitudinal, and lateral average (zero order)
  - Longitudinally and laterally averaged (one-dimensional)
  - Laterally averaged (2-dimensional)
  - No spatial averaging (3-dimenstional)

You MUST be able to match the spatial scale of the model to the real world problem!

Importance of Scale: Space and Time

- Watershed
  - Annual (steady state - SS)
  - Monthly
  - Daily
  - Less than daily (unsteady)
- Receiving Water
  - Annual (steady state)
  - Growing season
  - Monthly
  - Daily
  - Less than daily (unsteady - US)

TMDLs
Standards

You MUST be able to match the time scale of the model to the real world problem!

Empirical vs. Mechanistic Models

Empirical

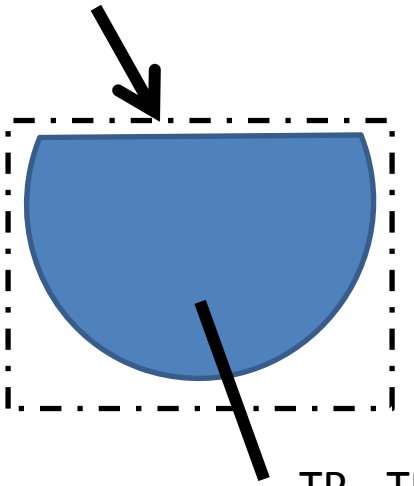
Based on observed data

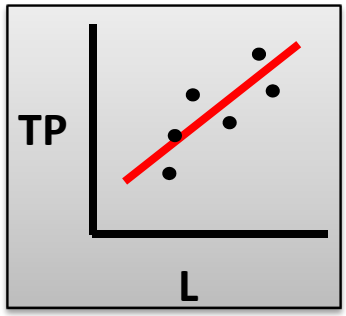
Mechanistic

Based on theory; process-based

Example: BATHTUB

$L_1, L_2, \ldots L_n$

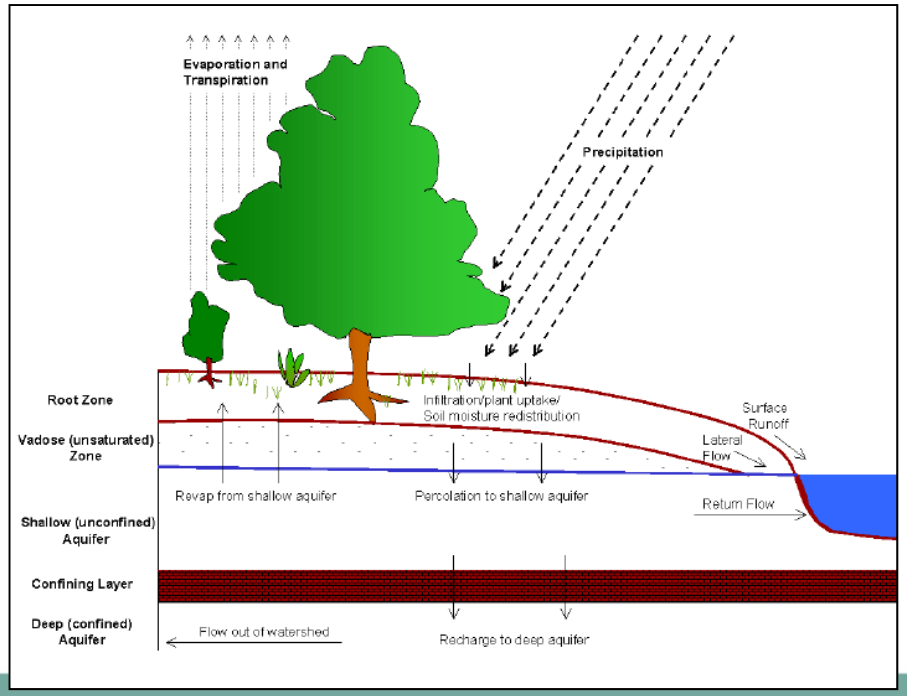




$TP_1, TP_2, \ldots TP_n$

$Chla_1, Chla_2, \ldots Chla_n$

Example: SWAT



Pros and Cons

Empirical

Pros

- Usually pretty simple/ cheap/easy to create
- Driven by data; can be more transparent

Cons

- Can only look at situations that are reflected by your data (timeframes, conditions)
- Best of you have lots of data
- Assume causality and no compounding variables

Mechanistic

Pros

- More completely represent the system – if have enough data
- Can better fill in gaps where you don't have any data (temporally, conditions) – if calibrated well

Cons

- More complex/expensive/ difficult to create
- Can require lots of data and knowledge about your system

Many models use a mixture of mechanistic and empirical approaches.

Examples of Common Models

<u>Hydrology</u>

Empirical

- Unit runoff
- SCS method
- Rational Method

Mechanistic/Mixed

- HEC HMS (US & SS)
- SWMM (US)
- P8 (US)

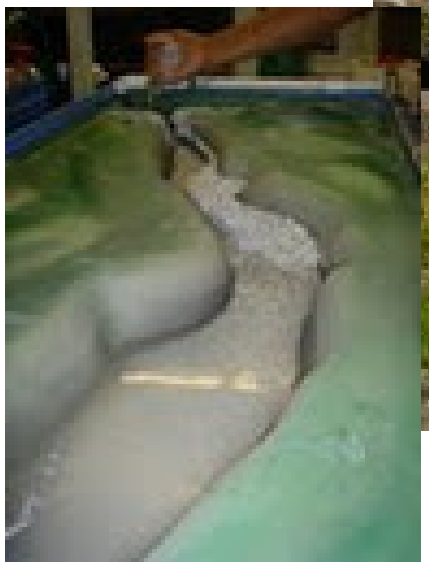
<u>Water Quality</u>

Empirical

- Load duration curves
- FLUX (empirical)
- BATHTUB (SS, zero order)
- RUSLE

Mechanistic/Mixed

- QUAL2E (1-d, SS)
- SWAT (US daily)
- HSPF (US less than daily)



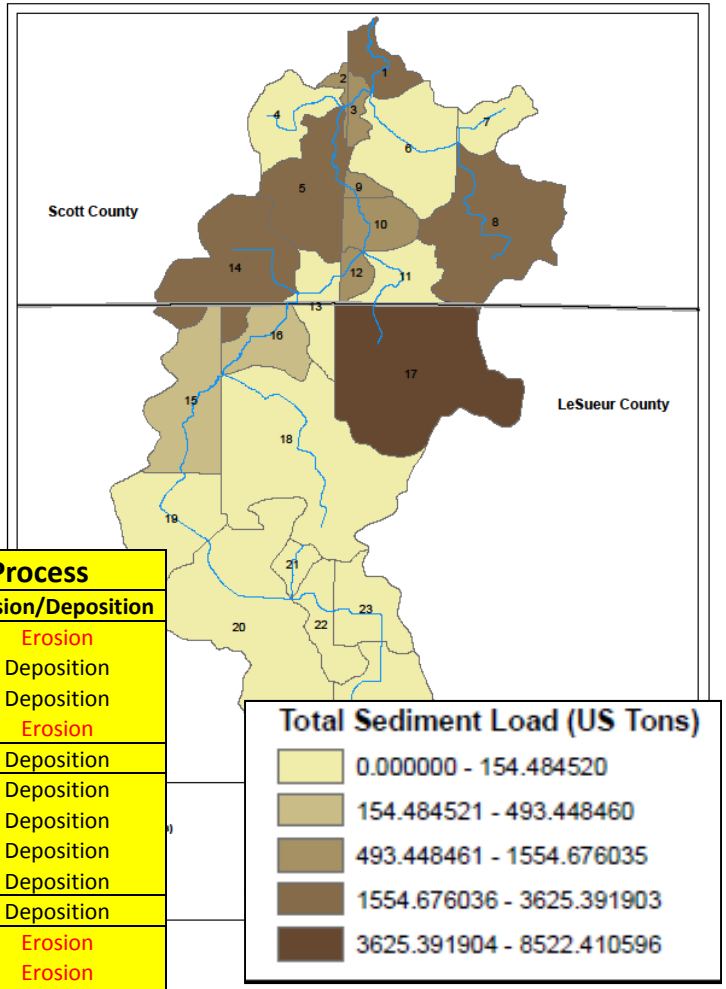
WHAT MODELS CAN AND CAN’T DO

Things Models Can / Can’t Do

- Can
  - Predict system behavior - direction and magnitude of the response (now and in future)
  - Provide absolute answer (when calibrated and validated)
  - Provide relative answer (compare alternatives) when not calibrated
- Cannot
  - Provide a guarantee – they are “weight of evidence” (can’t)
  - Provide the “right answer” if the wrong model selected
  - Prove something (weight of evidence)

Examples of Model Output

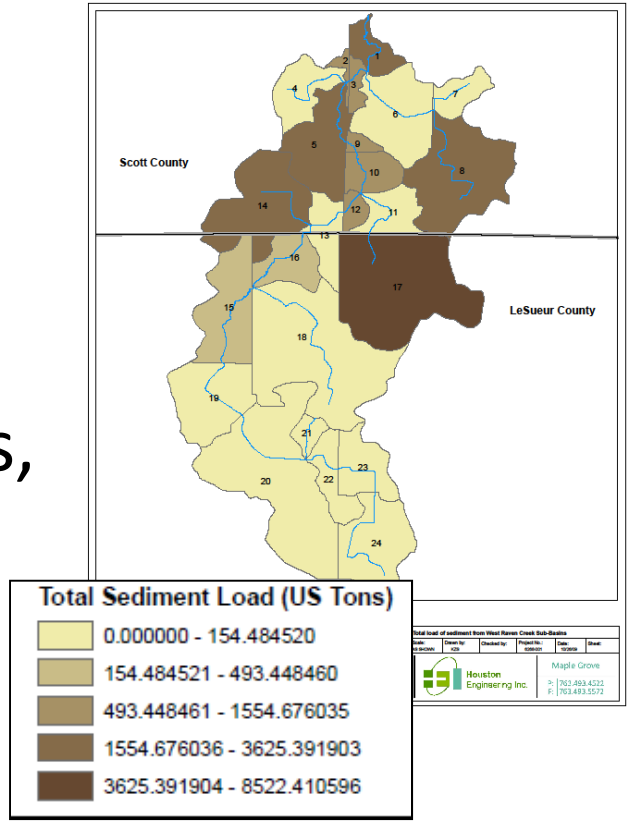
- Spatial understanding of contributions throughout the watershed
- Water, sediment, and nutrient yield throughout the watershed (by sub-basin)
- In-stream processes (i.e., erosion/ deposition)



Reach Output						In-Stream Process	
Reach		Flow in (m³)	Flow out (m³)	Sed in (tons)	Sed out (tons)	Sed in - Sed out	Erosion/Deposition
1	2004	9,698,209	9,662,555	2,032	2,128	*-96*	Erosion
	2005	6,757,056	6,716,113	1,061	903	*159*	Deposition
	2006	5,230,047	5,188,171	770	642	*129*	Deposition
	2007	7,836,210	7,797,584	1,402	1,540	*-138*	Erosion
	Average Annual	*7,380,381*	*7,341,106*	*1,317*	*1,303*	*13*	Deposition
2	2004	7,529,694	7,529,063	3,017	1,191	*1,825*	Deposition
	2005	5,179,933	5,179,171	1,469	504	*965*	Deposition
	2006	3,751,576	3,750,694	1,060	318	*742*	Deposition
	2007	5,994,920	5,994,186	2,011	862	*1,149*	Deposition
	Average Annual	*5,614,031*	*5,613,278*	*1,889*	*719*	*1,170*	Deposition
3	2004	7,641,428	7,632,245	1,306	1,527	*-221*	Erosion
	2005	5,273,866	5,263,102	629	652	*-23*	Erosion
	2006	3,832,640	3,821,263	437	411	*25*	Deposition
	2007	6,098,682	6,088,991	937	1,115	*-178*	Erosion
	Average Annual	*5,711,654*	*5,701,400*	*827*	*926*	*-99*	Erosion

Future Conditions – i.e., Scenarios

- Converting perennial cover to permanent cover
- Adding filter strips
- Temporary storage (e.g. wetlands, side inlet controls, small/shallow impoundments)
- Permanent storage
- Combinations of these scenarios



MODEL SELECTION FRAME WORK AND DEALING WITH UNCERTAINTY

Model Selection Framework

- Narrative goals
- Technical objectives
- Quantifying simulation quality
  - Calibration and validation
  - Quality assurance review steps
  - Ensuring proper documentation
  - Quantifying errors
  - Sensitivity Analysis
- Public domain or proprietary

These items are necessary to protect your fiscal investment and ensure proper use of the results

Specifications for *WATER QUALITY* MODEL DEVELOPMENT

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January 6, 2010

Example Narrative Goals and Technical Objectives

Receiving Water Model (Lake)

Example Water Quality Goals	Example Technical Objectives Corresponding to the Water Quality Goal
Lakes	
Assess and understand how the water clarity and amount and frequency of algal blooms respond to the quantity of nutrients entering and leaving the lake and evaluate potential strategies to improve water quality.	• Predict the growing season mean concentrations of total phosphorus and chlorophyll-a and a measure of clarity (e.g., secchi disc depth) as a result of current total phosphorus, dissolved phosphorus, inorganic nitrogen and total nitrogen loads. • Predict the depth and spatially-averaged lake water quality conditions as characterized by the growing season mean concentrations of total phosphorus and chlorophyll-a and a measure of clarity (e.g., secchi depth). • Explicitly identify and estimate the growing season total phosphorus load delivered to and returned by the sediment interacting with the water column. • Characterize the change in the growing season mean concentrations of total phosphorus and chlorophyll-a and a measure of clarity (e.g., secchi depth) as a result of internal and external reductions in dissolved phosphorus, total phosphorus, inorganic nitrogen and total nitrogen. • Statistically characterize the response of chlorophyll-a and a measure of clarity (e.g., secchi depth) to the change in dissolved phosphorus and inorganic nitrogen concentrations. • Assess the change in the growing season mean concentrations of total phosphorus and chlorophyll-a and a measure of clarity (e.g., secchi depth) as a result of altering the ratio of dissolved phosphorus and inorganic nitrogen delivered to the lake.

Example Narrative Goals and Technical Objectives

Receiving Water Model (River)

Rivers	
Determine whether low dissolved oxygen levels potentially cause the mortality of fish populations and the general impairment of aquatic life and to determine the maximum allowable amount of oxygen consuming inputs to a river.	• Estimate the diurnal change and minimum daily average dissolved oxygen concentration spatially-averaged for each 0.5-mile reach. • Quantify the change in the daily average mass of oxygen for each 0.5-mile reach of river, resulting from re-aeration, sediment oxygen demand, and consumption by oxygen demanding substances. • Estimate how the diurnal change and minimum daily average dissolved oxygen concentrations, spatially averaged for each 0.5-mile reach, respond to the change in reach averaged surface water temperature.

Example Narrative Goals and Technical Objectives

Watershed Water Model (Deterministic)

Example Water Quality Goal	Technical Objectives Corresponding to the Water Quality Goal
Deterministic	
Quantify the amount of nutrients and sediment leaving the landscape upstream of a lake from the contributing drainage area and prioritize the locations for implementing structural best management practices and agricultural conservation measures.	• Estimate the daily, monthly and annual average total phosphorus, dissolved phosphorus, inorganic nitrogen and total nitrogen loads (in pounds and pounds per acre) at the subwatershed scale (average subwatershed size of 1 square mile; maximum size of 5 squre miles) for dry, normal and wet hydrologic conditions. • Estimate the daily, monthly and annual loads and yields of total phosphorus and total suspended sediment leaving the landscape and delivered to a waterway at the subwatershed scale (average subwatershed size of 1 square mile; maximum size of 5 squre miles), for dry, normal and wet hydrologic conditions. • Estimate the annual average absolute (pounds) and percentage removals of total phosphorus and total suspended solids from existing structural BMPs including wet ponds, dry ponds, infiltration basins, filtration basins and similar practices.

Example Narrative Goals and Technical Objectives

Watershed Water Model (Empirical / Statistical)

Statistical	
Quantify the amount of water and nutrients delivered to a lake and describe the relative importance of the sources and losses.	• Quantify and describe the error in the estimated daily, monthly, and average annual flow and total phosphorus load at monitoring locations for the period of record of measured daily flows and grab sample total phosphorus concentrations. • Estimate the annual water balance and total phosphorus mass balance for a lake, with explicit quantification of the estimate error in the balance equations, for the period of record of measured daily flows and grab sample total phosphorus concentrations.
Determine the locations which are sources of sediment, where sediment accumulates and the rate of accumulation or loss along a river.	• Quantify and describe the error in the annual average flow and total suspended solids loads at monitoring locations along the river, for the period of record of measured daily flows and grab sample total suspended solids concentrations.

Specify Calibration and Validation

Objectives for Model Acceptance

	% Difference Between Simulated and Recorded Values		
	Very Good	Good	Fair
Hydrology/Flow	< 10	10 - 15	15 - 25
Sediment	< 20	20 - 30	30 - 45
Water Temperature	< 7	8 - 12	13 - 18
Water Quality/ Nutrients	< 15	15 - 25	25 - 35
Pesticides/Toxics	< 20	20 - 30	30 - 40

Caveats: 1) relevant to monthly and annual values; storm peaks may differ more.
2) highly dependent on quality and detail of input and calibration data.
3) purpose of model application.
4) resource availability (i.e., time, money, personnel).

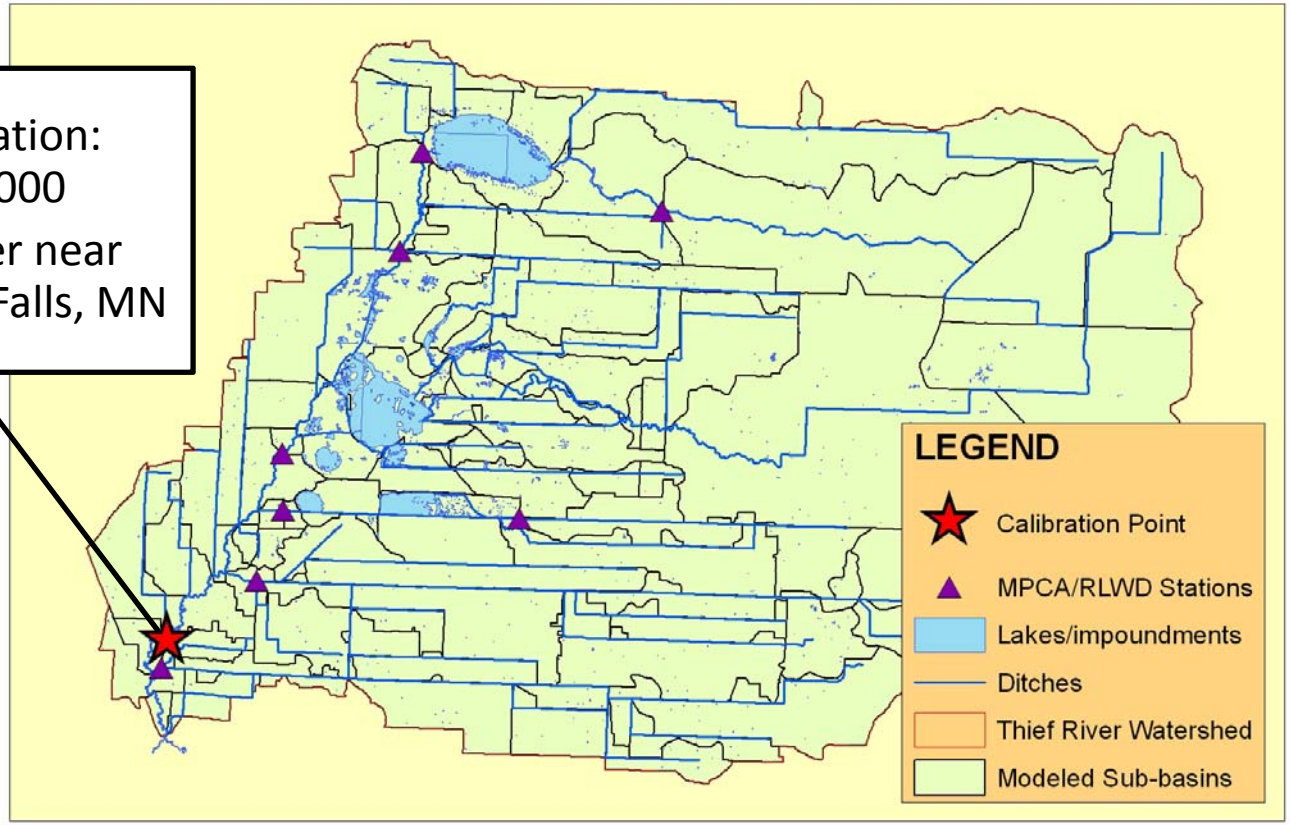
- Donigian, 2000

These should be specified in your contract.

Calibration

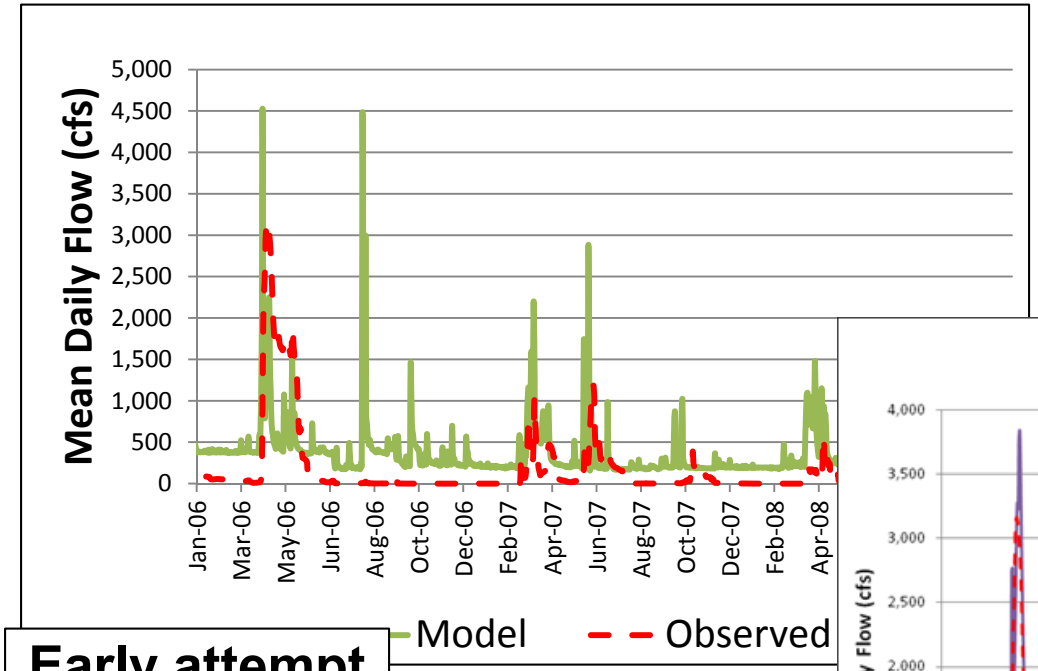
Calibration - the process of modifying the input parameters to a model until the output from the model matches an observed set of data (i.e., the model reflects "real world" conditions).

USGS Station:
05076000
Thief River near
Thief River Falls, MN



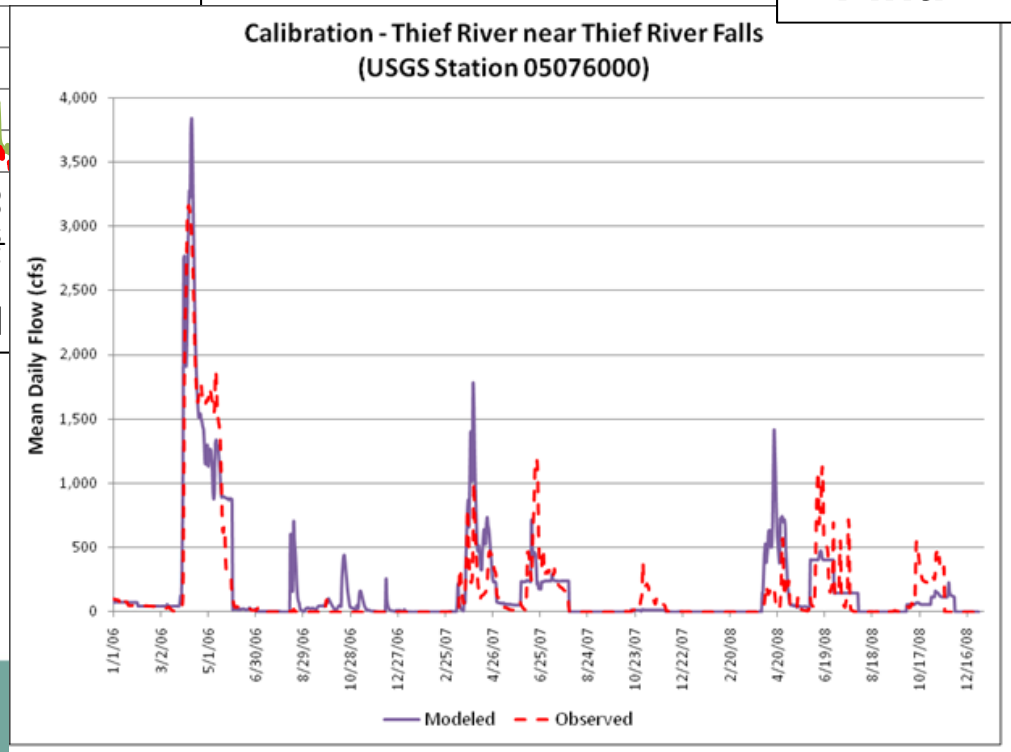
Calibrating Hydrology

Thief River Falls USGS Gauge Station



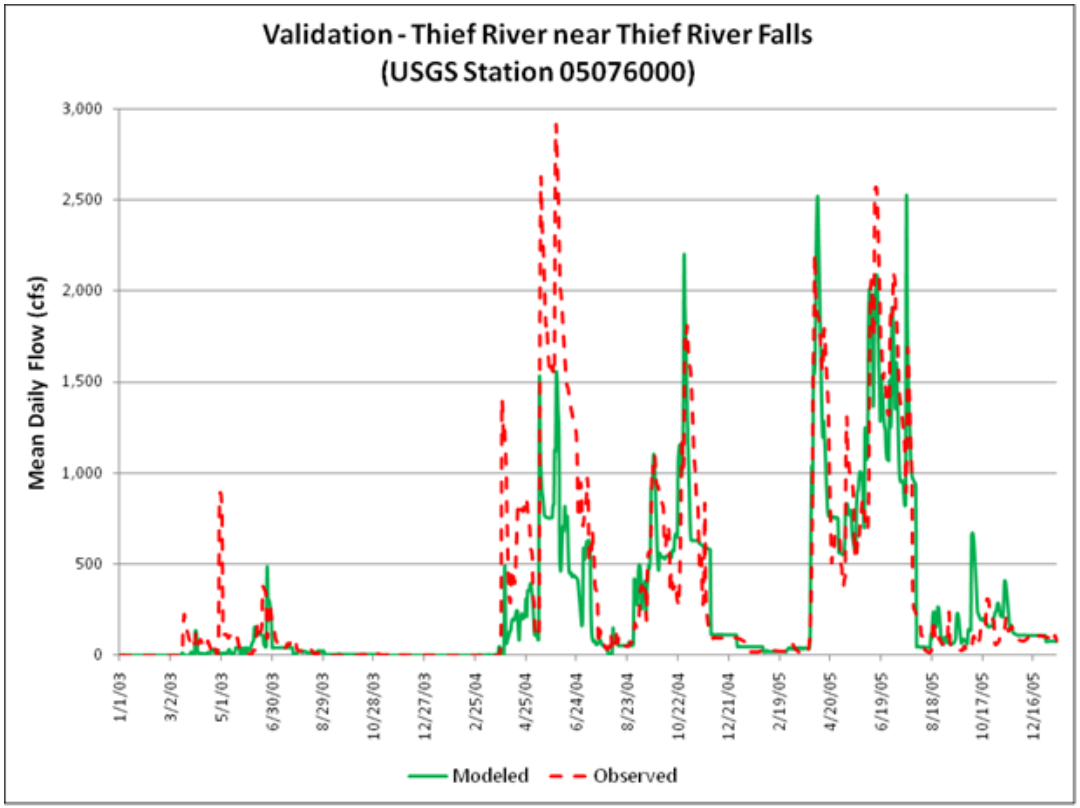
Early attempt

Final



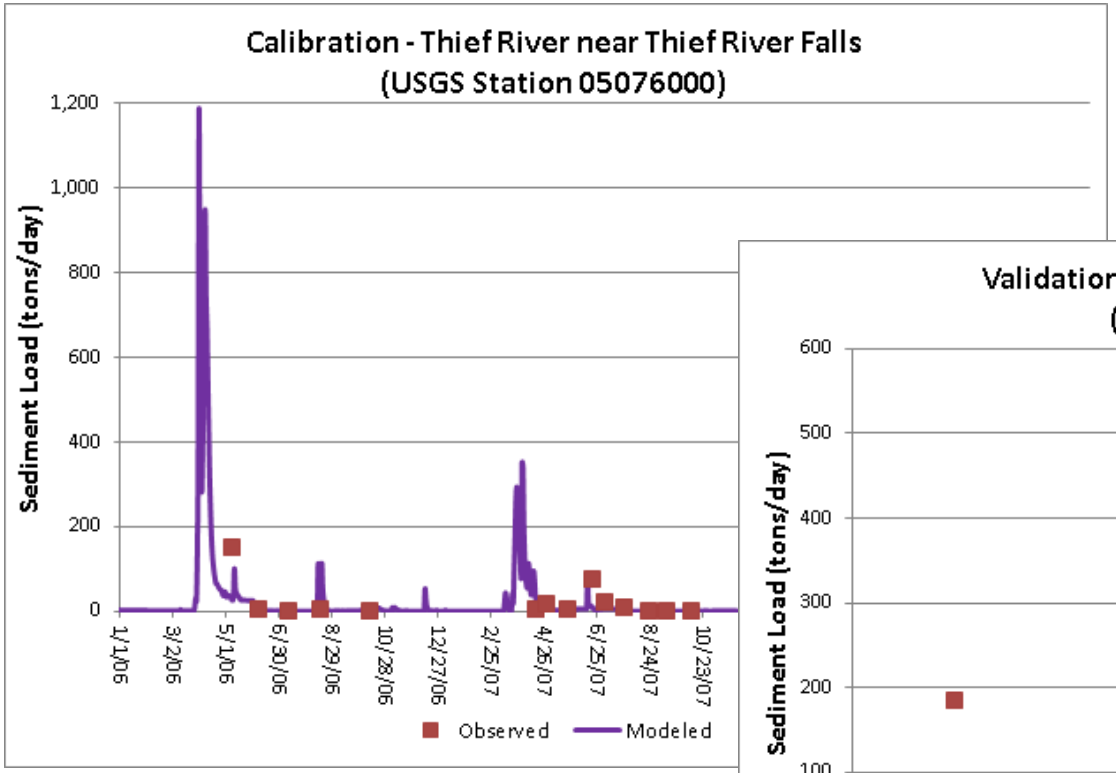
Validating Hydrology

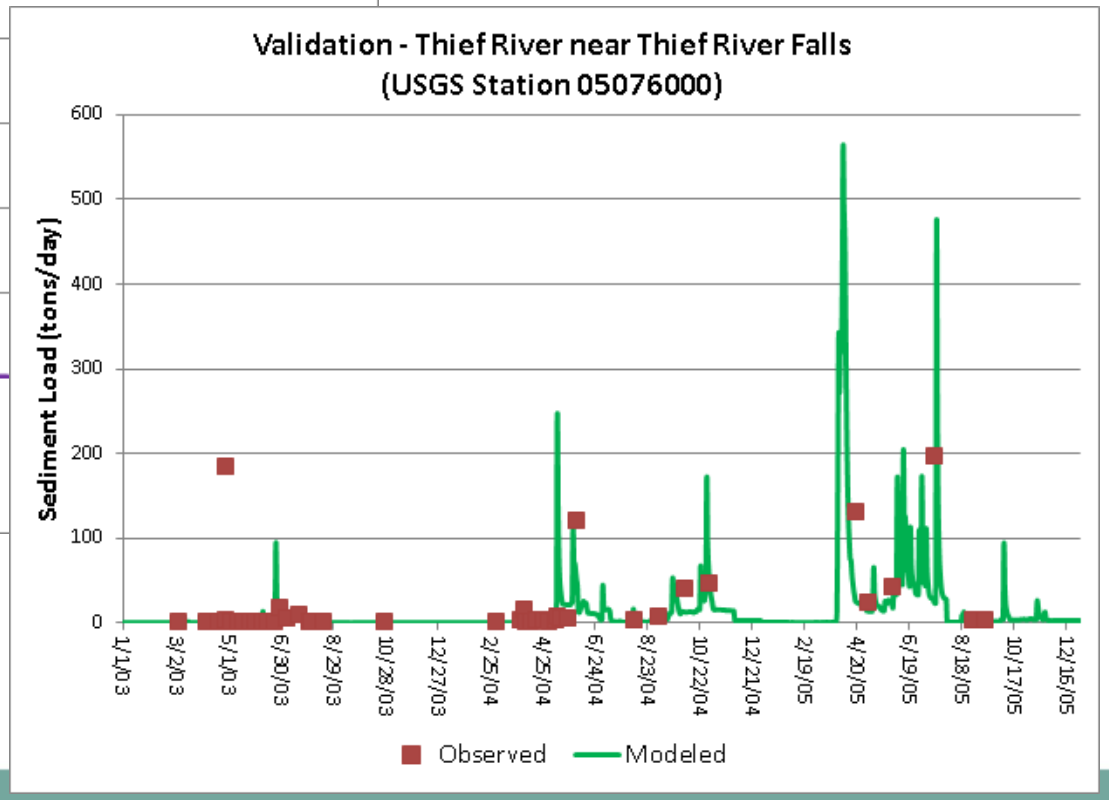
Validation - the process of verifying the model by comparing its output to observed data during a time period other than that used for calibration.



Sediment Load Calibration/Validation

Thief River Falls USGS Gauge Station





Simple Quality Assurance Review

- Does it run?
- Water and mass should balance (in – out ± error) = 0
- Schematic of how the system works physically
- Is it calibrated / validated – errors quantified.
- Plot model inputs & compare (% impervious; curve number)
- Plot model outputs and compare (e.g., against measured yields; annual runoff)

Dealing with Errors

"All models are wrong, but some are useful"

- George Box, Statistician

Three types of errors:

- Parameter
- Model
- Observational

Quantifying Error

- An error term should appear in the water and mass balances
- Calibration and validation provides a sense of model error
- Use sensitivity analysis (see if an assumption "matters") to assess parameter error
- Use stochastic (monte carlo) modeling methods
- Use long-term continuous simulation models

Knowing the magnitude of the error is important.

Checking Model Results

- Correct Amount of Water?
  - MN Hydrology Guide
  - Unit runoff from USGS Gages
  - Your monitoring data
  - Literature
- Loads / Concentrations
  - COE ERDC and literature values for yields
  - Your monitoring data
  - Common sense

Check not only central tendency, but distribution (e.g., quartiles) and range.

Ensuring Proper Documentation

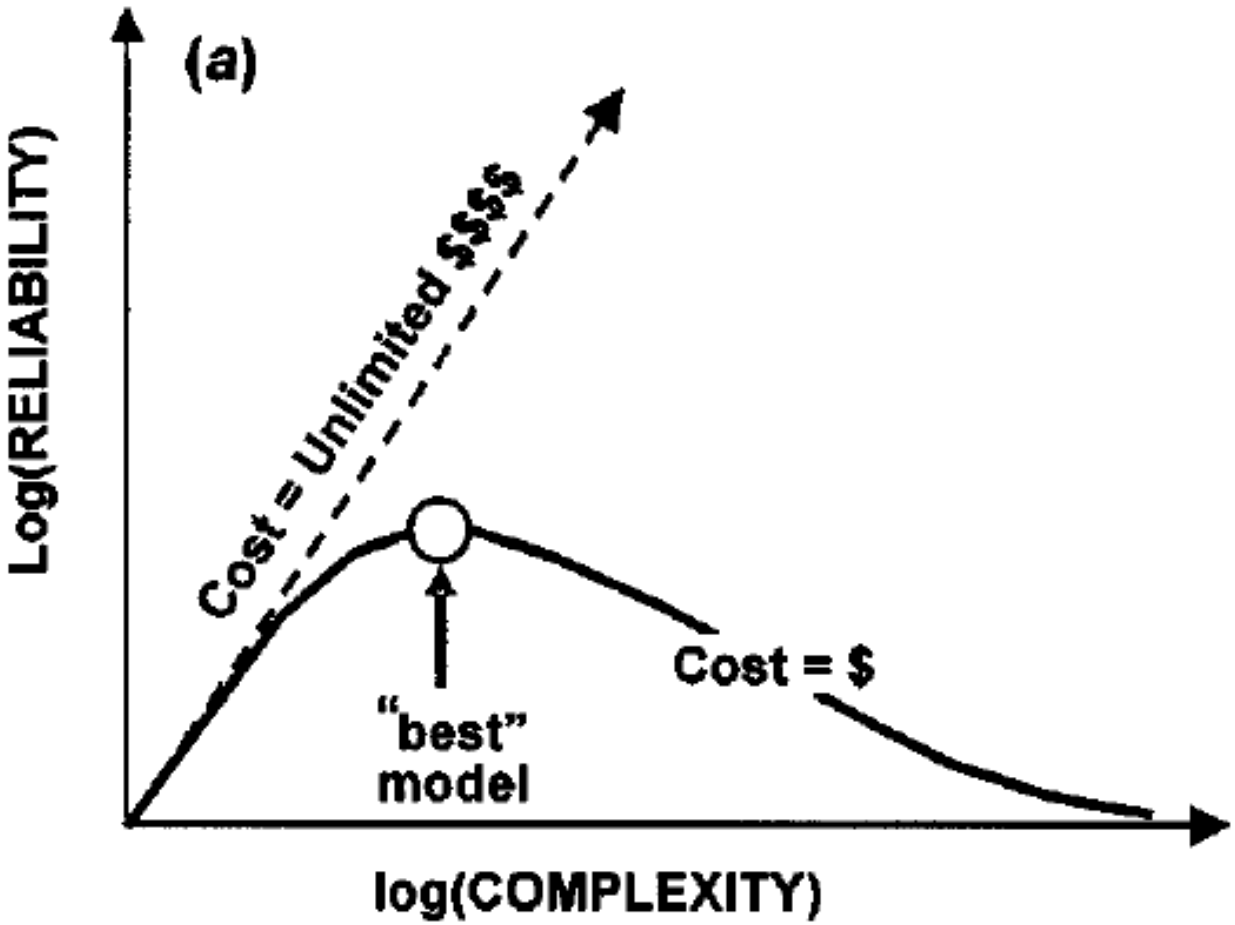
- Model Summary Table
- Model Report
  - Goals and Objectives
  - Maps
  - Assessment of Model Quality
  - Summary of Results
  - Input and output files
  - Field and survey data
  - Stick diagrams (schematics)

Public Domain vs. Proprietary Models

- Prefer public domain
- Some proprietary models use public domain engines (e.g., InfoSWMM used EPA-SWMM)
- Some proprietary models have their own methods / solution techniques – answers differ from public domain engine
- More likely others can run public domain model

This is Mark's opinion / preference.

Choosing the “Right” Model

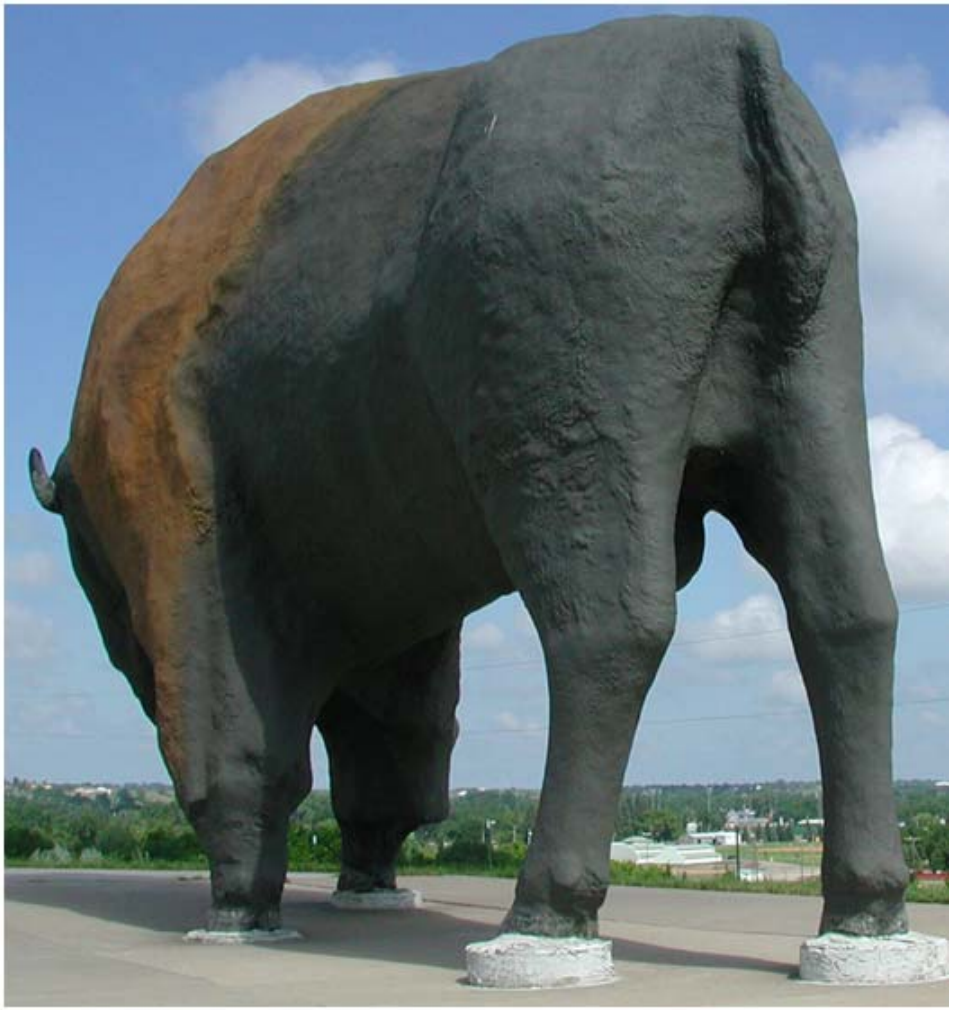


- Chapra, 1997

Model Selection Considerations

- the model is able to mathematically represent the dominant physical, chemical and biological processes occurring in the watershed or receiving water;
- the minimum model time step is equal to the temporal scale of the resource problem;
- the spatial scale of the water quality problem can be physically represented by the model discretization method;
- the chemical form of the parameters you want to model are state equation or computed from state equations within the model;
- the availability and adequacy of monitoring data for calibration and validation;
- the level of effort necessary to develop and apply the model (and therefore cost) is commensurate with the modeling accuracy required; and
- the ability to simulate the appropriate types of implementation strategies.

Knowing When You're Being Buffaloed



MODELING COSTS

How Much Should it Cost?

- Steady state generally less than unsteady.
- Finer spatial resolution, increases level of effort and cost.
- Multi-dimensional more.
- Number of alternatives more.
- Stricter calibration / validation more.
- More documentation more (maybe short term)?

The answer is it depends.

QUESTIONS (AND HOPEFULLY ANSWERS)?

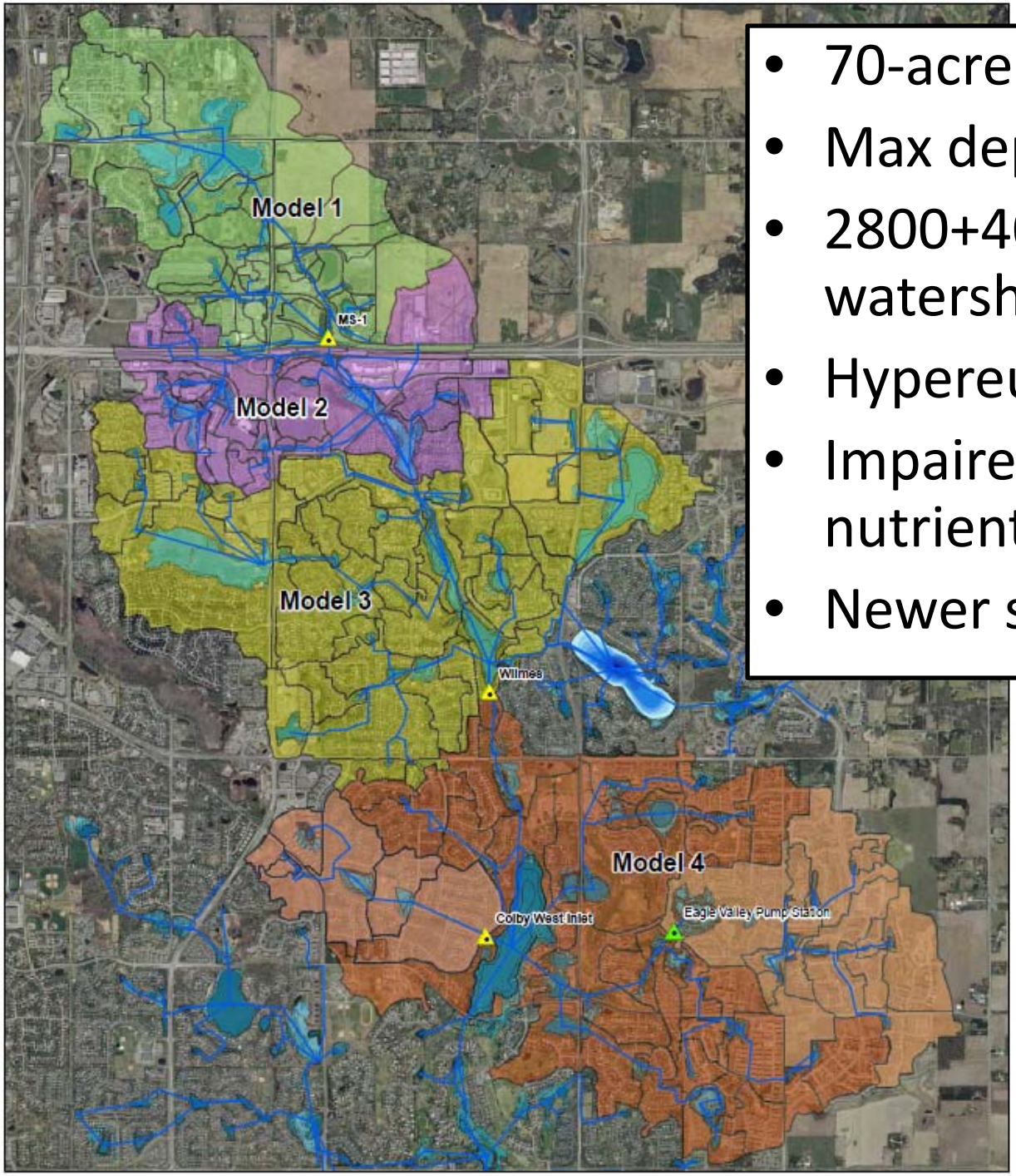
Presentation
http://www.houstoneng.com/archives/4311

Survey
http://www.surveymonkey.com/s/HHW3QNP

EXAMPLE MODELING APPLICATIONS

Example:
Colby Lake Management Plan

South Washington Watershed District



- 70-acre urban lake
- Max depth of 11 ft
- 2800+4000 acre watershed (97:1)
- Hypereutrophic
- Impaired for excess nutrients
- Newer suburban setting

Considerations / Modeling Approach

- Data availability:
  - Three years of comprehensive monitoring/flow data
  - Three watershed monitoring locations
  - Surface samples in Colby Lake
- P8 to simulate watershed loading of TSS and TP
- BATHTUB to simulate in-lake eutrophication
- Calibrated models to data from 2008/09
- Validated to 2010
- Ran 50-years of precip through P8 to create distribution of surface water runoff
- Ran Monte Carlo approach to consider in-lake response

Table 4: Volume, TSS, and TP Yields Predicted by the P8 Model for Calibration and Validation (June 1 to September 30)

STATION		YEAR	OBSERVED			P8 MODELED			DIFFERENCE MODELED VS. MEASURED			% DIFFERENCE MODELED VS. MEASURED		
			Volume (ac-ft)	TSS (lbs)	TP (lbs)	Volume (ac-ft)	TSS (lbs)	TP (lbs)	Volume (ac-ft)	TSS (lbs)	TP (lbs)	Volume (%)	TSS (%)	TP (%)
MS1 Monitoring Station		2008	73	7,816	35	65	6,700	29	-8	-1,116	-5			
		2009	57	5,698	24	104	8,013	42	46	2,315	17			
	Calibration		130	13,514	59	169	14,713	71	38	1,200	12	29%	9%	20%
	Validation	2010	359	38,311	154	255	16,993	98	-104	-21,318	-56	-29%	-56%	-36%
Wilmes Outlet Monitoring Station		2008	282	8,678	67	306	7,977	91	23	-701	24			
		2009	255	4,296	64	470	10,357	137	215	6,062	73			
	Calibration		537	12,974	131	776	18,335	228	239	5,361	97	44%	41%	74%
	Validation	2010	2,005	50,741	512	1,072	24,590	318	-933	-26,151	-194	-47%	-52%	-38%
Colby Lake West Monitoring Station		2008	37	4,012	19	21	5,046	14	-16	1,034	-4			
		2009	35	10,811	17	37	6,648	21	1	-4,163	4			
	Calibration		72	14,822	36	58	11,693	36	-14	-3,129	0	-20%	-21%	-1%
	Validation	2010	66	19,125	32	87	16,148	51	21	-2,977	19	32%	-16%	59%
Eagle Valley (Colby East 12) Pump Station		2008	21	2,286	11	58	621	16	37	-1,665	5			
		2009	95	28,866	46	83	838	22	-12	-28,028	-23			
	Calibration		116	31,153	57	141	1,459	38	26	-29,693	-18	22%	n/a*	n/a
	Validation	2010	129	37,585	63	171	2,178	48	42	-35,407	-15	33%	n/a	n/a

* The quality of the measured TSS and TP data are unknown at the pump station, and therefore an assessment of the calibration at this location was not made

Table 6: CNET Model Calibration Results for 2008 Summer Season (June through September) Mean Concentrations

	Calibration Coefficient	Measured	Modeled	Absolute Difference	Percent Difference
Total Phosphorus	0.56	181.4 ppb	201.3 ppb	19.9 ppb	11.0 %
Chlorophyll-a	1.15	52.9 ppb	65.3 ppb	12.4 ppb	23.4 %
Secchi Disk	0.92	0.30 meters	0.38 meters	0.08 meters	26.7 %

Table 7: CNET Model Validation Results for 2010 Summer Season (June through September) Mean Concentrations

	Measured	Modeled	Absolute Difference	Percent Difference
Total Phosphorus	103.5 ppb	89.3 ppb	-14.2 ppb	-13.7 %
Chlorophyll-a	52.0 ppb	38.7 ppb	-13.3 ppb	-25.6 %
Secchi Disk	0.73 meters	0.52 meters	-0.21 meters	-28.8 %

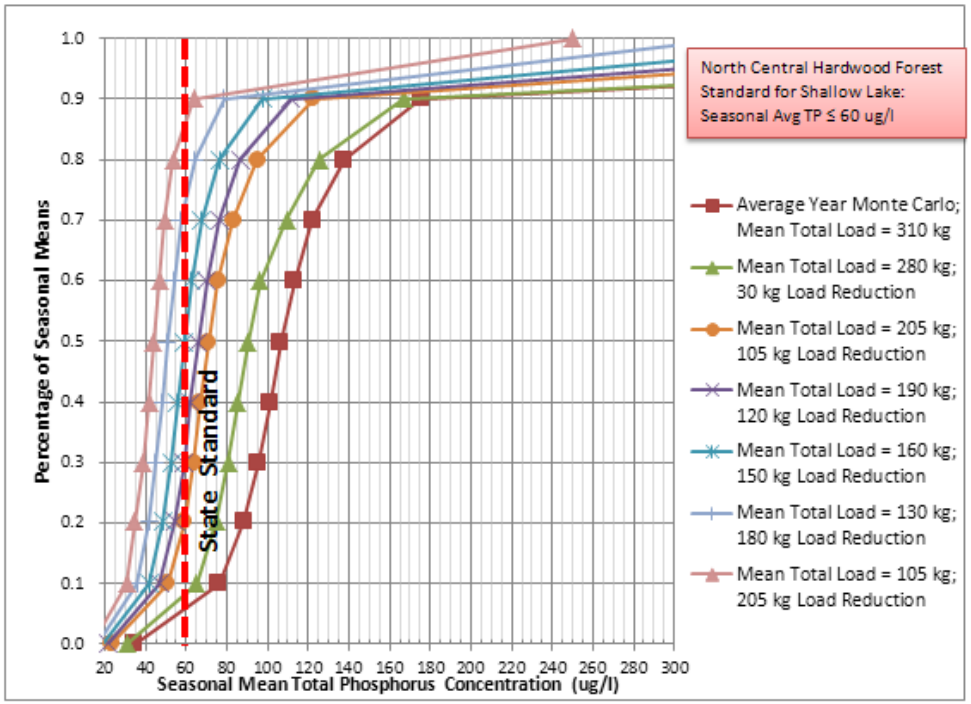
Table 5: Model Inputs used in the Monte Carlo Analysis

Model Input	Statistical Distribution	Basis for Distribution	Distribution Truncated at Extreme Values?	Correlation	
				Considered?	Input Correlated With
Precipitation	Beta	1961 – 2010 MSP National Weather Service Station	Yes (low)	Yes	Evaporation (0.38) Surface runoff (0.86) Surface load (0.45) Atmospheric Load (1.0)
Evaporation	Beta	2000 – 2010; 1961 – 2009 computed from precipitation data	Yes (low)	Yes	Precipitation (0.38)
Atmospheric Load	Beta	Distribution Assumed Same as Precipitation	No	No	Precipitation (1)
Surface Water Runoff Volume	Lognormal	1961 – 2010 calibrated P8 model	Yes (low)	Yes	Precipitation (0.86) Surface Load (0.80)
Surface Runoff Load	Lognormal	1961 – 2010 calibrated P8 model	Yes (low)	Yes	Precipitation (0.45) Surface Runoff Volume (0.80)

Notes:

Distributions generally were best fit for the 50-year period (1961-2010) of seasonal values.
Correlation coefficients were derived from actual data.
Atmospheric TP load distribution assumed to be the same as precipitation with equal coefficient of variation.
Value in parentheses is correlation coefficient.
See **Appendix B** for the statistical distribution parameters.
Statistical distributions were the "best fit" distribution, as determined by the Crystal Ball software.

Figure 10: Colby Lake Frequency Distribution of Seasonal (June through September) Mean TP Concentrations Resulting from Select Load Reduction Scenarios and Table of Data used to Produce the Graphical Illustration; Current Conditions = 310 kg/season



Non-exceedance Percentile	Average Year (current)	Load Reduction from Current Load for Average Summer Season					
		30 kg	105 kg	120 kg	150 kg	180 kg	205 kg
Mean	119.5	106.3	81.5	74.7	66.1	55.6	46.6
0%	35.0	30.7	23.3	21.3	18.9	15.9	13.4
10%	75.9	65.0	50.6	46.5	41.7	35.5	30.4
20%	88.3	74.4	59.0	54.3	48.6	41.5	35.2
30%	95.5	80.6	63.8	59.0	52.5	45.2	38.6
40%	101.3	85.2	67.0	62.2	56.0	48.1	41.4
50%	106.3	90.5	71.0	65.7	59.0	51.1	44.1
60%	113.1	96.6	75.4	70.1	62.8	54.0	46.6
70%	122.2	109.0	83.1	76.3	67.4	57.2	49.5
80%	137.7	125.3	95.1	86.7	76.3	64.0	53.4
90%	174.8	166.9	122.8	111.6	97.0	78.9	63.3
100%	756.3	753.9	545.6	488.4	415.7	326.4	250.1

Figure 9: Colby Lake Seasonal Mean (June through September) TP Concentrations under Select Load Reduction Scenarios; Current Conditions = 310 kg/season

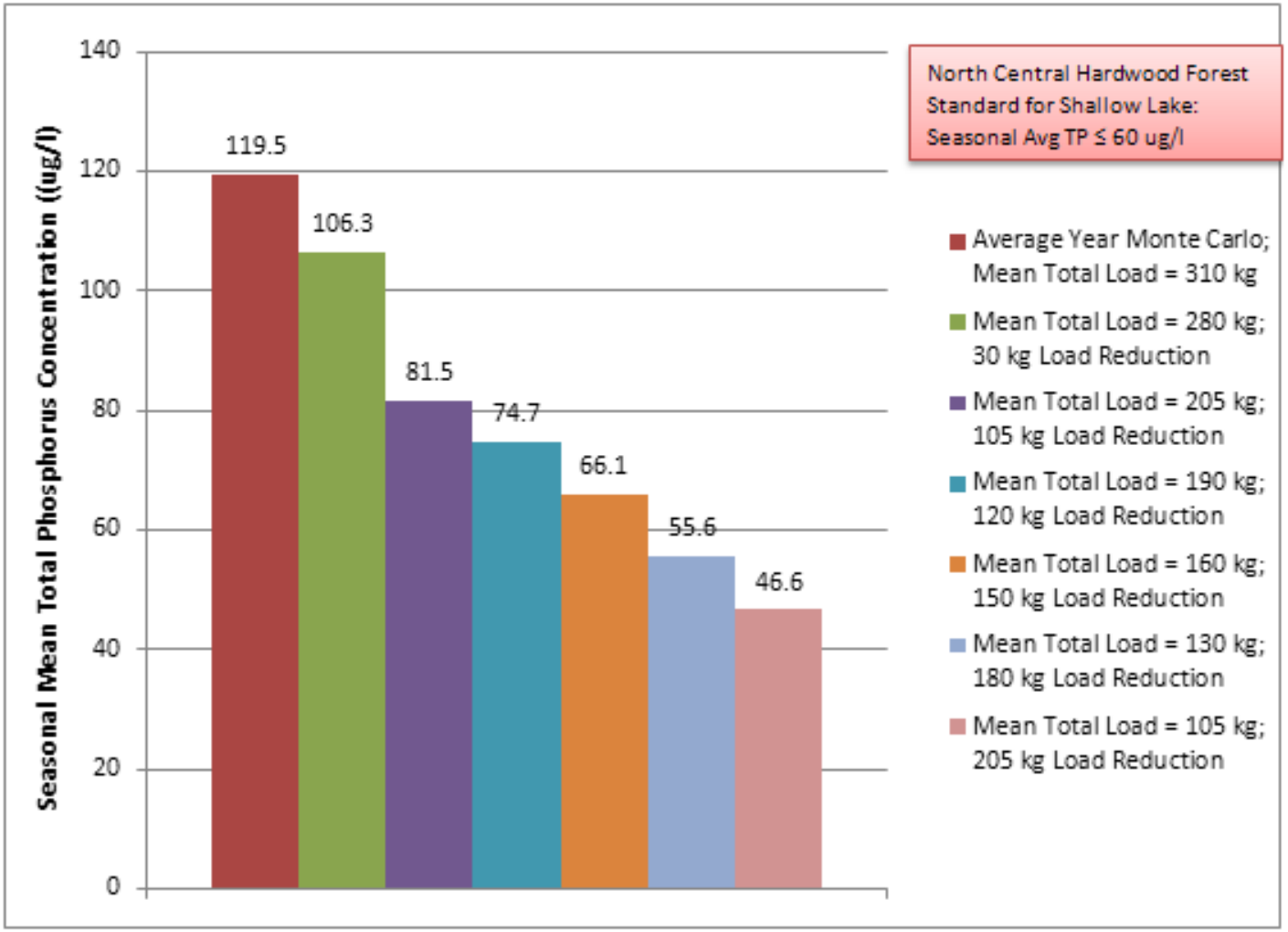


Figure 12: Colby Lake Frequency Distribution of Seasonal Mean Chl-*a* Concentrations under Select Load Reduction Scenarios; Current Conditions = 310 kg/season

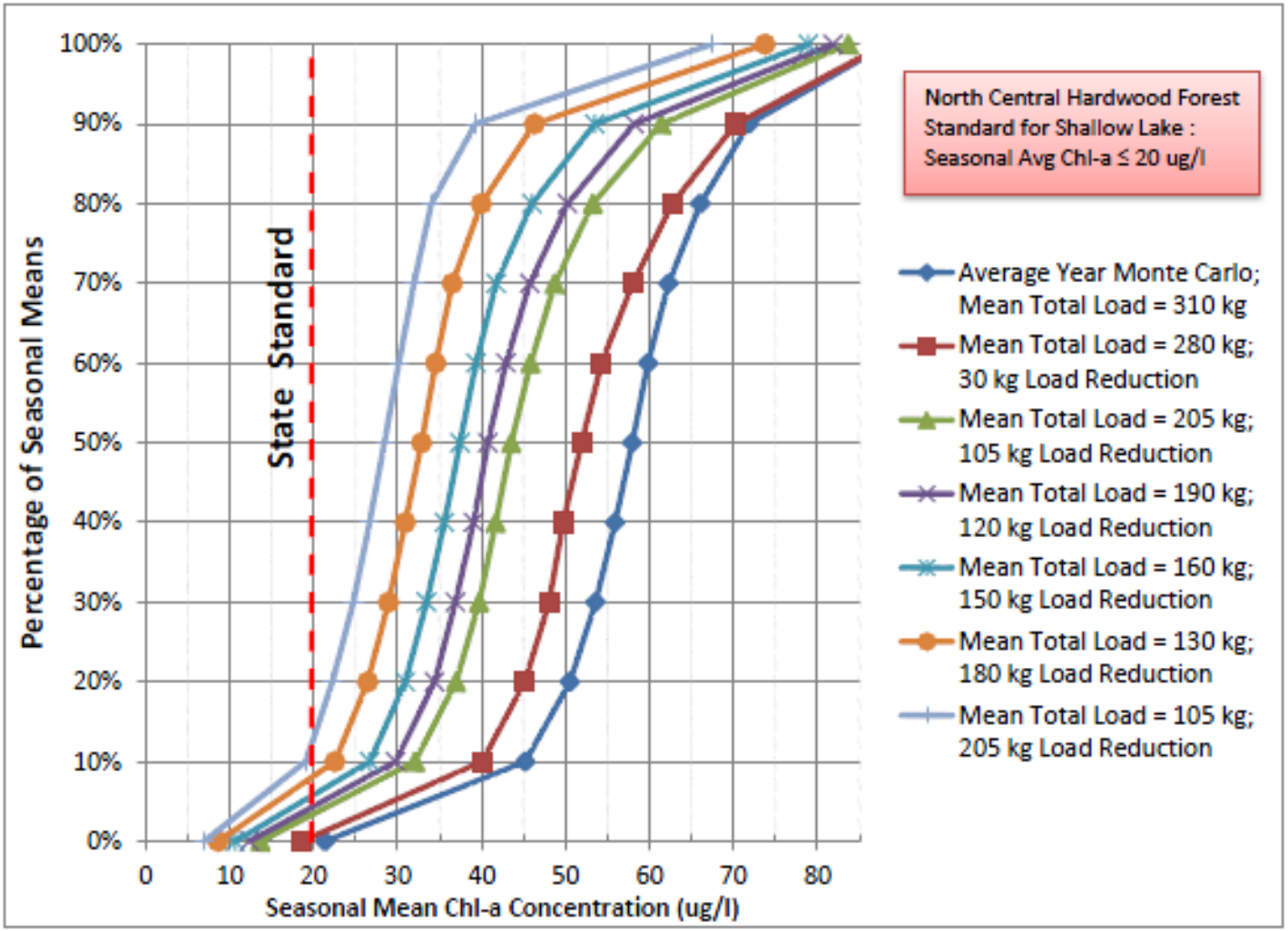
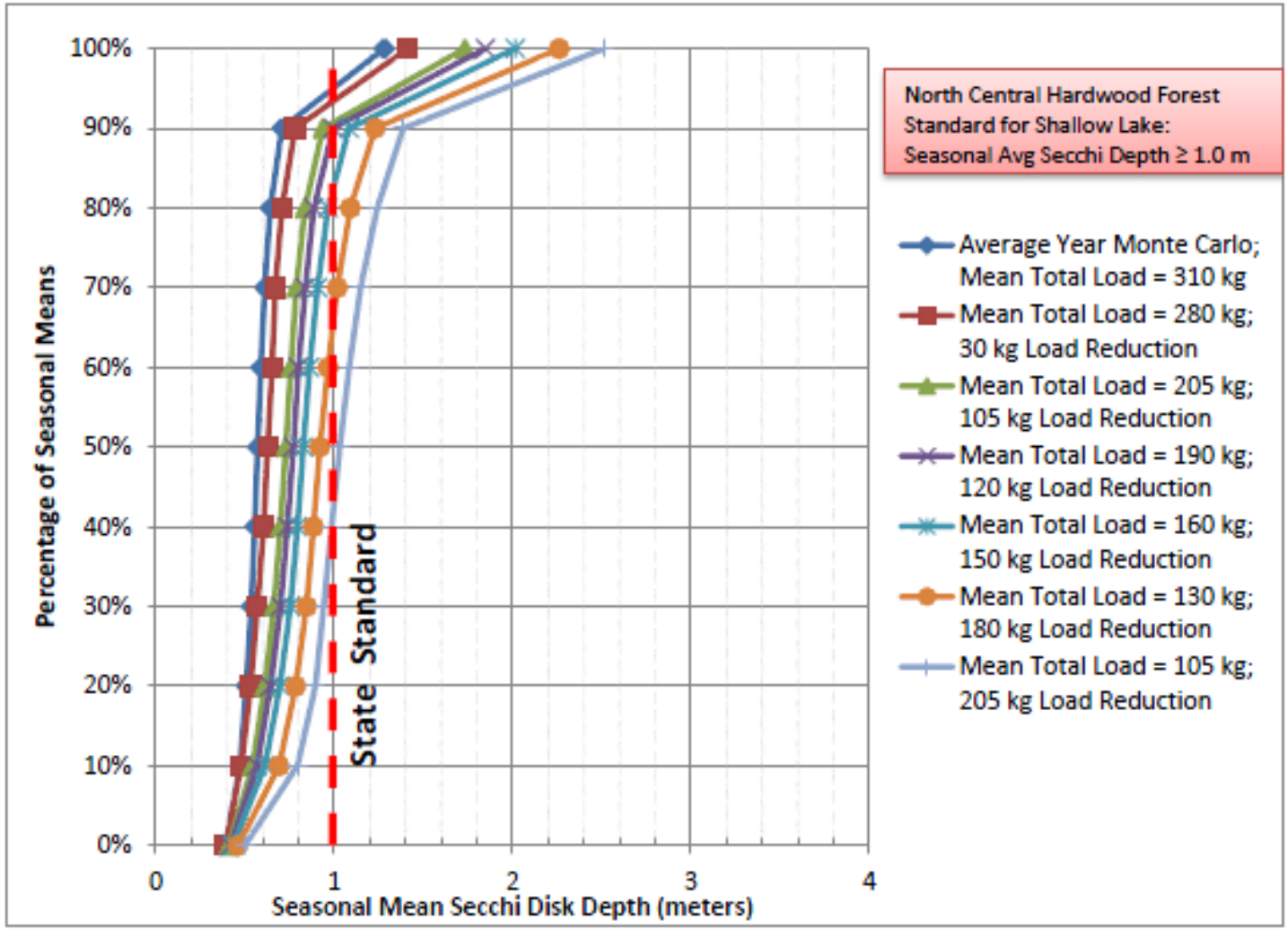
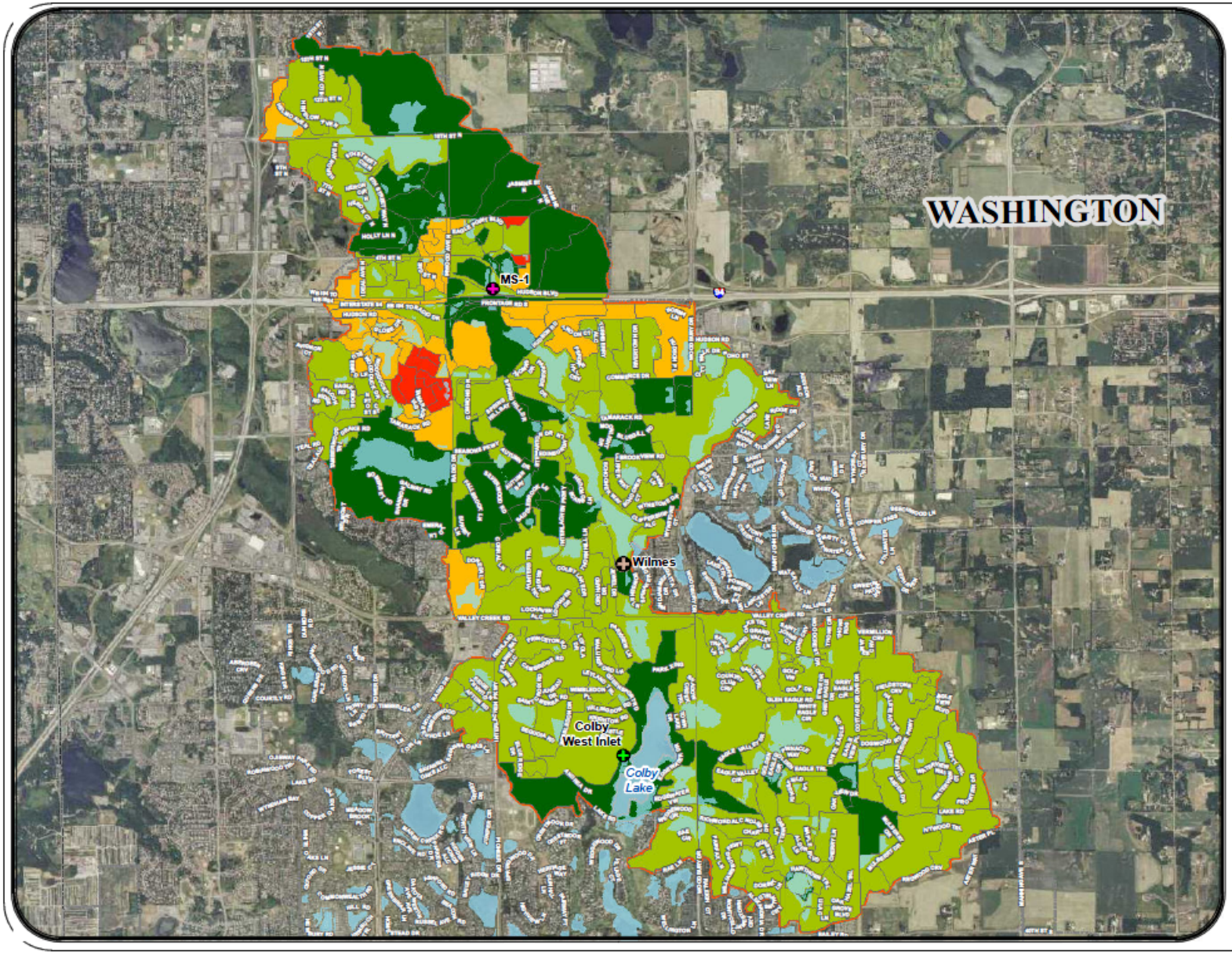


Figure 14: Colby Lake Frequency Distribution of Seasonal Mean Secchi Disk Depth under Select Load Reduction Scenarios; Current Conditions = 310 kg/season



Colby Lake P8 Watershed Model: Existing Conditions TP Yield



2010 Monitoring Sites

- Colby West Inlet
- MS-1
- Wilmes
- Retention Ponds/Storage Nodes

TP Yield (lbs/acre/yr)

- 0.18 - 0.35
- 0.35 - 0.55
- 0.55 - 0.75
- 0.75 - 0.95
- Colby Lake Watershed

0 1,750 3,500 7,000 Feet

Houston Engineering Inc.
Maple Grove

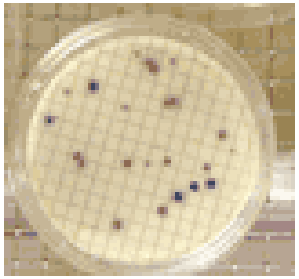
SUPPORTING SLIDES

What is a "Load"?

$$L = Q * C$$

Load (#/year)	Amount (volume/year)	Concentration (#/volume)

Concentration of bacteria: **CFU/100 m³**



Amount of water: **m³/day**

Bacterial load: **CFU/year**

Watershed Loading Model	Spatial Scale	Temporal Scale	Pollutants Addressed
P8	Subbasin	Daily	TSS, TP, TKN, Total Cu, Total Pb, Total Zn, Hydrocarbons
SWAT	HRU / Subbasin	Daily	Sediment, Nitrogen (NH_3, NO_2/NO_3, Org N), Phosphorus (Org P, Mineral P), algae, CBOD,D.O., bacteria, pesticides
HSPF	PERLNDs and IMPLNDs / Subbasin	15-minutes	Temperature, sediment (sand, silt, clay), D.O., BOD, Nitrogen (NH_3, NO_2/NO_3, Org N), Phosphorus (PO_4, Org P), Plankton (phytoplankton, algae as chl-a), bacteria, organics/pesticides, metals

Example: In-stream Processes of SWAT

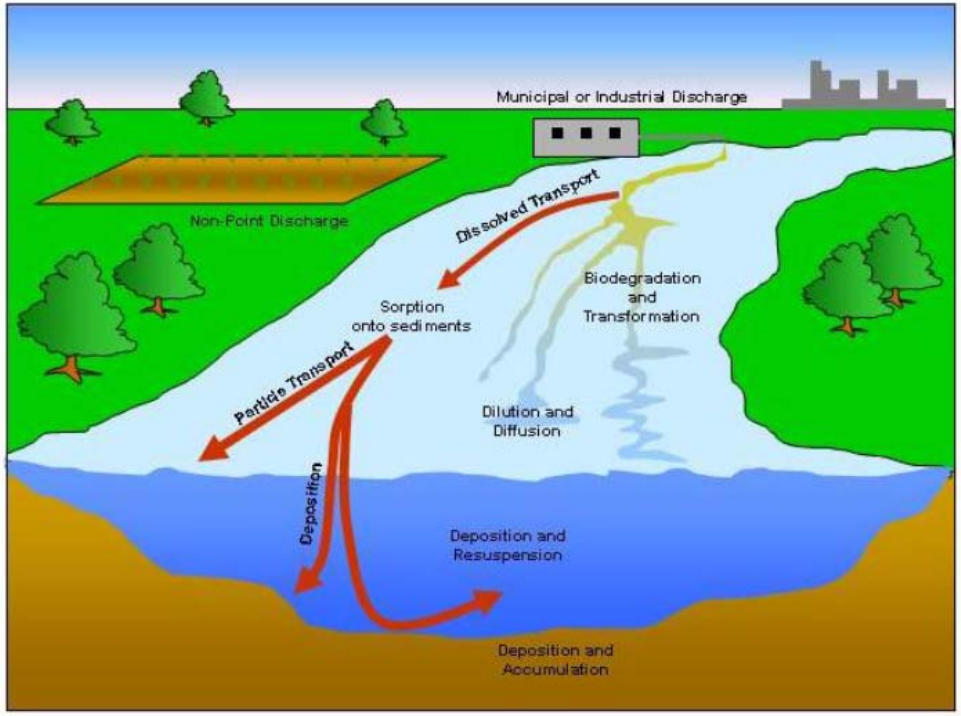
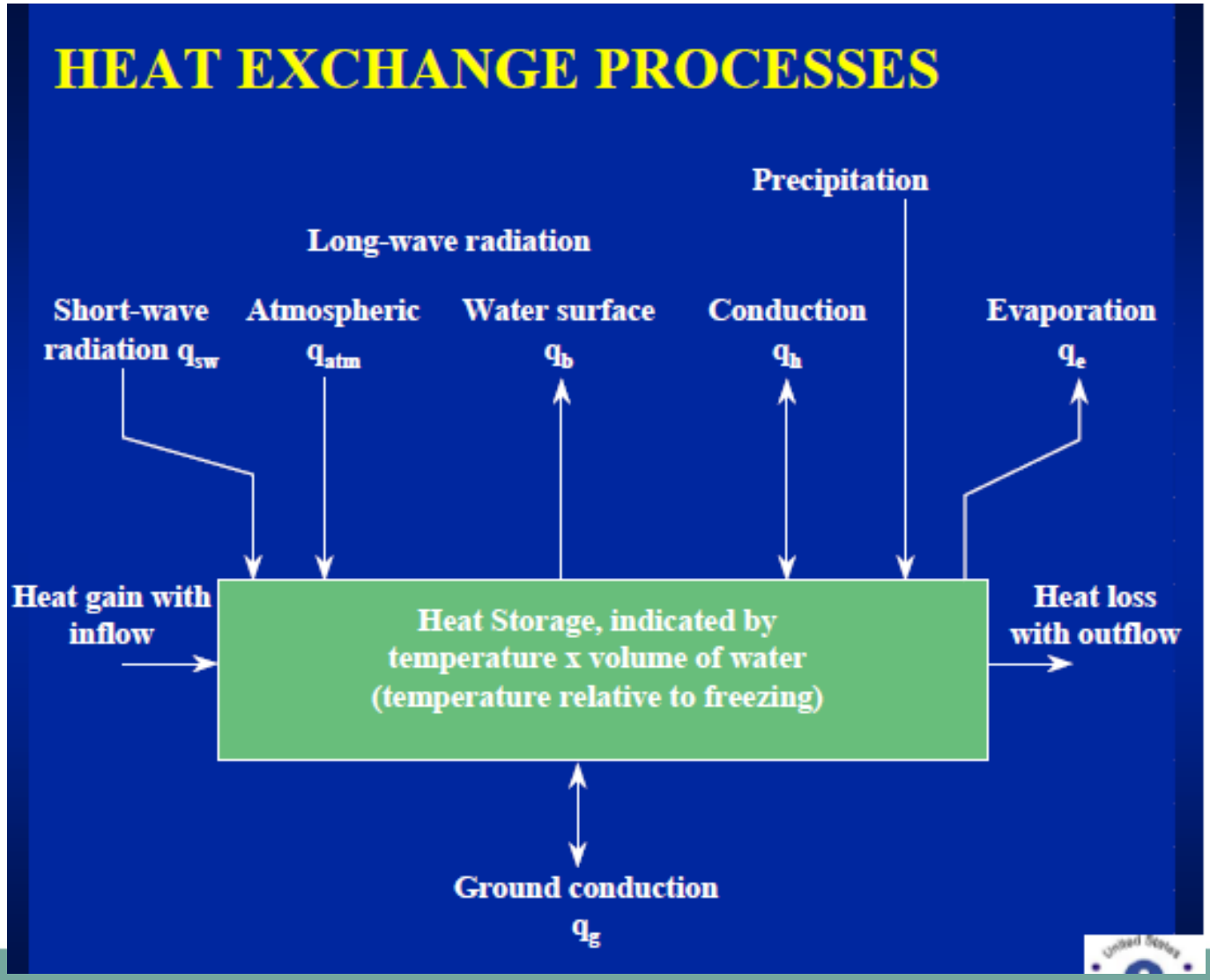


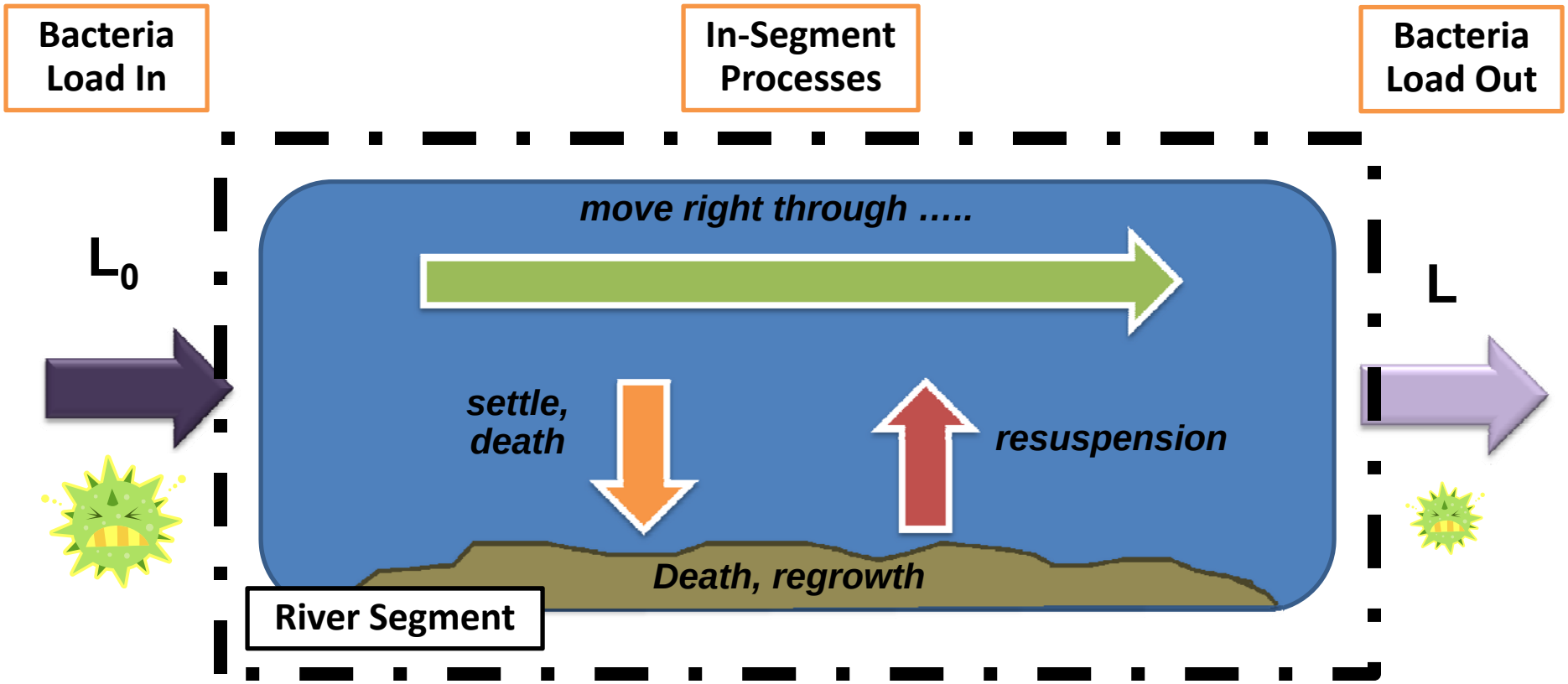
Figure 0.9: In-stream processes modeled by SWAT

Uses QUAL2E for in-stream water quality processes related to eutrophication and D.O.; addresses pesticide transformations; considers bacterial decay; includes some physical processes (limited ability to simulate in-channel erosion)

Example: Stream Temperature in HSPF



Example: “Net” Decay in TMDLBalance



In-segment processes as a “black box” approach,
where “net” decay = f(settling, death, regrowth, resuspension, etc.) = k

$$L = L_o * e^{-kT}$$